Some performance tests on open fires and the family cooker

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SOME PERFORMANCE TESTS ON OPEN FIRES AND THE FAMILY COOKER

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A Report from
The Woodburning Stove Group
Departments of Applied Physics and Mechanical Engineering,
Technical University of Eindhoven
And
Division of Technology for Society, TNO, Apeldoorn
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1. INTRODUCTION

by

K. Krishna Prasad

This report describes some tests conducted at the Eindhoven University of Technology on wood burning stoves - the only systems that poor people of this world seem to be able to afford for cooking their food. The work itself was initiated in response to a seemingly simple question posed by one of the authors of the Club du Sahel report on "Energy in the development strategy of Sahel". The question was: what is the efficiency of an open fire?

It was very soon realized that the answer to the above question could not be provided in terms of a single number. There were far too many variables involved and it seemed that a systematic study was essential to understand the processes governing the performance of wood-burning systems.

There was of course another part to the question though it was not explicitly stated. This part arose with the assumption that the traditional open fire has a very poor efficiency. A natural corollary to this assumption is: how can the efficiency of an open fire be improved? This in turn raised two additional questions. The first one was: why does the open fire give such a low efficiency? Secondly, what has been done to improve its efficiency?

The literature on the subject is quite meagre. It certainly does not match in size or quality what is available on other renewable energy conversion systems like bio-gas or solar energy. Whatever literature that exists on the subject of stoves to be used for cooking is by and large long on claims but quite short on serviceable engineering data.

All these different strands of thought culminated in the formulation of a project being funded by the Dutch Minister for development cooperation. The project is being jointly undertaken by the Technische Hogeschool, Eindhoven and TNO, The Netherlands Organization of Applied Scientific Research. The main ambition of the project is to develop adequate engineering data that would assist in the design, manufacture and operation of stoves for cooking purposes using wood (possibly charcoal) as fuel. The project will primarily focus its attention on the problems connected with stove usage in Sahel countries. It is hoped that the results obtained would have more general validity than suggested above.

The present report describes work that predates the commencement of the official project. It provides some results on open fires as well as on the family cooker, a design that was developed at the Appropriate Technology unit of the Technische Hogeschool Eindhoven. The open fire work is really by way of identifying the kind of parameters involved in determining its efficiency. A surprising feature of the work is that remarkably high efficiencies can be obtained from open fires under suitable conditions of operation. The family cooker results are primarily devoted to an investigation of the problems and prospects of constructing reliable heat balances in some of the newer designs. This has been done with a view to pinpoint the strengths and weaknesses of the modern efforts to overcome a rather old problem. A discussion section attempts in a qualitative manner to identify some of the factors that are to be considered while designing stoves for fuel economy.
2. EXPERIMENTS WITH THE OPEN FIRE

by

P. Visser\* and P. Verhaar

2.1 Introduction

One of the simplest devices in which wood can be burned for cooking food or heating water is to place three stones of roughly equal height around the fire and place the cooking vessel on these stones. Among the wood-stove research group this configuration is called "the open fire". In all less developed countries of the world the open fire is used in one shape or another.

Our experiments began with the simple aim of determining the efficiency of the open fire in order to have a standard for comparison with other wood-burning stoves we were going to test. It came as a surprise when we began to realize that many variables may possibly influence the performance of the open fire. This report describes the first series of experiments on the open fire carried out at the laboratory for Fluid Machinery of the Eindhoven University of Technology.

2.2 The experiments

One of the most striking aspects of the open fire is the conceivable number of variables that could influence its performance. To obtain some experience in handling an open fire and get some insight into the most important factors governing its performance a small series of experiments was set up. In a second series of experiments we tried to determine the influence of some specific parameters while care was taken to keep other parameters constant.

A table was covered with a layer of refractory bricks. The same kind of bricks (6 x 11 x 22 cm.) were used as stones for the fire, usually resting on their 6 x 22 cm. side forming a pan support 11 cm. high. For most of the experiments the bricks were placed in a star configuration (see figure 2.1). A number of experiments was done with the supporting bricks in a delta configuration (see fig. 2.2). Initially, some experiments were done with a square grate of 11 x 11 cm. placed in the space between the supporting bricks (see fig. 2.3). Later, more systematic experiments were done with a round grate of 26 cm. diameter and square holes of 1 x 1 cm., made from round steel bars of 6 mm. diameter (see fig. 2.4). In most of the experiments, a covered aluminium pan of 28 cm. diameter, 24 cm. height and 1 mm. thick was used. In most cases it contained 5 kg. of water.

The experiments were carried out in the laboratory where there was no wind or draft. Gaseous combustion products were exhausted to the outside of the building by means of a ventilator.

\*Student at the Eindhoven University of Technology. The open fire experiments constitute part of his graduation assignment for the Faculty of Mechanical Engineering.
The test procedure was the usual one of boiling water. The following measurements were made:

a) the quantity of water used before the start of the experiment;
b) the quantity of wood to be used in the experiment (based on the approximate time the experiment was to last), divided up into the desired charges;
c) the temperature of the water in the pan is continually recorded on a strip-chart recorder;
d) the time is taken as soon as the flames of the wood, lit with a propane torch hold; at that instant the pan is placed on the fire;
e) the time each new charge of wood is added to the fire;
f) the time the water in the pan starts boiling;
g) the time the water stops boiling;
h) the mass of water lost through boiling.

The average heat-flow from the fire is calculated from the combustion value multiplied by the total mass of wood used minus the mass of the last charge.

\[ Q_f = \frac{(m_f - m_l) \cdot g}{T} \] (kW)

Where:
- \( Q_f \) = average heat-flow from the fire (kW)
- \( m_f \) = mass of the last charge of wood (kg)
- \( T \) = time from the start of the experiment to the introduction of the last charge (s)

This procedure is adopted in order to get representative values for the fire in its stationary state.

The experiment is considered terminated when the water in the pan stops boiling. As the water usually continues to boil for a considerable time after the introduction of the last charge, the average heat-flow into the water is calculated using the efficiency.

\[ Q_w = \eta Q_f \] (kW)

**\text{A new charge is added when the fire has stopped giving off flames.}**

**\text{The time taken for the fire to burn up completely after adding the last charge is much longer than the time between two successive charges. The time between lighting the first charge and adding the second is a little longer but quite close to the time interval between other successive charges.}**
The moisture content of the wood is defined as follows:

\[ \phi = \frac{\text{mass of water in the wood}}{\text{mass of dried wood}} \]

The wood was always dried first in an electric oven at 105° C until its weight was constant. When wood with a certain moisture content was desired a weighed amount of dried wood was hermetically sealed in a plastic bucket together with a measured amount of water. After some days the water was completely absorbed by the wood.

After each experiment the efficiency was calculated as the ratio of net heat absorbed by the water in the pan to the mass of dry wood burned times the combustion value of the wood.

\[ \eta = \frac{m_w \cdot C(t_b - t_i) + m_v \cdot R}{m_f \cdot B} \]

where:
- \( \eta \) = efficiency (kg)
- \( m_w \) = initial amount of water in the pan (kg)
- \( m_v \) = amount of water evaporated during experiment (kg)
- \( m_f \) = amount of fuel burnt (kg)
- \( C \) = specific heat of water (kJ/kg.K)
- \( t_b \) = temperature of boiling water (°C)
- \( t_i \) = initial temperature of water in pan (°C)
- \( R \) = heat of evaporation of water at atmospheric pressure and 100°C (kJ/kg)
- \( B \) = combustion value of wood used (kJ/kg)

Values for the various quantities used were:

\[ C = 4.2 \text{ kJ/kg.K} \]
\[ R = 2256.9 \text{ kJ/kg} \]
\[ B = 19.883 \text{ kJ/kg} \]

The calorific value used above is an average of two measurements carried out by TNO. The values obtained were 20.860 and 18.905 kJ/kg. Thus the average value used above can produce errors of \( \pm 4.9\% \) in the efficiency values quoted in this report. It is useful to compare the measured calorific value with the average values quoted by Arola (1978). This is done in Table 2.1.
2.3 Results of initial tests

For all tests in this phase of work, 5 kg. of water was used in an aluminium pan of 28 cm. diameter and 24 cm. high. The diameter of the fire was 26 cm. and the wood used was white fir. The following variables were changed for different tests:

(a) size of fuel wood;
(b) total amount of wood burnt;
(c) charge size;
(d) moisture content of wood;
(e) configuration of the bricks;
(f) height of the pan from table surface / grate; and
(g) grate / no grate.

The reasons for choosing the fixed quantities were as follows. The pan was the largest size we could buy in one of the local department stores. 5 liters of water occupied about 1/3 of the vessel. This appears representative of porridge cooking in the Sahel countries. The bricks acting as a support for the pan were placed touching the perimeter of a circle of 26 cm. diameter thus allowing the pan to rest on 1 cm. of fire-brick. White fir was at the time the only readily available waste wood from the carpentry shop at the university. Other conditions and results can be seen in table 2.2.

The results in table 2.2 do not allow for comparison as the total burning times are widely divergent. Some general tendencies however, can be noted. A burning time of about one hour seems reasonable to diminish the effect of warming up the water when a higher rate of heat transfer occurs. Smaller pieces of wood tend to give a higher efficiency. The height of the pan above the fire-base seems an important parameter. The one experiment where wood with a moisture content of 10.8 % was used gave a rather high efficiency. The general figures for the efficiency were much higher than we had been led to believe from earlier publications. Detailed comparisons are presented in section 4.

2.4 Results of second series of tests

In this series it was decided to hold most of the variables considered in the previous section constant and study the influence of moisture content in wood and height of pan above the fire base. Both these sets were repeated with a grate. The variables mentioned below were held constant:

(a) aluminium pan of 28 cm. diameter and 24 cm. height;
(b) 5 kg. of water;
(c) size of fuel wood - 1,5 x 1,5 x 5 cm.;
(d) charge size of 100 g. of dry wood equivalent;
(e) total wood burnt - 1000 g. of dry wood equivalent;
(f) type of wood - white fir;
(g) star configuration for the supporting bricks; and
(h) fire diameter of 26 cm.
Experiments were done with wood with a moisture content ranging from zero to 30%. The height of the pan above the fire-base was varied from 5 to 22 cm. The grate used was round with an outside diameter of 26 cm. and 1 x 1 cm. holes made from round bars of 6 mm. diameter.

The results are summarized in tables 2.3 to 2.7 and are displayed as plots in figs. 2.5 to 2.7. Table 2.5 shows the results of check experiments carried out from time to time. Barring the first test in that table which was run for too short a time, the rest show a remarkable consistency among themselves. The variation among them is definitely within the experimental accuracy. Thus we can justifiably say that the results presented here indicate genuine physical effects.

The influence of moisture content on the efficiency is seen from table 2.3 and fig. 2.5. The moisture content of the wood generally has an adverse effect on the efficiency which is to be expected. Surprisingly the efficiency for low moisture content is slightly better than for completely dry wood. This could possibly be explained by the fact that rate of fuel consumption is lower than for absolutely dry wood. As a result there probably is more time for diffusion of air into the flames improving combustion which in turn may be responsible for the slight rise in efficiency. At higher moisture contents the influence of the moisture in the fuel becomes more pronounced decreasing the efficiency. The table also lists the efficiencies obtained after correcting for the heat used up to drive out the moisture (the numbers in parentheses under the efficiency column represent these corrected values).

Efficiency as a function of the height of the pan above the base of the fire is presented in table 2.4 and fig. 2.5. The highest efficiency is observed when the position of the pan is between 5 and 10 cm. above the base of the fire. Below 5 cm., the combustion was seriously impaired resulting in more smoke and a longer burning time for a fixed quantity of wood. At a position of more than 10 cm. above the fire base, radiation losses to the surroundings and dilution of combustion products by entrainment of cold air probably account for a drop in efficiency.

Tables 2.5 and 2.7 show the results for the fires with a grate for the above two cases. Figs. 2.5 and 2.6 also include these points. A grate in general improves the efficiency presumably by providing better access for air thus improving the rate of combustion.

Finally the heat output of the fire together with the net heat input to the water as a function of height above the base are plotted in fig. 2.7 for fires with and without grates.

These experiments indicate that an efficiency close to 30% can be achieved with an open fire.
### TABLE 2.1

**TYPICAL HEATING VALUES OF WOOD**

Values quoted by Arola (1978)

<table>
<thead>
<tr>
<th></th>
<th>Range</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Hardwoods</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>wood</td>
<td>17.600 - 20.700</td>
<td>19.900</td>
</tr>
<tr>
<td>bark</td>
<td>16.100 - 23.900</td>
<td>18.700</td>
</tr>
<tr>
<td><strong>Softwoods</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>wood</td>
<td>18.100 - 26.300</td>
<td>20.700</td>
</tr>
<tr>
<td></td>
<td>19.000 - 23.600</td>
<td>20.800</td>
</tr>
<tr>
<td>(white fir)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
### TABLE 2.2

SOME INITIAL EXPERIMENTS ON OPEN FIRES

<table>
<thead>
<tr>
<th>sl.no.</th>
<th>Dry Fuel wt., g</th>
<th>init. temp. of water, °C</th>
<th>time to boil, mts</th>
<th>total burn time, mts.</th>
<th>evap. water g</th>
<th>efficiency %</th>
<th>remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>600</td>
<td>19.5</td>
<td>21.5</td>
<td>-</td>
<td>200</td>
<td>17.9</td>
<td>200 g. charge; a</td>
</tr>
<tr>
<td>2.</td>
<td>600</td>
<td>19.5</td>
<td>22.0</td>
<td>-</td>
<td>200</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3.</td>
<td>800</td>
<td>18.5</td>
<td>18.5</td>
<td>-</td>
<td>100</td>
<td>12.1</td>
<td>400 g. charge; b</td>
</tr>
<tr>
<td>4.</td>
<td>800</td>
<td>20.0</td>
<td>18.0</td>
<td>-</td>
<td>100</td>
<td>12.2</td>
<td></td>
</tr>
<tr>
<td>5.</td>
<td>800</td>
<td>21.0</td>
<td>19.5</td>
<td>34</td>
<td>100</td>
<td>11.8</td>
<td>400 g. charge; c</td>
</tr>
<tr>
<td>6.</td>
<td>400</td>
<td>21.0</td>
<td>27.0</td>
<td>36</td>
<td>100</td>
<td>23.6</td>
<td>100 g. charge; a</td>
</tr>
<tr>
<td>7.</td>
<td>1.100</td>
<td>23.0</td>
<td>27.0</td>
<td>60</td>
<td>800</td>
<td>15.6</td>
<td>arbitrary charges; d</td>
</tr>
<tr>
<td>8.</td>
<td>1.000</td>
<td>24.0</td>
<td>29.0</td>
<td>80</td>
<td>1.000</td>
<td>19.3</td>
<td>100 g. charge; e</td>
</tr>
<tr>
<td>9.</td>
<td>700</td>
<td>24.0</td>
<td>34.0</td>
<td>75</td>
<td>700</td>
<td>22.8</td>
<td>50 g. charge; e</td>
</tr>
<tr>
<td>10.</td>
<td>812.3</td>
<td>25.0</td>
<td>32.0</td>
<td>100</td>
<td>700</td>
<td>19.5</td>
<td>100 g. charge; f</td>
</tr>
</tbody>
</table>

**NOTES:**
(a) size of wood: 1.5 x 1.5 x 5 cm; height: 11 cm; star configuration
(b)                          ; " : 18 cm;                    
(c)                          ; " : " ; triangular configuration
(d)                          ; " : " ; star configuration
(e)                          ; " : 1.5 x 1.5 x 5 cm; " : 11 cm;    ; a 12 cm diameter grate
(f)                          ; " : " ; " ; "    ; moisture content = 10.8%

**OTHER EXPERIMENTAL DETAILS:**

Fire diameter: 26 cm; Aluminium vessel of 28 cm diameter and 24 cm height; a lid always covered the vessel; oven-dry wood was used.
<table>
<thead>
<tr>
<th>sl.no.</th>
<th>moisture content, %</th>
<th>dry fuel wt., g</th>
<th>ini.temp. of water, C</th>
<th>time to boil, mts.</th>
<th>total burn time, mts.</th>
<th>evap. water g</th>
<th>efficiency %</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>5</td>
<td>1,200</td>
<td>22</td>
<td>28</td>
<td>90</td>
<td>1,200</td>
<td>21,8 (22,0)</td>
</tr>
<tr>
<td>2.</td>
<td>10</td>
<td>1,000</td>
<td>22</td>
<td>36</td>
<td>100</td>
<td>1,000</td>
<td>19,6 (19,8)</td>
</tr>
<tr>
<td>3.*</td>
<td>10,8</td>
<td>812,3</td>
<td>25</td>
<td>32</td>
<td>100</td>
<td>700</td>
<td>19,5 (19,8)</td>
</tr>
<tr>
<td>4.</td>
<td>15</td>
<td>1,000</td>
<td>15</td>
<td>50</td>
<td>120</td>
<td>850</td>
<td>18,6 (19,0)</td>
</tr>
<tr>
<td>5.*</td>
<td>15</td>
<td>1,000</td>
<td>14</td>
<td>68</td>
<td>110</td>
<td>300</td>
<td>12,5 (12,7)</td>
</tr>
<tr>
<td>6.</td>
<td>20</td>
<td>900</td>
<td>31</td>
<td>39</td>
<td>110</td>
<td>800</td>
<td>18,2 (18,8)</td>
</tr>
<tr>
<td>7.</td>
<td>25</td>
<td>1,000</td>
<td>24</td>
<td>45</td>
<td>92</td>
<td>900</td>
<td>18,8 (19,2)</td>
</tr>
<tr>
<td>8.a)</td>
<td>32</td>
<td>894,7</td>
<td>23</td>
<td>80</td>
<td>125</td>
<td>450</td>
<td>14,7 (15,3)</td>
</tr>
</tbody>
</table>

NOTES: (i) All experiments were carried out with a height of 11 cm except the one marked + which was carried out at a height of 18 cm.

(ii) Experiment marked * was carried out with moist wood from the tropical environmental room at the Department of Architecture at THE.

(iii) Fuel charge was 100 g at a time and pan was of 28 cm diameter and 24 cm height.

(iv) Experiment marked a) was started with an initial charge of dry wood.
TABLE 2.4

EFFECT OF HEIGHT ON OPEN FIRES

<table>
<thead>
<tr>
<th>sl. no.</th>
<th>height cm</th>
<th>ini. temp. of water, C</th>
<th>time to boil, mts.</th>
<th>total burn time, mts.</th>
<th>evap. water gms</th>
<th>efficiency %</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>6.0</td>
<td>24</td>
<td>30.0</td>
<td>100</td>
<td>1.000</td>
<td>20.5</td>
</tr>
<tr>
<td>2.</td>
<td>7.5</td>
<td>25</td>
<td>23.3</td>
<td>90</td>
<td>1.350</td>
<td>23.2</td>
</tr>
<tr>
<td>3.</td>
<td>9.0</td>
<td>22</td>
<td>24.0</td>
<td>80</td>
<td>1.300</td>
<td>22.9</td>
</tr>
<tr>
<td>4.</td>
<td>10.0</td>
<td>22</td>
<td>28.0</td>
<td>80</td>
<td>1.050</td>
<td>20.1</td>
</tr>
<tr>
<td>5.*</td>
<td>11.0</td>
<td>24</td>
<td>25.0</td>
<td>75</td>
<td>1.100</td>
<td>20.5</td>
</tr>
<tr>
<td>6.</td>
<td>14.0</td>
<td>22</td>
<td>37.0</td>
<td>80</td>
<td>750</td>
<td>16.7</td>
</tr>
<tr>
<td>7.</td>
<td>18.0</td>
<td>24</td>
<td>30.0</td>
<td>75</td>
<td>600</td>
<td>14.8</td>
</tr>
<tr>
<td>8.</td>
<td>22.0</td>
<td>22</td>
<td>44.0</td>
<td>75</td>
<td>300</td>
<td>11.6</td>
</tr>
</tbody>
</table>

NOTES: (i) 1 kg of fuel was burned in charges of 100 g at a time except in expt. no. 5 for which the total fuel used was 980 g.
(ii) 5 kg of water was used in a pan of 28 cm diameter and 24 cm height
(iii) Oven dry wood was used in the experiments.
TABLE 2.5

SOME CONTROL EXPERIMENTS

<table>
<thead>
<tr>
<th>sl.no.</th>
<th>dry fuel wt., g</th>
<th>ini. temp. of water, C</th>
<th>time to boil, mts.</th>
<th>total burn time, mts.</th>
<th>evap. water g</th>
<th>efficiency %</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>400</td>
<td>23</td>
<td>24</td>
<td>35</td>
<td>150</td>
<td>24.5</td>
</tr>
<tr>
<td>2.</td>
<td>1.000</td>
<td>21</td>
<td>27,5</td>
<td>75</td>
<td>1.050</td>
<td>20.2</td>
</tr>
<tr>
<td>3.</td>
<td>980</td>
<td>24</td>
<td>25</td>
<td>75</td>
<td>1.100</td>
<td>20.5</td>
</tr>
<tr>
<td>4.</td>
<td>1.000</td>
<td>22</td>
<td>23,5</td>
<td>72</td>
<td>1.150</td>
<td>21.3</td>
</tr>
</tbody>
</table>

NOTES: (i) All experiments were run with a brick height of 11 cm
(ii) Pan size: 28 cm diameter and 24 cm height.
<table>
<thead>
<tr>
<th>sl.no.</th>
<th>moisture content, %</th>
<th>dry fuel wt, g</th>
<th>init. temp. of water, °C</th>
<th>time to boil, mts.</th>
<th>total burn time, mts.</th>
<th>evap. water g</th>
<th>efficiency %</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>0</td>
<td>1.000</td>
<td>21</td>
<td>20.0</td>
<td>65</td>
<td>1.200</td>
<td>21.9</td>
</tr>
<tr>
<td>2.</td>
<td>5</td>
<td>1.000</td>
<td>22</td>
<td>21.0</td>
<td>65</td>
<td>1.300</td>
<td>22.6</td>
</tr>
<tr>
<td>3.</td>
<td>10</td>
<td>1.000</td>
<td>21</td>
<td>23.30</td>
<td>65</td>
<td>1.100</td>
<td>20.7</td>
</tr>
<tr>
<td>4.</td>
<td>15</td>
<td>1.000</td>
<td>24</td>
<td>28.30</td>
<td>70</td>
<td>1.130</td>
<td>20.8</td>
</tr>
<tr>
<td>5.</td>
<td>20</td>
<td>1.000</td>
<td>21</td>
<td>40</td>
<td>90</td>
<td>915</td>
<td>18.2</td>
</tr>
<tr>
<td>6.</td>
<td>25</td>
<td>1.000</td>
<td>20.5</td>
<td>46</td>
<td>110</td>
<td>720</td>
<td>16.5</td>
</tr>
</tbody>
</table>

NOTES:  
(i) All experiments were carried out with a height of 11 cm  
(ii) Fuel charge was 100 gr dry fuel equivalent at a time  
(iii) Pan was of 28 cm diameter and 24 cm height, aluminium  
(iv) Grate diameter 26 cm
TABLE 2.7

EFFECT OF HEIGHT ON OPEN FIRES WITH A GRATE

<table>
<thead>
<tr>
<th>sl.no.</th>
<th>height cm</th>
<th>ini. temp. of water, C</th>
<th>time to boil, mts.</th>
<th>total burn time, mts.</th>
<th>evap. water g</th>
<th>efficiency %</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>5</td>
<td>23</td>
<td>21,0</td>
<td>65</td>
<td>1.750</td>
<td>27.8</td>
</tr>
<tr>
<td>2.</td>
<td>7</td>
<td>22</td>
<td>17,3</td>
<td>60</td>
<td>1.500</td>
<td>25.2</td>
</tr>
<tr>
<td>3.</td>
<td>7</td>
<td>21</td>
<td>19,3</td>
<td>65</td>
<td>1.600</td>
<td>26.5</td>
</tr>
<tr>
<td>4.</td>
<td>9</td>
<td>21</td>
<td>20,5</td>
<td>65</td>
<td>1.600</td>
<td>26.5</td>
</tr>
<tr>
<td>5.</td>
<td>10</td>
<td>21</td>
<td>18,0</td>
<td>60</td>
<td>1.400</td>
<td>24.2</td>
</tr>
<tr>
<td>6.</td>
<td>11</td>
<td>21</td>
<td>20,0</td>
<td>65</td>
<td>1.200</td>
<td>21.9</td>
</tr>
<tr>
<td>7.</td>
<td>14</td>
<td>23</td>
<td>18,3</td>
<td>50</td>
<td>1.000</td>
<td>19.5</td>
</tr>
<tr>
<td>8.</td>
<td>18</td>
<td>21</td>
<td>22,3</td>
<td>50</td>
<td>0.800</td>
<td>17.4</td>
</tr>
<tr>
<td>9.</td>
<td>22</td>
<td>22</td>
<td>29,0</td>
<td>50</td>
<td>0.400</td>
<td>12.75</td>
</tr>
</tbody>
</table>

NOTES:  
(i) Grate diameter 26 cm  
(ii) The rest of the experimental conditions were as in Table 2.3
Fig. 2.1. Star configuration of bricks.
Fig. 2.3. Delta configuration of bricks.
Fig. 2.3. Small grate in position.
Fig. 2.4. Large grate in position.
Fig. 2.8. Effect of moisture on efficiency.
Fig. 2.6. Effect of height on efficiency.

- dry wood
- * fire with a grate
- o fire without a grate

\[ \eta (\%) \]

(height (cm))
Fig. 2.7. Heat output of the fire and net heat input to the water as a function of height.
3. THE FAMILY COOKER

by

M.O. Sielcken and C. Nieuwvelt

3.1 Introduction

The family cooker is a design that has attracted some attention in development circles as a possible solution for the wood-burning problem in rural areas of the third world. The design is based upon the so-called "Majo stove", which was being used in The Netherlands towards the end of World War II. It is an all metal stove, can take two pans and has a chimney with a damper. It is claimed that the design can burn a variety of fuels and is capable of producing an efficiency of about 20% (Attwood, 1979). In this chapter, we describe some tests conducted on the family cooker with charcoal as the fuel. The choice of charcoal was primarily due to inadequate ventilation facilities at the time in the laboratory. Since the completion of the tests described here, wood-burning tests have been taken up. As such the main emphasis in the work was to explore methods for obtaining reliable heat balances in cooking stoves with a view to apply these in subsequent work.

3.2 Design

The design proposed by Overhaart (1978) is shown in fig. 3.1. It essentially consists of a combustion chamber, a flue box and a chimney. The combustion chamber is built up of two concentric cylinders held together by four tubes for admitting air into the inner cylinder. Fuel is loaded on top of a grate that is located above the air tubes. A second pan-hole between the combustion chamber and the chimney can be used for purposes of pre-heating or keeping food warm. When not in use, a covering plate closes this hole.

Fig. 3.2 shows the gas flow path in the stove. A study of this figure suggests that there can be considerable heat loss from the outer cylinder of the combustion chamber. To estimate this effect, some tests were performed by insulating the outer cylinder with a 2 cm. thick layer of glass-wool which in turn was covered by a 0,3 mm. aluminium sheet.

Further details of construction of the stove are available in a manual prepared by Overhaart (1979).

The work reported here was carried out by Sielcken as his final assignment for the diploma from Hogere Technische School, Amsterdam.
3.3 Experimental details

The experimental approach was similar to the one that was reported in section 2. The details are summarized in table 3.1. The fire once started requires for its sustenance the chimney draft. A cold chimney is unable to provide this and requires preheating. This was done either by a propane burner or by burning a wad of paper at the bottom of the chimney. It was also necessary to maintain the fuel bed depth to about half the combustion chamber height to minimize the pressure drop across the fuel bed in this phase of operation. Otherwise, there was a tendency for the fire to die down. Once the fire is established, the stove can be operated with the full design depth.

The charge, the total amount of fuel burnt and the damper position were varied during the study.

Temperatures were continuously measured at several points along the gas flow path and on the metal surfaces by a set of chromel-alumel thermo-couples in stainless steel sheaths. The measuring points are indicated in fig. 3.2. The thermo-couples were hooked on to a central multi-channel data-logger (Modulog of Intercole Systems Ltd., Southampton, England) through a terminal at the experimental site. The data-logger produced punched paper-tape that was processed successively on a teleprinter and a Hewlett Packard plotter system (HP 9100 B calculator and HP 9125 A calculator plotter). Spot checks on the temperature were made at site with a Leeds and Northrup 914 Numatron digital thermometer connected to the terminal of the data-logger.

Carbon-monoxide and carbon-dioxide were monitored continuously with an infra-red gas analyzer (Binos CO-CO₂ analyzer, Leybold-Heraeus, Germany). The output of the analyzer was again connected to the data-logger mentioned above. The voltage output on the punched tape was converted to gas volumetric percentages with the calibration provided by the manufacturer. A similar instrument for oxygen was not available and a few spot checks were made with an Orsat apparatus.

This complex measuring system was chosen for two reasons. Firstly, multi-point strip chart recorders which would have been adequate for the purpose, were not accessible to the group at the time. The second reason involves a complex of arguments about the philosophy for testing wood-burning stoves which presumably have to be used in the Sahel-countries.

The first point to be considered in this connection was the cooking practice in the Sahel. A preliminary enquiry revealed that: (a) family sizes were large and as such large quantities of food were to be cooked; and (b) long periods of time were involved in the entire process of cooking. This indicated that the choices for the quantity of water and the duration of test both had to be large. The family cooker, being able to take the required pan size, was however able to hold just about 150 g. of charcoal. This charcoal got burnt in about 30 minutes - a period barely sufficient to bring 3 litres of water to boil.

More detailed information on this aspect is being at present obtained through a series of field tests being conducted by a Belgian group at the suggestion of Prof. Dr. Ir. G. de Lepelitre of de Katholieke Universiteit at Leuven, Belgium.
The above situation demanded that the stove required periodic refilling with fuel if the experiment was to be carried out for a period of the order of 2 hours. This period of time was also felt necessary for purposes of performance comparison of metal stoves with clay stoves which are claimed to perform better only when long durations of cooking are involved. Refilling with fuel required the pan to be taken out of its seat. All this meant that it would be difficult to achieve steady state operation during the course of the experiment. Thus measurements at isolated instants of time could result in unreliable estimates. Hence the decision for temperature and gas analysis measurements on a continuous basis. The results to be presented later completely justify the approach.

An experiment was terminated when the last charge of fuel got completely burnt. This usually coincided with the water ceasing to boil.

### 3.4 Efficiency

The definition of efficiency used was the same as the one in section 2. The calorific values of two samples of charcoal were measured by TNO*, Apeldoorn. The results were: 31.792 and 34.199 kJ/kg. An average value of 33.000 kJ/kg. was used in all the calculations reported. Thus on a calculated efficiency of 30 %, one can expect a departure of 1 percentage point due to non-uniformities of calorific value of charcoal used. It is also interesting to compare the calorific value used in the present work with those reported in the literature (see table 3.2). The present value is seen to be a representative one.

The results are summarized in table 3.1. The efficiency varies from 21 % to 34 % for different design and operation conditions. There was no effort made to carry out a study of the specific effect of different variables on the performance of the stove. Still the results can be used to discern certain trends.

Comparing run numbers 4 and 9, we see that a smaller charge of fuel is likely to produce a higher efficiency. Run numbers 9 and 17 show that operation of the damper results in a higher efficiency. Run numbers 9 and 18 show that it is beneficial to insulate the outer cylinder of the combustion chamber. The maximum efficiency recorded during the trials was 34.4 % and was obtained with an insulated stove and damper operation (run no. 19). For the insulated stove, the use of the second pan results in an increase of efficiency by 3 percentage points (run numbers 18 and 20). The water in the second pan (about half of the quantity in the first pan) reached a maximum temperature of 58° C.

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* The Netherlands Organization for Applied scientific research

** There were two reasons for this choice: (i) charcoal was being used in the experiments but our primary interest is in wood; and (ii) most of the effort in the investigation went into establishing methods that had to be used in obtaining reliable heat balances in cooking stoves.
3.5 Heat balance estimates

As stated earlier bulk of the effort in this phase of work went into drawing heat balances. The temperature, CO and CO₂ records obtained for run number 21 are shown in fig. 3.3. Also shown is the way in which the damper was operated during the course of the experiment. These records clearly illustrate the problems associated with the estimation of heat balances in this class of equipment.

The temperature recorded directly above the fire (corresponding to thermo-couple 100) shows large changes. The changes of the 35th and the 74th minute are clearly due to the refilling operation - the effect of this operation is noticeable for a period of about 15 minutes. We have puzzled about the other "gyrations" in the records, but it is difficult to explain them. While it might appear for a cursory examination of the records of other points in the gas flow path that such violent fluctuations do not occur, a closer look reveals that they are not insignificant. For example in a period of about 5 minutes from the 60th minute, the temperatures at positions 100 (on top of the fuel bed), 105 (at the centre of the flue box) and 107 (at the chimney entrance) show nearly 100 % change. Presumably this change is associated with fuel bed adjustment that can occur during the combustion in such batch process systems.

The following procedure was adopted to derive heat balances from the records of fig. 3.3. Arithmetic averages of temperatures were calculated for run numbers 13 and 21 the uninsulated and insulated cases respectively. These are shown in table 3.3. Similarly for run 21 average gas compositions are presented in table 3.4. For easy reference the experimental details for these two runs are appended as a note to the tables.

The heat balance for the family cooker type of stove comprises of the following elements:

(i) heat input (mass of fuel burnt corrected for moisture content multiplied by calorific value);
(ii) heat absorbed by water (including the heat used up for evaporation);
(iii) convective and radiative losses from the sides of the combustion chamber, the pan and the top-lid;
(iv) flue box loss;
(v) loss due to unburnt CO in the flue gas; and
(vi) sensible heat carried away by the chimney gases.

Barring the first two elements, which have been presented in the previous section as part of the efficiency calculation, the other elements in the list are subject to various levels of uncertainty. In the following, we describe in detail the methods that have been used in the present work to arrive at reasonable estimates for these elements.

Convective heat losses have been estimated by the following free convection correlation (Kreith & Black, 1980):

---

*Gas composition measuring system was not available at the time run no. 13 was carried out.*
\[ \overline{Nu} = C (Gr \text{ Pr})^n \]  \hspace{1cm} (3.1)

where \( \overline{Nu} \) is the mean Nusselt number given by

\[ \overline{h} \frac{L}{K} \]

with \( \overline{h} \) as the mean heat transfer coefficient in \( W / m^2K \)

\( L \), a characteristic length (height for the combustion chamber and pan sides, diameter for the pan lid) in m, \( k \), the thermal conductivity of air, \( W/mK \)

\( Gr \), the Grashof number given by

\[ \frac{g \beta \Delta T L^3}{\nu^2} \]

with \( g \), the acceleration due to gravity, \( m/s^2 \)

\( \beta \), volumetric expansion coefficient, \( K^{-1} \)

\[ \Delta T = T_w - T_\infty \]

\( T_w \), wall temperature, \( K \)

\( T_\infty \), environment temperature, \( K \)

\( \nu \), the kinematic coefficient of viscosity, \( m^2/s \)

\( C \) and \( n \) are dependent on the geometry of the surface under consideration as well as the value of \( Gr \text{ Pr} \).

The values used here were taken from a table provided by Kreith & Black and are:

\[ C = 0.59 \quad n = \frac{1}{4} \quad \text{for the combustion chamber and pan sides; and} \]

\[ C = 0.15 \quad n = \frac{1}{3} \quad \text{for the pan lid.} \]

The heat transfer coefficient estimated thus was used to calculate heat loss from

\[ Q_c = \overline{h} A (T_w - T_\infty) t \]  \hspace{1cm} (3.2)

where \( Q_c \) is the convective heat loss in kJ,

\( A \) the area of the surface concerned in \( m^2 \), and

\( t \) the duration of the experiment in s.

\( T_w \) was taken to be 120 °C for the pan sides, 100 °C for the pan lid and measured as 90 °C for the combustion chamber side. \( T_\infty \) was taken as 20 °C.

The radiative heat loss was estimated from (Eckert & Drake, 1972)
\[ Q_r = \sigma \varepsilon A (T_W^4 - T_{\infty}^4) t \]

where \( Q_r \) is the radiative heat loss in kJ,
\( \sigma \) the Stefan Boltzmann constant
\[ = 5.6697 \times 10^{-8} \text{ W/m}^2\text{K}^4, \]
and \( \varepsilon \) the emissivity.

The greatest uncertainty in this formula arises in the choice of \( \varepsilon \).

The following values were used in the present work:

<table>
<thead>
<tr>
<th>Surface Description</th>
<th>( \varepsilon )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blackened aluminium pan side</td>
<td>0.6</td>
</tr>
<tr>
<td>Pan lid</td>
<td>0.09</td>
</tr>
<tr>
<td>Insulated combustion chamber</td>
<td>0.09</td>
</tr>
<tr>
<td>Sheathing (case B)</td>
<td></td>
</tr>
<tr>
<td>Mild steel cover of the combustion chamber (case A)</td>
<td>0.66</td>
</tr>
</tbody>
</table>

The first value was picked as a value intermediate between a surface that is nicely coated with soot and an uncoated aluminium surface.

The rest of the values were obtained from Sparrow & Cess (1970).

The estimation of the remaining elements in the list requires the gas mass flow through the system. Direct measurement of mass flow was difficult because of the rather low velocities encountered in the equipment (see mass flow estimates later). Hence, it was decided to derive mass flow estimates from the mass of fuel burnt, an assumed fuel analysis and the combustion products analysis.

The fuel was assumed to be made up entirely of carbon, moisture and ash. The moisture content was measured and the ash content was assumed to be 4%. The latter assumption is reasonable if we note that: wood on the average has an ash content of 1% (Arola 1978); 25% charcoal is produced from wood (Earl 1975); and all the ash is held in the charcoal during the conversion process.

A second problem in this connection is the fact that oxygen content in the gas stream was not continuously monitored. This was overcome by noting that a definite quantity of N\(_2\) is associated with the oxygen in CO and CO\(_2\). Totalling the N\(_2\) percentage thus estimated along with the measured percentages of CO and CO\(_2\) would not add up to 100.

It was assumed that the remainder consisted of moisture from the fuel (a known quantity) and excess air. Details of this calculation for run number 21 are shown in appendix 1.

The composition shown in table 3.4 is the final result.

It is a matter of simplicity to calculate the mass flow through the system on the basis of a carbon balance between the fuel and the combustion products. The calculation details are again in appendix 1.

\*In future experiments ash formed after completion of burning will be collected and weighed.
The heat loss in the flue box is then estimated by

\[ Q_f = \dot{M}_g \left( \bar{C}_p \left( T_i \right) T_i - \bar{C}_p \left( T_e \right) T_e \right) \]  \hspace{1cm} (3.3)

where \( Q_f \) is the heat loss in the flue box in kJ
\( \dot{M}_g \), mass flow of gas in kg
\( \bar{C}_p \), a weighted mean specific heat of the combustion products evaluated at the relevant temperature in kJ/kg K
\( T_i \), temperature at the inlet to the flue box in K
(corresponds to location 104A in fig.3.2)
and \( T_e \), temperature at the exit from the flue box in K.
(corresponds to location 107 in fig.3.2).

The values of \( \bar{C}_p \) actually employed are also given in the appendix mentioned earlier.

The other two items in our list follow similarly.
The heat of combustion of CO was taken as 10.111 kJ/kg (Spalding 1955). The chimney loss was estimated in a manner similar to what was done for estimating the flue box loss.

The results of these calculations are summarized in table 3.5.

It is appropriate here to make a few observations on the reliability of the estimates presented in the table. The question of reliability is all the more important if we note that the primary purpose of drawing a heat balance is to isolate specific points of design that require research/development effort. This identification is further complicated by the fact that we are unable to account for nearly a sixth of the heat input. Thus the discussion that follows will centre around the factors that could have possibly contributed to the latter situation.

The first thing to note is that every item in the table is subject to errors of various types. The error in the heat input estimate arises due to the assumption about the calorific value of the fuel. For the present work, we have assumed an average of just two measurements resulting in an uncertainty of \( \pm 3.6\% \) in the heat input value. This implies that the unaccounted for loss can vary from 12 to 19.2%.

There is much more confidence in items 2 and 3 not only because of the many more measurements that we have done on these items, but also because these are relatively simple measurements to make.
All the other estimates in the table are subject to serious doubt. The loss from the pan accounts for nearly 10% of the total heat input, of which over 50% is by convection. The main error here arises due to the fact that the pan temperatures were not measured. There is reason to believe that our assumptions are not far off the mark and as such the convective loss could be considered quite reliable. The same thing cannot be true of the radiative loss. The temperature measurements are more crucial since radiation loss depends on the fourth power of temperature. Moreover the assumption of the emissivities of the surfaces concerned are indeed a matter of considerable speculation - a problem that we might not be able to overcome as part of the present project.

The heat loss from combustion chamber side is expected to be quite accurate. While the problem of emissivity remains here as well, it is not expected to be severe since this surface is not exposed to the flames.

The next three items are very questionable items indeed. The measurement of temperature of "hot" gases surrounded by "cold" walls by a thermocouple is subject to considerable radiation errors - this can be really serious in such low velocity systems as ours. Estimates of this error could not be derived because of unknown wall temperatures. The second problem is in connection with the estimation of mass flows. Direct measurement of mass flows seems to be extremely difficult.

A detailed assessment of the different techniques will be presented in a subsequent report. But it is sufficient for the present purposes to make an assertion that a carbon balance technique can be quite reliable for charcoal burning systems. The uncertainty in the present calculation procedure arises mainly due to air leaks in the system.

The first question we need to ask is about the possible effect of air leaks on the heat balance. We can identify three sources for the leak: (i) the first pan seat; (ii) the second pan seat; and (iii) the joints. The main effect of these leaks is to reduce the gas temperatures. Since we use gas temperatures for estimating the heat losses in the flue box and the chimney, we need to know to a reasonable approximation the amount of air that has leaked from each of the three sources mentioned above. This in turn requires measurement of gas composition at several stations along the gas flow path.

An attempt was made to estimate the extent of the leaks in this system. This proved rather difficult with our measuring system. We had only one meter for monitoring CO and CO2 and we had to use a valve to switch from one point to the next. As such the measurements were restricted to sampling just two points - the position on top of the fuel bed and in the chimney. Run number 22 in table 3.1 presents this result and fig. 3.4 gives the gas composition. A second test was conducted with most of leaks stopped with high temperature cement sealing. The results of this test are given under run number 23 in table 3.1 and fig. 3.5 presents gas analysis results.
The results of run number 22 were analyzed to obtain an idea of the extent of leaks in the system. The average CO₂-CO contents at the two monitoring stations are listed in table 3.6. The last row shows the ratios for the two components at the two monitoring stations. They show that the measurements as well as the averaging procedure are self-consistent. Using an average value for this ratio, it was estimated that a mass flow of nearly 9 kg. on top of the fuel bed became nearly 15 kg. in the chimney for run number 21. While this difference explains the unaccounted for heat loss in our heat balance, the outcome should be considered rather fortuitous since we are unable to clearly calculate the amount of air that is leaked from each of the sources mentioned earlier. Comparisons of run numbers 22 and 23 merely establish the fact that the efficiency of the stove is affected very little by the leaks. Of course they would affect to a certain extent the gain in heat by the second pan.

Finally, it should be mentioned that the heat loss estimation due to the formation of CO is expected to be quite accurate.

The above discussion reveals that the major errors in table 3.5 are likely to be in the estimation of the flue box loss and the chimney loss which together account for over 21 % of the heat input. These have been shown to be underestimates. By more measurements, it is possible to reduce the unaccounted for loss to something of the order of 10 % or less. Of course such an optimism may not be justifiable when the system is using wood as a fuel.
APPENDIX 1

ESTIMATION OF HEAT CARRIED BY THE COMBUSTION PRODUCTS IN THE FAMILY COOKER

The stoichiometric relation for the formation of p% of CO₂ and q% of CO by the combustion of solid carbon is given by

\[(p+q)\text{mol C} + \left(\frac{q}{2}\right)\text{mol O}_2 \to p\text{ mol CO}_2 + q\text{ mol CO} \ldots \text{(A 1)}\]

The nitrogen associated with \((p + q/2)\) mol \(\text{O}_2\) is \(3,76 (p + q/2)\) mol.

Thus for \(p = 8,9\%\) and \(q = 2,75\%\), the nitrogen percentage is \(38,63\%\).

Thus the three together make up a total of \(50,28\%\).

The remaining \(49,72\%\) is assumed to be water vapour and air.

Assuming that the water vapour in the combustion products is entirely due to the moisture in the charcoal, the volume of water vapour is estimated as follows. We further assume that the water vapour behaves as a perfect gas. Noting that: a perfect gas at a pressure of one atm. and \(0°C\) occupies \(22,4\) litres of volume; the molecular weight of water vapour is \(18\); and the mass of water vapour (5,2% by weight of dry fuel) is 22,249, we obtain the volume of water vapour to be

\[
\frac{22,24}{18} \times 22,4 = 27,68 \text{ litres.}
\]

In order to convert this into a percentage, we need to establish the actual volumetric equivalent of the mixture percentage calculated above. This can be obtained by rewriting equation (A1) as

\[
1g \text{ C} + \frac{1,87}{p+q} (p + \frac{q}{2}) \text{L O}_2 \to \frac{1,87}{p+q} p \text{ L CO}_2 + \frac{1,87}{p+q} p \text{ L CO} \ldots \text{(A2)}.
\]

The amount of carbon burned during the experiment after allowing for moisture and ash is 410,65 g. Thus the volume of combustion products generated over the period is

- \(\text{CO}_2 : 586,65 \text{ L}\)
- \(\text{CO} : 181,28 \text{ L}\)
- \(\text{N}_2 : 2.546,50 \text{ L}\)

totalling to 3314,43 L (all volumes refer to 1 atm. and \(0°C\)).

This volume corresponds to a percentage of \(50,28\%\). Thus the 27,68 litres of water vapour will correspond to \(0,42\%\). Thus the unused air flowing through the fuel bed is \(49,3\%\) of the total gas volume flow on top of the fuel bed. This leads to the gas composition presented in table 3.4.

\[\text{The constant 1,87 comes from } 22,4/12 \text{ where 12 is the atomic weight of carbon. Symbol L stands for litres.}\]
The total gas mass flow is then found from the densities of the different gases at 1 atm and 0 °C. These are summarized in table A1. A weighted mean specific heat of the gas mixture is calculated from the individual specific heats and their respective masses. These results are shown in table A2. These results have been used in the expression (3.3).
**TABLE A1**

TOTAL GAS MASS FLOWS FOR THE TEST PERIOD OF RUN NUMBER 21

<table>
<thead>
<tr>
<th>gas</th>
<th>volume in litres</th>
<th>density in kg/m$^3$</th>
<th>mass in kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO$_2$</td>
<td>586.65</td>
<td>1.977</td>
<td>1.159</td>
</tr>
<tr>
<td>CO</td>
<td>181.28</td>
<td>1.250</td>
<td>0.227</td>
</tr>
<tr>
<td>H$_2$O</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>O$_2$</td>
<td>682.92</td>
<td>1.430</td>
<td>0.977</td>
</tr>
<tr>
<td>N$_2$</td>
<td>5.115.3</td>
<td>1.251</td>
<td>6.399</td>
</tr>
<tr>
<td></td>
<td>total gas mass</td>
<td></td>
<td>8.784</td>
</tr>
</tbody>
</table>

**TABLE A2**

WEIGHTED MEAN SPECIFIC HEAT AT CONSTANT PRESSURE OF THE MIXTURE IN TABLE A1

(specific heat units: kJ/kg K)

<table>
<thead>
<tr>
<th>temperature in K</th>
<th>600</th>
<th>373</th>
<th>293</th>
</tr>
</thead>
<tbody>
<tr>
<td>gas</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CO$_2$</td>
<td>1.076</td>
<td>0.921</td>
<td>0.842</td>
</tr>
<tr>
<td>CO</td>
<td>1.0877</td>
<td>1.0459</td>
<td>1.0421</td>
</tr>
<tr>
<td>O$_2$</td>
<td>1.0044</td>
<td>0.9355</td>
<td>0.9203</td>
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<tr>
<td>N$_2$</td>
<td>1.0756</td>
<td>1.0446</td>
<td>1.0408</td>
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<tr>
<td>mixture</td>
<td>1.06535</td>
<td>1.03403</td>
<td>0.99859</td>
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</tbody>
</table>

**NOTE:** Data on density and specific heat are taken from Eckert & Drake (1972).
Fig. 3.1. The Family Cooker.
Fig. 3.2. Gasflow path and thermocouple locations in the Family Cooker.
Fig. 3.3. Temperature history, fluegas composition and damper position during run 21.
Fig. 3.4. Flue gas composition history at two locations and damper position during run 22.
Fig. 3.5. Flue gas composition history at two locations and damper position after sealing of leaks. Run 23.
# TABLE 3.1

**FAMILY COOKER: SUMMARY OF RESULTS**

<table>
<thead>
<tr>
<th>experiment no.</th>
<th>moisture in fuel (%)</th>
<th>fuel charge (g)</th>
<th>total amount of fuel (g)</th>
<th>water content in the pan (g)</th>
<th>water temperature (°C)</th>
<th>evaporated water (g)</th>
<th>time to boil (min.)</th>
<th>total burning time (min.)</th>
<th>damper position</th>
<th>efficiency (%)</th>
<th>remarks</th>
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<td>300</td>
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<td>16</td>
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<td>-</td>
<td>-</td>
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<td>a</td>
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<tr>
<td>02</td>
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<td>192</td>
<td>383</td>
<td>5030</td>
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<td>785</td>
<td>-</td>
<td>75</td>
<td>0°</td>
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<td>65</td>
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<td>0°</td>
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<td>220</td>
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<td>480</td>
<td>3140</td>
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<td>100</td>
<td>0°</td>
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<td>b,c</td>
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<td>600</td>
<td>3265</td>
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<td>-</td>
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<td>d</td>
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<td>400</td>
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<td>21</td>
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<td>0°-67°</td>
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<td>b,f</td>
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<td>150</td>
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<td>1260</td>
<td>33</td>
<td>90</td>
<td>0°</td>
<td>33,5</td>
<td>f,g</td>
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<tr>
<td>1600</td>
<td>21</td>
<td>$T_e = 58^\circ$C</td>
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<td></td>
<td></td>
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<td>1530</td>
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<td>b,f,g</td>
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<td>32,1</td>
<td>f,g</td>
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<tr>
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<td>Calorific Value, kJ/kg</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>-----------------------------------------------</td>
<td>------------------------</td>
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<td></td>
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<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>1. Bramé &amp; King (1967)</td>
<td>33.700</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2. Wiersum</td>
<td>29.000 - 30.200</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>3. Rose &amp; Cooper</td>
<td>33.100 - 34.750</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>5. Earl (1975)</td>
<td>29.310</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
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</tr>
<tr>
<td>6. Present measurements</td>
<td>31.792 &amp; 34.199</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>
a. A big pan was used with a diameter of 280 mm and height of 240 mm. For the other experiments a smaller pan was used with diameter 240 mm and height 180 mm.

b. Temperatures were recorded.

c. The chimney diameter was decreased from 110 mm to 45 mm by placing a metal ring on top of the exhaust.

d. A few gas composition measurements were done by an Orsat apparatus.

e. The height of the combustion chamber is increased by 50 mm.

f. The combustion chamber was insulated by 20 mm thick layer of glass wool and covered by an aluminium sheat.

g. A second pan was used; size: diameter 180 mm, height 110 mm.

h. CO and CO₂ content in the flue gases were monitored.
TABLE 3.3

TEMPERATURE DISTRIBUTION IN THE FAMILY COOKER
(TIME AVERAGES; TEMPERATURES IN °C)

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<th>position</th>
<th>case A</th>
<th>case B</th>
</tr>
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<td>100</td>
<td>429</td>
<td>466</td>
</tr>
<tr>
<td>103</td>
<td>338</td>
<td>376</td>
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<td>67</td>
<td>50</td>
</tr>
<tr>
<td>110</td>
<td>198</td>
<td>-</td>
</tr>
<tr>
<td>111</td>
<td>158</td>
<td>-</td>
</tr>
<tr>
<td>113</td>
<td>-</td>
<td>90</td>
</tr>
<tr>
<td>114</td>
<td>-</td>
<td>90</td>
</tr>
</tbody>
</table>

TABLE 3.4

GAS ANALYSIS OVER THE FUEL BED FOR CASE B

<table>
<thead>
<tr>
<th>component</th>
<th>% by volume</th>
</tr>
</thead>
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<tr>
<td>CO₂</td>
<td>8.90*</td>
</tr>
<tr>
<td>CO</td>
<td>2.75*</td>
</tr>
<tr>
<td>H₂O</td>
<td>0.42</td>
</tr>
<tr>
<td>O₂</td>
<td>10.36</td>
</tr>
<tr>
<td>N₂</td>
<td>77.60</td>
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</tbody>
</table>

* measured quantities

NOTES ON TABLES 3.3 AND 3.4.

<table>
<thead>
<tr>
<th>description</th>
<th>case A</th>
<th>case B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuelt burnt</td>
<td>600 g</td>
<td>450 g</td>
</tr>
<tr>
<td>moisture content</td>
<td>6.8%</td>
<td>5.2%</td>
</tr>
<tr>
<td>duration of experiment</td>
<td>200 mts</td>
<td>140 mts</td>
</tr>
<tr>
<td>damper: fraction open</td>
<td>0.585</td>
<td>0.276</td>
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</table>
TABLE 3.5
HEAT BALANCE ESTIMATES FOR THE FAMILY COOKER

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<th>kJ</th>
<th>%</th>
<th>kJ</th>
<th>%</th>
</tr>
</thead>
<tbody>
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<td>1. Heat input</td>
<td>18.539</td>
<td></td>
<td>14.116</td>
<td></td>
</tr>
<tr>
<td>2. Heat lost due to moisture evaporation</td>
<td>86</td>
<td>0.46</td>
<td>50</td>
<td>0.35</td>
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<tr>
<td>3. Heat absorbed by water in the pan</td>
<td>5.430</td>
<td>29.29</td>
<td>4.585</td>
<td>32.48</td>
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<td>4. Heat loss from pan:</td>
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<td></td>
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<tr>
<td>convection - sides</td>
<td>926</td>
<td>5.00</td>
<td>648</td>
<td>4.60</td>
</tr>
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<td>top</td>
<td>298</td>
<td>1.60</td>
<td>208</td>
<td>1.47</td>
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<tr>
<td>radiation - sides</td>
<td>710</td>
<td>3.83</td>
<td>497</td>
<td>3.52</td>
</tr>
<tr>
<td>top</td>
<td>33</td>
<td>0.18</td>
<td>23</td>
<td>0.16</td>
</tr>
<tr>
<td>5. Heat loss from combustion chamber:</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>convection</td>
<td>1.586</td>
<td>8.55</td>
<td>511</td>
<td>3.62</td>
</tr>
<tr>
<td>radiation</td>
<td>1.727</td>
<td>9.31</td>
<td>58</td>
<td>0.41</td>
</tr>
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<td>6. Heat lost in flue box</td>
<td>-</td>
<td>-</td>
<td>2.233</td>
<td>15.8</td>
</tr>
<tr>
<td>7. Heat lost due to formation of CO</td>
<td>-</td>
<td>-</td>
<td>2.285</td>
<td>16.2</td>
</tr>
<tr>
<td>8. Heat lost up the chimney</td>
<td>-</td>
<td>-</td>
<td>818</td>
<td>5.97</td>
</tr>
<tr>
<td>9. Unaccounted for loss</td>
<td>7.743</td>
<td>41.77</td>
<td>2.200</td>
<td>15.6</td>
</tr>
</tbody>
</table>
### TABLE 3.6

**EFFECT OF LEAKS ON GAS ANALYSIS AT TWO STATIONS**

<table>
<thead>
<tr>
<th></th>
<th>CO₂ (%)</th>
<th>CO (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>On top of fuel bed</td>
<td>8.87</td>
<td>2.76</td>
</tr>
<tr>
<td>In the chimney</td>
<td>4.86</td>
<td>1.57</td>
</tr>
<tr>
<td>Ratio between the two</td>
<td>1.825</td>
<td>1.758</td>
</tr>
</tbody>
</table>
4. DISCUSSION

by

K. Krishna Prasad and P. Verhaart

4.1 Introduction

The present chapter serves a three-fold purpose. It compares the results obtained in this work with some earlier results on open fires / traditional systems and charcoal stoves. Secondly, some design implications of the results obtained so far are pointed out. Finally, a few remarks are made on further course of work.

4.2 Present results compared with earlier results

The efficiencies quoted for open fires and traditional stoves vary wildly. Here is a sampling of the results known to the authors.

(a) Singer (1959)
A traditional 2-hole wood stove used in Indonesia has an efficiency of 6.1 to 7.3% while a three hole model shows an efficiency of 6.4 to 7.3%.

(b) Van Daelen (1978)
Several different types of open fires yielded efficiencies ranging from 2.5 to 17%.

(c) The Sahel Report (1978)
The three-stone open fire has an efficiency of 5 to 8% (these apparently are based on field observations).

(d) Salaria (1978)
A traditional Indian stove shows an efficiency of 12.3%; addition of a grate to the design increases the efficiency to 15.8%.

It is interesting to note that the efficiencies measured in our lab are consistently higher than those quoted above. The major difference between the earlier work and the present work lies in the care with which the fuel is prepared before firing and the rather controlled manner in which the charges are added at periodic intervals.

Similarly, we note below a series of results for charcoal stoves.

(a) Singer (1959)
a charcoal stove of Indonesian design (it does not have a chimney) shows efficiencies ranging from 30.5 to 36%.

(b) NBO - ECAFE study (1970)
A complicated design when operated with soft coke provided an efficiency of 20.7% (a chimney design).

(c) Salaria (1978).
A traditional Indian stove showed an efficiency of 9.6%; this increased to 20.3% (only 8.4 of which was absorbed by the main pan) with a chimney and a rather complicated heat recovery system.

(d) Openshaw (1979)
Field trials with a metal stove showed an efficiency of only 8% while a clay stove showed an efficiency of 15%. Both designs have no chimney.
The family cooker shows a range of efficiencies from 21 to 34.4%. Addition of a second pan is likely to increase the highest efficiency by 3 percentage points - this just about equals the best efficiency quoted by Singer for a relatively simple design.

4.3 Design implications

While we have far too few results to make any definite design recommendations, it appears worthwhile to make some tentative observations on certain essential features that lead to fuel economy in the design and operation of a stove.

At the very outset we wish to make two points which appear to us as indisputable. It is simply futile to speak about the efficiency of a stove as a universal attribute of a given design. The efficiency of a given design is a strong function of how it is operated. Our open fire results bear abundant testimony to this. When the charge was changed from 200 g. to 100 g., the efficiency changed from 17.9 to 23.6%. For a chimney design the efficiency is a strong function of how the damper is used during the operation of the stove. The second point is connected with the role of the geometry on the efficiency. When the height of the bricks was changed from 7.5 cm. to 22 cm. in the open fire experiments, the efficiency dropped from 23.2 to 11.5%. In conventional engineering work, such changes are taken very seriously. But wood stove literature is replete with designs and claims that happily ignore these basic features of good engineering design.

Fuel preparation is an important factor governing the efficiency achievements of a given design. Smaller pieces of wood do produce higher efficiencies. While we agree that our practice can be dismissed as something that can be achieved only within the precincts of a laboratory, we believe that this suggestion is worthy of serious consideration. The cost of preparing wood in small pieces should be measured against the savings that will accrue from afforestation programmes through increased efficiency of operation of stoves.

Similarly use of dry wood could result in considerable fuel economy. Of course this assertion cannot be directly proved from the present results as there is too much scatter in them due to non-uniformity of experimental conditions. However it is significant to note that the amount of heat required to drive out the moisture is usually a fraction of the amount of efficiency gain that can result from using dry fuel (see table 2.3).

A design consideration that is crucial for obtaining higher efficiencies is the height at which the pan is set from the fuel bed. The present results suggest that there are two regimes of variation of efficiency with height.
In the first regime - for heights between 6 and 11 cm. - there appears to be a maximum point in the efficiency-height curve. Generally speaking it appears that the height should not be too different from 7,5 cm. The second regime starts from about 11 cm.; increases of height beyond this value will result in drastic reduction in efficiency. As a matter of rule, whatever be the height, introduction of a grate will improve the efficiency of a stove (see fig. 2.7).

We now turn our attention to the family cooker. A number of design points emerge from the heat balance study presented in table 3.3. The first point is that the heat loss from the pan sides represents something like 8% of the total heat input to the system. This is a common drawback of most of the chimney systems that are on the market at the moment. One would expect that this loss could be prevented by sinking the pan inside the combustion chamber. Such a design would also show additional increases in efficiency due to the fact that the sides of the pan, instead of being exposed to the cold ambient, will be exposed to the hot combustion gases. This practice is fairly common in Indian homes that use hot water for bathing purposes. The only modern design that incorporates such a feature is the one due to Van Daele and De Lepeleire (1979), at least as far as the present authors' information goes. Of course one has to pay a price for this. Such designs can accept only one pan size unless special provisions are made to accept several pan sizes.

The second point that emerges from the study is the enormous difference an insulation cover makes for the heat loss from the sides of the combustion chamber. Insulating the sides reduces this loss by about 14 percentage points. Such reduction was anticipated in an initial heuristic analysis of the design. However the surprising discovery was that the prevention of this loss does not show up as an equivalent gain in the efficiency - there is a mere 3 percentage point increase in the efficiency. Apparently the heat thus saved is carried away by the combustion gases. The result taken at its face value suggests that a stove made out of clay, because of its better insulating properties, need not necessarily result in higher efficiencies. The preference for clay stoves should probably be based on considerations of economics rather than processes in a stove.

This brings us to the third question in our discussion on heat balance study of the family cooker - namely that of flue box loss which represents about a sixth of the heat input. Assuming that heat loss from the bottom is negligible, the possible maximum of heat recovery in the second pan on the basis of area ratios of the second pan hole and the total exposed area of the flue box was estimated to be about 370 kJ. This amount of heat is sufficient to raise the temperature of 2 litres of water by about 44°C, well short of boiling temperature of water if we start with cold water temperatures of the order of 20°C. This seems to be in reasonable agreement with the result of run number 20 in which 1.6 litres of water in the second pan increased in temperature by 37°C in a period of 90 minutes (in contrast to 140 minutes of the heat balance experiment). Thus the introduction of the second pan will increase the efficiency of the family cooker by about 2 percentage points. Of course a clay stove is likely to produce a slightly better result.
The fourth and final point concerns the presence of carbon monoxide on top of the fuel bed. The measurements indicate nearly 75% excess air availability on top of the fuel bed. Yet not all the carbon monoxide got burnt. This is a vital question since the carbon monoxide accounts for a sixth of the fuel used up in the experiment. The reason for the formation of carbon monoxide is held to be inadequate mixing. An obvious way of providing for this mixing is to increase the available combustion volume. With the present design such an increase in volume can only be achieved through a simultaneous increase of surface area with automatic increase in heat loss. In fact this is exactly what happened when we increased the height of the combustion chamber by 30 mm. (run number 15 in table 3.1). The efficiency decreased by about 1.6 percentage point in comparison with run number 11 which happens to provide the closest approximation to the experimental conditions of run number 15.

The detailed discussion presented above really raises more questions than it answers. But it also points to directions along which investigations are required in order to come up with acceptable solutions to the design problem of wood burning stoves for cooking. We shall suggest some of these directions in the next section.

4.4 A note on further work

It is the firm conviction of the present authors that a better understanding of the combustion characteristics of the open fires holds the key to the development of simple yet efficient designs of stoves.

Two variables have not been touched upon during the course of the present investigation: use of large pieces of wood and wind effects. Both these effects can to a certain extent establish the differences that are likely to occur between laboratory achievements and field realizations. A second question that needs to be looked into is the relationship, if any, that might exist between the charge size and the height of the bricks. The main question here would be whether greater heights (say higher than 11 cm.) can show increased efficiency if we use larger charges. The idea is that we would be bringing the top surface of the fuel bed in closer proximity to the pan bottom. A third feature that needs a closer examination is the limit of usefulness of a grate vis-a-vis fuel economy. For designs without chimneys introduction of a grate will provide a means of combustion control. Finally, it seems worthwhile carrying out gas analysis and temperature surveys in the open fires. Such surveys will yield valuable information about the amount of air entrainment at each height and the extent of combustion completion. Information of this nature could prove useful for designing naturally aspirated closed combustion chambers.

The main attention as far as the family cooker is concerned will now be diverted to the use of wood. The whole range of variables investigated with the open fires has to be covered for this design as well. A knotty problem that needs to be resolved is in connection with the drawing of heat balances. It should be stated here that reasonable heat balances could be obtained only through redundant measurements. Thus it is essential to measure temperatures and carry out gas analysis at several places in the gas stream. In addition many more surface temperatures need to be monitored. With the presently available equipment particularly for gas analysis, we are far from this basic requirement.
However, if it is possible to establish a steady periodic regime, the problem can presumably be tackled with the present equipment. Also the establishment of a steady periodic regime will make the process of drawing heat balances more comfortable and subject to much less uncertainty.

The rather optimistic statement above however may not be justified for wood burning systems. The stream of combustion products will inevitably contain unburned volatiles. Monitoring these should be considered a rather tough task. Moreover, wood contains nearly 40% oxygen. It is not clear at the present moment whether this oxygen participates in the combustion process and if so, how? This means that the technique adopted in the present investigation will certainly be unreliable. Estimation of air aspirated into the system can only be estimated through the monitoring of nitrogen. Direct measurement of mass flows would be highly desirable, but is beset with too many difficulties. Thus even the rather unsatisfactory state of the present heat balance may be difficult to achieve for a wood burning system.

We will wind up the discussion in this section in a speculatory note. In the previous section we pointed out the difficulty for providing adequate mixing in a closed combustion chamber. A design feature that could provide better mixing is through the introduction of secondary air on top of the fuel bed in a direction normal to the main flow direction. Such a procedure can be expected to lead to more complete combustion in a rather compact combustion chamber. Of course the design problem is tricky because optimum performance in a naturally aspirated system can be obtained only through proper matching of secondary air ports with fuel bed depth (which along with the chimney damper position will control the amount of primary air passing through the fuel bed). It seems very worthwhile investigating in sufficient detail the design proposed by Verhaart (1979) for the introduction of secondary air.
5. **CONCLUDING REMARKS**

by

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What has been established in the foregoing pages is that the task of designing a wood-burning stove is not a matter that could be disposed of in a few weeks of testing. The number of variables that enter into the picture are far too many. What appeared to us at the beginning to be very careful experimentation, has turned out to be not that careful at all when we started to interpret our data. We are nowhere near identifying a set of clearly defined performance parameters. These problems need much closer scrutiny than has been possible so far and it is expected that future reports from the group will shed more light on these aspects.
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