WOOD HEAT FOR COOKING

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CONTENTS

Foreword 1

HOWARD W EMMONS and ARVIND ATREYA: The science of wood combustion 5

C A ZAROR and D L PYLE: The pyrolysis of biomass: A general review 15

P VERHAART: On designing woodstoves 33

M SIDDHARTHA BHATT: The efficiencies of firewood devices (Open-fire stoves, chulahs and heaters) 73

J CLAUS and W F SULILATU: A comparison of the performance of three woodstoves 89

P D DUNN, P SAMOOTSAKORN and N JOYCE: The performance of Thai charcoal stove 107

HOWARD S GELLER: Fuel efficiency and performance of traditional and innovative cookstoves 119

C L GUPTA, USHA K RAO and U PREMA: Improved chimneyless fuelwood cookstoves (Pondicherry region) 141

P J T BUSSMANN, P VISSE and K KRISHNA PRASAD: Open fires: Experiments and theory 155

G De LEPELEIRE and M CHRISTIAENS: Heat transfer and cooking wood-stove modelling 189

C R CHAPLIN: Wood burning stoves: Material selection and thermal shock testing of fired ceramic bodies 201

A VAN GELDER, R HOSIER and W VAN DER DONK: Fuelwood production in developing countries: Toward an appropriate forest technology 213

JAS GILL: Fuelwood and stoves: Lessons from Zimbabwe 233

Author Index ................................................................. 249

Subject Index ............................................................... 253
WOOD HEAT FOR COOKING

Foreword

Over three years have gone by since the editorial board of Proceedings of the Indian Academy of Sciences (Engineering Sciences) took the innovative step of devoting two issues (Vol. 2) to the theme of Rural Technology.* The papers in these issues demonstrated in practice that the technologies relevant to the rural poor of the world pose interesting and challenging problems to the engineering scientist—a fact that has been intuitively felt for many years now. The journal now returns to the same theme but with a single item of hardware, at least in a generic sense—the woodstove.

It might be worthwhile to present the background against which this volume should be viewed. Roughly stated a little more than half the world’s population in 1980 ate food cooked on stoves fired for the most part by wood and, to a lesser extent, by agricultural/animal waste. Two features have emerged during the last ten years with respect to the supply and demand of energy for this population. World wood resources are depleting at a rapid rate. The Food and Agriculture Organization (FAO) estimated for the United Nations Conference on New and Renewable Sources of Energy held in Nairobi in 1981 that nearly one billion people are living in regions with either acute scarcity or deficit wood supply situation. This has resulted in enormous increases either by way of monetary outlays on fuel for the urban poor or by way of labour on the part of energy gatherers in the rural areas. FAO projected using “business as usual” assumptions that this population could grow to nearly 3 billion in 2000 AD. Thus the condition of the poor can be expected to grow much worse without active interventions from different directions.

The second feature is the energy consumed for the fundamental act of cooking both in relative and absolute terms in developing countries. Cooking energy accounts for over 2/3 of all the energy used in rural communities. And the annual per capita, energy consumption for cooking is estimated to be 10 GJ in these communities. The corresponding figure for Western Europe is about 2.5 GJ. Incidentally the latter includes energy consumption for refrigeration and a host of other appliances. Much of this difference is attributed to the inefficient use of fuel. From all accounts, introduction of woodstoves with superior performance is expected to make a significant contribution to the easing of the energy supply situation for the rural population in the developing countries.

Thus devoting a volume to the woodstove should be understood as recognition of the magnitude of the problem rather than as a decision signalling a change in the avowed policy of the journal to publish articles with a broad range of technical interest.

*The papers in these issues are collected now in a book, ‘Rural Technology’ edited by Amulya Kumar N. Reddy and can be ordered from the Academy.
The woodstove has some peculiarly unique features compared to many other technological products that are under active consideration for rural populations in the developing countries. Smulders (1982)* provided the following interesting comparison between a woodstove and a windmill. The physics of a woodstove is quite complex, combining as it does heat and mass transfer with chemical reactions, buoyancy effects, radiation, etc. The resulting product is relatively simple to make and costs very little. It is required in every home, has to be operated by a non-technical person and has, by and large, no commercial output. On the contrary, a windmill’s physics is in principle easier to grasp. Basically it can be understood using incompressible fluid flow theory, and temperature comes in only to determine the air density. However, a windmill is a comparatively complicated machine: it rotates; it experiences severe dynamic loads with the inherent wear and tear of components; and it is exposed to the vagaries of the weather. It requires a workshop or a factory with some level of sophistication to manufacture. Its cost (even in small sizes is at least two orders of magnitude higher than that of a woodstove. Finally, a windmill is operated by a professional—be it a farmer for increasing agricultural productivity by irrigation or an operator for supplying drinking water to a community.

Another feature of the woodstove for domestic cooking is its small size. This is its strength as well as its weakness—strength because testing can be carried out with relative ease and at a small cost on full scale prototypes, and weakness because modelling—the forte of engineering science—is presumed unnecessary for design and development of small devices. It is the editors’ contention that modelling is precisely what is required if one is to contemplate the availability, in a period of twenty years, of stoves with superior performance to a billion people or so living in diverse places with varying local resource situations.

These are some of the specific features that have prompted the editors in their selection of papers for inclusion in this volume. The papers can be grouped under four broad categories: (a) fundamentals; (b) a diversity of stoves and their performance characteristics; (c) modelling efforts; and (d) miscellaneous topics.

Emmons and Atreya provide a crisp account of the science of wood combustion as it is understood now. Some of the difficulties of applying these principles to practical stove designs are outlined in the paper. Zaror and Pyle review the pyrolysis of biomass with special emphasis on charcoal production. They cover a lot of ground ranging from the fundamentals of physical and chemical processes to a critical discussion of rigorous design procedures. Verhaart’s is the last paper in this group and is concerned with the designing of stoves. The paper attempts to draw up specifications for the design of an ideal woodstove and sketches several design ideas especially from the point of view of controlling the power level of the fire.

The next set of papers concern themselves with the performance of stoves in actual current use or stoves that are actively being promoted or expected to be promoted. Bhatt analyses various possible definitions of efficiencies of a stove and backs this up with supporting data for different stove types. Claus and Sulilatu study in detail the performance of a metal stove, a brick stove and a mud stove from different countries of the world. Dunn et al present the performance of the Thai charcoal stove. Geller discusses some measurements he carried out in the Ungra area in

users' homes on traditional stoves and compares these results with those obtained from the so-called Hyderabad cookstove. Gupta et al present a few results from field tests. The emphasis has been on the capability of local manufacturers to execute certain designs as well as user acceptability.

The third set opens with an elaborate study of the open fire by Bussmann et al. The study provides insights into the performance capabilities of an open fire under diverse conditions and suggests some computational procedures for evaluating efficiencies of an open fire. The paper by De Lepeleire and Christiaens using principles of heat transfer indicates several possible procedures for improving the performance of existing stove designs.

The final set of papers represents a miscellany associated with the woodstove trade. Chaplin lists the factors affecting the choice of materials and proposes a test method for evaluating the thermal shock resistance of ceramics for stove applications. Hosier et al provide a lucid description of the forestry problems in developing countries with a prescription for desirable tools for harvesting and cutting wood. In addition an economic analysis is carried out demonstrating the advantages of fast rotation forest crops. In the final paper, Gill graphically describes the users' strategies to cope with the fuelwood problem and their perception of the role of stoves in their lives, as he found them in Zimbabwe.

It is not the intention of editors to claim exhaustiveness in coverage of the work that is actually going on in the area of woodstoves. Far more work is being carried out, particularly at the field level. We believe, however, that this volume provides a representative cross-section of the technical thinking on the stove problem to date.

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Special Editors
The science of wood combustion

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Abstract. The purpose of this paper is to provide an introduction to the physical processes involved in the combustion of wood and other cellulosic fuels. This introduction is aimed towards the utilization of the cellulosic fuels as an energy source. A discussion of a design of the stove is also provided to aid the development of such a device.

Keywords. Pyrolysis; flames; charburning; heat; stove.

1. Introduction

Fire from natural causes has been known to man and animals from the beginnings of life on earth. A momentous event occurred when man discovered that fire could be controlled and used in many ways. The easy availability of wood and other cellulosic materials has provided an abundance of natural, renewable energy resource.

Even before fire was tamed, man no doubt knew that wood subject to fire first produced white smoke, then flamed, then glowed as a pile of embers and then cooled off as a small pile of grey ashes. Today with our extensive knowledge of the physical laws which govern the universe, our scientific knowledge of many of the details of the wood burning process has begun to be clarified but is far from complete. In this paper, we will briefly review some of what is now known about the burning properties of wood and the resultant fire.

The next major step in understanding combustion of any material is summarized in the fire triangle (figure 1). This emphasizes in a very useful way the essential components which permit a fire to continue to grow or by the control of which a fire can be extinguished. All three components—fuel, air and heat—are needed to start a fire, and the mixing of these three components is equally important. By removing the fuel, by smothering (removing the air), or by cooling (spray it with water), a fire may be extinguished. Useful as this picture is, it is still not fire science.

2. The science of fire

Perhaps a word would be useful at this point to make clear what we mean by a scientific understanding of fire (Emmons 1980) (or any other phenomena). A complete scientific understanding would make it possible to not only describe qualitatively what happens but to quantitatively calculate exactly what happens from beginning to end. We will not try to write the required book to present what is now quantitatively known but will rather review briefly each of the steps in a fire.
3. Pyrolysis

Wood, like all material bodies, is composed of atoms attached to one another. In wood, the atoms are attached to one another in strings thousands of units long. The cellulose molecule, as these long strings of atoms are known, is a polymer (Shafizadeh 1981; Modorsky 1975; Stamm 1964; Goos 1952). It doesn’t happen to be one which man can yet make but nature makes it with ease. Wood is made of these cellulose molecules and other molecules called lignin. These are arranged by the growing tree into a cellular form—a natural cellular plastic.

Like all materials composed mostly of atoms of carbon, hydrogen and oxygen, they are held together by interatomic forces. The temperature of a material is a measure of the violence of the atomic motions in the molecule. As the temperature of a material is raised, the atoms vibrate more and more vigorously. Eventually, the atoms vibrate so strongly that they separate, i.e., the molecule begins to come apart. The weakest linkage is between units of glucose, a group of 21 atoms. However, many other fragments are also produced and many of these fragments are very active chemically and join together again into new stable combinations. The detailed chemistry of the thousands of reactions between hundreds of chemical species is far from understood at the present time.

From a fire point of view, the carbon that is left behind as charcoal is the only solid produced by wood pyrolysis. All other materials are the gases that mix with air and burn as a flame.
The science of wood combustion

This complex chemistry occurs as the wood becomes hotter. However, as we all know, the wood in a fire soon turns black. The pyrolysis of the wood surface leaves a char layer of carbon and ash which then shields the interior virgin wood from direct heating from outside. Now the radiant heat from the fire falling on the surface of the char must conduct down through the char layer to heat and pyrolyse more virgin wood.

When wood is pyrolysed below a layer of char, the gaseous products produced have to get away somehow. Some merely diffuse through the layer of char. Since wood shrinks when it is changed to char, the char layer cracks. Some of the new pyrolysis gases flow out through the cracks in the char. This results in the hissing sound and the jet flames that one sees in an open wood fire. Some of the gases diffuse away from the surface into the virgin wood through the natural pores and there condense, to be repyrolysed later (Min 1975). Finally, those gases unable to escape remain in the pores and raise the internal gas pressure. The mechanical strength of the charring wood is soon exceeded and a small piece of glowing char is violently expelled from the fire. This process accounts for all the snapping and popping we always hear in a wood fire.

Wood begins to pyrolyse significantly at about 250°C and very actively at about 325°C.


In spite of this long list of important studies, useful results of the pyrolysis process are still almost entirely empirical.

4. The flames

The gases produced by pyrolysis consist of some 213 different compounds (Goos 1952; Modorsky 1975; Hileman et al 1976), some are very simple like carbon dioxide, carbon monoxide, and water, and some are complex organic molecules of 20 atoms or more. As these gases issue from the wood, they are hot, they have lower density than the surrounding air, and therefore these gases rise. As they rise, they mix with air and either cool off and partially condense into smoke or, if ignited, burn as a flame.

The flames from wood are almost wholly yellow in the optical wavelengths but also produce a lot of ‘heat radiation’ in the infrared (De Ris 1978; Modak 1977). The flames directly spread the fire upward by convective heating of pyrolysable fuels above them and heat the walls of the stove which warms the room. Far more important, however, is the radiant heating. In particular, the size and intensity of the flames themselves are controlled by the pyrolysis of the original fuel by the heat supplied from its own flames. Fire is an energy feedback process in which energy
from the flames heats and pyrolyses the fuel, that supplies the gases, that mix with
the air and burn, thus radiating energy which heats and pyrolyses the fuel, etc., etc.
The radiated energy also heats other as yet unignited fuel to spread the fire and heats
the walls of a stove or furnace, thus supplying the heat to cook our food and heat
our dwellings.

The reaction of fuel with oxygen of the air occurs in two places; one is on the
surface of the glowing charcoal and the other is in the flames. The exact chemical
processes taking place in the flames is so complex that it has not yet been clarified
except for a few (unimportant) cases. Even the burning of hydrogen in oxygen to
produce water is kinetically too complex to be fully clarified as yet.

What is understood is that the initial reactions in the lower part of the flames pro-
duce a great deal of carbon monoxide and free carbon. The carbon agglomerates
into small soot particles that are responsible for much of the energy radiated. The
carbon monoxide and soot then reacts in the upper part of the flame that cools by
the energy radiated. If the radiation is too high, the soot does not burn up but
leaves the flames as the black micrometer size particles which joins any smoke present
and moves away from the fire. All kinds of wood produce enough soot to produce
yellow flames, but few woods fail to burn all the soot before it gets out of the flames,
provided there is excess oxygen available. The production of soot in flames is an
active research area at the present time (Glassman & Yaccarino 1981; Lee & Tien
1981). This is important and will be noted again later in connection with the design
and operation of stoves.

5. The smoke

The large molecules in the pyrolysis gases which mix with air but are not ignited
condense into tiny micrometer-size droplets. The mixture of these and the un-
condensed gases has the familiar smell and appearance of wood smoke. This has
many effects. As the smoke moves up the chimney, it deposits on the walls and can
later cause a serious chimney fire. As it accumulates in the stove, the ignition may
be delayed until the smoke is thick enough to be flammable, after which it may burn
rapidly in a small explosion. If the smoke gets into the house, perhaps from an
unwanted fire, it will make it difficult to see and breathe. In fact, many of the organic
compounds in smoke are highly toxic, so that most people who die in fires are killed
by the toxic gas, not by the heat of the fire. Finally, some of the compounds in wood
smoke are known carcinogens. Thus, long term cancerous effects of breathing
smoke are possible, although to our knowledge has not yet been proven.

6. The air

The discussion above assumes that the pyrolysis gases find air with which to mix
and burn. Air is 21% oxygen and 79% atmospheric nitrogen (includes 1% argon
and small amounts of other gases). As the gas in a flame rises above its source, the
turbulent eddies mix it with the surrounding gases. Then, above the flames, the
products of combustion, the atmospheric nitrogen, and unused oxygen move away
from the fire.
This brings us to the question as to where the air comes from and where the flue gases go. In the open, the camp fire, the flames draw the air in from around the base and the hot product gases buoyantly rise away at the top. In a stove, however, provision must be made to admit the air in the place and the amount required. In an industrial furnace, the air and fuel flow are driven by a fan and a pump respectively. In a household wood burning stove, the fuel—wood—is put in every time someone thinks to check on the fire. The air is generally drawn in and the flue gases are removed by a chimney. The chimney takes the place of the industrial fan. The fact that the products of combustion are hot causes them to be lighter than air and hence they rise up through the vertical chimney and draw new air in at the bottom. The performance of a chimney depends upon the outside temperature, wind and surrounding structures, if any.

The air flow through a stove thus depends upon the performance of the chimney. However, it also depends upon the tightness of the house. If a house were built with no leaks around the windows and doors, the chimney would be unable to draw air through the stove, since there is no air supply below. It would merely reduce the pressure in the house. The fire would soon go out for want of oxygen. Almost no houses are really tight.

There is no reason to expect that the performance of the chimney and the leaks of the house give exactly the right air flow for a stove. Thus, further discussion of air flow control for a stove will be appropriate later.

7. The char

When discussing pyrolysis, we noted that the thermal decomposition of wood produced gases and char. The char amount varies with the kind of wood from 20 to 30% of the weight of the wood (Broido & Nelson 1975). Char, or charcoal, is largely carbon but contains small amounts of hydrogen and oxygen together with all the ash of the wood (Shafizadeh 1981). Carbon does not melt at ordinary pressures and changes to a gas (sublimes) at a very high temperature, 4000°C. Thus, the char, when it burns, reacts with oxygen on its surface. Since it is usually cracked and is always porous, the reacting ‘surfaces’ are largely inside.

Glowing char radiates a lot of energy. Unless there is a lot of oxygen present, it will soon radiate its energy away, will cool off and go out. As we all know, blowing at glowing charcoal (Evans 1975) makes it burn brighter and the fire spreads to adjacent areas. What we are doing is supplying more oxygen and the carbon responds by reacting faster. We also all know that if we had blown at the same rate at a match, the fire would be blown out. The flame gases can be blown away while the hot charcoal surface cannot move but instead reacts faster with the additional oxygen supplied. The burning of the charcoal is very important since about 30 to 60% of the heat of combustion of the wood is available from burning the char.

We spoke of burning the char in oxygen. In fact, the carbon being in great excess on the char surface produces mostly carbon monoxide, which, when it mixes with air and burns, produces the little bluish flames seen over the surface of a charcoal fire. Thus in fact a significant amount of char surface burning is carbon reacting with carbon dioxide to produce carbon monoxide which, being a gas, burns in a flame above the surface.
8. The heat

Wood primarily contains lignocellulosic materials, along with various extractives (≈ 7% dry basis), minerals and moisture. These components vary for different parts and species of the plant, for example, soft wood and bark contain more lignin than hard woods. The presence of lower molecular wt extractives (turpentine components) in natural fuels helps flaming combustion, since they readily evaporate. Both lignin (heat of combustion about 27,000 kJ/kg) and extractives (heat of combustion about 35,000 kJ/kg) have a higher heat of combustion than cellulose (about 17,000 kJ/kg) because of their lower degree of oxidation. For most fuels, chars, and volatiles, the heat of combustion correlates roughly with its carbon content as

$$\Delta H^{25^\circ C} = [394\cdot1 (\% C) + 230\cdot2] \text{ kJ/kg.}$$

This correlation is due to mutual cancellation of increase in heat content because of the presence of a greater number of hydrogen atoms in some fuels, and decrease because of the presence of oxygen in others. There are, of course, some extreme cases like CO₂. The heat of combustion of various natural fuels is given in table 1 (Shafizadeh 1981). The last column shows the heat of combustion of volatiles that are released. These burn in a flame with only about 70% combustion efficiency in free-burning fires. Combustion efficiency can be increased by increase in turbulent

<table>
<thead>
<tr>
<th>Fuel</th>
<th>Source</th>
<th>Type</th>
<th>$\Delta H_{\text{comb}}$ (kJ/kg)</th>
<th>Yield %</th>
<th>$\Delta H_{\text{comb}}$ (kJ/kg)</th>
<th>Yield %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cellulose</td>
<td>Filter paper</td>
<td>-17334</td>
<td>14-9</td>
<td>-29506</td>
<td>85-1</td>
<td>-15205</td>
</tr>
<tr>
<td>Douglas fir lignin</td>
<td>Klason</td>
<td>-26656</td>
<td>59-0</td>
<td>-31029</td>
<td>41-0</td>
<td>-20364</td>
</tr>
<tr>
<td>Popular wood</td>
<td><em>Populus</em> ssp. Excelsior</td>
<td>-19322</td>
<td>21-7</td>
<td>-29807</td>
<td>78-3</td>
<td>-16414</td>
</tr>
<tr>
<td>Larch wood</td>
<td><em>Larix occidentalis</em> Heart wood</td>
<td>-19456</td>
<td>26-7</td>
<td>-29995</td>
<td>73-3</td>
<td>-15615</td>
</tr>
<tr>
<td>Decomposed douglas fir</td>
<td><em>Pseudotsuga menzeisii</em> Punky wood</td>
<td>-21422</td>
<td>41-8</td>
<td>-29472</td>
<td>58-2</td>
<td>-15640</td>
</tr>
<tr>
<td>Ponderosa pine</td>
<td><em>Pinus ponderosa</em> Needles</td>
<td>-21527</td>
<td>37-0</td>
<td>-27564</td>
<td>63-0</td>
<td>-17983</td>
</tr>
<tr>
<td>Aspen</td>
<td><em>Populus tremuloides</em> Foliage</td>
<td>-21062</td>
<td>37-8</td>
<td>-26543</td>
<td>62-2</td>
<td>-17732</td>
</tr>
<tr>
<td>Douglas fir bark</td>
<td><em>Pseudotsuga menzeisii</em> Outer (dead)</td>
<td>-21430</td>
<td>52-8</td>
<td>-24259</td>
<td>47-2</td>
<td>-18267</td>
</tr>
<tr>
<td>Douglas fir bark</td>
<td><em>Pseudotsuga menzeisii</em> Whole</td>
<td>-23882</td>
<td>47-1</td>
<td>-26803</td>
<td>52-9</td>
<td>-21284</td>
</tr>
</tbody>
</table>

*Heating rate 200°/min to 400°C and held for 10 min.*
mixing and by providing some excess air. When the air supply falls below that stoichiometrically required, then the combustion is said to be ventilation-controlled. Numerous data (Harmathy 1972; Gross & Robertson 1965) on burning of wood piles in enclosures have shown that the rate of mass loss of the fuel is directly proportional to the supply of oxygen. In such a case, the heat release rate can be calculated by oxygen consumption. Krause (1979) have shown that within ± 5%, heat released is 420 kJ/kg mole of O\(_2\) for combustion reactions at 25°C to form various products.

9. The ash

A few percent of the weight of wood are various mineral substances that do not burn and are left over after all combustibles are removed. For the campfire, the ash is no problem; it is simply left behind to help fertilize the new growth. However, in a stove, the ash accumulates and after a few hundred pounds of wood are consumed, the stove has begun to fill up with the fluffy grey ash. Thus steps have to be taken to remove the ash. Wood ashes contain potassium carbonate which is an important fertilizer element and is good for the garden.

10. The stove

We have now touched briefly on all the aspects of the burning of wood. The details of the processes are understood more deeply than described above but the essential features have been introduced. The importance of these features is that they will all occur when wood is burned, whether we like it or not. Since they will all occur, we should design the stove so that they occur efficiently.

What do we mean, “efficiently”? The purpose of a stove is to provide heat at its top surface for the preparation of food and to provide heat for the warming of our dwellings in winter. A 100% efficient system would use all of the heat of combustion of wood, and put it to a useful purpose in the house. This is not possible since heat is the motive power which produces the chimney draft. Furthermore, the air used by the fire must be heated up to the flue gas temperature using some of the fire’s energy. Since dwelling comfort is one purpose of a stove, there are two ways to supply combustion air to the stove. The usual way is to take the air from the living space. This requires new cold outside air to come into the living space, thus producing uncomfortable drafts. This is poor design. A much better design, but one almost never used, is to have a connection to the stove directly from out of doors. Such an air supply would avoid drafts in the house but would be expensive and generally inconvenient.

The internal stove problems of “efficiency” are far more important and more difficult. In the first place, let us note that the energy feedback from the flames to the fuel is not an energy loss since it is returned in full measure when the fuel burns.

The real problem arises when we wish to regulate the rate of burning to fit our needs. We of course can build a large stove or a small one. The right size is not just one which can burn wood at the required maximum rate and no faster, but one which can hold a sufficient charge of wood so that it does not need recharging every few minutes.
But here is the first major difficulty. Suppose a charge of wood able to supply the required heat for overnight can be accommodated in the stove. What is to prevent the fire from growing very rapidly throughout the wood supply and consuming it in the first few hours? We cannot control the internal energy transfers between sticks and thus control the fire growth. The only practical control is the air supply. Thus dampers (valves in the air supply system) are used to adjust the air flow.

This controls the rate of fire growth all right. However, it does so by preventing the rapid burning of charcoal and by controlling the heat release in the flames. This reduces the energy feedback to the fuel, thus reducing its pyrolysis, which is what we wanted. However, the control of the heat release in the flames was accomplished by supplying insufficient air to efficiently burn all the fuel.

In most stoves, the air is admitted in the front near the bottom. Thus what flames there are still cause considerable wood pyrolysis, the flame combustion that is controlled is the burning of the pyrolysis gases are the top and back of the wood supply. These gases, mostly as smoke, go up the chimney unburned, a very inefficient process.

A few stove designs attempt to correct this loss without too rapid a fire build-up by admitting more air at the rear. The idea is good and it would no doubt work if there was an observation window at the back and someone continually regulated the extra air. For efficiency, the extra air should just burn all the smoke but nothing more. Any leftover air is a loss since it takes energy to heat it, only to lose it up the chimney. But even this would not be enough. Since the air at the front has been cut down to prevent rapid fire growth, the smoke and gases at the rear of the wood supply are no longer hot enough to burn even if more air is added.

In fact, for fire control, the smoke and gases must be below the pyrolysis temperature or the wood would still be pyrolyzing too fast. Thus, to burn the exhaust gases with more air also requires a pilot flame to guarantee that they ignite. No stove to our knowledge has provided any rear ignition source.

How can this problem be solved? There are only two possible ways; either limit the wood as well as the air, or install a rear air supply and an ignition source. Neither of these is practical so that all stoves are very inefficient as actually used and fill the chimney with flammable deposits. These deposits must be removed annually to prevent chimney fires.

Steps can be taken to get heat out of the hot gases into the air of the room. To do this requires a lot of heat transfer surface. The surface of the stove itself is generally not large enough to cool the flue gas down to a few hundred degrees (sufficient for good chimney action). Thus a few extra lengths of stove pipe between the stove and the chimney can remove the extra heat from the flue gases before they are lost up the flue.

Why not do away with the air supply at the front of the stove and control combustion at the rear. This would not guarantee wood pyrolysis at the desired rate and would make it difficult to keep a fire burning. It is essential to burn the charcoal produced in a fire and this requires a flow of air over the char surface. It is therefore customary to stack coal or leftover charcoal in front and wood at the back. Thus a front air supply is essential.

Finally, different kinds of woods differ greatly in their ease of ignition and rapidity of burning. This is particularly true of the effect of moisture in wood. Green wood can only be burned in a rapidly burning fire which can "dry it out" before it must
burn to continue the fire. Thus the best air supply to a stove must be experimentally determined using the actual wood available.

At various times in history, stoves were made of ceramics. This is fair for cooking purposes, but for home heating it is very poor because the low thermal conductivity of the ceramic keeps the heat inside instead of transferring it outside where it is wanted. The best stoves are made of thick (1/8 inch or more) sheet steel, welded at all joints so as to be airtight. Then a tight-fitting door is added to provide supply port for the wood. Finally, air holes are added at the desired locations. These should have a good screw type cover for air flow adjustment.

What about the future? It is possible to develop an electronic device (a computer chip) which would continuously monitor the fire efficiency and regulate amount and location of the air supply to guarantee high performance. This we say is possible, it's not clear that it will ever be economically worth doing.

11. Conclusions

Wood, when exposed to heat, pyrolyzes to produce hundreds of compounds that burn in a flame about it. These flames feed energy back to pyrolyze more material. As a result of pyrolysis, a charcoal layer is formed which thermally protects the virgin wood below it. This charcoal layer becomes thicker, reducing the supply of gaseous fuel and thus the vigour of flaming combustion. During this process, if oxygen is available, it reacts with the hot char to promote glowing combustion. In a stove, all these processes would occur simultaneously. The current scientific understanding of these component phenomenon is not mature enough to provide a reliable quantitative prediction, but, nevertheless, is very useful to provide direction. The final design of a stove should be determined experimentally for the available bio-fuel guided by what is currently known of the science of fire.

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The pyrolysis of biomass: A general review

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Abstract. Some of the technical issues involved in the design and operation of low
temperature biomass pyrolysis units are reviewed and discussed critically. It is shown
that a range of technical options for charcoal production linked with the production
of fuel gas and liquid streams exists, but much of the currently available technology
is thermodynamically inefficient. Some of the possible technologies for low-cost
production units are described. The development of rigorous design procedures is
discussed, together with some implications for related processes such as gasification.

Keywords. Biomass; charcoal; carbonisation; design procedures; economics; cellulose;
kilns; retorts; wood.

1. Introduction
The extraordinary importance of biomass—in particular wood and agricultural
residues—in the energy economies of developing countries has only recently been
appreciated by policy makers and engineers. Traditionally, wood has been burned
in very simple stoves for domestic and small-scale productive use, such as in baking,
brick-making etc. Some of the disadvantages of wood as fuel—such as its relatively
low calorific value, smoking propensity etc.—have led to the use of charcoal as a
fuel in both rural and urban locations. The production of charcoal is often carried
out in very simple earthen kilns (Earl 1975) but the requirements for some small
investment and operating skills and the fact that charcoal can be transported econo-
mically over fairly large distances have been amongst the elements, along with deve-
loping markets, which have led to increasing commercialisation in the supply of
these traditional fuels.

There are many issues—economic, social and technical—which need to be faced
if the policy implications of the changing features of traditional energy systems and
their interaction with the conventional energy systems are to be grasped adequately.
For example, experience with woodstove programmes shows very clearly how inti-
mate is the interaction between the broader social and economic context and the
effective diffusion of new technology. There is a danger that complexity and the
interdisciplinary nature of the overall problem might lead to the suggestion that
technical (or social, or economic, or cultural...) aspects in themselves are unimport-
ant. Clearly, this is untrue and, indeed, it will often be necessary to study one
component of the problem without necessarily implying that this component holds
in itself the key to the whole problem. In that context, we concentrate in this paper
on some of the technical aspects of pyrolysis.

A striking feature of traditional low temperature pyrolysis, as exemplified by the
production of charcoal, is its technical inefficiency. Often as little as 25–30% of the
calorific value of the wood or biomass feedstock is retained in the charcoal product. Even if the charcoal is subsequently used in a more efficient way than the wood might have been, the overall thermodynamic efficiency of the system may well favour the use of wood. In this review we seek to explore ways of improving the efficiency of the pyrolysis process, whether by altering the process conditions or adopting alternative process designs. In order to come to any judgement on the possibilities of, and limitations on, process improvement it is clearly important to have a clear picture of the fundamental physical and chemical processes at work, and we first review the state of knowledge on these aspects. Then the range of process designs is discussed, along with their advantages and disadvantages, and the discussion is illustrated by a more detailed description of a few operational designs. Finally the possibilities of a rigorous design procedure are discussed, together with some implications for related processes.

Although the review focusses on the technology of pyrolysis, we have attempted to avoid over-technical discussion in the hope that the review will be of value to a wider rather than a specialised readership. The scope of the review is, however, limited: we say nothing of the pre-processing steps, nor of the end uses of the range of products, in focussing on the core process. The range of process conditions considered is also limited (rather arbitrarily) to low temperature (less than 600-700°C, say), processes at relatively low heating rates, where the major primary influence on the decomposition of the feedstock is the temperature; we do not consider in any detail the behaviour of gasification systems where the chemical reactions between the gaseous and solid phases play a fundamental role although there is clearly some overlap between the behaviour of pyrolytic reactors and gasifiers such as in partial oxidation systems. Recent studies on the principles and application of gasifiers include reviews by Overend (1979) and SERI (1979).

2. Factors affecting biomass pyrolysis

In general the products from the pyrolysis of biomass include a solid carbon-rich residue (charcoal) and a range of volatile products (condensable and non-condensable). The amount and quality of the solid residue and the composition of the volatile fraction are strongly dependent both on the physical and chemical characteristics of the feed and on the process conditions.

Information on the subject is extensive and often disperse, since the pyrolysis of biomass, particularly cellulosic solids, has attracted attention not only in relation to fuels and chemicals production, but also as an important part of fire research. There are various comprehensive reviews available in the literature (e.g. Browne 1958; MacKay 1967; Shafizadeh 1968; Walker 1970; Roberts 1970) and these cover many aspects of cellulose and wood pyrolysis. Before reviewing the effects of some key parameters a few general comments on the chemistry of biomass pyrolysis may be in order.

Thermal decomposition of cellulosic materials proceeds through a complex series of chemical reactions, coupled with mass and heat transfer processes. The chemistry of pyrolysis is not completely understood, and the heterogeneous nature of the materials involved further complicates the picture. The general set of pyrolysis reactions of cellulose has been schematized by Shafizadeh (1968) as follows:
The pyrolysis of biomass

Cellulose → Charcoal, CO₂, CO, H₂O (+O₂ “glowing combustion”)

Cellulose → Levoglucosan → Combustible volatiles (+O₂ “flaming combustion”)

Those reactions directly affecting the cellulosic material are termed primary pyrolysis reactions, whereas secondary pyrolysis reactions refer to those involving intermediate decomposition products (e.g. the decomposition of volatiles or levoglucosan).

According to most authors two general pyrolysis pathways may be recognized: one, involving dehydration and charring reactions, leads to the formation of charcoal, CO₂ and H₂O; the second involves depolymerization and volatilization, and leads to the formation of combustible volatiles. These competitive schemes help to explain the extreme sensitivity of the pyrolysis products distribution on the type of feedstock and process conditions.

2.1 Effect of type of feedstock

The commonest raw materials for pyrolytic conversion systems are forestry and agricultural residues. As natural products they are heterogeneous and show great variations in physical and chemical structure, even within a single species.

Woody tissue has a fibrous structure and is made up of various types of small cells which in the living plant perform different physiological functions as well as providing mechanical support. Cells are cemented together by intercellular substances (i.e. middle lamellae) forming a very complex porous structure. The cell wall is composed primarily of cellulose, hemicellulose and lignin, whereas the middle lamella is mainly lignin. Within the cell cavity, and adhering to the walls, are other complex materials such as tannins, starch, resins, oils, dyes, etc. Cellulose is the major component of plant tissue (40-50% by weight of dry wood). (All percentages are by weight, based on dry wood weight, unless otherwise indicated). Other carbohydrates such as hemicelluloses (i.e. xylans, arabinogalactans, glucomannans, etc), and starch are also found in most species. Phenolic substances (chiefly lignin) amount to about 20-30% of the woody tissue. (Some typical examples of the chemical composition of woods are given in table 1).

<table>
<thead>
<tr>
<th></th>
<th>Cellulose</th>
<th>Hemicelluloses</th>
<th>Lignin</th>
<th>Ash</th>
</tr>
</thead>
<tbody>
<tr>
<td>Red pine</td>
<td>47.8</td>
<td>15.1</td>
<td>23.4</td>
<td>0.2</td>
</tr>
<tr>
<td>Yellow birch</td>
<td>42.6</td>
<td>26.6</td>
<td>18.8</td>
<td>0.3</td>
</tr>
<tr>
<td>Douglas fir</td>
<td>57.2</td>
<td>14.1</td>
<td>28.4</td>
<td>0.3</td>
</tr>
<tr>
<td>Beech</td>
<td>43.6</td>
<td>23.6</td>
<td>22.2</td>
<td>0.4</td>
</tr>
<tr>
<td>Black spruce</td>
<td>51.5</td>
<td>17.4</td>
<td>28.0</td>
<td>0.8</td>
</tr>
<tr>
<td>Tauary (tropical)</td>
<td>47.3</td>
<td>14.3</td>
<td>31.0</td>
<td>0.8</td>
</tr>
<tr>
<td>Teak (tropical)</td>
<td>37.0</td>
<td>12.2</td>
<td>30.5</td>
<td>1.4</td>
</tr>
</tbody>
</table>
These compounds become unstable with increasing temperature and their chemical structure eventually begins to break down at about 250°C, leading to the formation of many chemical products. Cellulose and hemicellulose are the main sources of volatile products, yielding only about 8–15% charcoal, whereas lignin yields nearly 50% of its weight of charcoal under typical pyrolysis conditions (e.g. maximum temperature: 400–550°C, atmospheric pressure, slow heating rate). The fraction of the volatile products which can be condensed depends on the material and the pyrolysis conditions; it settles into two phases. One is a phenolic tar phase containing a complex mixture of phenols, ketones, aldehydes, etc. The aqueous phase, or pyroligneous acid, consists mainly of acetic acid, methanol, and acetone. Table 2 shows some typical product yields for different species.

During pyrolysis the primary decomposition products may participate in further chemical reactions, depending on their residence time within the high temperature zone. The hot charcoal is said to catalyze secondary pyrolysis reactions which are very exothermic. Thus, large and reactive volatile molecules may undergo further decomposition leading to charcoal formation and smaller volatile molecules. The larger the size of the solid and the greater its internal resistance to gas flow, the greater the extent of secondary pyrolysis. The residence time of gaseous products within the solid matrix depends not only on the size of the material being pyrolyzed and its porous structure, but also on the grain orientation in relation to flow. Wood has an anisotropic structure, (i.e. its transport properties depend on the direction of the flow e.g. the ratio of the permeability to gas flow along the grain is as much as $10^4$ times that across the grain for some species (Roberts 1971)). Furthermore, internal forced convection due to the generation of internal pressure gradients couples with molecular diffusion; in fact, the quantitative analysis of the flow of volatiles inside the solid during pyrolysis has received little attention. Any attempt to calculate the residence time of volatiles within the solid requires the simultaneous solution of the set of equations describing the mass and heat transfer and the reaction kinetics taking place within the solid.

The moisture content of the feed affects both the solid internal temperature history (due to endothermic evaporation) and the total energy required to bring the charge to the pyrolysis temperature. At slow heating rates and small sample sizes (e.g. 10°C/min, diameter < 5 cm), most of the water is driven off before the main pyrolysis reactions start, and, therefore, their course is not influenced by the initial moisture content.

Since wood, and charcoal even more, have low thermal conductivities the temperature gradient within the pyrolyzing solid increases sharply with the thickness of the material. Accordingly, charring on the surface of thick pieces (say, larger than 20 cm

<table>
<thead>
<tr>
<th></th>
<th>Charcoal</th>
<th>Oil</th>
<th>Gas</th>
<th>Water</th>
</tr>
</thead>
<tbody>
<tr>
<td>Douglas fir bark</td>
<td>50–25</td>
<td>35–50</td>
<td>5–15</td>
<td>10</td>
</tr>
<tr>
<td>Rice hulls</td>
<td>35</td>
<td>40</td>
<td>10</td>
<td>15</td>
</tr>
<tr>
<td>Grass straw</td>
<td>20</td>
<td>20</td>
<td>15</td>
<td>5</td>
</tr>
<tr>
<td>Cow manure</td>
<td>45</td>
<td>45</td>
<td>15</td>
<td>10</td>
</tr>
</tbody>
</table>
diameter) occurs long before the inner regions are completely dried; the water vapour escaping through the hot outer zone of the solid is released violently, causing shattering of the outer charcoal zone and leading to the formation of cracks and fines.

Inorganic substances contained in the pyrolyzing solid accelerate dehydration and charring reactions, during both primary and secondary pyrolysis, increasing the charcoal yield and lowering tar formation. Furthermore, the addition of inorganic salts leads to drastic changes in the pyrolysis products distribution, according to the type and content of salt present during pyrolysis (see table 3). There is a great need for systematic and quantitative information on the effect of different types of salts on products yield.

In most practical situations the available raw material for pyrolysis is very heterogeneous, not only in composition, but also in physical structure and size, and its moisture content is usually high (say, about 30% (based on dry weight)). Particle size and moisture content are the only parameters relating to the feed that can be modified. The size distribution can be controlled by cutting or chopping and screening, whereas the moisture content may be reduced by drying. (Air seasoning may reduce the moisture only up to about 10-20%).

However, in many situations, economic rather than technical considerations are likely to limit the extent of these operations.

2.2 Effect of process conditions

The outcome of pyrolysis is strongly dependent on the thermal conditions of the process. The temperature level of pyrolysis and the heating history have a strong effect on the process yield. When high temperatures (say, above 700°C) are attained at very rapid heating rate (e.g. 1000°C/min), as for example in flash pyrolysis, the molecular disruption is extremely violent and the fragments are expelled so rapidly that those successive adjustments of the molecules that occur when the temperature is raised slowly and which lead to formation of charcoal have less opportunity to take place.

Cellulosic materials are relatively stable at temperatures below about 150°C, where mainly dehydration takes place. At higher temperatures, volatile components of wood (e.g. ether extractives) readily evaporate. Extensive depolymerization of cellulosic material starts at about 300°C, and usable charcoal (carbon content about 75% by weight) is obtained after the pyrolysis of feedstocks at temperatures higher than 350°C. The charcoal yield decreases with increasing process temperature, although its carbon content increases. At very high temperatures gas production is enhanced, whereas at moderate temperatures (say, below 450°C) the volatile fraction contains a considerable amount of condensable products (about 25% w/w (based on

<table>
<thead>
<tr>
<th>% w/w salt</th>
<th>Charcoal</th>
<th>Tar</th>
<th>H₂O</th>
<th>CO₂</th>
<th>CO</th>
</tr>
</thead>
<tbody>
<tr>
<td>None</td>
<td>30</td>
<td>46</td>
<td>19</td>
<td>4</td>
<td>1</td>
</tr>
<tr>
<td>0-14% w/w Na₂CO₃</td>
<td>85</td>
<td>3</td>
<td>8</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>8% w/w NaCl</td>
<td>51</td>
<td>6</td>
<td>29</td>
<td>7</td>
<td>7</td>
</tr>
</tbody>
</table>
Table 4 shows some reported charcoal yields as a function of process temperature.

Slow heating rates are said to enhance charcoal formation whereas very high rates lead to almost total conversion to volatile products (Lewellen et al 1976). Moreover, the charcoal yield is reported to increase when the solid is first pyrolyzed at low temperatures (say, 250°C) before completing the process at higher temperatures (Broido & Nelson 1975). Many of these conclusions are based on the study of very small pure cellulose samples (filter paper, 0·01 cm thick); however they do not agree with our findings in relation to wood pyrolysis. Indeed, we have found that the charcoal yield after wood pyrolysis is relatively insensitive to the temperature history (see table 5), at heating rates below 100°C/min.

Oxygen present in the surrounding atmosphere or trapped within the solid may participate in oxidation reactions with volatile products, or with the hot char itself. The extent of these reactions is strongly dependent on the local temperature and oxygen concentration, as well as the gas velocity relative to the solids. Moreover, oxidation reactions are highly exothermic and their occurrence sharply modifies the apparent energetics of the overall process.

Partial oxidation reactions are very important during the pyrolytic gasification of biomass, i.e. production of combustible gases by partial combustion of solid fuels, and the oxygen supply has to be carefully controlled to avoid excessive oxidation of the products.

Since oxygen may reduce the charcoal yield (by oxidation) its presence should be minimised within the reactor in char-producing systems. However, as is mentioned

<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>Charcoal yield (% w. dry wood)</th>
<th>% w/w C in charcoal</th>
</tr>
</thead>
<tbody>
<tr>
<td>300</td>
<td>51·4</td>
<td>73·2</td>
</tr>
<tr>
<td>400</td>
<td>40·6</td>
<td>77·7</td>
</tr>
<tr>
<td>500</td>
<td>31·0</td>
<td>89·2</td>
</tr>
<tr>
<td>600</td>
<td>29·1</td>
<td>92·2</td>
</tr>
<tr>
<td>800</td>
<td>26·7</td>
<td>95·7</td>
</tr>
<tr>
<td>1000</td>
<td>26·8</td>
<td>96·7</td>
</tr>
<tr>
<td>1100</td>
<td>26·1</td>
<td>96·4</td>
</tr>
</tbody>
</table>

Table 5. Effect of preheat on charcoal yield (final temperature 450°C. Pine (0·4 cm diameter) (Zaror (1982)))

<table>
<thead>
<tr>
<th>Preheating conditions</th>
<th>Final charcoal yield at 450°C (% w/w dry wood)</th>
</tr>
</thead>
<tbody>
<tr>
<td>None</td>
<td>26·7 ± 0·3</td>
</tr>
<tr>
<td>3 hr at 205°C</td>
<td>26·8 ± 0·6</td>
</tr>
<tr>
<td>3 hr at 260°C</td>
<td>25·9 ± 1·3</td>
</tr>
<tr>
<td>3 hr at 330°C</td>
<td>27·0 ± 0·8</td>
</tr>
<tr>
<td>12 weeks at 112°C</td>
<td>26·4 ± 0·7</td>
</tr>
</tbody>
</table>
The pyrolysis of biomass

below, some designs of pyrolytic reactor involve air being fed into the reactor to participate in the exothermic partial oxidation of part of the pyrolysis products in order to provide the energy to preheat the charge.

Due to the multiple chemical pathways involved in the pyrolysis of biomass it is almost impossible to modify the product distribution at will. However, careful selection of the process conditions and feedstock preparation may lead to some control of the products. There is a fair amount of information on this subject in the literature, but this must be used with caution since a good deal of the earlier work paid little attention to control of the experimental conditions. Moreover, there is a lack of data on the effects of sample size and the oxygen content of the atmosphere on the product yield.

In this respect, systematic experimental work on the pyrolysis of different types of raw materials under realistic and carefully controlled conditions is needed as part of the preliminary information required to undertake any serious design of improved pyrolysis systems.

When dealing with charcoal production, feedstocks of regular size and high lignin content are to be preferred, with processes at moderate working temperatures and an O₂-free atmosphere. Moreover, depending on the scale of production, the volatiles may be recovered, either to be marketed or used in situ as fuel.

However, there are a number of technical and economic considerations in relation to the recovery and marketing of volatiles. The condensable fraction is not only a very complex mixture of chemicals but is also corrosive due to the presence of acids (see table 6). Furthermore, separation procedures would increase the cost of the global operation up to unacceptable levels. As is discussed below, however, only about 50% of the potential energy of the wood is associated with the charcoal, which clearly indicates that improvements in the overall efficiency of pyrolytic conversion of biomass cannot be attained without an adequate recovery of by-products, either as a source of chemicals or as fuel.

There is still a great deal of research to be done into aspects related to effective ways of using the volatile products of pyrolysis, and it may be that, sooner rather than later, new separation methods and the use of adequate inorganic additives will lead to improvements in the efficiency of pyrolytic conversion of biomass.

Table 6. Average yield from pyrolysis of tropical wood (Earl 1975)

<table>
<thead>
<tr>
<th>Yields per 1000 kg dry wood</th>
</tr>
</thead>
<tbody>
<tr>
<td>Charcoal</td>
</tr>
<tr>
<td>Gas (c.v. = 10465 kJ/m³)</td>
</tr>
<tr>
<td>Methyl alcohol</td>
</tr>
<tr>
<td>Acetic acid</td>
</tr>
<tr>
<td>Esters</td>
</tr>
<tr>
<td>Acetone</td>
</tr>
<tr>
<td>Wood oil and light tar</td>
</tr>
<tr>
<td>Creosote oil</td>
</tr>
<tr>
<td>Pitch</td>
</tr>
</tbody>
</table>
In order to design suitable pyrolysis systems, information on the reaction kinetics is needed. Pyrolysis reactions are extremely complex, and, as noted above, are poorly understood; understanding of their kinetics is even more inadequate. However, schemes to describe the overall reactions have been successfully applied to describing pyrolysis, and a vast amount of research on the apparent kinetics (in terms of overall weight loss) of pyrolysis of cellulosic materials has accumulated in the literature (c.f. Roberts 1970).

In most studies the evolution of volatiles has been described by a single pseudo-first order reaction of the type:

$$\frac{dm}{dt} = A \exp \left(- \frac{E}{RT}\right) \cdot (1 - m),$$

where $A$ is pre-exponential factor ($\text{time}^{-1}$), $E$ is apparent activation energy ($\text{J mol}^{-1}$), $R$ = ideal gas constant ($\text{J} \cdot \text{mol}^{-1} \cdot \text{temperature}^{-1}$), $T$ = absolute temperature (K) and $m$ = mass of volatiles produced, as a fraction of the total volatiles obtained at total conversion.

Also, two or even three sets of consecutive (e.g. Tang & Neil 1964; Lipska & Parker 1966), or competitive (e.g. Bradbury et al 1979; Thurner & Mann 1981) reactions have been used as the basis of kinetic models.

Thermogravimetry and differential thermal analysis have been commonly used in studies of pyrolysis kinetics. Unfortunately, reported values of the kinetic parameters (i.e. apparent activation energy, frequency factor, and order of reaction) vary widely, reflecting the differences in experimental conditions as well as sample type and preparation.

For design purposes, these kinetic models may be suitable to predict the rate of volatile evolution and the time needed to attain a given degree of conversion under defined process conditions, providing that adequate kinetic parameters are used and that the heat and mass transfer associated with the pyrolysis process are also taken into consideration. Detailed prediction of the product spectrum is not yet possible.

Owing to the complexity of the chemical and physical processes taking place, there is great controversy on the enthalpy of the overall pyrolysis reaction. Reported values for the apparent overall energetics are scattered; in fact there is no consensus as to whether the overall process is exo- or endothermic. The measurement of an overall enthalpy of reaction is bedevilled in practice by experimental difficulties and uncertainties. Apart from the complexity and heterogeneity of the raw materials—which makes comparison very difficult—phase changes (e.g. evaporation of moisture, evaporation and condensation of tars, etc.) and the extent and range of chemical reactions occurring all significantly affect the overall measure. Very little data obtained under precisely controlled and observed conditions is available. However whatever its sign, the enthalpy change overall appears to be relatively small; it is strongly dependent on the extent of secondary pyrolysis and possible oxidation reactions.

### 3.1 Some considerations on the thermal efficiency of pyrolysis

The thermal efficiency of a process can be defined as the percentage of the heat input
that is effectively recovered. A proper measure of the thermal efficiency must correctly identify the boundaries of the process. For example, if the wood gas is recycled to the process it must not be included in an overall energy balance; similarly, the sensible heat of the products must be correctly allowed for.

As can be seen from table 7 only 30–70% of the potential energy in the wood is associated with the charcoal. Therefore, efficient utilisation of the volatile products is very important to the overall thermal efficiency of the process.

Assuming that the standard enthalpy of pyrolysis is about 6% of the standard heat of combustion of wood, Pyle (1977) found that the adiabatic pyrolysis temperature (i.e. in the absence of heat losses or inputs to the system) is about 470°C, this being extremely sensitive to the input moisture content of the wood (see table 8). In practice, this means that supplementary heating is necessary to drive off the moisture.

4. Pyrolysis systems

The simplest pyrolysis system is a carbonization kiln in which part of the charge or its products are burned to provide the necessary heat. Charcoal is obtained at the

| Table 7. Distribution of the heat of combustion of forest fuels (from Shafizadeh 1978) (cal/gr. fuel) (pyrolysis at 400°C for 10 min.) |
|-----------------|----------------|----------------|----------------|
| Fuel            | Charcoal   | Gas          | Total         |
| Cellulose       | -1050      | -3093        | -4143         |
| Douglas fir lignin | -4375      | -1995        | -6370         |
| Poplar wood     | -1546      | -3072        | -4618         |
| Larch wood      | -1914      | -2736        | -4650         |
| Decomposed douglas fir | -2944    | -2176        | -5120         |
| Ponderose pine  | -2438      | -2708        | -5146         |
| Aspen           | -2398      | -2636        | -5034         |
| Douglas fir bark (outer) | -3061   | -2061        | -5122         |
| Douglas fir bark (whole) | -3017   | -2691        | -5708         |

| Table 8. Effect of moisture content of feedstock on the estimated adiabatic pyrolysis reaction temperature (*) (Pyle 1977) |
|-----------------|----------------|
| Moisture content of feed (w. dry wood) | Adiabatic reaction temperature (°C) |
| Heat needed to raise exit temperature to 473°C | KJ/kg dry wood | % of c.v. wood |
| 0               | 473            | 0             | 0              |
| 10              | 368            | 280           | 1-4            |
| 20              | 263            | 560           | 2-8            |
| 30              | 158            | 840           | 4-2            |
| 40              | 53             | 1120          | 5-6            |

(*) assuming: standard enthalpy of pyrolysis = 6% of standard heat of combustion of feed charcoal yield = 35% by weight dry wood; heat capacity = 4 KJ/kgK volatiles yield = 65% by weight dry wood; mean heat capacity = 1-95 KJ/kgK
end of the operation and the overall efficiency is extremely low. The financial costs of the traditional processes are low. However, yields are also very low (i.e. around 15-20% by weight of the dry feed, which is about 50% of the possible yield using more efficient pyrolyzers). At present, kilns, whether earthen or made of brick or steel, are widely used in the rural areas of many Third World countries; the immense waste of potential energy resources inherent in their use has serious economic and ecological repercussions.

The different pyrolysis systems currently available, either commercially or in development, are discussed by Jacobs (1940), Stamm & Harris (1953), Earl (1975), Pyle (1977), Harris (1978) among others, and some examples are discussed in the following section. First, however, a few design principles are outlined in a brief description of the main operational features of pyrolysis systems, i.e. method of energy supply, and materials handling. Systems for gas production do not fall within the realm of the present paper. However, some of the considerations mentioned also apply to gasification systems (see e.g. Overend 1979).

In general, for any pyrolysis system the feed has to be heated to the temperature at which thermal decomposition takes place. Accordingly, heat can be transferred to the charge in two basic alternative ways, namely:

(i) direct heating, i.e. the feedstock is heated by direct contact with gaseous heat carriers—either recycle gas heated externally, or combustion gases at high temperature;
(ii) indirect heating, i.e. heat is transferred to the feed by conduction through a solid retaining wall.

The majority of pyrolysis systems are of the direct-heating type, and their heat transfer characteristics are related to the mode of operation and the specific design features. Three broad modes of operation can be identified.

(a) Batch mode: The feedstock is kept within the reactor until total conversion to charcoal has taken place. Gaseous material (either air to burn part of the charge in order to obtain the process energy, or heat-carrier coming from an external burner) may enter continuously into the reactor. The charcoal is removed after cooling, whereas the volatile products may be constantly removed during pyrolysis.
(b) Continuous mode: The solid charge is introduced and products withdrawn simultaneously in a continuous manner. This type has been widely used in large-scale plants to reduce operating costs. Owing to the heterogeneity of the materials involved and the complexity of the processes occurring, control and materials handling become relatively sophisticated and, hence, expensive.

The relative direction of the solid gas flow in the case of directly heated systems—i.e. counter current or co-current—is extremely important in gasification processes. Indeed, here, preheating and pyrolysis of biomass are coupled with oxidation and reduction (between gaseous reactants and between the charcoal and gas) reactions, and, therefore, the relative positions of the solid and gas phases as well as their residence time histories within the different zones in the reactor play a major role in determining the product yield. However, in the case of pure pyrolysis reactors the relative direction of the gas flow is important only insofar as it affects heat transfer in
the system. Most continuous, directly-heated, designs for charcoal production operate with counter current contact of gas and solid phases.

(c) **Semicontinuous mode**: Some reactor systems do not fit either of the types mentioned above, in that both the feed and the charcoal removal are intermittent; these are best classified in this category.

Within these broad categories, the main types of reactor design for pyrolysis of biomass can be briefly outlined.

(i) **Kilns**: As mentioned above, these are the most popular type of pyrolytic converter for biomass. Although the simpler designs may be cheap and easy to build and operate, the charcoal yield is very low, and even in more elaborate kiln designs by-product collection is minimal. The heating rate and the maximum temperature of pyrolysis are controlled by modifying the rate of air supply, *i.e.* controlling the extent of burning part of the charge. In practice, this is part of the char-making art.

A good deal of attention has been paid in recent years to the development of portable metal kilns. Because of corrosion the lifetime of such designs is often very short. This is reflected in high annual costs. As experience in Brazil has shown (Meyers & Jennings 1979) a better option for low cost applications may be the use of knock-down brick kilns.

(ii) **Vertical retorts**: The solid bed is directly exposed and permeated by the heating gas (figure 1). The most successful retorts of this type operate continuously: the feed is charged at the top and flows downwards, being dried and carbonized by ascending hot gases (*e.g.* Lambiotte system). Depending on the scale of production, the feeding and discharging mechanisms may prove complex and expensive. Moderate heating rates can be obtained, and the internal temperature profile may be controlled by varying the flow and temperature of the heating gases. A similar, but batch-operated version has also found some acceptance (Reichart process, Degussa 1932). In this latter design, however, the heating gas is introduced from the top of the retort.

In general, retorts accept large particles (say, pieces of wood up to 25 cm long), and, apart from charcoal, condensable volatiles may be easily collected. Moreover, since the oxygen content of the gas within the pyrolyzer is minimal, higher charcoal yields can be obtained.

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**Figure 1. Examples of reactor types**
Some versions of indirectly heated retorts, all of them batch-operated, are also found. One particularly interesting design, the Constantine portable kiln (Harris 1978) is described below.

(iii) Fluidized bed pyrolytic reactor: In this design the particulate matter is suspended (and agitated) in the upflowing gas stream (figure 1). It provides very rapid heating rates and because the solids are mixed, uniform internal temperatures. Because of the gas flow rates needed it is best suited for the gasification of small particles (e.g. sawdust, rice hulls, etc.), either by flash pyrolysis (very rapid heating rates and high temperature (> 800°C)) or partial oxidation. Needless to say, this type of design is of little relevance to small scale charcoal production. However, it may be of interest in relation to a more rational use of resources, when designing improved large-scale pyrolysis systems.

The necessary process energy is obtained in most cases, if not all, by combustion of a fraction of the feed or the pyrolysis products (charcoal or volatiles). Broadly speaking, two different systems can be distinguished (Bailie & Doner 1977) (see figure 2).

(a) One-reactor system: Some of the products (or feed) are combusted within the pyrolysis reactor itself. A typical example is the shaft furnace design, where a controlled flux of air is allowed into the pyrolysis zone so that part of the char and volatiles are partially oxidized thus furnishing the necessary heat to the rest of the charge.

(b) Two-reactor systems: Here preheating and pyrolysis take place in one vessel, whereas combustion of part of the products is carried out in a separate unit. The heat released by combustion is then transferred to the pyrolysis reactor. Typically, part of the volatile products are burnt in an external furnace and the hot combustion products are then recycled into the pyrolysis retort (e.g. Lambiotte system). Major technical advantages of a two-reactor system are that oxygen can be totally excluded from the pyrolytic reactor, and the process can be better controlled.

Apart from all the considerations mentioned above, the overall efficiency of the process is very much dependent on the process engineering. The more complex the system, the more sensitive it is to inadequacies in engineering details.

As an example of operating systems two proven pyrolysis designs (one capital-intensive, the other labour-intensive) are described below.

The Lambiotte system, developed by the Lambiotte Company in France in the 1940's, is still considered the highest point of wood carbonization today (Harris
1978). It is a directly-heated two-reactor system. The pyrolytic convertor is a vertical retort that operates continuously and the gas heat-carrier is recycled through a re-heating external combustion chamber. Air-dried wood blocks (30 cm long, 20–25% w moisture content) are fed to the top of the retort and, in its descent, the wood is first dried and preheated by the ascending hot gases and then carbonized by the recirculating flue gas (from the external combustion chamber) which is introduced in the middle section of the retort. Eventually, the charcoal is cooled by inert gases injected at the bottom of the retort, and discharged at the bottom. A fraction of the carbonizing gas is withdrawn from the upper section of the retort at about 350°C and returned at 550–700°C. Careful control of the temperature and flow of the recirculating gases as well as the solid flow rate within the reactor is necessary. The system was designed for large scale operation (say above 20 ton-charcoal/day), and although it involves large capital costs (estimated U.S. $2 million/unit of 55 ton charcoal/day capacity), it requires little labour (2 men/shift) and maintenance, and is thermally very efficient. By-products may be easily recovered since they leave the top of the retort at a relatively uniform rate and at a temperature just above the dew point.

The other design considered here is the Constantine portable retort (Harris 1978), developed in Australia to be used in developing countries. It is an indirectly-heated, vertical, batch-retort located above a fire box. The retort is a jacketed steel cylinder, and the hot gases coming from the furnace are directed through the jacket enveloping the inner vessel holding the charge, and also through a central chimney. The fire box uses wood waste and the pyrolysis volatiles as fuels. Air-dried wood blocks (30 cm long) are loaded and tightly packed inside the retort. When carbonization is complete, cooling of the charcoal is achieved by putting out the fire in the fire box and air is allowed into the jacket and central chimney. A complete cycle from loading to withdrawing cool charcoal may take about two days, depending on the size of the charge and its moisture content. Outputs of 1–2 ton charcoal/cycle/retort can be attained. It is simple and safe to operate and does not require as much skill as a kiln operation. The system is relatively portable and labour-intensive (e.g. a 2-ton charcoal/cycle/retort costs about U.S. $12,000, and needs 2–4 men/day) (Harris 1978). The system can be improved by using several retorts simultaneously (say, eight or more) linked to a specially designed central furnace.

5. Considerations in the design of pyrolysis systems

In any pyrolysis system, complex heat and mass transfer phenomena within the pyrolyzing solid, and between it and its immediate surroundings take place. These processes can be schematized as follows:

(a) Heat is transferred from the external environment to the solid surface (convection and/or radiation).
(b) Heat transfers from the surface into the interior (conduction).
(c) Heat transfers between the volatiles coming from the pyrolysis zone and the solid matrix (convection).
(d) Energy is locally produced or consumed during the different pyrolysis reactions.
(e) Local generation of volatiles due to chemical reactions.
(f) Flow and diffusion of volatiles to the surroundings.
(g) Diffusion of O\textsubscript{2} (if present) from the external atmosphere to the solid surface may take place leading to exothermic oxidation of outflowing volatiles and the solid surface.

The rate at which these different processes occur is dependent on the instantaneous solid internal temperature profile, its physical and chemical properties and dimensions, as well as environmental conditions (i.e. temperature, O\textsubscript{2} concentration, fluid dynamics) (Murty & Blackshear 1970, Roberts 1971).

A general mathematical model of the pyrolysis process is not only difficult to formulate but also extremely complicated to solve. Nevertheless, several simplifications can be made according to the general conditions of the process (i.e. mode of heating, temperature level, type of operation, etc.), and thus basic overall heat and mass transfer equations can be formulated.

For heterogeneous non-catalytic reactions involving solid particles, two rather simple idealised models are usually considered, namely, the continuous-reaction model and the unreacted-shrinking-core model (Levenspiel 1962). The former model visualises the chemical reactions as taking place simultaneously dispersed throughout the solid particle, possibly at rates varying with position within the particle. The latter model considers that the reaction occurs in a narrow front which advances into the unreacted solid, leaving behind completely converted material. Most solid-gas reaction systems are adequately described by the unreacted-core model since the gaseous reagents do not penetrate beyond the reaction front. However, in the case of pyrolysis, contacting of the solid with a fluid is not required for the reactions to proceed. Rather, the reactions are promoted by the local temperature distribution and the selection of a suitable model is thus closely related to the heat transfer features of the system. For instance, in those situations where a very large particle of low thermal diffusivity is exposed to a very hot environment (i.e. high heating rate) and, therefore, very large temperature gradients within the solid will be generated, an unreacted-shrinking core is likely to adequately represent reality. This might be the case in gasification systems where the solid undergoes very fast heating. On the other hand, the progressive conversion model fits better those cases of slow heating rates and moderate particle size, as occurs in most charcoal production systems.

Whether the overall rate of the process is controlled by chemical kinetics or by heat transfer considerations depends on the particular model assumed to describe the system, and its parameters (e.g. transport properties of the solid, environmental conditions, particle size, etc.). In most practical situations, the rate of the process is likely to be determined by a combination of heat and mass transfer and reaction kinetic effects.

In this respect, there are a number of mathematical models describing wood pyrolysis (and combustion) available in the literature. In a pioneering work, Bamford \textit{et al} (1946) combined the equation for heat conduction in a pyrolyzing solid with those for heat generation by a first order reaction. This basic model has later been used by several workers (e.g. Weatherford & Sheppard 1965; Tinney 1965;
The pyrolysis of biomass

Roberts & Clough 1963), and further improved by Kung (1972) and Murty (1972) who incorporated the effects of internal convection and variable transport properties, and by Kansa et al (1977) who also considered the effect of the physical structure on the volatiles flow. Fan et al (1977) utilized a volume reaction model to describe the pyrolysis of a solid, taking into account simultaneous heat and mass transfer phenomena in the particle. Maa & Bailie (1977) propose a mathematical model based on the unreacted-shrinking core model to describe the pyrolysis of a solid at high temperatures. Zaror & Pyle (1983) discuss model simplification.

Unfortunately, the lack of reliable experimental data on the dynamics of wood pyrolysis under realistic conditions (in relation to charcoal making processes) makes it difficult to select a simplified but at the same time accurate model that could be used for design and prediction purposes.

The design of reactors for heterogeneous processes is comprehensively discussed in the specialised literature. Moreover, wide experience with catalytic reactors, solid combustion systems and other processes involving thermal treatment of solids has accumulated during the last half of the century and could be adapted to designing efficient pyrolytic conversion systems.

An adequate description of the pyrolysis of solid fuels is a component of the proper engineering design of combustion systems, such as wood burning stoves.

Indeed, when wood is put into a hot environment it first starts to pyrolyse, releasing volatile products and producing charcoal. These pyrolysis products then become violently oxidised by oxygen, depending on the local temperature and oxygen concentration. One aspect in the design of wood burning stoves is to predict the rate of volatile generation for given specimen size and shape, and environmental conditions. As mentioned above, the rate at which volatiles are released can be described using the heat and mass transfer equations deduced for pyrolysis processes, using adequate boundary conditions. (The numerical solutions of these equations should not present major difficulties given current computing facilities.)

However, heat and mass transfer processes as well as the fluid dynamics within even the simplest wood burning stove are extremely complicated. Therefore, the major processes have to be modelled as accurately as possible, making adequate simplifications in order to facilitate numerical solutions. Needless to say, the pyrolysis of wood within the stove is only a minor part of the complex set of parameters involved in stove design. As mentioned by Verhaart (1981), engineering considerations (complex in themselves) interrelate with economic, social, and ecological factors, making the design of acceptable and efficient stoves extremely complex.

6. Conclusions

In this review we have attempted to survey some of the technical issues in the design and operation of low temperature biomass pyrolysis systems. It is shown that a range of technical options exists, but that much of the currently used technology is thermodynamically inefficient. Design methods are predominantly empirical and understanding of the mechanisms of pyrolysis and the development of rational design procedures are areas worthy of significantly greater attention than they have received to date. In particular there is a compelling need for reliable data on the pyrolysis products yield as a function of process conditions and type of feedstock; this must be
obtained under realistic and carefully-controlled conditions. The apparent kinetics and energetics of the pyrolysis of wood and agricultural wastes, with the object of charcoal production, need to be studied.

Models describing the overall kinetics of pyrolysis coupled to the main heat and mass transfer processes taking place during thermal decomposition have been developed in recent years. These promise to be adequate for design and prediction purposes providing that the different parameters involved are carefully selected; experimental data on the dynamics of wood pyrolysis is thus urgently needed. Moreover, pyrolysis systems aimed at charcoal production can be significantly improved if current experience in reactor engineering is adequately adapted to the specific features of biomass pyrolysis.

The main design criteria should be set according to the particular charcoal (and/or gas) production situation, since labour, raw material availability and costs, market, industrial and capital factors and other social and economic considerations differ widely from region to region, and imply the need for different technical solutions to the renewable energy supply challenge.
The pyrolysis of biomass

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On designing woodstoves

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Abstract. An analysis of the food-technological processes that play a role in the domestic preparation of food precedes an assessment of the energy requirements for cooking; this in turn leads to a list of specifications for an advanced type of wood-burning cookstove. After a review of the energy supply options, building materials for stoves and heat transfer mechanisms operative in food processing follows a discussion on health and comfort aspects of stoves. The use of natural draught to promote combustion and heat transfer is discussed next. This is contrasted with open fires and closed stoves as they are used at present. For both a combustion model is proposed and discussed, winding up with the conclusion that in the presently available closed stoves control of the power is difficult if at all possible. A final chapter of conclusions makes a case for an intensified research effort on improving combustion of woodfuels.

Keywords. Domestic food processing; cooking energy requirements; combustion of wood; open fire; closed stove model; natural draught; woodstove design.

1. Introduction

In order to design a machine or instrument one has to know what duties it is expected to perform. A number of secondary conditions also has to be met. When for instance one is asked to design an automobile we know that it has to transport a certain number of persons and a certain amount of luggage. Secondary conditions are the speed at which it must be able to travel, its fuel consumption, its lifetime, the maintenance- or repair intervals, the extent to which irregularities in the road surface result in vibrations noticeable to the passengers, the ease of operation and the amount of noxious gases emitted, to name just a few.

Engineering science has a number of more or less complete answers to the engineering problems just mentioned, each at its own price. The end product is a design in which all the relevant aspects have been assigned a certain order of priority. In general, designing is a step-wise operation (sometimes bearing more resemblance to Brownian motion). The result is a compromise between the perfect and the affordable, between the desired and the available. When the function of the device is defined, the first step is to find out which laws of mechanics, electricity or chemistry have to be brought into play in order to realise the desired function. Next a study is made of the way in which the elements can best be arranged in order to perform the desired function. The question of what materials to use then follows. This latter is a matter of cost which in turn has nearly everything to do with the availability.

To sum up, designing consists of four steps: (a) Define the functions, (b) find ways to realise the constituent processes, (c) define shape, materials and dimensions, (d) write specifications and manufacturing instructions.
The steps are the same, be it for designing an automobile or a wood-burning cookstove. If a need is felt for a newly designed woodstove, the designer should find (or be given) a clear idea of what his design should do. The surprising thing is that for something like an automobile which has existed for 80 odd years, far more exact specifications exist than for equipment that enables one to cook, using chemical energy from wood, even though this has been used for more than 80 centuries.

In this paper we will try to analyse the problem in a fairly broad sense, following more or less faithfully the items in the left half of the block diagram in figure 1. We will treat it as a request to use engineering knowledge and disciplines to find a way to economise on the use of firewood for making food edible. It is possible that a designer questions the relevance of such an assignment. For this person in particular the next paragraph is written.

2. Why woodstoves?

The observed chain of events leading to interest in woodstoves is roughly as follows.

Forests on our planet are decreasing in size by many square kilometers per day through human intervention.

A large part of the forests that are being chopped down is used for firewood.

The firewood is used to cook food.

As it is very desirable, not to say vitally important, that part of our planet's surface remain covered with forests, a number of government agencies is inciting, encouraging

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Figure 1. Considerations that may influence stove design.
and even financing action. The action is direct as well as indirect. Reforestation programmes as well as woodstove programmes are being implemented.

The chain of reasoning for the woodstove programmes is as follows:

Very much wood is used to do the thermal processing deemed essential to make food edible.

The inefficient part in the process is the stove in which the wood is burned.

With better stoves we can save wood.

3. Designing cooking stoves for the developing world

So far nearly all designing of wood-burning cooking stoves for the developing countries has taken place on the spot. Development workers, not usually with specific technical training, have as best as they could, made use of locally available materials and resources. The stoves that were built were designed to do the cooking tasks that were identified on site. From reading the relevant reports, one gets the impression that the cooking tasks are extremely specific, depending on the locality. The implication is that any one stove design can only be employed in a very limited area. Each small village would need its own stove design.

3.1 Is this really necessary?

When we look at Europe there is also a great variation in local dishes and cooking needs. Yet all cooking jobs get done on identical, mass-produced gas- or electric ranges, ovens and grills. And at quite a good efficiency! In the developing countries we see that before development workers introduced their stoves all cooking jobs were done on the simple open fire or on stoves closely related to it. If we then assume that what was done for Europe can be done for developing countries, we imply that a very limited number of designs can be developed that can cope with all possible cooking needs. Besides, it is very likely that the main dishes of the world can be classified into a very small number of groups. Krishna Prasad (1982a) gives eloquent examples of nearly identical dishes in very widely separated geographical areas.

3.2 What are those cooking needs?

In the following paragraphs we look into this. We first define the thermal food processing functions that are practiced most. These have been brought together in table 1.

4. Cooking processes

In table 1 the thermal food preparation processes are summarised. The processes can be divided into two groups: (i) The first group contains all those processes which in essence only need heat to reach the boiling point of water. After that the material
Table 1. Thermal food preparation processes

<table>
<thead>
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<th>Cooking functions</th>
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<tbody>
<tr>
<td>1 Boiling</td>
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<tr>
<td>1.1 Stewing</td>
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<tr>
<td>1.2 African beer (Dolo) boiling</td>
</tr>
<tr>
<td>1.3 Parboiling rice</td>
</tr>
<tr>
<td>2 Frying</td>
</tr>
<tr>
<td>2.1 Deep frying</td>
</tr>
<tr>
<td>2.2 Saucepan frying</td>
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<tr>
<td>2.3 Flat plate frying</td>
</tr>
<tr>
<td>3 Baking</td>
</tr>
<tr>
<td>3.1 Roasting</td>
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<tr>
<td>4 Grilling</td>
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</table>

has to be kept at boiling point temperature for a specified length of time. (ii) The second group needs a practically constant supply of heat at a temperature higher than the boiling point of water. Actually all subheadings under boiling amount to the same thing, the items are more or less arbitrary examples. They all have in common the constant temperature and may differ in the amount boiled and in the duration of the process.

Frying and baking differ in the medium with which heat is transferred to the food. While in frying the heat is transferred from the panbottom or flat plate via a thin layer or a bath of oil or fat to the food, in baking heat transfer is through air or combustion gases and through radiation.

In grilling heat is transferred mainly through radiation. After the functions we have to think of the mode of operation of the equipment. There is not only the matter of frequency but also of quantities and of whether operation is more or less continuous during the day. These variables are gathered in table 2. After we have defined the cooking needs we can think of how they can be met. On the way we will come across questions such as:

- How much food is processed at a time?
- How many times a day is this repeated?
- Do the quantities vary much?

The answers to these questions will tell us whether the final design will have to need a quick starting ability, widely and instantly variable output etc. The amount of food and the cooking function will eventually determine the energy output of the device.

5. Energy requirements

Food technology and food chemistry are well established technologies. Yet, to our surprise, information on the required energy for processing current foods is not readily available. Indirectly, however, a reasonable amount of information can be
gleaned from cooking books and journals of consumer organisations. The reason for this search is the idea that there must be a minimal energy requirement for the processing of a particular food. The energy actually used may well be many times this amount depending on how efficiently the process is executed.

5.1 Boiling

Probably the most important cooking process is boiling. Essentially energy is needed only to bring food and water to boiling point and to supply heat for the chemical reaction. The latter is usually only a small fraction of the first. To get some figures we will do an example involving the boiling of rice. What energy do we really need to boil 1 kg of raw rice? Part of the information from a cookbook, such as Wannee (1975), can be transformed into a mass balance:

\[ m_r + m_w = m_{br}, \quad (kg), \]

where: \( m_r \) is the mass of raw rice (kg), \( m_w \) is the mass of water (kg) and \( m_{br} \) is the mass of boiled rice (kg). According to the cookbook: If \( m_r = 1 \) kg, then \( m_w = 1.5 \) kg and consequently \( m_{br} = 2.5 \) kg. From the energy point of view we know that the rice and water have to be brought to boiling point. Next the rice and water have to remain at around boiling point for a certain length of time when chemical reactions take place transforming raw into boiled rice. Most chemical changes involve production or absorption of heat, the latter processes are called 'endothermic'. According to CIVO-TNO (1982), most food preparation processes are endothermic but the amount of heat involved is very slight. This being so, the total heat needed must be approximately equal to the heat required to bring the raw rice as well as the water to boiling point \( e.g. \)

\[ Q = (C_r^* m_r + C_w^* m_w^*) \cdot (373 - T_0), \quad (kJ), \]

where: \( Q \) is the process heat required (kJ), \( C_r^* \) is the specific heat of raw rice (kJ/kg.K), \( C_w^* \) is the specific heat of water (kJ/kg. K) and \( T_0 \) is the initial temperature of (rice and) water (K). After we have supplied the above net amount of heat we only need to maintain the mixture at boiling point. As rice grains are very small we may assume that by the time boiling point is reached the grains will also have reached that temperature throughout.

Let us see how much energy is required to boil a kg of rice. According to Polley et al (1980) the specific heat of rice is 1.76 kJ/kg. K. The specific heat of water

<table>
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<th>Operation</th>
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<tr>
<td>1 Frequency</td>
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<td>2 Quantities</td>
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<td>3 Batch cooking</td>
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<td>4 Sequential cooking</td>
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being $4.19$ kJ/kg. K and assuming an initial temperature of $25^\circ$C (or $298$ K), we obtain:

$$Q_r = 603.4 \text{ (kJ/kg)}.$$ 

If, according to Geller & Dutt (1982) rice needs energy for the chemical change to the tune of $172$ kJ/kg, this amount is added and we obtain:

$$Q_r = 775.4 \text{ (kJ/kg)}.$$ 

According to various sources (Krishna Prasad 1982b; Samootsakorn 1982; Islam 1980) in traditional rice cooking the rice is placed in the pan with excess water. In the course of the rice cooking process the excess water is either boiled away or decanted at a certain stage. (In the latter case the so-called ricewater is not always thrown away, it is widely used as food for sick infants and convalescents). We can calculate the energy consumption for both cases, assuming the average water requirements of rice that transpire from cooking books as well as from personal experience. As in the example the required water amounts to about 1.5 times the mass of rice. The amount of water used in the traditional recipe is taken as 6 times the mass of rice (Samootsakorn 1982). We first calculate the amount of heat used if all excess water is evaporated, this gives the most spectacular result. Next the amount of heat is calculated assuming the excess water is merely heated to boiling point.

If the excess water is boiled away, it means evaporating $4.5$ kg of water. This involves an additional amount of heat, $Q_a$, consisting mainly of heat of evaporation:

$$Q_a = 11,571 \text{ (kJ)},$$

which is roughly 15 times the net process energy required.

The next case is less spectacular. Here the excess water is only brought to boiling point. Thus we establish the minimum energy requirements for this manner of rice cooking. In this case $4.5$ kg of water is heated from say $20$ to $100^\circ$C, which implies an amount of heat:

$$Q_{at} = 1507 \text{ (kJ)},$$

which is about twice the net process heat. Back to actual rice cooking. Once boiling point is reached we only need to keep the mass of rice and water from losing heat. One way of doing this is by adjusting the fire such that only the heat losses from the pan are compensated. If the cooking stove allows for this we need only the process water and no more. Another way is to take the pan from the fire and wrap it up in insulating material such as straw or newspapers and leaving it for a certain length of time. Wannee (1975) even gives a recipe where the rice is kept boiling for 5 minutes after which the pan is wrapped in 10 or more old newspapers and left for 1 hour. This is the most energy economic way and, where the fire does not allow fine adjustment, it is the only way in which to boil rice without excess water. If we insist on completing the entire process on the fire and the latter cannot be turned down to any significant degree, we have to start out with such an amount of excess water in the pan that this has just evaporated at the end of the process. An additional
complication to this way of cooking is that the heat input rate may be such that stirring is imperative if burning of the rice is to be prevented. It is thinkable that where there is no proper understanding of the processes involved, recipes, very wasteful on energy, may come into existence and are handed down from generation to generation. Thus one can imagine the evolution of an instruction such as 'stir continuously over a large fire for half an hour'. When boiling is done with an open pan while stirring it is clear that a large amount of water will evaporate and, consequently, a large amount of heat is needed.

5.1a Parboiling rice A process that came into being in India is the parboiling of rice. Primarily developed as an aid in milling it consists of soaking the unhulled rice in hot water followed by steaming and drying. In addition to loosening the hulls it causes migration of some of the vitamins from the hull and bran-coat to the kernel thus enhancing the vitamin content of the hulled rice (Hawthorn 1981). Parboiling imparts a slightly yellow colour to the rice grains and affects the keeping properties adversely. In addition parboiled rice takes longer to boil (no figures available). In all, more energy has been expended on a given mass of rice by the time it is ready to be eaten if it was parboiled first. The minimum energy required is at least twice the amount needed for straight boiling.

5.1b Stewing The word suggests a lengthy process of slow boiling. As such most of the process could probably take place in a haybox.

5.1c Dolo beer brewing The thermal part of any beer brewing process is the boiling of the wort when it is kept at boiling point for a certain length of time. In the most energy-efficient case the minimum energy requirement is equal to the heat necessary to bring the wort to a boil. That beer brewing should not always be regarded as a luxury industry is emphasised by Hawthorn (1981) who states that in some areas beer is the only source of certain highly essential vitamins.

5.1d Warming through time For foods which come in small particles such as cereals and pulses not much time is required for the centre of the particle to reach boiling point when placed in boiling water. With dried pulses, however, there is the matter of moisture penetration to the interior. For cooking unsoaked dried beans in a pressure cooker the processing time given in the manual is about twice that of the same beans when soaked beforehand. For cooking dried beans at atmospheric pressure no directions could be found (evidently cooking unsoaked beans is such an absurdity that it is not even considered in the cooking books we consulted). It seems likely that the chemical process in the interior of the bean has to wait for the arrival of the water. It may even be so that the region where the cooking (in the chemical sense) takes place presents an obstacle to the diffusion of water. For larger food particles such as potatoes or other tubers we have to make allowances for the heat to penetrate. This could be in the form of recommendations to continue boiling for a specified amount of time before turning the fire down. The time required is a function of the size, specific heat, the density and the heat conductivity and of the shape. For simplicity's sake the latter will be assumed spherical. If we further simplify the problem by assuming that the particles are dropped into boiling water, the time necessary for the centre of a particle to reach a temperature very
close to boiling point can be calculated using methods that can be found in a standard text on heat transfer such as Jacobs (1967). Doing so we find that the temperature in the centre of a sphere with diameter $D$ with an initial temperature of 25°C when dropped into boiling water will reach 97°C when the dimensionless combination:

$$\lambda t / \rho C D^2$$

has a value of 0.1, where: $\lambda$ is the heat conductivity of sphere material (W/m·K), $t$ is the time since immersion (s), $\rho$ is the density of the sphere material (kg/m³), $C$ is the specific heat of the sphere material (J/kg·K), $D$ is the diameter of the sphere (m). With the values substituted for potatoes from Polley et al (1980) ($\lambda = 1.09$ W/m·K; $\rho = 976$ kg/m³; $C = 3520$ J/kg·K) can produce table 3. The actual cooking differs in that the potatoes are heated together with the water in the pan. The table does, however, give a good indication of the importance of cutting up the tubers into small and equal pieces if we want fuel economy.

5.2 Frying

Frying in all its variations is a non-uniform temperature process. The temperature of pan and heat transfer medium is well above boiling point while the interior of the food particles does not usually exceed boiling point. The input food loses water on its outer surface by evaporation while heat penetrates to its interior. Depending on the power per unit exposed surface area and thermal properties of the food, as

<table>
<thead>
<tr>
<th>Number of pieces per kg</th>
<th>Averaged diameter of pieces mm</th>
<th>Warming through time s</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>80.5</td>
<td>34</td>
</tr>
<tr>
<td>6</td>
<td>76</td>
<td>30</td>
</tr>
<tr>
<td>7</td>
<td>72</td>
<td>27</td>
</tr>
<tr>
<td>8</td>
<td>69</td>
<td>24</td>
</tr>
<tr>
<td>9</td>
<td>66</td>
<td>23</td>
</tr>
<tr>
<td>10</td>
<td>64</td>
<td>21</td>
</tr>
<tr>
<td>12</td>
<td>60</td>
<td>19</td>
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<tr>
<td>14</td>
<td>57</td>
<td>17</td>
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<td>16</td>
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<td>18</td>
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<td>14</td>
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<td>20</td>
<td>51</td>
<td>13</td>
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<tr>
<td>24</td>
<td>48</td>
<td>11</td>
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<tr>
<td>30</td>
<td>44</td>
<td>10</td>
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<tr>
<td>40</td>
<td>40</td>
<td>8</td>
</tr>
<tr>
<td>50</td>
<td>37</td>
<td>7</td>
</tr>
<tr>
<td>60</td>
<td>35</td>
<td>6</td>
</tr>
<tr>
<td>80</td>
<td>32</td>
<td>5</td>
</tr>
<tr>
<td>100</td>
<td>30</td>
<td>4</td>
</tr>
</tbody>
</table>

Table 3. Warming times for tubers as function of size
the outer layers lose moisture, the temperature of its outer surface rises and some thermal decomposition takes place. A crust is formed. The crust is an essential part of most fried foods. Frying in general can be expected to be a high power input process.

5.2a Deep frying A quest for data on power requirements for deep frying, suspected to be a mode of cooking requiring a very high heat flux, resulted in the meagre collection of table 4. Additional information from the Consumentengids (Anon 1980) tells us that indeed deep frying is a high power process. In a test of electric deep frying pans where the input was 2 kW, a charge of 180 g frozen blanched French fried potatoes took 5 minutes to fry to a reasonable state of cookedness. If we assume a heat transfer efficiency of 90\%, the net heat input to the oil was 1.8 kW which gives a figure of 10 kW/kg.

As heat transfer from oil to food takes place through the outer surface of the particles, it is probably more useful to attempt to derive the total surface area presented by a unit mass of French-fried potatoes. The cross-section is assumed square with a side of about 1 cm. The average length we take to be 5 cm. The density is 976 kg/m$^3$. This gives a specific surface area of:

$$A_s = 0.45 \text{ (m}^2/\text{kg}).$$

For this surface area we needed 10 kW so that we can calculate the net heat input per m$^2$:

$$p_s = 22 \text{ kW/m}^2.$$

This heat is needed at a temperature above boiling point, probably at around 180°C. We might expect that foods with similar deep-frying behaviour as potatoes have similar heating power requirements.

<table>
<thead>
<tr>
<th>Food</th>
<th>Energy in MJ per kg input</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Potatoes, French-fried</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Finish frying (frozen)</td>
<td>3.9-4.12</td>
<td>C.G.</td>
</tr>
<tr>
<td>From start to finish</td>
<td>4.36</td>
<td>SL</td>
</tr>
<tr>
<td>Blanching (pre-frying)</td>
<td>3.5</td>
<td>SL</td>
</tr>
<tr>
<td>Finish frying</td>
<td>1.94</td>
<td>SL</td>
</tr>
<tr>
<td>Fish fillets</td>
<td>4.11</td>
<td>SL</td>
</tr>
<tr>
<td>Fish sticks (frozen)</td>
<td>4.37</td>
<td>SL</td>
</tr>
<tr>
<td>Shrimps</td>
<td>3.68</td>
<td>SL</td>
</tr>
</tbody>
</table>

Sources: C.G. = Anon (1980); SL = Slade (1971)
5.2b *Saucepan frying*  Next on the list is saucepan frying. Here, from personal experience as well as through reasoning we can conclude that power requirements are considerably below those for deep frying. There is no circulation of oil or fat and this seriously limits the surface area of food particles exposed to hot liquid. In order not to burn the food the fire must be turned down to some extent. The highest power input is required when frying small wet particles like chopped onions or bean sprouts but even then it does not compare, energy-wise, with deep frying. It would be interesting to have figures on the power input required for baking pancakes. Pancakes are known under many different names the world over. It is a very convenient way to process cereals.

5.2c *Flat-plate frying*  Power requirements for flat-plate frying will probably be similar to those for saucepan frying of pancakes.

5.3 *Baking*

Here heat is transferred through radiation from the oven walls to the food. Essentially the process heat required is very close to the amount needed to heat the piece of food to boiling point with a little extra thrown in to brown the crust. The heat is supplied at a temperature well above boiling point, up to 250°C. The minimum amount of heat needed in practice will depend on how much intelligence and imagination was invested in the energy conscious design. At present gas-fired ovens are reputed to be rather wasteful of energy. Sielcken & Visser (1982) quote a figure of 6.7 MJ per kg (input) bread. Firing the oven seems to use most of the energy. The energy consumption appears practically independent of the amount of food placed in the oven. In the industrial production of bread, according to our source (Anon 1979), the energy used for baking comes to about 6.25 MJ/kg. The difference seems suspiciously small.

5.4 *Grilling*

Heat transfer being by means of radiation it is likely that in the grilling process much of the energy is radiated away uselessly. Again the net required amount of heat will be close to that which is needed to bring the food to boiling point plus a little extra for crust forming. We hope that with these rather elaborate exercises we have indicated the need for more data. In any other branch of engineering it would be considered quite odd for someone to clamour for a device without knowing what job it has to do.

6. *Specifications for a woodstove for cooking*

In this section a set of specifications has been drawn up. They have been for a part based on optimistic extrapolations of test results from existing stoves and partly on standards (Anon 1968) for domestic gas ranges that are in operation in the Netherlands (doubtless very similar standards are in operation in most other industrialised countries). From the foregoing paragraphs a designer must be able to formulate
a set of specifications for a good wood-burning cooking stove. Such a set of specifications might look somewhat like the collection below.

(i) At least half of the heat liberated by the wood on combustion should get transferred to the pan.
(ii) The heat output rate can be varied from full power (100%) to about 15% of full power.
(iii) The change from full power to minimum power and vice versa must be achieved within 30 seconds.
(iv) No dangerous, noxious or poisonous emissions may be given off.
(v) Pans must remain clean on the outside.
(vi) No other (auxiliary) energy sources such as electricity may be used.
(vii) Easy to light, full power is liberated within 2 minutes after a cold start.

The cookstove defined by these specifications is a device which might be accepted even in homes in the industrialised part of the world. It is nearly as good as the existing gas ranges and in some respects (time lag) better than electric ranges.

Other desirable properties have been taken from estimates of what should be possible with wood-burning stoves when attention is paid to the problem of clean combustion. As for the efficiency, a figure of around 50% has been achieved with a rather simple woodstove (Visser 1982) and it is the present practical limit for domestic gas ranges (of course, there is no objection at all to higher efficiencies). A turndown ratio of 21% was achieved by Knol (1981) with a heavy brick stove. It seems likely that a woodburning cooking stove complying with the above specifications, if it can be made, will remain an attractive piece of kitchen equipment for quite a number of years to come. It is, however, quite certain that more research of good quality will have to be done to achieve this result. In the following paragraphs the technical aspects involved in achieving the state of the art described in the specifications will be reviewed.

7. Energy supply

While other means of energy supply should certainly be examined, in this paper we shall confine ourselves to heat energy provided by the combustion of fuel. The main renewable fuels are: charcoal, wood and agricultural waste. Charcoal is the only real solid fuel among the three. It burns cleanly and odourlessly. It is a very convenient fuel which, because of its clean burning, can be used indoors without objection. In the traditional manufacturing process, however, only a fraction of the combustion value of the wood used is recovered in the form of charcoal.

The traditional food crops yield waste products, some of which can be used only as fuel, either directly or after some form of processing. In this light it is interesting to consider that roughly half of the biomass grown to produce agricultural crops consists of waste which can only be burned. The calorific value is roughly equal to that of wood (just as the foodcrop). This means that if the mass of fuel required for cooking does not exceed the mass of raw food to be cooked, all fuel needs for cooking agricultural products can be met by burning agricultural waste. The block diagram of figure 2 presents the most common options for energy from biomass.
Agricultural waste strongly resembles wood chemically, the only exception being the ash content which can be as high as 20% as in rice husks. Often agricultural waste occurs in finely divided form making it necessary to transform it into larger uniform particles for handling and firing convenience. As a final introductory remark we can state that the burning of wood is a chemical process of great complexity. For small scale application it is fraught with stifling constraints as we will see in the following sections.

7.1 Fuel supply

Taking the items in table 5 in order of appearance we start with the various ways fuel can be supplied to the combustion space. Of the various ways in which this can be done we mention the following:

7.1a Continuous supply This is how all liquid and gaseous fuels for any rate of heat output are handled. The fuel burns practically immediately upon entering the combustion space and the heat output rate is controlled by the flow of fuel. Air may be forcibly supplied or enter under influence of natural draught. For large heat output rates solid fuels are first ground to a fine powder which handles practically like a liquid. The powder is usually blown into the combustion space suspended in an airstream. There is no technical reason why powdered fuel burning cannot be done on a small scale. The process was developed for large scale applications and so far no need has been expressed for smaller scale applications. In industrialised countries the idea of centralised grinding plants and distribution by bulk transport is quite feasible. The burning of powdered fuel would, however, need an auxiliary energy supply either in the form of electricity or pressurized air (to power a fan, vibrator and igniter). For small woodburning cookstoves it does not appear a likely proposition in the immediate future.
Table 5. Combustion modes

<table>
<thead>
<tr>
<th>Combustion</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Fuel Supply</td>
</tr>
<tr>
<td>1.1 Continuous fuel supply</td>
</tr>
<tr>
<td>1.2 Batch fuel supply</td>
</tr>
<tr>
<td>1.3 Accumulated fuel</td>
</tr>
<tr>
<td>2 Character of combustion</td>
</tr>
<tr>
<td>2.1 Combustion of volatiles</td>
</tr>
<tr>
<td>2.1.1 Premixed flames</td>
</tr>
<tr>
<td>2.1.2 Diffusion flames</td>
</tr>
<tr>
<td>2.2 Combustion of char</td>
</tr>
<tr>
<td>2.2.1 Simultaneous burning</td>
</tr>
<tr>
<td>2.2.2 Sequential burning</td>
</tr>
<tr>
<td>2.3 Two-stage burning</td>
</tr>
<tr>
<td>2.3.1 CCMB gasification</td>
</tr>
<tr>
<td>2.3.2 Two-zone burning</td>
</tr>
</tbody>
</table>

7.1b Batch supply Solid fuel is supplied in charges. The charges can be very small such that for one cooking job a number of charges have to be supplied. We assume that the fuel is thrown on top of the fire, usually this is the case. When, therefore, a new charge is introduced, the wood is suddenly placed in an environment of very high ambient temperature. It will then immediately begin giving off volatiles. The smaller the charge, the more the burning will resemble that of the fire with continuous fuel supply. The larger the charge of fuel, the less stationary will be the behaviour of the fire. The power output of the fire will usually change from the instant of charging when part of the heat from the fire is absorbed by the fresh charge to the time when the generation of volatiles is at a maximum. At this instant the power output will be at a maximum, at least if sufficient oxidant can be provided under such conditions that nearly complete combustion takes place.

7.1c Stored fuel Here such an amount of fuel is stored in the stove that no refuelling during operation is necessary. Considerable ingenuity must be exercised to ensure that only the fuel that is taking part in the combustion process comes into touch with high temperatures. The temperature in the stored fuel must not rise above 200°C. This is a field that has not yet been sufficiently investigated for the use of wood. In the field of space heating equipment some progress seems to have been made recently.

7.2 Character of combustion

The character of combustion is mainly a matter of how the volatiles burn that are given off when wood is exposed to temperatures above 250°C. Table 6 gives some values (Adams 1980) for the amount of pyrolysis products given off under high heating rate conditions such as will occur in a fire. Under these conditions the water and tar escape from the fuelbed together with the gases in the form of vapour and aerosol respectively. The cloudy mixture is called smoke.
Table 6. Pyrolysis products of dry wood

<table>
<thead>
<tr>
<th>Pyrolysis products</th>
<th>Mass fraction</th>
<th>0.20</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass fraction of char</td>
<td>0.20</td>
<td></td>
</tr>
<tr>
<td>Mass fraction of water</td>
<td>0.25</td>
<td></td>
</tr>
<tr>
<td>Mass fraction of tar</td>
<td>0.20</td>
<td></td>
</tr>
<tr>
<td>Mass fraction of pyrolysis gas</td>
<td>0.35</td>
<td></td>
</tr>
</tbody>
</table>

Pyrolysis gas composition

<table>
<thead>
<tr>
<th>Mole fraction of methane</th>
<th>0.20</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mole fraction of carbon monoxide</td>
<td>0.45</td>
</tr>
<tr>
<td>Mole fraction of hydrogen</td>
<td>0.17</td>
</tr>
</tbody>
</table>

7.2a. *Combustion of volatiles.* The combustion of volatiles is a complex affair. One of the complications is the fact that the composition of the volatiles is not constant. It depends on the temperature at which the pyrolysis takes place and on the residence time of the volatiles at elevated temperatures on their way to the location where they are expected to burn. From a combustion point of view it is advantageous if the volatiles have to pass through a region of high temperature. Larger molecules tend to break down into smaller ones which in general burn more readily.

(i) Diffusion flames

A diffusion flame represents the most generally occurring kind of flame, certainly for wood fires. In its simplest form it consists of a jet of flammable gas escaping into the atmosphere. At the interface of air and gas the combustion reaction takes place, forming hot gaseous combustion products and heating the remainder of the gas to some extent. In addition, two more processes take place. One is entrainment of air. The high temperature of the combustion products results in a low density as a result of which the gases will rise vertically. At the interface of the moving gases and the surrounding air entrainment of air will take place. Another process taking place at the same time is diffusion of air into the jet of gas (through differences in partial pressure of the constituents). Where air diffuses into unburnt gas and the temperature is sufficiently high, combustion takes place. Diffusion flames may produce soot and a stream of unburnt chemical compounds. As stated above, for combustion a sufficiently high temperature must exist there where air and gas meet. Higher up in the diffusion flame the temperature can fall below ignition point when the entrained air lowers the temperature of the gas stream. Another effect arises from the long residence time of the flammable gas at higher temperatures when through partial oxidation hydrocarbons of progressively higher carbon content are formed.

(ii) Premixed flames

In technical practice most combustion of gases takes place in the so-called pre-mixed state. Before issuing from the burner the gas is mixed in a certain proportion with air. (Where a very hot flame is desired the gas is mixed with pure oxygen as in a welding torch). In domestic gas ranges too, the gas is mixed with air upstream
from the burner. The resulting flame is much less luminous than the diffusion flame and the volume occupied by the visible part is much smaller (at the same heat flow). A premixed flame is measurably hotter. It does not leave deposits like soot or tar on objects that come into contact with it. As the gas stream contains all ingredients (fuel and oxidant) that are necessary for combustion, a premixed flame can come much closer to a solid object at a lower temperature than a diffusion flame before the exothermal reactions are arrested. Obviously a premixed flame seems a desirable thing to strive for in a woodstove.

7.2c Combustion of char Char is really a solid fuel. Combustion takes place at its surface forming carbon dioxide and liberating heat. If the temperature is high and the gas passes more char on its way carbon dioxide is reduced to carbon monoxide. Carbon monoxide, next to being very poisonous, has an appreciable calorific value. From energy economic considerations alone it is therefore desirable to admit air downstream from the char bed to burn the the carbon monoxide.

7.2d Woodburning modes Apart from the character of combustion we can distinguish several modes of wood burning.

(i) Simultaneous burning

Char burns at the same time as the volatiles and at the rate it is produced. In real simultaneous burning the char has burnt up the instant the flames from the volatiles die down. This state of affairs is approached in a well-ventilated fire on a grate. It could be useful for constant power applications.

(ii) Sequential burning

Here char only starts burning after all volatiles have escaped. This situation occurs to some extent in an open fire without a grate. Direct access of air to the wood is difficult, the wood being more or less screened off by the volatiles. Heat for the pyrolysis process is supplied by radiation from the flames. It is probable that the char fire, being situated quite some distance below the pan, has little net heating effect on the pan. In a slightly different configuration we could visualise a 'charcoal breeder' stove. In this hypothetical stove only the volatiles are burned while the charcoal that is formed is shut off from air and can be used for other purposes later.

(iii) Two-stage burning

We can think of going one step further than in the last paragraph and deliberately create combustion in two stages, each taking place at a different location. Two arrangements are thinkable, the one representing a step further into sophistication than the other. The governing principle is that the volatiles are made to pass through a zone of high temperature where the large molecules originally present in the volatiles break down into smaller ones which are easier to burn.

7.3 Co-current moving bed gasification

Used in a less sophisticated form for generating gas for the spark ignition engines
of cars and trucks in both world wars in times of petrol shortage, the principles of the wood gas generator are not new. Groeneveld (1980) has not only investigated the technological parameters of the process but has also worked out design procedures for the construction of gas generators for any kind of biomass. In principle (see figure 3) air is made to flow downward through a pipe into the combustion space in the bottom part of a bunker filled with dry biomass. At the point of issue of the air, the char burns with a high temperature, forming a very hot mixture of carbon dioxide and nitrogen. A very small fraction of the heat dries the wood above the fire zone while, closer to the fire, volatiles are liberated from the wood. The volatiles have to travel through the fire zone where as a result of the high temperature large molecules are broken up into smaller ones. Downstream from the fire zone there is more char where two important chemical reactions take place.

Carbon dioxide is reduced to carbon monoxide.

Water vapour is transformed into hydrogen and carbon monoxide. As the reactions do not run to completion the resulting gas contains carbon dioxide as well as monoxide and water vapour as well as hydrogen. Even so the result is a clean burning gas having about 85% of the original combustion value of the input fuel. Most of the loss of combustion value has gone into sensible heat of the gas which

![Figure 3. Co-current moving bed gas generator.](image-url)
is reported to be about 700°C. The recent design efforts were directed toward obtaining a tar-free gas for feeding internal combustion engines. The gas is drawn from the generator by the engine which usually provides ample suction. There was therefore no direct stimulus to investigate a design using minimum suction. The smallest generator built so far was for feeding a 5 kW I.C. engine, it has a dry wood consumption rate of 1 g/s which is equivalent to a thermal power output of 18 kW. For cooking purposes a typical maximum power output would be in the order of 2 to 7 kW. The revolutionary stove designer thus puts his neck in the noose on two counts. One is the scaling down of the existing design by a factor of ten; the other is getting it to work using whatever suction can be got from natural draught.

7.4 Two-zone burning

This is less sophisticated than the process set out in the preceding paragraph. The only difference is the absence of the reducing char zone (see figure 4). The idea is that for use as a cooking stove there is less need for an entirely tar-free gas. The operation is that of a parallel flow reactor where the reactants have the same flow direction. In this way fresh wood is not prematurely exposed to heat. Having to pass through the hot char-burning zone, the large molecules in the volatiles are reduced in size facilitating combustion. The absence of the reducing char zone causes less pressure loss. Thus it may be possible to use natural draught as the driving force in a cookstove design using this principle. Such a stove can be expected to be more sensitive to the moisture content of the fuel than the former type.

8. Materials

As material for making stoves we can think of three categories viz metal, ceramics and mud.

8.1 Metals

Here we usually think of cast iron and steel and, to a lesser extent, of aluminium.

8.1a Cast iron Cast iron can be made into quite intricate shapes. It can stand rather high temperatures. As a material it is not expensive. The price of cast iron products depends mainly on labour costs for making the moulds and models. It is a good and durable material for stoves as well as for frying pans.

8.1b Steel Steel is mostly used in the form of sheet. From steel sheet woodstoves can be made by a number of technologies such as rolling, bending, rivetting and welding. It is more expensive per unit mass than cast iron but one needs less of it as the wall thickness is usually much less than for cast iron. The investment in equipment is less for working steel sheet than for casting iron.

8.1c Aluminium Aluminium is much easier to cast than iron. The melting point is too low and the heat conductivity too high for making stoves but it is a very good material for making pans and possibly flat top plates for stoves.
8.2 Ceramics

By ceramics we mean objects made of fired clay. There are kinds of fired clay that can stand the temperatures occurring in domestic-sized wood fires and that can stand up to high temperature gradients without cracking. The art of making ceramics in the form of pottery is widely practiced. Quite a number of types of charcoal
brazier is made by potters. The raw material, clay, is available in many locations and therefore cheap. The equipment for working it can be quite simple. Fired clay ware is quite sensitive to mechanical and sometimes to thermal shock.

8.3 Mud

The mud referred to in woodstove literature is a more or less undefined clay. It is used for constructing heavy stoves. The material is allowed to dry naturally and is not fired. The material is not very strong and there is widespread ignorance about simple testing methods for suitable clays which could probably be cleared up through a short consultation with any ceramics institute. In mudstoves there is a risk of much heat being absorbed by the thick walls.

9. Heat transfer mechanisms

The various ways in which heat can be transferred from the source to the food are summed up in table 7. The pros and cons of the various items will be discussed below.

9.1 Direct contact between flames and pan

9.1a Premixed flames As both fuel and oxidant are present in the mixture as it flows from the burner mouth the flame is less dependent on ambient air being present. It can therefore be brought much closer to the pan bottom without the latter interfering with the combustion process. Since, in addition, the flame volume is relatively small the rate of heat transfer to the pan can be high.

9.1b Diffusion flames Diffusion flames are completely dependent on ambient air in order to be able to burn. Wherever therefore the flame comes into touch with the pan bottom the combustion reaction cannot proceed for lack of oxygen as well as from the relatively low temperature. The result is often a deposit of soot and/or tar on the pan bottom. The heat release per unit volume is less in a diffusion flame

<table>
<thead>
<tr>
<th>Heat transfer modes</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Direct contact of flames with pan</td>
</tr>
<tr>
<td>1.1 Premixed flames</td>
</tr>
<tr>
<td>1.2 Diffusion flames</td>
</tr>
<tr>
<td>2 No contact of flames and pan</td>
</tr>
<tr>
<td>2.1 Complete combustion upstream</td>
</tr>
<tr>
<td>2.2 Metal plate between flames and pan</td>
</tr>
<tr>
<td>3 Direct heat transfer to food</td>
</tr>
<tr>
<td>3.1 From combustion gases</td>
</tr>
<tr>
<td>3.2 By radiation</td>
</tr>
</tbody>
</table>
than in a premixed flame. This in addition to the gap necessary between pan bottom and flame makes for a lower possible rate of heat transfer.

9.2 No contact of flames and pan

Two possibilities suggest themselves. One is to let the volatiles burn up completely before bringing the gases into touch with the relatively cool surface of the pan. In this way there is a chance of obtaining good combustion in a space with a high temperature imparting a high temperature to the resultant gases which then have an opportunity to give up a good part of their heat to the pan. The other option mentioned viz the metal plate between fire and pan does not look very attractive. One positive point is that if the top of a stove is hermetically closed by a metal plate there is no danger of air leakage into the space between combustion space and chimney. In that case the chimney draught could be employed to ensure good combustion and heat transfer inside the stove. The underside of the top plate could be given a suitable profile to extract heat from the combustion gases. In pans with a thick-machined bottom combined with a machined top surface of the plate there may be some hope of a satisfactory heat transfer rate.

9.3 Direct heat transfer to food

Two mechanisms of heat transfer suggest themselves here. One is convection from combustion gases directly to the food. This implies that the gases must be clean e.g. contain no soot, tar or heavy hydrocarbons. This is another way of saying that for convective direct heat transfer clean combustion is imperative. This mode of heat transfer is used in domestic (natural-, coal- or LP-) gas burning ovens. It is also made use of in combination with radiation, in that exclusively male pastime of barbecuing where the clean heat source is charcoal. Radiation is a direct heat transfer option from source to food where the combustion products do not necessarily have to be clean. In that case the design should be such that no combustion gases come into touch with the food being processed. We do not know of any practical applications of this latter option.

10. Health and comfort

Considerations of health and comfort are among the motley collection of constraints within which the designer has to function, generating new or improved stoves. Under the present heading the designer has to ask himself how he can contribute to making it easier to use a new stove and how operation can be made safer. The health hazards lie in parts of human bodies touching hot parts of a stove and in poisonous or otherwise dangerous emissions.

10.1 Burns

All other things being equal, the better stove is the one that has fewer hot parts exposed in unexpected places. To prevent children from touching hot parts the latter should be situated at table-top level. This also enables one to combine the
application of natural draught with safety aspects. Insulation of hot parts also combines safety with energy saving.

10.2 Smoke

Woodsmoke, the product of incomplete combustion of wood contains a large number of organic chemical compounds in varying concentrations. The presence of some of these compounds depends on the conditions of the burning process but according to various sources such as Todd (1981) the tar in woodsmoke contains noticeable quantities of polycyclic aromatic hydrocarbons, some of which are proven carcinogens. It is therefore not surprising to find that some industrialised countries have a legislation on the emissions of woodsmoke. As general health improves in the third world countries we can expect legislation concerning woodsmoke emissions to come into effect there as well. The implication is clear. If woodstoves are to have a future—and they must since in large parts of the world wood is the only available fuel—they will have to be made safe from the emission point of view. The solution lies in complete combustion. Some might object that complete combustion of a fuel does not guarantee the absence of oxides of nitrogen. As, however, gaseous pyrolysis products of wood have a fairly low calorific value, it is expected that the combustion temperatures will not be so high as to produce appreciable amounts of nitrous oxides. Since wood essentially contains only carbon, hydrogen and oxygen, we can therefore expect clean stack gases consisting only of nitrogen, water vapour and carbon dioxide if we can achieve complete combustion.

10.3 Soot and tar

A result of incomplete combustion and direct contact of flames with the pan is a deposit of soot and tar on the pan bottom. Besides the nuisance of having to clean the pans on the outside there is the regular contact of skin with soot and especially tar which may constitute a hazard to health. Here also the health aspects argue for clean combustion.

10.4 Comfort

A good stove should be comfortable to use. The parts that carry the pans should be at such a position (height, horizontal distance from fixed obstacles) that the pans can be put on and taken off without undue strain on the part of the operator. A closely related question, in this respect, is that of cooking posture. Should a design pay attention to observed cooking postures without going into the why's and wherefores? Does one put undue strain on operators by giving them stoves that carry pans at table-top level while they have been used to cook in a squatting position? Is the squatting position a matter of free choice or of necessity? The present author does not have the impression that making 'native squatters' do their cooking standing up brings discomfort.
11. Creative draughtsmanship

Confronted with the collection of conditions, physical and chemical phenomena and constraints from the foregoing, the question is what we can do to create equipment that can provide cooking process heat at a low fuel consumption and at a high comfort level. When we look at combustive heating devices in the wealthier part of the world, we see that invariably some form of mechanical power is involved in realising neat and controllable combustion. For instance, in oil burners both fuel oil and combustion air are mechanically pumped. Gases are delivered at such pressure that air can be inducted by ejector action of the jet of gas in the burner. Coal is mechanically ground and pneumatically transported to the burner and there mixed with more mechanically supplied air. In the woodstove “trade” we are faced with a very difficult fuel and with no source of mechanical power except natural draught. Traditionally draught is mainly used to remove the combustion products from the location of the stove after they have given off much of their heat content. Other applications, however, can be visualised as listed in table 8. We will explain some of the terms used in the table, pointing out possible advantages over other systems.

11.1 Chimney

A chimney can be used both to draw air into the combustion space to improve combustion as well as to overcome purposely introduced flow resistance under the pans. The latter improves heat transfer. To ensure correct functioning, however, any air leaks between air intake and the chimney must be eliminated. Especially around the pan seat leak tightness is not easily achieved. A further disadvantage is that the specific draught (pressure difference per unit height) is low because of the relatively low temperature of the gases entering the chimney. Careless design or operation can cause much of the heat of combustion to escape through the chimney. In the currently produced woodstove literature the role of the chimney appears to be confined to making stoves “smokeless”. Little is said about the effect on the performance of a stove. We will here describe some of the main effects.

As a result of buoyancy the column of (warm to hot) gases in the chimney creates a negative pressure at the part of the stove it is connected to. As a result air is drawn into the stove. If, therefore, a certain stove can function without a chimney, more air will be drawn into it when a chimney is fitted. Whether this will improve the stove’s performance depends on the latter’s design.

Table 8. Natural draught options

<table>
<thead>
<tr>
<th>Natural draught use</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Post heat extraction draught</td>
</tr>
<tr>
<td>1.1 Chimney</td>
</tr>
<tr>
<td>2 Pre heat extraction draught</td>
</tr>
<tr>
<td>2.1 Pre flame draught</td>
</tr>
<tr>
<td>2.2 Post flame draught</td>
</tr>
</tbody>
</table>
On designing woodstoves

55

The draught (negative pressure) created by a chimney depends on its height, on the temperature of the gases that flow through it and on its diameter. If an existing chimney is made 1.5 times as high it will, in a first approximation, draw about twice as much air through the stove per unit time as before. Depending on the design of the stove this might double the combustion rate in the stove. This, in turn, may produce hotter gas going up the chimney increasing the draught and thus further increasing heat losses. Another possible result of indiscriminately adding a chimney is that flames that were meant to flow around the pan are drawn away from it directly into the chimney, thus seriously decreasing the stove's efficiency.

11.2 Draught upstream from the pan

We can think of two ways in which draught can be used upstream from the pan.

11.2a Before complete combustion This may be the way to use the co-current moving bed (CCMB) and the simple two-zone burning principle. Hot gas from the generator which is placed as near to ground level as possible, travels through a vertical insulated pipe to table top level where part of the draught is used to create a strong premixed flame. The combustion being clean, no exhaust to outside the locality is necessary. Another part of the draught is used to draw air into the generator and through the charburning and reduction zone. The gas having a rather high temperature (700°C) has a moderately high specific draught.

11.2b After complete combustion Here the draught is used to achieve complete combustion as well as for increasing heat transfer to the pan. The set-up visualised is as in figure 5. The stove can be used for charcoal and should then have an adjustable power output. Primary air enters through the grate at the bottom, the amount of charcoal burning is then determined by the mass flow of air entering. The burning of the charcoal produces very hot nitrogen and carbon dioxide which is reduced to carbon monoxide by the charcoal downstream of the combustion zone. For that reason secondary air holes are provided downstream of the charcoal bed to supply air to burn the carbon monoxide to dioxide. The combustion part is built as close to ground level as possible while the insulated riser carries the very hot (1200...1400°C) gases to table top level where a seating arrangement for a pan is provided. The latter can be made in such a way that the flow resistance of the hot gases under the pan bottom ensures optimal heat transfer automatically for any size of pan. Due to the very high temperature of the combustion gases the specific draught is high. For wood the same stove might be used but there will be no direct control of the power output while volatiles are being evolved. The amount of wood in the combustion space and the size of the wood pieces will determine the rate of burning and the user can only work the two air controls to optimize combustion. Such a stove could be quite useful for one-shot operations such as getting water to boil and for food boiling with a haybox.

12. The present state of woodburning cookstoves

Back to the present now after this foretaste of possible future developments. What
we have here and now are the traditional open fire, some traditional closed stoves and a large number of 'improved' stoves built by development workers. Stoves in the latter category mostly have in common that they are heavy and made of clay. They vary mainly in the number of holes to accommodate pans. Most have only two—but some go so far as to have from four to six holes to, we must assume, efficiently cook the dishes of the world's poor.

Contrary to current practice we will in the next section sing the praise of the open fire, a cookstove that has been consistently ignored in woodstove literature so far. In a later section we will say something about closed stoves and their properties.

12.1 The open fire

The open fire is the oldest cooking stove in existence. Compared to more recent
and more elaborate wood-burning cookstoves it still has a number of points in its favour.

(i) It is quickly built up with a minimum expenditure of materials and time.
(ii) While in operation it provides light as well as heat.
(iii) As a combined space heater and cooking stove it has an efficiency close to 100%.
(iv) The state and condition of the fire is easily checked.
(v) The heat output rate can be varied more easily.
(vi) It is easily adapted to any size of pan.
(vii) Efficiency-wise it is competitive with most of the more elaborate wood-burning cookstoves.

Disadvantages when compared to the presently available (closed) cookstoves are the following.

(i) When a chimney is used there is less nuisance from smoke to the user even though the combustion may be worse (the effect on the environment may be quite another matter).
(ii) Some stoves have a higher heat transfer efficiency. When this is not offset by lesser range of control the same amount of food can be prepared using less fuel.
(iii) The adverse effect of wind on the heat transfer efficiency of some closed stoves is less than on the open fire.
(iv) Some closed stoves lose less heat to their immediate environment making things more comfortable for the operator.
(v) Accidental touching of hot parts causing burns is less easy in some closed stoves.

12.1a Operating the open fire: Using a Grate. In the open fire the air has free access to the fuel, control therefore is achieved through manipulating the fuel. The output can be controlled primarily through dosage of fuel and, to a lesser extent, through control of the size of the fuel pieces. Tests have shown that the major part of the heat output produced by the open fire comes from the combustion of the volatiles. To best utilise this heat the position of the pan in relation to the fuelbed must be such that access of air to the fire is assured; on the other hand the pan must be close enough to the firebed to absorb as much heat as possible. The optimal position of the pan, resulting from these considerations, is such that only a small fraction of the heat generated by the burning char is captured. This is easily seen from observation, at the instant the flames die down, the contents of the pan slowly stop boiling. Observation and measurements by Visser (1982) have shown that, particularly when no grate is used, the burning of char only begins after the volatiles have all escaped from the fuelbed. Only then can the air gain access to the char. When a grate is used the two burning processes take place more simultaneously and it can be expected that the burning char contributes to a higher extent than before toward heat input into the pan. A more sophisticated set-up could make use of two pan positions, one for making the utmost use of the heat output of the flames, the other for using the heat from the char.
12.1b Burning model of the open fire. The fuel is surrounded by air. In a first approximation we assume every piece to commence burning the instant it is placed on the fire. This being so the rate of evolution of volatiles is related to the outside surface area of the fuel pieces. Therefore the smaller the pieces, the higher the evolution rate of volatiles and the corresponding rate of heat production by the flames. When the open fire is operated by introducing charges of constant mass at time intervals which are so spaced that the desired average heat output rate is achieved we are practically operating an 'on-off' system of control. The only parameters governing the heat output rate versus time characteristic are the size and number of the fuel pieces (other things such as moisture content, density and kind of wood being constant). How this heat output rate varies with the dimensions of the fuel pieces was the subject of a short exercise in which a constant 'fire penetration rate' as defined by Tsuchiya & Sumi (1971) was assumed. The fire penetration rate is the velocity at which the char boundary advances into the virgin wood. The volume of wood that is pyrolysed per unit time is therefore equal to the fire penetration rate times the exposed surface area of the wood. Thus the dimension of the fire penetration rate is that of velocity.

In the following we assume the fire penetration rate to be constant, neglecting all complications for the sake of having a simple model. The numerical value of the fire penetration rate was calculated from some of the open fire experiments (Visser 1982) and found to be:

\[ c = 27.8 \times 10^{-6} \, \text{m/s}. \]

For the rate of heat release of \( n \) similar rectangularly-shaped pieces of wood the following expression is obtained for the combustion of volatiles only:

\[ p_v = 2 \times 0.8 \, cn \, \rho_w \, b_v \left\{ lb + lh + bh + 12 \, c^2 \, t^2 - 4 \, ct \, (l + b + h) \right\}, \quad (1) \]

where \( p_v \) is the rate of heat output (W), \( c \) is the fire penetration rate (m/s), \( n \) is the number of pieces of wood, \( \rho_w \) is the density of the wood (kg/m\(^3\)), \( b_v \) is the calorific value of the volatiles (J/kg), \( l \) is the length of a woodpiece (m), \( b \) is the width of a woodpiece (m), \( h \) is the height of a woodpiece (m) and \( t \) is the time (s). The coefficient of 0.8 in the expression denotes the fraction of the dry mass of wood that is evolved in the form of volatiles. A similar expression can be derived for cylindrical pieces:

\[ P = 0.4\pi cn \, \rho_w \, b_v \left\{ d (d + 2l) - 4ct (2d + l) + 12c^2 \, t^2 \right\}, \quad (2) \]

where \( d \) is the diameter of the woodpieces (m).

For spherical pieces the expression becomes:

\[ P_v = 0.8 \, \pi cn \, \rho_w \, b_v \left(d^2 - 4ctd + 4c^2t^2\right) \] (kW).

Using these expressions one gets a peak power that is in excess of what was actually measured, probably due to initial warming up of the pieces being neglected. Additionally the assumption that all wood pieces were immediately surrounded by hot gas may have been incorrect.
12.1c Conditions for efficient operation  We can give here some general recommendations that can result in decreased use of firewood when using an open fire. Following these pointers will also result in less smoke production and faster response of the fire to changing power output demands.

(i) Use wood in small pieces, not larger than say 20x20x60 mm;
(ii) Dry the wood before use, small pieces dry very much more rapidly;
(iii) Use a grate;
(iv) Use high power to bring the pan to boil (see table 9 for optimal combination of pan, food quantity and fire output);
(v) Add one piece of wood at a time to the fire to get a constant output;
(vi) When contents of pan have warmed throughout (see table 3 for larger food particles), transfer pan to a haybox for the remainder of the processing time.

It is appreciated that the above recommendations are not always practicable.

12.2 Closed stoves

The adjective 'closed' is primarily used to distinguish the object from the open fire set-up. The actual degree of 'closedness' of a stove in practice is a different thing again.

Table 9. Pan sizes, food quantities and optimal fire power for use with the open fire.

<table>
<thead>
<tr>
<th>Pan bottom diameter (cm)</th>
<th>Mass of (food and) water (kg)</th>
<th>Height of (food and) water in pan (cm)</th>
<th>Relative height of contents in pan</th>
<th>Open fire heat output rate (*) (kW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>12</td>
<td>0.50</td>
<td>4.4</td>
<td>0.51</td>
<td>1.58</td>
</tr>
<tr>
<td>14</td>
<td>0.85</td>
<td>5.5</td>
<td>0.57</td>
<td>2.16</td>
</tr>
<tr>
<td>16</td>
<td>1.31</td>
<td>6.5</td>
<td>0.60</td>
<td>2.80</td>
</tr>
<tr>
<td>18</td>
<td>1.93</td>
<td>7.6</td>
<td>0.63</td>
<td>3.56</td>
</tr>
<tr>
<td>20</td>
<td>2.71</td>
<td>8.6</td>
<td>0.65</td>
<td>4.38</td>
</tr>
<tr>
<td>22</td>
<td>3.68</td>
<td>9.7</td>
<td>0.68</td>
<td>5.30</td>
</tr>
<tr>
<td>24</td>
<td>4.86</td>
<td>10.7</td>
<td>0.70</td>
<td>6.30</td>
</tr>
<tr>
<td>26</td>
<td>6.29</td>
<td>11.8</td>
<td>0.71</td>
<td>7.42</td>
</tr>
<tr>
<td>28</td>
<td>7.93</td>
<td>12.9</td>
<td>0.72</td>
<td>8.60</td>
</tr>
<tr>
<td>30</td>
<td>9.85</td>
<td>13.9</td>
<td>0.74</td>
<td>9.86</td>
</tr>
<tr>
<td>32</td>
<td>12.1</td>
<td>15.1</td>
<td>0.75</td>
<td>12.22</td>
</tr>
<tr>
<td>34</td>
<td>14.6</td>
<td>16.1</td>
<td>0.76</td>
<td>12.68</td>
</tr>
<tr>
<td>36</td>
<td>17.5</td>
<td>17.2</td>
<td>0.77</td>
<td>14.22</td>
</tr>
<tr>
<td>38</td>
<td>20.6</td>
<td>18.2</td>
<td>0.77</td>
<td>15.82</td>
</tr>
<tr>
<td>40</td>
<td>24.3</td>
<td>19.3</td>
<td>0.79</td>
<td>17.54</td>
</tr>
<tr>
<td>42</td>
<td>28.2</td>
<td>20.4</td>
<td>0.79</td>
<td>19.36</td>
</tr>
<tr>
<td>44</td>
<td>32.7</td>
<td>21.5</td>
<td>0.80</td>
<td>21.22</td>
</tr>
<tr>
<td>46</td>
<td>37.5</td>
<td>22.6</td>
<td>0.80</td>
<td>23.22</td>
</tr>
<tr>
<td>48</td>
<td>42.7</td>
<td>23.6</td>
<td>0.81</td>
<td>25.24</td>
</tr>
<tr>
<td>50</td>
<td>48.3</td>
<td>24.6</td>
<td>0.81</td>
<td>27.46</td>
</tr>
</tbody>
</table>

(*) Heat transfer efficiency assumed 25%
12.2a Using long wood  There are stoves, for instance, fired with long pieces of wood. The fuel loading port, in that case, is permanently open. Control of combustion air is rather limited in that case. The intensity of the fire is controlled by the amount of wood present in the combustion space, by the diameter of the fuel pieces and by the airflow that is allowed to enter the combustion space. The latter is determined by the draught generated in the downstream part of the stove. The extent of control that can be exercised by manipulating dampers downstreams of the combustion space is limited. If the damper is closed beyond a certain point, the flames may come out of the fuel-loading port, possibly very effectively decreasing the net flow of heat into the pan but not at a high efficiency.

12.2b Using short wood  Stoves fired with shorter pieces of fuel can be closed more or less hermetically so that only air is admitted where it is considered useful. The air is controlled by manipulating sliding or hinged dampers or baffles. It is not always appreciated that combustion does not automatically occur when there is sufficient air. If, for instance, the temperature is not high enough combustion will not occur and if relatively cool objects protrude into the combustion space they may quench the combustion reaction. In all closed stove designs to date we see that the pan bottom forms part of the combustion space. Wherever this was the result of conscious designing it was done in an effort to capture as much of the radiant heat (which is mainly released by the burning char). For that, the surface area of the fire 'seen' by the pan must be as large as possible. This results in the pan bottom being situated quite close to the fuelbed which, in turn impedes combustion of the volatiles by presenting a relatively cool surface to the volatile reactants. This happens even where care was taken by the stove designer to ensure the access of secondary air to the combustion space.

12.3 The control problem in a closed woodstove:

An ideal of stove builders is to be able to build a stove which can be loaded with such an amount of fuel that uninterrupted operation is possible for an extended period of time. To be able to control the heat output rate to a fair extent is also an item high on their list of priorities. Closed stoves come in various stages of sophistication (or, more correctly, underdevelopment) where the air management is concerned. Beginning at the bottom of the scale we come across a number of alternative designs.

12.3a Stoves with no grate  The fuel rests on a flat surface inside the stove body. There may or may not be a damper to control the air intake. Fire conditions are rather similar to those for the open fire without a grate except that, in comparison, access of air is severely impeded. We may expect some degree of control through manipulation of the air intake either by an intake damper or by a chimney damper. When so desired, the fire is made to choke on its own combustion products whenever the damper is actuated in order to decrease the output. From this kind of stove we can expect a slightly better heat transfer efficiency than from the open fire even though the combustion will generally be less complete.
12.3b Stoves with a grate If no provisions were made for separate control of the air supply to below the grate and downstream from the fuelbed, we have a situation similar to an open fire with a grate being enclosed between walls. Any control of the output will come from oxygen starvation of the whole fire through manipulation of intake or chimney dampers. When, in an attempt to control the heat output rate a damper is actuated, the fire can choose for itself how to cope with the oxygen deficiency. At full power char will burn more or less simultaneously with the volatiles than in the set-up without a grate.

12.3c With air control to the grate In this class of stoves there is a means to control the air flow to the underside of the grate. The fire in this case consists of a layer of burning char directly on top of the grate. Depending on the stove construction, means of admitting air downstream from the fuelbed may or may not be provided. In all cases air flows through the burning char upward through the fuelbed. In this configuration it is quite probable that the flowrate of air through the fuelbed influences the behaviour of the remainder of the fuel including the rate of heat output. This must, however, not be confused with the notion that by this means we have full control of the rate of heat output (neither that what measure of control we do have happens at an acceptable combustion efficiency).

12.4 Model

In the following we will work out a model for a fire in a closed stove such as just described. In essence the fire consists of a column of fuel resting on a grate and enclosed with a wall on the vertical sides as shown schematically in figure 6. We stipulate that the volatiles leaving the top of the column do not, upon combustion, transfer heat back to the fuel. We wish to know whether by varying the air flow through the grate we can control the heat output rate. The great difference with the open fire is that there is no influx of air from the sides. Basically we have here a reactor with the reactants (fuel and air) in counterflow, fuel flowing from the top down and air flowing upward from the grate. Air comes in through the grate and first passes the char zone where part of the oxygen reacts with carbon forming carbon dioxide gas and releasing heat. The gas leaving the char zone will therefore have a high temperature depending mainly on the fraction of available oxygen that was converted to $\text{CO}_2$. This hot gas mixture passing through the column of fresh fuel will transfer part of its heat content to it when pyrolysis takes place. This results in a flow of volatiles leaving the top of the column. The question is now whether we can establish a relation between the power output of the char fire and the power output of the volatiles upon complete combustion. This in turn might indicate whether control by this means is possible. In the exercise we use the values from table 10.

12.4a Char combustion The mass and energy balance for the combustion of char is:

$$1 \text{ kg C} + 11\cdot46 \text{ kg air} = 3\cdot67 \text{ kg CO}_2 + 8\cdot79 \text{ kg N}_2 + 31 \text{ MJ},$$
In the above equation 11.46 kg is the (stochiometric) amount of air that is required if all the oxygen combines with carbon. This state of affairs does not occur in practical situations where a certain excess of air is necessary. We define the excess air factor $\lambda$ as follows:

$$\lambda = \frac{\text{actual amount of air}}{\text{stochiometric amount of air}}.$$  

The mass and energy balance then becomes:

$$1 \text{ kg C} + 11.46 \lambda \text{ kg air} = 3.67 \text{ kg CO}_2 + 8.79 \text{ kg N}_2 + 11.46 (\lambda - 1) \text{ kg air} + 31 \text{ MJ}.$$
The temperature of the gas mixture leaving the char zone can be calculated from a heat balance:

\[
\Delta T = \frac{31 \times 10^3}{1.46 \times 3.67 + 8.79 + 11.46 (\lambda - 1)}.
\]

Similarly an expression for the mean specific heat \( C_m \) of the gas mixture can be found:

\[
C_m = \frac{31 \times 10^3}{\Delta T (1 + 11.46\lambda)}.
\]

Values given in table 11 below were thus calculated for various \( \lambda \) values. The third column was computed assuming an initial reactants temperature of 25°C.
12.4b Pyrolysis To simplify the calculations we will assume the fire penetration rate to remain constant (and at the value derived earlier), down to a temperature of the surrounding gas of 600°C. In gas below this temperature the wood will remain unaffected. Under these conditions volatiles will be evolved at a rate consistent with equation (1) until such an amount of heat has been absorbed by the fresh wood that the temperature of the gas mixture has fallen below 600°C. As to the heat requirements for liberating volatiles, authors such as van Ginneken (1982) suggest that the amount of heat involved is very slight. Adams (1980) states that the pyrolysis process of wood consists of an initially endothermic part followed by an exothermic part. In total the pyrolysis process is approximately thermoneutral.

For a first approximation we set the pyrolysis heat equal to the specific heat of wood multiplied by its temperature rise from 25 to 400°C. For the specific heat of wood we use a value found in Eckert & Drake (1972), valid for oak with a moisture content of 20%. This was corrected for the oven dry condition and gave a figure of 2.12 kJ/kgK. The mass of wood will form a column of height \(Z\) on the grate which has a surface area of \(A\) (m²). The rate of char burning per unit grate surface area is \(k \text{ kg/m}^2\text{s}\). In our model the volatiles leaving the fuelbed do not upon ignition transfer heat back to the fuelbed, all heat the fuelbed receives is exclusively from the combustion of char.

The situation is then as follows. Air flows upward through the grate where part of it oxidises char. The resultant mixture of gases has a temperature dependent on the magnitude of the air excess factor \(\lambda\). The gas flows upward through the fresh fuel liberating volatiles so long as its temperature is above 600°C. The wood that is in contact with the hot gas (>600°C) will become pyrolysed at a rate corresponding to the fire penetration rate. The extent of the pyrolysis zone in \(Z\)-direction is then determined by the region that is occupied by gas at a temperature of 600°C or higher. After some time three or four different regions can be distinguished. Moving upward we pass the burning char zone, a zone of freshly-formed char, a region containing wood that is in the process of being pyrolysed and possibly a fourth zone consisting of as yet unaffected wood. The temperature reduction of the gas leaving the burning char comes about by heat transfer to fresh wood, it being heated to 400°C. The question is now which of the following quantities is limiting the production of volatiles. (a) The heat production of the char. (b) The total surface area of the fresh wood. In the first case the heat production of the char is such that only part of the wood can be pyrolysed at a time. In other words, the heat production of the char is less than the product of fire penetration rate, total initial surface area, density and pyrolysis heat of the wood. The evolution of volatiles will then be constant for so long as any virgin wood remains. As soon as the last piece of fresh wood is attacked the rate of evolution of volatiles will decay with time. In the second case the rate of evolution of volatiles will reach its peak almost immediately after the start. It will then begin to decrease with time. There is no constant rate of evolution of volatiles here.

Another question that might be raised is the matter of relative heat capacity of gas and wood. If the heat capacity of the gas is relatively high and the velocity at which it moves through the column of wood is low it is thinkable that the evolution of volatiles is limited by the surface area of wood that is getting exposed to hot gas. The evolution of volatiles will then increase only slowly. If, on the other hand, the heat capacity of the gas is low, more surface area of fresh wood will be available
than can be pyrolysed, the evolution of volatiles will quickly reach a constant value at which it will remain for as long as virgin wood is present. To get some feel of magnitudes we will do a few exploratory calculations.

12.4c Potential pyrolysis heat from the char

The rate of heat production by the char on the grate is:

\[ P_c = Ak \times 31 \times 10^3 \text{ (kW)} \]

This results in a mass flow of hot gas:

\[ \phi_g = \frac{P_c}{C_m} \text{ (kg/s)} \]

The velocity of the gas through the fuelbed in Z-direction can be found by dividing the volume rate of flow of the hot gas by the mean cross-sectional area of the column not occupied by wood. The latter quantity is equal to the void volume divided by the height Z. The void volume is:

\[ V_v = AZ - M_w/\rho_w \text{ (m}^3\text{)} \]

The free cross-sectional area is then:

\[ A_f = \frac{V_v}{Z} = A - M_w/Z\rho_w \text{ (m}^2\text{)} \]

The density of the gas is inversely proportional to the temperature. For convenience we have extended the fluegas density table from De Lepeleire et al (1981) and reproduced it in table 12. We shall use a constant mean density of the gas at the average of the temperature from table 11 and 600°C

\[ t_m = \frac{1}{3}(25 + \Delta T + 600), \text{ (°C)} \]

The mass flow of gas leaving the char is:

\[ \phi_g = Ak(1 + 11.46\lambda), \text{ (kg/s)} \]

The heat flow available for pyrolysis is:

\[ P_p = \phi_g C_m(\Delta T - 302), \text{ (kW)} \]

Substituting \( C_m \) from equation (3) and rearranging we get:

\[ P_p = Ak \times 31 \times 10^3 \left( 1 - \frac{302}{\Delta T} \right) \]

(4)

This gives the potential heat flow that can liberate volatiles (if the product of fire penetration rate and surface area of the fuel is not the limiting factor).
Table 12. Density of fluegas (at sea level) from complete combustion of wood. Moisture content 0-50 %. Air excess factor 1:4-3:0.

<table>
<thead>
<tr>
<th>Fluegas temperature °C</th>
<th>Fluegas density kg/m³</th>
</tr>
</thead>
<tbody>
<tr>
<td>2400</td>
<td>0.1297-0.1338</td>
</tr>
<tr>
<td>2000</td>
<td>0.1525-0.1573</td>
</tr>
<tr>
<td>1600</td>
<td>0.1851-0.1910</td>
</tr>
<tr>
<td>1200</td>
<td>0.2354-0.2429</td>
</tr>
<tr>
<td>1000</td>
<td>0.2978-0.2810</td>
</tr>
<tr>
<td>900</td>
<td>0.2956-0.3050</td>
</tr>
<tr>
<td>800</td>
<td>0.3232-0.3335</td>
</tr>
<tr>
<td>700</td>
<td>0.3564-0.3677</td>
</tr>
<tr>
<td>600</td>
<td>0.3972-0.4098</td>
</tr>
<tr>
<td>500</td>
<td>0.4485-0.4629</td>
</tr>
<tr>
<td>400</td>
<td>0.5152-0.5306</td>
</tr>
<tr>
<td>300</td>
<td>0.6051-0.6244</td>
</tr>
<tr>
<td>200</td>
<td>0.7330-0.7564</td>
</tr>
<tr>
<td>150</td>
<td>0.8197-0.8458</td>
</tr>
</tbody>
</table>

The specific volume of the gas in analytical form is:

\[ V_\varnothing = \frac{22.4T}{273} \left( \frac{3.67}{44} + \frac{8.79}{28} + \frac{11.46(\lambda - 1)}{29} \right) \left( \frac{1}{1 + 11.46\lambda} \right) \]

which can be rewritten:

\[ V_\varnothing = \frac{22.4 (0.00216 + 0.395\lambda)}{273(1 + 11.46\lambda)} \text{ (m}^3/\text{kg}) \]

As the term between parentheses in the numerator is \( \ll \lambda \), the expression can be simplified without introducing important inaccuracies to:

\[ V_\varnothing = \frac{\lambda T}{30.84(1 + 11.46\lambda)} \text{ (m}^3/\text{kg}) \]

which gives the specific volume of the gas leaving the char bed at absolute temperature \( T \) and at sea level pressure. The volume flow of this gas is:

\[ \varphi_v = Ak\lambda T/30.84 \text{ (m}^3/\text{s}) \]

Thus the velocity of the gas through the column of fresh fuel is:

\[ c_v = \frac{Ak\lambda T}{30.84\left\{ A - M_w/(\rho_w Z) \right\}} \]
12.4d Heat absorption potential of wood The heat flow that can be absorbed by the wood is governed by the exposed wood surface area, the fire penetration rate and the specific heat of the wood. This is assumed true for our model whenever the surrounding gas has a sufficiently high temperature (600°C minimal). When all the wood is surrounded by gas of sufficiently high temperature, the heat flow transferred to the wood for pyrolysis is:

\[ P_w = A_w \rho_w C_w (t_p - 25), \quad (\text{kW}), \]

where \( P_w \) is the pyrolysis power (kW), \( A_w \) is the total exposed wood surface area (m²), \( \rho_w \) is the density of the wood (kg/m³), \( C_w \) is the specific heat of the wood (kJ/kg.K) and \( t_p \) is the pyrolysis temperature (°C). The temperature at which the wood begins to pyrolyse we have assumed to be 400°C.

We can now derive an expression for the maximum possible heat flow that can be absorbed in the initial stage by the mass of wood contained in the column with height \( Z \). This pyrolysis heat can only be absorbed when all wood is enveloped in gas at a temperature equal to or above 600°C. Using the expressions (1) and (2) derived in the section on open fires we can write the equations for the maximum heat absorption rate for a pile of prismatic and cylindrical pieces of wood.

For prismatic pieces of dimensions \( b, h \) and \( l \) we get:

\[ P_w = 75OM_w cC_w (1/b + 1/h + 1/l) \quad (\text{kW}). \]

For cylindrical pieces of length \( l \) and diameter \( d \) we get:

\[ P_w = 75OM_w cC_w (2/d + 1/l) \quad (\text{kW}). \]

This heat absorption potential is an important quantity. If it comes out higher than the available pyrolysis power as developed in (4) the latter represents the limiting quantity and as a consequence there will be a period of constant volatiles production.

12.4e Volatile calorific value and pyrolysis energy The amount of heat required to pyrolyse a unit mass of wood is, as a consequence of our earlier assumptions:

\[ c_w (400 - 25) = 2 \cdot 12 \cdot 375 = 795 \quad (\text{kJ/kg}). \]

12.4f Calorific value of the volatiles A unit mass of wood decomposes (see table 6) into 0.2 mass units of char and 0.8 mass units of volatiles. The calorific value of the volatiles can be established through the following argument:

The calorific value of char is 31 MJ/kg;
The calorific value of wood is 18 MJ/kg.
One kg of wood produces 0.2 kg of char;

Therefore the combustion of 1 kg of wood can be said to produce:

\[ 0.2 \cdot 31 \text{ MJ} = 6.2 \text{ MJ of heat from the char and} \]
\[ 18 - 6.2 = 11.8 \text{ MJ from the combustion of the volatiles.} \]
12.4g *Power gain of pyrolysis* In table 11 we can see that for an air excess factor of 2 the resultant gas has an initial temperature of 1235°C. Cooling this gas to 600°C uses up about half its sensible heat content. When the heat of the char combustion products is used for pyrolysis in this manner we see that (at $\lambda = 2$) we have to burn an amount of char equivalent to:

$$2 \times 0.795 \text{ MJ} = 1.59 \text{ (MJ)}$$

to decompose one kg of dry wood, generating an amount of volatiles with a calorific value of 11.8 MJ and producing 0.2 kg of char. As the pyrolysis heat equals the combustion heat of 0.05 kg of char it is clear that in the stage under discussion the process produces 0.2 kg of char through the burning of 0.05 kg of char. The 'char breeding rate' has a value of 4, the process produces more char than it consumes. Another way of looking at the process is to relate the heat of combustion of the volatiles produced to the heat of combustion of the char that was burned to produce them. In this way we can define a gain factor (as with an amplifier) as follows:

$$g_c = \frac{P_v}{P_e} = \frac{11.8}{1.59} = 7.42.$$  

It says that in our model one unit of heat from burning char releases more than 7 times that amount of heat in volatiles. In a fire where both the char and the volatiles are consumed at the rate they are formed, perforce 0.8 kg of volatiles burn simultaneously with 0.2 kg of char. In this case we can speak of a stationary state and the gain factor attains a value:

$$g_{st} = \frac{11.8}{6.2} = 1.9.$$  

When this value is exceeded the char conversion exceeds the char consumption and there will be char left over after all volatiles have been released. This is what is seen to occur in all practical cases.

12.4h *Example* We will now do the calculations for a closed stove with the moderate heat production rate of 3 kW.

Data:

Grate surface area: $A = 7.854 \times 10^{-3} \text{ m}^2$
The mass of wood $M_w = 0.25 \text{ kg}$
Height of column $Z = 0.2 \text{ m}$
Length of wood $l = 0.05 \text{ m}$
Width of wood $b = 0.015 \text{ m}$
Height of woodpieces $h = 0.015 \text{ m}$.

From tests with an open fire on a grate the char heat production is estimated at 70 kW/m². Dividing this by the calorific value of char we get the char-burning rate:

$$k = \frac{70}{31 \times 10^3} = 2.258 \times 10^{-3} \text{ (kg/m}^2\text{s)}.$$
On designing woodstoves

The char bed heat output rate is:

\[ P_c = A_k b_c = 7.854 \times 10^{-3} \times 70 = 0.55 \text{ (kW)}. \]

The maximum initial power that can be absorbed by the wood is:

\[ P_w = 750 \times 0.25 \times 27.8 \times 10^{-6} \times 1.76 \times (1/0.015 + 1/0.015 + 1/0.05) = 1.4067 \text{ (kW)}, \]

which is larger than the heat production of the char. The maximum volatile power output is then:

\[ P_v = 0.55 \times (11.8/1.59) = 4.082 \text{ (kW)}. \]

To ensure an initial power output of 3 kW, the air supply has to be decreased to burn the char at:

\[ P_c = (1.59/11.8) \times 3 = 0.404 \text{ (kW)}. \]

The velocity with which the gas from the char bed passes through the fresh wood is given by equation (5)

\[ c_o = \frac{A_k \lambda T}{30.84 (A - M_w/p_w Z)} = 0.275 \text{ (m/s)}. \]

In order to have a total volatiles heat output rate of 3 kW this has to be reduced in the same ratio as the char powers \textit{viz.}

\[ c_o (3 \text{ kW}) = \frac{404}{550} \times 0.275 = 0.202 \text{ (m/s)}. \]

We can see that the whole column of wood (of 0.2 m tall) is permeated with combustion gas from the char bed in little under one second. At the conclusion of this example we see that in a practical case, according to our model, the heat production from the burning char is the limiting factor ensuring a period of constant power operation. At the end of the constant burning rate of volatiles, as a consequence, we will have a considerable amount of unburned char. If we had used pieces of wood so large that their total surface area would have restricted the initial rate of pyrolysis, there would never have been a constant rate of volatiles production.

12.4 Influence of moisture In order to achieve a balanced consumption rate of wood we could think of artificially increasing the amount of heat required to effect pyrolysis. One way one could think of is adding moisture to the wood. The following exercise goes into that question, supposing the heat of evaporation of moisture can be superimposed upon the pyrolysis heat. The pyrolysis heat would then have to be increased from 0.795 MJ to 3.1 MJ. This implies that an amount
of water would have to be added to 1 kg of dry wood representing a heat of evaporation of:

\[ 3.1 - 0.795 = 2.305 \text{ (MJ)} \]

The heat of evaporation of water being 2.257 MJ/kg, it means that:

\[ \frac{2.305}{2.257} = 1.021 \text{ kg} \]

of water have to be added to one kg of dry wood to achieve our ends. That means we have to use wood with a moisture content of \( \varepsilon = 102\% \) on a dry mass basis.

12.4j Rate of volatile generation A further matter of interest is the rate of volatiles production as a function of time. Following our model there will be an initial period where fresh wood surface is present in excess. This period is characterised by a steady volatiles production with an expected calorific value of around 7.5 times the char combustion rate. As the char boundary penetrates the pieces of wood nearer the char bed, higher situated layers of wood will commence charring. When the top layers are reached the volatiles production rate will decay with time to zero. At that point of time a large amount of char is still present in the stove (it should be clear that if we abolish the condition of volatile combustion separated in space from the fuelbed, the behaviour of the fire as a whole will be even more erratic, starting with a high power peak as the top layers of fresh fuel are pyrolysed by heat from the flames). In order to run the stove with small pieces of wood at a constant heat output rate we have to satisfy the following conditions.

(i) Ensure complete combustion of volatiles (at a fairly low temperature).
(ii) Combustion of volatiles must take place without interaction with the fresh fuel.
(iii) Initially primary air must be metered to ensure a char combustion rate of 13.5% of the desired stove heat output.
(iv) At the end of the steady volatiles burning period the primary air supply has to be gradually increased to allow the char to take over the total heat production.

The period of stationary volatiles production can be influenced by varying the size of the fuel pieces. The smaller the fuel particles, the longer the steady volatiles production period will be. Another quantity which directly affects the period of steady volatiles production is the amount of accumulated fuel.

12.4k Char burning rate A further problem in cookstovery of the above kind is the very low char-burning rate that is required. There may be some doubt as to whether such a low combustion rate can be sustained. For the 3 kW fire of our example, for instance, the char power is:

\[ \frac{3000}{7.42} = 404. \text{ (W)} \]
For a parallel flow fire the char burning rate for a 3 kW fire would be:

$$0.2 \times \frac{31}{18} \times 3000 = 1033.$$  \hspace{1cm} (W)

An additional advantage of the latter is that the volatiles in this case are exposed to a high temperature while passing through the char bed. In addition to a degree of cracking of the larger molecules the gas will have acquired a high temperature both of which will facilitate burning. In conclusion of this section we can say that according to our model the closed stove with counter flow is a difficult piece of equipment to obtain a constant power output from. To enable it to run at constant power the designer has to solve the problems of linking the primary and secondary air admittance valves such that initially a minimal flow of primary air is admitted together with a maximum flow of secondary air while at a later stage the secondary air is restricted as the primary air flow is increased to the maximum. Further the designer has to solve the two-pronged problem of

(i) getting the relatively cool volatiles to burn
(ii) doing this without sending heat back into the fresh fuel.

13. Conclusions

In the foregoing we have mentioned a number of aspects which should play a role (or already do so) in the design of wood-burning cookstoves. Some aspects have appeared time and again, under different headings. They play an important role in a number of the sections that together make up the design considerations of cookstoves. Of these we can mention clean burning. This has consequences for the versatility of the stove. We see that a clean burning stove can be used for heating pans but also for direct heat transfer to the food. Pan cleaning is easier and there are no dangerous emissions that threaten the users’ or other persons’ health.

It is probable that in order to achieve clean burning of wood the utmost use has to be made of natural draught, either after the first or after the second stage of combustion. This means that the heat has to be utilised at table top level in order to have some vertical distance for the draught to work in.

The currently built closed stoves operating in counter flow mode hold little promise from the aspects of either clean burning or control. An intelligent application of parallel flow operation appears to have far better prospects.

A matter which has not been explicitly mentioned is the uniform size of the fuel particles. It seems inevitable that this is a key condition for making any progress in combustion as well as for its control. Being able to control the heat output rate is of great importance in fuel conservation. The control of the heat output rate should be such that the process heat can be supplied for a large range of foods and quantities. For bringing to boil a large power output is desired while for keeping hot a minimal output is indicated. It might be sensible to follow existing standards such as the specifications for domestic gas-burning appliances of VEG (Anon 1968) to come to a range of standard output powers for wood-burning cookstoves.
We have tried to indicate that we need technological data on the domestic processing of foods and that a critical examination of existing cooking practices might lead to considerable savings in firewood, this latter being the professed aim of all woodstove activities.

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The efficiencies of firewood devices (Open-fire stoves, chulahs and heaters)

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Abstract. Firewood is a major energy source in India. Yet no minimum fuel efficiency standards have been set for firewood devices. This paper describes methods of determining the first law efficiencies of open fires, chulahs and other wood-based heaters. About thirteen different stoves have been tested and efficiency standards for stoves have been suggested.

Keywords. First law efficiency; testing methods; result reproducibility; fuel efficiency standards; firewood devices; open-fire stoves.

1. Introduction

Firewood, like animal power, is a traditional energy source in many tropical and developing countries. Surrounded by large tracts of forests, Indian civilization developed technologies like cookstoves, kilns for brick burning, tiles and pots and for lime making and tobacco curing, baking ovens and burning ghats all fuelled by firewood. These age-old practices continue even today. However, the annual firewood consumption is quite enormous: 130 million tonnes (1982) representing 20–25% of the total fuel consumption (Anon 1979). Most of this goes towards fueling cookstoves and cottage industrial processes. These are characterised by miserable inefficiency despite the shortfall in firewood. No minimum fuel efficiency standards have been set for these devices; in fact there are no Indian Standard codes for this major energy sector. Though some alternative technologies (e.g. solar energy) have been developed, improved high-efficiency devices are not available for applications other than cooking. In the cooking sector, interest is being shown only in the last two or three years.

2. Indices of performance evaluation

Generally the overall efficiency or device index or first law efficiency is considered to be an indicator of the energy-wise performance of a device. This is the ratio of the energy output to the energy input for a specific operation. Another indicator is the second law efficiency or the task index. This is the ratio of the actual work output to the maximum possible work for the same task (Anon 1975).

Yet another indicator is the specific per day consumption (SDC: the ratio of the wood consumed over a period to the product of the number of persons and the

A list of symbols appears at the end of the paper.
number of days in that period). This has been proposed as a measure of woodstove performance (De Lepeleire 1981). De Lepeleire feels that the overall efficiency varies with many more parameters than quantity of wood, climate and size and shape of utensils. Hence $sdc$ is an elegant and easy way of expressing cookstove performance. The concept can be extended to other tasks and the specific task consumption ($stc$) (the firewood required to produce one unit of output, e.g. wood required to produce one brick, wood required to cook one meal, etc.) can be evaluated. This paper aims at an analytical evaluation of existing firewood devices and for this purpose the first law efficiency is the most suitable parameter. The second law efficiency is important in energy conservation schemes for matching devices and tasks. The $stc$ is an appropriate index for finding firewood consumption patterns, predicting future firewood requirements and for designing working plans.

3. Overall efficiency (first law)

The overall efficiency is the ratio of the useful energy output to the total energy input,

$$\eta_0 = \left[ \frac{E_0}{E_t} \right] = \frac{\int_0^\tau P_0(\tau) \, d\tau}{\int_0^\tau P_1(\tau) \, d\tau}.$$  \hspace{1cm} (1)

The power output and input vary with time in all solid fuel stoves. When the power input and output are independent of time,

$$\eta_0 = \frac{P_0}{P_1}. \hspace{1cm} (2)$$

4. Overall efficiency of traditional chulahs and heaters

In the domestic sector a wide variety of stoves are used; there are open-fire cookstoves like the three-stone stove and three-brick stove; one-two-and three-pot stoves; and bathwater heaters. Big-sized wood-burning stoves are used for agricultural processing like arecanut-boiling, jaggery-making, beaten-rice making, parboiling paddy, etc. Cottage industries like liquor distillation and fabric dyeing use woodstoves. Wood is also a popular fuel in large-scale cooking as in hostels, hotels, canteens and for festivals.

A chulah is a device in which the partial combustion of firewood supplies heat to a pot placed on it. An open-fire chulah is made of three bricks or stones placed either in the form of an open rectangle or at 120° radially to each other. The space so enclosed forms a combustion chamber for burning firewood. Other chulahs are close-walled combustion chambers with openings for feeding firewood, for placing vessels and sometimes with chimneys for venting the exhaust gases. In the absence of a chimney, the opening for the vessel itself serves as an exhaust gas outlet.

The efficiency of the chulah should be independent of the material cooked or
heated in the pot (Sielcken & Nieuwevelt 1980, 1981). If the material is a liquid the heat (sensible + latent) transferred to it can be determined. If an empty pot is placed on the chulah there will be continuous mass transfer (hot air inside the pot going out and cold air replacing it) and it is difficult to find out the heat transfer to the pot. But the energy gained by the pot and its contents in both cases is identical for equal fuel-burning rates, if the experiments are conducted on the same stove.

The overall stove efficiency can be determined by finding out the heat transfer to the pot and its contents and the corresponding fuel input. Kerosene and electric stoves are tested by transferring the heat output to a pot containing a fixed mass of water placed on the stove (Anon 1965). Therefore the efficiency of firewood devices can also be evaluated by water-heating methods. Water is chosen because of its universal availability, convenience and the ease with which heat transfer to it can be evaluated. In case one chooses a solid, say an iron block or a gas, say air, as when an empty vessel is used, it will be difficult to evaluate the heat transfer.

4.1 Water evaporation method

In this method the chulah is lit and water ($M_1$) (about 5 litres) is placed on it. After complete burning of the fuel, the volume of water evaporated is found out by the difference in weight of the vessel contents before and after the test ($m$). This test is recommended by Krishna Prasad (1981).

If the boiling point is 98°C,

$$\eta_0 = \frac{E_0}{E_t} = \frac{[M_1S (98 - t_a) + mL]}{WC}.$$  

4.2 Constant heat output method

This test is recommended by Khanna (1975). The chulah is lit and water ($M_2$) (about 2 litres) is placed on it. When the temperature reaches 96°C, the water is removed and immediately another vessel is placed with the same quantity of water ($M_2$) at the same ambient temperature. The process is repeated till the end of the combustion period.

$$\eta_0 = \left[ \int_0^\tau P_0 (\tau') d\tau' \right] / E_t = \left[ \int_0^{\tau_1} P_{01} (\tau) d\tau + \int_{\tau_1}^{\tau_3} P_{02} (\tau) d\tau + \int_{\tau_3}^{\tau_3} P_{03} (\tau) d\tau \right] \ldots \left[ \int_{\tau_{n-1}}^{\tau} P_{0n} (\tau) d\tau \right] E_t^{-1}.$$  

The operating period of the stove is divided into $n$ intervals. These are unequal intervals but the energy output is constant in each of these, except in the last where it may not be possible for the water to attain 96°C. The highest temperature ($t_h$) is recorded.

Another factor is that no time is lost between two water heatings. As soon as the hot water (96°C) is taken out, the cold water pan is placed on the stove. Hence,

$$\tau_1 = \tau'_1; \ \tau_2 = \tau'_2; \ \tau_3 = \tau'_3 \ldots \ \tau_{n-1} = \tau'_{n-1}$$
\[ \int_{\tau_1}^{\tau_2} P_{o_1}(\tau)d\tau = \int_{\tau_1}^{\tau_3} P_{o_2}(\tau)d\tau = \int_{\tau_2}^{\tau_3} P_{o_3}(\tau)d\tau \ldots \]

\[ = \int_{\tau_{n-1}}^{\tau_n} P_{o_{n-1}}(\tau)d\tau = E_0 \]

\[ \eta_0 = \left[(n-1)E_0 + \int_{\tau_{n-1}}^{\tau} P_{o_n}(\tau)d\tau \right] E_i^{-1}. \]

If \((n - 1) = x \):

\[ \bar{E}_0 = M_2 S (96 - t_a) \int_{\tau_{n-1}}^{\tau} P_{o_n}(\tau)d\tau = M_2 S (t_b - t_a) \]

\[ \eta_0 = \left[x M_2 S (96 - t_a) + M_2 S (t_b - t_a)\right]/WC. \]

4.3 Constant temperature rise method

This is a modified version of the Indian Standard for electric stoves (Anon 1965) and is useful for nearly constant power output stoves. A fixed quantity of water is heated through a temperature rise \((\Delta T)\) of 20 or 30°C and the time \((\tau_{i+1} - \tau_i)\), is noted. The trial is repeated a number of times and the average time is calculated.

\[ \eta_0 = \left[\int_0^{\tau} P_0(\tau)d\tau \right] \left[\int_0^{\tau} P_i(\tau)d\tau \right]^{-1} \]

\[ = \left[\int_0^{\tau_1} P_{o1}(\tau)d\tau + \int_{\tau_1}^{\tau_2} P_{o2}(\tau)d\tau + \int_{\tau_2}^{\tau_3} P_{o3}(\tau)d\tau \ldots \right. \int_{\tau_{n-1}}^{\tau} P_{o_n}(\tau)d\tau \left[\int_0^{\tau} P_i(\tau)d\tau \right]^{-1}. \]

As in the previous case, the operating period is divided into \(n\) intervals, of unequal time but equal energy output. Unlike the last case, as soon as the vessel is removed from the stove, another vessel is not immediately placed on it. There is some time lag before another vessel is placed on it to enable the investigator to change the water, regulate the flame, blow the stove if needed and to record the readings. Therefore,

\[ \tau_1 \neq \tau'_1; \tau_2 \neq \tau'_2; \tau_3 \neq \tau'_3 \ldots \tau_{n-1} \neq \tau'_{n-1}. \]
The efficiencies of firewood devices

The loss of time during which the output is not measured (\(\tau_{loss}\)) is,

\[
(\tau'_1 - \tau_1) + (\tau'_2 - \tau_2) + (\tau'_3 - \tau_3) \ldots (\tau'_{n-1} - \tau_{n-1}),
\]

\[
\tau_{loss} = \sum_{i=1}^{(n-1)} (\tau'_i - \tau_i). \tag{11}
\]

If the total operating period is \(\tau\) the time during which the heat output is measured is,

\[
(\tau - \tau_{loss}).
\]

Taking \((n - 1) = x, E_0 = M_3 S \Delta T\) and

\[
\int_0^{(\tau - \tau_{loss})} P_i(\tau)d\tau = WC[1 - \tau_{loss} \tau^{-1}],
\]

\[
\eta_0 = x M_3 S(\Delta T) \tau [WC(\tau - \tau_{loss})]^{-1}. \tag{12}
\]

Equation (12) can be looked at from another viewpoint, for one constant energy output interval,

\[
\eta_0 = E_0/E_i = [E_0/\tau_j P_i], \tag{13}
\]

where \(\tau_j\) is the time clocked in one interval,

\[
\tau_j = (\tau_{i+1} - \tau_i).
\]

For the entire operation,

\[
\eta_0 = \bar{E}_0/(E_i)_{av} = \bar{E}_0 \left[ \frac{\left(\sum_{j=1}^{n} \tau_j/n\right)}{\tau} \right] E_i^{-1}. \tag{14}
\]

Taking \(n = x, E_0 = M_3 S \Delta T, E_i = WC\)

\[
\eta_0 = [M_3 S \Delta T] \left[ \frac{\left(\sum_{j=1}^{n} \tau_j/n\right)}{\tau} \right] WC^{-1}
\]

\[
= (M_3 S \Delta T \tau) (\tau_{mean} WC)^{-1}. \tag{15}
\]

As

\[
\frac{\left(\tau - \tau_{loss}\right)}{n} = \left(\sum_{j=1}^{n} \tau_j/n\right).
\]

Equations (12) and (15) are identical. By using the average time interval the overall efficiency is determined.
4.4 **Constant time method**

This test is another version of the Indian Standard for electric stoves (Anon 1965). A fixed quantity of water \( (M_s) \) is heated for a fixed time \( (\tau_c : 2, 3 \text{ or } 4 \text{ min}) \) and the temperature rise is noted. The trial is repeated and the average temperature rise is calculated \( (\Delta T_{\text{mean}}) \).

Using similar arguments as in the constant temperature rise method,

\[
\eta_0 = M_s S (\Delta T_{\text{mean}}) [W C (\tau_c/\tau)]^{-1},
\]

where \( \tau_c \) is the constant time interval. Equation (16) is similar to (15).

4.5 **Cooking simulation tests (cookstoves)**

This test is applicable only to cookstoves and was first reported by Geller (1981).

One cookstove operation consists of several preparations of food items. If \( j \) denotes the food item prepared (e.g. chapati, rice, sambar, etc.) and \( i \) denotes the constituents of one food item (e.g. the constituents of sambar like dal, water, vegetable, etc.), the cooking efficiency is,

\[
\eta_{\text{cr}} = \frac{\sum_{j=1}^{m} \left\{ \sum_{i=1}^{n} m_i C_{pi} \Delta T + m_i p_i \right\} + \{m_w L\}}{W C},
\]

The specific heat values \( (C_{pi}) \) of food items can be obtained from Charm (1963). The energy of chemical reactions occurring during the cooking process per unit mass of food item \( (p_i) \) is given in Suzuki et al (1976). The mass of the water evaporated \( m_w \) is got by the difference in weight of the constituent items and the final cooked item.

While water heating tests give the maximum possible device efficiency, the cooking simulation tests indicate the utilisation efficiency of the stove during the fire-burning period. The latter takes care of the loss of energy when the stove is not used between the cooking of two items. It also reflects on cooking practices like choice of vessel, amount of water evaporated, sequence of heating operations, etc. It gives the overall cooking efficiency in a more accurate sense than the other tests. In some cases the stove as such may have a high overall efficiency but due to bad cooking practices it may be used inefficiently. Cooking simulation tests thus indicate not only the stove efficiency but also reflect on the skills of the user.

4.6 **Process simulation tests for non-cookstove chulahs**

The tests now proposed are similar to cooking simulation tests and can be used in places where the equipment being heated are built into or are permanently attached to the chulah and where it is not possible to heat water in separate pans. This method can also be used where accurate values of the overall efficiency are needed because the output is calculated by theoretical means. The energy requirements for accomplishing a particular task can be determined. The firewood consumption for the task (an accurate account of which can be obtained from the user on the basis
of how much he spends in a particular time span, say a week or month) is taken as the input

\[ \eta_{0t} = \frac{E_t}{WC}. \]  

(18)

For example, firewood is used in jaggery manufacture in Sirsi, a town in the Western Ghats, in Karnataka State. Here 16 tins (20 litre capacity) of fresh juice yields 3 tins of jaggery during a day's operation. This means that for every tin of jaggery, 4.34 tins of water is evaporated. The energy requirements for this evaporation can be calculated assuming that the energy for the chemical reactions occurring during the process is negligible.

In another example, the task energy for liquor distillation is determined as 255 kcal/kg of liquor distilled, assuming that the boiling point of alcohol is around 78°C and the latent heat of vaporisation is 204 kcal/kg. Usually a drink is distilled twice and hence about 510 kcal is needed for a kg.

### 4.7 Indirect method

In hotels and in large scale cooking as for marriage, the stove owners resent testing of their stoves as their work is hampered. In such cases an indirect test now proposed can be used. The energy output for the task is estimated by performing a full or scaled version of the test on an electric stove. The overall efficiency of the electric heater is determined by a standard test.

For the task performed on the electric stove, the corresponding firewood requirement is estimated by the user's experience.

\[ (E_t)_{E.\text{heater}} = (E_t)_{F.\text{device}} \]  

(19)

\[ \eta_0(F.\text{device}) = \left[ \frac{E_t}{E_t^T} \right] (F.\text{device})^T \]  

(20)

\[ \eta_0(E.\text{heater}) = \left[ \frac{E_t}{E_t^T} \right] (E.\text{heater})^T \]  

(21)

\[ (E_t)_{E.\text{heater}} = (\eta_0 E_t) (E.\text{heater}) \]  

(22)

\[ \eta_0(F.\text{device}) = \frac{(\eta_0 E_t) (E.\text{heater})}{(E_t)_{F.\text{device}}} \]  

(23)

### 4.8 Approximate method

In certain cases if the users can spare the stove in its normal burning condition for about 10 min, the efficiency can be determined by an approximate method now proposed by the author. This method is applicable only to those stoves where the log diameter is nearly constant and the same number of logs are used all through the burning operation. Under these conditions the burning rate and the power output are nearly independent of time.
Water \( (M_4) \) (1 to 5 litres) is heated and the temperature rise is noted in the short period \( (\tau_i) \) (5-10 min)

\[
\eta_0 = p_0 p_1^{-1} = M_4 S \Delta T \left[ \frac{(WC/\tau) \tau_i}{(WC/\tau)} \right]^{-1},
\]

where \( (\tau_i) \) is the period for which the test was conducted and \( \tau_i \ll \tau \).

This test can be used for stoves in hotels and hostels. The power input data \( (W, \tau) \) are obtained from the users.

5. Conditions for efficiency measurement

5.1 Power levels

For a particular combustion chamber volume, the efficiency decreases with increase in power input (Sielcken & Nieuwevelt 1980). In most cases the power ratings are very low during pick up and shut down. These two constitute 5–10% of the stove operating time. Between these, steady burning occurs but the power output is deliberately varied during cooking depending on the food item. The efficiency measurement must be done at a constant power level.

5.2 Small errors

(a) Temperature rise of water In the constant temperature rise and constant time methods, the actual temperatures are not specified. If the temperature rise is between 30 and 50°C or 60 and 80°C the measured heat output is the same but the actual heat output is not. This is because the pot losses vary with temperature. To avoid this error, the actual temperatures must be standardised for accurate experiments. The error, however, is less than 1% of the overall efficiency and can be ignored where this accuracy is not needed.

(b) Depth of thermometer in water By holding the thermometer at two extremes of a litre of water in a normal-sized aluminium pan, the difference can be 1% of the overall efficiency.

(c) Presence or absence of lid

5.3 Overall efficiency

If the sensible heat to the pan is considered, the output will increase. If the leftover heat (charcoal production at the end of combustion) is considered, the input will decrease. If the heat contribution from starting materials (twigs, oil, kerosene, rags, etc.) is considered, the input will increase. These considerations can affect the input power by 10–15%.
5.4 Calorific value

The question of whether to consider the higher calorific value (HCV) or the lower calorific value (LCV) as the real energy input is debatable. The author feels that the LCV is a more realistic estimator.

5.5 Load conditions

The efficiency of stoves varies with the pot conditions: mass of the pot ($m_p$), thickness of the pot ($t_p$), thermal conductivity of the pot ($k$), specific heat of the pot ($c$), surface area of the pot exposed to the flame and hot gases ($A_f$), surface area of the pot open to the environment ($A_p$), surface area of the pot through which heat losses take place ($A_s$), temperature of fluid ($T_f$), temperature of ambient air ($T_a$), wind velocity ($V$), thickness of soot deposit on the pot ($t_s$), emissivity of pot material ($\epsilon$), water evaporation rate ($R$) and area of water evaporation surface ($A_c$).

The variation due to changes in any of these conditions with efficiency can be found out by keeping the fuel conditions constant. For identical stoves only the pot efficiency component varies and this is proportional to the overall efficiency. The variation of the overall stove efficiency with changes in the above conditions can be expressed by dimensionless relationships, by using the $\pi$ technique (Langhaar 1951).

\[
\eta_0 = \frac{V_0}{F(m_p, t_p, K, C, A_f, A_p, A_s, T_w, T_a, V, t_s, \epsilon, R, A_c)},
\]

\[
\eta_0 = \frac{V_0}{C(\epsilon) \pi_{j=1}^9 (S_j)^{\nu_j}},
\]

where

\[
S_1 = m_p^{1/3} k^{1/6} T_a^{1/6} R^{-1/3} t_p^{-1/6},
\]

\[
S_2 = m_p^{1/4} C^{1/8} t_p^{-1/4} R^{-1/4},
\]

\[
S_3 = m_p V t_p^{-1} R^{-1},
\]

\[
S_4 = A_f t_p^{-2} \quad S_5 = A_p^{1/2} t_p^{-1},
\]

\[
S_6 = A_s t_p^{-2},
\]

\[
S_7 = A_c t_p^{-2} \quad S_8 = t_s/t_p \quad S_9 = T_w/T_p.
\]

If identical vessels and quantities of water are placed over the stove, the efficiency variation with other conditions is,

\[
\eta_0 = \frac{V_0}{C_1(\epsilon) S_1^{\nu_1} S_2^{\nu_2} S_3^{\nu_3} S_9^{\nu_9}}.
\]

Equation (27) is important in the evaluation of open-fire cookstoves especially in variable wind conditions.

5.6 Fuel conditions

The efficiency depends on the fuel conditions: height of log ($h$), length of log ($l$), moisture ($f$), calorific value ($C$), volume-to-surface area ratio ($V/A$), density ($\rho$), number
of logs \((n)\), cross area of logs \((a)\), fuel-burning rate \((B)\), flame temperature \((T_\text{fl})\), etc. When there is variation in these quantities the average value is selected (weighted mean).

The variation in these conditions with overall stove efficiency can be found out if the load set up (vessel conditions and fluid in vessel) is kept constant. Then for identical stoves, the overall efficiency can be considered as a function of these parameters.

\[
\eta_0 = F(\rho, f, l, a, h, V/A, n, C, B, T_\text{fl}, T_\text{a}).
\]  

(28)

Using the \(\pi\) theorem (Langhaar 1951) the overall efficiency is written as,

\[
\eta_0 = A(nf) \pi_{j=1}^5 (D_j)^{\alpha_j},
\]  

(29)

where

\[
D_1 = l^{1/2} \rho^{1/4} C^{3/8} B^{-1/4},
\]

\[
D_2 = al^{-2} \quad D_3 = hl^{-1} \quad D_4 = (V/A)l^{-1}, \quad D_5 = T_f T_a^{-1}.
\]

If log sizes are standardised then (29) reduces to,

\[
\eta_0 = A_1 D_1^{\alpha_1} D_5^{\alpha_5}.
\]  

(30)

6. Types of stoves tested

Three types of cookstoves were tested for their efficiency by methods described in § 4. The readings were taken at the users’ sites. Stoves suited for a family size of five were selected. The stoves were three-stone stove, portable mud stove and two-pot stove. The portable mud stove available in the market consists of a cylindrical baked mud chamber with a 90° sector cut-off, a closed bottom, an open top and three vessel mounts at the top. The two-pot stove is a high mass stove (60 kg). It is the conventional built-in cookstove used in most homes in southern India.

The bathwater heater tested was a stove with a built-in brass vessel whose bottom is in contact with the combustion chamber. There is a smoke pipe for venting exhaust gases.

The arecanut boiling chulah (from Ramana Koppa village, Chickmaglur District, Karnataka State) was similar to a bathwater heater but had grates to remove ash from the combustion zone. There was better insulation and optimized dimensions.

The jaggery-making chulah (from Sirsi town, Karnataka State) was a circular mud wall (1 brick thickness) with a sectorial opening at the bottom for feeding fuel and with circular holes all round near the top for escape of exhaust gases. The jaggery pan was placed directly over this wall leaving no interspace for escape of smoke.

The beaten-rice making chulah was a semi-spherical pan built into a baked mud combustion chamber. The chamber has a fuel feed opening and a circular hole at the top corner of the mud stove for escape of exhaust gases.
The efficiencies of firewood devices

The chulah for parboiling paddy is similar to a bathwater heater but with the vessel not built into the system and without a smoke pipe.

Liquor distillation stoves (small-scale) are small circular mud structures over which big oil drums are placed.

The fabric dyeing stove is similar to a bathwater heater except that it is very large.

Hostel stoves are three-stone stoves or similar versions made of bricks. A variety of stoves are used in hotels but a design with mud walls, no grate, no chimney and three independent pot openings was tested. A common three-stone stove used for mass cooking was tested.

7. Results and discussions

Table 1 gives the test results of four different designs of stoves. For a particular design, one series refers to tests referred to in § 4 conducted simultaneously or after a short time interval. Six such series of tests were conducted. The trends were consistent and the typical values are shown in the table. These refer to readings taken for one particular series and not for different series. The power outputs denote average values during the operating period, i.e. ratio of total heat output to total time.

Table 1. Performance of domestic firewood devices

<table>
<thead>
<tr>
<th>Stove type</th>
<th>Testing method</th>
<th>$B$ (g/min.)</th>
<th>$P_o$ (kW)</th>
<th>$\eta_%$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Three stone stove</td>
<td>4.1</td>
<td>13.2</td>
<td>0.37</td>
<td>10.7</td>
</tr>
<tr>
<td>(process temperature</td>
<td>4.2</td>
<td>12.4</td>
<td>0.29</td>
<td>8.9</td>
</tr>
<tr>
<td>$=100-190^\circ$C)</td>
<td>4.3</td>
<td>14.3</td>
<td>0.52</td>
<td>13.7</td>
</tr>
<tr>
<td></td>
<td>4.4</td>
<td>13.7</td>
<td>0.46</td>
<td>12.9</td>
</tr>
<tr>
<td></td>
<td>4.5</td>
<td>14.0</td>
<td>—</td>
<td>5.7</td>
</tr>
<tr>
<td></td>
<td>4.7</td>
<td>13.2</td>
<td>0.33</td>
<td>9.5</td>
</tr>
<tr>
<td></td>
<td>4.8</td>
<td>12.9</td>
<td>0.42</td>
<td>12.2</td>
</tr>
<tr>
<td>Portable mud stove</td>
<td>4.1</td>
<td>10.1</td>
<td>0.50</td>
<td>16.8</td>
</tr>
<tr>
<td>(process temperature</td>
<td>4.2</td>
<td>10.8</td>
<td>0.46</td>
<td>14.2</td>
</tr>
<tr>
<td>$=100-190^\circ$C)</td>
<td>4.3</td>
<td>12.1</td>
<td>0.64</td>
<td>18.2</td>
</tr>
<tr>
<td></td>
<td>4.4</td>
<td>11.3</td>
<td>0.61</td>
<td>18.6</td>
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<tr>
<td></td>
<td>4.5</td>
<td>10.5</td>
<td>—</td>
<td>6.3</td>
</tr>
<tr>
<td></td>
<td>4.7</td>
<td>12.6</td>
<td>0.51</td>
<td>14.0</td>
</tr>
<tr>
<td></td>
<td>4.8</td>
<td>10.4</td>
<td>0.47</td>
<td>15.7</td>
</tr>
<tr>
<td>Two pot opening stove</td>
<td>4.1</td>
<td>14.5</td>
<td>0.55</td>
<td>12.3</td>
</tr>
<tr>
<td>(process temperature</td>
<td>4.2</td>
<td>12.7</td>
<td>0.36</td>
<td>9.2</td>
</tr>
<tr>
<td>$=100-190^\circ$C)</td>
<td>4.3</td>
<td>14.3</td>
<td>0.73</td>
<td>16.7</td>
</tr>
<tr>
<td></td>
<td>4.4</td>
<td>15.9</td>
<td>0.77</td>
<td>15.8</td>
</tr>
<tr>
<td></td>
<td>4.5</td>
<td>14.9</td>
<td>—</td>
<td>6.2</td>
</tr>
<tr>
<td></td>
<td>4.7</td>
<td>13.6</td>
<td>0.53</td>
<td>12.7</td>
</tr>
<tr>
<td></td>
<td>4.8</td>
<td>15.9</td>
<td>0.68</td>
<td>14.1</td>
</tr>
<tr>
<td>Bath water heater</td>
<td>4.6</td>
<td>70.8</td>
<td>3.46</td>
<td>15.9</td>
</tr>
<tr>
<td>(process temperature</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$=45-60^\circ$C)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Table 2. Testing conditions for domestic firewood devices

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
<th>Three-stone stove</th>
<th>Portable mud stove</th>
<th>Two-opening stove</th>
<th>Bath water heater</th>
</tr>
</thead>
<tbody>
<tr>
<td>$h^*$</td>
<td>cm</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>$l^*$</td>
<td>cm</td>
<td>45</td>
<td>60</td>
<td>65</td>
<td>80</td>
</tr>
<tr>
<td>$f^*$</td>
<td>% dry</td>
<td>8</td>
<td>12</td>
<td>10</td>
<td>12</td>
</tr>
<tr>
<td>$C^*$</td>
<td>kcal/g</td>
<td>3-8</td>
<td>4-2</td>
<td>4-4</td>
<td>4-4</td>
</tr>
<tr>
<td>$a^*$</td>
<td>cm$^2$</td>
<td>7-5</td>
<td>12-6</td>
<td>12-6</td>
<td>10-8</td>
</tr>
<tr>
<td>$n$</td>
<td></td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>$m_p$</td>
<td>kg</td>
<td>0-6</td>
<td>0-3</td>
<td>0-3</td>
<td>?</td>
</tr>
<tr>
<td>$t_p$</td>
<td>cm</td>
<td>0-5</td>
<td>0-15</td>
<td>0-15</td>
<td>0-5</td>
</tr>
<tr>
<td>$k$</td>
<td>cal/s/cm$^2$/unit temp. grad.</td>
<td>0-0015</td>
<td>0-48</td>
<td>0-48</td>
<td>0-26</td>
</tr>
<tr>
<td>$c$</td>
<td>cal/g°C</td>
<td>0-8</td>
<td>0-22</td>
<td>0-22</td>
<td>0-09</td>
</tr>
<tr>
<td>$A_f^+$</td>
<td>cm$^2$</td>
<td>400</td>
<td>380</td>
<td>380</td>
<td>2900</td>
</tr>
<tr>
<td>$A_p^+$</td>
<td>cm$^2$</td>
<td>590</td>
<td>560</td>
<td>560</td>
<td>17,800</td>
</tr>
<tr>
<td>$A_t^+$</td>
<td>cm$^2$</td>
<td>320</td>
<td>300</td>
<td>300</td>
<td>960</td>
</tr>
<tr>
<td>$V$</td>
<td>m/s</td>
<td>2-5</td>
<td>2-7</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>$A_c$</td>
<td>cm$^2$</td>
<td>450</td>
<td>440</td>
<td>420</td>
<td>—</td>
</tr>
</tbody>
</table>

*Average values of different logs  †Approximate values

Table 3. Overall efficiencies of agro-processing firewood devices

<table>
<thead>
<tr>
<th>Stove</th>
<th>Testing method</th>
<th>$B$ (g/min.)</th>
<th>$P_g$ (kW)</th>
<th>Process temp. ($^°C$)</th>
<th>$\eta_h$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arecanut boiling stove</td>
<td>4-6</td>
<td>75</td>
<td>4</td>
<td>100</td>
<td>17-6</td>
</tr>
<tr>
<td>Jaggery making stove</td>
<td>4-6</td>
<td>400</td>
<td>2-25</td>
<td>85</td>
<td>1-9</td>
</tr>
<tr>
<td>Beaten rice making stove</td>
<td>4-6</td>
<td>150</td>
<td>1-125</td>
<td>85</td>
<td>2-5</td>
</tr>
<tr>
<td>Stove for parboiling of paddy</td>
<td>4-1</td>
<td>120</td>
<td>1-75</td>
<td>100</td>
<td>4-8</td>
</tr>
</tbody>
</table>

Table 4. Testing conditions of agro processing firewood devices

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
<th>Arecanut boiling stove</th>
<th>Jaggery-making stove</th>
<th>Beaten rice making stove</th>
<th>Stove for parboiling of paddy</th>
</tr>
</thead>
<tbody>
<tr>
<td>$h$</td>
<td>cm</td>
<td>12</td>
<td>7</td>
<td>11</td>
<td>12</td>
</tr>
<tr>
<td>$l$</td>
<td>cm</td>
<td>130</td>
<td>120</td>
<td>130</td>
<td>130</td>
</tr>
<tr>
<td>$f$</td>
<td>% dry</td>
<td>10</td>
<td>11</td>
<td>8</td>
<td>12</td>
</tr>
<tr>
<td>$C$</td>
<td>kcal/g</td>
<td>4-3</td>
<td>4-2</td>
<td>4-2</td>
<td>4-3</td>
</tr>
<tr>
<td>$a$</td>
<td>cm$^2$</td>
<td>120</td>
<td>45</td>
<td>95</td>
<td>110</td>
</tr>
<tr>
<td>$\rho$</td>
<td>g/cm$^3$</td>
<td>0-65</td>
<td>0-60</td>
<td>0-67</td>
<td>0-57</td>
</tr>
<tr>
<td>$n$</td>
<td></td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
</tbody>
</table>

All these are average values of the different logs
The efficiencies of firewood devices

Table 5. Overall efficiencies of some small industrial firewood devices

<table>
<thead>
<tr>
<th>Stove</th>
<th>Testing method</th>
<th>( B ) (g/min.)</th>
<th>( P_0 ) (kW)</th>
<th>Process temp. (°C)</th>
<th>( \eta ) (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Liquor distilling stove</td>
<td>4-6</td>
<td>230</td>
<td>1-2</td>
<td>78</td>
<td>1-7</td>
</tr>
<tr>
<td>Fabric dyeing stove</td>
<td>4-1</td>
<td>305</td>
<td>2-9</td>
<td>103</td>
<td>3-1</td>
</tr>
<tr>
<td>Hostel cookstove*</td>
<td>4-1</td>
<td>326</td>
<td>1-8</td>
<td>100–190</td>
<td>1-8</td>
</tr>
<tr>
<td>(150 persons)</td>
<td>4-8</td>
<td>326</td>
<td>4-2</td>
<td>100–190</td>
<td>4-2</td>
</tr>
<tr>
<td>Hotel cookstove†</td>
<td>4-1</td>
<td>36–72</td>
<td>0-45–1-25</td>
<td>100–190</td>
<td>4-3</td>
</tr>
<tr>
<td></td>
<td>4-8</td>
<td>60</td>
<td>0-63</td>
<td>100–190</td>
<td>5-8</td>
</tr>
<tr>
<td>Mass gathering*</td>
<td>4-1</td>
<td>375</td>
<td>2-18</td>
<td>100–190</td>
<td>1-9</td>
</tr>
<tr>
<td>cookstove (150 persons)</td>
<td>4-8</td>
<td>375</td>
<td>3-0</td>
<td>100–190</td>
<td>2-6</td>
</tr>
</tbody>
</table>

*Variable power stoves—the power output is varied by adjusting the fuel feed.
†Hotel stoves occur in a very wide variety of sizes, shapes and power ranges. The power inputs vary between 8 and 360 kW and power outputs between 0-4 and 25 kW.

Process temperature of 100°C denotes boiling and process temp. of 190°C denotes frying

Table 6. Testing conditions of small industrial firewood devices

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Units</th>
<th>Liquor distilling stove</th>
<th>Fabric dyeing stove</th>
<th>Hostel cookstove</th>
<th>Hotel cookstove</th>
<th>Mass gathering stove</th>
</tr>
</thead>
<tbody>
<tr>
<td>( h )</td>
<td>cm</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>( l )</td>
<td>cm</td>
<td>60</td>
<td>60</td>
<td>65</td>
<td>60</td>
<td>70</td>
</tr>
<tr>
<td>( f )</td>
<td>% dry</td>
<td>14</td>
<td>12</td>
<td>16</td>
<td>16</td>
<td>14</td>
</tr>
<tr>
<td>( a )</td>
<td>cm²</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>( C )</td>
<td>kcal/g</td>
<td>4-4</td>
<td>4-4</td>
<td>4-4</td>
<td>4-4</td>
<td>4-4</td>
</tr>
<tr>
<td>( \rho )</td>
<td>g/cm³</td>
<td>0-69</td>
<td>0-69</td>
<td>0-69</td>
<td>0-69</td>
<td>0-69</td>
</tr>
<tr>
<td>( n )</td>
<td>—</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>2</td>
<td></td>
</tr>
</tbody>
</table>

All these are average values of the different logs

The mean, standard deviation, etc., of \( B, P_0 \) and \( \eta_0 \) were worked out for the different series of tests but no conclusive results could be deduced from these. This may be because the fuel burning rate showed substantial variation (— 50 to + 75% of the mean burning rate).

An important observation is that for a particular stove, the overall efficiency is inversely proportional to the fuel burning rate. Thus the fuel burning rate has to be maintained at a fixed value with as little variation as possible. This can be achieved by standardizing the fuel conditions.

7.1 Standardization of power output

Another observation is that the overall efficiency varies inversely as the output power. This is also true of kerosene stoves, oil and gas burners, metallurgical furnaces, thermal power plant boilers and other combustion systems. A general relationship between efficiency and power for a particular system can be found as follows:

\[
\eta_0 = K (P_0)^{-n},
\]
where $k$ and $n$ are constants. This is valid in liquid and gaseous fuel combustion where uniformity in fuel burning rate can be maintained, but cannot be applied to solid fuel combustion as the variable parameters are too many. Under such circumstances, it is advisable to specify a power output level at which all similar devices can be evaluated. For cookstoves catering to family sizes below 10 this could be fixed at either 0.8 kW or at 1 kW output with an allowable variation of $\pm 10\%$. By preliminary trials it is possible to find out the burning rates at which this power output can be attained. The stove must be tested at this output. In the case of multipot stoves, the power output of the main pot opening must be fixed. This can be taken as 0.75 kW ($\pm 10\%$).

Similarly for bigger cookstoves, bathwater heaters, agro-processing stoves, cottage industrial chulahs, etc., power levels must be standardised. Only the efficiency measured at this level must be taken as valid.

7.2 Standardisation of testing methods

For cookstoves, water evaporation method (see § 4.1) is convenient and accurate. The constant heat output method (see § 4.2) is a laborious process. The methods described in §§ 4.3 and 4.4 are approximate whereas the one given in § 4.5 accounts for non-technical inefficiencies such as lack of the use of the stove (with the fire burning) between cooking two items, reheating of food product because of bad planning of the cooking sequence, etc. Hence the methods 4.1 and 4.5 can be adopted as standard tests.

In cases where the stove efficiency is high but the utilisation of the heat is poor, 4.5 will show a low value. Thus to distinguish between the energy conversion capability of the stove and the ability of the user to put the output energy to optimum use, an efficiency ratio of the cooking simulation test efficiency to the water evaporation test efficiency, both performed at the same power output level, is suggested. Such a ratio is an index of the user's ability.

In cases where only the stove performance, irrespective of the user's utilisation ability is desired, 4.1 is the best.

For non-cookstove chulahs, the efficiency can be evaluated by test 4.1 for operations requiring temperatures at 100°C or more. Test 4.6 is most appropriate for lower temperatures.

Methods 4.7 and 4.8 are not recommended for standards but these are useful in places where one needs a quick figure without going into much experimentation. These tests can also be used for random checking of devices.

8. Conclusions

In countries like India where wood-based energy systems contribute significantly to the national energy supply, there is a need for introduction and enforcement of fuel efficiency standards. There is no national or international uniformity in the concepts of overall efficiency and the conditions in which they are measured.

This paper identifies eight methods of overall efficiency measurement and suggests the best choice for any given situation as follows:

(a) To determine cookstove efficiency strictly from its design considerations,
irrespective of the user’s capacity for utilizing the output heat energy, the water evaporation method may be used

(b) To determine the combined performance of a cookstove based on its design considerations as well as the user’s capacity for utilising the heat output, the cooking simulation test may be used.

(c) To assess the user’s capability for utilising the output heat energy irrespective of the stove performance, the efficiency ratio: ratio of the efficiency by cooking simulation test to efficiency by water evaporation method (both measured at the same power output level) may be used. This test must be conducted while the users themselves are operating the stove.

(d) To determine the efficiency of a stove when the owners do not allow the testing to take place as the load cannot be disturbed, the indirect method may be used.

(e) To determine the efficiency of a stove if the user can spare its use for a few minutes, or if a quick check is needed the approximate method may be used.

(f) For non-cookstove chulahs where the loads are operated at 100°C or more, the water evaporation method may be used.

(g) For non-cookstove chulahs where the loads are operated at 100°C or more and the main function of heating is to remove moisture from a liquid, the process simulation test may be used.

(h) For non-cookstove chulahs where the loads are operated below 100°C, the process simulation test is suggested.

Once the testing method is finalized the following conditions must be standardized:

(a) Fuel conditions: height of log, length of log, moisture, calorific value, volume to surface area ratio, density, number of logs, cs area of log, fuel burning rate, etc.

(b) Load conditions: mass, thickness, thermal conductivity, specific heat, emissivity of pot material; surface area of pot to environment, surface area of pot through which heat losses take place, wind velocity, thickness of soot on pot, etc.

(c) Power output: 0.75 kW or 1 kW with an allowable variation of ±10%.

As with kerosene stoves, diesel burners and gas heaters, the efficiency of firewood devices varies inversely as the power output but it is not possible to establish relationships between the two parameters as the variables are too many. Hence while quoting efficiency values one must specify the power output or determine the efficiency at the specified power output.

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List of symbols

\( C \) calorific value of fuel (lower)
\( E_{i,0} \) energy input, output
\( \bar{E}_0 \) energy output per interval
\( E_t \) task energy output
\( M_t \) mass of water taken for test
\( P_{i,0} \) power input, output
\( S \) specific heat of water
\( t_a \) ambient water temperature
\( W \) mass of fuel burnt in one operating period
\( \eta_0 \) overall efficiency
\( \eta_{ot} \) overall task efficiency
\( \tau \) one operating period
A comparison of the performance of three woodstoves

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Division of Technology for Society, T.N.O., P. O. Box 342, 7300 AH Apeldoorn, Netherlands

Abstract. This paper deals with the results obtained in an elaborate measuring programme for three wood burning stoves used for cooking food; a metal stove, a brick stove and a mud stove. A description of the stoves used for testing the experimental set-up is described together with the general outline of the measuring programme. The main part of the paper is dedicated to a comparison of the three stoves. Characteristics dealt with are the efficiency, the combustion performance and the heat balance of the stoves. Under similar test conditions stove efficiencies appear to be 18 to 22% for the mud stove, 15 to 23% for the brick stove and 25 to 30% for the metal stove. The combustion performance of the mud stove is very poor; the flue gases of the brick stove have the lowest CO-content. Some practical means to improve stove efficiency are presented.

Keywords. Woodstoves; efficiency; combustion performance; heat balance.

1. Introduction

In the developing countries 60-95% of the energy is consumed as wood. Cooking energy accounts for the major part (at least 75%) of this wood consumption. Scarcity of wood has already resulted in an energy crisis for the population of these countries and has stimulated afforestation programmes and the development of fuel conserving stoves burning wood.

In the framework of a research programme to improve stove efficiencies, it was decided to investigate the performance of real stoves in more detail by testing them in a research laboratory. The aim of these tests was to get better insight in the performance of stoves and to gather information so that stove designers and field-workers could undertake improvement of stoves.

Three stoves have been selected and subjected to an elaborate measuring programme in the laboratories of TNO at Apeldoorn, Holland. These tests are reported in separate reports: the metal stove performance by Nievergeld et al (1981), the brick stove by Claus et al (1981) and the mud stove by Claus et al (1982).

This paper summarises the results obtained and presents a comparison of the three stoves on the basis of efficiency, combustion performance and heat balances.

2. Stoves investigated

The main characteristics of the selected stoves were:

2.1 Metal wood stove (figure 1)

This stove was constructed according to a prototype design developed by De Lepeleire.
The stove essentially consists of a fuel supply shaft, a combustion chamber, a flue gas channel and a stack. The combustion chamber has a grate and the combustion air is controlled by a manually operated damper on the bottom side of the grate. There are two panholes and the insertion depth of the pans into these holes can be varied using an adjustable rim.

2.2 Heavy wood stove made of bricks, sand and concrete (figure 2)

This type of stove is already in use in the rural areas of the third world. The stove consists of a cylindrical combustion chamber without a grate, a flue gas channel, a heating chamber and a stack. The bottom and top plate are made of concrete, the walls of ordinary brick and the space between the in- and outside walls is filled up with sand. The combustion air is controlled by a damper in the fuel supply hole. There are two panholes in which the pans are positioned at a fixed distance of 0.15 m from the bottom plate.

2.3 Mud stove made of a mixture of clay, cow dung, ash and sand (figure 3)

This stove was constructed in accordance with design rules supplied by the Indonesian Dian Desa Field Work Centre and the Intermediate Technology Development Group at Reading (U.K.). It consists of a combustion chamber without a grate and with a fixed fuel supply opening through which long wood sticks can be inserted. The combustion chamber is connected to a heating chamber by a flue gas channel. There are two panholes. The panhole of the heating chamber is provided with four
cutaways for transportation of the flue gases. A gap above the fuel supply opening prevents cracking of the wall. The stove has no stack.

3. Experimental set-up

The measurements were performed in the laboratories for combustion and heat transfer research of TNO in the Netherlands. It was possible to use advanced measuring techniques and study the stove behaviour without the influence of wind or draft. The following measurements were carried out:

— Mass of water and fuel wood, using a balance and a stopwatch, combustion rate using a load cell.
— Temperatures of water, flue gases and stove body, using chromel-alumel thermocouples.
— CO₂, CO, O₂ and Cₓ Hᵧ content of the gases, using an infrared, a paramagnetic and a flame ionisation analyser respectively.
Thermocouples, load cells and gas analysers were connected to a scanning unit and a digital voltmeter, which in turn were connected to a Hewlett Packard 21 MX computer with a disc memory. Every 20 seconds all measuring points were scanned. Conversion of the voltage signals to temperatures, gas concentrations and weights was effected by standard software making use of the calibration curves provided by the manufacturers of the measuring equipment.

Figure 4 (plate 1) shows the experimental set-up. The fuel used in the experiments was oven-dry white fir with a density of 350 kg/m³ ± 10%. The size of the wood pieces was 0.02 × 0.03 × 0.2 m. The wood properties are given in table 1.

The charging procedure was dependent on the type of stove. The fuel was ignited with a Bunsen burner. The start of the experiment was taken to be the moment at which the wood first caught fire. The end of the experiment was considered to be the moment at which the temperature in the first pan started to drop at the end of a firing period in which on the average 10 charges of wood were burned. Different heat outputs were obtained by changing the number of wood pieces per charge and the time between two charges. The stove was always fired with two pans filled with water on top. The size of the pans depended on the panhole diameter of the stove.
4. Accuracy of measurements

To check the accuracy of the measurements a special heat balance was drawn up for the metal stove. In order to avoid non-stationary effects resulting from the combustion of wood the stove was fired with natural gas.

The results of this experiment are presented in table 2. This table shows that the procedure adopted yields quite satisfactory results. The amount of heat that cannot be accounted for is \(-3\%\), which is a very good result for measurements of this nature. The formulas used for the heat balance calculations are given in Appendix I.

5. Parameters investigated

Extensive trials have been performed to determine the effect of fuel and stove parameters such as:

— amount of wood burnt;
— moisture content of the wood;
— size and number of wood pieces;
— heat output of the fuel;
— magnitude of the combustion and damper opening;
— stack draft;
— size of baffle in flue gas channel;
— depth of pans in the stove.

<table>
<thead>
<tr>
<th>Table 1. Wood properties (White fir) (dry bases)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ash</td>
</tr>
<tr>
<td>Carbon</td>
</tr>
<tr>
<td>Hydrogen</td>
</tr>
<tr>
<td>Oxygen</td>
</tr>
<tr>
<td>Gross calorific value</td>
</tr>
<tr>
<td>Net calorific value</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table 2. Heat balance of metal stove fired with natural gas</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat output of the fire</td>
</tr>
<tr>
<td>Percentage of heat in</td>
</tr>
<tr>
<td>— First pan</td>
</tr>
<tr>
<td>— Second pan</td>
</tr>
<tr>
<td>— Sensible heat in flue gases</td>
</tr>
<tr>
<td>— Radiation and convection to the environment</td>
</tr>
<tr>
<td>— Unburnt constituents</td>
</tr>
<tr>
<td>Unaccounted for</td>
</tr>
</tbody>
</table>
The results are presented in reports from the Woodburning Stove Group of TH Eindhoven and TNO (Nievergeld et al 1981; Claus et al 1981, 1982).

In this paper the most important general results will be discussed in relation to the following three main characteristics of the stove: (a) efficiency (b) combustion (c) heat balance.

6. Efficiency

The efficiency of wood stoves is defined as the ratio of the amount of heat absorbed by the water in the two pans and the amount of sensible heat supplied by the fuel. Because of the effect of the different operating conditions on stove performance it is not possible to prescribe a unique value to the efficiency of a stove. In essence there is an efficiency range which depends, among other things, on the operating range of the stove and on the manner in which the stove is controlled.

In table 3 the efficiency ranges of the three stoves are given together with the operating ranges. The table presents the efficiencies as determined for the stoves with the accessory pans. These data show the metal stove to be the most efficient one. This is due to the bigger pans used and to the insertion depth of 0.05 m of the pans in the combustion and heating chamber.

The insertion depth of the pans inside the stove is an important variable influencing stove efficiency. The effect of this variable was studied in detail for the metal stove (Nievergeld et al 1981). In figure 5 the results of these measurements are presented. It is clear that there is a linear increase in stove efficiency with increasing depth of the pans in the stove. Between 0 m and 0.07 m depth the total heat transfer surface is increased with a factor of 2 and the efficiency by a factor of 1.6. This effect is illustrated in figure 6, in which the relative values of stove efficiency are plotted against the relative values of the heat transfer surface. Up to a value of 1.5 the increase in efficiency of the second pan is proportional to the increase in heat transfer area. For higher values this increase becomes less, probably because of the effect of the

<table>
<thead>
<tr>
<th>Table 3. Stove efficiencies.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
</tr>
<tr>
<td>Operating range (kW)</td>
</tr>
<tr>
<td>Measured values</td>
</tr>
<tr>
<td>First pan</td>
</tr>
<tr>
<td>Diameter (m)</td>
</tr>
<tr>
<td>Insertion depth (m)</td>
</tr>
<tr>
<td>Efficiency range (%)</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Second pan</td>
</tr>
<tr>
<td>Diameter (m)</td>
</tr>
<tr>
<td>Insertion depth (m)</td>
</tr>
<tr>
<td>Efficiency range (%)</td>
</tr>
<tr>
<td>Overall efficiency range* (%)</td>
</tr>
</tbody>
</table>

*Values of stove efficiencies and operating range are to be considered separately.
Figure 5. Efficiency of metal stove as a function of the insertion depth of the pans.

Figure 6. Efficiency of the metal stove as a function of the heat transfer surface of the pans.
pan insertion depth on the flow distribution around the pan. For the first pan the increase in efficiency, is smaller than proportional right from the beginning of insertion. The most probable explanation for this is that the radiative and convective heat transfer to the side of the pan is much smaller than to the bottom.

Another variable that can easily be used to influence stove efficiency is the excess air factor. This factor can be controlled by a combustion air damper. For the metal stove investigated, the damper appeared unable to control the fire probably because of air leaks around the pans and the loading door. For the brick stove the damper worked properly. In figure 7 the efficiency of this stove is plotted against the excess air factor. It must be kept in mind, however, that the excess air factor influences combustion performance as well, so that there are limitations to the use of this means for increasing efficiency. In this respect it is worth mentioning that exploratory experiments with the brick stove clearly showed that a baffle in the flue gas channel between the two chambers of the stove increased the efficiency of the stove without appreciably influencing the CO-concentration. This measure therefore deserves further investigation.

In figure 8 the heat flux density to the bottom of the first pan is plotted as a function of the heat load for the brick and the mud stove. The heat flux is calculated from the measured efficiencies taking into account the heat loss from the pan to the surroundings. For the calculation of these losses a heat transfer coefficient between water and surroundings of 10 W/m²K was used and for the heating up period the average water temperature was assumed to be 60°C. Taking into account the accuracy of the measurements and the calculations it can be concluded that the heat flux density is the same for the two stoves. There is an indication that the values for the mud stove are slightly higher probably due to a lower excess air factor.

![Figure 7](image_url)  
*Figure 7. Efficiency of the brick stove as a function of the excess air factor and CO concentration.*
Because the combustion chambers of the two stoves have the same volume and nearly the same height one can conclude that within the range investigated the heat flux density is independent of the pan diameter used. This leads to the practical conclusion that for the stoves of this type the pan diameter is an important means to effect efficiency. In figure 8 the only measurement with the metal stove for zero insertion depth of the pans is also indicated.

7. Combustion performance

Another important criterion for the usefulness of a wood stove is its combustion performance. This performance can be judged on the basis of the flue gas composition. In this respect the CO-concentration is one of the most illustrative values.

In figure 9 CO-concentrations are plotted against heat load for the three stoves investigated. From this figure it can be concluded that the brick stove is by far the best from the point of view of combustion performance. The main reason for the better performance of the brick stove in comparison with the mud stove, is that it is provided with a chimney. This stack introduces so much draft that the amount of combustion air is about 2.5 times larger (Claus et al. 1982). When the brick stove is compared with the metal stove it appears that in spite of the fact that the metal stove also has a stack, the excess air factor for the brickstove is higher as well. Another explanation may be that in hot metal stove the pan is inserted 0.05 m into the stove. The single measurement carried out for an insertion depth of 0 m indicates that in
this case the CO-concentration may drop to values similar to those for the brick stove (Nievergeld et al 1981). For the brick stove the flue gas analysis was extended with measurements of soot and $C_xH_y$.

The values measured are given in table 4. The soot concentration measurements show that the average concentration in the flue gases during a cooking period is of the order of 10 mg/m$^3$. This corresponds to 0.02% of the amount of wood that is burned.

For the brick stove the relationship between the CO-concentration and the efficiency is shown in figure 7. This figure shows that a higher efficiency is accompanied by a poorer combustion performance, and although this stove is the best of the three stoves investigated the CO-concentrations are still so high that they are unacceptable for health reasons. A further investigation of the stove behaviour to diminish the CO-concentration will be necessary.

8. Heat balance

To understand stove performance and deduce measures to improve stove efficiency it is of vital importance to know how the heat supplied by the fuel is used. It is
necessary therefore to draw up a heat balance of the stove. Since the combustion and heat transfer processes in the stoves are highly non-stationary in character, these heat balances have to be calculated on the basis of time-averaged values of the different amounts of heat.

To illustrate the typical differences among the stoves a heat balance is presented for each stove for a heat load of about 5 kW, this being the heat load at which all three stoves are operating (Table 5). The differences in the amount of heat absorbed by the two pans have already been discussed in § 6.

Considering the metal stove it is obvious that two measures are possible to improve the efficiency of the stove, namely a better insulation to decrease the heat losses to the environment and an improvement of the combustion performance to decrease the excess air and at the same time increasing the combustion efficiency. The latter measure holds for all three stoves under consideration. It can be specified only after a thorough study of the combustion of wood in stoves of this type. A study of this character was, however, far outside the scope of the present experiments. Fitting insulation is a simple and directly applicable means. This measure has been investigated and has proved to be successful (Nievergeld et al 1981). When the stove was insulated with a 0.02 m thick glasswool layer, the heat lost to the environment decreased by 22% and, what is more important, the heat absorbed by the pans increased by 13% absolute. For the ceramic stoves the accumulated heat is the major part of the heat balance. It does not change much with the variables investigated and remains in the order of 30 to 40% of the heat input. In fact this heat is not always completely lost, because it can be used partly for heating up water directly after the cooking has been finished or contributes to the next cooking period by keeping the inside wall of the combustion chamber warm.

---

### Table 4. Combustion performance of the brick stove

<table>
<thead>
<tr>
<th>Operating range</th>
<th>4.5-9 kW</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂</td>
<td>3.7-9.3 %</td>
</tr>
<tr>
<td>CO</td>
<td>0.2-0.6 %</td>
</tr>
<tr>
<td>C₅H₇</td>
<td>150-1300 ppm</td>
</tr>
<tr>
<td>Soot</td>
<td>10 mg/mm³</td>
</tr>
</tbody>
</table>

### Table 5. Heat balances of three wood stoves.

<table>
<thead>
<tr>
<th></th>
<th>Metal stove</th>
<th>Brick stove</th>
<th>Mud stove</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat load kW</td>
<td>5.14</td>
<td>5</td>
<td>5.02</td>
</tr>
<tr>
<td>First pan %</td>
<td>18.6</td>
<td>13.4</td>
<td>13.9</td>
</tr>
<tr>
<td>Second pan %</td>
<td>8.9</td>
<td>3.4</td>
<td>5.6</td>
</tr>
<tr>
<td>Flue gas %</td>
<td>22.7</td>
<td>30.2</td>
<td>13</td>
</tr>
<tr>
<td>Unburned CO</td>
<td>7.4</td>
<td>2.7</td>
<td>5.5</td>
</tr>
<tr>
<td>C₅H₇</td>
<td>?</td>
<td>0.6</td>
<td>4.8</td>
</tr>
<tr>
<td>Environment %</td>
<td>41.7</td>
<td>2.7</td>
<td>6.6</td>
</tr>
<tr>
<td>Accumulated %</td>
<td>—</td>
<td>37</td>
<td>39.6</td>
</tr>
<tr>
<td>Unaccounted for %</td>
<td>0.7</td>
<td>10.1</td>
<td>11</td>
</tr>
</tbody>
</table>
It therefore depends on the use that is made of the stove in what manner this heat contributes to its efficiency. When for instance for the brick stove after cooking the pans are filled with water and the damper and stack are closed, the water can easily be heated to 60°C using the accumulated heat (figure 10). This contributes 2% to the overall efficiency of the stove. To get a better insight in the accumulated heat and temperature distribution in the stove calculations have been made using a computer program based on the finite-elements method (Ree et al 1974).

Figure 11 presents the comparison between measured and calculated surface

![Figure 10. Water temperature as a function of time for the brick stove.](image)

![Figure 11. Measured and calculated wall temperatures of the brick stove.](image)
temperatures of the brick stove using this computer model for a one and a half day period with different cooking periods. There appears to be a good agreement between measurements and calculations.

To improve stove behaviour with respect to the heat accumulated in the stove walls a further study into the behaviour of the stove body should be made to optimise stove wall construction and adapt it to the user’s requirements. The computer model will be very useful in this respect.

9. Conclusions

From a comparison of the performance of the three wood stoves the following conclusions can be drawn:

— When compared under similar test conditions the mud stove has an efficiency range from 18 to 22%; the brick stove of 15 to 23%. The metal stove with the pans inserted in the combustion chamber has an efficiency between 25 and 30%.
— Of the three stoves investigated the combustion performance of the brick stove is the best. This is mainly the consequence of the application of a stack and a properly functioning combustion air damper. The combustion performance of the mud stove is poor.
— Practical means improve the performance of a wood stove are:

  use pans with a diameter as large as possible;
  insert the pans into the stove;
  insulate metal stoves;
  apply a baffle in the flue gas channel between the combustion and heating chambers;
  use a proper combustion air damper.

— Most of the possible measures to improve stove efficiency lead to poorer combustion. A baffle in the flue gas channel seems to be a favourable exception.
— For health reasons it is absolutely necessary to provide a wood stove with a stack.
— To improve the performance of heavy brick or clay stoves a further study should be made into the thermal behaviour of the stove to optimise the stove wall construction and adapt it to the user’s requirements.

Appendix I

Formulas used for heat balance and efficiency calculations

— Pan efficiency

\[ \eta = \frac{M_w \cdot C \cdot (T_b - T_t) + M_s \cdot L}{M_f \cdot H} \times 100\% \]
— Sensible heat in flue gases

\[ Q_s = \frac{0.946 \cdot [\text{CO}_2] + 0.594}{H} \cdot C_{pm} (T_g - T_0) \times 100\% \]

— Heat losses of stove body to the surroundings

Convection

\[ Q_{\text{con}} = \frac{\alpha \cdot A \cdot (T_s - T_0)}{M_f \cdot H} \times 100\% \]

The heat transfer coefficient \( \alpha \) is calculated using the relation (Mc Adam)

\[ \text{Nu} = 0.53 (\text{Gr} \times \text{Pr})^{1/4} \]

inserting the physical properties of the one for the average temperature between the stove wall and the surroundings.

Radiation

\[ Q_{\text{rad}} = \frac{\varepsilon \cdot A \cdot C_s \cdot (T_s^4 - T_0^4)}{M_f \cdot H} \times 100\% \]

The actual emissivity of the surface was determined experimentally.

References


Claus J, Sulilatu W & Verwoerd M 1982 The performance of the Lowon wood stove, Research report for the Woodburning Stove Group

De Lepeleire/van Daele 1981. Personal communication

Mc Adams in Heat transmission


List of symbols

\( \alpha \) heat transfer coefficient (W/m²K)

\( \varepsilon \) emissivity of surface

\( A \) surface area of stove body (m²)
Performance of woodstoves

\[ C \] specific heat of water (kJ/kg·K)
\[ C_{pm} \] mean specific heat of flue gas (kJ/nm³·K)
\[ C_s \] Stefan-Boltzmann constant (W/m²·K⁴)
\[ H \] net calorific value of fuel (kJ/kg·K)
\[ L \] vaporization heat of water at atmospheric pressure and 100°C (kJ/kg·K)
\[ M_f \] mass of fuel burned (kg)
\[ M_w \] mass of water at the start of the experiment (kg)
\[ M_s \] mass of water evaporated (kg)
\[ T_b \] boiling temperature (K)
\[ T_g \] flue gas temperature (K)
\[ T_i \] water temperature at the start of the experiment (K)
\[ T_0 \] temperature of surroundings (K)
\[ T_s \] surface temperature of stove body (K)
\[ [CO_2] \] CO₂ content of dry flue gases
\[ [CO] \] CO content of dry flue gases
\[ Gr \] dimensionless Grashof-number
\[ Nu \] dimensionless Nussell-number
\[ Pr \] dimensionless Prandtl-number
Figure 4. Experimental set-up with the brick-stove
The performance of Thai charcoal stove

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Abstract. Wood and charcoal used for cooking accounts for nearly 50% of the energy consumption in Thailand. Deforestation has become a problem and the continuing population growth puts ever increasing demands on the wood and fuel supply. This report looks at the performance of a typical Thai charcoal stove used under 18 different operating conditions and identifies the major heat losses. When used in the most economic mode, the major losses are to the stove wall and in generating steam. Heat transfer to the pan is primarily by radiation, convective heat transfer is poor and the heat in the flue gas is mainly wasted. By controlling the air input a saving of about 30% in the charcoal can be made.

The Thai stove as developed over the past 200 years is probably not far from the best that can be achieved using local low-cost materials.

Keywords. Thai stove; charcoal stove; useful heat; stove parameters; fuel use; heat balance; heat transfer; burning rate.

1. Introduction

In Thailand, wood and charcoal make an important contribution of 50% of the total energy consumption, and is mainly used as a cooking fuel. About 97% of total households (both in urban and rural areas) used wood and charcoal for cooking (FAO 1970 cited by Barnard & Ratasuk 1980). The average annual consumption of wood per capita is estimated as 1.79 m^3. Charcoal has traditionally been used for cooking with the Thai stove for more than 200 years. Rice is the main dish and is cooked for 3 meals a day. An average of 0.3-0.5 kg of charcoal is normally used to cook 0.5 kg of rice per meal for a family of 5 persons.

The increase in wood fuel and charcoal consumption and the expansion of agricultural land have resulted in large scale destruction of the forest areas of Thailand. The rate of deforestation during 1960-1974 has averaged 0.77 million ha per year (4.8 million rai, 6.25 rai = 1 ha).

The satellite photo survey made in 1974 showed that forest areas in Thailand amount to only 19 million ha or about 37% of the country's total land area. It is considered that at least this area should be preserved as the water-shed areas for the country (Tuntawiroon 1980).

There is a national plan to recover the forest areas by reforestation and also for planting fast-growing trees as fuel crops, nevertheless, the limit of land resource is a constraint in increasing the supply of fuel crops.

At present, there is no real alternative to wood fuel and charcoal for cooking, especially in the rural areas. The increase in population will increase the demand of wood consumption but the supply is limited. In order to balance the demand and
supply of wood fuel and charcoal for cooking, the more efficient use of these fuels is desirable.

This report looks at the performance of a traditional Thai charcoal stove, sensitivity to changes in dimensions, determines the heat balance and identifies the main heat losses. It attempts to identify worthwhile improvements in performance which might be achieved by cheap and simple changes in design.

2. A good stove, efficiency and effectiveness

What is a good stove? A good stove will—

(i) cook well—depends on:
   - nature of food,
   - quantity of food,
   - method of cooking,
   - cooking utensils

(ii) be economical in fuel use,

(iii) have low cost and long life,

(iv) use local material,

(v) be safe in use,

(vi) be acceptable to local people.

To achieve the appropriate design and produce the fuel saving stoves, the basic concept of ‘a good stove’ will depend on many factors, not only technical but cultural as well.

A wide range of efficiencies for traditional and improved stoves are quoted in the literature and it is not easy to make meaningful comparisons between the various designs. It is essential that the measurements should reflect accurately the traditional cooking practice.

Efficiency defined as (heat to the pan/total fuel consumed) may be misleading; a more relevant criteria is effectiveness which is the fuel used (calorific value) to cook the meal.

Figure 3. Dimensions of the Thai stove.
3. The Thai charcoal stove

The Thai stove is shown in figures 1 and 2 (plates 1 and 2). It are traditionally made of clay, ash and rice husk, but there are local variations in the materials and mixtures used. The stove can be cylindrical or conical in shape and is clad in aluminium or zinc sheet for protection. Handles are usually added to facilitate carrying the stove.

There are various sizes of the Thai charcoal stove and utensils which depend upon the amount of food, the type of food and the method of cooking.

The stove used in the investigation is typical of the stove used by a Thai family to cook rice and other food dishes. The dimensions are given in figure 3.

4. Experimental design

4.1 Experimental conditions and parameters

Three stove parameters were varied during the investigation namely; the area of the air aperture \((a)\), the distance between the charcoal bed and the pan \((V)\), and the number of holes in the grate \((G)\).

Area of the air aperture \((A)\)

\[
A_1 = 2,500 \text{ mm}^2, \quad A_2 = 5,000 \text{ mm}^2, \quad A_3 = 10,000 \text{ mm}^2.
\]

Distance between the charcoal bed and the bottom of the pan \((V)\)

\[
V_1 = 100 \text{ mm}, \quad V_2 = 150 \text{ mm}, \quad V_3 = 170 \text{ mm}.
\]

Number of holes in the grate \((G)\)

\[
G_1 = 16, \quad G_2 = 37.
\]

Diameter of holes = 15 mm

Therefore the total number of experimental combinations were \(3 \times 3 \times 2 = 18\).

4.1a Useful heat. ‘Rice must be brought to the boil quickly’, 10 min is typical but it must be less than 15 min, otherwise the quality of the cooked rice will be poor. The cooking process involves bringing the rice to the boil, simmering and after draining away the surplus water, vapourising away some of the remaining water to obtain the required dryness. Although the cooking process will vary in detail from place to place and on the type of rice being cooked (glutinous or non-glutinous rice) it is typical that the complete cooking process for 0.5 kg of rice mixed with 3 kg of water will take 30 min.

To simulate the rice cooking process the following water boiling test was conducted. The useful heat is the heat used in a 30 min period to raise the temperature of the water from 20°C to boiling point and then to continuously boil for the remainder of the period.
4.1b Fuel use. In all the tests 450 g of charcoal was loaded into the stove and allowed to burn until well alight, reweighed and then replaced in the stove. Immediately after the 30 min test period the charcoal was removed and weighed. This was done on a 2 g resolution weighing machine and was in addition to the continuous weighing on the main weighing machine (resolution 25 g) and used as a check. In order to reduce the experimental time and to make each test comparable with the others, each test was started with an inside stove wall temperature at about 330°C and with the outside stove wall temperature at about 110°C.

4.2 Measurements

The measurements made to analyse the performance of the stove were:

- effectiveness (total fuel used),
- air supply and excess air,
- burning rate of the charcoal,
- combustion efficiency,
- heat balance.

Figure 4. Block diagram of the Thai stove data acquisition system.

Figure 5. Instrumentation and measuring points of the basic Thai stove.
The data acquisition system was based on an *Apple* computer as shown in figure 4 and the measuring points are shown in figure 5. Measurements were recorded every minute over a period of 30 min. The data of temperature and gas analysis were recorded automatically.

The average air flow was measured by an air flow meter and was recorded by hand every 5 min. The mass of the charcoal was also recorded by hand.

To measure the losses at various temperatures calorimetric tests were made of the stove, pan and lid, using an electric heater. These results were later compared with those obtained by calculation using natural convection and radiation theory and gave good agreement.

![Figure 6. Charcoal used as a function of aperture area (A).](image)

![Figure 7. Charcoal used as a function of the distance (V) between the charcoal bed and the pan bottom.](image)
5. Stove performance analysis

Of the three variable parameters the air aperture \((A)\) had the most effect on the stove's performance, the number of holes in the grate \((G)\) also made a significant contribution to the air flow except for the smallest aperture.

The performance was not so sensitive to the change in the distance between the charcoal bed and the pan; however, the range of the variation of this distance was not large and the trend was to improve the effectiveness of the stove as the distance \((V)\) was reduced. The effect of these parameter changes on the quantity of charcoal used is shown in figures 6 and 7.

5.1 Effectiveness

All the test cooker combinations conformed to the cooking profile that water should boil within 15 min and that the water should continuously boil for the remainder of the 30 min period.

The combination with the best effectiveness was \(A1V1G1\). This burnt the least charcoal (244 g) over the test period. \(A3V3G2\) was the worst combination and burnt the most charcoal (340 g) over the same test period.

5.2 Air supply, excess air and combustion efficiency

The total air supply was increased from 3·6 m\(^3\) to 7·2 m\(^3\) by increasing the size of the air aperture \((A)\). Almost 50% of total air supply to all combinations is excess air. This correlates with the combustion efficiency as measured from the CO content averaged over the test period which varied between 96% and 99% for all the combinations. The CO content was highest at the start and towards the end of the test period, but once the fire had become well established the CO content was less than the resolution of the gas analyser (0·01%).

5.3 Burning rate of charcoal

The burning rate of charcoal was averaged by the mass of charcoal used over the whole 30 min period of the test. The combination with the best effectiveness \((A1V1G1)\) had an average burning rate of 8.13 g/min and the worst combination \((A3V3G2)\) was 11.33 g/min.

5.4 Heat balance and heat transfer

Heat losses were calculated using standard convection and radiation theory and were used to give the overall heat balance. The temperature of the charcoal bed varied between about 600°C and 1,000°C and the flue gas temperature between about 500°C and 750°C. The temperatures were on average about 860°C and 670°C respectively. No correlation between these temperatures and the three variables \((A, V, G)\) could be detected, the variation in the temperature must be attributed to the random burning characteristic of the charcoal and to the position of the thermocouple probes. The heat input into the pan did not vary much from test to test. The difference in heat output from the charcoal between \(A1V1G1\) and \(A3V3G2\)
was 3,015 kJ, 2,532 kJ of this extra heat appears in the flue gas of A3V3G2 as seen by comparing the two Sankey diagrams of figures 8 and 9.

Calculation of the heat transfer from the charcoal bed to the pan by forced convection and radiation shows that the radiated heat transfer is dominant, being about 5 to 7 times that of the convected heat transfer. The low velocity of the gas over the pan is responsible for this, the Reynolds number only being a few hundred. Since it is not practical to increase the surface area of the pan the best results will be obtained when the heat in the flue gas is small but at a high temperature. This will occur when the excess air is reduced to that which is just sufficient for satisfactory combustion of the charcoal. If the air supply is reduced too much the temperature of the charcoal will fall, reducing the heat radiated, there will be a point where the reduced heat transfer will result in an unacceptable long time for the water to boil.

Since heat transfer is mainly by radiation the size of the pan is not critical so long as it covers the top of the stove.
6. Discussion of the results

Of the three variable parameters \((A, V, & G)\) the performance was dominated by the air aperture \((A)\). There was a 39\% increase in the charcoal used from the best test \((A1V1G1)\) to the worst test \((A3V3G2)\). Keeping the grate size and the charcoal to pan distance fixed to the smallest valves \((V1, G1)\) there was a 30\% increase in the charcoal used from the smallest air aperture \((A1)\) to the largest \((A3)\).

When the cooking process is started with a cold stove about 1,500 kJ of extra heat is supplied to the stove wall when compared to the cooking process started with a hot stove. This lowers the efficiency to about 30\%. In practice this means that it takes about 1 or 2 min longer to reach boiling point and less steam is produced, but the same amount of charcoal is used, therefore the effectiveness of the stove as defined for these tests is the same for a cold stove as a hot stove.

7. Conclusion

The best configuration of those tested was \(A1V1G1\), i.e. the stove with the smallest air aperture, the smallest distance between the charcoal bed and the pan bottom and the grate with the least holes.

With this configuration the two main heat losses were, the heat to generate steam and the heat stored in the stove wall. The loss by steam could be reduced by using the air control to reduce the heat input to the pan after the water has reached boiling point. It is, however, typical Thai cooking practice to boil away a large amount of the water while cooking the rice, particularly the glutinous variety, where steaming is part of the cooking procedure. Some resistance to a change of this practice might be expected.

The other major loss to the stove wall could be reduced by making the stove smaller, the test stove was made large to accommodate the changes in dimension between the charcoal bed and the pan bottom. The distance of 100 mm between the charcoal bed and the pan used in the best configuration is about the minimum that can be used without losing some of the stove's versatility, e.g. for cooking large quantities of food and sometimes wood is used instead of charcoal.

The Thai stove, as developed over the years, is probably not far from the best that can be achieved using readily available local materials. It is much superior to the simple metal charcoal stove found in Africa (Openshaw 1979) which is little more than a metal "radiator." There can be little doubt that a stove could be built using heat shields, modern materials and insulators which would be superior to the Thai stove but the cost would be out of the reach of most users and the local material content would be largely lost.

The heat input to the pan is not sensitive to dimensional changes. If sensible use is made of the air aperture control by closing it down after the fire has become established, the charcoal used can be reduced by at least 30\% without any significant reduction of the heat input into the pan.

The economic use of charcoal is very much in the hands of users. Recommendation can be made such as: (a) proper use of the air control, (b) do not overload the stove with charcoal, (c) keep the stove away from draughts, (d) keep the bottom of
the pan black. But the real spur to economy will be price and scarcity; while charcoal is available at affordable prices, old practices are not likely to change.

However, the heat stored in the stove walls is significant if the stove is only used for a short period. Over 50% of the heat produced during the 30 min test period when starting from cold goes into heating the stove walls, a modified design which reduces the heat capacity of the stove without any loss of its insulating properties might be worth pursuing.

It is recognised that these results on the Thai charcoal stove were limited to one test at each configuration on one stove and that further work will be necessary before general and final conclusions can be drawn.

About half the charcoal used in Thailand is made by traditional methods. The efficiency of such convertors is low, typically less than 25%, this may be raised to around 40% by the use of simple portable metal kilns and to higher values by retorts. The overall system efficiency can best be improved by changing the charcoal production method rather than stove design.

The authors wish to thank Mr Stephen Joseph of ITDG and his staff for their co-operation, the use of their equipment and instrumentation in this project.

References

Tuntawiroon N 1980 Contemporary South East Asia (Thailand: Natl. Dev., Resource Depletion & Environ. Deterioration) Vol. 1 No. 4
Figure 1. A typical Thai stove.
Figure 2. Thai stove with clay liner and kiln fired grate.
Fuel efficiency and performance of traditional and innovative cookstoves

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Abstract. Fuel efficiency and other cookstove performance parameters have been evaluated in an attempt to progress toward more efficient stoves for a particular locale, to develop and test methodologies for analysing cookstove fuel economy, and to gain insights into the performance of woodburning cookstoves in general. In the first part of this study, fuel consumption and efficiency were measured during the preparation of meals in 13 households. It was found that fuel consumption averages 3.6 kg/meal (s = 2.1 kg/meal) and that efficiency averages 5.9% (s = 2.2%). The use of aluminium rather than clay pots correlates with higher than average efficiencies. The magnitude of the various cooking energy losses was estimated to point out the opportunities for increasing fuel efficiency. While no particular energy loss mechanism dominates, the more significant energy losses are (i) heating of excess air, (ii) heat carried away by the combustion products, (iii) heating of the stove body and floor, (iv) energy contained in the charcoal residue, and (v) cooking water evaporation. Techniques for reducing these energy losses are suggested. Tests comparing the efficiency of traditional cookstoves and cookstoves containing a flue, chimney, and tightly fitting pots (the Hyderabad stove design) were then carried out. The Hyderabad cookstoves did not prove to be more fuel-efficient than the traditional stove when a means for controlling the draft or regulating the heat input rate to the pots is not provided. When the Hyderabad stove is equipped with a damper and recessed pots, a fuel savings of the order of 30% is realized in the laboratory. The innovative Hyderabad stove still requires field testing and user evaluation. This limited series of experiments suggests that new woodburning cookstoves should be carefully designed, constructed and operated.

Keywords. Cookstoves; improved stoves; traditional fuels; fuel wood; firewood; woodburning; fuel efficiency; energy conservation; rural energy; village energy consumption.

1. Introduction

It is well-known that fuel wood is the primary energy source in rural areas of developing countries. In India, fuel wood represents more than 35% of the total national energy demand (Prasad et al 1979). Furthermore, about 80% of the fuel wood in India is used for domestic cooking. In addition, it is recognized that cooking with fuel wood is carried out very inefficiently at the present time in rural areas of developing countries (Makhijani & Poole 1975; Morgan et al 1979).

Because of low cooking efficiencies and growing fuel wood scarcities, there have been a number of attempts to develop and introduce more fuel efficient cookstoves in developing countries. However, these efforts have been unsuccessful for the most
part (Joseph 1979). One of the shortcomings in many improved stove projects has been a lack of scientific stove design and analysis (De Lepeleire et al 1981). Also, there have been relatively few assessments of traditional stoves and cooking practices to serve as a foundation for developing improved stoves. In contrast, experience at Astra has shown that it is necessary to take a scientific approach to rural technologies and to understand the existing practices and technologies in a rural area before trying to develop and introduce modified or new technologies (Reddy & Subramanian 1979).

With this perspective, an analysis of the performance of the cookstoves found in the vicinity of Astra’s Ungra Extension Centre was carried out**. This assessment, described in detail in an earlier report (Geller 1982), is summarized in the next section. Following the study of traditional stoves, a number of innovative stoves (all similar in design) were tested. A comparison of the fuel economy of new and traditional stoves is presented in the third section.

The overall objectives of this study are to: (i) progress toward more fuel-efficient stoves for a particular rural locale in India; (ii) develop and test methodologies for evaluating the fuel economy of cookstoves; and (iii) gain insights into the performance of woodburning cookstoves in general.

2. Experiments with traditional stoves

2.1 Description of cookstoves and cooking conditions

The typical cookstove used in the Ungra village area is shown in figure 1 (plate 1). The resident normally constructs the stove from one or more local and freely available materials; namely, soil (sandy clay), termite mound dirt, and surki (brick powder). The three pot-opening stove shown in figure 1 is predominant in the Ungra area although a few of the smaller families use a two-opening stove. The dimensions of three opening stoves are 80–120 cm in length, 40–60 cm in width and 15–20 cm in height. The pot openings are usually 10–20 cm in diameter and the width of the front opening is 12–20 cm.

Both fired clay and aluminium pots are used by Ungra area villagers. The cooking vessels are supported on three raised mounds located around each pot opening.

An earlier energy consumption survey showed that wood accounts for about 95% of the cooking fuel used in the Ungra area (Astra 1981). Approximately 48% of this firewood consists of gathered twigs and branches, about 34% is purchased mainly in the form of twigs and branches, and about 19% is cut from trees on one’s own land. The energy survey conducted by Astra revealed a total fuelwood demand for cooking of approximately 600 kg/capita/year. This represents more than 70% of the total amount of energy consumed in the Ungra area.

The most common meal in the Ungra area consists of rice, sambar (a vegetable and pulse soup), and a very thick porridge made from ragi flour (a millet). Figure 1 (plate 1) shows how ragi is cooked. In some cases, only one grain item (rice or ragi) is eaten. Meals are generally prepared twice a day at approximately 7 a.m. and 7 p.m.

**Ungra village is located in Tumkur District of Karnataka State approximately 115 km south-west of Bangalore.
During cooking, the cook crudely controls the heat output from the fire by regulating the fuel feeding rate. Most of the water heating and cooking occurs on the centre pot opening. During the simmering stage of cooking, the pots are rotated between the centre and side openings in order to maintain them at or near the boiling point and to minimize the cooking time. Pot covers are used during most of the cooking operation. Upon completion of cooking, unburnt wood is removed from the fire but the coals are not extinguished. Often, the hot coals are utilized to heat water for drinking or cleaning.

Since the traditional cookstove does not contain a flue and chimney, the burning gases and combustion products are released into the kitchen. This can cause a health hazard as well as discomfort for the cook (Geller 1982). Furthermore, the broad fuel opening and the lack of a flue and chimney result in the fire being only partially confined. In many homes, radiation from the flames serves as the major source of light in the vicinity of the cookstove. In addition, the broad fuel opening makes it possible for wood to protrude from the stove. Thus, firewood generally is not cut less than 30 cm in length in the Ungra area.

2.2 Field tests

In order to begin to understand cookstove performance and cooking fuel economy in the Ungra area, fuel consumption and other efficiency-related parameters were measured during the preparation of actual meals by villagers. The tests were carried out in thirteen households in the Ungra area while the evening meal was prepared. During each test, the following measurements were made:

(i) the weight of the empty pots, cooking water, food, full pots upon completion of cooking, wood consumed and any charcoal reclaimed upon completion of cooking;
(ii) the temperature of the ambient air, cooking water at the start of cooking, and the contents of the pots during cooking;
(iii) the time required for cooking.

In addition, samples of the fuel and any recovered charcoal were taken for moisture content and calorific value analysis. A drying oven and bomb calorimeter were used for these measurements.

The measurements are first used to calculate fuel consumption per meal as well as specific fuel consumption in terms of both family size (kg fuel/person/meal) and the quantity of food cooked (kg fuel/kg food/meal). In addition a dimensionless cooking efficiency is calculated. The determination of cooking efficiency corrects in part for differences in foods and fuels between meals.

The cooking efficiency is defined as the fraction of the energy in the fuel which has been utilized for heating the cooking medium and the food to the cooking temperature plus the energy absorbed by the food as it cooks. Thus, for the foods

\*In previous definitions of cooking efficiency by the author, the energy utilized for heating the pots to the cooking temperature was also included as useful energy (Geller 1982, Geller & Dutt 1982). This factor has been removed because, strictly speaking, pot heating is not an integral part of the cooking operation. The change in definition results in a very small reduction in average cooking efficiency (0.1%).
prepared in the Ungra area, cooking efficiency is given by

\[
\varepsilon_0 = \frac{\sum_{i=1}^{n} [M_{mi} C_{mi} + (M_{fi} C_{fi}) (T_{ci} - T_a) + M_{fi} K_f]}{M_w E_w - M_r E_r}
\]

The summation in equation (1) is over the different food items. For each item \(i\), \(M_{mi}\) and \(M_{fi}\) are the weights and \(C_{mi}\) and \(C_{fi}\) are the specific heats of the cooking media and foods respectively. \(T_a\) is the initial temperature of the cooking media and foods (normally the ambient temperature) and \(T_{ci}\) is the cooking temperature of item \(i\). \(K_f\) is the energy required for the chemical reactions which take place during cooking a unit of item \(i\). \(M_w\) and \(E_w\) are the mass and calorific value of the fuel consumed and \(M_r\) and \(E_r\) are the mass and calorific value of any charcoal recovered upon the completion of cooking. Equation (1) applies to one complete cooking cycle.

The constants used in the efficiency calculations include \(C_{fi} = 1.88\) KJ/kg°C for rice, ragi and dried pulses, \(C_{fi} = 3.89\) KJ/kg°C for fresh vegetables, \(K_f = 172\) KJ/kg for rice, ragi flour, and dried pulses, and \(K_f = 0\) for fresh vegetables (Geller & Dutt 1982).

Table 1 presents the characteristics of the 13 field tests along with fuel consumption and efficiency results. All of the meals were prepared on three-opening stoves. The average household size for the sample is 6.9 members (adults and children counted equally). This is 8% greater than the average household size in the villages studied. The woods used in the tests have an average moisture content of about 13% and an average calorific value (HHV) of approximately 18.4 MK/kg. The cooking time is 1-24 hours on the average and is in the range of 1-1.5 hours for all except one of the meals.

Table 2 shows the mean, standard deviation, and coefficient of variation (cov) for the various test parameters. Cov, a normalized measure of variability, is equal

<table>
<thead>
<tr>
<th>Household size</th>
<th>Predominant pot type*</th>
<th>Quantity of food cooked (kg/meal)</th>
<th>Firewood consumed (kg/meal)</th>
<th>Cooking time (hr)</th>
<th>Efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>C</td>
<td>1.55</td>
<td>2.90</td>
<td>1.25</td>
<td>3.0</td>
</tr>
<tr>
<td>4</td>
<td>Al</td>
<td>2.29</td>
<td>1.58</td>
<td>1.08</td>
<td>7.3</td>
</tr>
<tr>
<td>4</td>
<td>Al</td>
<td>1.73</td>
<td>3.40</td>
<td>1.00</td>
<td>3.7</td>
</tr>
<tr>
<td>5</td>
<td>Al</td>
<td>2.35</td>
<td>2.15</td>
<td>1.05</td>
<td>7.3</td>
</tr>
<tr>
<td>6</td>
<td>Al</td>
<td>2.47</td>
<td>3.51</td>
<td>1.00</td>
<td>5.7</td>
</tr>
<tr>
<td>6</td>
<td>C</td>
<td>2.87</td>
<td>4.15</td>
<td>1.17</td>
<td>3.6</td>
</tr>
<tr>
<td>7</td>
<td>C</td>
<td>2.39</td>
<td>2.16</td>
<td>1.25</td>
<td>6.4</td>
</tr>
<tr>
<td>8</td>
<td>Al</td>
<td>3.02</td>
<td>2.06</td>
<td>1.25</td>
<td>9.1</td>
</tr>
<tr>
<td>8</td>
<td>Al</td>
<td>4.42</td>
<td>2.35</td>
<td>1.20</td>
<td>8.4</td>
</tr>
<tr>
<td>9</td>
<td>Al</td>
<td>4.55</td>
<td>3.99</td>
<td>1.50</td>
<td>6.7</td>
</tr>
<tr>
<td>9</td>
<td>C</td>
<td>5.07</td>
<td>8.12</td>
<td>1.25</td>
<td>3.2</td>
</tr>
<tr>
<td>10</td>
<td>C</td>
<td>4.82</td>
<td>8.03</td>
<td>2.17</td>
<td>3.5</td>
</tr>
<tr>
<td>11</td>
<td>Al</td>
<td>2.96</td>
<td>2.51</td>
<td>1.00</td>
<td>8.2</td>
</tr>
</tbody>
</table>

*C — clay; Al — aluminium
Table 2. Statistical analysis of field test data

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Mean</th>
<th>Standard deviation</th>
<th>Coefficient of variation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel consumption (kg/meal)</td>
<td>3.61</td>
<td>2.13</td>
<td>0.59</td>
</tr>
<tr>
<td>Specific fuel consumption (kg wood/capita/meal)</td>
<td>0.55</td>
<td>0.264</td>
<td>0.48</td>
</tr>
<tr>
<td>Specific fuel consumption (kg wood/kg food/meal)</td>
<td>1.21</td>
<td>0.465</td>
<td>0.38</td>
</tr>
<tr>
<td>Efficiency (%)</td>
<td>5.9</td>
<td>2.2</td>
<td>0.37</td>
</tr>
</tbody>
</table>

to the standard deviation divided by the mean. For the 13 meals which were monitored, fuel consumption averages 3.6 kg/meal (s = 2.1 kg/meal) and efficiency averages 5.9% (s = 2.2%). There is a moderately strong correlation between fuel consumption and the quantity of food cooked (r = 0.77). However, there are poor correlations between either specific fuel consumption or efficiency and the quantity of food cooked or household size. Furthermore, it is seen in table 2 that the degree of variability decreases as the sophistication of the test parameter increases from fuel consumption to efficiency.

In this series of tests, pot type has a strong correlation with efficiency. The average efficiency for meals in which two or more clay pots are used (5 tests) is 3.9% while the average efficiency for meals in which two or more aluminium pots are used (8 tests) is 7%. The averages from these two subsets are statistically different at the 1% level of significance.* The lower efficiency associated with clay pots may be due to one or more of the following factors: (i) greater resistance to heat transfer into the clay pot, (ii) heat loss due to transpiration through the porous clay material, (iii) greater emissivity from the surface of the clay pot, or (iv) increased water evaporation due to less tightly fitting pot covers.

It has been pointed out that the cook's ability to regulate the heat input rate to the pots can have a significant effect on efficiency (Dutt 1978). Excessive heat transferred into the pots during cooking will be dissipated through water evaporation. Figure 2 shows that the degree of water evaporation declines as efficiency increases for the 13 tests. Explanations for the variation in the amount of water evaporation include different levels of operator control, variation in fuel quality (e.g., size or dryness) or variations in pot cover fit between the 13 tests.

2.3 Laboratory tests

Having established an overall cooking efficiency of only 6%, the salient question concerns the whereabouts of the unutilized energy. A series of laboratory tests were carried out to estimate the magnitude of the different energy loss mechanisms. The objective of this analysis is to gain an understanding of the relative importance of the different energy losses. A highly accurate analysis of the energy losses has not been

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*This does not conclusively prove that the use of aluminium pots is more fuel efficient than the use of clay pots. There may be other factors such as pot size, diet, or income which correlate well with pot material and one of these factors might cause the variation in efficiency.
attempted due to the unconfined nature of the stove, the nonhomogeneity of wood during combustion, and the need for simultaneous measurement of many factors for a more rigorous analysis.

In this analysis, most of the energy losses are estimated based on periodic measurements which are averaged over the entire burning cycle (Geller 1982). Many of the measurements were carried out during simulated cooking tests where only water is heated and simmered.

The measurements performed include:

(i) The cooling rate versus temperature difference relationship for pots containing hot water;
(ii) The exposed surface area of the pots;
(iii) The percentage of CO$_2$, CO and O$_2$ in the combustion gases released from the cookstove;
(iv) The temperature of the gases released from the stove;
(v) The temperature at various points on the inside surface of the stove;
(vi) The inside surface area of the stove.

The methods used to measure and calculate the different energy losses are presented in detail in Appendix A.

The results of the measurements carried out during the energy loss analysis are listed in Appendix B. Figure 3, the cooking energy balance for the Ungra area, shows the energy loss estimates. It is seen that no particular energy loss mechanism dominates. The largest energy losses are the heating of excess air, the heat content of the combustion products, heating of the stove body and floor, and the energy contained in the charcoal residue. Cooking water evaporation is also a significant energy loss since it accounts for about one-third of the energy transferred to the pots. Figure 3 shows that approximately 24% of the energy contained in the fuel is not
Potential energy losses which have not been analysed include gaseous hydrocarbons and carbon particles in the smoke and radiation escaping through openings in the stove.

It is conceivable that certain stove design modifications could reduce the larger energy losses and thereby increase fuel efficiency. The energy loss due to heating of excess air might be reduced by limiting the size of some of the openings to the combustion chamber. Also, dampers could be provided in the stove for better control over the air supply rate. A reduction in the heat loss from the combustion products as well as from excess air could result if heat transfer from the flames and hot gases to the pots is improved. In order to accomplish this, it would be desirable to increase the residence time of the flames and gases near the pots, expose more pot surface area to the flames and gases, and induce turbulence in the flames and gases. Closing up the stove so that the pots fit tightly in the openings and introducing a flue containing baffles should help achieve these objectives.

The energy loss to the stove body and floor can be reduced by minimizing the inner surface area of the stove or by lining this surface with an insulating material. It may be possible to recover some of the heat transmitted to the stove and floor by extinguishing the fire before cooking is completed and finishing cooking using the heat stored in the stove. Also, it may be possible to incorporate a water tank into the stove body. The energy loss due to the unreclaimed charcoal can be avoided if the charcoal is extinguished and then reused as a cooking fuel. As an alternative, charcoal production could be decreased by utilizing a grate in the combustion chamber. The water evaporation loss can be reduced by using tight-fitting pot covers and by controlling the heat input rate to the pots during the simmering stage of cooking.
Figure 4. Design of a typical Hyderabad cookstove (Raju 1966).
Fuel efficiency and performance of cookstoves

3. Experiments with new stoves

3.1 Description

A number of alternative mud cookstoves have been designed and developed in India over the past 35 years. One of the best known stoves is the “Hyderabad Smokeless Chula” (Raju 1966). Figure 4 shows the design of a typical Hyderabad chula (cookstove). This stove includes a chimney, pot openings which permit the pots to fit tightly on the top of the stove, a flue to carry the hot gases from the firebox to the chimney, and one large pot opening which is intended for water heating rather than cooking. The stove body is made of mud or mud combined with termite mound dirt, cow dung, ash, or chopped straw. The chimney can be made of bricks, metal pipe, asbestos-cement pipe, or fired clay tubes. One major benefit of the Hyderabad stove is that the smoke is released away from the cook and usually outside of the home.

The designers of the Hyderabad stove state that a 20–40% reduction in fuelwood consumption should result if this stove is used instead of the traditional open cookstove (Raju 1966). However, this claim is not supported by laboratory or field test data and it does not appear that the Hyderabad stove or similar alternative cookstoves have been widely adopted in India. The Hyderabad cookstove does have some features which, based on the energy loss analysis for the traditional stove, could lead to a reduction in fuel consumption compared to the traditional stove. Therefore, a series of tests comparing the efficiency of the Hyderabad and traditional stoves was carried out.

For this evaluation, three Hyderabad stoves similar to the design shown in figure 4 were tested along with a traditional three pot-opening mud stove. Table 3 lists the dimensions and the features of the four stoves. The first Hyderabad stove is based on the original design and includes a recessed pot for water heating as shown in

<table>
<thead>
<tr>
<th>Table 3. Characteristics of stoves used for comparison tests</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
</tr>
<tr>
<td>----------------</td>
</tr>
<tr>
<td>Length of stove body (cm)</td>
</tr>
<tr>
<td>Width of stove body (cm)</td>
</tr>
<tr>
<td>Height of stove body (cm)</td>
</tr>
<tr>
<td>Chimney material</td>
</tr>
<tr>
<td>Inner cross-section area of chimney (cm²)</td>
</tr>
<tr>
<td>Height of chimney (cm)</td>
</tr>
<tr>
<td>Diameter of first pot opening (cm)</td>
</tr>
<tr>
<td>Diameter of second pot opening (cm)</td>
</tr>
<tr>
<td>Diameter of third pot opening (cm)</td>
</tr>
<tr>
<td>Pot openings with provision for pots to drop into stove</td>
</tr>
<tr>
<td>Area of fuel opening (cm²)</td>
</tr>
<tr>
<td>Damper</td>
</tr>
</tbody>
</table>
figure 4. Also, this stove does not contain a damper. The second Hyderabad stove is a slightly modified design. This stove includes an easily adjusted metal damper in the flue between the combustion chamber and the second pot opening. In addition, the second pot opening is widened in order to expose more pot surface area to the flame and combustion gases. Pot seats cut out of asbestos-cement sheet are used to reduce the size of the second and third openings for smaller pots. The third Hyderabad stove has a damper as well as the provision to lower pots into the stove on both the second and third openings. The asbestos-cement sheets fit around the neck of the pots when they are lowered into the stove.

3.2 Procedure for comparison tests

In order to both standardize and simplify the comparison of the Hyderabad and traditional stoves, a simulated cooking test is used. The simulation test involves only the heating and boiling of water and is patterned after the cooking routine in the Ungra area.

The simulation test proceeds in the following manner:

(i) The wood to be used in the test is weighed;
(ii) Pots 1 and 2 are filled with 2 litres of water and pot 3 with 2–3 litres;
(iii) The initial water temperature is recorded;
(iv) The fire is started and pot 1 is heated to a boil on the main opening with pots 2 and 3 on the side or second and third openings;
(v) After pot 1 reaches a boil, pots 1 and 2 are switched and pot 2 is heated to a boil;
(vi) After pot 2 reaches a boil, the pots are left in place and the fire is maintained for 15 minutes to simulate the simmering stage of cooking;
(vii) At the completion of the test, the charcoal residue and any unused wood are weighed, the final temperature in each pot is recorded, and the amount of water evaporation is measured;
(viii) Samples of the fuelwood and charcoal are taken for calorific value analysis.

Each stove is tested at least three times using either aluminium or clay pots. The same operator conducts all of the tests using similar fuel (casurina or lantana species) in most of the trials. During the tests, fuel is fed to the fire as needed; i.e., the fuel feeding rate is not standardized. Recent simulated cooking experiments with both shielded fires and heavy stoves containing a flue and chimney indicate that efficiency is not highly sensitive to the overall burning rate (Krishna Prasad 1981). Hence, the lack of control over the fuel feeding rate should not introduce significant error in the simulation tests.

Two methods are normally used for calculating the ‘heat utilized’ or efficiency in simulation cooking tests (Geller & Dutt 1982; Joseph & Shanahan 1980). In the first method, the heat utilized is solely the energy in the fuel which contributes to water heating. The efficiency in this case is given by

\[ \epsilon_1 = \frac{\sum_{i=1}^{m} \left[ M_{pi} C_{pi} (T_{ci} - T_a) \right]}{M_w E_w - M_r E_r}, \]
where the summation is over the different pots, $T_{ci}$ is the final water temperature in pot $i$, and $T_a$ is the initial temperature.

Since a significant fraction of the energy transferred to the water is likely to result in water evaporation during a simulation test, the efficiency is also calculated including evaporative energy as heat utilized. In this case

$$
\epsilon_a = \frac{\sum_{i=1}^{n} [M_{pl} C_{pl} (T_{cl} - T_a) + M_{wi} L]}{M_w E_w - M_r E_r},
$$

where $M_{wi}$ is the mass of the water evaporated from pot $i$ and $L$ is the latent heat of evaporation. The calculation of efficiency with water evaporation included as heat utilized corrects in part for differences in heat input rate to the pots between different tests.

The calorific value of fuelwood and charcoal samples was measured using a bomb calorimeter in some tests and was indirectly measured through moisture content analysis in other tests (Geller & Dutt 1982). In all of the simulation tests, the energy content of the charcoal residue is subtracted from the energy content of the fuel consumed. This partially normalizes for variations in fuel type, fuel feeding rate, and burning conditions between tests.

Two additional analyses were conducted with the Hyderabad stoves. The first analysis involved measuring the temperatures in the firebox and in the flue near the base of the chimney. The temperatures at these two positions were measured and the damper position noted 30 times during a simulated cooking test using the Hyderabad-II stove. This experiment was carried out to evaluate the effectiveness of the damper. The temperature measurements were made using chromel-alumel thermocouples.

The other analysis consisted of ten tests comparing fuel consumption with Hyderabad-I stove and the traditional stove during cooking. The same cook and pots were used and similar types and amounts of food were prepared during each meal. From these tests, specific fuel consumption (kg fuel/kg food/meal) is calculated. This set of cooking tests provides a check on the simulation tests.

### 3.3 Results of the stove comparison tests

Table 4 shows the simulation test results. It is seen that fuel consumption is about 15% lower on the average when aluminium pots are used rather than clay pots on the traditional stove. However, the simulation test efficiency $\epsilon_a$ is greater when clay pots are used. This is due to an increase in the water loss from evaporation (because of poorly fitting pot covers and transpiration) with clay pots.

Table 4 also shows that the first Hyderabad stove uses slightly more fuel and yields a slightly lower efficiency on the average compared to the traditional stove (both tested with aluminium pots). Based on a T-test analysis, the average efficiency is not significantly different for these two stoves. The failure to realize an increase in efficiency with the Hyderabad-I stove is attributed in part to an increase in test time compared to the traditional stove. The average time to heat the first pot to a boil is 26 minutes with the Hyderabad-I stove and only 17 minutes with the traditional stove. Furthermore, the pot on the third opening of the Hyderabad stove reaches
Howard S Geller

Table 4. Simulation test comparison of traditional and Hyderabad stoves*

<table>
<thead>
<tr>
<th>Stove type</th>
<th>Pot type</th>
<th>Average test time (min)</th>
<th>Average fuel consumption (kg)</th>
<th>Average burning rate (kg/hr)</th>
<th>Average efficiency $\epsilon_1$ (%)</th>
<th>Average efficiency $\epsilon_2$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Traditional</td>
<td>Clay</td>
<td>38</td>
<td>1.44 (0.35)</td>
<td>2.24 (0.46)</td>
<td>9.5 (2.3)</td>
<td>17.2 (2.4)</td>
</tr>
<tr>
<td>Traditional</td>
<td>Aluminium</td>
<td>38</td>
<td>1.22 (0.14)</td>
<td>1.93 (0.21)</td>
<td>9.5 (1.6)</td>
<td>14.5 (2.1)</td>
</tr>
<tr>
<td>Hyderabad-I</td>
<td>Clay</td>
<td>47</td>
<td>1.74 (0.18)</td>
<td>2.20 (0.13)</td>
<td>8.8 (1.4)</td>
<td>15.7 (2.8)</td>
</tr>
<tr>
<td>Hyderabad-II</td>
<td>Aluminium</td>
<td>38</td>
<td>0.97 (0.12)</td>
<td>1.54 (0.28)</td>
<td>11.7 (1.7)</td>
<td>19.0 (2.7)</td>
</tr>
<tr>
<td>Hyderabad-III</td>
<td>Aluminium</td>
<td>41</td>
<td>0.76 (0.04)</td>
<td>1.11 (0.05)</td>
<td>13.5 (0.5)</td>
<td>22.0 (0.8)</td>
</tr>
</tbody>
</table>

*Numbers in parentheses are the standard deviation

Table 5. Cooking test comparison of traditional and Hyderabad-I stoves*

<table>
<thead>
<tr>
<th>Stove type</th>
<th>Average quantity of food** (kg/meal)</th>
<th>Average cooking time (min)</th>
<th>Average fuel consumption (kg/meal)</th>
<th>Average specific fuel consumption (kg fuel/kg food/meal)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Traditional</td>
<td>0.79 (0.16)</td>
<td>1.23 (0.08)</td>
<td>1.62 (0.53)</td>
<td>2.02 (0.40)</td>
</tr>
<tr>
<td>Hyderabad-I</td>
<td>0.86 (0.13)</td>
<td>1.32 (0.30)</td>
<td>2.11 (1.07)</td>
<td>2.36 (0.93)</td>
</tr>
</tbody>
</table>

*Numbers in parentheses are the standard deviation; **Weight of rice, ragi, and dried beans prior to cooking

...a boil at approximately the same time as the pot on the first opening. These results suggest that there is a need for control over the draft as well as control of the heat input rate to the different pots with stoves containing a flue and chimney.

The results of the cooking test comparison, shown in table 5, confirm the simulation test results. Once again, no significant difference in fuel economy was observed between the Hyderabad-I and traditional stoves. Based on this result, it is concluded that the simulation test utilized in this study is a reliable indicator of relative fuel economy in the Ungra area.

It is seen in table 4 that there is substantial increase in efficiency when the adjustable damper is included and used (Hyderabad stoves II and III). In tests with clay pots, the efficiency of the Hyderabad-II stove is 23% and 31% higher than the traditional stove for $\epsilon_1$ and $\epsilon_2$ respectively. These differences are statistically significant at the 10% and 5% levels. The increased efficiency is due to a reduction in the fuel-burning rate during the simulation test with no change in the time required to complete the test.

The fuel efficiency ($\epsilon_1$ or $\epsilon_2$) increases an additional 15% on the average when the pots on the second and third openings are lowered approximately 10 cm into the...
stove (Hyderabad-III stove). This modification improves the heat transfer to the pots and reduces the heat loss from the surface of the pots. The difference in the efficiency of the Hyderabad-III stove and the traditional stove is significant at the 1% and 0.5% level for $e_1$ and $e_2$ respectively.

The evaluation of the temperatures in the firebox and in the flue near the base of the chimney provides additional evidence of the benefit from using a damper in the Hyderabad stove. When the damper remains open, the temperature at a point in the firebox divided by the temperature near the base of the chimney averages 1.33. This ratio increases to 1.74 on the average when the damper in the flue is approximately two-thirds closed. Hence, less heat is lost up the chimney when the damper is used.

4. Conclusions

The analysis of the performance of the traditional cookstove revealed a number of design options which might provide a significant improvement in fuel efficiency. Some of these possibilities were explored with the original and modified Hyderabad stoves. It was observed, however, that building a 'smokeless stove' does not automatically provide fuel savings. When the Hyderabad stove was equipped with a damper and recessed pots, a fuel savings of the order of 30% was obtained. This modified design still requires field testing and user evaluation.

One broad conclusion from this limited set of tests (if such generalizations are possible) is that new woodburning cookstoves require careful design, construction and operation in order to conserve significant quantities of fuel. A similar conclusion was stated in a recent review of improved woodstove projects in West Africa (Wood 1981). These findings imply that:

(i) Improved stoves should be designed and evaluated in a scientific manner. In particular, the behaviour of the chimney, damper and other design components should be well understood so that these features provide fuel efficiency when incorporated into a stove design.

(ii) Stove builders (possibly professional stove makers) should be trained in stove construction and the basic principles related to fuelwood conservation during cooking. With proper training, stove builders would be less likely to construct stoves with excessive draft, poor heat transfer to the pots, or other inefficient characteristics.

(iii) Users should be taught how to operate their stove for maximum fuel savings. In this study, for example, it was found that fuel consumption is sensitive to regulation of heat input rate to the pots, proper use of a damper, and the type of pots used.

Even if a new stove design proves to be technically sound, the stove must satisfy a variety of other criteria in order to achieve the overall objectives of acceptance and fuel savings (Joseph 1979; Geller 1982). Cost, physical and cultural fit, and complexity are especially important in this regard.
(a) **Cost**

Existing stoves and to a large extent firewood are acquired without a capital expenditure in the Ungra area at the present time. Furthermore, capital is a very scarce resource in this locale. Therefore, a new stove should be low cost or, if possible, cost-free. While it should be possible to construct the Hyderabad stove for Rs. 60/- ($8.00) or less, this may still be too expensive for the majority of the residents in the Ungra area.

(b) **Physical and cultural suitability**

A cookstove may serve other functions besides cooking food. For example, it was pointed out that the open stove also provides light in Ungra kitchens. A closed or partially closed stove may be rejected if an alternative light source is not readily available. Such "side effects" are likely to be of greater importance in communities where, because of limited financial resources, it is difficult to purchase technical fixes (e.g., the electrical hook-up for a light bulb in the case just mentioned). In order to recognize these crucial side effects, there needs to be an awareness of the physical and cultural context in which cooking plays a part.

(c) **Complexity**

Functions such as positioning a damper or lowering pots into the stove during cooking seem straightforward to an engineer. However, such adjustments may not be made by the cook because other preoccupations (such as preparing a meal as quickly as possible) and/or a lack of awareness of their importance. Thus, a new cookstove should be simple to operate and, if possible, provide fuel savings over a wide range of operating conditions.

One major outcome from this study is that the development of more fuel efficient cookstoves is not as easy as one might guess—seemingly simple woodburning cookstoves present complex technical problems in combustion and heat transfer. Also, there are a host of non-technical concerns which need to be taken into account in the design of new stoves. While it is hoped that this study contributes a small piece to the puzzle of woodburning cookstoves performance and improved stoves, it is clear that much more work is needed in areas such as field performance and the role of various design features.

The author is deeply indebted to Professor A. K. N. Reddy for his suggestions and encouragement during the course of this study. Some of the tests were conducted by Mr N V Aruna and Mr H I Somashekar; their efforts proved to be extremely helpful. While many others at ASTRA also provided assistance, special thanks are due to Dr K S Jagadish, Dr N H Ravindranath and Mr P Rajabapaiah. The author is grateful to the residents in the Ungra area who made this study possible by opening their kitchens to a foreigner. Finally, appreciation is extended to ASTRA and the Indian Institute of Science for hospitality during his stay in India and to the United States Government for supporting the author through the Fulbright-Hays programme.
Appendix A. Methodology for computing energy losses

(a) Cooking water evaporation

The estimation of the energy loss due to the evaporation of cooking water, EL(1), is based on water loss measurements in the cooking efficiency tests.

(b) Pot surface losses

The energy loss from the surfaces of the pot and pot cover, EL(2), is estimated from

\[
EL(2) = \sum_{i=1}^{n} U_{pi} A_{pi} (T_i - T_a) \tau_i, \tag{A.1}
\]

where the summation is over \( n \) number of pots, \( U_{pi} \) is the overall heat transfer coefficient for pot and pot cover \( i \), \( A_{pi} \) is the area of pot and pot cover \( i \) exposed to the atmosphere when the pot is on the stove, \( T_i \) is the average temperature of the contents of pot \( i \), and \( \tau_i \) is the cooking time for pot \( i \).

The overall heat transfer coefficient \( U_{pi} \) is determined empirically for both clay and aluminium pots by measuring the cooling rate \( \frac{dT_i}{d\tau} \) and temperature difference \( T - T_a \) over time for a pot containing a known amount of hot water. Neglecting the thermal mass of the pot,

\[
\frac{dT_i}{d\tau} = \frac{U_{pi} A_{pi}}{\rho_{H_2O} V_{H_2O} C_{H_2O}} (T - T_a), \tag{A.2}
\]

where \( \rho_{H_2O}, V_{H_2O}, \) and \( C_{H_2O} \) are the density, volume and specific heat of water respectively. \( U_{pi} \) is derived from the slope of the best fit line between \( \frac{dT_i}{d\tau} \) and \( (T - T_a) \).

(c) Sensible heat in the combustion products

This energy loss category applies to the combustion of dry wood, i.e., it does not include heating of excess air or heating and evaporation of moisture in the fuel. The energy loss due to the heat in the combustion products when they are released from the stove is given by

\[
EL(3) = M_w (1 - F_m) \sum_{i=1}^{n} Q_i \Delta H_i, \tag{A.3}
\]

where \( M_w \) is the mass of wood consumed, \( F_m \) is the fraction of moisture in the wood, \( Q_i \) is the average quantity of combustion product \( i \) per kg of dry wood, and \( \Delta H_i \) is the difference in the enthalpy content of product \( i \) between the average temperature at the point of release and the ambient temperature.

The quantities of the combustion products are calculated assuming that the elemental composition of dry wood is 52% carbon, 41% oxygen, 6% hydrogen and 1% ash by weight (Tillman 1978). Also, it is assumed that all of the oxygen present
in the wood reacts during combustion and that the fuel is completely converted to \( \text{CO}_2 \), \( \text{CO} \), and \( \text{H}_2\text{O} \). Using these assumptions, the overall combustion reaction per kg of dry wood is

\[
43.3 \text{ moles C} + 30 \text{ moles H}_2 + (X + 12.81) \text{ moles O}_2 + 3.76 \text{X moles N}_2 \rightarrow 43.3 \text{ Y (1 - Z) moles CO}_2 + 43.3 \text{ (1 - Y) (1 - Z) moles CO} + 30 \text{ moles H}_2\text{O} + 3.76 \text{X moles N}_2.
\] (A.4)

\( X \), the number of moles of atmospheric oxygen used in combustion is given by

\[
X = 21.65 (Y - Z - YZ) + 23.85.
\] (A.5)

\( Y \), the fraction of reacting carbon converted to \( \text{CO}_2 \), is given by

\[
Y = F_{\text{CO}_2} (F_{\text{CO}_2} + F_{\text{CO}})^{-1},
\] (A.6)

where \( F_{\text{CO}_2} \) and \( F_{\text{CO}} \) are the fractions of \( \text{CO}_2 \) and \( \text{CO} \) respectively in the dry combustion products released from the stove. \( Z \), the fraction of carbon in the fuel remaining as charcoal residue upon the completion of cooking is given by

\[
Z = M_r [0.52 M_w (1 - F_m)]^{-1}.
\] (A.7)

The \( \text{CO}_2 \) and \( \text{CO} \) percentages in the combustion gases were measured using an orsat analyser and a Bacharch CO analyser. The temperature of the gases was measured using a chromel-alumel thermocouple. Because the traditional cookstove does not contain a flue or chimney, it is impossible to precisely define a point of release for the combustion products. It is assumed that the gases are released in the gap between the top of the stove and the bottom edge of the pot on the centre opening. The gases were sampled in this zone every 10 minutes during simulated cooking tests.

The fuel quantity and moisture content values used in the energy loss calculations are the averages obtained in the field cooking efficiency tests \((M_w = 3.61 \text{ kg and } F_m = 0.113)\).

**d) Sensible heat in excess air**

The energy loss due to the heating of excess air drawn into the cookstove is given by

\[
\text{EL (4)} = M_w (1 - F_m) Q_a \Delta H_a,
\] (A.8)

where \( Q_a \) is the average number of moles of excess air per unit of dry wood and
Fuel efficiency and performance of cookstoves

$\Delta H_a$ is the difference in the enthalpy content of air between the average temperature at the assumed point of release and the ambient temperature. $Q_a$ is given by

$$Q_a = 4.76 F_{O_2} (1 - 4.76 F_{O_2})^{-1} Q_{cp}, \hspace{1cm} (A.9)$$

where $F_{O_2}$ is the fraction of oxygen in the dry combustion products released from the stove and $Q_{cp}$ is the quantity of the dry combustion products (CO$_2$, CO, and N$_2$) per unit of dry wood. $F_{O_2}$ is also measured using an orsat analyser. $Q_{cp}$ can be determined from equations (A.4), (A.5), (A.6) and (A.7).

(c) Heating and evaporation of moisture in the fuel

The energy loss due to heating the moisture in the fuel to the boiling point, evaporating the moisture, and heating the water vapour to the average temperature at which the gases are released from the stove is given by

$$EL(5) = M_w F_m \left[ C_{H_2O}(T_c - T_a) + L + \Delta H_{H_2O} \right], \hspace{1cm} (A.10)$$

where $L$ is the latent heat of evaporation and $\Delta H_{H_2O}$ is the difference in the enthalpy content of water vapour between the average temperature at assumed point of release and the boiling point $T_c$.

(f) Evaporation of water originating as hydrogen in the fuel

The energy loss due to evaporation of water resulting from the bound hydrogen in the wood must be taken into account since the higher heating value of wood is used. This energy loss is given by

$$EL(6) = M_w (1 - F_m) Q_{H_2O} L, \hspace{1cm} (A.11)$$

where $Q_{H_2O}$ is the amount of water produced per unit of dry wood. Based on the assumed combustion stoichiometry (equation (A.4)) and the molecular weight of water, $Q_{H_2O} = 0.54 \text{ kg per kg of dry wood}$.

(g) Heating of the stove body and the floor

If (i) the stove body and floor are considered to be semi-infinite solids, (ii) the temperature of the inner surface within the stove is suddenly raised from $T_a$ to $T_s$, and (iii) the temperature is maintained at $T_s$ for time $\tau$, then the energy loss to the stove body and floor is given by

$$EL(7) = 2k A_s (T_s - T_a) (\tau/\pi a)^{1/2}, \hspace{1cm} (A.12)$$

where $k$ and $a$ are the conductivity and thermal diffusivity of the stove and floor material and $A_s$ is the surface area through which heat is transferred.

The assumption that the stove is a semi-infinite solid is reasonable since the rise
in the temperature averaged over the outer surface of the stove is only about 15°C and at the end of the cooking period. This energy loss is estimated utilizing the average cooking time from the efficiency tests, 1-24 hours, and the thermal properties of sandy clay soil with a 15% moisture content, \( k = 3.31 \text{ KJ/hr m } ^\circ\text{C} \) and \( a = 1.33 \times 10^{-3} \text{ m}^2/\text{hr} \). Due to widely varying temperatures in different regions of the stove, the heat loss to the stove body and floor is estimated separately inside and outside the combustion chamber. In each region, the surface temperature used to calculate this energy loss is an average for different positions as well as for different times. The temperature at 12 points on the inner surface was measured throughout simulated cooking tests using chromel-alumel thermocouples.

(h) **Carbon monoxide**

Combustion is not complete if there is any carbon monoxide (CO) present in the gases released from the stove. The chemical energy loss due to unburned CO is given by

\[
\text{EL (8)} = M_w (1 - F_m) Q_{co} E_{co},
\]

where \( Q_{co} \) is the number of moles of CO released from the stove per unit of dry wood and \( E_{co} \) is the amount of heat released when CO reacts with \( O_2 \) to form \( CO_2 \). \( Q_{co} \) is given by equations (A.4), (A.6) and (A.7). \( E_{co} \) equals 285 kJ/mole.

(i) **Charcoal**

Since the fire is usually not extinguished when cooking is completed in the Ungra area, there is an energy loss in the form of unreclaimed charcoal. The use of the burning charcoal to heat cleaning or drinking water, a common practice in the Ungra area, is not taken into account in the analysis of the energy losses during cooking. The energy loss due to charcoal residue is given by

\[
\text{EL (9)} = \frac{M_w}{\tau} Q_r E_r,
\]

where \( Q_r \) is the charcoal production rate per unit of wood burned. \( Q_r \) was measured during simulated cooking tests. The thermal energy loss from the charcoal residue is neglected because it is less than about 3% of the chemical energy loss.
# Appendix B.

## Energy loss measurements

<p>| | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Overall heat transfer coefficients</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(a) Clay pots</td>
<td>64.9 kJ/hr m² °C</td>
</tr>
<tr>
<td></td>
<td>(b) Aluminium pots</td>
<td>34.7 kJ/hr m² °C</td>
</tr>
<tr>
<td>2.</td>
<td>Exposed surface area of cooking pot and cover</td>
<td>0.20 m²</td>
</tr>
<tr>
<td>3.</td>
<td>Average temperature of combustion gases and excess air when released from the stove</td>
<td>390°C</td>
</tr>
<tr>
<td>4.</td>
<td>Average percentage of CO2 in the dry gases released from the stove</td>
<td>9.5%</td>
</tr>
<tr>
<td>5.</td>
<td>Average percentage of CO in the dry gases released from the stove</td>
<td>0.2%</td>
</tr>
<tr>
<td>6.</td>
<td>Average percentage of O2 in the dry gases released from the stove</td>
<td>13.8%</td>
</tr>
<tr>
<td>7.</td>
<td>Average temperature of the inner surface of the stove</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(a) Within the combustion chamber</td>
<td>285°C</td>
</tr>
<tr>
<td></td>
<td>(b) Outside the combustion chamber</td>
<td>120°C</td>
</tr>
<tr>
<td>8.</td>
<td>Inner surface area of the stove</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(a) Within the combustion chamber</td>
<td>0.16 m²</td>
</tr>
<tr>
<td></td>
<td>(b) Outside the combustion chamber</td>
<td>0.42 m²</td>
</tr>
<tr>
<td>9.</td>
<td>Charcoal production rate</td>
<td>0.085 kg/kg wood/hr</td>
</tr>
<tr>
<td>10.</td>
<td>Calorific value of the charcoal</td>
<td>29.7 MJ/kg</td>
</tr>
</tbody>
</table>

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Figure 1. Cookstove and ragi-making in the Unga area.
Improved chimneyless fuelwood cookstoves (Pondicherry region)

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Tata Energy Research Institute, Field Research Unit, Care Sri Aurobindo Ashram,
Pondicherry 605 002

Abstract. This paper reports the results of an experimental study designed to improve the thermal efficiency of existing two-holed chimneyless fuelwood cookstoves sold by potters around Pondicherry. User and potter acceptability were treated as decisive and the price increase was limited to 20% for the minimal modification made. Net efficiency increased from 10.1% to 12.5% for the most commonly used clay pot (with lids on) in the laboratory water-boiling tests. Field users' survey revealed a score of 77% satisfaction on all counts and long term fuel savings of 28-38%, depending upon the mix of agricultural wastes and fuelwood used.

Keywords. Fuelwood; cookstoves; Pondicherry; energy conservation; chimneyless stove; thermal efficiency

1. Introduction

It is now fairly well recognised that the energy crisis for underdeveloped countries is two-fold: shortage of fuelwood for the common man and of oil for industry and the richer sections. Apart from the already evident price escalations, this shortage could lead to land-use competition between fuel and food, as forest cover is getting progressively diminished. Domestic energy consumption studies by Gupta et al (1980) showed that more than 95% of domestic energy is used for cooking and nearly 75% of it is in the form of fuelwood for both rural and semi-urban communities. Further, 90% of households in rural areas, 75% in suburban areas and 25% in urban areas were found to be using fuelwood cookstoves in the Pondicherry region. Improving the thermal efficiency of fuelwood cookstoves is thus an immediate and environmentally desirable means of energy conservation. However, any improved cookstove to be effective must be acceptable to households. This implies that they should have minimal negative side effects in terms of requirements of space, cost, local availability, cooking time, quality of food cooked and operational convenience. These constraints are universally decisive even though their definition and relative weights are essentially specific to each community.

2. Design approach

The usual approach of trying to design thermally optimal cookstoves in the laboratory and then exploring their acceptability has mostly recorded the dismal failures of technically viable designs resulting in very restricted applicability after considerable promotion, e.g. the HERL chulah (Raju 1956). We have taken the

*A list of symbols appears at the end of the paper
alternative route of recognizing the decisive character of these effectiveness criteria and have attempted to achieve a practically optimal solution in any single step of an essentially multistage constrained optimization problem. In the light of the above approach, the commonly adopted strategies for improving the efficiency e.g. addition of chimney, increasing the number of cooking holes, incorporation of dampers and grates for regulating excess air have not been considered for the first phase. Missing dampers, leaking roofs because of faulty chimney installation, more cooking holes than the items a family can afford to cook have all been noted in practice. We have restricted ourselves to the locally available and most widely used two-holed, non-chimney, grateless, potter-made cookstoves, which uses mostly casuarina logs as fuelwood. Figure 1 (plate 1) shows the stove sold in the market and figure 2 (plate 1) shows its use at home, where it is normally built into a clay platform. It normally sells for Rs. 2 per piece in the market.

3. Improved cookstove

The conventional cookstove has mounts on both the cooking holes for placing pots and the flame usually leeps out of the first hole and the second pot is heated mainly by the remaining flue gases. In the modified cookstove, mounts on the fire hole have been knocked off so that the cooking pot fits tightly and the second pot receives all of the flue gases and a bit of the flame. Figures 3 and 4 (plate 2) show the stove as sold and as used. Stove specifications are detailed in appendix A. In effect, the second hole provides something of a chimney action. The residence time of flue gases could not be increased in the first hole as the local potters were not willing to raise a ridge in the connecting passage between the holes. For this simple modification not to violate any effectiveness criteria, this reservation was accepted at the first stage.

4. Laboratory test procedure

Commonly used clay as well as aluminium vessels have been used in the performance tests. Also, since most local cooking involves stirring of the ingredients, tests were done with lids on the pots as well as with open pots. The laboratory tests used were boiling water tests with two litres of water in the first pot and one litre in the second. Cooking tests are with the food normally cooked but with stoves not built into platform. For a test to be completed, both pots must come to the boil. Test procedure and measurements are generally in accordance with the suggested ITDG procedure (Joseph & Richolson 1979). Relevant equations for calculating heat balances have been mainly derived from Ballaney (1980) and the ASHRAE guide (1965) and are given in appendix B. The CO fraction could not be measured and has been computed from excess air versus CO₂ percent correlation. Two efficiency values have been computed: one, treating the heat used in the evaporation of water from the pots as a loss is called net efficiency and the other including it as an output is called overall efficiency. The calorific value of oven-dry fuelwood has been determined in a Bomb calorimeter and the computed value has been corrected for the moisture content of the wood and charcoal formation for each test.
5. Laboratory test results

Tables 1 and 2 summarise the significant test results from a series of nearly 150 tests conducted over a two-year period (1980–1981). Table 1 gives the stove performance parameters and it shows that for clay pots with lids on the performance improved by nearly 25% over the conventional cookstove. Fuel used and burning rate are also reduced. By using lids on pots, there is consistent increase in the cooking efficiency both for clay and aluminium pots. Even though aluminium pots show a higher efficiency, their use is not suitable for certain types of local cooking and also aluminium is an energy-intensive metal. Reduced production of charcoal, increased CO₂ present in the flue gases and decreased air-fuel ratio indicate better combustion. Designating pot 1 as the one on the firehole and the latter one as pot 2, the higher temperature of pot 2 at the time of the boiling of pot 1 in the modified cookstove and the reduced time difference between the boiling of the two pots indicate more equitable heat distribution. Higher flue gases temperatures are presumably because of reduced volume of flue gases. The increased duration of the test for the modified cookstove was not noticed till feedback from the field indicated increased cooking time. This is a rather negative consequence of the modification. It is proposed to increase residence time of flue gas to reduce flue gas temperatures as well as cooking time but a locally acceptable modification has yet to be found.

Figure 5 shows a set of typical temperature versus time curves for laboratory tests on both types of cookstoves. Time-averaged values from such curves are used for the heat balance calculations shown in table 2. The stove-wall temperature represents a mean of seven measurements on various parts of the stove wall so as to give a fairly representative value. For the cooking test, the cooking energy of foods used has been taken from Popali et al (1980). Cooking test efficiency figures are lower than the corresponding water boiling test figures but the improvement is maintained.

From table 2, it can be seen that the cookstove, the type of pot used, cooking with lids on or off and the degree of wetness of fuelwood from a highly complex and closed loop thermal system as almost all values of \( Q_1 \) to \( Q_{29} \) change in absolute as well as fractional magnitudes. From integrated system tests reported in this study, it is, therefore, difficult to draw any conclusions regarding the separate contribution of each factor. Heat taken up by combustion processes (\( Q_7 \) to \( Q_{11} \)) together accounts for 50 to 60% of the input for simulated water boiling tests (after correcting for unaccounted balances, which are larger for clay pot tests) and 60 to 70% for the cooking test. In all cases, the lower figure is for the modified cookstove. Flue gases account for almost half of the heat used in combustion, and evaporation of moisture in the wood accounts for another 17%. Stove and pot losses are determined by wall temperatures, stove surface area, heat capacity and duration of test. These losses are slightly more for the modified cookstove primarily because of the longer duration of the test, as the wall temperatures are actually lower.

6. Field studies

6.1 Controlled tests

Eight households from four villages, normally using fuelwood for cooking but
Table 1. Stove performance parameters

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Boiling water tests</th>
<th>Cooking tests</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Clay pots lids on</td>
<td>Al. pots lids on</td>
</tr>
<tr>
<td></td>
<td>CON</td>
<td>IMP</td>
</tr>
<tr>
<td>Net efficiency (%)</td>
<td>10</td>
<td>13</td>
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<tr>
<td>Overall efficiency (%)</td>
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<td>17</td>
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<tr>
<td>Time taken to boil (minutes)</td>
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<td>46</td>
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<tr>
<td>Temperature of water in pot 2 at pot 1 boil (°C)</td>
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<tr>
<td>Amount of dry fuelwood used (grams)</td>
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<tr>
<td>Moisture content of wood used (%)</td>
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<td>17</td>
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<tr>
<td>Amount of charcoal produced (grams)</td>
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<td>20</td>
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<tr>
<td>Burning rate (g/min)</td>
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<td>8</td>
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<tr>
<td>Air-fuel ratio</td>
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<td>5</td>
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<tr>
<td>Flue gas temperature (°C)</td>
<td>135</td>
<td>180</td>
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</table>

Key: * CON — Conventional two-holed cookstove
* IMP — Improved two-holed cookstove
### Table 2. Stove heat balance analysis

<table>
<thead>
<tr>
<th>Parameters</th>
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</tr>
<tr>
<td>Q₁₅</td>
<td>1114</td>
<td>586</td>
<td>1758</td>
<td>848</td>
<td>1026</td>
</tr>
<tr>
<td>Q₁₆</td>
<td>94</td>
<td>94</td>
<td>123</td>
<td>116</td>
<td>80</td>
</tr>
<tr>
<td>Total Input (kJ)</td>
<td>9060</td>
<td>7325</td>
<td>10874</td>
<td>11204</td>
<td>7349</td>
</tr>
<tr>
<td>Output (accounted) %</td>
<td>77</td>
<td>77</td>
<td>83</td>
<td>80</td>
<td>94</td>
</tr>
</tbody>
</table>

Values of Q₁ to Q₁₂ and total input are in kJ
having different range of incomes and domestic energy mix, were provided with modified cookstoves. Casuarina firewood (20 kg) was supplied to them, once for using in the new stove and once in their traditional stove. The number of days for which this fuel was consumed in the new cookstove and in the traditional cookstove was noted (table 3). The results showed a saving of one day’s fuel for every three days both with casuarina fuelwood and agricultural wastes used as fuel, if both stoves had two cooking holes. In the case of a switch from the conventional one-holed to modified two-holed one, there was a fuel saving of three days for every ten days of cooking.

6.2 Users survey

After noting the encouraging results from controlled field tests, 104 stoves were distributed in eight villages. Users had a fair distribution of income levels so as to reflect different fuels used, cooking habits, types and items of food and family sizes. The results of the survey are presented in table 4. Fuel savings of 28, 38 and 30%
Table 3. Controlled field tests

<table>
<thead>
<tr>
<th>Income group</th>
<th>Village</th>
<th>Family size</th>
<th>Cooking</th>
<th>Lighting</th>
<th>Appliances</th>
<th>Total</th>
<th>20 kg wood consumed in</th>
<th>20 kg wood consumed in</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>(MJ/cap/day)</td>
<td></td>
<td></td>
<td></td>
<td>Owner’s stove</td>
<td>Improved stove</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Cooking hours</td>
<td>Cooking days</td>
</tr>
<tr>
<td>Economically</td>
<td>Saram</td>
<td>Ad 2 Ch 3</td>
<td>26.86</td>
<td>0.63</td>
<td>—</td>
<td>27.49</td>
<td>21</td>
<td>12**</td>
</tr>
<tr>
<td>weaker section</td>
<td>Indiranagar</td>
<td>2 5</td>
<td>11.30</td>
<td>2.68</td>
<td>—</td>
<td>13.99</td>
<td>14</td>
<td>4</td>
</tr>
<tr>
<td>Lower income group</td>
<td>CMC</td>
<td>3 1</td>
<td>4.61</td>
<td>0.36</td>
<td>—</td>
<td>4.97</td>
<td>31</td>
<td>10**</td>
</tr>
<tr>
<td></td>
<td>Ariyur</td>
<td>2</td>
<td>33.84</td>
<td>3.06</td>
<td>—</td>
<td>36.90</td>
<td>17</td>
<td>8</td>
</tr>
<tr>
<td>Middle income group</td>
<td>CMC</td>
<td>5 1</td>
<td>12.24</td>
<td>0.36</td>
<td>0.14</td>
<td>13.90</td>
<td>26</td>
<td>6.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5</td>
<td>37.09</td>
<td>0.72</td>
<td>1.89</td>
<td>39.70</td>
<td>9</td>
<td>2.5**</td>
</tr>
</tbody>
</table>

Ad = adult; Ch = children; Com = commercial fuels like kerosene, LPG, lignite and charcoal; N.C. = non-commercial fuels like fire-wood, cowdung, agricultural wastes; CMC = Chinna Mudaliar Chavady; hours = cooking time (hours) in given days.

*Single-holed stove
**Fuel used; agricultural wastes
Table 4. Field survey of improved cookstove users

<table>
<thead>
<tr>
<th>Village</th>
<th>No. of households in which</th>
<th>No. of households who feel improved stove consumes</th>
<th>Long-term fuel savings (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Stoves distributed</td>
<td>Condition unknown</td>
<td>Broken</td>
</tr>
<tr>
<td>Ariyur</td>
<td>29</td>
<td>5</td>
<td>1</td>
</tr>
<tr>
<td>Chinna Mudaliar Chavady</td>
<td>5</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Indiranagar</td>
<td>8</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Kurichikuppam</td>
<td>4</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Noonankuppam</td>
<td>13</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>Pillayarkuppam</td>
<td>30</td>
<td>17</td>
<td>2</td>
</tr>
<tr>
<td>Poothurai</td>
<td>5</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Reddichavady</td>
<td>11</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Total</td>
<td>104</td>
<td>29</td>
<td>6</td>
</tr>
</tbody>
</table>

Notes:
* Economically weaker section (ews-annual income less than Rs. 4,200/-) use all agricultural wastes like tapioca roots, sugar-cane wastes, dried plants etc.
* Low income group (lig-annual income between Rs. 4,200/- and Rs. 7,200/-) use mixed fuels (mostly logs of casuarina and cashew) and all agricultural wastes.
* Middle income group (mig-annual income between Rs. 7,200/- and Rs. 14,400/-) use casuarina fuelwood logs.
Chimneyless cookstoves

are reported from groups using agricultural wastes, mixed fuels and fuelwood respectively. Households reporting satisfactory performance in terms of fuel saving and cooking time were in the majority and constituted nearly 77\% (53 out of 69). Six households had broken stoves and twenty nine could not be contacted or did not respond.

In fact, there is a persistent demand for these stoves in some villages. However, it has not yet been possible to convince the potter to market these as a normal item in his stock in the open market. Some of the pertinent observations by users are less smoke, difficulty in removing the excess ash formed where agricultural wastes are used, breakage of the front part of the top band, availability of only one size and less warmth in the room during winter.

7. Conclusions

(a) The improved cookstove has shown improvements of 25 and 17\% in the net efficiency over the existing cookstove for clay and aluminium vessels, when used with lids on. In actual cooking tests, there was a decrease of 3\% as compared to the water boiling tests conducted in the laboratory.

(b) To sustain improved performance, pots must have lids for the maximal time consistent with cooking practice.

(c) In stove studies, the stove, cooking vessels, fuels used, food type and amount and method of cooking have to be treated as an integrated thermal system. There cannot be a single universally efficient cooking stove.

(d) The field users' survey revealed an absolute satisfaction score of 77\% and fuel savings of 28 to 38\% depending upon the mix of agricultural wastes and fuelwood used.

(e) Field acceptability should be treated as the decisive criterion for choice of improvement strategy. In matters of cooking, a multistage optimization has better chances rather than a technical optimum.

The authors would like to thank Stephen Joseph, Howard Gellei and Yvonne Shanahan for many stimulating discussions and for access to some critically needed literature.

Appendix A. Stove specifications

<table>
<thead>
<tr>
<th></th>
<th>Mass (kg)</th>
<th>Surface area (m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conventional two-holed</td>
<td>4.835</td>
<td>0.08</td>
</tr>
<tr>
<td>Improved two-holed</td>
<td>5.160</td>
<td>0.121</td>
</tr>
<tr>
<td>Clay pots</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pot 1</td>
<td>1.255</td>
<td>0.246</td>
</tr>
<tr>
<td>Lid</td>
<td>0.435</td>
<td>-</td>
</tr>
<tr>
<td>Pot 2</td>
<td>0.855</td>
<td>0.152</td>
</tr>
<tr>
<td>Lid</td>
<td>0.295</td>
<td>-</td>
</tr>
<tr>
<td>Aluminium pots</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pot 1</td>
<td>0.185</td>
<td>0.212</td>
</tr>
<tr>
<td>Lid</td>
<td>0.048</td>
<td>-</td>
</tr>
<tr>
<td>Pot 2</td>
<td>0.150</td>
<td>0.181</td>
</tr>
<tr>
<td>Lid</td>
<td>0.037</td>
<td>-</td>
</tr>
</tbody>
</table>
Appendix B. Heat balance equations

\[ \eta_1 = \frac{\sum \left[W_i \cdot S \cdot (T_b - T_i)\right]}{H_w \cdot W_w + H_k \cdot W_k - H_c \cdot W_c} \times 100 \]

\[ \sum \left[W_i \cdot S \cdot (T_b - T_i) + LH \cdot W_e\right] \]

\[ \eta_2 = \frac{H_w \cdot W_w + H_k \cdot W_k - H_c \cdot W_c}{\times 100,} \]

\[ Q_1 = \sum \left[S \cdot W_i \cdot (T_b - T_i)\right], \]

\[ Q_2 = \sum \left[LH \cdot W_i\right], \]

\[ Q_f = \sum \left[S_f \cdot W_f \cdot (T_f - T_i) + (CE \cdot W_f)\right], \]

\[ Q_3 = \sum \left[S_p \cdot W_p \cdot (T_p - T_a)\right], \]

\[ Q_4 = \sum \left[\epsilon \cdot \alpha \cdot A_p \cdot f \cdot (T_p - T_s) \cdot (T_p - T_a)\right], \]

\[ Q_5 = S_i \cdot W_s \cdot (T_s - T_a), \]

\[ Q_6 = \epsilon \cdot \alpha \cdot A_s \cdot f \cdot (T_s - T_a) + h \cdot A_s \cdot f \cdot (T_s - T_a), \]

\[ Q_7 = S_g \cdot W_g \cdot (T_a - T_a), \]

\[ Q_8 = 0.01 \cdot M \cdot W_w \cdot (2491.9 + 1.92 \cdot T_g - 4.18 \cdot T_a) \text{ (kJ)} \]

\[ Q_9 = 9 \cdot H_2 \cdot W_w \cdot (2491.9 + 1.92 \cdot T_g - 4.18 \cdot T_a) \text{ (kJ)} \]

\[ Q_{10} = HF \cdot CO/(CO_2 + CO) \cdot C_w \cdot W_w, \]

\[ Q_{11} = H_c \cdot W_c, \]

\[ Q_{12} = H_a \cdot W_a, \]

\[ W_g = \frac{4 \cdot CO_2 \text{ (%) } + O_2 \text{ (%) } + 700}{3 \cdot CO_2 \text{ (%) } + CO \text{ (%) }} \times C_w \cdot W_w \]

\[ \text{Excess air} \% = \frac{20 \times 100}{CO_2 \text{ (%) } - 100} \]

References

ASHRAE guide and data book 1965 (New York, ASHRAE Inc.) Chapter 18, 276
Joseph S & Richolson J 1979 Stove testing—notes on stove designs and testing data sheets (London: ITDG publication)
Popali S C, Yardi N R & Jain B C 1980 in Rural technology (ed.) A K N Reddy (Bangalore: Indian Academy of Sciences) p. 45
List of symbols

\( A \) area (m\(^2\))
\( C_w \) carbon fraction of wood (0.485)
\( C_E \) cooking energy of food (cereals = 0.157 MJ/kg; vegetables = 0.106 MJ/kg)
\( C_O \) percent carbon monoxide in flue gases
\( C_{O_2} \) percent carbon di-oxide in flue gases
\( H_A \) heating value of ash (13.392 MJ/kg)
\( H_c \) heating value of charcoal (29.25 MJ/kg)
\( H_k \) heating value of kerosene (46.077 MJ/kg)
\( H_w \) heating value of oven-dry wood (20.925 MJ/kg)
\( H_\text{H}_2 \) hydrogen fraction of wood (0.06)
\( H_F \) heat of formation of carbon monoxide (22.256 MJ/kg)
\( h \) heat transfer coefficient: \( 5.4 \times 10^{-4} \text{ MJ/m}^2\text{K for } T < 100^\circ\text{C} \)
\( 7.8 \times 10^{-4} \text{ MJ/m}^2\text{K for } T < 200^\circ\text{C} \)
\( L_H \) latent heat of vaporization of water (2.2599 MJ/kg)
\( M \) percent moisture in wood on dry weight basis
\( Q_1 \) sensible heat utilized by water
\( Q_2 \) heat utilized in evaporating water
\( Q_f \) heat utilized in cooking food
\( Q_3 \) capacity effect of pot
\( Q_4 \) heat losses from pot
\( Q_5 \) capacity effect of stove
\( Q_6 \) heat losses from stove
\( Q_7 \) heat losses from flue gases
\( Q_8 \) heat losses in evaporating moisture in fuelwood
\( Q_9 \) heat losses in evaporating moisture formed due to combustion of wood
\( Q_\text{H}_2 \) heat losses due to incomplete combustion
\( Q_{10} \) heat remaining in charcoal
\( Q_{11} \) heat remaining in ash
\( S \) specific heat of water (4.186 kJ/kg °K)
\( S_f \) specific heat of food (MJ/kg °K)
\( S_g \) specific heat of flue gases (1.004 kJ/kg °K)
\( S_p \) specific heat of pots used (clay = 1 kJ/kg °K; al. = 0.85 kJ/kg °K)
\( S_s \) specific heat of stove material (MJ/kg °K)
\( T \) temperature (°K)
\( \overline{T} \) time-averaged temperature (°K)
\( t \) time of test (minutes)
\( W \) weight (kg)
\( \varepsilon \) emissivity
\( \sigma \) Stefan-Boltzman constant (3.402 \times 10^{-8} \text{ MJ/m}^2\text{°K min.})
\( \eta_1 \) net efficiency
\( \eta_2 \) overall efficiency
Subscripts

- $A$: ash
- $a$: ambient
- $b$: boiling point of water
- $c$: charcoal
- $e$: water evaporated
- $f$: food
- $g$: dry flue gases
- $i$: water taken initially
- $k$: kerosene
- $p$: pot
- $s$: stove
- $w$: dry fuelwood
Figure 1. Traditional two-holed cookstove.

Figure 2. Traditional cookstove as used at home.
Figure 3. Improved two-holed cookstove.

Figure 4. Improved cookstove as in use.
Open fires: Experiments and theory

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Department of Applied Physics, Eindhoven University of Technology, Eindhoven
The Netherlands

Abstract. The open fire is used by millions of households around the world to perform a variety of tasks, the principal one being that of cooking in third world countries. Its virtues are simplicity of design and nearly zero cost. In this study we use it as a convenient tool for investigating certain general characteristics of woodburning stoves for cooking.

The paper is in three parts. The first part delineates the influence of fuel, operating and design characteristics of open fires on the efficiency as determined by water boiling tests. The second part provides an insight into certain physical characteristics of wood-fires through instantaneous weight-loss measurements. In particular this part helps to explain the results of the first part. The final part provides an ad hoc theoretical model which enables the calculation of radiant and convective heat transfer to a pan placed on an open fire. The theoretical calculations compare favourably with experimental results.

Keywords. Open fires; efficiency; performance; combustion of wood; power level of a fire; buoyant turbulent plumes; heat transfer; moisture content.

1. Introduction

Part of the work of the Woodburning Stove Group, Eindhoven, is aimed at getting a better understanding of the woodburning processes. This work has until now been restricted to open fires for three important reasons (Krishna Prasad 1980). First of all it appears that the traditional stoves of an overwhelming majority of the poor people of this world are open fires or their close relatives. Secondly, laboratory tests in Eindhoven showed surprisingly high efficiencies, which lends a whole new perspective to the design of improved stoves and thirdly, if we are able to understand the open fire it will provide very useful guidelines for designing more efficient stoves. The work reported here is both experimental and theoretical in nature. A first series of experiments was conducted to observe the effect of varying selected parameters which were expected to affect the fire behaviour (§ 2). A second series of experiments was done to explain the results of the first set (§ 3). This second series was supported by theoretical work concerning convective and radiative heat transfer (§ 4).

2. Efficiencies of open fires

2.1 Definitions and parameters

Two terms have caused lot of confusion and need explanation: the efficiency and the performance of a stove/fire. With the performance is meant the whole set of rela-
tionships among the variables, which determine the behaviour of the stove/fire in practice. The efficiency, on the other hand, is a measure of the fuel consumption of the stove/fire to accomplish a specified task under a regime of well-defined operational procedures. The definitions show that the stove performance has a much broader meaning than the efficiency. The latter is ‘only’ directed to the energy balance. The definitions above are analogous to those used for a machine like the centrifugal pump, an object which is very familiar in mechanical engineering.

The parameters that were varied in the experiments are:

- the power output of the fire
- the wood species
- the moisture content of the wood
- the size of the woodblocks
- the position of the pan above the fuelbed
- the use of a grate.

The parameters mentioned can be divided into two groups. The first four are related to the properties and the use of the fuel, while the remaining parameters describe the pan-fuelbed configuration. Here another source of confusion appears: while the configuration can be described easily and accurately, the fuel parameters are prone to much uncertainty. Going more into detail the problem arises as follows. Because wood is a solid fuel, it is not available on tap but has to be loaded into the fire in a batch process. The way this is done by the operator depends on so many factors that it may well be that every individual operator will have his/her own unique way of operating. A second factor which confounds the problem is the fuel quality. The fuel quality is used as a catch-all term to denote the wood species, the as-fired moisture content in the wood, the size of the wood actually employed in the fire etc.

The results of a series of experiments will not match when fuel parameters are varied in addition to the variable actually examined. It appears that the heat output of the fire and the fuelbed behaviour are seriously affected when for instance the fuel loading procedure or the fuel quality is changed. The consequence is that laboratory experiments have to be subjected to a fixed scheme of fuel preparations and fuel loading. Only then experimental data can be compared.

The factors mentioned here will obviously create problems when laboratory results are related to practical situations.

2.2 The standard water boiling tests

The experimental procedure unless otherwise specified is as follows. White fir wood is cut into pieces of $20 \times 20 \times 67$ mm and dried to constant mass in an oven at $105^\circ$C ($\approx 48$ hr). This wood we call oven-dry. The wood is then divided in lots of 100 grams each, which are charged to the fire at fixed time intervals of 8 minutes. The fire is built on a grate with a diameter of 0.18 m. At the start of the experiments the fire is lit with a propane burner ($\approx 30$ s). In the course of an experiment a total amount of about 600 g of wood is fed to the fire in charges of 100 g each. In this way a fire with a nominal power of 3.9 kW is generated. The experiments stop when all the wood has been burnt. In the experiments 5 kg of water in a pan 0.13 m above the

*The power rating of a wood-fire can be defined in a number of ways. See § 3 for a discussion of the problem.
Open fires

157

fuelbed is brought to the boil and is kept boiling. Some water will evaporate and escapes as steam. The pan is made from aluminium, has a diameter of 0.28 m, a height of 0.24 m and is always used with a lid. The efficiency of the fire is taken to be the ratio between the heat absorbed by the water in the pan and the heat released by the wood under the assumption of complete combustion.

At the end of the experiments the overall efficiency is calculated using the formula:

\[ \eta = \frac{m_{w, i} \cdot C \cdot (T_b - T_i) + m_{w, e} \cdot L}{m_f \cdot B_f} \times 100\% \]

where \( \eta \) = efficiency (%), \( m_{w, i} \) = initial amount of water (kg), \( m_{w, e} \) = amount of water evaporated during the experiment (kg), \( m_f \) = amount of the fuelwood burnt (kg), \( C \) = specific heat of water at 50°C and 1 atm (J/kg·K), \( T_b \) = temperature of boiling of water (°C), \( T_i \) = initial temperature of water (°C), \( L \) = heat of evaporation of water (J/kg) and \( B_f \) = combustion value of fuelwood (J/kg). The asterisk denotes multiplication.

It should be noted that this efficiency definition says nothing about the usefulness of the absorbed heat. It can be argued that the escaping steam does not contribute to the efficiency of cooking. Less fuel would be used by adjusting the fire to keep the contents of the pan at boiling point. In the standards of performance for domestic gas ranges indeed the efficiency is defined as the heat absorbed by the water to reach boiling point divided by the upper calorific value of the gas used (VEG 1968). Moreover, as the relevant experiments last until boiling point is only reached, higher efficiency numbers are obtained in this way*. However, as long as one restricts oneself to measuring comparative efficiencies, what method one uses to calculate efficiencies is a trivial matter (Krishna Prasad 1981). The efficiencies as a function of the variables mentioned earlier are given in figure 1 and are discussed in the next section.

*This appears to be true only for open fires. For closed stoves it can be the other way around.
2.3 Efficiencies

2.3a The power range of the fire One of the factors which is of major significance for the performance of a stove is the power range it can produce with a reasonable efficiency. As with most other equipment this aspect is of crucial importance for the use of the device in practice. Once this point is accepted it follows that newly designed stoves should at least be able to compete in this respect with the traditional stove, the open fire. The power has been varied by varying the time interval between two fuel charging operations. The upper and lower limit are determined by the surface area of the grate*. It stands to reason that different power ranges will be obtained if charges different from 100 g are used, but it is expected that the results will be analogous.

2.3b The wood species In several publications (e.g. Joseph 1979) it is claimed that the efficiency of a stove is strongly dependent on the wood species used; that heavy tropical hardwoods burn differently from the light white fir used in laboratory experiments. Among others this statement is used to explain the remarkable difference between laboratory and field experiments. This feature, if valid, would also be of the utmost importance for designing stoves. The value of this assertion was investigated by performing tests with different wood species.

As the density of the wood is emphasized as a characteristic in publications, it is taken as the parameter to characterize the wood. In our opinion this choice is more or less arbitrary, probably other properties can be used as well (mass fraction of fixed carbon, thermal conductivity etc.).

2.3c The moisture content of the wood The moisture content is defined on a dry wood basis and is expressed as the mass fraction of water to dry wood. This means that the moisture content of wet green wood can be up to 200%. For air-dried wood normally used it varies between 10% and 30%, depending on the relative humidity of the ambient air (Sha 1974). It will be clear that the combustion value of wood is influenced by the moisture content. That is why the wood used in laboratory experiments is dried in an oven where the moisture content is reduced to zero. It is realized that wood used for cooking purposes is not prepared like this but, to be able to compare results from different laboratory tests, fuel preparation is imperative. As with the different wood species some authors claim that the stove efficiency is strongly dependent on the moisture content (Evans 1981). That is why in a series of experiments this was investigated. The desired moisture content was obtained by adding a calculated quantity of water to the oven-dry wood. To let the wood absorb the moisture evenly, it was left for some days in a sealed container. The weight of the charges that the fire was fed with was corrected for a dry wood content of 100 g.

2.3d The size of the woodblocks The last fuel parameter which has been examined is the size of the woodblocks. Again there appears to exist a lot of confusion about the influence of this parameter. Two earlier series of experiments performed by the Woodburning Stove Group gave contradictory results (Krishna Prasad 1981). On the one hand experiments on the De Lepeleire/Van Daele stove (a closed light weight

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*In these experiments the fuel as far as possible was spread over the total surface of the grate.
metal stove with two potholes) showed that, for the range investigated, the size of the woods species had no significant influence on the efficiency of the stove. On the other hand the efficiency of the Family Cooker (another closed light weight metal stove with two potholes) nearly tripled when the volume-surface area ratio of the woodblocks was increased from 2 to 6. It is clear that extra attention must be paid on the preparation of the fuel when a stove or a fire is sensitive to this parameter. The influence of the fuelblock size has been investigated in these experiments.

2.3e The position of the pan above the fuelbed The next variable to be discussed belongs to the second group of parameters: those which describe the pan-fuelbed configuration. To get some general feeling of the way they influence the heat transfer from the fire to the pan, a first sketchy treatment is given regarding the physical processes involved. The combustion of the wood takes place in two stages; the combustion of fixed carbon or charcoal in the fuelbed and the combustion of volatiles in the flames. Here the radiative and convective heat transfer play an important role. Radiation carries away the heat released in the fuelbed while convection is the dominant transfer process in the flames. To make optimum use of the radiation heat, it is desirable to reduce the fuelbed-pan distance as much as possible, however, this is at the expense of convection heat which is benefited by a distance large enough to combust all the volatiles. To study the described influence of the distance between fuelbed and pan, a series of experiments was performed in which this distance was varied.

2.3f The use of a grate The results of the experiments discussed in the previous paragraph seem to underline the relative importance of radiant heat transfer from the smouldering charcoal to the pan. This heat quantity is dependent on several factors like temperature, fuelbed-pan distance, fuelbed diameter and pan diameter. To get the maximum amount of radiant heat absorbed by the pan, the fuelbed must be concentrated on an area as small as possible. However, the minimum size of the fuelbed depends on the air quantity needed to burn the charcoal. Because the air has to be entrained from the surroundings, the larger the fuelbed the more air will be available for combustion.

The use of a grate in a stove is expected to facilitate the accessibility of air to a fuelbed. It essentially promotes the combustion of charcoal that remains after the volatiles are driven out of wood. In general a grate will generate higher power outputs from a given fuelbed area. In order to quantify these effects, the earlier experiments with variable power output were repeated without a grate.

2.4 Discussion

The experiments (figure 1, table 1) yield a lot of rather unexpected results. It appears that variation of the power output, the wood species, the moisture content of the wood and the sizes of the woodblocks do not influence the efficiency of the open fire; this is in contrast with what field workers involved in stove dissemination programs expected. It is believed that the misconceptions are based on the visual observations one can make in operating a fire. For instance: driving the fire with oven-dry wood is completely different compared to operating it with wood with a 25% moisture con-
Table 1. Series of experiments with different wood-sizes

<table>
<thead>
<tr>
<th>Sizes woodblocks (mm)</th>
<th>Volume Surface area (mm$^2$)</th>
<th>Efficiency (%)</th>
<th>$P_{\text{max}}$ (kW)</th>
<th>Fuelbed weight (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>15 × 15 × 50</td>
<td>3.26</td>
<td>25.9</td>
<td>6.28</td>
<td>20</td>
</tr>
<tr>
<td>20 × 20 × 67</td>
<td>4.35</td>
<td>26.4</td>
<td>5.13</td>
<td>27</td>
</tr>
<tr>
<td>32 × 32 × 111</td>
<td>6.99</td>
<td>25.7</td>
<td>4.04</td>
<td>55</td>
</tr>
</tbody>
</table>

tent. In the latter situation lighting the fire is a task which needs much attention and care; the wood burns only very slowly and the fuelbed becomes much thicker when oven-dry wood is used. Apparently these differences do not show up in efficiencies. But, as pointed out before, the efficiencies form only one part (though an important one) of the picture we can draw of a stove. Consequently the efficiencies do not give a correct overview of the experiments. That is why in the next section an attempt is made to fill this gap. It is attempted there to provide a better description of the fully time-dependent burning process.

The fuelbed-pan distance is the only parameter which has a profound influence on the efficiency. Here the highest efficiency (36%) of all the tests is found at the minimum distance of 70 mm. This is simply an unsettling result if one realizes that so far it is taken for granted that the open fire, used for cooking purposes, shows at best a 15% efficiency. It is unsettling if one realizes that stoves recently being designed, introduced and sold, show in the laboratory a maximum efficiency of 25%!! This result will be explained with reference to the experimental and theoretical work to be discussed later.

The efficiency results camouflage the usefulness of a grate in a stove. With and without the grate, the measured efficiencies lie in the range of 22 and 26%. However, the importance of a grate lies in the fact that more wood can be burnt per unit area of the fuelbed surface in a given time. More importantly, the use of a grate enlarges the power output range obtainable from a given fuelbed surface area. The ratio between the maximum and minimum powers is increased from 2 (2.6 kW $< P < 5.2$ kW) to 3 (2.6 kW $< P < 7.8$ kW) with the introduction of a grate.

These results suggest design modifications to traditional stoves that can result in considerable savings in fuel consumption. Introduction of a grate into the traditional stoves will require a smaller fuelbed surface area to generate the same power output as the earlier design. With a corresponding reduction in the fuelbed-pan distance (such a reduction can be expected to maintain the combustion quality since the airation of the fire will be much better with a grate), the efficiency can be increased by a few percentage points. The second aspect of the design, namely, the increase of power ratio from 2 to 3, results in lowering the minimum power of the fire from 2.6 kW to 1.7 kW. Such a lowering of the minimum power is of decisive importance in reducing the fuel consumption particularly for simmering that requires very little power. More experimental work is necessary to confirm these expectations.

Behaviour similar to the one described above is of importance in operating the fire with wood of different species, moisture content and size. As will be shown in the next section, the power range will change with the changes in these parameters. However, it is not possible to state the direction of this change without additional experimental evidence.
3. The time-dependent burning process

3.1 Introduction

According to Brame and King (1976) wood consists, from a chemical point of view, mainly of cellulose and lignin, a modified form of cellulose. The remainder is minerals and resin or gum. The cellulose, lignin and resin or gum form the combustible part of the wood. Elementary chemical analysis of different wood species give similar results. Due to the fact that they are chemically very similar, the combustion value of different wood species does not vary much (see table 2).

Although the composition of wood is known, this does not mean that the combustion of wood is completely understood. A schematic view of the burning process (Wagner 1978 and Brame & King 1967) is shown in figure 2. According to them the process runs as follows. When wood is heated it first loses its moisture, at about 350°C it starts releasing volatiles consisting of CH₄ and CO but also of vapours and tiny droplets of a mixture of viscous organic liquids such as tar. At 550°C these volatiles ignite, burning with the well-known bright yellow flames. The remainder of the wood, after the expulsion of the volatiles, is mainly charcoal, which burns at its surface with a faint, bluish flame at about 800°C. After the charcoal has burnt, the remainder is ash, consisting of mineral matter, mainly SiO₂. In a real fire these processes occur more or less simultaneously although at different locations.

Table 2. Properties of oven-dry wood

<table>
<thead>
<tr>
<th>Species</th>
<th>Common name</th>
<th>Density (kg/m³)</th>
<th>Volatile fraction</th>
<th>Charcoal fraction</th>
<th>Combustion value</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Lower</td>
</tr>
<tr>
<td>Botanical name</td>
<td>Common name</td>
<td></td>
<td></td>
<td></td>
<td>(MJ/kg)</td>
</tr>
<tr>
<td>Piecea abies</td>
<td>White fir</td>
<td>400</td>
<td>0.828</td>
<td>0.168</td>
<td>18.7</td>
</tr>
<tr>
<td>Dyera constulata</td>
<td>Jelatong</td>
<td>440</td>
<td>0.796</td>
<td>0.187</td>
<td>17.8</td>
</tr>
<tr>
<td>Chlorophora regia</td>
<td>Iroko</td>
<td>580</td>
<td>0.781</td>
<td>0.219</td>
<td>18.1</td>
</tr>
<tr>
<td>Shorea</td>
<td>Meranti</td>
<td>600</td>
<td>0.829</td>
<td>0.169</td>
<td>16.9</td>
</tr>
<tr>
<td>Quercus robus</td>
<td>Oak</td>
<td>620</td>
<td>0.845</td>
<td>0.152</td>
<td>17.0</td>
</tr>
<tr>
<td>Fagus sylatica</td>
<td>Beech</td>
<td>650</td>
<td>0.784</td>
<td>0.214</td>
<td>18.1</td>
</tr>
<tr>
<td>Intisia bijuga</td>
<td>Merbau</td>
<td>850</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 2. Stages in woodburning related to temperature.
For the purposes of this work it is fortunately not necessary to know the precise nature of the complex chemistry of the combustion of wood. Even the schematic description given above is quite complex to handle in a real wood-fire. Thus we have to make further simplifications. We assume that it is sufficient to distinguish two phases of combustion, namely, that of charcoal and volatiles. This requires only some general data on wood. First of all the mass fractions of wood which are converted to respectively volatiles and charcoal need to be known. Generally at higher temperatures the fractions are 0.8 and 0.2 respectively (Brame & King 1967). This is confirmed by an analysis done by TNO (Netherlands Organisation for Applied Scientific Research) on the wood species used in the experiments (see table 2). A second class of quantities which are of interest is formed by the combustion value of the volatiles as well as of the charcoal. The combustion value of charcoal is taken to be 33 MJ/kg as suggested by Brame & King. The combustion value of the volatiles can be calculated, using the formula

\[ B_f = (1 - v) \times B_c + v \times B_v \text{ (MJ/kg)}, \]

where \( B_f = \) combustion value of fuelwood (MJ/kg), \( B_c = \) combustion value of charcoal (MJ/kg), \( B_v = \) combustion value of volatiles (MJ/kg) and \( v = \) mass fraction wood converted to volatiles and knowing the combustion values of wood; these have been measured by TNO. The objective of the experiments described below is a better understanding of the time-dependent burning process. This is later used to explain the efficiency results of the previous section. Special interest is given to the weight of the fuel as a function of time for two reasons. In the first place it offers us the possibility to calculate the heat release of the fire as a function of time. This is done as follows; once the fuel weight is recorded, the fuel weight-loss becomes a known quantity. Thereupon this fuel weight-loss, in combination with the assumed description of the burning process, determines the heat released in the fire as a function of time. This is done as follows; once the fuel weight is recorded, the fuel weight-loss becomes a known quantity. Thereupon this fuel weight-loss, in combination with the assumed description of the burning process, determines the heat released in the fire (see also § 3.3). Secondly, the fuel weight measurements give information on the fuelbed thickness and, as such, on the pan-fuelbed distance which in its turn appeared to have an enormous influence on the measured overall efficiencies.

3.2 Experimental set-up*

3.2a Fuel weighing The weighing equipment for the fuel has to satisfy three requirements.

(i) The fire is to be fed with charges of 100 g of fuelwood. To be able to say something useful about the behaviour of the fuelbed, a minimal accuracy of 5 g is necessary.
(ii) The output of the equipment should be compatible with a data acquisition system so that the data can be processed automatically.
(iii) The equipment should be insensitive to temperature changes.

A loadcell is a device that satisfies these three requirements. The one of the desired accuracy, however, could only take a maximum load of 20 N. Because the open

* A detailed description of the experiments reported in this section is available in Visser (1982).
fireplace with stones and grate weighed about 10 kg, this weight had to be balanced so that only a very small part of it would burden the loadcell. For this reason a platform balance was built (see figure 3). The balance was constructed in such a way that firstly the recorded signal of the loadcell under the balance was insensitive to the position of the fire on the platform and secondly the mass of the three-stone stove with a grate could be balanced completely by counterweights.

3.2b Data acquisition. Every 10 seconds the weight of the fuel was measured. This measuring and gathering of data was done by means of a data acquisition unit, (HP 3497A) controlled by a microprocessor HP 85. After measuring, the data were stored on tape which was processed after the experiments. The set-up of the measuring system is schematically shown in figure 4. The next paragraph is devoted to the analysis of the data gathered in the way just described.

3.3 Fuel weight-loss experiments

A characteristic picture of the fuel weight as a function of time is given in figure 5. The experimental procedure is as follows. At time $t = t_1$, a charge of 'c' kg of wood is added to the fuelbed. This charge 'catches' fire and burns until at time $t = t_1 + \Delta t$ a fresh charge of 'c' kg is added, and so on. In general the power of a fire of a given configuration can be varied within certain well-defined limits by changing $c$, $\Delta t$ or both. In the experiments reported in this investigation, variation in power has been accomplished by changing $\Delta t$ and holding $c$ constant at 100 g. The power is defined by

$$P_n = \frac{cBf}{\Delta t} \quad (\text{kW}),$$

Figure 3. Platform balance with acting forces.

Figure 4. Scheme of data processing.
where $\Delta t$ is measured in seconds. This we call the nominal power of the fire. The figures of the power mentioned in the previous section correspond to the nominal power. As we shall see later, the type of operation we have chosen leads to other definitions of the power from a fire. The record shown in figure 5 is characteristic for a batch operation. The records of this type serve as valuable tools for understanding wood fires in operation.

### 3.3a Fuelbed build-up

The refuelling at $t = t_1 + \Delta t$ does not always mean that the wood charged at $t = t_1$ has completely burnt. Figure 5 shows, for instance, that the amount of wood left from the third charge is equal to ‘$a$’ gram. In the graph the accumulated mass of unburnt wood just before recharging becomes larger as time progresses and is equal to ‘$b$’ gram at the end of the experiment. This process is called the fuelbed build-up. Figure 6 shows the nature of this process for three power levels 2-6, 5-2 and 7-8 kW.

**Figure 5.** Fuel weight and power as a function of time.

**Figure 6.** Fuel weight-loss curves for different powers.
It is possible to distinguish two regions in these weight-loss curves on the basis of a change in slope. The point at which a drastic change in slope occurs in general coincides with the disappearance of flames (the point is marked in figure 6a). After this point only the charcoal in wood burns. For the low power end (figure 6a) the fresh charge is added almost towards the end of burning of the previous charge. Any attempt to lower the power to below the value shown in figure 6a will result in an insufficient amount of burning charcoal on the fuelbed for a fresh charge to reignite without the assistance of an external pilot flame. For the high power end (figure 6c) the fresh charge is added even before the flames disappear. In this case there is a rapid build-up of fuelbed. Attempts to increase the power beyond that of 7-8 kW result in the fuel falling off the grate. The corresponding situation for an open fire without a grate—driving a fire above a maximum power limit—will result in an increased fuelbed diameter. For a closed stove, exceeding the high power limit results in the choking of the combustion chamber with fuel. A given design of a stove will thus permit a well-defined range of powers to be obtained from it.

In general, after an initial period of unsteady operation, 'a periodic steady state' regime of burning will be established. In this regime the weight loss curves will be congruent with one another—of course this will not be achieved in a strict mathematical sense. The fuelbed weight just before each charge is added will remain reasonably constant. Figure 7 shows a plot of the fuelbed weight just before a fresh charge is added as a function of time for a 10 kW fire. It is interesting to see that the fire without a grate has not attained steady state during the experimental period. Moreover the fire operated with larger blocks has a larger fuelbed and takes longer time to reach steady state than the one operated with smaller blocks of wood.

Another consequence of the method of operation adopted in this investigation needs to be pointed out. Figure 8 shows the water temperature response for the three power levels 2-6, 5-2 and 7-8 kW. At low power, it is seen that the temperature curve exhibits distinct plateaus that correspond roughly to the disappearance of flames. In addition, it is also observed that at the high temperature end there is a distinct dip in the temperature curve. This suggests that the power level from the charcoal bed is insufficient to balance the heat losses from the pan. These are not observed for the case of the other two power levels. The experiments reported here were run over a period of 1 hour. In all the experiments when the flames disappeared after the last
charge, the water kept boiling for a little over 6 minutes at the low power end to nearly 17 minutes at the high power. In some of the experimental closed stoves tested by the Eindhoven/Apeldoorn group, this charcoal heat is sufficient to keep the water boiling for over 30 minutes (Nievergeld et al 1981 and Stielcken 1982). In other words, the charcoal heat from wood fires when used consciously, can contribute to savings in fuel consumption.

The above description leads to the concept of an average power of a wood stove. By defining the end of the experiment to coincide with the time at which the water temperature falls below boiling point, we obtain the average power by

\[ P_{av} = \frac{m_f B_f}{t} \]  (kW),

where \( m_f \) = total mass of fuel used in the experiment (kg) and \( t \) = total duration of the experiment in seconds (measured according to the above definition).

The values of average powers for corresponding nominal powers are shown in table 3. The extent of the difference between the two can be taken as a measure of charcoal heat available in a given stove configuration as a function of power, fuel type, moisture content and wood block size. The table also shows the mass of charcoal left behind on the grate at the end of each experiment. It must be remembered however that all of this is not combustible matter; some proportion of it is ash. No attempt has been made in these experiments to separate ash from charcoal and weigh them separately. Since we know the ultimate analysis of the wood and the quantity of wood burnt during the experiment it is possible to provide an upper limit on the amount of ash on the grate at the end of an experiment. It is an upper limit because a certain amount of ash is carried away as fly ash by the flames. The table thus provides two entries for each experiment for the energy content of the mass left behind on the grate (as a percentage
Table 3. Nominal power, average power and charcoal at the end of the experiment

<table>
<thead>
<tr>
<th>No.</th>
<th>Nominal power (kw)</th>
<th>Average power (kw)</th>
<th>Charcoal at the end of experiment</th>
<th>Zero ash</th>
<th>100% ash</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( P_n )</td>
<td>( P_{av} )</td>
<td>% of total heat</td>
<td></td>
<td></td>
</tr>
<tr>
<td>With grate</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>3.1</td>
<td>2.9</td>
<td>18.3</td>
<td>13.8</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>3.9</td>
<td>3.4</td>
<td>15.1</td>
<td>9.7</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>5.2</td>
<td>4.5</td>
<td>14.0</td>
<td>6.8</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>6.2</td>
<td>5.1</td>
<td>23.7</td>
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</tr>
<tr>
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<td>7.8</td>
<td>5.6</td>
<td>19.4</td>
<td>10.4</td>
<td></td>
</tr>
<tr>
<td>Without grate</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>2.7</td>
<td>2.7</td>
<td>23.8</td>
<td>19.3</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>3.1</td>
<td>2.8</td>
<td>27.0</td>
<td>22.5</td>
<td></td>
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<tr>
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<td>3.9</td>
<td>3.4</td>
<td>31.4</td>
<td>26.0</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>5.2</td>
<td>4.3</td>
<td>40.0</td>
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<tr>
<td>With moisture</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>% Moisture</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>0</td>
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<td>9.7</td>
</tr>
<tr>
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</tr>
<tr>
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<td>10</td>
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<td>3.4</td>
<td>17.3</td>
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</tr>
<tr>
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<td>15</td>
<td>3.9</td>
<td>3.5</td>
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</tr>
<tr>
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<td>20</td>
<td>3.9</td>
<td>3.5</td>
<td>17.3</td>
<td>11.9</td>
</tr>
<tr>
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<td>25</td>
<td>3.9</td>
<td>3.3</td>
<td>17.3</td>
<td>11.9</td>
</tr>
<tr>
<td>Wood species</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>16</td>
<td>Meranti</td>
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<td>3.4</td>
<td>40</td>
<td>39.8</td>
</tr>
<tr>
<td>17</td>
<td>Beech</td>
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<td>3.5</td>
<td>19.5</td>
<td>17.7</td>
</tr>
<tr>
<td>18</td>
<td>Oak</td>
<td>3.9</td>
<td>3.5</td>
<td>19.5</td>
<td>18.3</td>
</tr>
</tbody>
</table>

of the energy content of the wood burned) corresponding to the assumption of: (a) all ash is carried away as fly ash; and (b) all ash is retained on the grate. The percentages are not insignificant. The only effective way to use this heat is to recover the charcoal, quench it and store it for future use. It is obviously not a convenient procedure from a user’s point of view.

3.3b The heat release from the fire The weight-loss records presented in the previous paragraphs can also be utilized for estimating the heat release from the fire. The primary assumptions behind these estimates are that the combustion of wood takes place in two phases (solid phase combustion of charcoal and gaseous phase combustion of volatiles) and the fuelbed consists of only charcoal and the uncombustible ash. This latter assumption is valid for the entire combustion process at low powers and for the steady state period at modest power levels. For large power levels however the assumption is not true. Under these conditions the fuelbed will consist of wood in various stages of thermal decomposition. It would be speculative to identify the proportion of charcoal and volatiles burnt for each charge with the present
experimental technique. However, as the discussion in the next section will point out, it is quite ineffective to operate a stove of a given configuration at such high power levels.

In order to be able to separate the total mass flow in volatiles and charcoal flow it is assumed that the charcoal burning rate is constant during the period between two fuel loadings. Alternative assumptions for charcoal burning are discussed in the Appendix. Once the charcoal burning rate is known, the volatiles mass flow can be calculated simply, using:

\[ \dot{m}_v = \dot{m} - \dot{m}_c, \]

where, \( \dot{m}_v = \) mass flow of volatiles from the fuelbed (g.s\(^{-1}\)), \( \dot{m} = \) total mass flow from the fuelbed (g.s\(^{-1}\)), and \( \dot{m}_c = \) mass flow of the charcoal from the fuelbed (g.s\(^{-1}\)).

When the mass flows are multiplied with the proper combustion values, we get the heat release per second from the volatiles (\( P_v \)), from the total woodfire (\( P_w \)) and from the charcoal (\( P_c \)). A sample result of refashioning the fuelbed weight data in the way described above is given in figure 5. The figure shows the rate of heat output of the fire subdivided into the contributions from the charcoal as well as from the volatiles. The lowest, block-shaped, curve represents the rate of heat output of the charcoal. The lower of the parabola shaped curves represents the rate of heat output of the volatiles while the topmost curve shows the total rate of heat output. The charcoal heat output being block-shaped is a result of the assumed constant charcoal burning rate. In reality the curve may not be linear. Since the calculated point of time at which the power of volatiles becomes zero synchronizes with the disappearance of the flames, the assumption mentioned is good as a first approximation (see Appendix for a more elaborate discussion).

3.4 Results and discussion

In this section the results of the weight-loss experiments are presented and discussed. The measurements have been performed in experiments in which the overall efficiencies, shown in § 2.3 were determined. The fuel weight-loss results are presented in the same order as the overall efficiency results from the section mentioned. The results of each series of experiments are condensed into two graphs. The first one shows the fuelbed weight as a function of time and is constructed in a manner similar to figure 7. The second graph shows the power from the volatiles (how fiercely the fire burns) related to one of the parameters. The averaged maximum volatiles power \( P_{v,\text{max}} \) is taken as the quantity which describes the fierceness of the fire. Therefore the maximum volatiles power per charge has been measured and the average value per experiment has been calculated.

3.4a The power level of the fire The first quantity varied is the power level of the fire with a grate. The experimental results are shown in figure 9. The fuelbed weight curves show that a steady state within the experimental time of one hour is only reached when the power level is below 5.5 kW. Above this power the fuelbed continues to build-up and eventually the grate will be too small to hold all the charcoal. As a result the conclusion drawn on the basis of the standard water boiling tests, that
the power for this fire could be varied from 2·6 to 7·8 kW has been premature and must be revised, it ranges only from 2·6 kW to about 5·2 kW (a turn down ratio of 2). The experiments also show that the maximum amount of charcoal the grate can hold is about 100 g. Adding another 100 g of fresh wood becomes impossible; there is not enough space left which is the reason why experiments with large power levels have to be terminated prematurely. For large fuelbeds (>50 g charcoal or >0·2 g charcoal per cm²) the fuelbed becomes conical in shape and starts to affect the fuelbed-pan distance. Small fuelbeds on the other hand can be spread evenly over the grate and do not influence the distance substantially.

We now introduce a third power definition for a stove design. We will call it the design power of a stove. It defines the maximum power that a stove can deliver under steady state operation. It seems that, from the results obtained here, it is feasible to operate open fires with a power of about 30% higher than the design value for durations of the order of 1/2 to 1 hour. It can be expected that the closed stoves exhibit similar tendencies in their operation (see for example Delsing 1981 for a non-chimney closed stove operation qualitatively illustrating fuelbed build-up). However, when closed stoves are operated at powers exceeding the design power on a regular basis, they will demand frequent maintenance by way of removal of tarry deposits in passages and walls of the stove. When this maintenance is not provided performance may deteriorate rapidly and may even lead to drastic reductions in the lifetime of stoves. Thus for safe and durable operation of a stove, it is essential to operate it at or near its design power level.

The graph of the averaged maximum volatiles power, \( P_{v, \text{max}} \), as a function of the nominal power shows a very remarkable feature of the fire. The maximum power of the volatiles is more or less a constant and does not change apparently with the nominal power of the fire. Only the number of times this maximum is reached in the course of the experiment will change, because this number is directly related to the number of refuellings. The value of \( P_{v, \text{max}} \) lies between 5 and 5·5 kW. It is interesting to note that this power is virtually equal to the design power discussed above. The implication of this is not clear at this moment and requires further investigation. Knowing that 70% of the heat is released in the flames, this means that the upper limit of the power range can be taken to be 5·25/0·7 = 7·5 kW. This estimation is made on the basis of maximum volatiles power;
consequently the upper limit will be somewhat lower in practice and will be in the region of the upper limit estimated on the basis of the fuelbed weight graph (see figure 9). Hence it can be stated that not only the burning rate of the charcoal but also the burning rate of the volatiles limits the fire’s capacity to accept more wood per unit of time. Thus, neither all the charcoal nor all the volatiles will have burnt at the moment of recharging when the fire is driven at a power of more than 5 to 6 kW on the 0·18 m grate.

The energy picture of the fire which can now be drawn is as follows. The radiation heat transfer efficiency from the fuelbed to the pan is constant over the whole power range from 2-6 to 5-5 kW, due to the fact that the fuelbed-pan distance is not influenced by varying the power. The radiation heat transfer only increases slightly at higher power levels ($P_n \geqslant 6$ kW), when the fuelbed thickness begins to affect the pan-fuelbed distance. Not only the radiation heat transfer efficiency but also the convection heat transfer efficiency is independent of the total power. This becomes clear when it is realised that the convection heat is completely determined by the process that takes place in the flames: the combustion of volatiles.

The quantity which describes this combustion process, $P_v^{\text{max}}$, remains constant over the whole series and so will be the convection heat transfer efficiency. As a result the convection heat, radiation heat and consequently the total efficiency is independent of the nominal power.

3.4b The wood species The results of the series of experiments in which the wood species have been varied are shown in figure 10. From the figure one can see that the fuelbed as well as $P_v^{\text{max}}$ are strongly affected by the wood species used. A second conclusion to be drawn is that the density of wood is clearly not a sufficient criterion for the fire behaviour. The variations shown by the fuelbed weight and $P_v^{\text{max}}$, both as a function of the density, are simply too large for that. No attempt has been made to find a quantity other than the density that governs the behaviour of the fire better and is characteristic for the wood species.

On the basis of the figures one could expect variations in the efficiencies too; however, this does not happen. At present it is hard to explain why not. The difficulty arises due to the fact that only rough guesses can be made of the role the radiant heat transfer process plays and because even that is too much as far as the convection

![Figure 10. Fuelbed weight as a function of time and $P_v^{\text{max}}$ for different wood species.](image-url)
heat contribution is concerned. For this the reader is referred to § 4 where an attempt is made to fill this gap and a model for the convection and radiation heat transfer process is proposed.

Merbau is the heaviest wood tested and shows an exceptionally high build-up of the fuelbed. The other heavy woods like Oak and Beech on the other hand show completely different results.

3.4c The moisture content Although the efficiency numbers for the experiments with different moisture content of the wood do not vary, this does not mean that the fire is not affected at all (see figure 11). The picture the fuelbed weight results offer is characteristic for this series of experiments. The picture shows that the experiments go through two stages. In the initial phase the fire has just been lit and burns very slowly, consequently a fuelbed is built up. The time this period lasts and the maximum weight the fuelbed reaches depend on the moisture content. After this phase the fuelbed is apparently hot enough to evaporate the moisture without any problem. The second and final period has then begun; the wood starts to burn rapidly, almost as if it is dry. The initial period of the fire is not only influenced by the moisture content of the wood but also by the way the fire is lit. In the experiments special care is given to this aspect and a standard lighting procedure is followed. But even then small deviations from this procedure, which have serious consequences for the fuelbed, cannot be prevented. That is why in the initial period the 10% moisture-content-fuelbed-weight curve lies above the curve from the fuel containing 20% moisture.

It is believed by the authors that especially the initial period of burning has contributed strongly to the impression one has formed in practice concerning the use of moist wood. This happens even though the fire burns as if fed with oven-dry wood, once the initial burning problems have been overcome.

The efficiency number, from the standard water boiling tests can be explained now following the same line of reasoning as for the experiments with different power levels. Due to the fact that $P_{v, \text{max}}$ is not dependent on the moisture content, the convection heat transfer efficiency will be a constant, at least when the fuelbed-pan distance is not influenced by the fuelbed thickness. This last-mentioned assumption is satisfied because, once the initial period is past, the maximum fuelbed weight is less than 50 g and the fuelbed thickness is between 1 cm and 2 cm. Due to the

![Figure 11. Fuelbed weight as a function of time and $P_{v, \text{max}}$ for different moisture content of the fuelwood.](image)
fact that in the final period the fuelbed weight is nearly independent of the moisture content, the radiation heat transfer efficiency will be constant too. As a result the total heat transfer will be nearly constant.

3.4d The size of the wood blocks The influence of the size of the wood blocks on the building up of the fuelbed and on $P_{v, \text{max}}$ can be clearly seen in table 1. A possible reason for the behaviour is the following. The volume-to-surface area ratio for the small woodblocks is half that of the big blocks. So, for the same volume of wood, the surface area for the reactions to take place is twice as large for the small blocks as for the big blocks. Not only can the volatiles escape more easily but the charcoal will also burn faster. Consequently the volatiles power will be higher and the fuelbed weight will be less. From the experiments it must be concluded that the power can be much smaller when the bigger blocks of wood are used for the same charge weight. Moreover the experiments suggest that the discussion on bundling little pieces of wood and cutting big blocks into smaller ones, in order to get better combustion, is more a discussion on adjusting the power of the fire to accomplish a specified task. The efficiency of the open fire has nothing to do with it.

3.4e The position of the pan A detailed study on the relationship between efficiency numbers and the position of the pan will be given in § 4. This is the reason why the results of the fuelbed weight experiments are given here without using them to explain the efficiency results. One may conclude from the graphs shown, that the position of the pan influences the way the fire burns. There is already a small increase in fuelbed thickness when the pan-fuelbed distance is decreased, but more pronounced is the influence the distance has on $P_{v, \text{max}}$ (see figure 12). This feature becomes exceptional if one remembers that the maximum power of the volatiles $P_{v, \text{max}}$ did not change when the nominal power of the fire was varied! This result seems to suggest that, in order to get a lower power from a fire with fixed fuelbed diameter, one has to add not only less wood but has also to reduce the pan-fuelbed distance.

3.4f The use of a grate The last section of this part concerns the use of a grate. To study this the experiments with varied nominal power are done both with and without a grate (figure 9). The experiments with a grate have already been discussed.

![Figure 12. Fuelbed weight as a function of time and $P_{v, \text{max}}$ for different distances between fuelbed and pan.](image-url)
Because of the fact that the experiments without a grate show analogous results, the reader is referred to that section for background information. The main results of the experiments without a grate are:

— The design ranges only from 2.6 to 3.5 kW
— As a result of the small fuelbed thickness and the constant $P_{\text{v, max}}$ the total efficiency must be constant. This explains the water-boiling test results.

As already concluded from the water-boiling tests, the size of the fire with a grate can be smaller than without one. This conclusion is underlined once more by the fuelbed weight graph. Without a grate a steady state is only reached for powers less than 3.5 kW, while the fire with a grate can produce powers up to 5.5 kW. Not only better access is provided for air to burn the charcoal, but also to combust the volatiles. This results in a smaller fuelbed weight and a higher $\bar{P}_{\text{v, max}}$. The fire burns more fiercely with a grate.

The experiments with different wood species, moisture content and pan-fuelbed distance have not been carried out to identify their influence on power ranges from a stove. These are left to a later date.

4. A theory for open fires

4.1 Introduction

The efficiency results presented in § 2 provide a gross estimate of the influence of several parameters governing the fire on the heat picked up by the water in the pan. The weight loss experiments of § 3 provide some qualitative insights into radiation heat transfer for the configuration. The main question of convective heat transfer to the pan could not be answered even in a qualitative sense by the previous sections. The reason for this is that convective heat transfer is closely connected with the combustion of volatiles. We believe that an insight into these processes will lead at least to first guesses on the rules governing the dimensioning of combustion spaces in wood burning stoves.

The convective heat transfer processes are far too complex to attempt experimental investigation. We have therefore chosen to look at the problem with a simple theoretical model. The model consists of three distinct parts:

(a) The first part enables the calculation of temperature, velocity and mass flows in the fire above the fuelbed.
(b) The second part proposes a procedure to estimate the fuelbed temperature.
(c) Finally the results from (a) and (b) are used to evaluate the heat transfer from the fuelbed and the fire to a pan filled with water hanging above the fire.

4.2 The fire

The fire has been modelled by considering it to be composed of three regions.
— The region where the pyrolysis of wood takes place, charcoal is being burnt and volatiles are released.
— The region of the visible flames, where volatiles from the fuelbed react chemically with entrained air and hence heat is liberated.
— The region of hot rising gases where no combustion occurs, air is entrained and temperature drops rapidly with increasing height above the fuelbed.

This section aims at getting a better understanding of the physical processes in the second and third regions mentioned, the column of hot rising gases with and without combustion. In these regions the entrainment of ambient air plays an important role; it takes care of the oxygen supply.

Making use of the so-called entrainment assumption, the model enables calculation of the values of the temperature and the velocity attained in the flames. It is not necessary therefore to get insight into the chemical processes. This would be a very complex task due to the many different hydrocarbons that are involved in the burning of wood. Thus the detailed knowledge of the combustion process is replaced by some gross estimations. The value of the charcoal-volatiles ratio and the specific heat of combustion are the only quantities that are needed. The fire problem thus reduces to the process of a rising gas column above a source in which initially heat is released.

The work of Lee & Emmons (1961) is taken as the starting-point for the construction of the model. Lee & Emmons investigated a turbulent plume above a steady two-dimensional finite source of heated fluid in a uniform ambient fluid. By solving the fundamental equations of motion they obtained analytical expressions for plume width, buoyancy force and gas velocities as a function of the height above the source. A similar model was developed by Steward (1970) for circular fires taking into account the liberation of heat by combustion in the first part of the hot gas column. This was done by introducing a source term in the energy equation. For solving the problem Steward rewrote the continuity equation in such a way that this model gave only the height above the fuelbed at which a given amount of air was entrained. Steward’s model thus explained trends in experimental flame height data. It was found that a numerical evaluation of his model gave close agreement with the flame height data with all points falling near a curve which represents 400% excess air. That is why a model of the type of Steward is believed to give the best theoretical results for different classes of fires (Cox & Chitty 1980).

Due to the interest in woodstoves the results of Steward’s model are considered inadequate. The main difference between the present model and the work of Steward lies in the manner in which the continuity equation is implemented. The straightforward approach of Lee & Emmons is chosen for the purpose.

4.2a The flame model. The problem of the rising gas column above the fuelbed is considered to be a turbulent-free convection problem. The fundamental equations of mass momentum and energy make up the basis of the model (see figure 13 for the geometry). In arriving at these equations the following assumptions are made.

(i) The volatiles leaving the fuelbed and the air that is entrained in the convection column behave like ideal gases; the gas properties of volatiles and air are the same.
(ii) The convection column has reached a steady state.

(iii) The driving force is the buoyancy; pressure gradients are neglected. The pressure differences in vertical direction, due to the hydrodynamic pressure gradient is of no significance for this situation. The radial pressure difference is neglected because the transverse accelerations are small relative to those in the vertical direction;

(iv) Turbulent flow is fully developed and thus molecular transfer mechanisms are neglected relative to turbulent processes.

(v) Turbulent temperature and density variations are small relative to turbulent velocity variations.

(vi) Radiant heat losses from the flames need not be taken into account.

Under the foregoing assumptions the fundamental equations reduce to the continuity equation

$$\frac{\partial}{\partial z} \rho u - \frac{1}{r} \frac{\partial}{\partial r} r \rho v = 0,$$

the momentum equation for the $z$-direction

$$\frac{\partial}{\partial z} \rho u^2 - \frac{1}{r} \frac{\partial}{\partial r} r \rho u v = (\rho_a - \rho) g - \frac{\partial}{\partial z} \rho u_f^2 - \frac{1}{r} \frac{\partial}{\partial r} r \rho u_f v_f,$$

and the energy equation

$$\frac{\partial}{\partial z} \rho u c_p T - \frac{1}{r} \frac{\partial}{\partial r} r \rho v c_p T = \dot{w},$$

where $\rho$, $u$, $v$, $T$ give the time-averaged values of the density, the axial velocity, the radial velocity and the temperature, while $u_f$ and $v_f$ give the turbulent fluctuations of the velocities. The quantity $\dot{w}$, the source term in the energy equation, denotes the heat release per unit volume per second by combustion. $\dot{w}$ becomes zero at the height where no further combustion takes place.

The first term on the right side of the momentum equation represents the buoyancy force, while the other two terms give the contribution of turbulence to the
momentum transfer. The term \( \frac{\partial}{\partial z} \rho u_j^2 \) can be neglected because it is of smaller order of magnitude than the last term, representing the Reynolds stress gradient (Eckert & Drake 1972).

Because the flow is axisymmetric: \( v = 0 \) at \( r = 0 \). Using this and integrating the continuity equation with respect to \( r \), we get

\[
\frac{d}{dz} \int_0^\infty \rho u r \ dr = r \rho u |(z, \infty)\.
\]

The equation states that the increase in the ascending mass flow is due to the entrainment of ambient air. Using the same arguments as for integrating the continuity equation and noting that the Reynolds stress is zero for both \( r = 0 \) and \( r = \infty \), integration of the momentum equation with respect to \( r \) gives:

\[
\frac{d}{dz} \int_0^\infty \rho u^2 r \ dr = \int_0^\infty g (\rho_a - \rho) \ r \ dr,
\]

which states that the increase of vertical momentum in the hot gas column is due to the buoyancy force. Finally integrating the energy equation with respect to \( r \) gives:

\[
\frac{d}{dz} \int_0^\infty \rho u c_p T \ r \ dr = r \rho v c_p T |(z, \infty) + \int_0^\infty \dot{w} \ r \ dr,
\]

which states that the increase in energy flux over the convection column is caused by the energy content of entrained air plus the combustion heat released.

Before the integrated equations lead to solutions, some more assumptions have to be made. They concern firstly the shape of the velocity and temperature profile, which are assumed to have a top-hat shape. Thus if \( b \) represents the plume radius then for

\[
r < b \rightarrow T = T(z), \ u = u(z),
\]

\[
r > b \rightarrow T = T_a, \ u = 0.
\]

Secondly it is assumed that the way in which air is entrained can be described by the entrainment assumption for strongly buoyant flames

\[
rv |(z, \infty) = a (\rho/\rho_a)^{1/2} ub,
\]

where \( a \) is the entrainment constant. Thirdly it is assumed that volatiles burn instantaneously with entrained air and that the air quantity needed is the stoichiometric amount plus the excess amount. Details of the actual solutions to these equations are available elsewhere (Bussmann & Krishna Prasad 1982).

4.2b Model calculations and discussion Figure 14 presents some of the more significant results obtained through computation from the model. The temperature,
width of the flame/plume, and the velocity have been plotted as a function of height measured from the fuel bed. The power of the fire, excess air factor and percentage of volatiles have in turn been used as parameters.

Before going into the discussion of these results, a few other observations are in order. The Froude number for small wood fires is of the order of $10^{-2}$. Calculations show that the plume diameter first decreases until the local Froude number is larger than unity. This explains the characteristic neck observed in flame photographs. Far from the fuelbed the Froude number becomes unity with a balance between entrained air flux and buoyancy, which maintains the velocity constant (Lee & Emmons 1961). The consequence of the small initial Froude number is that the fire conditions at the fuelbed are not of much importance. Calculations performed with different fuelbed temperatures and diameters show that they have only marginal influence on the flame heights, flame temperatures, plume diameters and gas velocities. Of course the fuelbed diameters and temperatures are of significant importance in stoves as they determine the radiant heat transfer to the pans.

Turning now to the results, the temperature and diameter profiles of the flame show a sharp discontinuity. This is really a consequence of the fact that the source term in the energy equation is set to zero abruptly when the air entrained by the flame reaches a predetermined value (determined by the excess air factor) signifying the
end of combustion. Figure 14a shows that the power of the fire does not influence the maximum temperature in the system. It influences only the flame height which increases according to $P^{2/5}$. This agrees with the findings of Steward (1970) using a simpler model. This could serve as a first approximation for a scaling law for the design of combustion volumes in stoves. The maximum velocity attained in the system also increases with the power of the fire. The fire diameter profiles clearly show the characteristic neck near the fuelbed (as pointed out earlier).

In the present model the excess air factor is taken as a parameter. The actual value needs to be picked from experimental results. As is to be expected increase of excess air reduces the maximum temperatures, increases flame heights and reduces maximum velocities (figure 14b). The mass fraction of volatiles leaving the fuelbed is not exactly known but will vary around 0.8 (Brame & King 1967). The question is whether all of it will burn. Emmons (1980) points out that flaming combustion burns only a limited fraction of the volatiles. For example polystyrene-foamed plastic burns only 50% of the mass pyrolyzed, the remainder appears a dense cloud of soot, unburned and partially burned volatiles. The experiments on open wood fires (see later) do not suggest this level of unburned volatiles. However, this possibility is included in the analysis by letting the mass fraction vary parametrically. The results shown in figure 14c show simply the expected behaviour due to incomplete combustion.

Because of lack of experimental results on small wood fires it is difficult to check the validity of the model. Therefore a series of experiments was performed to compare experimentally determined flame heights with those predicted by the model. In each experiment the power of the fire was held constant by adding predetermined quantities of oven-dry wood at known intervals of time. After the charcoal bed had built up, there ensued a steady state period for the burning as could be determined by the fuelbed thickness and flame heights. The flames were photographed roughly 20 times over a period of 15 minutes.

The power could be varied by varying the fuelbed diameter. The flame height corresponding to a certain power level was taken as the distance between the top of the fuelbed and the visible flame tip on the photographs averaged over the twenty photographs. The results are shown in figure 15. The model calculations first of all explain the experimentally observed trends in flame heights for the wood fires tested. As stated before the flame height appears proportional to $P^{2/5}$. The excess air factor required for a quantitative agreement with the experiments lies between 1.5 and 2.5. A value of 2 adequately represents the data. The fact that Steward required

![Figure 15. Flame height as a function of the power output.](image-url)
an excess air factor of 4 for agreement with experiments is attributed to the rather low value of entrainment factor he used. A value for the latter of 0-08 represents the conditions in the fire better (List & Imberger 1973).

The present experiments did not include measurement of the velocities and the temperatures. In order to evaluate these results from the model, the experimental results of Cox & Chitty (1980) were used. These experiments were done on simulated fire plumes produced by burning natural gas as a diffusion flame on a porous refractory burner. The axial velocity at the flame height level in their experiments correlated according to

\[ U_0 = C P^{1/5} \]

The 1/5th power law is consistent with the height-power correlation mentioned earlier. The constant \( C \) was found to be 1-867. In the present model \( C \) depends strongly on the heating value of the fuel, stoichiometric air-fuel ratio and excess air factor. Using an excess air factor of 2, as determined in the present work (Cox & Chitty did not report this quantity), the programme was rerun for natural gas. \( C \) from the calculations was found to be 1-633. The temperature predicted by the model is 1730 K and the measured temperatures were only 1250 K.

If we note that the present model employs top hat profiles and the measurements were at the axis of the fire, the discrepancy in velocity could be considered modest. The overprediction of the temperature should be attributed to several reasons. Firstly, the measurements did not correct for radiation errors. The error was estimated to be about 20% at 1250 K. This will bring the actual temperature up to 1500 K. Secondly the model does not include radiation losses and the possibility of incomplete combustion. Considering the crudeness of the model, the agreement between experiment and the model should be judged reasonable. The problem with the model is that it underpredicts velocity, but overpredicts the temperature. This requires further investigation.

4-3 The fuelbed

The fuelbed temperature is the quantity of interest for the radiation heat transfer from the fuelbed. So far nothing has been said about the way this temperature is determined. As in the section on combustion of volatiles nonexisting insight into chemical process is replaced with some gross estimates to arrive at temperatures. The only quantities needed are the charcoal-volatiles ratio of wood, the specific heat of combustion of charcoal and the air quantity needed to burn the charcoal completely. According to Brame & King the first two quantities are equal to respectively 4(—) and 33 MJ/kg. The third quantity, the stoichiometric amount of combustion air, can be easily calculated. Air (11-6 kg) is needed to burn 1 kg charcoal completely.

In § 2-3 it is stated that radiation carries away the heat released in the fuelbed. This is however only approximately true. Part of the heat released will be carried away by the gases involved in the charcoal combustion. For 1 kg of charcoal this amount is estimated to be:

\[ m_o C (T_{0,v} - T_a) \] (J),
where \( m_g \) = amount of combustion gas generated while burning 1 kg charcoal completely (kg), \( C \) = specific heat of combustion gases (J/kg K), \( T_{0\,g} \) = temperature of the combustion gases at the fuelbed (K) and \( T_a \) = temperature of the ambient air (K). Assuming \( T_{0\,g} = 1100 \) K, which is the temperature at which the charcoal starts to burn (Wagner 1978), the gases carry away 28% of the heat released in the fuelbed. Knowing this, the energy balance of the fuelbed can be drawn

\[
\dot{m}_c B_c = \dot{m}_g C (T_{0\,g} - T_a) + \varepsilon \sigma (T_0^4 - T_a^4) A, \quad \text{J/s.} \tag{15}
\]

The first term denotes the heat production in the fuelbed (see § 2.3), the second term give the heat flow carried away by the combustion gases and the last term is the radiation heat flow from the fuelbed, where \( \varepsilon \) is the emissivity, \( \sigma \) is the Stefan-Boltzmann constant and \( T_0 \) the mean fuelbed temperature. \( T_0 \) can be calculated now and is used to evaluate the radiation heat from the fuelbed to different surfaces.

The main assumption made in the above model is that no excess air is involved in the burning of charcoal. Since both theory and experiment are quite difficult for evaluating this, we have chosen to live with the crude assumption of zero excess air. The assumption results in an overestimate of the mean temperature of the fuelbed. The extent of this overestimate, it is to be noted, is also dependent on the accuracy of \( T_{0\,g} \) we have used.

4.4 The open fire with a pan

The model presented in § 4.2 and the mean fuelbed temperature \( T_0 \) calculated according to (15), are used to get insight in the way heat is transferred from the fire to a pan filled with water hanging above the fuelbed. In the calculations a distinction is made between convective and radiative heat transfer.

4.4a Convection The rising column of hot gases produced by the flames which envelop the pan is treated as an axisymmetric hot gas jet impinging on the pan bottom. The amount of convection heat withdrawn from the gases by the pan \( (\dot{Q}_c) \) is calculated using the heat transfer relation:

\[
\dot{Q}_c = h \cdot A \cdot (T_a - T_p) \quad \text{(W)}, \tag{16}
\]

where \( h \) = the heat transfer coefficient (W/m²-K), \( A \) = the pan surface area (m²), \( T_a \) = the gas temperature (K) and \( T_p \) = the pan temperature (K).

The values of \( h \) and \( T_a \) depend strongly on the conditions at the pan surface. They are obtained from existing semi-empirical formulas. When applied to small wood-fires, the conditions under which these formulas were derived are not always met. As we have no alternative the formulas are used nevertheless. At the same time this problem makes it clear that one should be careful with the value one places on the results obtained. A schematic view of the fuelbed-flames-pan configuration is given in figure 16. As the hot gas jet comes close to the pan bottom a stagnation point flow regime is created. The gases turn by an angle of \( \frac{1}{2} \pi \) and thereby form an axisymmetric wall jet. When the pan bottom edge is reached, the flow direction
will change once more. Due to the buoyancy force the gases turn again by an angle of $\frac{1}{4}\pi$ and then flow alongside the pan wall, forming a two-dimensional wall jet.

The two different flow regimes distinguished at the pan bottom also have their own characteristic heat transfer properties. The way a distinction is drawn between those flow regimes is based on the work of Era & Saima (1976) and van der Meer & Hoogendoorn (1979). For the radius $r$ smaller than a characteristic length $D$, the stagnation point heat transfer formulas are used, while for $r > D$ the axisymmetric wall jet formulas are applied. The value of $D$ depends on the position of the pan above the fuelbed ($z_{\text{pan}}$). On the one hand when $z_{\text{pan}}$ is larger than the flame height, $D$ is assumed equal to the width of the hot gas plume at the flame tip. On the other hand when $z_{\text{pan}}$ is smaller, $D$ equals the calculated width at the pan height. The value of $D$ is not much affected by $z_{\text{pan}}$.

More important is the assumption that the combustion of volatiles is stopped when they touch the pan bottom. In other words $z_{\text{pan}}$ determines the amount of unburnt volatiles.

In the stagnation point region a second assumption is made namely that the gas temperature is constant and equal to the gas temperature calculated with the flame model (see § 4.2). The assumption emerges from experimental data gathered by Era & Saima (1976) and from the top-hat temperature profile assumption made before. Era & Saima investigated the flow characteristics of a wall jet produced by gases impinging on a plate from an axisymmetric nozzle close to the plate. Era & Saima confirmed Hertel's quasi-empirical equation (Hertel 1962) for the increasing mass flow rate $\dot{m}$ in an axisymmetrical wall jet.

$$\dot{m}/\dot{m}_i = 0.877 - (r/D),$$

where $\dot{m}_i$ is the mass flow rate of the impinging jet (kg/s). The formula shows that the mass flow rate in the wall jet at $r = 1.14D$ equals the mass flow rate of the impinging jet. Apparently hardly any ambient air is entrained in the stagnation point region and consequently the hot gases will not mix with the cold gases from the surroundings, leaving the temperature constant. Because of the constant temperature it is not necessary to know the heat transfer coefficient as a function of the position under the pan. The coefficient can be averaged over the whole stagnation point region and that is why the Nusselt number relation proposed by Schlünder & Gnielinski (1967) is used:

$$\text{Nu} = \frac{\bar{h} \cdot D}{k} = 1.03 \cdot Pr^{0.42} \cdot Re^{0.5} \cdot (r_i/D)^{-0.65},$$
where \( \text{Nu} \) = the averaged Nusselt number, \( \text{Pr} \) = the Prandtl number, \( \text{Re}_D \) = the Reynolds number in the impinging jet with diameter \( D \), \( h \) = the averaged heat transfer coefficient (W/m\(^2\)·K), \( k \) = the thermal conductivity (W/m\(^2\)·K) \( D \) = the characteristic length (m), \( r_1 \) = the radius of the stagnation point area (m).

The Nusselt number relation has been derived for a turbulent impinging jet flow (\( \text{Re} > 2000 \)) with a distance between nozzle and plate larger than \( D \) but smaller than 12\( D \) (1 < \( z_n \)/\( D \) < 12). Although the Reynolds numbers in the fire are much smaller, the flow is believed to be turbulent due to the combustion process involved. For the open fire configuration being considered, the ratio \( z_n/D \) is mostly smaller than unity. It is believed however that this ratio does not affect the Nusselt number relation much. The gases have impinged on the Pan bottom, they turn and form an axisymmetric wall jet. This flow regime extends from the end of the stagnation point region at \( r = D \) to the edge of the pan bottom. The mass flow rate in the wall jet is given by Hertel’s quasi-empirical equation mentioned before. The mass flow increases towards the edge of the pan bottom due to the entrainment of cold air and consequently the temperature will drop. The equation for the decay of the temperature is given by Era & Saima (1976):

\[
\frac{T_g - T_a}{T_p - T_a} = 0.9 \ (r/D)^{-1.06}.
\]

The formula shows that the gas temperature \( T_g \) is strongly dependent on the position under the pan. Thus, in contrast to the working procedure in the stagnation point region, the heat transfer coefficient cannot be averaged; local heat transfer coefficients must be used. These are obtained from the Nusselt number relation for the axisymmetric wall jet region of a turbulent jet (\( \text{Re}_D > 2000 \)) proposed by Hrycak (1978):

\[
\text{Nu} = \frac{h (r) \cdot D}{k} = 0.32 \ \text{Pr}^{0.53} \ \text{Re}_D^{0.7} \ (r/D)^{-1.23}.
\]

The dependence of the heat transfer coefficient on the distance between nozzle and plate appeared to be negligible (proportional to the distance to the power of 0.16). Once the hot gases reach the edge of the pan bottom they turn by an angle of \( \frac{1}{2} \pi \) due to the buoyancy force. The way the flow behaves at the corner is not precisely understood. The calculation problems that arise from this are overcome by making the following assumptions. Firstly it is assumed that no extra air will be entrained at the pan bottom corner, which means that the gas temperature is not subjected to an extra decrease and consequently that the calculated heat transfer based on this temperature gives a high estimate. Secondly it is assumed that the flow will not separate from the pan wall at the corner but will develop immediately into a two-dimensional wall jet with initial temperature \( T_s \), density \( \rho_s \), velocity \( u_s \) and jet width \( b_s \). The temperature is derived from the energy balance under the pan:

\[
\dot{m}_i \cdot C \ast T_i - \dot{m}_g \cdot C \ast T_g = \dot{Q_c} + (\dot{m}_g - \dot{m}_i) \cdot C \ast (T_g - T_s), \text{(W)}.
\]
The left side of the equation denotes the heat flow difference between the gases in the fire (impinging jet) and the gases at the pan bottom corner. The first term on the right side gives the absorbed convective heat flow by the pan bottom, the second term gives the heat flow needed to warm the entrained cold gases.

Making use of Hertel’s quasi-empirical equation for the mass flow in the axisymmetrical wall jet under the pan, $T_s$ and $p_s$ can be calculated. The velocity $u_s$ is assumed to be equal to the velocity at the corner just under the pan. Referring to the article of Era & Saima again, the expression for $u_s$ for small Reynolds numbers becomes:

$$u_s = (0.03 \, \text{Re}_D)^{0.6} \frac{D}{r_{\text{pan}}}.$$

Knowing $u_s$, $p_s$ and $\dot{m}_s$, the width of the two-dimensional wall jet $b_s$ can be calculated using the expression for the mass flow:

$$\dot{m}_s = \pi r_{\text{pan}} b_s p_s u_s.$$

The equation for the decay of the temperature in a two-dimensional turbulent wall jet together with a Nusselt number relation is given by Seban & Black (1961). They are respectively:

$$\frac{T}{T_s} = 7.7 \frac{\rho_s}{\rho_a} \left( \frac{L + 12}{b_s} \right)^{-0.6}$$

and

$$\text{Nu}_s = h \frac{(L)}{k} = 0.25 \text{ Pr} \text{ Re}^{0.75} \left( \frac{L + 12}{b_s} \right)^{-0.6},$$

where $L =$ the position at the pan wall (m).

The temperature and the heat transfer coefficient are known now over the whole pan outer surface. Consequently the convection heat absorbed by the pan can be calculated.

4.4b Radiation The amount of radiation heat produced in the fuelbed and absorbed by the pan ($\dot{Q}_r$) can be calculated using the formula:

$$\dot{Q}_r = A F_{j-p} \sigma (T_0^4 - T_p^4) \text{ (W)}.$$

where $\dot{Q}_r =$ radiation heat absorbed by the pan, $A =$ fuelbed surface, $F_{j-p} =$ view-factor and $T_p =$ temperature of the pan. Here it is assumed that the emissivity constants of both the fuelbed and the pan are unity and that the gases between pan bottom and fuelbed form a non-absorbing medium. The fuelbed temperature is calculated according to § 4.3. The only unknown quantity left is the viewfactor.
The viewfactor used for two radiating parallel disks at distance $z_{\text{pan}}$ and radii $r_0$ and $r_p$ is taken for this purpose (Sparrow & Cess 1970)

$$F_{\text{p} \rightarrow \text{p}} = \frac{1}{2r_0^2} \left( \frac{z_{\text{pan}}^2}{r_0^2} + r_0^2 + r_p^2 - \left[ \frac{z_{\text{pan}}^2}{r_0^2} + \frac{z_{\text{pan}}^2 + (r_0 + r_p)^2}{2} \right]^{0.5} \right).$$

Once the viewfactor and the fuelbed temperature are known, the radiation heat transfer can be calculated.

5. Results and discussion

Some of the results of the heat transfer calculations are shown in figures 17, 18 and 19. Before discussing the results a little more should be said about the parameters of the flame model used in the calculations. The value of the parameters is chosen in such a way that the calculations for an open fire without a pan give the measured flame
Open fires

heights and gas temperatures. This results in an excess air factor of 2 together with an entrainment constant of 0.08 and a volatiles-charcoal ratio of 4. These parameters have not been varied anymore. To get an idea of their influence, the reader is referred to § 4.2. Other quantities which have been kept constant are the fuelbed diameter, the pan diameter, 0.18 m and 0.28 m respectively, and the combustion value of wood (18.7 MJ/kg).

Turning now to the results, figure 17 shows the calculated total efficiency as a function of the power output of the fire, together with the separate contributions of the convective and radiative heat transfer at the pan bottom and the convective heat transfer to the pan wall. In contrast to the measured efficiencies, the calculated total efficiencies appear to be dependent on the power. This, however, is really due to the assumption made in the calculations that the power of the fire is proportional to the nominal power, while in § 3.4 it has been shown that the volatile power is independent of the nominal power. The shape of the convection heat contribution curves can be explained as follows. For small powers the pan is above the flames. Consequently entrained cold air will decrease the temperature of the gases before they reach the pan, resulting in poor heat transfer. For large powers on the other hand, the pan is hanging in flames and, as it is assumed that the combustion stops when the volatiles impinge on the pan bottom, the combustion is not complete, again resulting in low heat transfer. The maximum efficiency is reached when (for a certain power) the flame tip just touches the pan bottom. As is shown in figure 17, the radiation heat transfer efficiency is not influenced by the power. This efficiency is only dependent on the view factor or, in other words, on the fuelbed-pan distance. In the figure the results of experiments with different wood species are shown too. For these the averaged maximum volatile power, $P_{e, \text{max}}$, (see figure 10) has been taken as the quantity that determines the convection heat transfer efficiency. This is taken instead of the volatile power averaged over the whole experiment time. The calculations appear to agree remarkably well with the experimental results; not only qualitatively but also quantitatively. An exception is formed by the heaviest wood, Merbau, probably due to its exceptionally high fuelbed build-up.

The next set of results is shown in figure 18. In this figure the efficiencies as a function of the distance between fuelbed and pan is drawn, while the power of the fire is kept constant. Here too the total efficiency curve together with the radiation heat curve and the two convective heat curves are presented. The convection heat efficiency curves show a discontinuity at the position where the flame height becomes smaller (or larger) than the pan-fuelbed distance. Before this point is reached the convection heat transfer efficiency increases with the distance because the amount of unburnt volatiles lessens. Due to the view factor the radiation heat transfer decreases with increasing distance. This efficiency loss is balanced by the gain of convection heat, resulting in a nearly constant total efficiency for distances smaller than the flame height. The experimental results shown in figure 1 seem to contradict this. An explanation for this is given below.

It has been concluded in § 2.3 that the distance is one of the few parameters which influences the efficiency. Not only the efficiency but also the volatile powers are influenced (see figure 13). Although in the experiments with varied distance, the wood has been added to the fire at the same fixed time intervals, the fire behaved differently when this distance was changed. That is why in the last set of calculations
not only the distance was varied but (on the basis of figure 12) also the power of the fire. The results are shown in figure 19 together with the experimental results of § 2.3. Instead of the slightly increasing total efficiencies of figure 18, the calculated efficiencies decrease as the experiments show. A reason for this might be that the assumption of the combustion of the volatiles stopping when they impinge on the pan bottom, is not completely valid. This is confirmed by visual observations because there are flames leaking alongside the pan when the distance is small. It is probably better to assume that combustion continues until the gas temperature becomes too low. With that assumption the convection heat transfer for small distances becomes larger. As a result the calculated total efficiencies become larger and the shape of this curve will resemble the one of the radiation heat. This, however, needs further investigation.

Appendix

The heat release rate from the fire

This appendix will discuss the method of computing the heat release rate from the fire using the wood weight-loss curves. The discussion centres around the possible assumptions one can make about the rate of burning of charcoal in the fuelbed.

Figure 20 gives a schematic representation of the weight-loss of a charge of 100 g. The local slope of the curve is a measure of the instantaneous burning rate of wood. Or if we assume complete combustion, it is also a measure of the instantaneous thermal power of the fire. At the end of the charging interval, \( t_c \), the fuelbed weight is \( 'a'g \). We note that, under steady state operation, \( a \) has the same value at the end of each charging interval. We will limit our discussion to the steady state mode.

Since there is no accumulation of combustible matter in the fuelbed under steady state operation, it is to be expected that 100 g of wood is burnt in every charge cycle. Thus we need some assumption to separate the total weight-loss curve into two power streams corresponding to the burning of volatiles and charcoal. To do this we know

![Figure 20. Schematic fuel weight-loss curve of a wood-fire.](image)

The heat release rate from the fire using the wood weight-loss curves. The discussion centres around the possible assumptions one can make about the rate of burning of charcoal in the fuelbed.

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Figure 20. Schematic fuel weight-loss curve of a wood-fire.
the weight of fuel at the end of each charging cycle and the weight of charcoal in the fuel (this is assumed to be equal to the fixed carbon in the fuel as determined from its proximity analysis). What we need to know further is the rate of burning of either charcoal or volatiles independently. We consider here the rate of burning of charcoal.

There are three possible assumptions one could make about the burning rate of charcoal:

(i) The first one is to assume that the charcoal weight-loss curve is similar to the measured wood weight-loss curve. This appears an unsatisfactory assumption if we note that there is likely to be a phase difference between the burning cycles of charcoal and volatiles, according to the Wagner model for the combustion of wood. The implication of this is while 100 g of wood is burnt in a given cycle, there is no reason to assume that the charcoal burnt in that cycle came from the wood that was charged in the same cycle. A reasonable interpretation of the Wagner model is that the burning of charcoal from the previous charge is used to drive the volatiles from the present charge of wood. This assumption is represented by the curve B in figure 20. Curve A is the measured weight-loss record.

(ii) The second alternative is a linear assumption between the known points (0, \( a - 20 \)) and \((t_e, a)\). Twenty grams is the amount of fixed carbon in 100 g of wood. Line C in figure 20 represents this assumption.

(iii) The third alternative attempts to identify the point at which the flames disappear on the total weight-loss-curve. Such a point is always present whenever the power levels are less than or equal to the design power of the configuration. The linear assumption (ii) is retained, but is shifted to make the gradient of the total weight-loss curve equal to the gradient of the charcoal weight-loss line at the point of disappearance of flames. This is represented by line D in figure 20.

The first assumption has been rejected as unrealistic. The third assumption is difficult to implement in practice because the point at which flames disappear cannot
be unambiguously identified. A lower/higher charcoal content than the correct one will be the result (figure 20 shows the case for lower charcoal content).

It was found from an examination of many weight-loss curves that the line C after P (see figure 20) follows very nearly the total weight-loss curve. Visual observations of the flame confirm that point P is quite close to the point at which the flames disappear.

A final comment needs to be made on the linearity assumption. Experiments conducted with charcoal in a shielded charcoal burner showed weight-loss curves that are remarkably linear from the beginning to the end of the experiment as can be seen from the partial record shown in figure 21. This is an additional support for the method of analysis adopted in this investigation.

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Heat transfer and cooking woodstove modelling

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Abstract. Some examples are given about very practical woodstove design rules derived from theoretical analysis. First the effect of insulating lids on the pans, and insulating stove walls are discussed. Second, a correlation is demonstrated between the stove geometry and performance in terms of net power density and convection efficiency. It is shown that the stove design involves a compromise between power and efficiency (or time and wood saving), but that performance is not inherent to the design: it depends on the user's skill and care as well.

Keywords. Woodstoves; lid; heat transfer; heat flux density; efficiency; stove geometry.

1. Introduction

The woodstove problem is not simple at all: this has to do with the complexity of the firewood and its combustion, and with heat transfer problems as well. Puzzling questions arise from field experience. A scientific approach can give some answers, or quantify to some extent correlations that now are felt by intuition. In some cases it can demonstrate astonishing design rules.

Of course not any research in a laboratory will go right to the goal. Even scientific research will not formulate the final and optimum designs giving comfort, wood-and time-saving to the user at a reasonable price. On the other hand the trial and error approach and experience will not—in due time—produce convincing suggestions. A few examples may demonstrate that a scientific approach can come in touch with very practical problems, and the answer to them.

2. A lid on a cooking pan has often been recommended

It reduces the evaporation losses when the pan is heated up to the boiling temperature. In this stage the power should be high to reduce the duration and thereby the thermal losses to the environment. Heat is lost from the pan walls by radiation and convection, but by evaporation as well. Water vapour is transported by diffusion and convection in the air just above the water. It is well known that a lid can strongly reduce these phenomena.

When simmering the lid is less decisive, as vapour under pressure can escape. Therefore the power control of the fire is most important. However, the necessary power to keep simmering depends on the heat losses to the surroundings. These are two-fold: from escaping vapour, and by heat transmission through the pan walls including the lid. Often the lid offers a relatively important loss surface. Notice
that when simmering with a lid on, the air is gradually expelled from the pan and replaced by saturated steam, which condenses on the pan walls and the lid. To which extent can the heat loss through the lid be reduced? This is an interesting question for investigation, be it by estimates, and orders of magnitude.

With an aluminum lid, 0.5 mm thick, the heat loss through the lid on a boiling pan can be written:

\[ q = \frac{Q/A = k (T_B - T_0)}{1/a_i + 1/\lambda + 1/a_e} (100 - 30) \text{ W/m}^2 \]

where \( T_B \) = boiling temperature (100°C), \( T_0 \) = environment temperature (for example 30°C), \( a_i, a_e \) = inside and outside heat transfer coefficients and \( t, \lambda \) = thickness and conductivity of the lid.

The inside heat transfer coefficient \( a_i \) with condensing steam is very high when compared with the outside coefficient where natural convection of air is involved, possibly augmented by wind. The conduction resistance of an aluminum lid is negligible in this context.

If the outside coefficient can be estimated to be about 10 W/m² K then the heat loss can be written as

\[ q \approx a_e (T_B - T_0) \approx 700 \text{ W/m}^2. \]

This is not negligible for a simmering pan.

If the lid had a serious thermal resistance, the top loss would be reduced. Imagine for example a wooden lid, 3 cm thick (figure 1) the conductivity is about \( \lambda \approx 0.15 \text{ W/mK} \). With this lid the heat loss is reduced to

\[ q \approx 3.3 (T_B - T_0) \approx 233 \text{ W/m}^2; \]

that is one third of the losses of the aluminum lid. It must be stressed that the losses discussed here are not the dominant losses: steam leakage as dictated by the fire power is often more important. Therefore, the flexibility in fire power control is most important with simmering operations. Still: a wooden lid is more comfortable than an aluminum one as one can handle it with bare hands. It is better as to heat economy.

If it is interesting as to price (which very often will be the case in a rural environment) it is an interesting suggestion to have wooden lids. Of course, this was theory. It would be fine to check these conclusions by experiment: this will be discussed later.
3. Thermal properties of stove walls are important:

This is generally accepted. However, to which extent do these important properties influence the stove performances? Consider for example steady state heat transfer from a hot gas flowing in a narrow gap. One of the walls forming the flow path is kept at constant temperature (100°C), the opposite one is transmitting heat to the surroundings. This model looks like what happens in a shielded stove between the side wall of the pan and the shield; or it is like the convection flow under a second pan, or still like radial shielded flow under a pan bottom (figure 2).

The flowing gas transfers heat by convection to the pan and to the stove wall as well. Whereas the pan is kept about 100°C by the cooking process, the opposite stove wall gets a temperature which results from an energy balance (figure 3). In steady state, the inside stove wall temperature $T_s$ will be at a level where convection, radiation and conduction heat transfers balance each other.

$$a_i (T_a - T_s) = Z (T_s^4 - T_B^4) + k (T_s - T_0),$$

where $a_i$, $Z$, $k$ are convection, radiation and conduction heat transfer coefficients. $T_a$, $T_B$, $T_0$ are gas, pan and environment temperatures.

From experimental and theoretical background, the convection coefficient can be estimated as a function of geometry, flow and temperature data. The same is true for the radiation coefficient $Z$, if the emissivities involved are estimated to be about 0.9.

The conduction coefficient in fact includes the conduction resistance of the stove wall and the outside convection coefficient $a_e$ for convection and radiation. The latter depends on the wind situation; it can be estimated as about 10 W/m² K with negligible wind.

![Figure 2. Different convection situations, close the model presented for indirect radiation.](image)

![Figure 3. Indirect radiation model](image)
Now, as a result of combined convection heat transfer and indirect radiation, the pan receives more heat if the stove wall is hot (above 100°C) and less if it is cold (below 100°C).

\[ q_{\text{pan}} = q_{\text{conv.}} + q_{\text{rad.}} \]

\[ = \alpha (T_\alpha - T_B) + Z (T_s^4 - T_B^4). \]

This can be written:

\[ q_p = \alpha \left[ 1 + \frac{Z}{\alpha} \left( \frac{T_s^4 - T_B^4}{T_\alpha^4 - T_B^4} \right) \right] (T_\alpha - T_B) = \alpha' (T_\alpha - T_B). \]

It is as if indirect radiation from the stove wall apparently influenced the convection heat transfer. The relative importance of this phenomenon can be expressed by the ratio \( \alpha'/\alpha \). Some results about this model are shown in figure 4. It appears that, even with a thin wall \( (k \approx 10 \text{ W/m}^2\text{K}) \) the heat flux into the pan is increased with 20 to 30%, depending on the temperature of the gas. On the other hand, if the stove wall was perfectly insulated \( (k=0) \), the increase would be from 30 to 40%.

From this rather simple theoretical approach it can be seen that a shield is very important. Insulation of the shield does improve the heat transfer to the pan, but probably many people would expect more than a factor 1.5...So far the model was about steady state conditions. What about dynamic responses?

It has been shown (Krishna Prasad 1981) that a 3 mm metallic stove wall heats up rapidly. In a modelled example a steady inside surface temperature is achieved in about 10 min. A 2 cm ceramic wall gets the same inside temperature after about 20 minutes and then runs hotter. A 13 cm clay wall needs about one hour to get the same inside temperature, and goes on increasing in temperature. However, after 2 hr it is still well below the temperature of the ceramic wall...

Without going into sophistication, one can easily state that the heat flux into the pan (and this is the important thing) is increased if the stove wall is warmer than the pan; otherwise the useful heat flux is decreased. There is no need for a further model to see that the response of the stove wall should be faster than the response of

![Figure 4. Heat gain \( \alpha'/\alpha \) = function of temperature \( T_s \) (computed) by indirect radiation](image)
the pan, if fast and fuel-saving operation is wanted. Certainly many ‘improved’ stoves have been too heavy and too slow to be good enough. Notice that the temperature response of the wall surface is controlled not by the wall thermal conductivity, nor by the wall density, but mainly by a ratio of these qualities: the temperature diffusivity

\[ a = \frac{\lambda}{\rho c} \]

with \( \lambda = \) thermal conductivity, \( \rho = \) density, and \( C = \) specific heat. In fact, there is only a limited choice in materials when looking after the temperature diffusivity. This is because often lighter materials have lower conductivity, and therefore there is only a small change in temperature diffusivity. Taking this into account, a fast response requires thin walls. Often ‘improved’ woodstoves have too thick walls, possibly because the material used—mud— was not good enough to make better designs.

4. Stove wall and insulation

A simulation of stove wall and pan lid insulation has been tested, as illustrated in figure 5. Experimental results are shown in figure 6. Notice that the plots give the net heat flux density into the pan, that is the heat flux into the pan bottom

![Figure 5. Test layout for power density measurement.](image)

![Figure 6. Experimental heat flux density](image)
less the heat losses to the surroundings. The lid insulation was done with a layer of vermiculite (expanded mica). The trends as expected from theory do appear. In this experiment the influence of the lid insulation was far stronger than the effect of stove wall insulation...

5. Stove geometry

The stove geometry is said to have a main influence on the performances, for example net power and efficiency. This is true. But it can be shown with a theoretical model that a good woodstove is a compromise between power and efficiency. On the other hand it can be demonstrated by theory that the practical performance depends on the skill and talent of the user as well: performance as such is not inherent to the stove design.

A burning woodstove is a complex system where very different phenomena are involved. For example: combustion, heat transfer by radiation, heat transfer by convection, and dynamic responses to non steady operation conditions, etc. The present mathematical model is limited to convective heat transfer in a natural draft stove: steady state operation is supposed. The stove geometry is as in figure 7 and includes:

- a combustion chamber;
- a convective heat transfer zone with given width \( D \), flow path length \( L \) and a uniform free height \( d \);
- a chimney height \( H \);
- it is supposed that the pressure drops due to fluid flow in the combustion chamber and the chimney are negligible. Friction pressure drops are concentrated in the heat transfer zone;
- the walls of the combustion chamber and the chimney are supposed to be adiabatic. The heat transfer in the system is concentrated in the heat transfer zone \( DL \) and mainly by convection;

![Figure 7. Convection model with natural draft.](image-url)
— the combustion quality is represented by the temperature $T_1$ (of the gas) at the inlet of the heat transfer zone;
— The physical (transport) properties of the flue gas are supposed to be equal to those of air. Transport properties have been taken constant at the mean temperature (inlet $T +$ outlet $T)/2$.

The flue gas temperature ($T_1$) at the inlet of the heat transfer zone seems to be a suitable index of the combustion quality, as it is closely linked with the combustion efficiencies. We do not insist here on the conditions which are required (quality and size of wood, fire geometry, etc.) to achieve a given temperature.

The problem now can be formulated as follows:

Given: a known stove geometry ($D, L, d, H$), an ambient temperature $T_0$, a boiling temperature $T_B$, a known combustion quality $T_1$, find the heat release and transfer to the stove, and the transfer efficiency (= transfer/release). Or, in other words: find the stove performance (net power and efficiency).

The following steps are involved in the solution:

(a) The flue gas flow is computed from the balance between the chimney draft and the flow resistance.
(b) The heat transfer is computed as a function of the temperatures and the flue gas flow. Inversely, the flue gas flow is expressed as a function of the heat transfer.
(c) In actual steady state the flows $V_0$ as computed from (a) and (b) must be equal. This gives a correlation between geometric data on the one hand and a temperature function on the other hand, which is the key to the solution.
(d) From the foregoing the chimney temperature $T_2$ can be derived, and hence the heat release and transfer too. This can be expressed as a power density ($W/cm^2$) on the pot bottoms. From the given and computed temperatures, the heat transfer efficiency can be derived as well.

5.1 Flow analysis

The flow in the heat transfer zone might be laminar under normal conditions. Therefore, the pressure drop $\Delta P_1$ can be written as

$$\Delta P_1 = 12 \frac{L}{d^2} \cdot \frac{w}{\eta_m} = \left(12 \frac{T_m}{T_0} \frac{V_0}{d^3} \frac{L}{D} \right),$$

where $\eta_m =$ viscosity of flue gas at temperature $T_m$, $T_n =$ mean temperature $= (T_1 + T_2)/2$, $T_2 =$ chimney temperature and $V_0 =$ flue gas flow at reference temperature $T_0$. The chimney draft $\Delta P_2$ equals $\Delta P_2 = g \cdot \rho_0 \cdot H (1 - T_0/T_2)$. From $\Delta P_1 = \Delta P_2$ it appears that

$$g \cdot \rho_0 (1 - T_0/T_2) \left(\frac{T_0}{T_m} \frac{1}{12 \eta_m} \right) = \frac{V_0 L}{d^3 D \cdot H}.$$
or \( (V_0)_F = \frac{g_0}{12 \eta_m} \cdot (1 - T_0/T_2) \left( \frac{d^3 DH}{L} \right) \left( \frac{T_0}{T_m} \right) \),

where \((V_0)_F\) is the volume flow rate as derived from flow analysis.

### 5.2 Heat transfer analysis

The heat transfer in a short duct with laminar flow can be described with the well-known correlation:

\[

\text{Nu} = 1.86 \left( \frac{\text{Re} \cdot \frac{d_h}{L}}{\text{Pr}} \right)^{1/3} \left( \text{if \ Re} \cdot \frac{d_h}{L} > 7.55 \right),

\]

where \(\text{Nu}, \text{Pr}\) and \(\text{Re}\) are dimensionless numbers currently used in heat transfer and defined as follows:

\[

\text{Nu} = \frac{a \cdot d_h}{\lambda}, \quad \text{Pr} = \frac{v}{\nu}, \quad \text{Re} = \frac{w \cdot d_h}{\nu},

\]

where

- \(a\) = the heat transfer coefficient,
- \(d_h\) = the hydraulic radius,
- \(\lambda\) = the heat conductivity of fluid,
- \(w\) = the flow velocity,
- \(\nu\) = the kinematic viscosity (\(\eta/\text{density}\)),
- \(\alpha\) = the temperature diffusivity.

Thus:

\[

\frac{1.86}{2^{1/3}} \frac{\lambda_m}{a_m^{1/3}} \left( \frac{V_0}{DL \cdot d^2} \right)^{1/3} \left( \frac{T_m}{T_0} \right)^{1/3} \left( \frac{T_1 - T_2}{V_0} \right)^{1/3} \left( \frac{DL}{d} \right)^{2/3},
\]

where \(\lambda_m, a_m\) are heat and temperature conductivities of the flue gas at the mean temperature \(T_m\), \(\alpha\) is the heat transfer coefficient.

The total heat transfer \(Q\) to the area \(A = DL\) can be derived:

\[

Q = \alpha \cdot A \cdot \Delta T_m = \frac{1.86}{2^{1/3}} \frac{\lambda_m}{a_m^{1/3}} \cdot \left( \frac{T_m}{T_0} \right)^{1/3} \left( \frac{T_1 - T_2}{V_0} \right)^{1/3} \left( \frac{DL}{d} \right)^{2/3},
\]

where \(\Delta_1 = T_1 - T_B, \Delta_2 = T_2 - T_B\). Of course, we also can write

\[

Q = V_0 \cdot \rho_0 \cdot C_m \left( T_1 - T_2 \right),
\]

when \(C_m\) stands for the specific heat of the flue gas at the mean temperature \(T_m\).

From the foregoing it appears that

\[

\frac{1.86}{2^{1/3}} \frac{\lambda_m}{a_m^{1/3}} \cdot \left( \frac{T_m}{T_0} \right)^{1/3} \left( \frac{T_1 - T_2}{V_0} \right)^{1/3} \left( \frac{DL}{d} \right)^{2/3} = V_0 \cdot \rho_0 \cdot C_m \left( T_1 - T_2 \right)
\]

and hence

\[

(V_0)_H = \frac{1.86^{3/2}}{2^{1/2}} \frac{\lambda_m}{a_m} \cdot \frac{T_0}{T_m} \cdot \left( \frac{1}{\ln \frac{\Delta_1}{\Delta_2}} \right)^{3/2} \cdot \frac{DL}{d}.
\]
5.3 Overall approach

Obviously the volume-flows as derived from flow and heat transfer analysis are equal.

\[(V_0)_F = (V_0)_H.\]

This means:

\[
\frac{g \rho_0}{12 \eta_m} \left( 1 - \frac{T_0}{T_2} \right) \frac{d^3 DH}{L} = \frac{1}{21^{3/2}} \cdot a_m \cdot \frac{1}{\left( \ln \frac{\Delta_1}{\Delta_2} \right)^{3/2}} \cdot \frac{DL}{d}.
\]

After rearrangement we find an equality between a temperature function on the one hand and a geometric function on the other hand.

\[
F = \frac{21^{3/2} \left( \frac{1 - T_0}{T_2} \right)}{1.86^{3/2} \cdot a_m \cdot 12 \nu_m} \cdot \left( \ln \frac{\Delta_1}{\Delta_2} \right)^{3/2} = \left( \frac{L^2}{d^4 \cdot H} \right) = G,
\]

where \(a_m\), \(\nu_m\) are fluid properties at a temperature \(T_m\). This temperature function \(F\) can be tabulated with \((T_0, T_B, T_f)\) as given parameters, \(T_2\) as the prime variable. Inversely, as \(G = F\) from a known \(G\)-geometry, \(F\) is known, and so is \(T_2\). The next steps are simple. The temperature efficiency \(\eta_T\) of the stove is

\[
\eta_T = \left( \frac{T_1 - T_2}{T_1 - T_0} \right) \cdot \frac{C_{m_1}}{C_{m_2}}, \quad \text{with } C_{m_1} \text{ at } (T_1 + T_2)/2
\]

The net heat transfer \(Q\):

\[
Q = V_0 \rho_0 \ C_m \ (T_1 - T_2).
\]

\(V_0\) is known from the heat transfer analysis (§ 5.2) for example:

\[
Q = 1.794 \lambda_m \cdot \frac{T_1 - T_2}{\left( \ln \frac{\Delta_1}{\Delta_2} \right)^{3/2}} \cdot \frac{DL}{d}.
\]

From this the heat flux density (in \(W/cm^2\)) can be computed.

\[
q = \frac{Q}{D \cdot L} = 1.794 \lambda_m \cdot \frac{T_1 - T_2}{\left( \ln \frac{\Delta_1}{\Delta_2} \right)^{3/2}} \cdot \frac{1}{d}.
\]

Obviously the intermediate step (finding the chimney temperature \(T_2\)) can be eliminated.
5.4 Some results

A rather direct plot of some results is given in figure 8. Notice that these apply for

\[ D = 0.3 \, m, \quad L = 0.3 \, m, \quad H = 2 \, m. \]

When \( d \) is 1 cm, for example, we find with fair combustion \( (T_1 = 800^\circ C) \) an efficiency of about 18\%, power density of about 1.8 W/cm\(^2\). If the free height \( d \) is reduced to 0.5 cm, the efficiency increases (up to 0.65), but the power density decreases to less than 1 W/cm\(^2\). The stove model is a compromise indeed.

From this simplified model it appears that the free height under the pot bottom is the dominant factor \( (d \) appears with a fourth power\!). Gain in efficiency is associated with a loss of power and inversely: power reduction increases the efficiency. One of the consequences is that the control of the net heat transfer should be difficult. These statements are in fair agreement with common experience.

Notice the drastic influence of the combustion quality, as expressed in \( T_1 \): the heat transfer efficiency can be affected up to about 40\%. Poor firing (exuberant air factors and/or non complete combustion) reduces the heat release and at the same time the transfer efficiency, and therefore increases significantly the overall specific wood consumption of the system.

Other results are shown in figure 9. With a moderate combustion quality \( (T_1 = 600^\circ C) \) the influence has been investigated of the chimney height \( H \) when a single pan is used over the flue gas duct, and the influence of having two pans after each other instead of one.

The answer on the first issue looks very reasonable: 1 W/cm\(^2\) higher chimney gives better performances. For example, for a power density of an extra 1 metre chimney

![Figure 8. Convection heat transfer computed from the model.](image-url)
increases the possible efficiency from 19 to 31\%. Inversely, with the same efficiency the higher chimney gives more power.

The answer about the pans looks puzzling at first sight. Having a second pan after the first one would reduce the overall performance even more than to cut one meter from the chimney. Most people expected an increase in performance. The point is that, when two pans are used, the flow path length is doubled, and so is the flow resistance. Therefore, with a gap $d$ set for similar efficiency the gas flow $V_0$ and thus the power will go down. The other way around: to maintain the same specific power, the gap must be increased, with lower efficiency as a consequence.

What to do when a two pan stove is needed? According to this model the pans must be put in parallel. In this case the resistance of the flow path is low, as it is short and wide. Sufficient power is feasible with a small gap $d$, which gives high efficiency.

5.5 Comments

It must be stressed here that the model is rather rigid and limited: all of the pressure drops and heat transfers are said to be concentrated in the heat transfer zone. In fact pressure drops and heat losses will occur in other places as well. Obviously this will reduce the performance of the system. Pressure drops outside the heat transfer zone (for example when an air damper is used) will reduce the power, but without gain in efficiency. On the other hand heat transfers outside this zone are losses: they do reduce the efficiency without any gain in power.

Beyond this no radiation has been taken into account.
Another weakness of the model is in the simplification about the flow patterns and the gas transport properties. Therefore this kind of analysis is not good enough to predict the performance of a particular stove design. But the tendencies shown are there and have been confirmed by experiments on prototypes.

6. Conclusions

From the foregoing some very practical suggestions do appear.

(a) A wooden lid on a pan is easy to handle even with bare hands and saves more wood and time than an aluminum lid.

(b) An insulating shield around a fire is a good thing; not only does it reduce direct losses to the surroundings, it increases the heat flux to the pan by indirect radiation as well.

(c) As to stove design, some rules do appear:

(i) Systems with natural draft are limited in performance, showing an imperative link between power and efficiency. Forced draft might move the performance limits but seems to be prohibitive in practice. We should remember here that power and efficiency are closely linked with the economic factors—time and wood consumption—in the cooking process.

(ii) The higher the chimney, the higher the performance (power and efficiency) can be.

(iii) Pressure drops should be concentrated under the pot bottom. This means that the chimney should be wide. Control dampers upstream or downstream should be avoided to the extent possible as they reduce the power without increasing the efficiency: it is preferable—if necessary—to control the flow and power by reducing the flue height under the pot bottom by moving the pot and/or moving the flue duct bottom.

(iv) A stove should be closely adapted to the size and shape of the pots used, given the dramatic influence of the distance $d$.

(v) A stove system with a good geometry remains sensitive to efficient combustion, or in other terms, sensitive to intelligent and careful use.

(vi) The foregoing statements, derived from a simple model, are in fair agreement with common experience. Fair cooking with fuel wood is a complex venture where pots, stoves and the users' care are involved.

References

Wood burning stoves: Material selection and thermal shock testing of fired ceramic bodies

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Abstract. The overall design philosophy of wood-fired stoves is reviewed. The factors affecting the choice of materials are discussed and the relative merits of various alternatives considered. Detailed consideration is given to the development of an appropriate method for evaluating thermal shock resistance of ceramics for stove applications. The method proposed requires the measurement of impact strength subsequent to repeated shocks for comparison with tests on unshocked samples. Tests are described with results which show that this method can effectively discriminate between ceramics of different composition or firing temperature.

Keywords. Stoves; design; ceramics; impact; thermal shock.

1. Introduction

The Intermediate Technology Development Group (ITDG) has been involved since 1979 in a study of wood burning stoves. The ITDG programme is concerned with assessing various designs of stoves and ultimately issuing information for guidance of designers, either as recommended procedures for assessing and improving stove performance, or instructions for the manufacture and operation of a particular design of stove (Joseph & Shanahan 1981).

The work described here, which is a part of the ITDG programme, relates to the problems associated with selecting and optimising the materials from which to manufacture stoves. Up to the present time specifically different material requirements have not been identified for individual designs. The study has been in broad general terms, and experimental investigations have been restricted to fired ceramics.

2. Methodology

The approach adopted has been very much that of a design strategy (Jones 1980) starting by considering ‘needs’ from which a specification can be drawn. The evaluation of alternative solutions is in terms of their ability to meet that specification. Conventionally this type of process may involve several iterations of different stages before a satisfactory solution emerges. The point of development currently reached in the stove materials study is that, having first considered the problem from the cook’s point of view, it has become apparent that effective means of assessing alternative materials must be evolved before realistic comparisons may be made. It has been found that particularly for ceramic materials, existing test methods are of only limited relevance here.
3. Needs

Essentially the basic need may be stated in terms of preparing food at a lower cost. This cost must encompass prime capital cost of equipment, maintenance cost, fuel cost, social cost, etc., etc. It is unrealistic to expect a small scale project to make much impact on such a broad problem and we have therefore limited our study to wood burning stoves and have further made the conscious decision, irrespective of whether it is more or less beneficial, not to consider changes in the type of food, its preparation or the way in which it is cooked.

Specifically then, we are concerned with the design and construction of efficient wood-burning stoves, the most appropriate solution in a given community being dependent on their established cooking habits and the local availability and cost of skills and materials.

4. Performance specifications

Ultimately comparisons between specific materials cannot be made without reference to the geometrical design features of the stove, or conversely the choice of a particular material must impose severe constraints on the shape and size of the stove which in turn limits the situations for which that type of stove will be satisfactory. In other words the various design decisions concerning shape, size, choice of material, etc. are interdependent. However, it is reasonable to identify in qualitative terms some general requirements for stove materials and use these as a basis for considering the relative merits of alternatives. These requirements are reviewed below in terms of three groups of factors to be considered in the selection of material. The groups are 'economic', 'mechanical and thermal', i.e. the response of the material to the operational environment as determined by its physical (and chemical) properties and 'design', i.e. the factors which limit the design flexibility. These distinctions are to some extent artificial but are considered helpful in formulating the problem.

4.1 Economic factors

(i) Cost: Low cost is an overriding parameter but should be assessed in terms of total cost including material cost, manufacturing cost, transport cost (if any) and replacement cost or lifetime.

(ii) Technology: With this type of product it is necessary to consider the local availability of the technical resources for manufacture (this point is arguably an aspect of cost but is worthy of separate emphasis). It is also desirable that the technology associated with the material employed be, to some extent, familiar to the end user: the cook. This is clearly advantageous in so far as abuse and maintenance or repair are concerned.

4.2 Mechanical and thermal factors

(i) Strength and stiffness: Any stove is subjected to mechanical loading from its own weight, the weight of cooking pots, the attachment of a chimney and other externally applied loads. The material must exhibit a minimum level of strength. Low strength
can be accommodated to some extent by careful design—avoiding stress concentrations and choosing appropriate thicknesses—but there are clearly limits.

(ii) Impact resistance: The ability to absorb impact energy must be considered as a separate issue from strength (Gordon 1968). To have a reasonable life a stove must be capable of sustaining the occasional knock. The resistance of the stove structure to this type of loading is largely determined by the toughness, or work-of-fracture, of the material and the size and distribution of defects, but it is also affected by structural factors like local compliance, or flexibility, and inertia.

(iii) Thermal stress resistance: Thermal stresses result from local steady state variations of temperature which by virtue of mechanical constraints and thermal expansion generate stresses. The magnitude of thermal stress is proportional to thickness, Young’s modulus of elasticity and temperature gradient which in turn is proportional to conductivity. The stress is, however, alleviated by the compliance of the restraining structure.

(iv) Thermal shock resistance: When a material is subjected to rapid heating or cooling a situation somewhat similar to that encountered under thermal stress develops except that the magnitude of stresses developed will be less in materials with high heat capacity per unit volume. In a cooking stove the commonest cause of thermal shock is spilling water onto the outside surface of the hot stove. This form of shock has the added complication of steam generation which may be especially damaging to a material with open surface pores. If the thermal loading is thought of in terms of strain then the resistance of a material is most easily conceived as its ultimate tensile strain, but is more properly considered in the same way as impact resistance (Hasselman 1969).

(v) Limiting temperature: For any material there is a limit to the maximum operating temperature. This need not necessarily be determined by melting or dissociation but by increased susceptibility to oxidation or solid state phase changes which, after repeated cycles can lead to swelling and distortion.

(vi) Insulation: Efficient stove operation calls for a degree of insulation to minimise heat loss from the outer surface. This will be determined by the thickness and conductivity of the stove wall. But note that heat stored in the stove body is effectively lost, thus the duration of cooking times is an essential consideration in aiming at a design compromise between insulation and heat capacity.

4.3 Design factors

(i) Formability: The shape of the interior has a considerable effect on the efficiency of a wood-burning stove. Heat must be reflected back to the point of combustion and the air and flu gases must be ducted to mix and flow as required. These requirements can only be met by fairly complicated shapes usually involving double curvature. Thus the freedom to form material to a predetermined shape is an important consideration.
Sealing: Also related to the ‘fabrication’ process is the need to seal the body of a stove with no unwanted air or flu gas leakage.

5. The alternatives

In view of the overriding cost limitations the list of alternatives can be kept fairly short but unfortunately in some cases there are almost endless variations within the broad material categories. The principal alternatives are briefly reviewed below with comments on their advantages and disadvantages in the light of the requirements discussed above.

(i) Sheet steel:
   * For: excellent strength, shock and impact resistance.
   * Against: high cost (which may be offset by low quantity needed), rapid oxidation and distortion at high temperature, high conductivity which with low thickness gives high heat losses, only simple shapes can readily be fabricated, sealing difficult unless welded.

(ii) Cast iron:
   * For: moderately complex shapes can be cast without too much trouble, good impact, strength and thermal shock resistance.
   * Against: fairly sophisticated manufacture required, heavy, high cost, poor insulation, high temperature cycling leads to distortion.

(iii) Unfired or air-dried clays:
   * For: very cheap, unsophisticated technology.
   * Against: very low strength leads to massive stoves, high thermal capacity, must be built in situ.

(iv) Fired ceramics:
   * For: low cost, easily shaped, local technology, reasonable weight, excellent thermal stability.
   * Against: brittle, require careful design and material control, properties highly dependant on composition and manufacturing techniques.

(v) Cementitious materials:
   * For: potentially cheap and strong.
   * Against: brittle if unreinforced, high temperatures lead to ‘conversion’ which can be counteracted to some extent by fibre reinforcement but at increased cost (Hannant 1978).

The above represents a very simplified list and omits in particular the opportunities offered by various combinations such as sheet metal lined with refractory ceramics or ferro-concrete with a refractory lining. Neglecting for the present these ‘hybrid’ solutions, ceramic materials seem to present the most acceptable general solution, provided the problems of impact, thermal stress and thermal shock can be adequately
resolved. The practical aspects of the ITDG stove materials study have been concentrated in this area.

6. Thermal shock testing

Those mechanical properties of a ceramic material which influence its resistance to impact and thermal stress have the same relationships to its resistance to thermal shock. A material which is resistant to thermal shock is likely to be resistant to thermal stress though the reverse is not necessarily the case. Also if resistance to shock is due, at least in part, to the material’s defence against crack propagation then a ceramic which is resistant to thermal shock will also show some degree of resistance to mechanical shock or impact.

The most successful attempts at developing refractories which are insensitive to thermal shock have concentrated on achieving near-zero expansion coefficients, minimising surface flaws and inducing a compressive surface prestress. Attempts which ‘spoil’ the fracture process can also be very successful. One way that this can be done is by using a very porous medium in which cracks cannot propagate readily due to lack of material continuity. However, while this method may be all right for space shuttle tiles, it will not fare too well if there are open surface pores when the shock is induced by cold water on a hot body. In this situation not only does the effective increase in surface area give rise to increased rates of heat transfer, but the confined generation of steam within the material can exacerbate the thermally induced stresses.

In selecting a method to evaluate the resistance of stove ceramics to thermal shock we were conscious of a number of specific requirements:

(i) The method should be relevant to the stove application, i.e. shock from temperature levels such as experienced at the surface of stoves and involving direct measurement of the effects of shock.

(ii) The method should be fairly simple, being easy to reproduce and not requiring highly trained investigators.

(iii) It should not require sophisticated or expensive equipment that could not be either purchased or manufactured readily, anywhere within reason.

(iv) Results should be quantitative and reproducible, i.e. it is necessary that results from one laboratory can be compared directly with results from another laboratory.

(v) Low cost.

At present there does not appear to be a satisfactory test which is generally accepted in the ceramics industry (Hodson 1979). Some workers favour indirect approaches, measuring all the relevant parameters like expansion coefficient and conductivity, but this is a very tedious and complex route which must leave an element of uncertainty even when all the parameters are assessed. The more sophisticated techniques involve ‘residual strength’ measurements in which samples are shocked and bending strength after shock is compared with the bending strength of similar examples which have not been shocked (Hasselman 1969; Mai & Atkins 1975). No one seems to favour the standard tests such as the spalling test described in British Standard (1967).
At the outset a direct shock method was considered essential. A temperature of 400°C was considered the highest realistic temperature that might be expected on the surface of a ceramic stove, and was therefore chosen as the temperature from which to shock samples. To achieve a severe shock samples were to be plunged directly in a bucket of cold water (20-25°C). To minimise variation an extrusion method was used in manufacturing samples, the dimensions chosen being 25 mm diameter by about 85 mm in length, 25 mm being considered representative of stove wall thicknesses.

In exploratory tests a series of 30 samples was subjected to repeated thermal shock: dry samples placed in the oven at 400°C for one hour, quenched in cold water with mild agitation (as in hardening of carbon steels) then dried in an oven at 110°C before returning to the furnace. This process was repeated 15 times without fracture occurring in any of the samples. However, it was apparent that many of the samples had fine cracks after some ten or so cycles. This was evident from the way in which the still warm samples dried after quenching: circumferential lines round the sample drying at a slower rate than the remainder. But once dry the cracks were not visible.

Therefore a test was required which would indicate the damage caused by quenching. One possible approach was a residual strength test, but a bending test on this type of sample was thought to involve too many problems in terms of the equipment required and interpretation of results. Therefore an impact type of test was thought more appropriate since the measurement would be simple and would reflect the severity of surface cracking as well as the toughness of the material.

Ceramics are essentially brittle materials so the energy required to fracture samples is not great. This rules out the conventional type of impact test in which a pendulum falls from a set height, fractures the sample, then carries a fast-and-loose pointer up a scale to indicate energy lost. The fracture energies would be of a similar order to the kinetic energy imparted to the broken bits, increasing further the scatter and uncertainty in the results. The method adopted therefore was to use a very light pendulum and subject the sample to repeated blows of ever increasing energy until the sample fractured, the energy required to break the sample being the final value recorded. The method is open to criticism, especially as to the effect of repeated blows; however, results obtained to date seem significant.

There are two alternative approaches to using this form of impact test for thermal shock testing. Both methods require destructive testing of half of each batch of samples in an unshocked condition. This establishes the base toughness of the material. The samples to be shocked may be subjected to a low level of impact after each shock and the number of shocks to induce fracture under a standard blow recorded. Alternatively, samples may be given the same number of shocks then the impact test with increasing energy used again to establish the toughness—comparison with results obtained from unshocked samples quantifies the effect of shock treatment.

The second of these two alternatives was finally selected since it limited the number of shock cycles, avoided the need to interrupt cycling for impact tests (which would prolong testing) and eliminated the necessity to set a limit for the energy of repeated impacts which, if an inappropriate value was chosen, would seriously affect the sensitivity of tests. Also the value would inevitably need to be different for different materials in order to obtain sensible results, thus complicating comparison, while with the method involving a fixed number of shocks the "residual impact" measurement is of the same nature as the unshocked method making comparison straight-
forward, both between shocked and unshocked samples as well as between shocked samples of different materials.

7. Apparatus

Figure 1 shows the essential elements of the impact apparatus. A cylindrical steel mass (94.9 g) was suspended on a pair of light threads to swing with an arc of radius 380 mm measured to the centre of the mass. Two strings are required to ensure the pendulum swings in the same vertical plane and a cylindrical weight was chosen so that, even with an element of rotation about the axis of the cylinder, impact occurs in the same point on the sample. A cylindrical sample also has advantages in this respect, provided the c.g. of the weight is level with the sample axis on impact, furthermore it was considered desirable to rotate the sample slightly after each impact to vary the plane of bending. The sample is supported in simple bending (as in a Charpy test) but with the supports underneath the sample tilted upwards to maintain contact with the vertical supports. The 'span' was set for 60 mm.

The frame of the apparatus was built from a proprietary pre-drilled angle iron but any convenient system may be used which gives reasonable rigidity. The precise dimensions are not critical and may be varied slightly from those given above without significantly affecting results provided the measurements are quoted in Joules as opposed to height and provided dimensional changes do not result in a significant

Figure 1. Schematic representation of impact testing apparatus. Note inclined supports for sample to ensure contact with vertical plates.
change in impact velocity. However, if both the mass and radius are significantly reduced the angle of the string to the vertical may approach 90° for tougher samples, when the string support system is inoperable. Span, sample diameter and energy increments (in our case 10 mm height increments) must clearly be fixed.

Measurement of the starting height must refer to the height through which the c.g. of the mass is raised from the point of impact. In the apparatus described above the measuring device consisted of a rule taped to a weight in a vertical position. The weight could then be slid across the horizontal bench for measurement at different points round the arc.

Release of the pendulum must not accelerate or retard the natural swing. This requires care but the problem can be overcome by using a small electromagnet (the solenoid from an old telephone relay was used in the prototype) and the energising current switched off to release.

8. Samples

In choosing the range and quantity of samples to be tested the primary consideration was to validate the technique and secondly to make some exploratory investigation of the effects on thermal shock resistance of firing conditions and additives to a clay body.

To minimise manufacturing variables a single batch of each of the different clay mixes were extruded through a die with 25 mm exit diameter (see figure 2). For each firing 25-30 samples were prepared to ensure at least ten unflawed samples for impact testing both unshocked and after shock treatment. Table 1 shows the range of compositions and firing conditions. The firing temperatures of 800, 900 and 1000°C were selected as being representative of what can be achieved in 'bonfire' firings at the lower end, up to fairly simple down draft kilns.

9. Discussion of results

The results obtained are summarised in table 2. In the majority of sets of data it is apparent from the standard deviations that significant inferences may be drawn as regards the effects of composition or firing temperature.

Figure 3 shows the variations of impact strength with firing temperature. From figure 3(a) we may infer that with a red clay/ash mixture, while firing in a
Table 1. Schedule of materials tested

<table>
<thead>
<tr>
<th>Clay body</th>
<th>Additives</th>
<th>Firing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Red clay</td>
<td>Fine siliceous sand 50 pts.</td>
<td>800, 900 and 1000°C oxidising</td>
</tr>
<tr>
<td>100 pts.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Red clay</td>
<td>Fine brick grog 50 pts.</td>
<td>800, 900 and 1000°C oxidising</td>
</tr>
<tr>
<td>100 pts.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Red clay</td>
<td>Wood Ash 50 pts.</td>
<td>800, 900 and 1000°C oxidising</td>
</tr>
<tr>
<td>100 pts.</td>
<td></td>
<td>800, 900 and 1000°C reducing</td>
</tr>
<tr>
<td>Red clay</td>
<td>Wood Ash 25 pts.</td>
<td>800, 900 and 1000°C oxidising</td>
</tr>
<tr>
<td>100 pts.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Red clay</td>
<td>Fine charcoal 25 pts.</td>
<td></td>
</tr>
<tr>
<td>100 pts.</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Notes: 1. Proportions all measured by volume.
2. Reducing atmosphere obtained by packing the test pieces in wood chips inside a second enclosure within the electric kiln.

Table 2. Impact energies (×10⁻³ J) for each clay mixture at different firing temperatures.

<table>
<thead>
<tr>
<th>Additive</th>
<th>800°C</th>
<th>900°C</th>
<th>1000°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sand</td>
<td>96 (9-5)</td>
<td>157 (10-8)</td>
<td>141 (25-7)</td>
</tr>
<tr>
<td></td>
<td>94 (10-8)</td>
<td>134 (10-3)</td>
<td>132 (13-2)</td>
</tr>
<tr>
<td>Grog</td>
<td>98 (8-1)</td>
<td>195 (52-1)</td>
<td>253 (30-1)</td>
</tr>
<tr>
<td></td>
<td>48 (7-5)</td>
<td>76 (17-1)</td>
<td>99 (19-0)</td>
</tr>
<tr>
<td>Ash (oxidising)</td>
<td>113 (20-1)</td>
<td>251 (39-3)</td>
<td>251 (17-4)</td>
</tr>
<tr>
<td>Ash (reducing)</td>
<td>25 (13-8)</td>
<td>44 (14-4)</td>
<td>40 (12-7)</td>
</tr>
<tr>
<td>Ash + charcoal</td>
<td>97 (19-2)</td>
<td>71 (20-0)</td>
<td>177 (33-0)</td>
</tr>
<tr>
<td></td>
<td>23 (11-2)</td>
<td>44 (7-0)</td>
<td>49 (10-9)</td>
</tr>
</tbody>
</table>

Each block gives mean impact energies of unshocked samples above, shocked below with standard deviations in brackets.

Reducing atmosphere gives somewhat lower impact strengths than when fired in an oxidising atmosphere, both materials perform equally badly after shock treatment. Figure 3(b) shows the effects of fine brick grog additions to be essentially similar to those of ash but with superior resistance to thermal shock.

Figure 3(c) is of special interest in that it shows that, although sand is inferior as regards its effects on impact in the unshocked state, there is virtually no degradation in impact strength as a result of the 20 shocks from 400°C to cold water, i.e. the
Figure 3. Results of thermal shock testing showing impact energies in the shocked and unshocked states as a function of firing temperature. Each graph shows results for a different mix (see table 1).
(a) Red clay + ash: (i) unshocked, oxidising; (ii) unshocked, reducing; (iii) shocked, oxidising; (iv) shocked, reducing.
(b) Red clay + grog: (i) unshocked; (ii) shocked.
(c) Red clay + sand: (i) unshocked; (ii) shocked.
(d) Red clay + ash and charcoal: (i) unshocked; (ii) shocked.

The shock temperature difference is below the critical value required to initiate propagation from existing flaws (Hasselman 1969).

Figure 3(d) shows results obtained from samples of a mixture of red clay with wood ash and fine charcoal. These samples had been prepared following some earlier measurements obtained from a very limited number of samples of a grey London clay with added 50% by volume of fine charcoal. These samples had shown interest in having exceptionally high porosity combined with high initial impact strength but very low shock resistance. The results from these latter samples are included in figure 4 in which impact energy for all the samples tested is plotted against apparent porosity (measured by vacuum impregnation method, BS 1902 Part 1A, 1966). There is a general trend towards lower thermal shock resistance with increased porosity and while a trend is hardly discernible for unshocked impact resistance, there
does seem to be more potential for high toughness at higher porosity. Although these results cover a different range of porosities there is some parallel with the findings of Smith et al (1976) who observed that in alumina with induced porosity, strength after thermal shock decreased with increasing initial strength.

It is considered that with the fairly high porosities seen here the ingress of water to the sample surface and subsequent generation of steam during quenching, may have a significant effect on the stresses developed.

10. Conclusions and future work

(i) The method proposed for assessing thermal shock resistance can be used to provide meaningful data for the comparison of different materials or different treatments.

(ii) The method is especially suited to studies of ceramic materials for wood burning stoves since it does not require expensive or elaborate apparatus other than an oven or furnace to maintain the upper temperature for shock treatment. This should mean that workers in different institutions can perform their own tests to evaluate local materials and these results can also be compared with those obtained elsewhere. It must be stressed however that great care must be taken in sample preparation so as not to introduce unwanted and misleading variations.

(iii) As yet no direct experience has been obtained to establish the relevance of test results to practical stove experience.

(iv) Preliminary observations on the effects of additives to a clay body have established a basis of confidence from which work can proceed. This area of study is now being expanded. For example work has been started to investigate the role of porosity by applying different surface treatments such as burnishing.

(v) The consideration of alternative stove materials continues. In some communities ceramics have been demonstrated to provide a durable stove material but elsewhere experience has been less satisfactory. This programme should help in the identification of suitable ceramics but the optimum design solution may well lie elsewhere. A particularly attractive proposition is the hybrid design combining, say, a refractory ceramic with a more robust outer skin, the alternatives are considerable.
The author wishes to acknowledge financial support from oda, and also to thank Mr S Joseph for fruitful discussions, Mrs Jenny Trussell and Mr Hamish McGregor for help with preparation and testing of samples.

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Fuelwood production in developing countries: Toward an appropriate forest technology

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Abstract. This paper addresses the need for appropriate forest technology as a solution to the rural fuelwood shortage in developing countries. Many such solutions are proposed with little reference to existing local needs and resources. Complex wood harvesting technologies require a long time to diffuse through a population. Therefore, increases in productivity can be better achieved through focusing on the improved maintenance and deployment of proper hand tools. Evidence from Kenya is used to demonstrate the improvements that can be made in hand-tool production and maintenance. Most fuelwood users currently manage trees to produce firewood in the form of fuelwood sticks, not large logs. Appropriate fuelwood production systems should be developed, based on the principles of coppicing and pollarding, short rotation periods, and producing small diameter fuelwood sticks. A hypothetical fuelstick project is discussed to show that not only are such systems possible, but they can be economically superior to conventional solutions.

Keywords. Appropriate technology; axes; coppicing; forest technology; fuelwood production; fuelwood sticks; pangas; rural energy; short rotation period; tool maintenance.

1. Introduction

Tremendous attention, in recent years, has focused on the concept of 'appropriate technology'. Although a great deal of conflict and confusion still prevail in any discussion of the term, some consensus can now be claimed for its definition and implications. Appropriate technology is a technology or production system that is accessible to the bulk of the world's poor, built around local resources, suited to local socio-cultural conditions, and not harmful to the environment (Prasad 1982). The design of a successful appropriate technology will depend not only on a comprehensive understanding of the technical processes involved, but also on a thorough analysis of the socio-economic circumstances in which the technology is to be utilized.

Although the appropriate technology question has made an impact on nearly every discipline associated with rural development, there are still fields which have not begun examining the appropriateness of their discipline's solutions to the needs of the population at hand. For the most part, forestry is one of these areas as yet untouched by the appropriate technology argument. Forest plantations operate on similar rotation periods, with similar planting distances, and are harvested using similar tools and equipment nearly everywhere in the world. Despite the fact that nearly 50% of all roundwood produced in the world is used for fuelwood in the developing countries (FAO, 1981), foresters have made very few attempts to fit their
production techniques to the needs of those actually using the wood produced. There has been virtually no thought given to the development of an appropriate forest technology.

This paper represents an initial step toward the development of an appropriate forest technology suited to the needs of the fuelwood shortage in developing countries. It will address two areas of concern. The first issue to be discussed is the appropriateness of tools used for harvesting wood resources in developing countries and consider the most effective ways to increase their productivity. The next section will focus on the issue of the suitability of the production systems proposed by foresters to the needs of those actually using fuelwood in developing countries. The discussion of both issues will begin with a presentation of general principles and will finish with the discussion of an example drawn from the authors' experiences in Kenya and other developing countries.

2. Tools for harvesting wood

The first section of this discussion will summarize the tool improvements that have led to large increases in worker productivity over the last several centuries in mid-latitude forestry. Then factors containing forest-worker productivity in developing countries will be addressed. These factors, particularly the problem of appropriate tools, will then be highlighted with examples drawn from a case study in Kenya.

2.1 Development of wood harvesting technologies

If for the moment it is assumed that a cubic meter of wood is uniform and logging conditions can be held constant across logging systems, the iso-product curve in figure 1 can be used to represent the different combinations of labour and capital (or machine) inputs that can be used to harvest one cubic meter of roundwood.

As labour has become relatively more expensive, tools and equipment have been developed which have enabled the increasing substitution of capital (or machinery) for labour in forestry activities in industrialized countries. This has resulted in a movement toward the northwest on the iso-product curve. In most labour-surplus developing countries, forest harvesting activities utilize a relatively greater component of labour per unit of output than is common in industrialized countries, a position corresponding to the lower right-hand portion of the iso-product curve. What is the nature of these technological developments and substitutions that have resulted in an increased productivity per unit of labour?

![Figure 1. Iso-product curve for labour and machine inputs (after Sundberg 1978)](image)
Silversides (1978) describes the dynamics of tool development for forestry in eastern Canada. His example (represented in figure 2) shows that wood harvesting processes are constantly changing in accordance with changing wood-use rates and technological capabilities.

In 1850 crosscut saws were introduced into wood harvesting operations in eastern Canada. Until this time trees were felled, limbed and cut into log lengths by axe. The crosscut saw gradually replaced the axe and was itself then replaced by the one-man bow-saw. This perhaps was influenced by the rise in production of pulpwood which utilized smaller trees. Immediately after World War II the chain saw was introduced on a large scale and superceded the bow-saw. In the 1960's tree-felling machines were introduced and are gradually replacing the powered hand-saw. Figure 2 shows the deployment of these tools over the years. Note that the period required for the adoption of each successive technology grows shorter. Nearly one hundred years were required for crosscut saws to replace axes, while machine-harvesters have nearly replaced chain saws in less than thirty years. This can be explained by two factors. First, as workers become more skilled and educated, they find it easier to adapt to new technologies. Second, since each new technology has brought a decrease in the amount of labour required per unit of output, fewer workers have to learn how to use the new technologies. The diffusion process has been greatly simplified.

From this discussion, it can clearly be seen that the trend in forest harvesting technologies is from hand tools, to power saws, to harvesting machines, a trend corresponding to a northwesterly movement on the iso-product curve in figure 1. Although this trend can be seen to exist in forestry operations throughout the world, the period of adoption may vary greatly depending on the local situation. For example, Kanta (1978) notes that the era of development for forestry tools in Finland lasted twenty years, from 1940 to 1960. At that point, machine power based on cheap

![Figure 2. Acceleration in technology of cutting or felling of trees on company logging operations in eastern Canada (after Silversides 1978)](image-url)
fuel began to replace muscular power in forest work throughout Finland. Within that period, the number of axe models in use was reduced from 54 to 2. Other tools experienced similar homogenization as certain forms were found to be more efficient than others. Also important to the improved tools were the improved maintenance methods. The development of maintenance methods enabled the achievement of greater output with less muscular power and increased safety in forest work.

A number of different stages can be identified in the example of tool development and deployment in Finland as presented by Kantola (1978). These include the teaching of current knowledge; the inventory of existing tool models; the actual development of new tools; the development of maintenance techniques; the development of working techniques; and the teaching of the newly developed techniques. All of these stages add to the complexity of the adoption of a new harvesting technology. While the actual tool development may take a short time, the education and training of workers to use those tools requires considerable time. While it may be possible to shorten the total adoption time by effecting a technology transfer, it is extremely difficult to shorten the education, training, and dissemination periods as these are dependent upon the number of workers to be educated as well as their pre-existing knowledge base.

2.2 Forest technology in developing countries

Before making suggestions regarding appropriate forestry tools for improving labour productivity in developing countries, it is necessary to understand the conditions which constrain this productivity at a low level. Although many reasons come to mind, three will be mentioned and discussed here: worker health, the distribution of proper tools, and the maintenance of those tools.

The first of these factors, worker health, dictates that the productivity of forest workers in tropical developing countries is low because of the poor health of the workers. Strehlke (1979) found that in a west African logging enterprise, despite the fact that free health services were provided, more work days were lost through disease than through accidents. Heat stress can decrease the human capacity to perform heavy work by nearly two thirds (Sundberg 1978). Nutritional inadequacies can severely limit the ability of workers to perform strenuous manual labour. A detailed analysis of this problem lies outside the scope of this paper. To raise the productivity of forest workers in this regard necessitates the improvement of nutritional standards and health care facilities in tropical developing countries, a task which entails no small effort in itself. For a more detailed examination of the question of worker health and safety in tropical countries, see Strehlke (1979), Staudt (1974) and Hansson et al (1966).

The second factor constraining worker productivity in developing countries is a lack or shortage of well-designed hand tools. Cortes (1978) stressed the need for the use of labour-intensive methods instead of capital-intensive methods to increase the requirement of manpower to create additional jobs in forestry. In the Philippines, Cortes compared several forestry work methods on their technical feasibility, economic competitiveness and social desirability. Among the comparisons made were the following: large chain saw vs small chain saw vs two-man crosscut saws; crawler tractor vs four-wheel skidder vs farm tractor vs carabao for log-skidding; and manual vs mechanical log-loading. The right hand tools to be used for each
activity were supplied. Preliminary studies showed that the Philippine forestry sector is characterized by the lack of proper hand tools to be used in the performance of the various wood harvesting and forestry activities. In general, Cortes' study showed that labour-intensive methods in forestry are technically and economically feasible, while the cost and productivity estimates derived compare favourably with those from capital-intensive methods.

Regarding Cortes' study a few remarks have to be made. Economic and technical feasibility are central in this study. His conclusion about the lack of proper hand tools in use is very interesting, but can this imperfect situation be solved by simply providing the right tools for the job to be done? To produce and distribute the needed hand tools and maintenance techniques is a tremendous task and will take years. The question is whether labour intensification as discussed by Cortes is very realistic.

A joint study by the Philippine Bureau of Forest Development, the ILO, and the Government of Finland (1977) states that after having considered the alternatives, 'improved' labour-intensive techniques in forestry operations in the Philippines have great opportunities. They are technically feasible, economically attractive, and represent the least-cost alternative. In addition, their use leads to improved labour productivity with the labour-displacement caused by machine methods. In other words, it is best to continue through the progression of stages found in figure 2.

Experience from other tropical countries is also relevant here. Chandra (1978) describes the Indian experiences in the development and use of simple tools in forestry. Over a period of nearly 25 years, improved hand tools have become more common. Formerly the universal tool used in forestry throughout most of India was the axe. The multi-purpose use of the axe is extremely wasteful. Chandra states that the reason for such large scale use of the axe is that forestry works were mostly carried out through the agency of private contracts, and wastage of wood in the forests did not affect the contractors financially. Awareness for reducing wastage of wood in logging tools was introduced through the Logging Training Centre at Batote in 1958 and later through the Logging Training Centres Project in 1965. Since then, numerous people have been trained in the use and maintenance of improved logging tools. Such tools have become popular. As a result of the increased popularity of the tools, there is a demand for such tools indigenously. The improved hand tools which have been developed and are being manufactured in India are axes with oval eyes, handsaws of peg-toothed and raker-cutter type, bow-saws with fixed and adjustable frames, lifting hooks, stemtightener, and other such forestry equipment. From this experience in India, Cortes' (1978) proposal for the use of proper hand tools appears to make a great deal of sense.

The third constraint limiting the productivity of forestry workers in developing countries is the improper maintenance of the tools that do exist. Improperly sharpened axes and saws not only waste considerable human energy in the cutting process, but they also increase the probability of accidents, which cause injuries to workers and further constrain productivity. The fact that tools are frequently used by workers unfamiliar with their proper maintenance is a reflection of both the lack of training given to workers and the short-cuts that have been taken in developing and disseminating the new technology.

The lack of maintenance given to forestry tools can be seen in sub-optimal productivity levels at any given technological level. In figure 2, this could be represented by a dotted line shadowing the upsweeping portion of the line denoting production
by each new technology. These lines, the actual percentage of production achieved, become dominant and peak after each of the ancillary solid lines, denote that the actual production of the tools disseminated lags behind the dissemination of the tools themselves, attributable to the improper use and maintenance of these tools. This lag can be shortened through education and training, pricing policies, encouraging the efficient use of wood resources, and programmes subsidizing the provision of proper maintenance tools.

2.3 Case study: Pangas and axes in Kenya

In the preceding section, it was argued that the limited deployment of proper hand tools and the poor maintenance given to tools already being utilised are two of the factors limiting forest-worker productivity in developing countries. It is by posing solutions to these problems that foresters can make their science more appropriate to the needs of those in developing countries. This section will provide a specific example of how this can be done based on research experience with pangas (machetes) and axes in Kenya.

2.3a Pangas The panga or machete is by far the most important tool used for felling trees and collecting fuelwood by the rural population in Kenya. Women and children who are responsible for gathering wood in nearly 90% of the Kenyan rural households (Hosier 1982) rely on the panga as their primary tool. It enables them to cut fuelwood ranging from 2–5 cm in diameter, which they then tie in bundles and carry home for use as fuelwood. This is not to say that pangas are not used for heavier felling work. In recent years, it has become common for women in the wood-short high potential areas to purchase a standing tree from someone else, and to fell it with only a panga. These trees can range up to 35 or 40 cm in diameter. In fact, a problem arises because pangas, being the primary tool in rural Kenya, are used not only for wood harvesting and preparation, but also for cultivation, fencing, digging, and even as a hammer. This means that it is often difficult, if not impossible, to maintain them properly.

Except for a few surviving colonial relics, the pangas used in Kenya are manufactured locally by Kenyan Engineering Industries (KEI). Standards have been established and are monitored by the Kenyan Bureau of Standards (1979). These standards include specifications regarding the steel content of the blade, the moisture content of the wood used in the handle, the rivets used to connect the blade to the handle, and the protection of the blade by a rust-resistant grease or varnish. Pangas with curved blades are produced in 30, 40 and 45 cm sizes, and those with straight blades are produced in 40 and 45 cm sizes. The blade is sharpened at the factory with a cutting angle of 35°.

During 1981, roughly 183,000 pangas were produced in Kenya. Roughly 55% of these were curved, while the remainder were straight. If it is assumed that there are 2·25 million rural households in Kenya (population 1979=15 million) and each household has one panga, then, using the 1981 production estimates, the average panga lasts roughly 12 years. This appears to be a long period of time, particularly given the low quality of the production and maintenance of these tools.

Production of pangas frequently encompasses shortcuts which result in a faulty product. Problems are frequently encountered with the handles which readily split...
and fall off. The surface of the handle is not smooth and little effort is taken by the manufacturer to shape the handles to fit a human hand. Those using the pangas often develop blisters and cuts due to the poor handle construction which can result in rivets protruding from the handle. Not only are there problems with the handles, but there are problems with the blade. The anti-rust compound used is rarely sufficient and most pangas develop a coat of rust while still on the store shelf. The relatively long lifetime estimated for pangas is attributable more to the resourcefulness and frugality of the people than to the quality of the tool.

However, there are some serious shortcomings with the techniques commonly used in Kenya to sharpen and maintain pangas. For sharpening pangas, people usually look in their immediate vicinity for a suitable stone with a flat surface and a fine structure. Files are rarely used for sharpening because the cost is prohibitive. A file costs roughly twice as much as a panga does. The result is that most pangas are either dull or badly sharpened.

The problems of sharpening a panga can be explained with the help of figure 3. The original cutting edge of the panga is designed at 35° to give optimal results (Profile I). The penetration is good and the cutting ability is sufficient. If the cutting-edge is enlarged by sharpening (Profile II), both the penetration and cutting ability are decreased until they approximate those of a maul or splitting axe. In Profile III, the cutting edge is too small, which means both penetration and cutting ability are excellent, but the blade life will be tremendously shortened.

A file is the best tool for removing steel from the blade. A whetstone will remove much less steel, with the end result that the cutting edge is eventually enlarged. Another problem with pangas sharpened on a large flat stone is that frequently the cutting edge is composed of two different angles (see figure 4). The reason for this is that the sharpener's posture can change as he or she shifts the blade from one hand to the other. As a result, a small angle occurs on one side and a relatively large one occurs on the other. The problem with this situation is that not only is the resulting blade unable to penetrate the wood properly, but the probability of misfire and injury is also increased.

A number of solutions exist to the problem of poorly managed and maintained pangas in Kenya. The first of these could be that people would stop using pangas for jobs they are not designed for. This is a rather unrealistic solution, since it
implies that people will have to buy other tools for those jobs. It is more realistic to try to improve the sharpening techniques commonly used. In this case, it is essential that people are able to obtain good files at affordable prices. Files with built-in sjablon to check the angle of the cutting edge would be preferable. But providing people with files is relatively simple. The difficult task is that of teaching them how to properly use them. This is a time-consuming task which requires extension work and the preparation of a clearly comprehensible manual. Finally, closer attention to detail on the part of manufacturers and perhaps a raising of industrial standards will result in a higher quality of panga being sold on the market.

2.3b Axes The distribution and use of axes in Kenya differs greatly from that of pangas. While pangas are a subsistence good used by the entire rural population for nearly every imaginable chore, axes are owned and used by a much smaller portion of the rural population that is concerned with the felling of trees in some form of business enterprise. Forest workers and charcoal burners are among those most likely to own and use an axe. This is attributable both to the price of the axes on the market, which are triple the price of pangas, and also to the added productivity gained from an axe. Most women and children gathering fuelwood do not need axes as they are interested in small sticks. This latter is a point which shall be returned to later.

Because a variety of axes are imported into Kenya, there exist no quality standards or estimates of production or sales. However, a brief description of the axes on the market can be given to demonstrate how far they diverge from ideal designs. The first thing that is noticeable when examining local axes is the head. As demonstrated in figure 5, there are two features which distinguish the commonly-used axe from an optimally designed axe. The first is the eye. All axes sold in Kenya have a round as opposed to an oval eye. The round eye allows the head to swing around the handle which can result in personal injury. The second feature is the round backside. Since axes are inevitably used as hammers at some stage, the round backside which if not reinforced is liable to break. Such breakage renders the axe unsafe, if not entirely useless. The second noticeable factor is the handle. The handles used for axes in Kenya are round, frequently made from softwood, and almost never have a broad end to ensure a safe grip. Axe-users in Kenya prefer to make their own handles rather than purchase those supplied commercially.

An axe is a well-designed tool and its maintenance is fairly complex and technical. The shape of the blade is very important. The shape from a new, unused axe is optimal. To keep this optimal shape, one must take care that with sharpening this shape does not change. Figure 6 shows some examples of wrong shapes due to wrong sharpening.

Number 1 shows an axe that has been sharpened only in the middle. The result is too large a contact-area. The penetration, therefore, is very low.
Number 2 shows the opposite situation. Here the contact-area is very small, which means the cutting ability and penetration are very good, but an axe like this is extremely dangerous as the probability of a misfire is great. Number 3 shows the intermediate-size contact area found on a well-maintained axe.

In addition to the contact area, the cutting edge and curve of an axe must be carefully maintained to ensure its safe performance. The problem of the cutting edge is similar to that of the cutting edge on pangas. In addition, if the curved face of an axe is not maintained, it either will penetrate poorly or will stick in the wood. In order to maintain an axe properly, several sjablons are necessary to ensure uniformity in the shape and profile of the blade.

The axes used in Kenya are, by and large, poorly built and inadequately maintained. Again, this results in unsafe work conditions and low productivity. The curves are frequently eliminated from blades as they are ground against flat stones. Since files are not used for sharpening, the resulting cutting edges are either uneven or too wide to cut effectively. These factors combine to greatly reduce the utility of the axes currently used in Kenya.

As is the case with pangas, the dissemination of knowledge about the proper maintenance and design of axes will take considerable time. Since manufacturing standards do not yet exist, the establishment of standards regarding eye shape, flat backs, and handle design would result in an improved quality of axe. However, the difficult task lies in the education of those using axes regarding proper maintenance techniques. The dissemination of files and sjablons is a necessary step, but careful instruction is needed to employ them properly. The proper maintenance of an axe requires more time and skill than the maintenance of a panga. The one respect in which axe maintenance programmes will be simplified is that fewer people need to be trained, since fewer people use them.

3. Forest production systems

The preceding discussion has attempted to show the difficulties of introducing and disseminating forest technologies on a large scale. As many as 20 years are required to diffuse a relatively simple technology like an axe through a large population. The introduction of improved technologies to a broad popular base requires not only technical knowledge, but knowledge of the economic and social constraints binding the population at hand. Appropriate forest harvesting tools is one area in which foresters should study the present situation before deciding which technology-package is appropriate. This section will discuss the issue of appropriate forest technology in another context: that of the forest or wood production systems for alleviating fuel-wood shortages.
3.1 Forest solutions to the fuelwood problem

Most forest technology has been developed to produce industrial roundwood, the feedstock for the wood-based industry in the Western World. In the USA, Canada and the Scandinavian countries, managed forests are found in large, isolated areas. Hence, the forest technology has been concentrated on the development of production systems for these circumstances. Highly productive machines and labour-extensive systems have evolved. Individual trees are spaced far apart and are given twenty to thirty years to mature.

Feedstock for the wood industry in western, industrialized countries is increasingly being imported from developing countries. To obtain the roundwood from tropical forests, a great deal of investment has taken place to ensure that the output from these forests is acceptable. Most of these industries use a forest technology developed for the forests in Northern Europe, Canada and the USA, involving sophisticated machines and tools for which trained personnel are required. These systems are fine for the production of timber to be used as industrial feedstock, but are they necessarily appropriate for the production of woodfuel to supply the energy needs of the population? Fuelwood and charcoal consumption accounted for over 80% of all roundwood produced in developing countries in 1979 (FAO, 1981). The capital-intensive systems of forest plantation management developed in Western countries may be appropriate for the production of industrial feedstock, but they do not appear to be the production systems that are best suited to supplying the fuelwood needs of a largely rural population. How can appropriate production systems be designed? Such systems can only be designed on the basis of a careful examination of the systems currently in use to produce fuelwood.

3.2 Current fuelwood production systems

The first point to be raised regarding the current status of fuelwood production systems in many developing countries is the location of such systems. While some of the wood used as fuel is gathered from existing forests, most of it is not. For example, the majority of the 90 million people living on Java use wood as their primary fuel. If the average per capita consumption is between 1 and 2 cubic meters per annum (Arnold & Jongma 1978), then roughly 90 million cubic meters would have to be produced on Java annually. If all this wood were to be drawn from forest, it would mean that nearly 3 million hectares of fuelwood plantation should be under careful management in Java alone. Since the total forest area in Java and Madura is only 2.9 million hectares, one million of which is teak forest managed for timber production, the population must have other systems of obtaining their fuelwood.

In Kenya, a recent study of the fuelwood cycle has looked into the question about the source of wood supplies (Beijer Institute 1982). From the data gathered in Kenya, it appears that only 25% of fuelwood needs are supplied by the trees in forests. Again, a fuelwood supply system that falls outside the classification of closed natural forests is being used by the local population to supply their fuelwood needs. In both cases, fuelwood is being harvested not from forest trees, but 'trees outside the forest'. In Kenya, 45% of the fuelwood used was drawn from trees on agricultural land. Another 25% was derived from trees in the rangeland areas. In Java, most farmers maintain a home garden, a small area around the house containing trees that are
managed to produce firewood. Trees outside the forest provide fuelwood to the bulk of the rural population in developing countries.

Foresters need to place the category of ‘trees outside the forest’ alongside natural forests and forest plantations as an important wood production system to be studied. Little or no attention has been given to these production systems to date, with the end result that there is almost a complete absence of knowledge about how and where fuelwood and charcoal are produced in developing countries. Since fuelwood is the most important fuel throughout most of the tropics, questions about local fuelwood growing systems and management strategies will become increasingly pertinent. Detailed analyses of the existing fuelwood production systems are important to ensure and improve future fuelwood supplies.

When observing local fuelwood production systems, several factors become apparent. The first has to do with the diameter of the wood being gathered. Women and children carrying wood have bundles composed primarily of small sticks of less than 7 cm diameter. These sticks are either collected in the surroundings, pollarded from trees, or purchased in the neighbourhood. Wood of a larger dimension is frequently sold in the markets in town or used to produce charcoal. Statistical estimates on the use of small diameter fuelwood sticks are simply unavailable as no one has, to date, examined such questions. However, a mensuration exercise investigating the frequency and volume of trees on agricultural land resulted in a series of graphs resembling figure 7. The heavy line represents the normal frequency distribution of trees encountered in forest plantations or woodlots. The lighter line represents the observed frequency of trees on agricultural land. Note that there are fewer trees of a small diameter than would normally be expected. At the same time, there are more trees of an intermediate and large diameter than would normally be the case. The simplest explanation for this observation is that people are cutting the small diameter trees, but not the intermediate and large diameter ones. Two possible reasons for this selective cutting come to mind. The first of these is that as pangas are used for fuelwood harvesting throughout most of Kenya, these small trees are the only ones which can be conveniently cut. In this respect, the harvesting technology determines the size of trees that can be harvested. The second of these reasons is that the women using the fuelwood actually prefer wood sticks that are of a small diameter. It is easier to manipulate in the fireplace; it ignites more quickly; and it is more convenient to gather than larger diameter firewood. The evidence from Kenya as well as experiences from other countries confirm the observation that most of the fuelwood used in the rural areas of developing countries is of a small diameter a ‘fuelwood stick’ variety.
The second observation about current systems of fuelwood production relates to
the species that are used. It is only natural that foresters shall have a predisposition
to trees with a large straight trunk and few branches since their objective is to produce
timber as industrial feedstock. Hence, tropical foresters use species such as *pinus spp.*
and *eucalypt spp.* on a relatively long rotation basis to supply their timber. Farmers
in developing countries are interested not in growing industrial feedstock, but in
growing firewood. As a result, the species they select are different from those of the
forester. Their predilection is toward fast-growing trees and shrubs that can be
coppiced or pollarded on a relatively short rotation basis to yield fuelwood sticks.
In Java, for example, *Caliandra calothyrsus* is grown for fuelwood. The plants are
coppiced annually, and the wood is sold to the market. In 1979, one of these sites
yielded nearly 50 cubic meters per hectare (van Gelder, personal observation). Many
of these species have been overlooked by foresters, and should be more closely examined
for their merits as firewood crops. The US National Academy of Sciences (NAS 1980)
has compiled a book on species that might be useful for firewood production,
but which have been largely ignored.

The third general observation about present fuelwood production systems is that
farmers in developing countries manage trees in much the same way as they would
manage other agricultural crops. While foresters are inclined to plant trees 2
meters or more apart and to wait for over ten years for them to mature, farmers
plant close together and manage the trees and shrubs on a relatively short rotation.
This is possible only because the objective is to produce fuelwood sticks. As such,
there is little problem of competition between plants as they are harvested before
getting too large. In Kenya, farmers frequently grow *Acacia mearnsii* (black
wattle) as a tree crop by direct seeding. The plants are often spaced less than one
half meter apart and coppiced at the end of each year. The bark is then sold to
produce tannin, and the wood is used either as fuelwood by the family or as charcoal
by the tannin factory.

A great deal of research needs to be done into the present systems used for fuelwood
production by farmers in developing countries. Foresters have abandoned research
into optimal pollarding schemes in Western industrialized countries, but this topic
has now become particularly relevant to the fuelwood situation in tropical, developing
countries. In addition, there is very little known about the yields that can be expect¬
ed from trees grown outside the forest. These are just two of the areas into which
more research needs to be done. It is only through carefully studying these systems
that forestry solutions appropriate to the needs of those facing a fuelwood shortage
can be identified.

3.3 Appropriate fuelwood production systems: A numerical example

In the preceding section, it was argued that the design of appropriate fuelwood
production systems necessitates a thorough understanding of the presently used fuel
wood production systems as well as the priorities and resources of the final end-user.
It was also maintained that although a great deal of research needs to be done into
these production systems, several safe observations can be made on the basis of
experience. Rural inhabitants in developing countries are more interested in the
production of fuelwood sticks than in the production of trees with large trunks. They
prefer tree-shrub species that respond well to pollarding or coppicing. And they tend
to manage trees on a short rotation, small planting distance; this is similar to how they manage agricultural crops. These are the characteristics that should be incorporated into any appropriate system for fuelwood production in developing countries.

In this section, such a system will be proposed for use as a fuelwood plantation or woodlot in Kenya. The short rotation fuelstick scheme will be compared to a ten-year rotation eucalyptus woodlot scheme, as the latter represents a conventional forestry solution to the fuelwood problem. Although such comparisons can be made on a technical basis, economics should have the final say in such comparisons. For this reason, the following discussion will necessarily focus on the economic appraisal of the two systems.

3.3a Economic consideration The fuelstick scheme that is being proposed for consideration here is built around the principles derived in the preceding discussion. The proposed planting distances are kept to a minimum and the resulting tree-shrubs are to be coppiced annually. In economic terms, this means that the production function being employed is different from those which are normally used by foresters. This contrast can be seen in the two curves contained in figure 8. The curve peaking at B represents the production function or growth curve of a conventional woodlot scheme. The curve to its left, peaking at A, is the production function representing the same species planted according to fuelstick specifications. Due to the close planting distances, the curve rises, peaks and falls off much more quickly than does its conventional counterpart. It is designed to yield less gross timber than the conventional scheme and to do it in a short period of time. Since two plantings of the fuelstick scheme can mature in the time necessary for the maturation of one planting of the conventional scheme, in simple production terms, the projects are roughly equivalent. In economic terms, however, the projects are vastly different.

Samuelson (1976) provides an excellent review of the literature on the economically optimal forest rotation period. He notes that foresters frequently advocate allowing forest stands to mature to their points of maximum production, points A or B in figure 8. He argues that while such a rotation period will maximize the amount of timber that is physically produced, it is not the economically optimal period as it fails to account for land rent, labour costs, and interest rates. The optimal sustained yield rotation period will be that period of \( n \) years such that the discounted value of the timber produced exactly equals the discounted value of wage and rent payments. This means that the forests represented in figure 8 should be harvested long before they peak at points A and B. This means that for the economic evaluation which

![Figure 8. Production functions for two alternative projects.](image)
follows, land rent, wage payments, material purchases, and interest rates must all be included.

3.3b Comparative analysis This section examines two hypothetical, but feasible, fuelwood production schemes to see which is more appropriate as a solution to the fuelwood problem. The projects are set in Kenya. The first scheme is a fuelstick scheme using small planting distances and a high yielding, quick rotation fuelwood crop, *Calliandra calothyrsus*. It is a tree-crop particularly suited for small-scale production but one that has not been used in Kenya. The second is a more conventional woodlot, employing eucalyptus under conventional planting distances and a ten-year rotation. Such a scheme can be seen on innumerable large-scale forest plantations. Although both projects are hypothetical, the details of each are based on information from Kenya and elsewhere.

The first scheme is a fuelstick production scheme using *Calliandra spp.*. The trees are to be planted by direct sowing using a 1 m planting distance (10,000 plants/ha). The NAS (1980, 36) estimates that after one year’s growth, this species can yield 5–20 m$^3$ per hectare by coppicing. From the second year to roughly the twentieth year, yields of 35 to 65 m$^3$ are possible. The yield estimates used in this analysis are taken from the NAS information, but are deliberately conservative in four ways. First, the yield figures apply only to the second and subsequent years following each planting. No yield is assumed at the end of the first year. Second, the yield estimate used is 30 m$^3$ per hectare, a value that is lower than the range given by the NAS. Third, each stand is assumed to need replanting at the end of five years. The NAS figures maintain that coppicing on the same stand can continue for up to twenty years. Finally, uprooting, an expensive process, is used to clear the ground for the next planting. No yield is estimated from the uprooted plants. The estimates were deliberately held at conservative levels in a crude attempt to compensate for uncertainties, particularly those surrounding the introduction of this new exotic to Kenya.

Table 1 summarizes the technical specifications of the hypothetical fuelstick project* and table 2 presents those of the conventional woodlot**. The land value used in both cases corresponds to an approximation of the opportunity cost of not producing maize on the 1 ha plot***. The eucalyptus woodlot is to be started by seedling transplants and will be harvested at the end of ten years. Two thinnings take place,

* The figures for labour were obtained through use of the following assumptions and observations. Seeding was assumed to take place at a rate of 2 seeds/min. Weeding was also assumed to take place at a speed of 2 plants/min. Uprooting was estimated to require 5 min/tree. Cutting of fuelsticks is assumed to take place with a machete, and is set at the rate of 1 stere meter = 0.44 man days based on observation in Indonesia (van Gelder’s personal observation). The price of labour is set at 20 Ksh/day, a figure approximating the minimum wage (10.5 Ksh = 1 US $). The price of wood is based on personal observations made in the rural areas of Machakos District, Kenya.

** The eucalyptus yield figures are based on information about *Eucalyptus saligna* in Kenya (FAO, 1979, p. 93). For labour inputs, it was assumed that one man could plant 100 seedlings/day. Weeding was assumed to require the same input (3.5 days) as under the fuelstick scheme. Harvesting is assumed to be 25% more efficient than under the fuelstick scheme, as axes are used instead of machetes.

*** The opportunity cost of not using the land for agriculture was computed by taking a figure of 3 tons per hectare as an average output level for the highlands of Kenya (under double cropping). This was then broken down into 33 bags of maize selling at 120 Ksh/bag (an average price) for a total of approximately 4000 Ksh. The net was obtained by multiplying an estimate for the value of labour required to cultivate 1 ha of maize (120 days) by the minimum wage (20 Ksh) and subtracting from the total to get 1600 Ksh. This was taken as an assumed maximum rent for 1 ha of agricultural land.
Table 1. Estimated undiscounted costs and benefits for 1 ha fuelstick scheme (*Calliandra Calothyrsus*)

<table>
<thead>
<tr>
<th>Measure</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Year</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1) Labour (Man days)</td>
<td>s 14</td>
<td>c 11</td>
<td>c 11</td>
<td>c 11</td>
<td>s 14</td>
<td>c 11</td>
<td>c 11</td>
<td>c 11</td>
<td>c 11</td>
<td>u 110</td>
<td>364</td>
</tr>
<tr>
<td>2) Labour costs (at 20 Ksh/day)</td>
<td>560</td>
<td>220</td>
<td>220</td>
<td>220</td>
<td>2420</td>
<td>560</td>
<td>220</td>
<td>220</td>
<td>220</td>
<td>2420</td>
<td>7280</td>
</tr>
<tr>
<td>3) Seed costs (0.05 Ksh at 0.50)</td>
<td>500</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>500</td>
</tr>
<tr>
<td>4) Land rent (Ksh)</td>
<td>1600</td>
<td>1600</td>
<td>1600</td>
<td>1600</td>
<td>1600</td>
<td>1600</td>
<td>1600</td>
<td>1600</td>
<td>1600</td>
<td>1600</td>
<td>17,900</td>
</tr>
<tr>
<td>5) Total costs (Ksh)</td>
<td>2660</td>
<td>1820</td>
<td>1820</td>
<td>1820</td>
<td>4020</td>
<td>2160</td>
<td>1820</td>
<td>1820</td>
<td>1820</td>
<td>4020</td>
<td>25,680</td>
</tr>
<tr>
<td>6) Production (m³)</td>
<td>30</td>
<td>30</td>
<td>30</td>
<td>30</td>
<td>—</td>
<td>30</td>
<td>30</td>
<td>30</td>
<td>30</td>
<td>30</td>
<td>240</td>
</tr>
<tr>
<td>7) Benefits (175 Ksh/m³)</td>
<td>5250</td>
<td>5250</td>
<td>5250</td>
<td>5250</td>
<td>—</td>
<td>5250</td>
<td>5250</td>
<td>5250</td>
<td>5250</td>
<td>5250</td>
<td>42,000</td>
</tr>
</tbody>
</table>

Note: Under labour: s = seeding, w = weeding, c = coppicing, and u = uprooting; 10.5 K kenyan Shillings (Ksh) = $1 US.
Table 2. Estimated undiscounted costs and benefits for 1 ha woodlot (*Eucalyptus sp*)

<table>
<thead>
<tr>
<th>Measure</th>
<th>Year</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>1) Labour (Man days)</td>
<td></td>
<td>p 25</td>
<td>w 3·5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>116·5</td>
</tr>
<tr>
<td>2) Labour cost (at 20 Ksh/day)</td>
<td></td>
<td>570</td>
<td></td>
<td>180</td>
<td></td>
<td>260</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2330</td>
</tr>
<tr>
<td>3) Seedling cost (0·6 Ksh/plant)</td>
<td></td>
<td>1500</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1500</td>
</tr>
<tr>
<td>4) Land rent (Ksh)</td>
<td></td>
<td>1600</td>
<td>1600</td>
<td>1600</td>
<td>1600</td>
<td>1600</td>
<td>1600</td>
<td>1600</td>
<td>1600</td>
<td>1600</td>
<td>1600</td>
<td>17,900</td>
</tr>
<tr>
<td>5) Total costs (Ksh)</td>
<td></td>
<td>3670</td>
<td>1600</td>
<td>1600</td>
<td>1600</td>
<td>1600</td>
<td>1600</td>
<td>1860</td>
<td>1600</td>
<td>1600</td>
<td>2920</td>
<td>21,730</td>
</tr>
<tr>
<td>6) Production (m²)</td>
<td></td>
<td>20</td>
<td>30</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>250</td>
</tr>
<tr>
<td>7) Benefits (175 Ksh/m²)</td>
<td></td>
<td>3500</td>
<td>5250</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>43,750</td>
</tr>
</tbody>
</table>

*NOTE:* Under labour; p = planting, w = weeding, t = thinning, and c = clear felling. 10·5 Kenyan Shillings (Ksh) = $1 US.

Table 3. Net annual cash flow of fuelstick project and conventional woodlot (in Ksh)

<table>
<thead>
<tr>
<th>Project</th>
<th>Year</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuelstick project</td>
<td></td>
<td>-2660</td>
<td>3430</td>
<td>3430</td>
<td>3430</td>
<td>1230</td>
<td>-2160</td>
<td>3430</td>
<td>3430</td>
<td>3430</td>
<td>1230</td>
<td>18,220</td>
</tr>
<tr>
<td>Conventional woodlot</td>
<td></td>
<td>-3670</td>
<td>-1600</td>
<td>-1600</td>
<td>-1600</td>
<td>1720</td>
<td>-1600</td>
<td>3390</td>
<td>-1600</td>
<td>-1600</td>
<td>32,080</td>
<td>23,920</td>
</tr>
</tbody>
</table>
one in year 5 and the second in year 7. These two thinnings together yield 50 m$^3$ and final clearfelling yields 200 m$^3$ for an average yield of 25 m$^3$/ha.

Net annual cashflow for each project is given in table 3. In terms of total, undiscounted net benefits, the conventional woodlot has a higher value of output. This is due not only to the greater total wood output under the woodlot scheme (250 vs 240 m$^3$) but also to the greater labour requirements of the fuelstick scheme (364 days vs 116.5 days). However, this higher output comes only at the end of the ten-year period, whereas the fuelstick project yields firewood evenly throughout the ten-year project period.

For an economic evaluation, it is not sufficient to compare gross net benefits without considering the time value of money. Table 4 presents each project’s net present value (NPV) evaluated at various discount rates. Both projects have positive NPVs over the range of interest rates examined. However, if they are to be viewed as mutually exclusive projects, the switching value, that is the discount rate at which the NPV for two projects is equal (UNIDO, 1972, p. 193), is important. The switching value is close to 4%, which means that if the government, or other body undertaking the project, uses a discount rate of less than 4%, the eucalyptus woodlot would yield greater net benefits. On the other hand, if the initiating body held that a higher discount rate was appropriate, then the fuelstick project would be the superior alternative.

Another measure frequently used to evaluate the benefits from a project is the internal rate of return (IRR). Unfortunately, this method is not reliable for projects which have one or more years with a negative cash flow that occur in the middle of a project's life span (Major 1977). Both projects being examined here have a negative cash flow at some intermediate point in the project cycle. However, sensitivity analysis varying interest rates was done in order to ascertain how high the interest rate would have to rise for both projects to cease being profitable. These estimates are found in the final column of table 4. The woodlot scheme loses its attractiveness at 19.5% while the fuelstick scheme maintains a positive NPV at interest rates as high as 100%. The economic viability of the fuelstick project is much more resistant to rises in the interest rate than is the conventional woodlot scheme. This resiliency on behalf of the fuelstick project can be traced to the relatively short payback period of the project. The fuelstick project has a positive accumulated net cash flow after one and one half years, while the conventional woodlot does not achieve a positive accumulation until the tenth year. The quick return to capital of the fuelstick project contributes quantitatively and qualitatively both to its attractiveness as an investment alternative and to its viability as a potential solution to the fuelwood shortage. The fuelstick project demonstrates a much shorter payback period than the conventional woodlot scheme. Although no reinvestment of early returns was

<table>
<thead>
<tr>
<th>Table 4. Net present value of projects at various discount rates</th>
</tr>
</thead>
<tbody>
<tr>
<td>Discount rate</td>
</tr>
<tr>
<td>-------------------</td>
</tr>
<tr>
<td>Fuelstick Project</td>
</tr>
<tr>
<td>Conventional woodlot</td>
</tr>
</tbody>
</table>


considered in this analysis, the inclusion of such calculations would serve to make the fuelstick project a much superior alternative, as early returns could be reinvested to increase total net returns.

3.3c Caveats The preceding example has shown that by altering their proposed production systems to be more consistent with local needs and resources, foresters can find methods of producing fuelwood that are not only fit to be classified as appropriate technologies, but also more economically attractive than conventional forestry alternatives. The caveat is that more research needs to be done into the technical and social requirements of projects of this variety before they can be successfully implemented. For example, field trials for probable species would have to be undertaken to see how well the species perform under Kenyan conditions. Calliandra was indigenous to Central America and transported to Indonesia where it has achieved a large popularity. This does not mean that it will do well in Kenya. Other environmental concerns, such as the impact of such schemes on soil fertility should also be examined. This particular species, *Calliandra calothyrsus*, is leguminous and would be assumed to have a positive impact on soil. But only controlled field trials can verify and quantify the magnitude of these environmental effects.

Careful analysis would also have to be done into the social systems to be involved with these projects. From the preceding analysis, the fuelstick schemes appear to be competitive as woodlots, and larger fuelstick projects would have greater employment benefits than an equivalent conventional woodlot. However, if the goal of the scheme is to enable each farmer to be self-sufficient in fuelwood, this same production system could be adapted as an on-farm agroforestry scheme. A survey of rural energy consumption in Kenya (Hosier 1982) has shown that annual wood consumption in the highlands averages roughly 6 cubic meters per year. Using the fuelstick example from the previous section, each household could produce this quantity of wood on about one quarter hectare of land (2500 m²). While such a plot could constitute a single plot of 50 by 50 meters, it could just as easily be used as a hedge between property or as intercropped line plantings to shade crops.

Perhaps the biggest question regarding the production of fuelsticks on farms relates to the labour requirements of fuelstick production. On small farms in Africa, the objective is frequently to maximize the return to labour, not maximize the return to land. This may actually require a different planting and harvesting scheme. Rough survey estimates (Hosier 1982) show that the average rural household must allocate roughly 10 hr/week to gathering wood, or nearly 500 hr/year. The hypothetical fuelstick project required on average of 364 days/year or roughly 300 hr. At first glance, then, the on-farm fuelstick scheme appears to represent labour savings. However, just as the labour requirements do not occur equally in every year of production, neither do they occur uniformly throughout the year. As a result there are liable to be seasons of peak labour requirements, just as with agricultural crops. As both these tasks are likely to be performed by women, attention must be paid to seasonality in the labour requirements.

Finally, all of these components will have to be evaluated by way of social benefit-cost or multi-objective analysis. The economic analysis just presented provides a first step toward the fuller analysis. From the preliminary economic analysis, the project appears to be viable, but there are other concerns such as investment effects, redistribution impacts, and environmental quality. Social benefit-cost analysis
appears to provide the best framework for pulling these diverse analyses together for a systematic evaluation of projects of this variety.

4. Conclusion

This paper has addressed the need for appropriate technology in the field of forest resources, with particular reference to fuelwood production systems in developing countries. It has been argued that the resources and needs of the local population must be carefully examined before proposals regarding fuelwood projects are undertaken. The systems that are often utilized are built around Western concepts of industrial forest production and are therefore inappropriate for fuelwood production in tropical developing countries.

The first area in which forest technology was evaluated is that of wood-harvesting technologies. In most developing countries, forestry, particularly fuelwood production schemes, will have to rely on the use of proper hand tools for harvesting. Evidence from Kenya is used to demonstrate that many such tools are badly maintained. Considerable increases in forest-labour productivity can be made by improving the maintenance given to wood harvesting tools.

The second area addressed is that of fuelwood production systems. While many forestry solutions to the fuelwood shortage are posed by foresters, they frequently focus on the establishment of woodlots or plantations operating on a long rotation period. Since the users of fuelwood appear to prefer small-diameter fuelsticks produced on short rotation or pollarding management systems, it makes sense to change the proposed solution to fit the user’s priorities. Short rotation, closely-planted fuelwood stick projects are proposed as an appropriate strategy to increase fuelwood production. A numerical example is employed to demonstrate that, despite a number of caveats, such systems are economically viable and possibly superior to conventional forestry solutions.

The Beijer Institute Kenyan Fuelwood Project provided the medium through which the content of this paper evolved. Thanks are to be given to Dirk Hoekstra and Peter Huxley of ICRAF for input and comments used in the paper. Much of the material in this paper has appeared in separate working papers of the Kenyan Fuelwood Project. Professor K. Krishna Prasad deserves thanks for having provided the impetus to pull them together into this final form.

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Fuelwood and stoves: Lessons from Zimbabwe

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Abstract. Laboratory tests on traditional open fires as methods of cooking give values of thermal efficiency varying from 12–30%. These are significantly higher than values which are widely quoted in the literature.

The results of a research visit to Zimbabwe indicated that in three villages fuel efficiency did not appear to be the main determinant of choice of cooking method; villagers had changed from their traditional mode of cooking to stoves which they perceived to consume substantially more fuel. These stoves enabled meals to be prepared more quickly which the women found useful during the busy months. The increased labour costs could be borne because fuel was gathered during the slack season.

Keywords. Rural energy; traditional stoves; thermal efficiency; fuel consumption; stove design; fuel shortage.

1. Introduction

A fuel shortage is widely perceived to exist in the non industrialized countries, especially relating to cooking activities, and expected to become more acute. Strategies to overcome this shortage have on the whole tended to be based on the assumptions that traditional modes of cooking are very inefficient and that fuel collection is an increasing burden for the rural population, this burden falling particularly on women and children of poor families. Cooking stoves which have a high efficiency will therefore be highly desirable to the rural poor.

In order to assess the validity of these assumptions, a literature search was conducted, and a research visit undertaken to Zimbabwe (in central Africa). Some of the findings are presented in this paper.

1.1 Traditional modes of cooking: Literature review

In the rural areas of Asia, Africa and S. America cooking is traditionally done on open fires or simple variations of these, in particular with the addition of rocks or stones which act as supports for cooking utensils. One very common arrangement appears to be the 3-stone fireplace (figure 1). This has been observed not only in Zimbabwe (Ascough 1981), but also in Bangladesh (Islam 1980), Guatemala (Evans 1979), Ghana (Martin 1979), Nigeria (Ay 1980), sub-Saharan Africa (Frida 1980), and Tanzania (Mnzava 1980).

It is widely believed that the thermal efficiency of traditional open fireplaces as modes of cooking are very low, and several publications give values less than 10%, without any source of reference (e.g. Hammer 1978; Knowland & Ulinski 1979;
However, recent empirical studies of traditional fireplaces have indicated thermal efficiencies which are significantly higher, ranging from 12–30% depending on factors such as wind speed, size of the firewood, height of pot above fire, etc (Brattle 1979; Joseph & Shanahan 1981; Prasad 1980).

1.2 Research visit

A large amount of work has already been done in India on rural energy (Prasad et al 1974; Reddy & Prasad 1977; Rajabapaiah et al 1979; Reddy & Subramanian 1979; Reddy et al 1979). Hence, it was felt that a study in another country might provide a usefully different perspective. Since the three-stone fireplace appeared to be widespread it was decided to undertake a study visit to Zimbabwe, a country in which this mode of cooking appeared to be commonly used.

Zimbabwe has a land area of nearly 400,000 square kilometres. Its population at the end of 1977 was estimated at 6-86 million: with the predominant groups being roughly 6-5 million Africans, 0-25 million Europeans, 10,300 Asians and 23,000 coloureds (Ndlela 1981). The peasant farming population is the largest single group in the economy—4 million in 1977, primarily growing maize in a subsistence type economy. The income level per capita per annum was estimated to be Z$ 28 (Rs 350) in 1977, with an average of 5% growth rate over the previous decade (Whitsun Foundation 1978). Assuming the same growth rate the average income level per year would be Z$ 38 (Rs 470) by 1981.

Around 85% of the population (i.e. 6 million people) use wood as a source of energy for cooking and heating (Whitsun Foundation 1980). Average annual firewood consumption per person is thought to be about 1 m$^3$ (Forestry Commission 1978); assuming this to be air dry wood with a moisture content of 25%, the calorific value will be 14-5 MJ kg$^{-1}$. Assuming that the density of local indigenous timber is 680 kg m$^{-3}$ (Johnston 1980), then this represents 10 GJ consumption per year per person. A recent study estimated that a critical firewood shortage affected 58% (2.3 million people) of the Communal Land population (Whitsun Foundation 1980).

There are four major seasons: hot (September to early November, main rainy (November to late March), post rainy (April to May when the chance of rain decreases and temperatures start to fall), and winter (May to August)—see figure 2.
2. Methodology

2.1 Study areas

Villages (see table 1) in three areas were chosen for the study representing varying degrees of firewood scarcity (Whitsun Foundation 1980): Mukweva and Munondo in Inyanga North Communal Land (little firewood problem); Ellenvale and Doornhoek in Zimbiti Communal Land (both in an area of moderate firewood shortage); and Chitsvatsva in Seke (an area known for its acute firewood shortage). Direct measurement of the daily firewood consumption was undertaken in Mukweva and Ellenvale whilst a questionnaire survey, (covering agricultural activity, seasonal variations in fuel consumption, and perceptions of tasks such as food preparation and fuel collection) was undertaken in all the areas. Given constraints such as time, lack of detailed demographic information, etc., households selected for measurement of fuel consumption in each village, were chosen such that each stove type was represented in the sample. Income levels were a sensitive issue (and difficult to determine given the nature of the rural economy) and so this was not pursued directly. However, the type of stove used by each of the families could be used as a 'surrogate' measure of income level.
2.2 Firewood consumption

The firewood consumption of five families in both Mukweva (out of eight families), and Ellenvale (out of eleven families) was measured over a period of 18 days (November 8–26) and 8 days (November 30–December 7), respectively. These families were requested to use firewood only from a pile which was weighed every 24 hours and replenished (with a known mass of firewood) as necessary. A record was also made of the meals cooked over the previous 24 hours and the number of people who had eaten. In addition, each family was observed cooking its meal in the evening, and the following morning and afternoon. In this way the amount of food cooked and firewood consumed was measured, and a record made of the cooking process.

2.3 Moisture content

Five samples (weighing between 0.5 g and 6 g) were cut from each of the firewood piles and immediately placed in plastic bags. These were then weighed on a chemical balance to within 0.001 g. The moisture content was determined by drying these samples in an oven at 105°C for 23 hours and recording the oven dry mass, using the formulae:

\[
\text{Moisture content} = \frac{\text{wet mass} - \text{dry mass}}{\text{dry mass}} \times 100\%.
\]

3. Results

3.1 Seasonal variation in agricultural and domestic activity

Women undertook agricultural activity in addition to cooking and fuel collection. Peak agricultural labour demand occurs between November and April, which the women in these villages regarded as the busiest months.

The staple diet was sadza (a thick porridge-like substance made from ground maize and water), and eaten with a relish (typically boiled cabbage or other vegetables, or beans). Vigorous stirring was required during the final stages of cooking sadza—stirring the mixture was easier if both hands could be used, this required the pot to be reasonably stable on the stove. Sadza would be cooked twice a day (midday and evening), whilst tea would be made in the morning and eaten with cold sadza left over from the previous evening. The number of pots heated on the stove at the same time varied over the year: 2–3 pots (e.g. tea, sadza and relish), heated simultaneously from November to April (the busiest months), whilst one pot at a time was heated during the rest of the months (see figure 2).

Firewood (in the form of small logs varying from 2–10 cm in diameter and 0.5–1 m in length) and maize cobs were used as cooking fuels in all three areas visited. Cattle manure was used as a fuel only in Chitsvatsva where it was burnt during the post rainy and hot season; in the rainy season the manure would be washed away. Villagers in Chitsvatsva also used roots as a fuel supplement.

Firewood was collected by women and girls and carried as headloads, or by men and boys and carried by cart (figure 3, plate 1). No collection of firewood was reported.
during the rainy season (November to April), since once wood got wet it became very heavy and difficult to burn. Hence, the usual practice was to collect enough firewood during the dry season (and store it in a pile) to last through to the end of the rains. In Mukvewa, Ellenvale and Doornhoek firewood was reported to be collected from June till October, and from May till October in Chitsvatsav. Maize cobs were collected and used during August and September, (when they were in season).

3.2 Mode of cooking

All the householders interviewed had a separate cooking hut. Three types of ‘stove’ were observed on the fireplace (see Appendix A) in the centre of this hut: ‘3-stones’ (figure 1), ‘4-stones’ (figure 4 and figure 5, plate 1) or an iron frame (figure 6 and figure 7, plate 2); rulers shown in each figure are 30 cm in length. The 4-stones were user built and consisted of 4 mounds of clay, (or termite mound), linked by 4 metal bars in the shape of a square with two additional metal bars forming the diagonal supports. The iron frame was made and sold by urban based artisans at around Z $3–5 (Rs 60–100). Virtually all the villagers using the iron frame or 4-stones reported that they had previously used 3-stones inside the cooking hut prior to the change in cooking ‘stove’ (villagers’ reasons for this change

Figure 4. 4-stone fireplace (all dimensions in cm).

Figure 6. Iron frame stove (all dimensions in cm).
are given in § 3.5). The vast majority of these villagers had moved their 3-stones outside the cooking hut, where they were sometimes used to heat water for bathing, and a few times a year, to brew beer. Villagers in Chitsvatsva reported that animal manure was used as a fuel when cooking outside owing to the fumes. Women who continued to use the traditional 3-stones inside the cooking hut expressed a desire to change to the iron frame, but said that they could not afford to buy one.

3.3 Firewood consumption data

Heaviest use of fuel was reported during the cold months of June and July when consumption was said to be one-and-a-half to twice as high as the rest of the year.

Annual figures for energy consumption per capita have been calculated assuming that daily consumption for the winter months of June and July is twice as high as the measured daily consumption in table 2. These calculations give results which vary from 10 GJ to 26 GJ. On the whole most of these figures are substantially higher than the average figure of 10 GJ calculated from other researchers.

Average moisture contents of the wood samples taken from the wood piles for most of the families were between 10% and 17% (see table 2).

3.4 Heat utilization data

Data on the measured heat utilization during cooking (table 3) for the various families is too limited and the conditions too varied to draw statistically significant conclusions in comparing the heat utilization of the various stove types. However, the results do indicate that wood can be burnt at high rates in the iron frame—power

<table>
<thead>
<tr>
<th>Village household</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
<th>G</th>
<th>H</th>
<th>I</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mukweva</td>
<td>4.7</td>
<td>3.3</td>
<td>3.8</td>
<td>4.3</td>
<td>3.5</td>
<td>2.2</td>
<td>3.8</td>
<td>4.4</td>
<td>1.7</td>
</tr>
<tr>
<td>Ellenvale</td>
<td>4.5</td>
<td>3.2</td>
<td>3.7</td>
<td>4.3</td>
<td>3.5</td>
<td>2.2</td>
<td>3.8</td>
<td>4.4</td>
<td>1.7</td>
</tr>
<tr>
<td>A&lt;sub&gt;n&lt;/sub&gt;</td>
<td>4.7</td>
<td>3.3</td>
<td>3.8</td>
<td>4.3</td>
<td>3.5</td>
<td>2.2</td>
<td>3.8</td>
<td>4.4</td>
<td>1.7</td>
</tr>
<tr>
<td>n</td>
<td>17</td>
<td>15</td>
<td>13</td>
<td>15</td>
<td>4</td>
<td>8</td>
<td>8</td>
<td>6</td>
<td>5</td>
</tr>
<tr>
<td>f</td>
<td>15</td>
<td>11</td>
<td>6</td>
<td>18</td>
<td>11</td>
<td>7</td>
<td>10</td>
<td>10</td>
<td>5</td>
</tr>
<tr>
<td>m.c.</td>
<td>10</td>
<td>10</td>
<td>37</td>
<td>11</td>
<td>11</td>
<td>27</td>
<td>12</td>
<td>17</td>
<td>23</td>
</tr>
<tr>
<td>c.v.</td>
<td>17</td>
<td>17</td>
<td>13</td>
<td>17</td>
<td>17</td>
<td>14</td>
<td>17</td>
<td>16</td>
<td>15</td>
</tr>
<tr>
<td>E&lt;sub&gt;comp&lt;/sub&gt;</td>
<td>25</td>
<td>26</td>
<td>10</td>
<td>26</td>
<td>25</td>
<td>21</td>
<td>20</td>
<td>16</td>
<td>20</td>
</tr>
<tr>
<td>Stove type inside</td>
<td>Z</td>
<td>Z</td>
<td>Y</td>
<td>Z</td>
<td>Z</td>
<td>Z</td>
<td>X</td>
<td>Z</td>
<td>Z</td>
</tr>
</tbody>
</table>

Key:
A<sub>n</sub>—No. of adult units—using the dietary table of coefficients produced by the League of Nations (1932);

n—number of days over which firewood consumption measured;
f—mean firewood consumption (kg);
m.c.—percentage moisture content of firewood (dry basis);
c.v.—calorific value (MJ/kg);
E<sub>comp</sub>—energy consumed per adult unit per annum 462 f × c.v./A<sub>n</sub>

Stove type—Z: iron frame;
Y: 4-stones; X: 3-stones.
Table 3. Heat utilization data

<table>
<thead>
<tr>
<th>Household</th>
<th>$T_f$ (°C)</th>
<th>$T_i$ (°C)</th>
<th>Time to $T_f$ (min)</th>
<th>$M_w$ (kg)</th>
<th>$P_o$ (kW)</th>
<th>Pan</th>
<th>H.U. (%)</th>
<th>Stove</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>80-0</td>
<td>27-5</td>
<td>9-7</td>
<td>4-95</td>
<td>21-2</td>
<td>Metal</td>
<td>8-8</td>
<td>Iron frame</td>
</tr>
<tr>
<td>B</td>
<td>87-5</td>
<td>28-5</td>
<td>11-0</td>
<td>2-56</td>
<td>9-3</td>
<td>Metal</td>
<td>10-3</td>
<td>Iron frame</td>
</tr>
<tr>
<td>C</td>
<td>93-5</td>
<td>29-1</td>
<td>9-0</td>
<td>2-68</td>
<td>4-2</td>
<td>Metal</td>
<td>33-8</td>
<td>4-stones</td>
</tr>
<tr>
<td>D</td>
<td>92-2</td>
<td>25-2</td>
<td>22-5</td>
<td>2-68</td>
<td>5-1</td>
<td>Clay</td>
<td>11-0</td>
<td></td>
</tr>
<tr>
<td>H</td>
<td>96-6</td>
<td>21-0</td>
<td>14-2</td>
<td>1-98</td>
<td>4-4</td>
<td>Paint can</td>
<td>18-9</td>
<td>3-stones</td>
</tr>
<tr>
<td></td>
<td>96-6</td>
<td>24-0</td>
<td>14-4</td>
<td>2-57</td>
<td>6-1</td>
<td>Paint can</td>
<td>14-9</td>
<td></td>
</tr>
</tbody>
</table>

$T_f$—final temperature of water; $T_i$—initial temperature of water; $M_w$—mass of water being heated; $P_o$—power output of burning fuel; H.U.—heat utilization (see Appendix B).

outputs of up to 21 kW were measured—and between 2 and 5 litres of water could be brought close to boiling in 10 minutes or so. Heat utilization of the iron frame, with a metal pan, varied from 8% to 10%, whilst a value of 34% was obtained for 4-stones, and 15% to 19% for the 3-stones.

3.5 Villagers’ reasons for changing mode of cooking

The primary reason given by the majority of villagers surveyed for changing from 3-stones to the iron frame ‘stove’ was that the new ‘stove’ enabled the user to ‘cook many things’ simultaneously. Food could also be cooked more quickly as burning fuel in the iron frame gave out more heat than with 3-stones. Both these factors were considered to be extremely useful when people were in a hurry, since food could be cooked quickly.

In some cases, the most important reason appeared to be the modern image associated with the iron frame; 3-stones were considered to be ‘old fashioned’. Perceptions such as the relative merit of having less smoke, more heat, stable pots etc., though all mentioned showed no definite pattern (see Appendix C).

Whilst one of the villagers in Doornhoek using 4-stones commented that she used 50% more fuel than with the 3-stone fireplace, another in Mukweva did not perceive any difference. Users of the iron frame were aware of a 1.5 to 3 fold increase in fuel consumption relative to their 3-stone fireplace. But despite this relative fuel economy none of the villagers thought that 3-stones had any advantages.

4. Discussion

4.1 Efficiency of traditional modes of cooking

A literature survey showed that very little experimental work has been done to measure the efficiency of the traditional open fire and its variations. Given the number of confident pronouncements of the low efficiencies of these modes of cooking it is
quite surprising to discover that the results of the laboratory tests by Brattle (1979), Joseph & Shanahan (1981), and Prasad (1980) suggest that the 3-stone method of cooking is not as inefficient as is widely quoted in the literature. Values of heat utilization in the field would be expected to be lower (figures of 15% and 19% were obtained in this study) than tests carried out in the laboratory.

4.2 Research findings

4.2a Methodology/fuel collection practices Villagers surveyed indicated that they did not generally collect firewood during the rainy season (November to April) owing to the difficulty of carrying and burning wet wood. This activity would also compete the high labour requirements of agricultural work during that period. This effectively means that firewood collected in the slack season has to be sufficient to last through the rainy season. Hence, any methodology attempting to determine the firewood consumption by only measuring the firewood collected for part of the year could be open to considerable error. The methodology used in this study to determine the firewood consumption measured the depletion per day of a known quantity of firewood left outside the cooking hut. Errors would be introduced if wood from elsewhere was used for cooking, or if another household used wood from this pile. The latter is believed to be unlikely as each of the households had large firewood piles of their own.

4.2b Mode of cooking In the villages visited there appears to have been a widespread shift from the traditional 3-stone fireplace to either a user built '4-stones' or an iron frame 'stove'. The shift has also been noted in many other areas of Zimbabwe*. The change appears to have taken place despite the additional labour and financial costs** involved: 4-stones require a morning or so to construct, and then have to be repaired every six months or so, while the iron frame stove costs Rs 60–100. This expenditure represents around 13–20% of the average per capital income of Rs 470 per year.

In addition, increased fuel consumption was apparent to the villagers, in that the iron frame stove was thought to use 1.5 to 3 times as much fuel as 3-stones. However, it would not be unreasonable to expect the cooks to be aware of such significant increases in cooking fuel consumption.

Values of heat utilization with the iron frame (8% to 10%) were lower than for the 3-stone fireplace (15% to 19%). Overall, the results suggest that the iron frame consumed more firewood than the 3-stone fireplace, but enabled food to be cooked more quickly and provide greater space heat, owing to the higher burning rates of the wood.

The highest value of heat utilization, viz 34%, was obtained with the 4-stone fireplace, which fell to 11%, when a clay pot was used instead of a metal pan and it took two and a half times longer to heat the water. However, this would not be unexpected since clay is not as good a conductor of heat as a metal, and also substantially more water would be evaporated during heating; the energy associated with evaporated water was ignored in the calculation of heat utilization. Both these would increase

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*Iron frame observed to be common in many other parts of Zimbabwe (Ascough 1981; McGarry 1982).
**3-stones have merely to be collected from the surrounding area.
the time to heat the water (compared with the metal pan) and reduce the calculated value of heat utilization.

It is important to note that despite this change in cooking device, the iron frame and 4-stones were placed on the traditional fireplace at the centre of the cooking hut. Hence, the social aspect of gathering around a fire had been retained.

Villagers in Chitsvatsva appeared to be under greater fuel stress than the other villages surveyed, in that animal manure was being used as a fuel supplement, and firewood was being collected over more months of the year. Animal manure was used when cooking out of doors (owing to the fumes) on their 3-stone fireplace during the dry season, and also possibly as a strategy to minimize overall fuel consumption: cooking with the iron frame was perceived to consume substantially more fuel than with 3-stones.

This change from the 3-stone fireplace appears to be connected to the following: Zimbabwean women provide most of the labour for agriculture as well as for cooking and fuel collection. Since agricultural labour demand varies over the year, increases in this workload would be felt more acutely during the period of peak labour demand. The busiest time of year is from November to April when the women prefer to cook quickly and have transferred to the iron frame even in areas of fuel shortage.

The finding that stove users rated features such as faster cooking and convenience to fuel savings has also been reported in Indonesia and Sri Lanka (Joseph 1982) and in Senegal (Evans 1982).

It must be pointed out that although time was saved because cooking could be done more quickly, this would have to be offset against the additional labour time which had to be spent in fuel collection owing to the relatively higher fuel consumption of the iron frame. However, since fuel is collected during the slack season whilst fast cooking is required in the peak agricultural season, higher fuel consumption costs incurred during agricultural peak labour demand period are affordable, because they are borne during the part of the year when labour is not in high demand. It is crucial to note that the villagers were only able to do this because they could collect and store sufficient firewood during the slack season to last them through the busy months.

There were additional user perceived benefits brought about by the change, namely less smoke, a modern ‘image’, greater space heat, stabler pots, and faster cooking, which no doubt added to its attraction.

A guide for stove design for villagers would need to take into account the key features identified from the measurements of heat utilization (such as the ability to bring 2–5 litres to boil in about 10 minutes), fuel efficiency and the following:

—allow up to 3 pots to be heated simultaneously;
—provide space heat (only required for a few months of the year):
—produce little smoke,
—have a long lifetime,
—cost less than ZS$ 5 (Rs 100).

5. Conclusions

One response to the perceived fuel shortage in the non industrialized countries has been to promote the design and dissemination of fuel-efficient stoves. In this it
has been assumed that traditional stoves are inefficient, and that the burden on the rural population in fuel collection is becoming very high. Recent laboratory tests suggest that the 3-stone fireplace (observed to be used in Africa and Central America) is not as inefficient as is commonly quoted. Moreover it has to be borne in mind that cooking has to regarded as a system comprising fuel, stove, cooking pots and cooking practices which will all affect the ‘efficiency’ of heat transfer from the fuel to the food. For example, metal cooking pots will have better heat transfer characteristics than clay ones. Stoves are also likely to serve a variety of other functions besides simply cooking e.g. as a source of space heat, they may provide a community focus and also have a symbolic value in which the concept of high thermal ‘efficiency’ may have little value or meaning.

In the four villages investigated there appears to have been a shift to stoves which the users perceived as using substantially more fuel than their traditional method of cooking. The major reason given was faster cooking times.

Additional labour owing to increased fuel consumption could be tolerated because fuel was collected in the slack agricultural season, whilst fast cooking was required during the period of peak labour demand.

Fuel efficiency does not appear to be the main determinant of choice of cooking method in these villages, hence stove designs are more likely to be acceptable to users if they also take into account factors such as convenience, ‘image’, provision for space heat etc.

I would like to thank Steve Cousins, Martin Fodor, Catherine Lippold and Robin Roy of the Open University for the many stimulating and useful discussions they provided. I also much appreciated the help given to me by Jeremy Ascough, Brian McGarry and Caroline Michaslik during my stay in Zimbabwe. Thanks must also go to the Energy Research Group, Alternative Technology Group and Travel Committee of the Open University and the Intermediate Technology Development Group for their progressive attitude in funding the research visit. But, above all I would like to acknowledge my debt to the villagers in the study areas who cooperated unreservedly and so tolerantly accepted the intrusion in their lives.
Appendix A

Stove type inside and outside cooking hut in villages surveyed

<table>
<thead>
<tr>
<th>Communal land/ village</th>
<th>Q</th>
<th>F</th>
<th>P</th>
<th>T</th>
<th></th>
<th>Inside</th>
<th>Outside</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inyanga North</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mukweva village</td>
<td>5</td>
<td>5</td>
<td>25</td>
<td>8</td>
<td></td>
<td>5 (A)</td>
<td>6 (C)</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>(B)</td>
<td></td>
<td></td>
<td></td>
<td>1 (C)</td>
<td></td>
</tr>
<tr>
<td>Munondo village†</td>
<td>—</td>
<td>—</td>
<td>72</td>
<td>8</td>
<td></td>
<td>5 (A)</td>
<td>6 (C)</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>(B)</td>
<td>1</td>
<td>(C)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Households within 5 km of Munondo†</td>
<td>—</td>
<td>—</td>
<td>124</td>
<td>19</td>
<td></td>
<td>19 (A)</td>
<td>7 (C)</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>(B)</td>
<td>1</td>
<td>(C)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Zimbiti</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ellenvale village</td>
<td>5</td>
<td>5</td>
<td>21</td>
<td>11</td>
<td></td>
<td>9 (A)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>(C)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Doornhoek village</td>
<td>11</td>
<td>—</td>
<td>75</td>
<td>11</td>
<td></td>
<td>7 (A)</td>
<td>4 (C)</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>(B)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>(C)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Seke</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chitsvatsva village</td>
<td>3</td>
<td>—</td>
<td>23</td>
<td>6</td>
<td></td>
<td>3 (A)</td>
<td>3 (C)</td>
</tr>
</tbody>
</table>

Q—No. of households surveyed with questionnaire;  
F—No. of households daily consumption of firewood measured;  
P—Population surveyed;  
T—Total no. of households in Kraal.  
*Stove type: A—iron frame 'stove'; B—4-stone fireplace; C—3-stone fireplace.  
†Survey of stove type only.

Appendix B

Heat utilization

Heat utilization (H.U.) was calculated using the following expression:

\[
H. \text{ U.} = \frac{(M_w \times C_w \times d T)}{E_c} \times 100\%,
\]

where \( M_w \) = mass of water being heated (kg); \( C_w \) = specific heat of water (4.184 \( \text{kJ kg}^{-1} \text{K}^{-1} \)); \( dT \) = temperature change in time \( t \) (K\(^{-1}\)); \( E_c \) = energy released by fuel in time \( t \) (MJ kg\(^{-1}\));

and,

\[
E_c = B. \text{ R.} \times t \times E_m,
\]

where, B.R. = burning rate (g min\(^{-1}\)); \( t \) = time in minutes; \( E_m \) = calculated energy content of firewood at moisture content \( m \) (dry basis) MJ kg\(^{-1}\); where, following Bialy (1979);

\[
E_m = \frac{2.4 \times (780 - m)}{100 + m}\text{ MJ kg}^{-1}.
\]

The burning rate was determined by measuring the quantity of fuel at the beginning and end of the cooking process, from which:

\[
B. \text{ R.} = M_{fi} - [M_{fe} + M_{ch}(29/E_m)] \text{ g min}^{-1},
\]

where \( M_{fi} \) = mass of firewood initially (kg); \( M_{fe} \) = mass of firewood at the end of cooking (kg); \( M_{ch} \) = mass of charcoal at end of cooking (kg);

Note. The calorific value of charcoal has been taken to be 29 MJ kg\(^{-1}\).
## Appendix C

Summary of reasons given for changing mode of cooking from 3-stones (with ranking*)

<table>
<thead>
<tr>
<th>Household</th>
<th>Doornhoek</th>
<th>Chisvatsva</th>
<th>Ellenvale</th>
<th>Mukvewa</th>
</tr>
</thead>
<tbody>
<tr>
<td>New stove type</td>
<td>A B C D E F G H I J K L M O P Q R S T U</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Less smoke</td>
<td>1 2 1 1 1 1 2 2 2 2 2 2 1 1 1 2 3 1 1 1 1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>More heat</td>
<td>3 1 2 2 2 5 3 5 4 2 5 4 4 2 3 4</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bigger logs</td>
<td>2 3 3 3 4 3 6 3 4 3 4 3 4 3 4</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Modernization</td>
<td>1 1 1 4 2 1 1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stable pots</td>
<td>6 5 1 5 2 2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Faster cooking</td>
<td>4 4</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Firewood can be put from all sides</td>
<td>3</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Consumption relative to 3-stones</td>
<td>1.5 1.5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>2 2 2 2 2 2 3 3 3 2 2 2</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The perceived advantages for changing to the iron frame are given by households C, D and U all of whom still had 3-stones inside the cooking hut.

**Key:**

Stove type: X — 3-stones *i.e.* no change; Y — 4-stones; Z — iron frame.

*Scale of ranking*

1 — most important reason; 6 — least important reason.
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Figure 3. Firewood collection by cart.

Figure 5. 4-stone fireplace in use
Figure 7. Iron-frame stove in use
## AUTHOR INDEX

<table>
<thead>
<tr>
<th>Author</th>
<th>Page Numbers</th>
</tr>
</thead>
<tbody>
<tr>
<td>De Ris J</td>
<td>7</td>
</tr>
<tr>
<td>Drake R M</td>
<td>64, 176</td>
</tr>
<tr>
<td>Doner D</td>
<td>26</td>
</tr>
<tr>
<td>Dunn P D</td>
<td>107</td>
</tr>
<tr>
<td>Dutt G S</td>
<td>38, 122, 123, 128, 129</td>
</tr>
<tr>
<td>Earl D E</td>
<td>15, 21, 24</td>
</tr>
<tr>
<td>Eckert E R G</td>
<td>64, 176</td>
</tr>
<tr>
<td>Emmons H W</td>
<td>5, 174, 177, 178</td>
</tr>
<tr>
<td>Era Y</td>
<td>181, 182</td>
</tr>
<tr>
<td>Evans I</td>
<td>9, 158, 233, 241</td>
</tr>
<tr>
<td>Bailie R</td>
<td>26, 29</td>
</tr>
<tr>
<td>Ballaney P L</td>
<td>142</td>
</tr>
<tr>
<td>Bamford C H</td>
<td>7, 28</td>
</tr>
<tr>
<td>Barnard G</td>
<td>107</td>
</tr>
<tr>
<td>Basting W J</td>
<td>100</td>
</tr>
<tr>
<td>Birath H</td>
<td>216</td>
</tr>
<tr>
<td>Black L H</td>
<td>183</td>
</tr>
<tr>
<td>Blackshear P</td>
<td>7, 28</td>
</tr>
<tr>
<td>Bradbury A</td>
<td>22</td>
</tr>
<tr>
<td>Brame J S S</td>
<td>161, 162, 178</td>
</tr>
<tr>
<td>Brattle L</td>
<td>234</td>
</tr>
<tr>
<td>Brodios A</td>
<td>7, 9, 20</td>
</tr>
<tr>
<td>Browne F L</td>
<td>16</td>
</tr>
<tr>
<td>Bussmann P J T</td>
<td>155, 176</td>
</tr>
<tr>
<td>Cess</td>
<td>184</td>
</tr>
<tr>
<td>Chaiken R</td>
<td>29</td>
</tr>
<tr>
<td>Chandra R</td>
<td>217</td>
</tr>
<tr>
<td>Chaplin C R</td>
<td>201</td>
</tr>
<tr>
<td>Charm SE</td>
<td>78</td>
</tr>
<tr>
<td>Chitty R</td>
<td>174, 179</td>
</tr>
<tr>
<td>Christiaens M</td>
<td>189</td>
</tr>
<tr>
<td>Claus J</td>
<td>89, 94, 97</td>
</tr>
<tr>
<td>Clough G</td>
<td>7, 29</td>
</tr>
<tr>
<td>Crank J</td>
<td>7, 28</td>
</tr>
<tr>
<td>Cortes E V</td>
<td>216, 217</td>
</tr>
<tr>
<td>Cox G</td>
<td>174, 179</td>
</tr>
<tr>
<td>Degussa A G</td>
<td>25</td>
</tr>
<tr>
<td>Delsingh J</td>
<td>169</td>
</tr>
<tr>
<td>G</td>
<td></td>
</tr>
<tr>
<td>Gelder A Van</td>
<td>213</td>
</tr>
<tr>
<td>Geller, Howard S</td>
<td>38, 78, 119, 120, 121, 122, 124, 128, 129, 130</td>
</tr>
<tr>
<td>Ginneken</td>
<td>59, 64</td>
</tr>
<tr>
<td>Glassman</td>
<td>8</td>
</tr>
<tr>
<td>Gnielinski V</td>
<td>181</td>
</tr>
<tr>
<td>Goss A W</td>
<td>6, 7</td>
</tr>
<tr>
<td>Gordon JE</td>
<td>203</td>
</tr>
<tr>
<td>Groeneveld M J</td>
<td>48</td>
</tr>
<tr>
<td>Gross D</td>
<td>11</td>
</tr>
<tr>
<td>Gupta C L</td>
<td>141</td>
</tr>
<tr>
<td>Hamter T</td>
<td>233</td>
</tr>
<tr>
<td>Hannant D S</td>
<td>204</td>
</tr>
<tr>
<td>Hansson J E</td>
<td>216</td>
</tr>
<tr>
<td>Harmathy T Z</td>
<td>11</td>
</tr>
<tr>
<td>Harris A C</td>
<td>26, 27</td>
</tr>
<tr>
<td>Harris E E</td>
<td>24</td>
</tr>
<tr>
<td>Hasselman D P H</td>
<td>203, 205, 210</td>
</tr>
<tr>
<td>Havens J A</td>
<td>7</td>
</tr>
<tr>
<td>Hawthorn J</td>
<td>39</td>
</tr>
<tr>
<td>Hertek H</td>
<td>181</td>
</tr>
<tr>
<td>Hileman F D</td>
<td>7</td>
</tr>
</tbody>
</table>
## Author Index

<table>
<thead>
<tr>
<th>Author</th>
<th>Pages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hoogendoorn G J</td>
<td>181</td>
</tr>
<tr>
<td>Hodson P</td>
<td>205</td>
</tr>
<tr>
<td>Hosaka H</td>
<td>78</td>
</tr>
<tr>
<td>Hosier R</td>
<td>213, 218, 230</td>
</tr>
<tr>
<td>Howard J B</td>
<td>20</td>
</tr>
<tr>
<td>Hryceak P</td>
<td>182</td>
</tr>
<tr>
<td>I</td>
<td></td>
</tr>
<tr>
<td>Imberger J</td>
<td>179</td>
</tr>
<tr>
<td>Islam M N</td>
<td>38, 233</td>
</tr>
<tr>
<td>J</td>
<td></td>
</tr>
<tr>
<td>Jacobs M</td>
<td>40</td>
</tr>
<tr>
<td>Jacobs P B</td>
<td>24</td>
</tr>
<tr>
<td>Jain B C</td>
<td>143</td>
</tr>
<tr>
<td>Jas Gill</td>
<td>233</td>
</tr>
<tr>
<td>Jennings H</td>
<td>25</td>
</tr>
<tr>
<td>Johnston J C</td>
<td>234</td>
</tr>
<tr>
<td>Jones J C</td>
<td>201</td>
</tr>
<tr>
<td>Jongma J</td>
<td>222</td>
</tr>
<tr>
<td>Joseph S</td>
<td>120, 128, 131, 142, 158, 201, 234, 240, 241</td>
</tr>
<tr>
<td>Joyce N</td>
<td>107</td>
</tr>
<tr>
<td>K</td>
<td></td>
</tr>
<tr>
<td>Kalekar</td>
<td>7</td>
</tr>
<tr>
<td>Kansa E</td>
<td>29</td>
</tr>
<tr>
<td>Kantola</td>
<td>215, 216</td>
</tr>
<tr>
<td>Kanuary A M</td>
<td>7</td>
</tr>
<tr>
<td>Khanna S K</td>
<td>75</td>
</tr>
<tr>
<td>Kindelan M</td>
<td>7</td>
</tr>
<tr>
<td>King J G</td>
<td>161, 162, 178</td>
</tr>
<tr>
<td>Knol M</td>
<td>43</td>
</tr>
<tr>
<td>Knowland W</td>
<td>233</td>
</tr>
<tr>
<td>Kotnot P</td>
<td>37, 40</td>
</tr>
<tr>
<td>Krause Jr R F</td>
<td>11</td>
</tr>
<tr>
<td>Krishna Prasad K</td>
<td>35, 38, 75, 120, 128, 155, 157, 158, 176, 192, 213, 234</td>
</tr>
<tr>
<td>Kubota K</td>
<td>78</td>
</tr>
<tr>
<td>Kung H</td>
<td>7, 29</td>
</tr>
<tr>
<td>L</td>
<td></td>
</tr>
<tr>
<td>Langhaar H L</td>
<td>81</td>
</tr>
<tr>
<td>Lee S L</td>
<td>174, 177</td>
</tr>
<tr>
<td>Lepeliege G D</td>
<td>74, 120, 189</td>
</tr>
<tr>
<td>Levenspiegel O</td>
<td>28</td>
</tr>
<tr>
<td>Lewellen P C</td>
<td>20</td>
</tr>
<tr>
<td>Lindholm</td>
<td>216</td>
</tr>
<tr>
<td>Lipska A</td>
<td>22</td>
</tr>
<tr>
<td>List E J</td>
<td>179</td>
</tr>
<tr>
<td>M</td>
<td></td>
</tr>
<tr>
<td>Maa</td>
<td>29</td>
</tr>
<tr>
<td>MacKay G D</td>
<td>16</td>
</tr>
<tr>
<td>Madorsky S L</td>
<td>6, 7, 19</td>
</tr>
<tr>
<td>Mai Y W</td>
<td>205</td>
</tr>
<tr>
<td>Major D C</td>
<td>229</td>
</tr>
<tr>
<td>Makhijani A</td>
<td>119</td>
</tr>
<tr>
<td>Malan D H</td>
<td>7, 28</td>
</tr>
<tr>
<td>Mann M</td>
<td>22</td>
</tr>
<tr>
<td>Martin S</td>
<td>7, 233</td>
</tr>
<tr>
<td>Meyers H</td>
<td>25</td>
</tr>
<tr>
<td>Meyvis J</td>
<td>89, 94, 97, 98, 99, 166</td>
</tr>
<tr>
<td>Min K</td>
<td>7</td>
</tr>
<tr>
<td>Miyamani K</td>
<td>29</td>
</tr>
<tr>
<td>Mnzava E M</td>
<td>233</td>
</tr>
<tr>
<td>Modak</td>
<td>7</td>
</tr>
<tr>
<td>Mohan S R</td>
<td>234</td>
</tr>
<tr>
<td>Moore R E</td>
<td>211</td>
</tr>
<tr>
<td>Morgaan R P</td>
<td>119</td>
</tr>
<tr>
<td>Murty K</td>
<td>28, 29</td>
</tr>
<tr>
<td>N</td>
<td></td>
</tr>
<tr>
<td>Ndela D B</td>
<td>234</td>
</tr>
<tr>
<td>Neil W K</td>
<td>7, 22</td>
</tr>
<tr>
<td>Nelson M A</td>
<td>9, 20</td>
</tr>
<tr>
<td>Nieuwevelt C</td>
<td>75, 80</td>
</tr>
<tr>
<td>Nievergeld K</td>
<td>89, 94, 100, 166</td>
</tr>
<tr>
<td>O</td>
<td></td>
</tr>
<tr>
<td>Openshaw K</td>
<td>114</td>
</tr>
<tr>
<td>Omichi M</td>
<td>78</td>
</tr>
<tr>
<td>Overend R</td>
<td>16, 24</td>
</tr>
<tr>
<td>P</td>
<td></td>
</tr>
<tr>
<td>Parker W</td>
<td>22</td>
</tr>
<tr>
<td>Perlee H</td>
<td>29</td>
</tr>
<tr>
<td>Peters W A</td>
<td>20</td>
</tr>
<tr>
<td>Polley S L</td>
<td>37, 40</td>
</tr>
<tr>
<td>Poole A</td>
<td>119</td>
</tr>
<tr>
<td>Popali S C</td>
<td>143</td>
</tr>
<tr>
<td>Prasad C R</td>
<td>234</td>
</tr>
<tr>
<td>Prasad N B</td>
<td>119</td>
</tr>
<tr>
<td>Prema U</td>
<td>141</td>
</tr>
<tr>
<td>Pyle D L</td>
<td>15, 18, 20, 23, 24, 29</td>
</tr>
<tr>
<td>R</td>
<td></td>
</tr>
<tr>
<td>Rajabapaiah P</td>
<td>234</td>
</tr>
<tr>
<td>Raju S P</td>
<td>127, 141</td>
</tr>
<tr>
<td>Ramanayya K V</td>
<td>234</td>
</tr>
</tbody>
</table>
## Author Index

<table>
<thead>
<tr>
<th>Author Name</th>
<th>Pages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rata Suk S</td>
<td>107</td>
</tr>
<tr>
<td>Reddy A K N</td>
<td>120, 234</td>
</tr>
<tr>
<td>Ree Hvd</td>
<td>100</td>
</tr>
<tr>
<td>Richolson J</td>
<td>142</td>
</tr>
<tr>
<td>Roberts A F</td>
<td>7, 11, 16, 18, 22, 28, 29</td>
</tr>
<tr>
<td>Tinney E R</td>
<td>7, 28</td>
</tr>
<tr>
<td>Todd J J</td>
<td>53</td>
</tr>
<tr>
<td>Tsuchiya Y</td>
<td>58</td>
</tr>
<tr>
<td>Tuntawiroon N</td>
<td>107</td>
</tr>
</tbody>
</table>

**S**

<table>
<thead>
<tr>
<th>Author Name</th>
<th>Pages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Saima A</td>
<td>181, 182</td>
</tr>
<tr>
<td>Sakai Y</td>
<td>22</td>
</tr>
<tr>
<td>Samootsakorn P</td>
<td>38, 107</td>
</tr>
<tr>
<td>Samuelson P A</td>
<td>225</td>
</tr>
<tr>
<td>Sathyararayan S R C</td>
<td>234</td>
</tr>
<tr>
<td>Schluender E U</td>
<td>181</td>
</tr>
<tr>
<td>Seban R A</td>
<td>183</td>
</tr>
<tr>
<td>Shafisadeh</td>
<td>6, 9, 10, 16, 22, 23</td>
</tr>
<tr>
<td>Shanaahan Y J</td>
<td>128, 201, 234, 240</td>
</tr>
<tr>
<td>Sheppard D</td>
<td>28</td>
</tr>
<tr>
<td>Shivadev U K</td>
<td>7</td>
</tr>
<tr>
<td>Siddhartha Bhattacharyya</td>
<td>73</td>
</tr>
<tr>
<td>Sielecken M O</td>
<td>42, 75, 80, 166</td>
</tr>
<tr>
<td>Silversides C R</td>
<td>215</td>
</tr>
<tr>
<td>Smith R D</td>
<td>211</td>
</tr>
<tr>
<td>Snyder O P</td>
<td>37, 40</td>
</tr>
<tr>
<td>Sotter J G</td>
<td>18</td>
</tr>
<tr>
<td>Sparrow</td>
<td>184</td>
</tr>
<tr>
<td>Stamm A J</td>
<td>6, 24</td>
</tr>
<tr>
<td>Staude F J</td>
<td>216</td>
</tr>
<tr>
<td>Steward F R</td>
<td>174, 178</td>
</tr>
<tr>
<td>Strehlke B</td>
<td>216</td>
</tr>
<tr>
<td>Subramanian D K</td>
<td>120, 234</td>
</tr>
<tr>
<td>Sulilatu W F</td>
<td>89, 94, 97, 98, 99, 166</td>
</tr>
<tr>
<td>Sumi K</td>
<td>58</td>
</tr>
<tr>
<td>Sunberg U</td>
<td>216</td>
</tr>
<tr>
<td>Suzuki K</td>
<td>78</td>
</tr>
<tr>
<td>Tanaka T</td>
<td>22</td>
</tr>
<tr>
<td>Tsuchiya Y</td>
<td>58</td>
</tr>
<tr>
<td>Tuntawiroon N</td>
<td>107</td>
</tr>
</tbody>
</table>

**U**

<table>
<thead>
<tr>
<th>Author Name</th>
<th>Pages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ulinski C</td>
<td>233</td>
</tr>
<tr>
<td>Uska K. Rao</td>
<td>141</td>
</tr>
<tr>
<td>Vasudevarajav V A</td>
<td>141</td>
</tr>
<tr>
<td>Verhaart P</td>
<td>29, 33, 120</td>
</tr>
<tr>
<td>Verwoerd M</td>
<td>89, 94, 97</td>
</tr>
<tr>
<td>Visser P</td>
<td>42, 43, 57, 58, 120, 155</td>
</tr>
<tr>
<td>Vlak V</td>
<td>234</td>
</tr>
</tbody>
</table>

**V**

<table>
<thead>
<tr>
<th>Author Name</th>
<th>Pages</th>
</tr>
</thead>
<tbody>
<tr>
<td>van der Donck W</td>
<td>213</td>
</tr>
<tr>
<td>van der Meer Th H</td>
<td>181</td>
</tr>
<tr>
<td>Vasudevarajav V A</td>
<td>141</td>
</tr>
<tr>
<td>Verhaart P</td>
<td>29, 33, 120</td>
</tr>
<tr>
<td>Verwoerd M</td>
<td>89, 94, 97</td>
</tr>
<tr>
<td>Visser P</td>
<td>42, 43, 57, 58, 120, 155</td>
</tr>
<tr>
<td>Vita</td>
<td>234</td>
</tr>
</tbody>
</table>

**W**

<table>
<thead>
<tr>
<th>Author Name</th>
<th>Pages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wagner W</td>
<td>161, 180</td>
</tr>
<tr>
<td>Walander W</td>
<td>29</td>
</tr>
<tr>
<td>Walker J R</td>
<td>7, 16</td>
</tr>
<tr>
<td>Wannee C J</td>
<td>37, 38</td>
</tr>
<tr>
<td>Weatherford W</td>
<td>28</td>
</tr>
<tr>
<td>Williams F A</td>
<td>7</td>
</tr>
<tr>
<td>Wood T S</td>
<td>131</td>
</tr>
</tbody>
</table>

**Y**

<table>
<thead>
<tr>
<th>Author Name</th>
<th>Pages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yaccarino P</td>
<td>8</td>
</tr>
<tr>
<td>Yardi N R</td>
<td>143</td>
</tr>
</tbody>
</table>

**T**

<table>
<thead>
<tr>
<th>Author Name</th>
<th>Pages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tang W K</td>
<td>7, 22</td>
</tr>
<tr>
<td>Thurner F</td>
<td>22</td>
</tr>
<tr>
<td>Tillman D A</td>
<td>133</td>
</tr>
<tr>
<td>Zaror C A</td>
<td>15, 20, 29</td>
</tr>
</tbody>
</table>
SUBJECT INDEX

Appropriate technology
   Fuelwood production in developing countries: Toward an appropriate forest technology 213

Axes
   Fuelwood production in developing countries: Toward an appropriate forest technology 213

Biomass
   The pyrolysis of biomass: A general review 15
   Biomass production of biomass: A general review 15
   Biomass pyrolysis: A general review 15
   Biomass pyrolysis: A general review 15
   Biomass pyrolysis: A general review 15
   Biomass pyrolysis: A general review 15
   Biomass pyrolysis: A general review 15
   Biomass pyrolysis: A general review 15
   Biomass pyrolysis: A general review 15
   Biomass pyrolysis: A general review 15
   Biomass pyrolysis: A general review 15
   Biomass pyrolysis: A general review 15
   Biomass pyrolysis: A general review 15
   Biomass pyrolysis: A general review 15
   Biomass pyrolysis: A general review 15
   Biomass pyrolysis: A general review 15
   Biomass pyrolysis: A general review 15
   Biomass pyrolysis: A general review 15
   Biomass pyrolysis: A general review 15
   Biomass pyrolysis: A general review 15
   Biomass pyrolysis: A general review 15

Burning rate
   The performance of Thai charcoal stove 107

Carbonisation
   The pyrolysis of biomass: A general review 15

Cellulose
   The pyrolysis of biomass: A general review 15

Ceramics
   Wood burning stoves: Material selection and thermal shock testing of fired ceramic bodies 201

Charburning
   The science of wood combustion 5

Charcoal
   The pyrolysis of biomass: A general review 15

Charcoal stove
   The performance of Thai charcoal stove 107

Chimneyless stove
   Improved chimneyless fuelwood cookstoves (Pondicherry region) 141
   Closed stove model
     On designing woodstoves 33
   Combustion performance
     A comparison of the performance of three woodstoves 89
   Combustion of wood
     On designing woodstoves 33
     On designing woodstoves 33
     Open fires: Experiments and theory 155

Coppicing
   Fuelwood production in developing countries: Toward an appropriate technology 213

Cooking energy requirements
   On designing woodstoves 33

Cookstoves
   Fuel efficiency and performance of traditional and innovative cookstoves 119
   Improved chimneyless fuelwood cookstoves (Pondicherry region) 141
   Domestic food processing
     On designing woodstoves 33

Design
   Wood burning stoves: Material selection and thermal shock testing of fired ceramic bodies 201
   Design procedures
     The pyrolysis of biomass: A general review 15

Economics
   The pyrolysis of biomass: A general review 15

Efficiency
   A comparison of the performance of three woodstoves 89
   Heat transfer and cooking woodstove modelling 189
   Open fires: Experiments and theory 155

Energy conservation
   Fuel efficiency and performance of traditional and innovative cookstoves 119
   Improved chimneyless fuelwood cookstoves (Pondicherry region) 141

Firewood
   Fuel efficiency and performance of traditional and innovative cookstoves 119
   Firewood devices
     The efficiencies of firewood devices (Open-fire stoves, chulahs and heaters) 73

First law efficiency
   The efficiencies of firewood devices (Open-fire stoves, chulahs and heaters) 73

Flames
   The Science of wood combustion 5

Forest technology
   Fuelwood production in developing countries: Toward an appropriate forest technology 213
   Fuel efficiency
     Fuel efficiency and performance of traditional and innovative cookstoves 119
   Fuel efficiency standards
     The efficiencies of firewood devices (Open-fire stoves, chulahs and heaters) 73
   Fuel shortage
     Fuelwood and stoves: Lessons from Zimbabwe 253
<table>
<thead>
<tr>
<th>Subject Index</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Fuelwood sticks</strong>&lt;br&gt; Fuelwood production in developing countries: Toward an appropriate forest technology 213</td>
</tr>
<tr>
<td><strong>Fuel use</strong>&lt;br&gt; The performance of Thai charcoal stove 107</td>
</tr>
<tr>
<td><strong>Fuelwood</strong>&lt;br&gt; Fuel efficiency and performance of traditional and innovative cookstoves 119</td>
</tr>
<tr>
<td><strong>Fuelwood Production</strong>&lt;br&gt; Fuelwood production in developing countries: Toward an appropriate forest technology 213&lt;br&gt; Improved chimneyless fuelwood cookstoves (Pondicherry region) 141</td>
</tr>
<tr>
<td><strong>Heat</strong>&lt;br&gt; The Science of wood combustion 5</td>
</tr>
<tr>
<td><strong>Heat Balance</strong>&lt;br&gt; The performance of Thai charcoal stove 107</td>
</tr>
<tr>
<td><strong>Heat balance</strong>&lt;br&gt; A comparison of the performance of three woodstoves 89</td>
</tr>
<tr>
<td><strong>Heat flux density</strong>&lt;br&gt; Heat transfer and cooking woodstove modelling 189</td>
</tr>
<tr>
<td><strong>Heat transfer</strong>&lt;br&gt; Heat transfer and cooking woodstove modelling 189&lt;br&gt; The performance of Thai charcoal stove 107&lt;br&gt; Open fires: Experiments and theory 155</td>
</tr>
<tr>
<td><strong>Impact</strong>&lt;br&gt; Wood burning stoves: Material selection and thermal shock testing of fired ceramic bodies 201</td>
</tr>
<tr>
<td><strong>Improved stoves</strong>&lt;br&gt; Fuel efficiency and performance of traditional and innovative cookstoves 119</td>
</tr>
<tr>
<td><strong>Kilns</strong>&lt;br&gt; The pyrolysis of biomass: A general review 15</td>
</tr>
<tr>
<td><strong>Lid</strong>&lt;br&gt; Heat transfer and cooking woodstove modelling 189</td>
</tr>
<tr>
<td><strong>Moisture content</strong>&lt;br&gt; Open fires: Experiments and theory 155</td>
</tr>
<tr>
<td><strong>Natural draught</strong>&lt;br&gt; On designing woodstoves 33&lt;br&gt; The pyrolysis of biomass: A general review 15</td>
</tr>
<tr>
<td><strong>Open fire</strong>&lt;br&gt; On designing woodstoves 33&lt;br&gt; Open fires: Experiments and theory 155</td>
</tr>
<tr>
<td><strong>Open fire stoves</strong>&lt;br&gt; The efficiencies of firewood devices (Open-fire stoves, chulahs and heaters) 73</td>
</tr>
<tr>
<td><strong>Pangas</strong>&lt;br&gt; Fuelwood production in developing countries: Toward an appropriate forest technology 213</td>
</tr>
<tr>
<td><strong>Performance</strong>&lt;br&gt; Open fires: Experiments and theory 155</td>
</tr>
<tr>
<td><strong>Pondicherry</strong>&lt;br&gt; Improved chimneyless fuelwood cookstoves (Pondicherry region) 141</td>
</tr>
<tr>
<td><strong>Power level of a fire</strong>&lt;br&gt; Open fires: Experiments and theory 155</td>
</tr>
<tr>
<td><strong>Pyrolysis</strong>&lt;br&gt; The science of wood combustion 5</td>
</tr>
<tr>
<td><strong>Result reproducibility</strong>&lt;br&gt; The efficiencies of firewood devices (Open-fire stoves, chulahs and heaters) 73</td>
</tr>
<tr>
<td><strong>Retorts</strong>&lt;br&gt; The pyrolysis of biomass: A general review 15</td>
</tr>
<tr>
<td><strong>Rural energy</strong>&lt;br&gt; Fuel efficiency and performance of traditional and innovative cookstoves 119&lt;br&gt; Fuel wood production in developing countries: Toward an appropriate forest technology 213&lt;br&gt; Fuelwood and stoves: Lessons from Zimbabwe 233</td>
</tr>
<tr>
<td><strong>Short rotation period</strong>&lt;br&gt; Fuelwood production in developing countries: Toward an appropriate forest technology 213</td>
</tr>
<tr>
<td><strong>Stoves</strong>&lt;br&gt; Wood burning stoves: Material selection and thermal shock testing of fired ceramic bodies 201&lt;br&gt; The science of wood combustion 5&lt;br&gt; Stove design&lt;br&gt; Fuelwood and stoves: Lessons from Zimbabwe 233</td>
</tr>
<tr>
<td><strong>Stove geometry</strong>&lt;br&gt; Heat transfer and cooking woodstove modelling 189</td>
</tr>
<tr>
<td><strong>Stove parameters</strong>&lt;br&gt; The performance of Thai charcoal stove 107&lt;br&gt; Thai stove&lt;br&gt; The performance of Thai charcoal stove 107&lt;br&gt; Testing methods&lt;br&gt; The efficiencies of firewood devices (Open-fire stoves, chulahs and heaters) 73</td>
</tr>
<tr>
<td><strong>Thermal efficiency</strong>&lt;br&gt; Improved chimneyless fuelwood cookstoves (Pondicherry region) 141&lt;br&gt; Fuelwood and stoves: Lessons from Zimbabwe 233</td>
</tr>
<tr>
<td><strong>Traditional fuels</strong>&lt;br&gt; Fuel efficiency and performance of traditional and innovative cookstoves 119</td>
</tr>
<tr>
<td><strong>Thermal shock</strong>&lt;br&gt; Wood burning stoves: Material selection and thermal shock testing of fired ceramic bodies 201&lt;br&gt; Traditional stoves&lt;br&gt; Fuelwood and stoves: Lessons from Zimbabwe 233</td>
</tr>
</tbody>
</table>
Subject Index

Tool maintenance
- Fuelwood production in developing countries: Toward an appropriate forest technology 213

Useful heat
- The performance of Thai charcoal stove 107

Village energy consumption
- Fuel efficiency and performance of traditional and innovative cookstoves 119

Wood
- The pyrolysis of biomass: A general review 15

Woodburning
- Fuel efficiency and performance of traditional and innovative cookstoves 119

Woodstoves
- Heat transfer and cooking woodstove modeling 189
- A comparison of the performance of three woodstoves 89

Woodstove design
- On designing woodstoves 33
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