ON THE DESIGNING OF HIGH POWER KEROSENE STOVES

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Executive Summary

Increasing population and dwindling tree resources can be expected to lead to the substitution of kerosene in place of wood as a household energy source in urban Africa. A test programme on kerosenee stoves - mostly of Asian origin - carried out by the Eindhoven University of Technology showed that they had a maximum power output of 2 kW (World Bank 1985) A complementary field study carried out in Niger in the framework of the UNSO/NER project, UNSO/NER/X02/B, showed that these power outputs in combination with the measured efficiencies resulted in unduly long cooking times for the average meal in Niger. A preliminary analysis of the available designs indicated that a simple scaling up procedure would price the stove out of the market.

It is against this background that the World Bank awarded a R&D contract to the Eindhoven University of Technology:

i. to develop a high power, low cost kerosene wick stove;
ii. to use the information obtained during the course of the work to recommend measures to adapt existing stoves

Splitting-up the work in two parts suggests that two different design tasks are involved. However, both tasks overlap to a large extent. Improving existing designs can not be done without some basic understanding of the physics involved. Very little published information on this subject is available. In the limited scope of the present work, it was really impossible to carry out detailed investigations. As such many ad-hoc decisions to limit the scope of the work were made. Thus the work reported here must be thought of as a first step in designing of kerosene stoves. That is why the report tries to give more than merely descriptions of the experiments performed. It is also meant to be a starting point for more research, development and design work. Consequently an important outcome of the work has been the deeper insight obtained in the physical processes. It was shown that:

i. the transport capacity of the wicks is not the limiting factor in getting a high maximum power.
ii. the maximum and minimum power are determined by the size of the free wick end and the temperature.
iii. the temperature and thus the power, can be increased considerably by closing the gap between outer flame holder and shield.
iv. complete combustion at maximum power can be achieved by making the flame holders higher without changing the air hole density
v. the temperature on the tank can be reduced with 25 % by adding a radiation shield to the inner flame holder

vi. the life time of the wicks can be increased by preventing oxygen coming in the direct vincinity of the wicks

The work resulted in two prototype stoves: the modified Thomas Cup and the Pet stove which fulfil the objectives set in the terms of reference. Both stoves have the characteristis which make them suited for testing at the family level. This is the conclusion drawn on the basis of the tests performed on the laboratory models of the stoves mentioned. However, the prototypes are not yet ready for large scale production. The final design can only be fixed in close collaboration with the stove manufacturer. Only thereafter, the technical drawings can be made and the specifications per stove part given.

When the work started it was not at all clear whether it was possible to improve and re-design the wick stoves in such a manner that the objectives could be met. Therefore it was decided to include in the experimental programme a set of pressurized stoves. A separate part of the report deals with these stoves. The pressurized stoves tested belong to the category of classic primus stoves. As an outcome of this work it was concluded that:

i. For a given pressure in the kerosene tank, the power primarily depends on the diameter of the nozzle. The theoretical relation between pressure, nozzle diameter and power output are confirmed by measurements.
ii. Empirical relations exist between:
    a. the nozzle diameter and the nozzle - burner head distance
    b. the nozzle diameter and to the burner head diameter.

The experiments showed that it is possible to design a pressurized kerosene burner which fulfils the terms of reference (taking into account the quality of the pumps). However, the vapour jet burners are very sensitive to impurities (little sand particles) in the kerosene; they clog the nozzle easily.

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1. INTRODUCTION

1.1. Background

In September 1985 an extensive survey on kerosene stoves for developing countries, based on work carried out at the Eindhoven University of Technology, was published by the World Bank (World Bank 1985). The report revealed that most kerosene stoves in use have a rather low maximum power which, in combination with the measured efficiencies, would result in unduly long cooking times when used for the preparation of the average quantities of food in a country like Niger. In April 1986 supplementary information was obtained which revealed the existence of the Thomas Cup stove, a "high" power kerosene wick stove which appeared to be very popular in Indonesia. It was against this background that the UNSO/NER project nr UNSO/NER/X02/B studied the possibilities in Niger for substituting wood by alternative energy sources for the household sector. The project showed that kerosene was an interesting option. For the first time in a Sahel country, kerosene stoves were succesfully tried out at the family level (Madon 1986).

However, from a technical point of view the stoves still have some important drawbacks:

i. the maximum power is still quite low in comparison to the woodstoves and gas stoves, resulting in longer cooking times.
ii. at maximum power the stoves burn with yellow flames which soot the pan and give a foul smell.
iii. it is difficult to adjust the fire to simmering power, which results in an unnecessarily high fuel consumption.
iv heat transfer to the marmite is very sensitive to wind.
v. wicks wear out very quickly.
vi. the fuel reservoir is insufficiently shielded from the heat generated in the burner. Consequently after some time kerosene vapor escapes from the reservoir causing fire risks and loss of fuel.
vii. fuel spills easily from the reservoir when the stove is accidentally tilted.

1.2. Terms of reference

Following the UNSO/NER project it was decided to improve / re-design the kerosene stove to take care of the problems mentioned above. A terms of reference was drawn up for the work involved, as follows:

i. to develop a high power, low cost kerosene wick stove with the following characteristics:
   a. maximum power > 4.0 kW;
   b. minimum power < 0.7 kW;
   c. thermal efficiency > 50%;
   d. adapted to cooking habits in Niger (touo preparation; use of spherical pots), and
   e. low cost

ii. to use the information obtained during the course of the work to recommend measures to adapt existing stoves such as the Thomas Cup for cooking conditions in Niger.

1.3. Workplan

Splitting-up the work in two parts, as was done in the terms of reference, suggests that two different design tasks are involved. However, it is our strong conviction that both tasks overlap to a large extent. Improving the existing design can not be done without some basic understanding of the physics involved. On the other hand it would take much longer than 6 manmonths, compressed in a period of 4 months, to design a kerosene stove which really is revolutionary in design and fulfils all the requirements mentioned.

When the work started it was not at all clear whether it was possible to improve and re-design the Thomas Cup wick stove in such a way that all objectives could be met. Therefore it was decided to include in the experimental programme a set of pressurized stoves. The way wick stoves and pressurized stoves work is completely different in nature. That is why a separate part of the report deals with the pressurized stoves.

This line of thinking finally led to the following workplan:

i. Improvement of the Thomas Cup wick stove on:
   a. thermal insulation of the kerosene reservoir to prevent evaporation
   b. protection against wind
   c. lifetime of the wick, and
   d. sturdiness/stability of the stove.

ii. Re-designing the Thomas Cup wick stove in order to improve:
   a. the maximum power output;
   b. the minimum power output;
   c. the combustion quality; at maximum power output the stove burns with yellow flames, which blacken the pot and smell;
   d. all points mentioned under point 1

iii. Assess the possibilities for pressurized stoves.

1.4. Plan of the report

It is the strong conviction of the authors that kerosene will play an important role in the process of substituting wood as an domestic energy source in the urban areas of West Africa. Contrary to the state of affairs during the improved woodstove boom, there are many kerosene stoves on the market. However, they are not well adapted for use in Niger. In this sense it is good to remember one of the lessons from the early attempts to disseminate improved wood stoves: the stove market will accept only technically sound designs. It is stressed however, that this requirement is not the only one.

It would be an illusion to think that the work presented in this report is the final word on designing kerosene stoves. That is why the report tries to give more than mere descriptions of the experiments performed. It is also meant to be a starting point for more research, design and development work.

It has been stated before that the work can be split in two parts: the sections 2 to 8 which deal with the wick stoves (part 1) and the sections 9 to 12 on pressurized stoves (part 2).

Section 2 gives a general description of the wick stoves. A general description of the physical processes involved is given in section 3, while in section 4 the stove characteristics are defined. These three sections have been written for those who want to take up the subject for further research, design and development. In section 5 and 6 attention is focussed on the experiments performed. In section 5 the test methodologies are presented, whereafter in section 6 the experimental data are presented and discussed. The work has finally led to two prototype stoves which are discussed in section 7. Part 1 is concluded by a general discussion on the results obtained and the work still to be done.

Part 2 deals with pressurized stoves. In section 9 the stove and the stove parts are discussed. In section 10 the experiments are discussed while this part is also concluded with a discussion on the results and future work.

PART 1: WICK STOVES

2. Stove description

The kerosene wick stove is known since 1916 and appeared on the American market around 1927 (Romp 1937). In figure 2.1 a drawing of a generic form of wick stove is given. The stove consists of five main parts:

- i. the fuel reservoir
- ii. the wick holder with control mechanism, between the tank and the combustion chamber
- iii. the annular combustion chamber formed by the top of the wick holder and the inner and outer flame holder (two perforated concentric cylinders which form the annulus)
- iv. the shield, a non-perforated metal cylinder around the combustion chamber, which creates a second annulus with the outer flame holder. The shield protects the combustion chamber against wind and reduces the heat losses to the environment
- v. the pan support

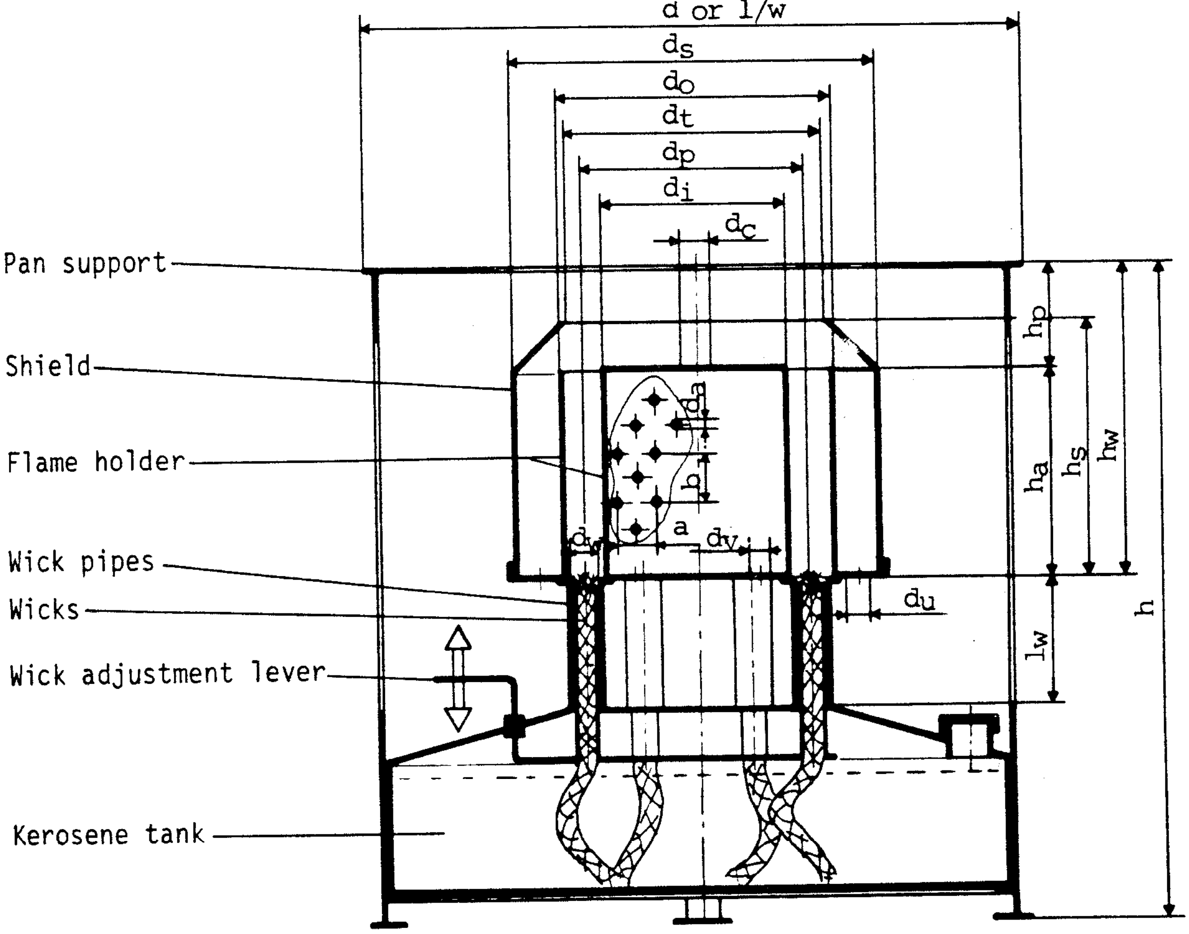


Fig. 2.1: Wick stove with seperate pan support (World Bank 1985). Detailed dimensions of the Thomas Cup wick stove are given in Annex 1.

3. Kerosene transport and combustion

In this section the main physical processes occuring in a wick stove will be discussed briefly. Attention will be given to:

i. the transport of kerosene from the fuel reservoir, through the pores of the wick, to the free wick end in the combustion chamber;
ii. the evaporation of the kerosene at the free wick end;
iii. the combustion of kerosene; and
iv. the air flow from the surroundings, through the perforated flame holders to the combustion chamber.

3.1. Transport rate

The theory for heat pipes (Dunn and Reay 1978) can be used to describe the transport of kerosene from the tank via the wicks to the flame holder. The capillary force is the driving force. In order for the wick to operate, the maximum capillary head (dPc)max must be greater than the sum of the pressure drop, dPl, required to transport the kerosene through the wick and the gravitational head, dPg. Thus:

$$(dP_c)_{max} > dP_l + dP_g \qquad (N/m^2)$$

The maximum capillary head is given by:

$$(dP_c)_{max} = \frac{2 \cdot \sigma}{r} \qquad (N/m^2)$$

where σ : the surface tension of the kerosene and (N/m)
r : the effective radius of the pores (m)

To calculate dP_l, Darcy's law can be used. Thus:

$$dP_l = \frac{\mu \cdot l \cdot m}{\rho \cdot K \cdot A} \qquad (N/m^2)$$

where μ : viscosity of the kerosene (kg/m.s)
l : the length of the wicks (m)
m : the transport rate (kg/s)
ρ : the density of kerosene (kg/m^3)

K : the wick permeability and (m^2)
A : the cross sectional area of the wicks (m^2)

The permeability, K, takes into account the pore size, distribution and tortuosity.

The gravitational head is simply given by:

$$dP_g = \rho \cdot g \cdot h \qquad (N/m^2)$$

where g : the gravitational acceleration (m/s^2)
h : the distance between wick tip and kerosene surrface (m)

The above shows a method to optimise the transport rate of the kerosene: decreasing the transport height and increasing the cross sectional area of the wicks. The possibilities to increase the transport rate by reducing the size of the capillary are limited. Not only the capilary head is increased but also the flow resistance of the wick.

The capillary limit or wicking limit which is the maximum kerosene flow rate is given by:

$$(m)_{max} = \frac{\rho\,\sigma}{\mu} \cdot \frac{K\,A}{l} \cdot \left(\frac{2}{r} - \frac{\rho\,g\,h}{\sigma}\right) \qquad (kg/s)$$

3.2. Kerosene evaporation rate

The vapor flux (F) at the wick tips is given by the expression given below.

$$F = k \cdot (P_{k,w} - P_{k,c}) \qquad (kg/m^2s)$$

where k : a transport constant (s/m)
Pk,w: the vapour pressure at the wick (Pa)
Pk,c: the vapour pressure in the combustion chamber

k depends on the geometry of the evaporating surface, the flow around the wick and the properties of the medium. For simple geometries and flow conditions, k is given by the Sherwood correlations (Rietema 1976). Pk,c, for most situations, is neglegibly small. Pk,w on the other hand is given by:

$$\ln (P_{k,w}) = A + \frac{B}{(T+C)}$$

where A, B, C : constants
T : the kerosene temperature, which should remain below its boiling range (180°C-235°C)

The above shows the important influence of the temperature on the rate of evaporation (provided the temperature remains below boiling point). Above boiling point the kerosene starts boiling in the wick. At that point it appears as if the wick takes over control; it becomes extremely difficult to manipulate the power output. The problem occurs when the wick lever is raised to get a high power after a period of low power combustion. During the latter phase the temperatures near the wick have become so high that a so-called vapor lock is created in the wicks which block the liquid kerosene flow.

3.3. Combustion

Glassman (1977) states that the combustion of hydrocarbons can occur in two different modes, leading to yellow or blue flame combustion respectively. The mode of combustion depends on the specific reaction rate (k) which in its turn is a function of temperature only. The Arrhenius plot is shown in figure 3.1.

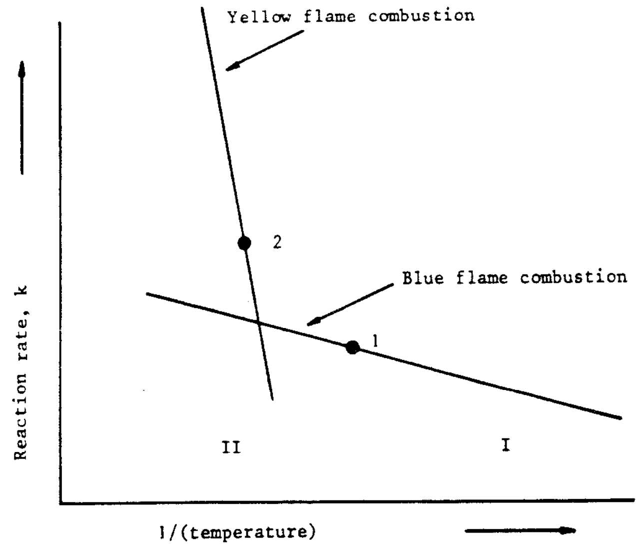


Fig. 3.1: Arrhenius plot of the Semenov steps in hydrocarbon oxidation (Glassmann 1977)

From the figure one can see that the specific reaction rate increases with increasing temperature along line I. From point 1 onwards, the reaction is fast enough and blue flame combustion occurs. With increasing temperature point 2 is reached from where the yellow flame combustion starts.

3.4. Air flow

The air flow through the stove is determined by the balance between the draft, created by the column of hot combustion gases, and the flow resistance of the small air holes in the flame holders. In figure 3.2 a schematic picture is given of the stove together with the pressure differences across the inner and outer flame holder. It is assumed that the gases which enter the combustion chamber via the outer and inner flame holder have uniform temperatures T1 and T2 respectively. T1 is equal to the ambient temperature while T2 is somewhat higher (the inner flame holder is nearly closed at the top and consequently the gases are heated up).

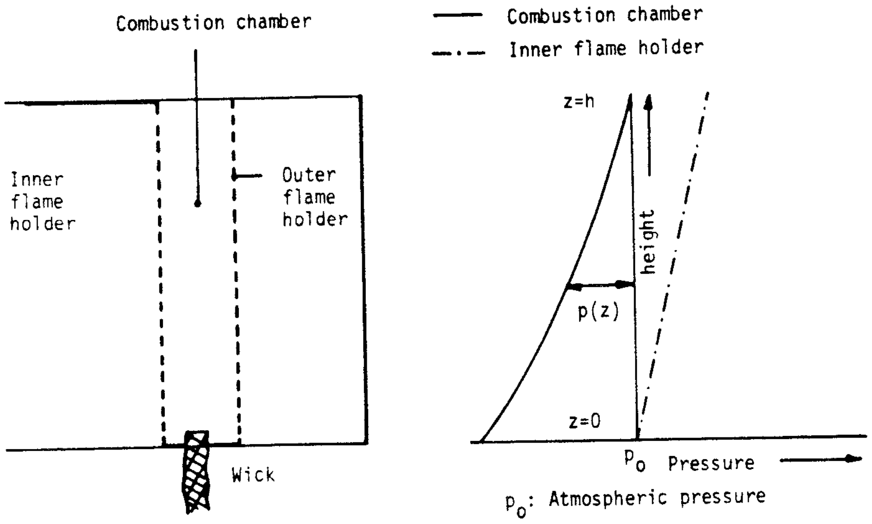


Fig. 3.2: Pressure as a function of the combustion chamber height

The mass, momentum and energy equation are given below.

Mass: $d(\rho\, v\, A) = \rho_1\, v_1\, a_1\, dz + \rho_2\, v_2\, a_2\, dz$ (kg/s)

where ρ : the density of the gases (kg/m3)
v : the velocity of the gases (m/s)
A : the area of the combustion chamber (m^2)
$a\, dz$: the area of the air holes in the flame holders over the height dz (m^2)

The equation states that the increase with height of the mass flow in the combustion chamber (left hand side) is due to the air flow through holes in the inner and outer flame holder (right hand side)

Momentum: $$\frac{dp}{dz} = (\rho_1 - \rho) \cdot g - \frac{d\ \rho v^2}{dz}$$

where p : the pressure difference between the combustion chamber and the surroundings.
$\rho 1 - \rho$: the density difference between the gases in the combustion chamber and the ambient air.
g : the gravitational acceleration

The equations states that the pressure difference changes with height (left hand side) due to the differences in weight of the column of combustion gases (first term right hand side) corrected for the dynamic pressure of the combustion gases (second term right hand side).

Energy: $$\rho\ v\ Cp \frac{dT}{dz} = \frac{B}{S} \frac{d(\rho v)}{dz} - Cp\ (T - T_1) \frac{d(\rho v)}{dz}$$

where T : the temperature (K)
Cp : the specific heat (kJ/kg.K)
B : the combustion value of kerosene (kJ/kg)
S : the stoichiometric amount of air (kg)

The energy equation states that the temperature increase with height (left hand side) is caused by the combustion of kerosene (first term right hand side) corrected for the heat needed to raise the temperature of the cold combustion air. In the equation it is assumed that:

i. the combustion process depends on the quantity of the incoming air flow only and
ii. the heat losses to the environment are negligibly small.

The set of equations is completed with two equations which describe how the incoming combustion air flow is related to the pressure difference over the flame holder.

Inner flame holder: $$1/2\ \rho_2\ (v_2)^2 = -\ p + (\rho_1 - \rho_2).g.z$$

Outer flame holder: $$1/2\ \rho_1\ (v_1)^2 = -\ p$$

The model predicts that the temperatures in the stove (the combustion process) are not affected by:

i. the power
This is only true as long as there are yellow flames above the stove.
ii. the diameter of the stove.
Which means that the quantity of kerosene burnt in the combustion chamber can be increased or reduced by changing the diameters of the inner and outer flame

holders, keeping the width of the combustion chamber constant.

iii. a reduction in the width of the combustion chamber when the porosity of the flame holders is increased to the same extent.

These conclusions all need to be verified by experiments. The combustion assumption probably will prove to be a gross simplification of the actual process. It does not take into consideration the completeness of mixing of the air with the kerosene vapour and neglects any influence of the temperature on the combustion process.

4. Stove characteristics.

The main objective of the present work is to improve the wick stove on fuel consumption (Mker) and the time needed for preparing a typical meal (t). Both quantities are determined by the efficiency, the maximum power and the minimum power. The cooking time and fuel consumption can be calculated once relevant data become available. The calculation procedure used in this report follows the one presented in the World Bank report mentioned before (World Bank 1985). Based on this procedure, Bussmann and Krishna Prasad (1985) give simplified expressions for t and Mker. In deriving these, the cooking task is modelled through the water equivalent of the food cooked Mw and the simmer time ts. Moreover it is assumed that:

i. steam production is an inevitable, albeit useless, part of the simmering process. Thus one has to start with a quantity of water larger than a given final quantity Mw.
ii. the efficiency of the stove is not a strong function of its power.
iii. the difference between initial and boiling temperature is 75°C.

$$M_{ker} = M_w \cdot \left(\frac{315}{\eta} + 1.14 \cdot \frac{Pmin \quad ts}{Mw}\right) \qquad (kg)$$

$$t = t_s + M_w \cdot \left(\frac{315}{\eta} + 0.14 \cdot \frac{Pmin \quad ts}{Mw}\right) \qquad (s)$$

where Mw : the water equivalent of food cooked (kg)
η : the efficiency (-)
Pmin: the minimum power (kW)
ts : the simmering time (s)
B : the combustion value of kerosene (kJ/kg)

From the above expressions it is clear that the efficiency of a stove is not the sole governing quantity for achieving fuel economy. The latter is strongly influenced by the minimum power and the simmer time.

In the sections 4.1 to 4.4 the stove characteristics are discussed in more detail.

4.1. Maximum power

In the World Bank report on kerosene stoves, the maximum power is defined as the power level at which the blue flames turn yellow (yellow flames are felt to be undesirable because they soot the pan). In the present report we will call this level the blue flame maximum power. When the control setting of the wicks is pushed to its limits, the kerosene will burn with yellow flames and a good deal of the flames are outside the flame holder. We will call this burning rate the yellow flame maximum power. This power level determines the stove's capacity to transport kerosene from the reservoir via the wicks to the flame holder. For all stoves the maximum power with a pan on top is somewhat lower than the power measured during the experiments without pan. This is probably caused by a reduction in the flow of combustion gases due to the extra flow resistance introduced by the pan.

4.2. Design power

In section 3.3 we have seen that the difference between blue flame and yellow flame combustion lies in the temperature of the vapour air mixture. Consequently blue flame combustion is not necessarily identical with complete combustion. Thus, it seems more appropriate to define the maximum power taking into account the flame height above the burner (whether or not yellow flame combustion takes place). That is why we will define a third power level, the design power. It is the power level at which the flame holder is completely filled with flames, while the height of the flames above the flame holder are minimal. For most stoves the maximum blue flame power luckily is equal to the design power

4.3. Minimum power

The world bank report defined the minimum power as the power level at which blue flames are just visible in the flame holder. Therefore the wicks need to be raised well above their minimum position. In the latter position, most kerosene stoves burn with yellow flames. This is considered undesirable from the point of view of wick life-time and too low a power for any cooking operation. Here we add that the minimum power defined in this way also depends on the concentricity of the flame holders. A stable yellow flame tongue will appear, when this is not carefully ensured.

4.4. Efficiency

The important influence of the efficiency on fuel consumption will be clear. Together with the maximum power of the stove it also determines the boiling time. The kerosene stoves described in the World Bank report have a low maximum power. This feature will be a major constraint in disseminating kerosene stoves provided it is not balanced with high efficiency numbers.

5. The test methodologies.

Most of the experiments involved efficiency and power output measurements. The methodologies used will be discussed in this section. Nearly all tests were supplemented with temperature recordings of different stove parts. The recordings were used to get a better understanding of the physical processes involved. Details of the experimental set-up will be given.

5.1. The power output

The power output during an experiment is inferred from the weight loss during burning at a constant rate:

$$P = \frac{Mf \cdot B}{dt}$$

where: P = the power output of the stove (kW)
Mf = the fuel consumed (kg)
B = the lower calorific value (kJ/kg)
dt = the time interval in seconds (s)

In this report, two series of tests can be distinguished. In the one series the power output of complete stoves is determined while in the other the same is done for single open wicks.

a. Stoves

To measure the power output of a prototype stove, it is placed on a balance. The stove is lit, a stop-watch is started and the weight recorded as a function of time. Once the stove burns steadily the power is determined using the formula given above. The power output is determined over a period of about 15 minutes.

b. Single wicks

In a series of experiments the burning rate of a single wick was determined. The power output of one wick is very small and for reasons of accuracy, firstly an experiment of two hours duration was chosen and secondly three identical wick set-ups were mounted on one support.

5.2. Efficiency

Before starting on the efficiency tests, it is necessary to select the size of the pan to be used, since significant efficiency variations can result from varying the pan size.

Unlike the tests presented in the World Bank report mentioned, it was decided not to change the pan size according to the maximum power a given stove can produce. All tests, unless specifically mentioned, were done with pan number three. The choice of the size to be used was based on the fact that pan number 2 and 3 form 70 % of the total number of marmites used regularly in a Sahel country like Niger. Thus, a stove well adapted to the local cooking habbits should show high efficiency numbers for these pan sizes.

The stoves (with the fuel) were weighed and lighted and a preweighed pan with water (whose initial temperature was measured beforehand) was placed on the stove and a stop-watch started. The water was brought to the boil and kept boiling for some time. The tests lasted for about 1 hour. The weight of the marmite at the end of the experiment was recorded. All the tests were performed on marmites with their lids on. Marmites were filled to 2/3 of their capacity (5kg of water for pan no 3) as recommended by CILSS (CILSS 1986).

The efficiencies for the tests conducted here were computed from:

$$\eta = \frac{Mw \,.\, (Tb - Ti) \,.\, Cp \; + \; Me \,.\, L}{Mf \,.\, B}$$

where: η = efficiency
Mw = initial mass of water (kg)
Tb = boiling temperature of water (C)
Ti = initial temperature of water (C)
Cp = specific heat of evaporation = 4.2 (kJ/kg.K)
L = latent heat of evaporation = 2256 (kJ/kg)
Me = mass of evaporated water (kg)
Mf = fuel used in the tests (kg)
B = lower heating value of the fuel (kJ/kg)

5.3. Temperature measurements

As with wood, combustion of kerosene appears to be a complex phenomenon. In order to get a better understanding of the processes involved it was decided to monitor the temperature of both flame holders and the shield. Therefore:

i. three thermo-couples were mounted on the wick holder (top of the wick tubes);
ii. three thermo-couples were placed at each location mentioned; at the top, at the middle and at the bottom of both the inner flame holder, the outer flame holder and the shield.

Two thermo-couples were mounted to watch for possible explosion risks:

iii. one on the lid of tank
iv. one in the kerosene in the tank.

5.4.Experimental set-up

All weights were measured with a Sartorius electronic precision balance (type: 3826 MP8; range: 0-30 kg; accuracy: 1 g). All temperatures were recorded with Chromel-Alumel thermo-couples. Weights and temperatures were scanned every minute. This was done by means of a data acquisition unit, (HP-3497A) controlled by a microprocessor HP-85. The data were stored on floppy disk and processed after the experiments on an IBM XT personal computer with the LOTUS II programme.

6. Experimental work

6.1. Introduction

Starting point of the design exercise were the experiments performed in the framework of the UNSO/NER project nr. UNSO/NER/X02/B. The experiments revealed that, for use in a Sahel country, a wick stove design like that of the Thomas Cup stove would hold most promise.

The efficiency of the Thomas Cup appeared to be very sensitive to: firstly the distance between burner and pan; secondly the size of the pan and thirdly the wind conditions. Due to the latter parameter, differences of 10% in the absolute sense were found between results of the experiments performed. The experimental results are summarized in figure 6.1, where the efficiency of the stove is shown as a function of the distance between the pan bottom and the burner top. The pan size (annex 2) has been taken as a parameter while the power output of the fire was kept constant at 2.7 kW, a level at which both blue and yellow flames are visible.

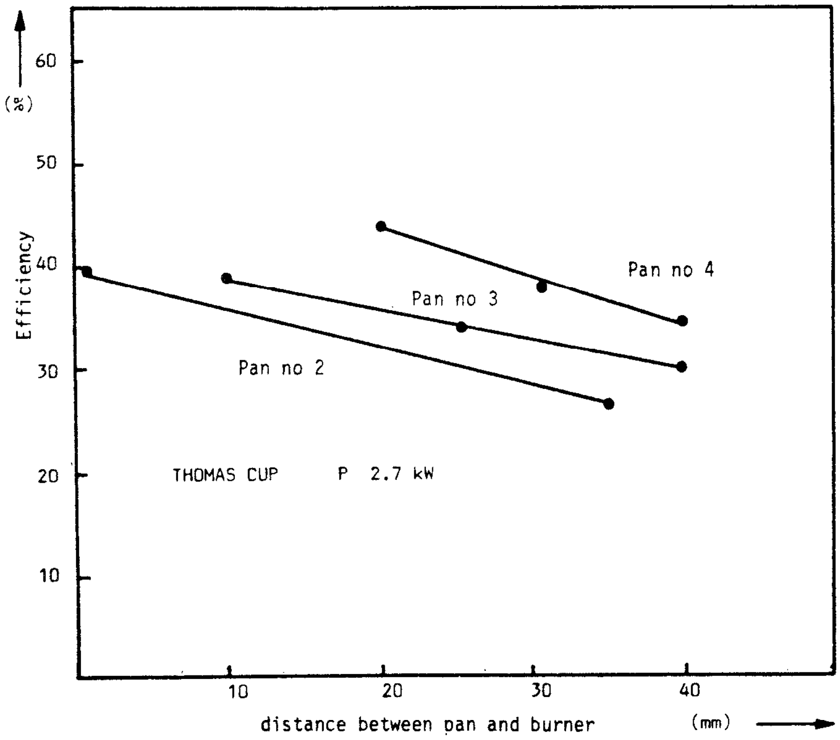


Fig. 6.1: Efficiency of the Thomas Cup as function of the distance between pan and burner

Another important outcome from the Niger work was the differences observed in performance between the Thomas Cup and Swan 20 wick stoves. Both stoves originate from Indonesia and are probably made by the same manufacturer. They look very much alike but the Thomas Cup showed a much better power range; a fact which could not be explained. Insight into the differences would give useful information for designing the high performance stove. That is why a closer look was taken at both stoves. The main constructional differences are summarized below (see also figure 2.1 and annex 3). They involve:

i. the height of the wick tubes. The wick tubes differ by 20% in height.
ii. the porosity of the flame holders. The total cross sectional area of the air holes in the flame holders of the Thomas Cup is 30% higher ($21cm^2$ against 16 cm^2)

A series of experiments was performed to study the effect of these differences on the power output. The influence of the wick holder was studied by measuring the power with the flame holders removed and the kerosene burning freely at the wick tips in the open air. The control mechanism was set to its minimum so that the wick tips came level with the top of the wick tubes. The results are shown in table 6.1. The measured free burning wick powers are nearly the same and consequently the difference in performance of the stoves under field conditions can not be attributed to the wick holders.

	Thomas Cup	Swan 20
Yellow flame maximum power	3.8 - 2.3 kW	2.8 kW
Blue flame maximum power	2.5 kW	2.1 kW
Free burning wick power	0.53 kW	0.56 kW

Table 6.1: Power levels of the Thomas Cup and Swan 20

As a next step the blue flame maximum power was measured. This experiment revealed the inflence of the porosity of the flame holders. The Thomas Cup, having flame holders with a 30% larger porosity, has a blue flame maximum power which is 20% higher.

After measuring the blue flame maximum power, the wicks were pushed up to the limit and the yellow flame maximum power was measured. The Swan 20 gave a steady yellow flame maximum power level of 2.8 kW during 35 minutes. The power level of the Thomas Cup on the other hand was not steady at all. During the first five minutes of the experiment the stove produced large flames (3.8 kW) but the power output rapidly decayed. In the last 15 minutes of the experiment the power level of the stove was only 2.3 kW. The experiment was stopped by pushing down the wick lever as a result of which there was a mild explosion It appeared that the wicks of the Thomas Cup had burnt completely. The explosion occured when the smouldering wicks came too close to the kerosene reservoir. Comparison of the results of table 6.1 with earlier measurements (Bussmann & Visser 1986) showed that the Swan 20 gave much higher powers in the present series of experiments than was expected. The difference can probably be attributed to the concentricity of both flame holders. Small deviations from the latter result in an asymmetric, low power combustion. The influence of the concentricity on the maximum power levels appears to be much more important than that of the porosity of the flame holders.

6.2. Yellow flame maximum power output

a. Single wick experiments

A series of experiments was performed to determine the wick's capacity to transport kerosene from the reservoir and to evaporate fuel in the flame holder. The set-up used to study the phenomena is shown in figure 6.2. The wicks studied were of the type used in the Thomas Cup. They are made of cotton, have a diameter of about 8 mm and fit in a wick tube with a (slightly smaller) diameter of 7 mm. The free end of the wicks were shielded with a metal cylinder with a larger diameter to prevent air coming in the direct vicinity of the wick and thus protecting the wicks from burning.

L1: Length of the wick protector
L2: Length of the wick tube
L3: Length of the free end of the wick
L4: Height above the kerosene surface
D1: Diameter of the wick protector
D2: Diameter of the wick tube

A : Wick protector
B : Wick tube
C : Wick
D : Support
E : Kerosene level

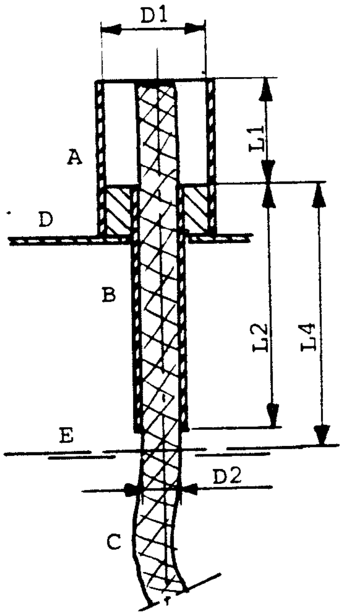


Fig. 6.2: Experimental set-up single wick experiments

Four parameters were varied:

i. the length and diameter of the wick protector (L1 and D1) to vary the evaporating surface area of the wick;
ii. the length of the wick tube and the height of the free

wick end above the kerosene (L2 and L4) to study the influence of the wick's flow resistance on the kerosene transport.

For each experiment these variables together with the power output per wick are listed in table 6.2

	D1 mm	L1=L3 mm	L2 mm	L4 mm	P Watt
A	12	20	50	45	85
				73	79
				100	52
B	12	20	100	45	83
				73	78
				100	37
C	18	20	50	45	118
				73	124
				100	98
D	18	20	100	45	110
				73	99
				100	80
E	18	40	50	45	113
F	27	20	50	45	298
G	27	40	50	45	203

Table 6.2: Data from single wick experiments

The experiments A, B, C, D in the table show that the wick power decreases with increasing height of the free wick end above the kerosene (L4). This is true for short (A and C) and long wick tubes (B and D) as shown in figure 6.3a. These experiments also show that the power output per wick decreases with increasing length of the wick tubes (L2). This can qualitatively be explained by the increased resistance to flow.

The kerosene must evaporate before it can burn. The experiments C,E,F and G show that the rate of evaporation largely depends on the length of the free wick end (L3) and the diameter of the wick protector (D1). This also was expected on the basis of the theory given in section 3.1. The influence of the free space around the wick is explicitly shown in figure 6.3b. The graph does not need further discussion. A power output of 300 Watts per wick is feasible!

The experiments also revealed that the protection of the wick by the wick protector is sufficient: for over two hours there was no sign that the wick was burning away. However, due to the high powers generated, the temperature in the wick tube became very high too. The wick changed colour from white to light brown and the performance deteriorated. According to the theory discussed in section 3.1, the temperature of the wick also plays an important role in the evaporation process. The role of this parameter will be studied in the next section.

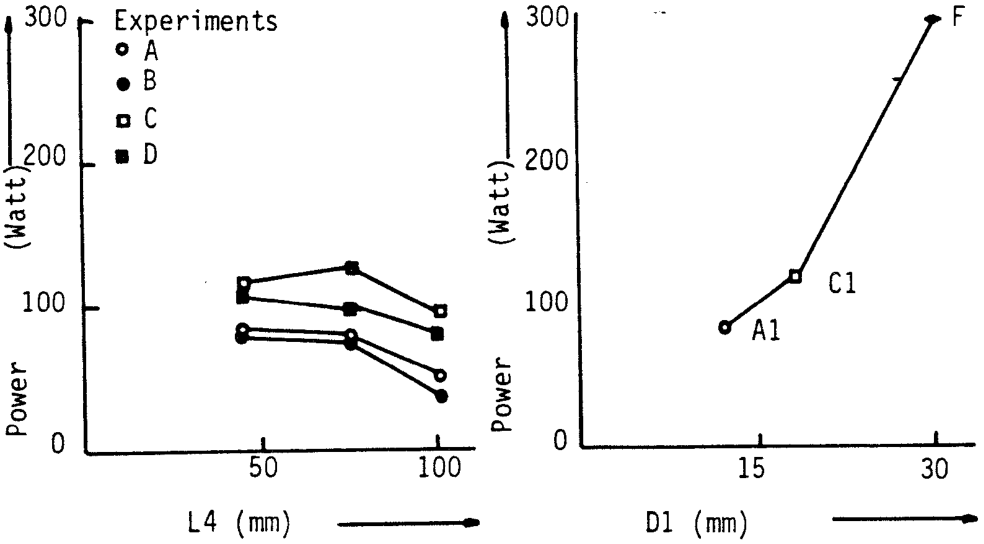


Fig. 6.3: Power output from a single wick

From the single wick experiments it is clear that a power of 300 W per wick is feasible. For a stove with 20 wicks, like the Thomas Cup, this would mean a yellow flame maximum power of 6 KW. Thus, the kerosene transport capacity of an ordinary cotton wick is sufficient to meet the high power requirements provided the hydraulic head is not too high, flow resistance in the wick tube is kept low and enough space is given for the evaporation process to take place.

b. Stove experiments

In figure 6.4 data has been assembled from power output experiments performed on the different prototype stoves during the first 3 months of the work. In the figure the power output is shown as a function of the wick holder temperature. The free wick end is taken as a parameter. The lines drawn give the best least square fit. The figure clearly is in qualitative agreement with the model proposed in section 3.2. The conclusion drawn on the basis of this graph is that in order to get high powers from the wicks it is essential to increase the wick holder temperature. This was achieved by closing the annular gap between the outer flame holder and the shield. Due to the closing, the flow of cold air alongside the flame holder is reduced. Consequently the temperatures in the stove rise and so does the maximum power.

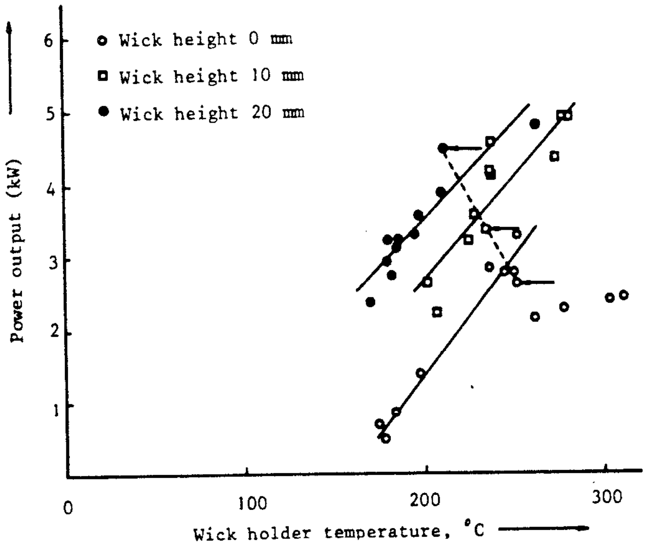


Fig. 6.4: Power as a function of the wick holder temperature

The effect discussed above is shown in figure 6.5. By opening the gap mentioned, the yellow flame maximum power is decreased from 4.5 kW to 3 kW.

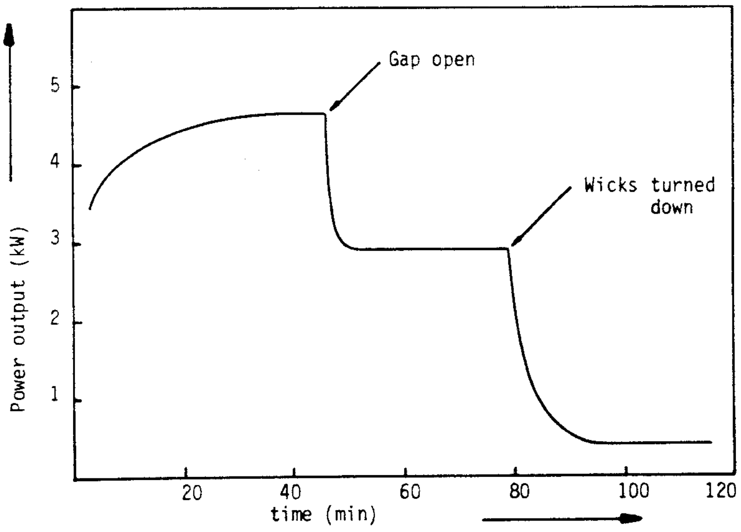


Fig. 6.5: Decreasing the yellow flame maximum power by opening the gap between shield and flame holder

c. Stove experiments with pan

The burning process is to a large extent determined by the flow of ambient air, through the pores of the flame holder to the combustion chamber. The driving force is the draft created by the hot combustion gases. This draft being small explains the observed drop in the power output when a pan is placed on top of the stove. A sample result is given in figure 6.6.

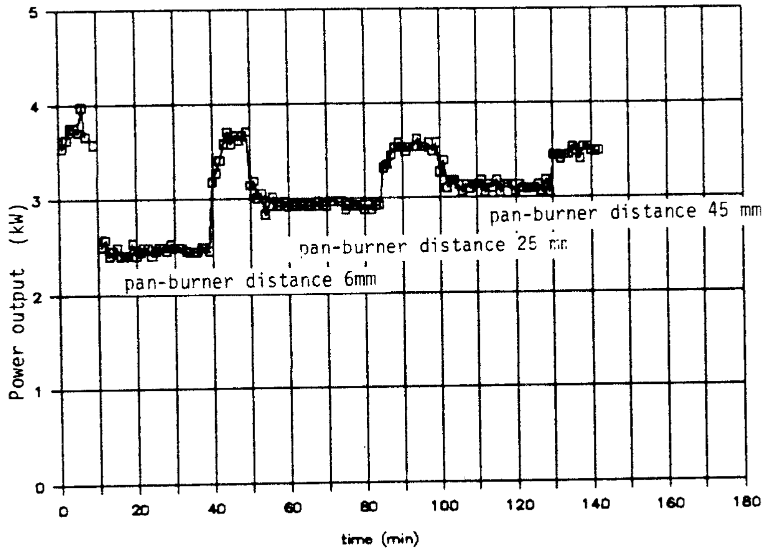


Fig. 6.6:

The graph clearly indicates that the maximum power can only be measured when a pan is placed on top of the stove. It seriously complicates the measurements because the flow resistance introduced by the pan not only depends on the pan size but also on the distance between pan bottom and burner.

An interesting phenomenon occurs when the pan is placed on a stove which produces yellow flames. When the distance between pan and burner is kept small (< 15 mm), the yellow flames suddenly disappear and only blue flames are observed. The change in colour of the flames does not mean that the combustion is completed at a lower height above the stove once a pan is place on top of it. The combustion remains incomplete; also the blue flames blacken the pan. To understand what is happening we refer to figure 3.1 where it was shown how the combustion mode depends on the temperature. On the basis of this figure it is believed that relatively the cold pan surface reduces the temperature of the combustion gases to such a level that only blue flame combustion is possible. However, the process is still not well understood. No time was available to study the phenomenon in detail.

6.3. Design power

A series of experiments was performed in which the design power was determined as a function of the height of the flame holder. The hole size and the number of holes per cm^2

(hole density) were kept equal to those of the original Thomas Cup; 1.4 mm diameter and 2 holes/cm^2 respectively. The lower 20 mm of the flame holders were not perforated in order to protect the wicks. A series of experiments was done with an outer flame holder which was not closed at the top. The results of this series are shown in the figure 6.7

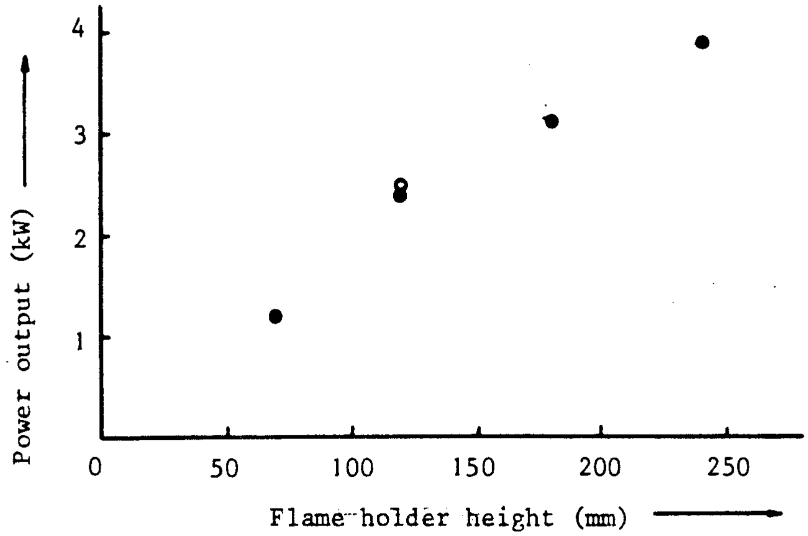


Fig. 6.7: The design power as a function of the height of the flame holder

The influence of the flame holder height on the blue flame combustion becomes clear. The design power increases from 1 kW to 4 kW when the flame holder height is increased from 70 mm to 240 mm. A flame holder of 240 mm is considered too high (double the original) because it probably will lead to stability problems under the cooking habits in the Sahel. The graph also shows the result of an experiment in which the number of holes per cm^2 was doubled; the design power was not influenced by this change. No time was available to perform experiments in which the hole density in the flame holders was varied and thus this result is not well understood.

6.4. Minimum power

In the previous paragraphs it was shown that the maximum power was increased by closing the annular gap between outer flame holder and shield (figure 6.5). Main reason for this behaviour was the temperature increase in the direct vicinity of the wicks. As a result, however, also the minimum power was increased. It became nearly impossible to extinguish the stove after an experiment. Consequently, for getting a low minimum power, closing the annular gap appeared to be counter productive. To solve the problem the following solutions were considered:

i. Increasing the travel of the wick lever.
The increased span can be used to get a minimum wick position well below the wick holder. As a result the rate of evaporation is decreased due to:

a. the lower temperature of the wick tube further down the wick holder
b. the longer transport distance of the kerosene vapor from the wick to the flame holder; which is a diffusion controlled process

ii. Insulating the wick holder from the flame holder.
The wick holder temperature is, to a large extent, determinded by conduction of heat from the flame holder. This transfer of heat can be reduced by using two rings of insulation material between the wick holder and the flame holder (see figure 6.8). As a result, the wick holder temperature will decrease and so will the rate of evaporation when the wicks are at their lowest level.

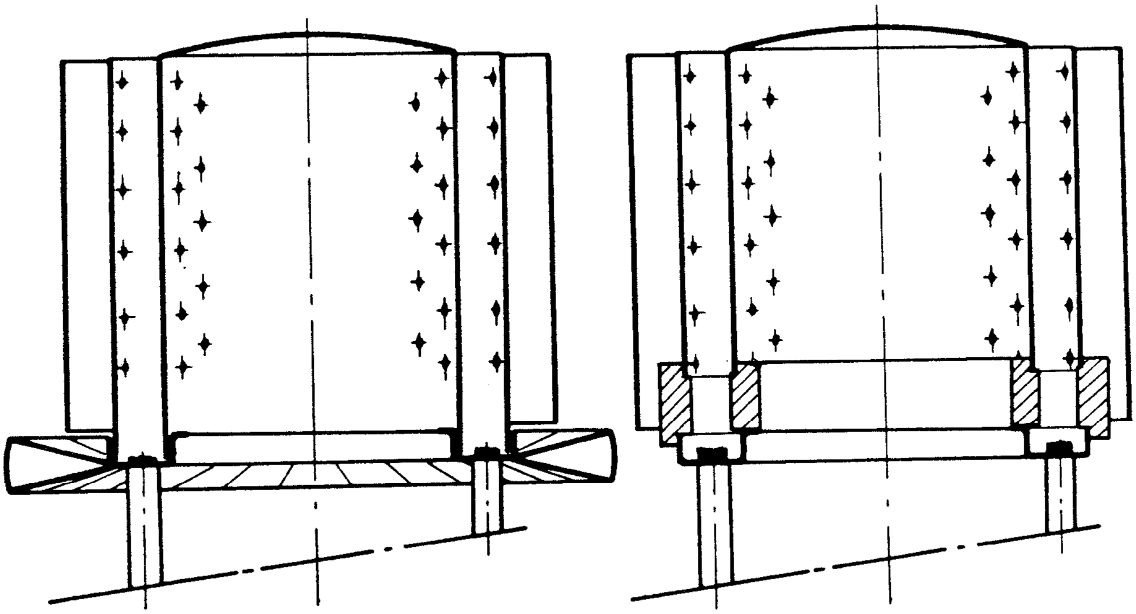


Fig. 6.8: a) Cooling fins at the wick holder. b) Insulating rings between flame holder and wick holder.

iii. Cooling the wick holder with cooling fins.
It is expected that the same effect is obtained by cooling the wick holder with cooling fins. If so, the use of cooling fins is prefered for two reasons. Firstly the use of insulation material weakens the mechanical strength of the stove and secondly the uncertain availability of the material will hamper the production.

The first option does not need further discussion, it was directly incorporated in the design of the final prototypes. For obvious reasons there are limits to the extent to which the wicks can be moved up and down. Too high a wick will burn; too low a wick will cause safety problems. The second and third option (insulating rings and cooling fins respectively) were studied for their influence on the power range. A series of experiments was performed on the prototypes (without a pan on top), shown in figure 6.8.

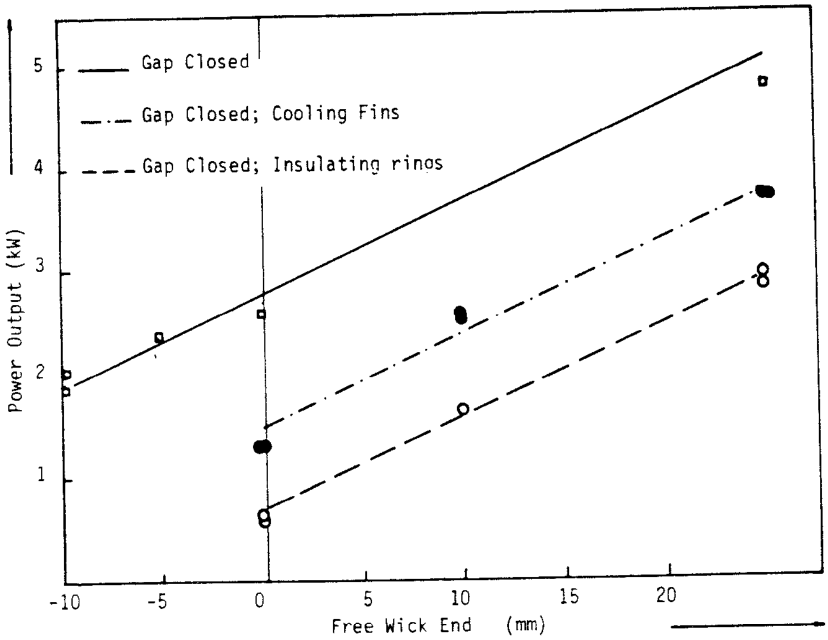


Fig. 6.9: Power output as a function of the free wick end

The results are summarized in figure 6.9 where the power output is shown as a function of the length of the free wick end and is compared with the experimental data obtained with a stove without insulation and fins. The figure clearly shows that the maximum and minimum power levels are reduced when insulation or fins are used. The positive effect at the low power end results in a negative effect at the high power end.

6.5 Power control

On the basis of the data presented in the previous chapter the wick setting was calculated for the three prototype stoves to give a minimum power of 1 kW and a maximum power of 4 kW. The results are shown in table 6.3.

Stove:	Wick height at Pmax:	 Pmin:
1. Closed gap; no fins; no insulation	15 mm	-25 mm
2. Closed gap; fins; no insulation	30 mm	-10 mm
3. Closed gap; no fins; insulation	40 mm	0 mm

Table 6.3 Calculated wick setting for maximum and minimum power

All three stoves need a wick travel of 40 mm to get the required maximum and minimum power. It means an increase of 15 mm over the travel of the wicks in the Thomas Cup which only was 25 mm. Moreover, it should be kept in mind that the data used in the calculations are from tests without pan on top of the stoves. It implies that under actual operation the travel may have to be larger still. It not only will lead to safety problems when the wicks are turned too far down in the wick tubes but also to problems with the life time of the wicks when they are pushed too far up in the combustion chamber.

What happens to the wick holder temperature when the wicks are turned down is shown in figure 6.4. The solid lines represent the data already discussed in section 6.1. The dotted line in the graph gives the trajectory which one of the stoves followed when the wick setting was changed. The wick holder temperature increases and the power decreases, when the wick lever is lowered.

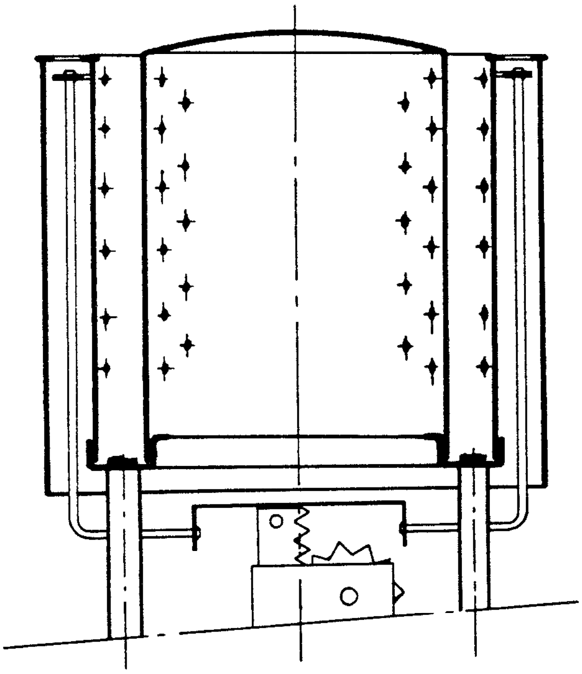


Fig.6.10: Wick stove with new control mechanism.

This graph together with the data presented sofar suggests that cooling is only needed when the stove has to deliver the minimum power. This finally led to the control mechanism shown in figure 6.10. A ring between the shield and the outer flame holder is fixed to the wick lever. It closes the annular gap when the wicks are in the highest position; thus blocking the cooling air flow alongside the outer flame holder and thus maximising the power output. As soon as the wicks are lowered the annular gap is opened; the flow of cold air between shield and flame holder is increased and the temperature and power output decrease. A series of experiments was performed to check this design idea. A sample result is given in figure 6.11.

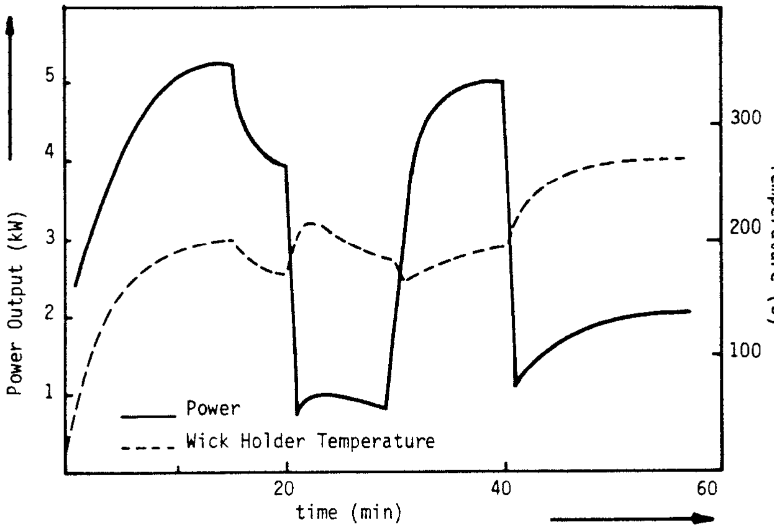


Fig.6.11: Power and wick holder temperature of prototype stove with new control mechanism

In the figure the power output and wick holder temperature during an experiment are shown of a stove without pan on top. The experiment is discussed in detail because it reveals a rather unexpected behaviour of the stove.

At t = 0 min	the stove has been lit and the power, together with the temperatures in the stove, gradually increase.
At t =10 min	the stove has reached its maximum power of about 5 kW.
At t =15 min	the annular gap is opened and, as a result, the power drops to 4 kW.
At t =20 min	the wicks are set in their minimum position where they come level with the wick holder and the power further drops to about 1 kW.

Sofar nothing special has happened the stove behaved as expected. The test was continued however, to determine the turn down ratio while leaving out the intermediate step of opening the annular gap before fully turning down the wicks.

At t =30 min	the wicks were pushed to their maximum again and the power increased to 5 kW.
At t =40 min	both the annular gap was opened and the wicks were turned to their minimum (wick holder level). At first instance the power decreases again to 1 kW but after some time the power goes up to 2 kW!

The temperature curve, also shown in the figure, reflects the power behaviour. The cooling effect of opening the annular gap at t = 40 apparently does not balance the increased heat generation near the wick holder. Consequently to fulfil the minimum power requirement it is necessary to have the minimum position of the wicks 5 to 10 mm below the wick holder level.

6.6. Efficiency

A series of efficiency measurements was performed on two Thomas Cup like prototype stoves; the WSG1 and WSG2. The WSG1 has flame holders which, at the bottom, have not been perforated in order to protect the wicks from burning off. The WSG2 not only has similar flame holders but also a annular gap between outer flame holder and outer shield which is closed at the top. Both stoves have a conical pan holder which direct the combustion gases towards the pan surface and protect the fire against wind. The experimental results are summarized in the figures 6.12a, 6.12b and 6.12c.

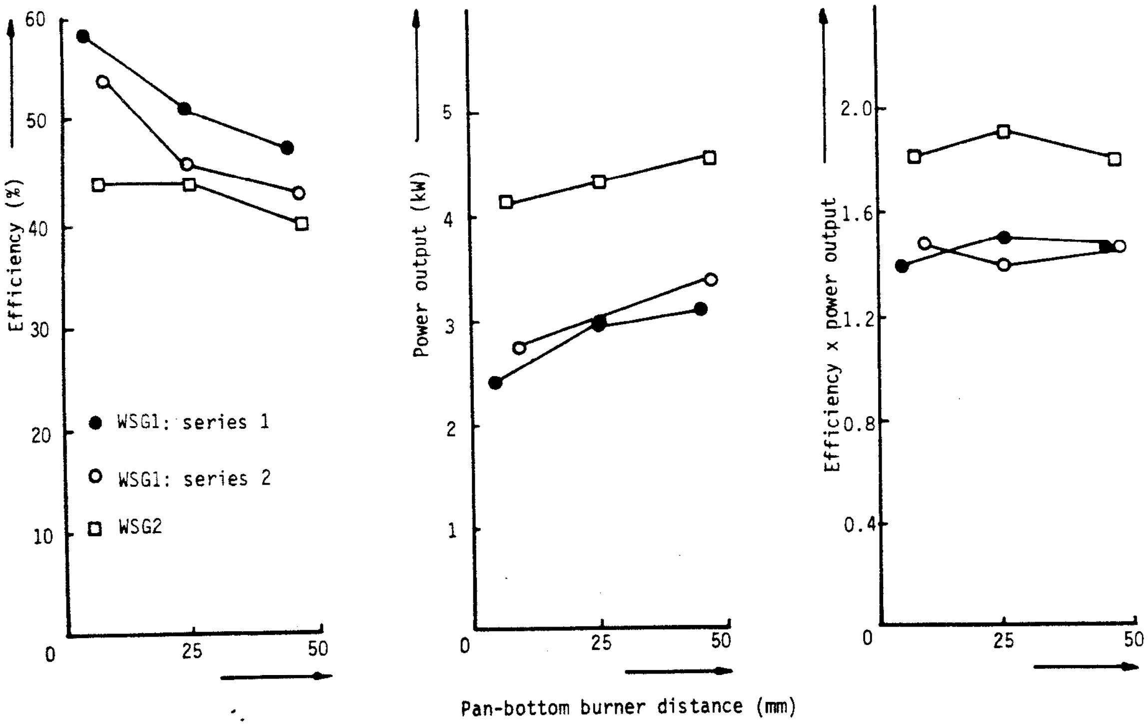


Fig.6.12: Efficiency and power output of the WSG1 and WSG2 as a function of the pan-burner distance

Figure 6.12a and 6.12b show the important influence of the pan-burner distance on the efficiency and the power. The efficiency of the WSG2 is a few percentage points lower for all distances. This is due to the much higher shield temperatures which result in increased radiation and convection heat losses. However, for distances smaller than 30 mm, the efficiency numbers still lie between 45% and 50% which is judged reasonable taking into account the diameter of the pan and the high power. Figure 6.12b shows the main advantage of the WSG2. The maximum power output of the stove has been considerably increased for all pan-burner distances. The stove fulfils the 4 kW maximum power requirement in the terms of reference. Moreover, the influence of the pan-burner distance on the power is decreased in a relative sense (the decrease in absolute numbers remains the same). Figure 6.12c finally shows the product of the efficiency and power output. This product is a measure for the time to bring a given quantity of food to the boil. The larger the product, the shorter the boiling time. In this sense the WSG2 is clearly superior to the WSG1.

6.6. Safety

a. Insulation

The reservoir, filled with kerosene, immediately below the burner is a serious source of danger. During actual operation in the field the kerosene sometimes started burning on the tank; also the temperature of the tank became too high. High temperatures on the tank occur when the wicks are turned down and consequently explosion / burning risks appear during simmering conditions (low power levels and long cooking times). Closing the annular space between outer flame holder and shield to get higher maximum powers resulted in even higher temperatures, did not improve this state of affairs. It was decided to look for means to overcome this problem. Firstly a radiation shield was introduced and secondly the tank was covered with insulating material (see figure 6.13).

The effect of both measures on the kerosene tank temperature is shown in figure 6.14. The experiments were performed on the original Thomas Cup. The experiments lasted 1 hour in which the stove was operated at two different power levels. For the first 30 minutes the power was kept at 3.6 kW whereafter it was reduced to 2.8 kW. In the figure the temperature history of the tank during the experiments is shown. A temperature reduction of 25% (with radiation shield) and 45% (with radiation shield and insulation) was obtained.

Of equal importance for the explosion/burning risks is the question whether the wick tubes are well fixed and do not allow the kerosene to leak onto the tank. If this condition is not met, extinguishing the fire becomes a hazardous operation; attempts to blow out the stove will lead to the kerosene catching fire. However, in all the final prototypes the fire goes out gently; no blowing is needed.

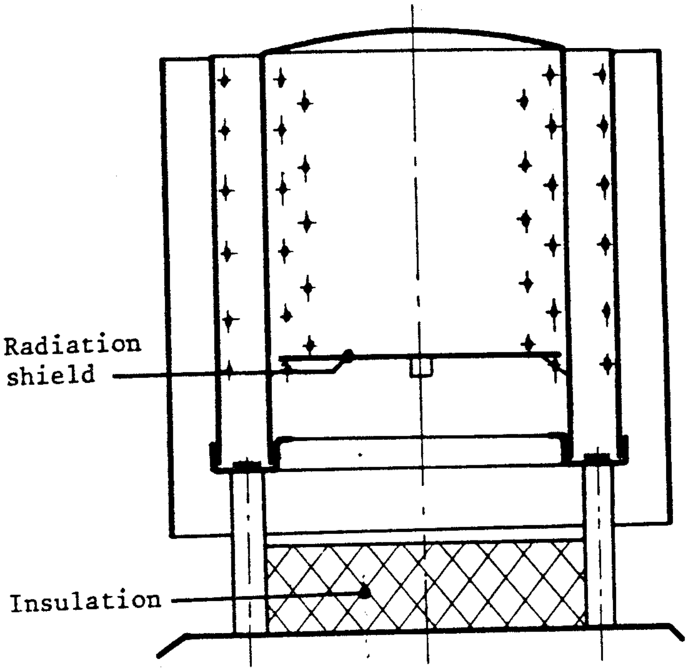


Fig.6.13 : Radiation shield and insulation

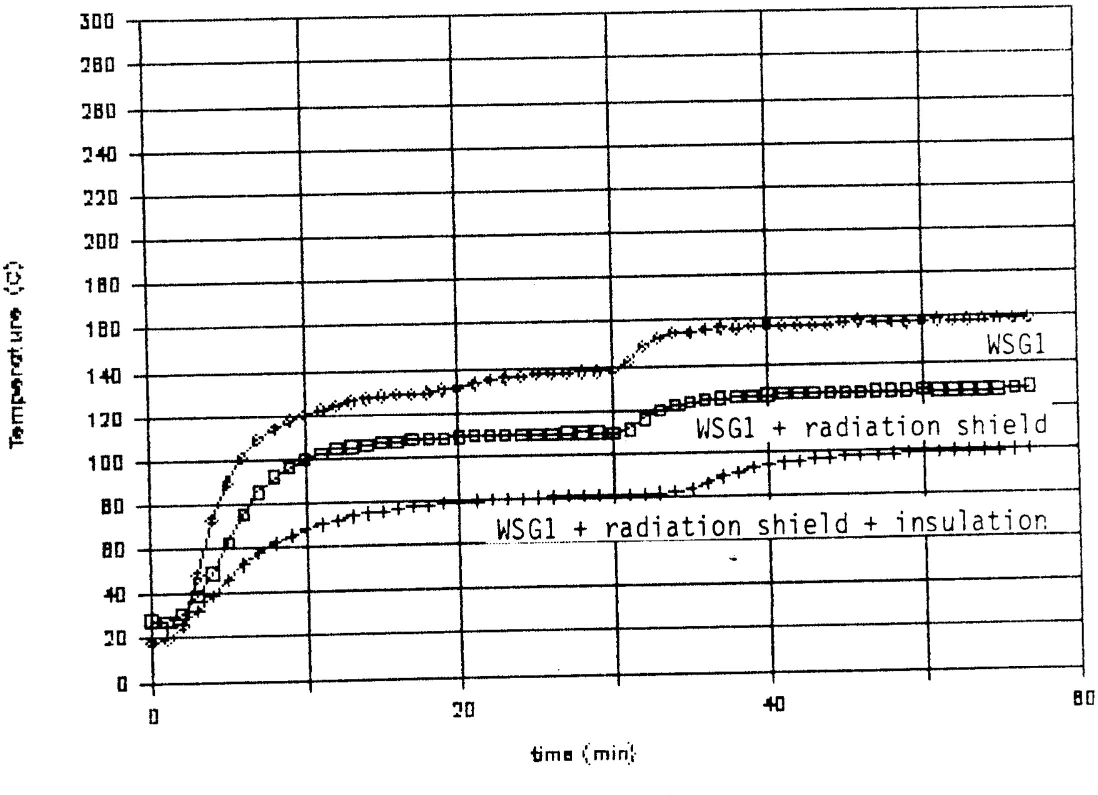


Fig.6.14: Temperature of the kerosene tank

A last point to mention is the risks caused when the wicks have been burned off and the hot tips come closer to the fuel tank than normally when they are turned down; thus leading to higher explosion risks. This problem is discussed in the next section

6.7 Life time of the wicks

The early experiments with the original Thomas Cup stove (section 6.1) showed that the detoriation of the wicks is one of the problems to overcome in designing a high power kerosene stove. The single wick experiments of section 6.2 offered a solution to the problem. They revealed that the wicks can transport the kerosene at a much higher rate than they do in the Thomas Cup and that they can do so for long periods of time. However, adequate protection must be provided against oxygen coming in the direct vincinity of the wicks. Therefore:

i. the flame holders must neatly fit on the wick holder (air leaks should be avoided);
ii. the first 20 mm of the flame holders should not be perforated, thus leaving the wicks enough space to freely evaporate the kerosene. This also implies that the maximum wick level should not exceed the 20 mm.

7. Prototypes

The tests performed laid a basis for designing the kerosene stoves as mentioned in the terms of reference. It resulted in two different prototype stoves which were manufactured by the workshop of the Eindhoven University of Technology. In this section, the prototype stoves will be discussed in more detail. The decisions made in arriving at them will be explained. The first prototype discussed is our Pet stove which differs most from the Thomas Cup. The second prototype is an improved and adapted version of the Thomas Cup.

7.1. The Pet stove

The stove is shown in the photographs. Dimensions are given in the technical drawings provided. In this section the different stove parts will be discussed starting from the tank and ending at the pan support.

Fuel reservoir

The fuel reservoir of the stove can hold 3 litres of kerosene which makes the reservoir somewhat larger than the one of the Thomas Cup. However, it is believed that the content of the fuel tank is not a critical factor. Storage of kerosene in small quantities is not difficult and, moreover, in most developing countries the distribution system of kerosene is well developed. Main improvement incorporated in the design of the fuel reservoir is the lid. The reservoir will not run over even when the stove is in an inclined position.

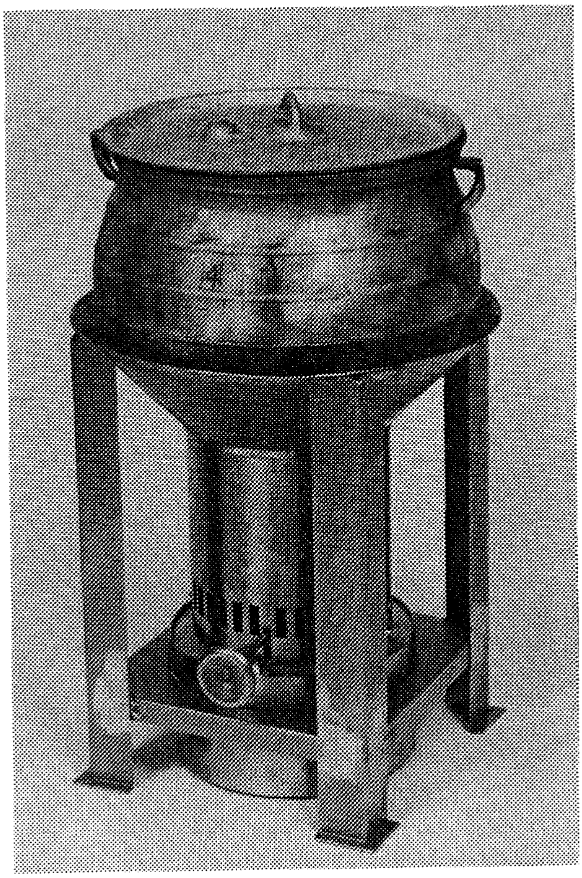
Wicks

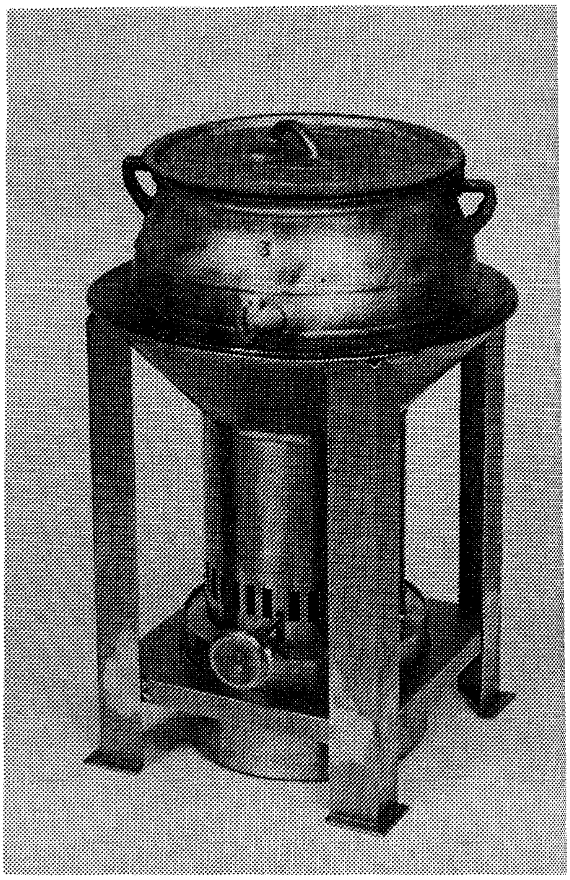
The two questions which had to be answered were:

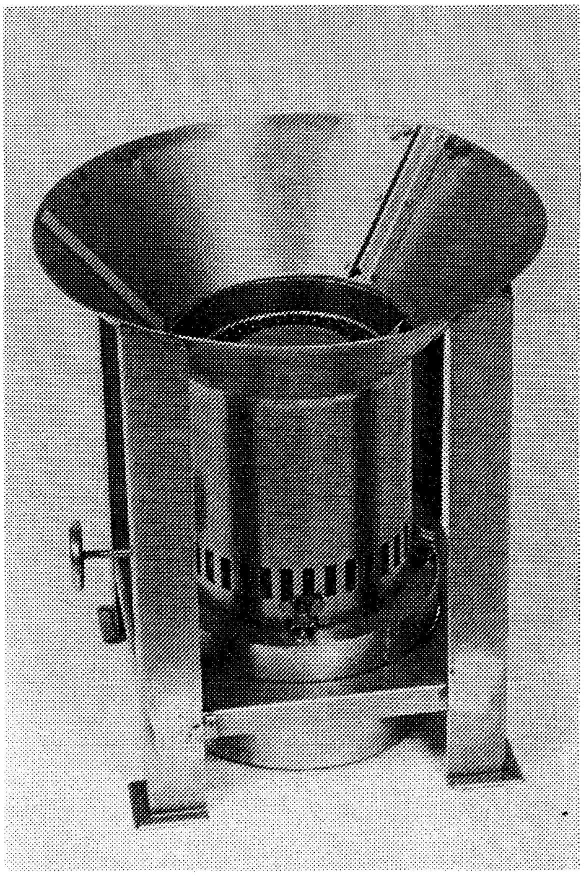
i. How many wicks should be used and
ii. What kind of wick material should be used.

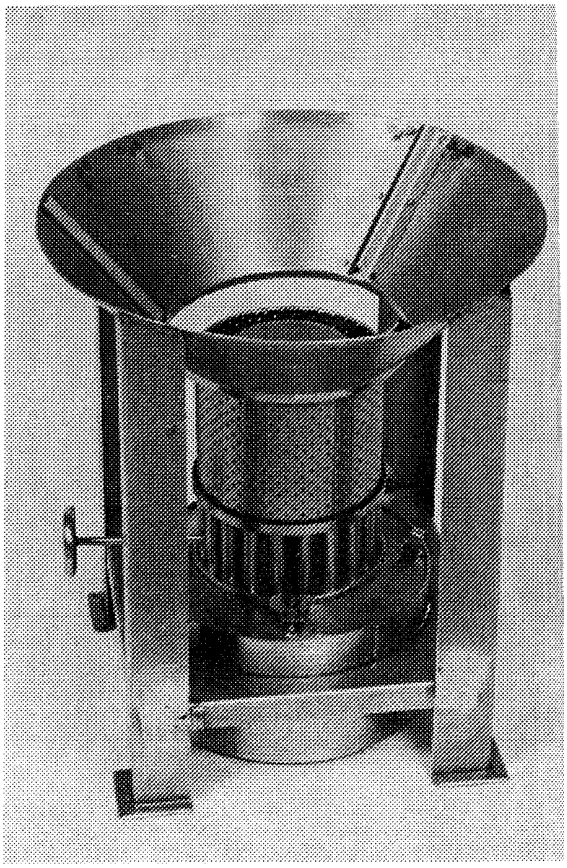
The work was started under the assumption that increasing the number of wicks was the only way to increase the maximum power. The assumption was based on the World Bank report (1985) where the wick hole surface area showed a strong correlation with the power. However, in the repor mentioned, the temperature had not been taken into account while the present work shows the importance of this parameter. The present understanding suggests that even a lesser number of wick could fulfil the 4 kW maximum power requirement. This would make the burner more compact; thus reducing material and, more important, assembly costs. No time was available to study this aspect. The final burner proto-type has 20

IMPROVED THOMAS CUP









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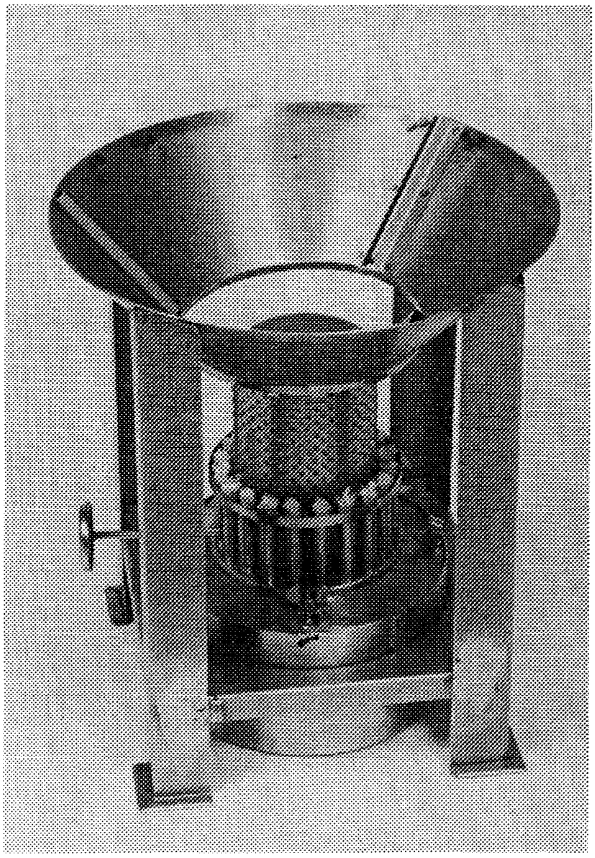
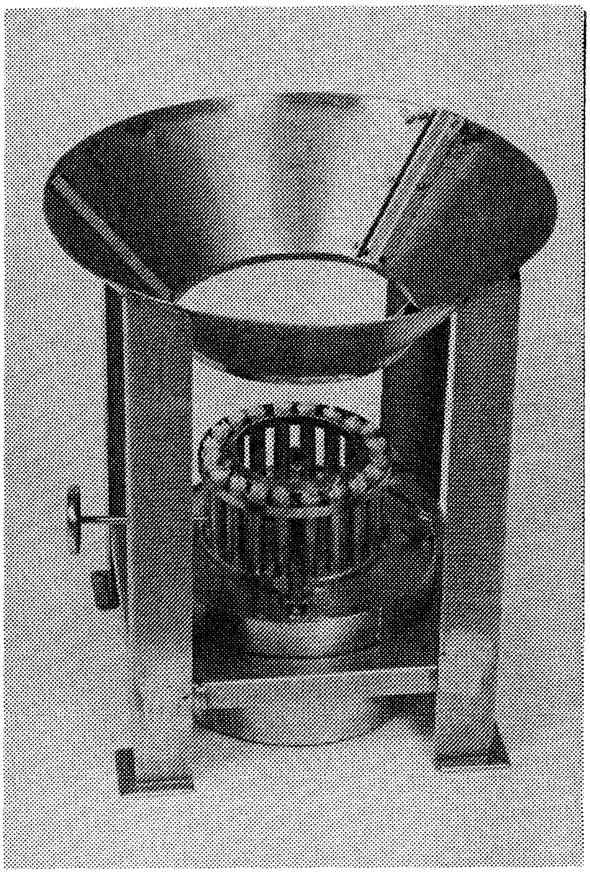
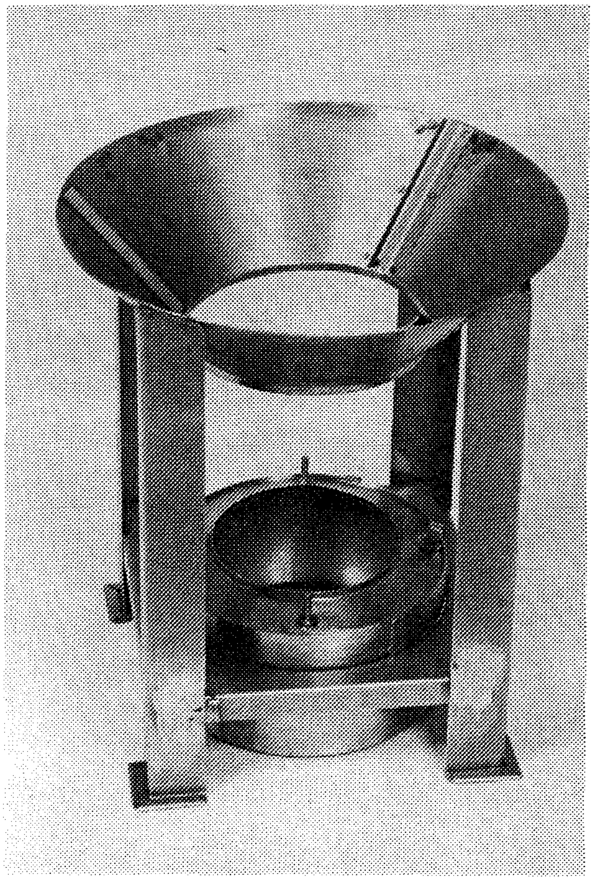
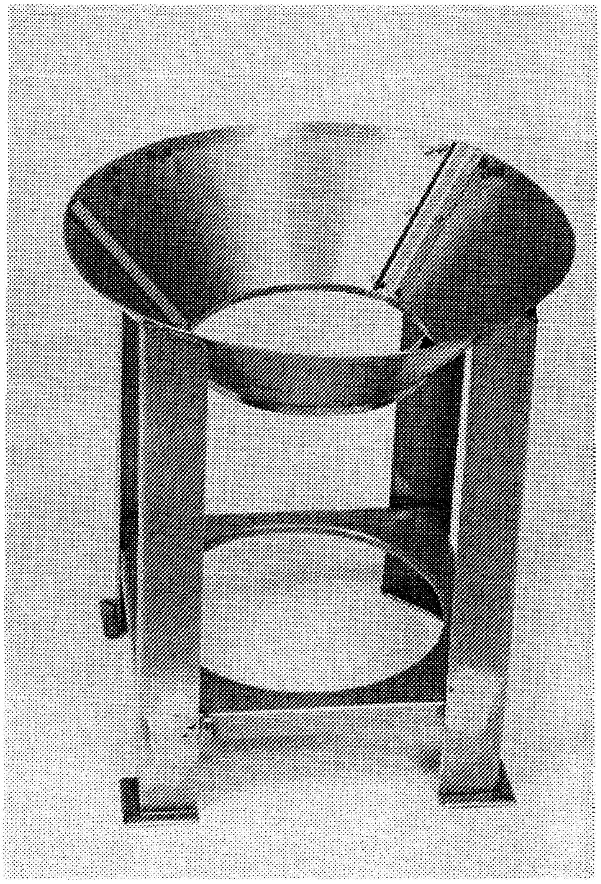








wicks, the same number as the Thomas Cup.

An important result from the experiments is that the cotton wicks, normally in use in the wick stoves, are considered perfectly fit to perform their task provided firstly that they are not in direct contact with oxygen and secondly that the temperature near the wicks does not become too high. The latter condition is important because above 300°C the wicks detoriate quickly.

Wick holder

The wick holder of our Pet stove has been improved on the point of kerosene leaks. Firstly the wick tubes are made of cold drawn pipes; this in contrast with the wick tubes of the Thomas Cup which are made of rolled steel sheet. Secondly special attention is given to the fitting of the wick tubes on the kerosene tank and the combustion chamber. Tolerances of less than xx mm are recommended to optimize the safety of the stove during operation.

Control Mechanism

The control mechanism of our Pet stove is operated with a single knob, which moves two seperate parts:

i. The ring which closes the annular gap between shield and outer flame holder to obtain the maximum power and
ii. The travel of the wicks from a maximum of +25 mm above the wick holder to a minimum of -15 mm below the holder.

It implies that the total wick travel has been increased from 25 mm to 40 mm. In fact the minimum power requirement can be obtained with the wicks not completely in their minimum position. At this minimum power level it is easy for the fire to go out unintentionally. This is important because the fire can not be observed when the pan is on top of the stove. This suggests that the total number of wicks should be split in two groups which can be manipulated separately. In this case one only has to turn down one group of wicks leaving the other group undisturbed, to get the minimum power. In the initial stage of the work this idea was considered in order to fulfil the maximum power requirment. When it appeared that it would not be too much of a problem to get 4 kW from 20 wicks the idea was abandoned, because it complicates the construction. Only after the prototypes had been made the idea came back into the picture, this time to fulfil the minimum power requirement. However, no time was available to check the ease of operation with such a control mechanism.

Flame holder

Combustion is complicated and a difficult process. Attempts to get a more intense blue flame combustion within the flame holders by doubling the number of air holes and increasing the diameter of the air holes from 1.4 mm to 1.8 mm, proved futile. A first attempt was made to mathematically describe the combustion air flow, which is so closely related to the combustion process, to get a better understanding of the results. No time was available neither to calculate air flows and temperatures or to check the validity of the model with experiments. However the model will give a direction for future work.

The height of the flame holders increased the quantity of kerosene burnt in the combustion chamber. However, a taller stove also increases heat losses and decreases the mechanical stability. Consequently a compromise had to be found. The height of the flame holders of the final prototype was chosen to be 140 mm (against 100 mm for the original) from which 20 mm at the bottom are not perforated thus leaving the wicks 20 mm annular space to evaporate the kerosene. The size of the air holes and the hole density was kept the same as in the original Thomas Cup.

Shield

The function of the shield is to protect the stove against wind. It does not have critical dimensions.

Pan Support.

The conical pan support has an angle of 45° . It is made in such a way that it can hold the aluminium round bottom pans no 2, 3, 4. The distance between burner and pan being minimal for pan no 2 (± 5 mm, 15 mm and 25 mm for pan no 2, 3 and 4 respectively).

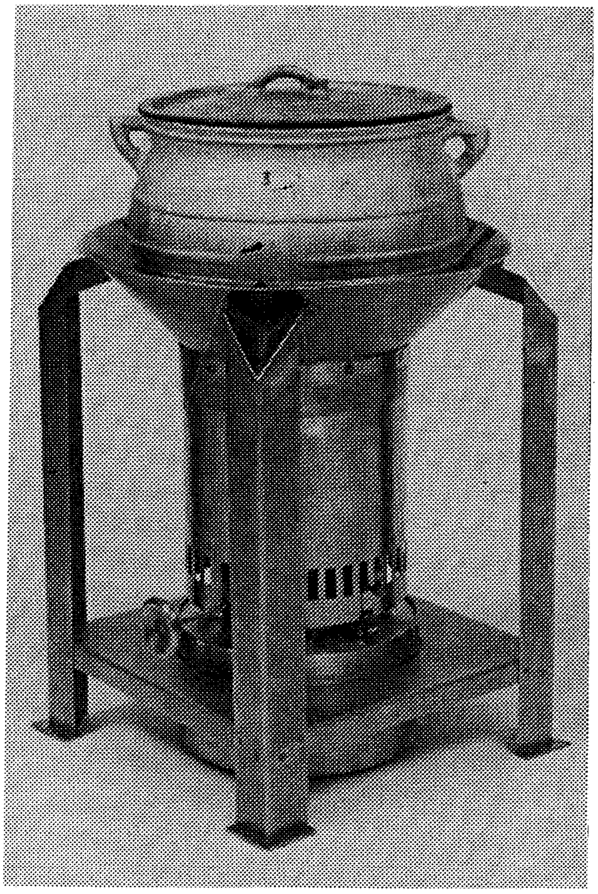
Frame

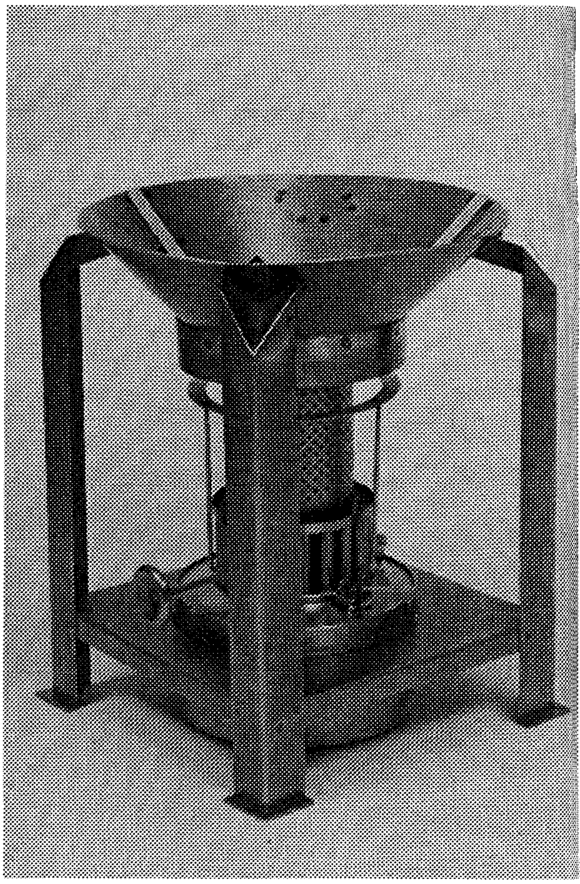
The frame of the Thomas Cup was clearly too weak to support the pan during the preparation of tuou. This supporting stucture has been strengthened. Moreover, the basis of the stove has become wider also improving the stability.

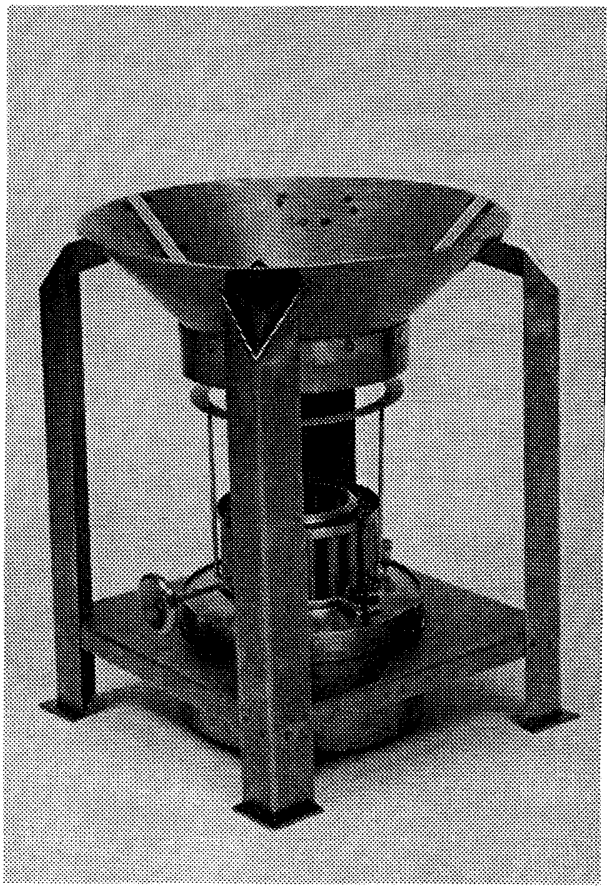
7.2 The modified Thomas Cup

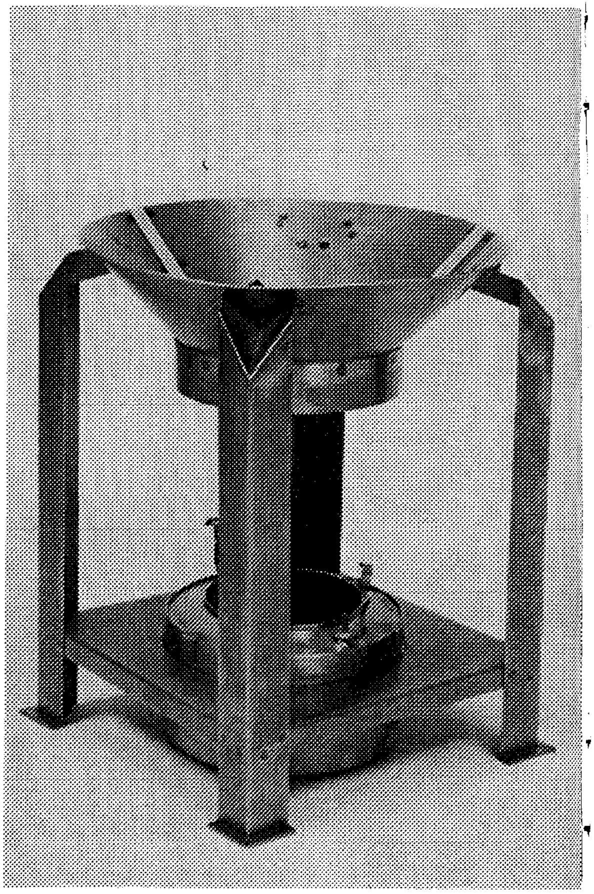
The stove is also shown in the photographs and details are given in the drawings. The stove design does not incorporate all the improvements of our Pet stove and resembles the Thomas Cup to a large extent. The modifications made are listed below:

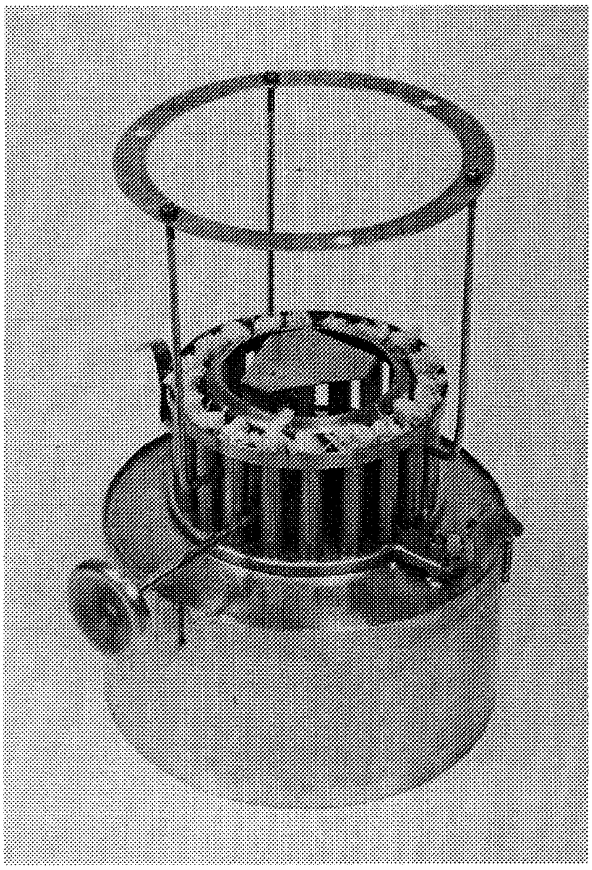
i. Fuel reservoir, wick holder, wicks and pan support are identical to those of the Pet stove.

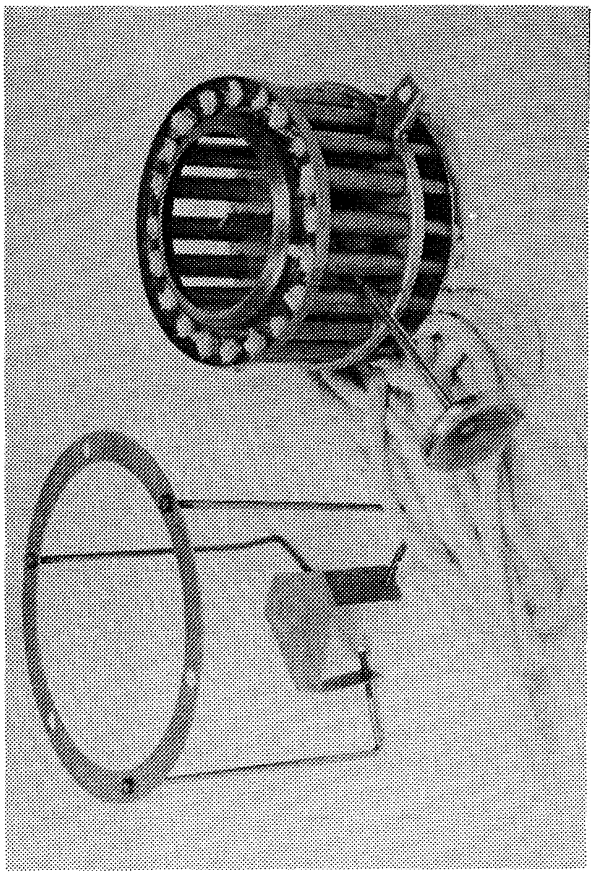


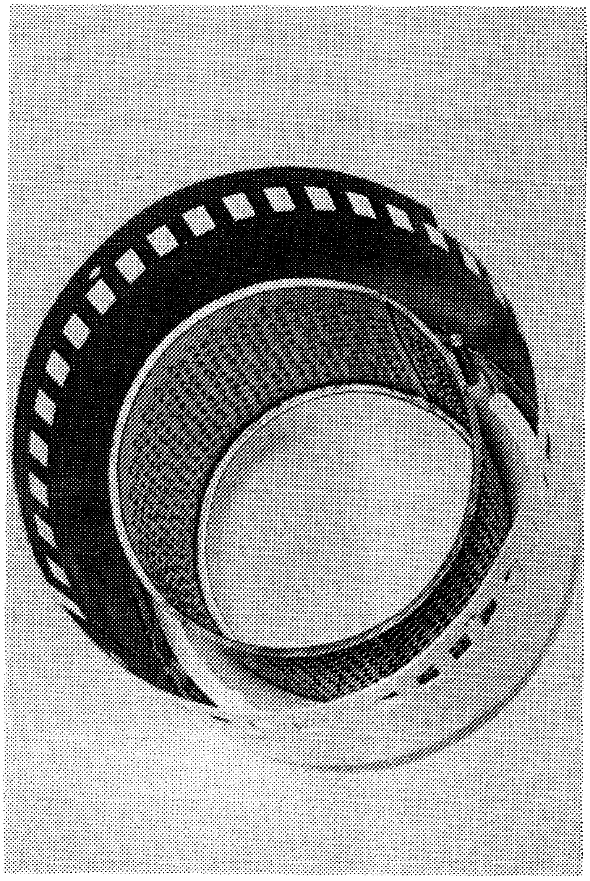


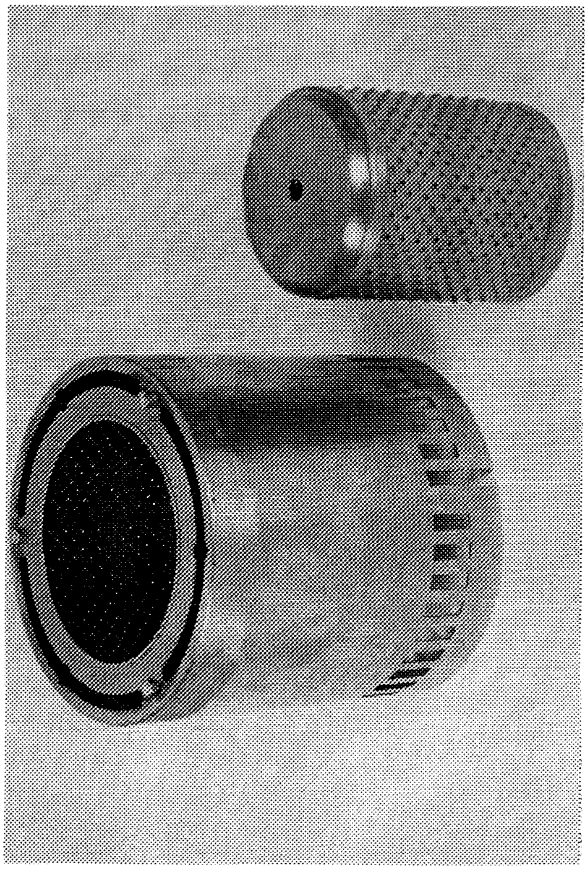












ii. The control mechanism has the same wick travel as the Pet stove but does not close the gap between shield and outer flame holder.
iii. The first 20 mm of the flame holders are not perforated. However, the height and the density of the air holes are kept equal to those of the Thomas Cup.
iv. The frame of the stove has been strengthened. However, the basis of the frame has not been increased.

7.3. Stove Characteristics

The final prototypes became available the last week of January and the second week of February. Due to time constrains only a few experiments could be performed on the stoves. The most important results are shown in table 7.1

Stove:	Pet Stove	Improved Thomas Cup
Pan no 2		
Maximum power	3.2 kW	1.7 kW
Efficiency	37.2 %	49.4 %
Minimum power	0.5 kW	0.5 kW
Pan no 3		
Maximum power	3.3 kW	kW
Efficiency	44.1 %	%
Minimum power	0.5 kW	kW
Pan no 4		
Maximum power	3.7 kW	2.1 kW
Efficiency	49.2 %	58.9 %
Minimum power	0.5 kW	0.5 kW

Table 7.1: Characteristics of the final prototypes

This last series of experiments again showed the important influence air leaks have. The power output of the Pet stove was raised to 6 kW when extra air at the flame holder basis was allowed to enter.

8. Discussion

An important outcome of the work has been the deeper insight obtained in the physical processes which play a role in a kerosene wick stove. It was shown that:

i. the transport capacity of the wicks is not the limiting factor in getting a high maximum power.
ii. the maximum and minimum power are determined by the size of the free wick end and the temperature.
iii. the temperature and thus the power, can be increased considerably by closing the gap between outer flame holder and shield.
iv. complete combustion at maximum power can be achieved by making the flame holders higher without changing the air hole density
v. The temperature on the tank can be reduced with 25 % by adding a radiation shield to the inner flame holder
vi. the life time of the wicks can be increased by preventing oxygen coming in the direct vincinity of the wicks

Due to the time constraints most of the work must be called surface scratching. Consequently most data can only be explained qualitatively. It is believed that more compact burners can be built when additional work is done to improve the flame holders (changing the diameter and the density of the air holes).

The work resulted in two prototype stoves: the modified Thomas Cup and the Pet stove which have been presented in the previous section. The main advantages of the Pet stove over the improved Thomas Cup are:

i. the capacity to bring the food faster to the boil
ii. the capacity to combust more kerosene before the process is quenched by the cold pan bottom
iii. the better stability.

Both stoves have the characteristis which make them suited for testing at the family level. This is the conclusion drawn on the basis of the tests performed on the laboratory models of the stoves mentioned. The final prototypes only became available the last week of January and the second week of February (at the end of the project). Consequently only a limited number of experiments were performed on the final prototypes

The prototypes, as they are now, still are not ready for large scale production. The final design can only be fixed in close collaboration with the stove manufacturer. Thereafter only, the technical drawings can be made and the specifications per stove part given.

PART 2: THE VAPOUR JET BURNERS

9. The stoves

9.1. Introduction

The vapour jet burners have been described in the World Bank report (1985). For the sake of completeness the description is recapitulated below. In the vapour jet burners the kerosene is available at a higher pressure than atmospheric, which is achieved by having a hermetically sealed fuel container in which a small hand-pump is incorporated. Due to the pressure difference, the kerosene rises and arrives in the hot vapourizer where it evaporates and leaves through a small nozzle in a high velocity jet. In the free space between nozzle and the flame holder/stabilizer, the jet mixes with air to enable the mixture to burn with a premixed blue flame.

9.2. Overall dimensions

In total 10 burners were included in the tests. Details of the burners are given in table 9.1 and figure 9.1.

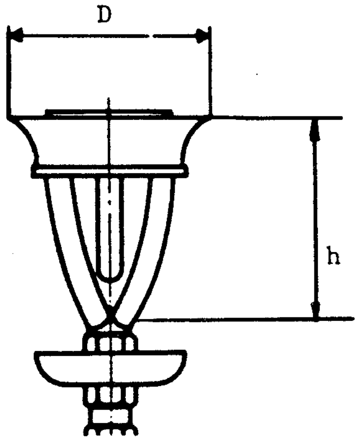


Fig. 9.1: vapour jet burner

Country	Name	Nozzle diam. (mm)	Burner h (mm)	D (mm)
Indonesia	Zeppelin	0.30	61	38.5
	Penguin	0.60	74	47.0
	Butterfly	0.65	100	60.0
	Bee&Butterfly	0.75	114	69.5
	Champion	0.80	117	69.5
India	Naaz de Lux	0.35	53	38.0
			53	38.0
	Super JLH	0.40	71	43.4
		0.45	71	43.4

Table 9.1: Summary of the burners tested

Where h is the distance between the nozzle and the burner head and D is the diameter of the burner head. The nozzle diameters were measured with a microscope. In figure 9.2 the data from table 9.1 is shown in graphical form.

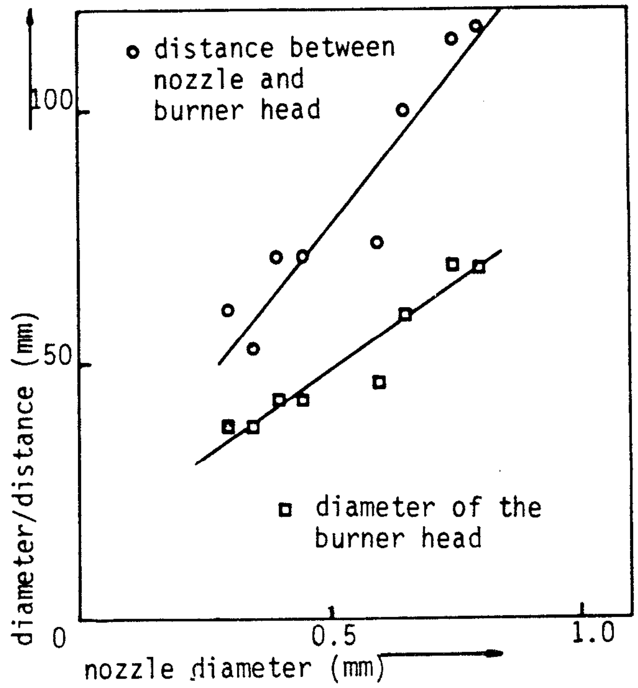


Fig. 9.2: Burner dimensions as a function of the nozzle diameter

From the figure empirical expressions can be inferred. They relate the nozzle-burner head distance (h) and the burner head diameter (D) with the nozzle diameter (d). The expressions are given below:

Nozzle - Burner head distance:

$$h = 17 + 122 * d \qquad \text{(mm)}$$

Burner head diameter:

$$D = 15 + 67 * d \qquad \text{(mm)}$$

No time was available to test all stoves. That is why, on the basis of table 9.1, the Bee & Butterfly and the Super JLH burner were selected and used in the experiments. The Bee & Butterfly and the Super JLH being a big and small burner respectively. The burners were tested together with the nozzles of different diameter of the other stoves.

9.3. The Pump

The power output of a vapour jet burner is a function of the nozzle diameter, the vapour temperature and the pressure difference. They are related according to the formula:

$$P = C \cdot A \cdot \sqrt{dp \cdot \frac{Ta}{T}} \qquad (kW) \qquad (3)$$

where C : a constant
A : the cross sectional area of the nozzle (m^2)
dp : the pressure difference (Pa)
Ta : the ambient temperature (K)
T : the vapour temperature at the nozzle (K)

From the formula the influence of the pressure difference becomes clear. For a given nozzle diameter, the maximum pressure difference and the maximum power are higher when the pump is better. Therefore the pumps were tested on their maximum pressure built-up and compared with two bicycle pumps. Table 9.2 gives the results of these tests.

Bicycle tyre foot pump	686 kPa
Bicycle tyre hand pump	441 kPa
Handpump for Indonesian stoves	176 kPa
Handpump for Indian stoves	147 - 196 kPa
Colombian stove	196 kPa

Table 9.2: Maximum pressure of pumps (100 kPa=1 atmosphere)

It is clear that the performance of the stove pumps is poor compared with the bicycle pumps. It explains why some small and all large kerosene stoves in Indonesia have a bicycle tube valve on the kerosene reservoir.

A good impression of the quality of the pumps can be obtained without measuring the pressure: a good pump already gives a pressure build up after a few strokes.

9.4. The nozzles

The quality of the nozzles appeared to be of the utmost importance. A burr in one of the nozzles caused the nozzle to form a cloud of kerosene vapour instead of a vapour jet. For safety reasons this nozzle had to be excluded from further testing. A second nozzle which came with the stoves was choked-up completely and could not be used.

10. Experiments

Firstly the power ranges of the two burners selected (Super JLH and the Bee&Butterfly) were determined for different nozzle sizes. Secondly the efficiency was measured as a function of the power and the pan bottom - burner head distance.

10.1. Experimental set-up

For the intended series of experiments it was essential to have control over the power output of the stove. This was obtained with a pressure governor valve. When a stove is used without such device the pressure will drop as kerosene is consumed, the air volume of the tank increases and thus the pressure and power will drop. The pressure was measured with a Wallace & Tiernan PennWalt manometer FA-145 (range: 0-1000 kPa; accuracy: 1 kPa).
The fuel tank was placed on a Sartorius balance (range: 0-30 kg; accuracy: 1 g) to record the fuel weight loss; the time was recorded with a stop watch.For the efficiency measurements, a aluminium round bottom pan (size 3; diameter: 300 mm) was filled with water and hung above the burner at a fixed distance.

10.2. The power output

The theoretical relation between the power output and the pressure was given in formula 3 (section 9.3). The experiments with the burners (Super JHL; Bee & Butterfly) were performed for different nozzle diameters. The pressure was varied from 5 kPa to 200 kPa. Each experiment lasted about 15 minutes in which the pressure was kept constant at selected values. The results are summarized in the table 10.1.

The experiments with the Bee & Butterfly were performed twice. The results with the nozzle of 0.65 mm diameter reproduce within the experimental accuracy. On the basis of formula 3 it was expected that the stove would give a higher power output with the 0.80 mm nozzle, but the experiments showed the contrary. During the series with the 0.80 mm nozzle, the flame blew away from the burner, indicating that the nozzle was damaged.

BEE & BUTTERFLY						SUPER JHL					
Nozzle diameter:						Nozzle diameter:					
0.65 mm		0.65 mm		0.80 mm		0.30 mm		0.40 mm		0.60 mm	
dp kPa	P kW	dp kPa	P kW	dp kPa	P kW	dp kPa	P kW	dp kPa	P kW	dp kPa	P kW
								6	0.9	5	1.9
				25	1.4			16	1.3	10	2.4
37	5.4	25	3.7					25	1.6	24	3.8
		49	6.1			49	1.4	49	2.1		
								50	2.3		
50	6.4			50	2.8					50	5.8
				51	2.0					50	5.8
63	7.5	74	7.5								
				74	3.2						
84	8.5										
98	9.2			99	3.2	99	1.8	99	3.0		
		100	8.4							100	8.4
113	9.9										
128	10.4			124	3.4						
143	10.9	148	10.7	148	3.6	148	2.4	148	3.9	149	10.5
158	11.4										
171	11.8			172	3.8						
188	12.4										
		196	13.0	195	4.0	197	2.8	195	4.6	197	12.6

Table 10.1: Power output as a function of the pressure.

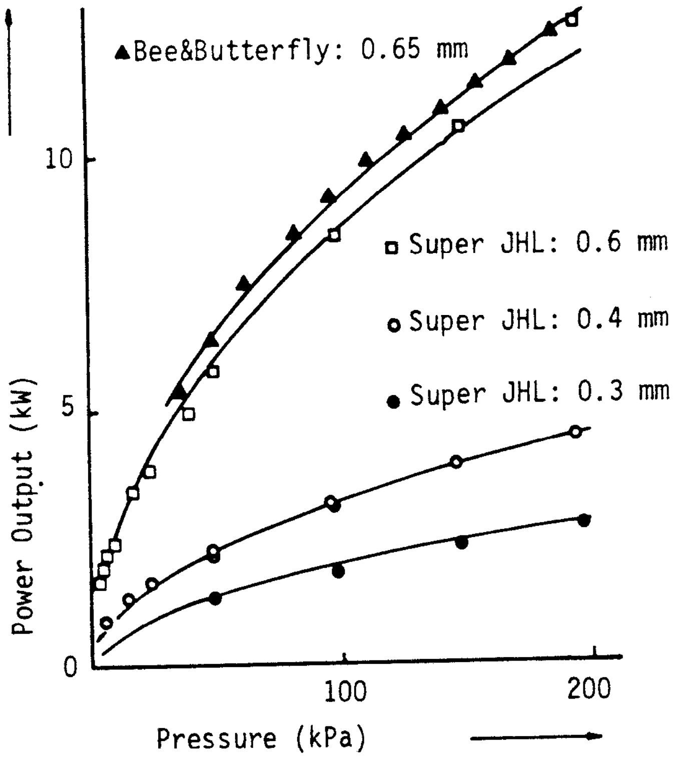


Figure 10.1: Power output as a function of the pressure.

In figure 10.1 the results are shown in a graphical form. The dots represent the experimental data, while the drawn curves represent the best fit assuming the power output is proportional to the square root of the vapour pressure. The graph shows that the proportionality of the power to the root of the pressure is confirmed by experiments. Moreover, within the experimental accuracy, the differences between the curves can be attributed to the difference in the nozzle diameter. The influence of the kerosene vapour temperature, on the other hand, can be neglected.

10.3. Efficiency

On the basis of the power plots presented in the previous chapter, the SUPER JHL with nozzles of 0.4 mm and 0.6 mm was selected for the efficiency tests. Taking into account the quality of the pump, the power range of these stove/nozzle combinations are given below

Nozzle	Pmin	Pmax
0.4 mm	0.9 kW	4.6 kW
0.6 mm	1.9 kW	12.6 kW

Each efficiency test lasted for about 60 minutes.

a. Influence of the power output

A series of experiments was performed in order to establish the influence of the power output on the efficiency. The distance between between pan and burner was kept constant at 6 mm. The results are shown in table 10.2 and figure 10.2. The power-efficiency curve measured with the 0.6 mm nozzle lies a few percentage points higher. It indicates that there are other parameters besides the power and the pan-burner distance which are important. Apparently all burner dimensions should be chosen according to the nozzle size.

b. Influence of distance between pan and burner

In a second series of experiments the power was held constant while the distance (d) between burner and the pan was varied. The results of the tests are summarized in figure 10.3 and table 10.3. The figure clearly shows the reduction of the efficiency with increasing pan-burner distance. As was expected, the experiments with the 0.6 mm nozzle showed higher efficiency numbers. However, direct comparison is not possible due to the different power levels used in the series.

Nozzle:	0.6 mm	0.4 mm
Power kW	eff. %	eff. %
1.0		54
1.3		54
1.7	56	
2.0		49
2.2	53	
2.7		46
3.3		44
3.4	53	
4.9	46	

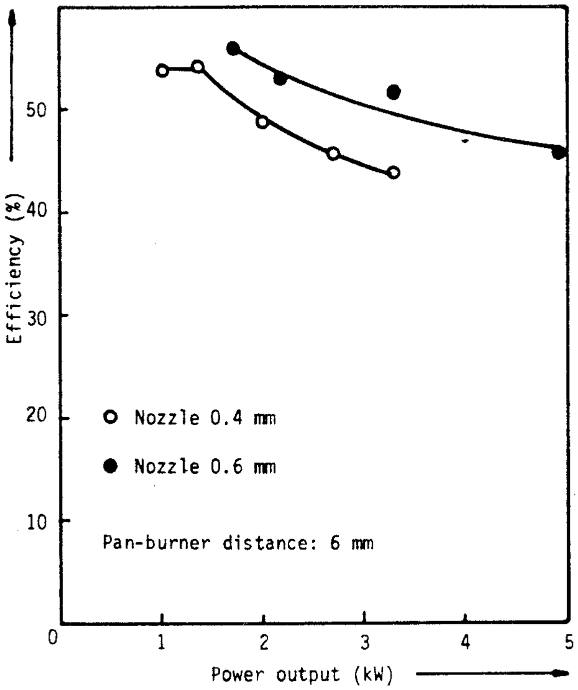


Table 10.2 and Figure 10.2 : Influence of the power output on the efficiency.

Nozzle: Power:	0.6 mm ≃5.5 kW	0.4 mm ≃3.4 kW
d mm	eff. %	eff. %
0		46
6		44
11	50	
21	46	37
35	33	28

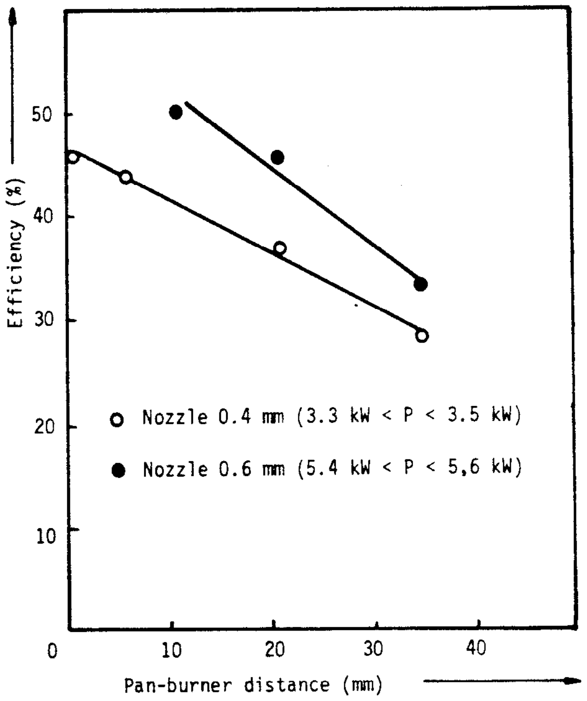


Table 10.3 and Figure 10.3: Influence of the distance between pan and burner on the efficiency

11. Discussion

The vapour jet burners tested belong to the classic primus like stoves. For a given pressure in the kerosene tank, the power primarily depends on the diameter of the nozzle. The theoretical relation between pressure, nozzle diameter and power output was given in section 9.3. This relation was confirmed by measurements. The theoretical relations between the power output and the other burner dimensions are much more complicated. It goes beyond the scope of the present report to derive them here. Instead table 9.1 and figure 9.2 gave the empirical data from the stoves tested. The nozzle diameter was related to firstly the nozzle - burner head distance and secondly to the burner head diameter.

The objectives of the work, given in the terms of reference, were to design a stove with a maximum power larger than 4 kW. Taking into account the quality of the pumps which came with the stoves, this means that the nozzle diameter should be larger than 0.35 mm. On the other hand the nozzle size is restricted by the minimum power requirements. The experiments revealed that a minimum power smaller than 1 kW is not feasible with a nozzle of 0.6 mm. Thus the diameter of the nozzles to be considered range from 0.4 mm to 0.5 mm. The vapour jet burners are very sensitive to impurities (little sand particles) in the kerosene. They clog the nozzle easily. The larger the nozzle diameter, the less important this problem. This finally leads to a nozzle diameter choice of 0.5 mm.

Once the nozzle diameter is known, the other burner dimensions can be found using the empirical expressions given in section 9.2. The dimensions are summarized in table 11.1.

The choice of the nozzle described above implies that it is not necessary to improve on the quality of the pumps. It suffices when the maximum pressure delivered is higher than 150 kPa (1.5 atmosphere).

The efficiency measurements clearly showed the influence of the distance between pan and burner head. On the one hand this distance should be kept as small as possible while on the other hand the pans of different sizes should not be allowed to touch the burner

Pump:	traditional
Tank:	traditional
Burner:	
Nozzle diameter	0.5 mm
Burner head diameter	48 mm
Distance nozzle - burner head	78 mm

Table 11.1: dimensions of the vapour jet burner.

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Annex 1

	Thomas Cup	Swan
Outer cylinder		
Diameter of the holes:	1.4 mm	1.4 mm
Number of holes:	41*19=779	32*19=608
Inner cylinder		
Diameter of the holes:	1.4 mm	1.4 mm
Number of holes:	33*18=594	25*17=425
Diameter of top hole:	9.6 mm	17.2 mm
Hole area		
Outer cylinder:	1199 mm2	936 mm2
Inner cylinder:	914 mm2	654 mm2
Top:	72 mm2	232 mm2
Wick tubes		
Diameter:	6.0 mm	6.1 mm
Length:	60 mm	50 mm

ADDENDUM

Research Proposal to Develop Kerosene Stoves

The work presented in the final kerosene report (Bussmann et al 1987) could be called at best superficial. Due to time constraints it concentrated on getting a qualitative description of the processes involved in the combustion of kerosene. As a result choices were made on a rather ad hoc basis. No time was available to look at existing stove designs (or to study design ideas) which differed too much from the usual.

It would be the purpose of the work proposed to break new ground to arrive at new prototype stoves. The work certainly also would lead to a deeper insight into the technical aspects of kerosene stoves for cooking purposes which in its turn would facilitate the improvement of existing commercial stove designs.

The prototypes designed by the WSG (Pet stove) improved the existing designs on the power range, the stability and the life-time. However, they only marginally improved on the combustion quality. It led to the unsatisfactory situation that the combustion in the present prototype stoves has not been completed when the gases leave the stove. Consequently, as with existing stoves, energy is lost; pans are blackened and toxic gases liberated.
Although the WSG prototypes are kept as small as possible they are rather bulky compared with some Japanese kerosene space heaters. It indicates that a better insight in the combustion process might lead to a more compact burner. Not only material would be saved but probably also the efficiency increased. However, compact burners might lead to higher temperatures demanding the use of more expensive materials. Clearly there is an optimization problem here that requires closer examination. An increase in the efficiency has the advantge that the maximum power requirement could be lowered without affecting the time in which food is brought to the boil.

The tests performed and literature studied sofar revealed a completely new aspect of the combustion process. They showed that combustion of kerosene in blue and yellow flames is not necessarily identical to complete and incomplete combustion respectively. The deeper consequences of this insight are not yet clear but are believed to become important in designing a compact burner. Therefore the combustion process needs to be studied with respect to:

i. The air supply.
   - The quantity of air required
   - The spatial distribution of the air supply
   - The flow resistances distribution

ii. The combustion volume
   - The mixing between air and kerosene vapour

iii. The temperature
   - The temperature distribution in the stove
   - The temperature criteria for blue and yellow flame combustion

All these aspects relate to the design of the combustion chamber (the flame holder). Indirectly they also influence the kerosene evaporation rate and thus the power. This effect should be taken into account in designing a more compact burner. Moreover, the power control mechanism of the Pet stove is still needs improvements especially at the low power end. Thus quantitative data are needed on

iv. The kerosene evaporation rate at the free wick end as a function of:
   - the temperature
   - the surface area of the wicks
   - the flow conditions around the wicks

v. The ratio between maximum and minimum power for different wick settings

During the course of the work a methematical model to describe the fluid flow, heat transfer and combustion processes will be developed to assist in guiding the experimental work

The Pet prototype was adapted to the cooking habits in Niger. This implies that the pan support has been designed in such a way that the prototype can hold spherical aluminium pans of different sizes. As a result the distance between burner and pan increases with the pan size and so does the power output. To design stoves for wider use it is therefore required to:

v establish a rationale to relate the pan size with the power

vi determine the differences in the performance of the stove when spherical and flat bottom pans are used respectively.

The work finally should result in a new generation of designs which are more compact and perform better. These prototypes are laboratory models in essence, which are not yet production ripe versions. To arrive at that stage additional work needs to be done. Therefore:

vii. collaboration must be established with a possible producer.

In some countries in the Sahel projects are executed to introduce kerosene stoves. The intention of the proposed work is to arrive at a stove model which finally can be tried out in the field. Therefore the national energy laboratories will be invited to participate in and contribute to the work proposed.

Time scales: 2 years from the start of the project

Personnel: - 2 years of a full time research engineer
- 2 years of a half time technician
- 2 years of a 0.2 time supervisor

Costs:	- Personnel:	Dfl 275.000
	- Material/equipment:	Dfl 20.000
	- Overhead at 15%	Dfl 45.000
	- TOTAL	Dfl 340.000

Depending on the particiation of a national laboratory in a developing country the cost can incrase by another Dfl 150.000.