Eindhoven University of Technology

MASTER

Kerosene stoves and single wick fuel burning

Verhoeven, N.A.

Award date:
1989

Link to publication

Disclaimer
This document contains a student thesis (bachelor's or master's), as authored by a student at Eindhoven University of Technology. Student theses are made available in the TU/e repository upon obtaining the required degree. The grade received is not published on the document as presented in the repository. The required complexity or quality of research of student theses may vary by program, and the required minimum study period may vary in duration.

General rights
Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain

Take down policy
If you believe that this document breaches copyright please contact us providing details, and we will remove access to the work immediately and investigate your claim.

Download date: 20. Mar. 2025

Technische Universiteit Eindhoven

Faculteit Technische Natuurkunde

Vakgroep Transportfysica

Kerosene Stoves and Single Wick Fuel Burning

N. A. Verhoeven

februari 1989

R-977-A

Verslag van het afstudeerwerk
verricht in de interfacultaire werkgroep
Houtkachels

Afstudeerhoogleraar : prof. dr. ir. G. Vossers
Afstudeerbegeleiders: prof. dr. K. Krishna Prasad
ir. C. Nieuwvelt
ir. P. Verhaart

Met dank aan alle medewerkers
van de werkgroep voor de
plezierige medewerking

voor mijn vader en moeder

Contents

page no.

List of figures

List of tables

List of symbols

Pnom	the blue flame maximum power output (W)
Pmax	the yellow flame maximum power output
dp	wick pitch diameter (m)
dw	distance pan bottom burner head top (m)
Eff.	heat transfer efficiency (%)
Pmin	minimum power output (W)
s.t.p	standard temperature and presure; a temperature of 0 ^{0}C and a presure of 101 325 N m^{-2}
b	plume radius (m)
T	temperature (K)
T_a	ambient temperature (K)
r	distance from the plume centre (m)
z	height (m)
u	velocity in z-direction (m s^{-1})
U	velocity in z-direction (m s^{-1})
ρ	density (kg m^{-3})
ρ_a	ambient density (kg m^{-3})
$v_{z,\infty}$	velocity in $r \to \infty$ at height z (m s^{-1})
α	entrainment constant (-)

1. Summary

A study was made of the properties of six different kerosene wick burners and of the burning at a single wick.

The flame length theory of Bussmann et. al. was tested for single wick flames and proved to be wrong for these very small flames.

The aim of the study was to gain some ideas for improving existing kerosene wick stoves and for building new ones, for use in Sahelian countries.

The experiments were carried out with:
a mass balance, to determine the mass rate
and a gas analysis setup, to determine the CO/CO_2 ratio of the fuel gas.

In case of complete combustion the mass rate and the power output are directly related.

For the kerosene burners the heat transfer efficiency and three different power outputs were determined. The measured heat transfer efficiencies are all around 50 % and the power output varies from 0.9 kW to 7.2 kW.

A number of single wick experiments was carried out under different circumstances. The mass rate through a wick with free wick length of 5 mm reached values up to 6 mg s^{-1}, which under clean combustion conditions equals approximately 250 W.

A remarkable result is that the rate of fuel consumption dramatically decreases when the draft around a wick is increased above a certain value. This phenomenon is preceded by a large CO emission.

2. Introduction

2.1 Use of Energy in the Third World

A very important energy source for over half the world's population is fuelwood. This enormous wood consumption, in combination with natural catastrophes, like large rainfall or no rainfall at all, is already having a really devastating effect on the ecological environment of the Third World. The effects are not only noticeable during flood disasters but also in the accelerating growth of the deserts and subsequent loss of large agricultural areas.

The effects mentioned above not only influence the environment but also the supply of fuelwood and its derivative, charcoal. Food must be cooked before it becomes edible. So for more than half the world's population fuelwood is as essential to survival as food itself. With a growing population in these areas, the discrepancy between fuelwood supply and -consumption is even more striking. It is known for several years now that, if no adequate actions are taken, by the year 2000 the fuelwood supply for some 1000 million people will be so critical that they will no longer be able to cook their food sufficiently.

The fuelwood deficit must be tackled from different fronts simultaneously. One must ensure a reasonable and continuous supply of firewood; this is possible by large scale afforestation programs. One must ensure that the available firewood is used as efficiently as possible. One must look for available substitute fuels and ensure that these are also used as efficiently as possible. In the Sahel, substituting LPG or kerosene for fuelwood and charcoal is an important way of reducing deforestation due to fuelwood consumption.

An indirectly related problem to the shortage of fuelwood, but very related to the cooking conditions, is the hazardous emission of poisonous flue gases, containing mostly carbon monoxide. It should be clear that increasing the efficiency of a cookstove should never result in an increase of poisonous flue gas emission. Every newly developed cookstove should not only be very efficient but also burn cleanly. In both aspects the Woodburning Stove Group (WSG) at Eindhoven University of Technology (TUE) has extensive expertise and experience.

2.2 The Woodburning Stove Group

The Woodburning Stove Group started as an informal association of people from the faculties of Physics and Mechanical Engineering at the Eindhoven University of Technology and the Division of Technology for Society at TNO, Apeldoorn. The group was formed in March 1980, with the aim of developing a set of design rules for efficient wood burning cookstoves for use in the Third World. Since the beginning some of the significant achievements of the group are:

(a) The group has developed a unique research facility to study heat transfer, fluid flow and combustion in biomass burning devices.

(b) The group has extensively studied open fires, closed stoves of single pot stoves and two-pot stoves.

(c) This research has enabled the group to come up with designs specially suited to households, institutions and commercial enterprises in different Third World countries.

(d) Over the years the members of the group have provided technical advice to projects in 17 countries.

Another highlight of the group was the achievement of P.J.T. Bussmann in 1988 with his dissertation 'Woodstoves Theory and Applications in Developing Countries'.

At the moment of writing this report the work of the Woodburning Stove Group in Eindhoven is concentrated on three projects:

(1) the wood burning bakery oven project;

(2) the clean combustion project;

(3) the kerosene wick stove project.

The laboratory work on the woodbakery oven project started in the beginning of 1987 with the building of a working scale model of a bread bakery oven. The work on clean combustion involves two woodstoves, the cogenerating stove and the downdraft stove. The work on kerosene wick stoves is concentrated on the combustion of the fuel at a single wick under different circumstances.

2.3 The Kerosene Wick Stove Project

The work on kerosene stoves started in 1983 at the instance of the Energy Assessment Division, of the Energy Department of the World Bank. The main purpose of the work was to provide reliable data on kerosene stoves of diverse designs, as an aid to policy planners for selection of design. A result of the test programme was that none of the commercially available kerosene stoves at that moment had a maximum power output above 2 kW (World Bank, 1985). In the test programme two major types of stoves, each with its own advantages and disadvantages, were found: the kerosene pressure-burner and the kerosene wick stove. A complementary field project in Niger showed that the power outputs of the wick stoves, in combination with their efficiencies, resulted in an unduly long cooking time for the average meal in Niger (Bussmann, 1986), although for the first time in a Sahelian country kerosene stoves were succesfully tried out at the family level (Madon, 1986). It is against this background that the World Bank in 1987 awarded an R&D contract to the Woodburning Stove Group in Eindhoven. The purpose of this project was:

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

A direct result of this work was the development and building of a high-power kerosene stove, the Pet Stove. The Pet Stove has the various adjustments suggested by the results of the R&D work. In the report of this R&D work (Bussmann, 1987) it is clearly stated that the Pet Stove is still a prototype and not yet ready for large-scale production. At that moment a new high-power kerosene stove was discovered on the commercial market, the Thomas Cup 36. In field studies in Burkina Faso (Sulilatu, 1988) and in Cape Verde (Bussmann, 1988) both stoves were tested and showed disappointing results towards power output and efficiency. Another problem of the kerosene wick stoves, found during field studies, was that, even if the wicks were protected as suggested by the R&D work, they wear out very quickly (Bussmann, Sangen, Sulilatu and Visser, internal communication 1988). On the whole the kerosene wick stove is a promising stove for developing countries, due to the easy maintenance, the low purchase price and the possibility of local manufacturing of the stove by small-scale industries and artisans (Sulilatu, 1988 & Sangen, 1988).

2.4 Plan of the Report

The following chapter presents a brief description of the kerosene stoves needed in the Sahel, a small history of kerosene wick burners, the operating principles of wick burners and some results of previous work, most of them carried out in Third World countries. Chapter 4 contains a description of the burning of alcohol and kerosene and it presents the assumptions which led to the flame length theory of Bussmann et. al. In this chapter the computer programme, whose design is based on the flame length theory, is presented as well. In chapter 5 a very extensive description of the tested burners is given, in tables as well as in figures. Also the three, in essence different power outputs of the stoves are explained. Chapter 6 contains the different single wick setups, which were used to get a better impression of the fuel burning at such a wick. The chapter is written in the order in which the experiments were carried out. The measurement setups and methods are explained in chapter 7. This chapter contains schematics of the mass rate, the heat transfer and the gas analysis setup; it also explains how the flame length was measured.

The different experiments and their results are discussed in chapter 8. For convenience this chapter is split into two sections; the first section is about kerosene stoves and the second one is about the single wick fuel burning. The first section contains the different power outputs of the burners, the heat transfer efficiencies of the stoves and the flue gas quality of the Pet Stove. The second section contains different mass rates and flue gas qualities of single wick setups. Chapter 9 gives conclusions and recommendations that evolved from this work.

A set of appendices is included, containing recommendations for kerosene stoves, some measured data and the entire computer programme and its functioning.

3. Kerosene Stoves

3.1 Kerosene Stoves for Cooking in the Third World

In the report 'On the Designing of High Power Kerosene Stoves' (Bussmann, 1987) the following specifications of a kerosene wick stove, suitable for a Sahelian country, are given:

(a) maximum power > 4.0 kW;
(b) minimum power < 0.7 kW;
(c) thermal efficiency > 50 %;
(d) adapted to cooking habits in Niger (touo preperation, use of spherical pots);
(e) low cost.

A more extensive specification regarding requirements for kerosene stoves for the Sahel is given by E.T. Ferguson in appendix A.

The method most generally used to prepare food is boiling (A Woodstove Compendium, 1981). Raw food is placed in a pan with water and put on a stove. The stove at this point is on its maximum power output. The power output is decreased when the water in the pan starts boiling. The use of maximum power shortens the warming up time. The low power is needed to keep the water and food combination at the boiling point without evaporating too much water. The useless evaporation of water leads to a large energy loss, which has nothing to do with the actual cooking of the food. The low power should, in view of fuel economy, be as small as possible, although it should give enough energy to keep the water and food at boiling point. With a very low stable minimum power and a large maximum power, in combination with a large heat transfer efficiency, a stove is suitable for the differently sized Sahelian pans.

3.2 History of Wick Stoves and Kerosene Burners

Although the use of mineral oil and its residues for burning and other purposes has been recorded since ancient times, the major breakthrough in the application of fuel oil for technical purposes is not more than one hundred years old.

With respect to the constructive development of kerosene lamps, which are in principle identical to kerosene wick stoves, the following remarks, made over half a century ago (Romp, 1937), may be of interest:

> "Nowadays people very often speak disparagingly of oil lamps, which are seen to be ridiculously primitive devices, but it is often forgotten that they are the result of very elaborate and painstaking research done half a century ago. Readers who are interested in this matter are recommended to read Stepanoff's book 'Grundlagen der Lampentheorie' (1894), for which he was awarded the Nobel prize."

Remarkable is a similar statement on woodstoves in a review of the dissertation of P.J.T Bussmann (1988), in two dutch newspapers in 1988 (Eindhovens Dagblad & Volkskrant):

> "That woodstoves are not the simple construction they seem to be, is proven by the many difficult mathematical formulae in this dissertation."

Kerosene lamps were originally made with cord wicks, like those of candles, but very soon annular wicks with air admittance in the centre proved to reduce the tendency to soot considerably, obviously because the centre, being exposed to a strong radiation of heat, then consisted of thermally stable air instead of unstable hydrocarbons. This construction change can still be found in the different stove designs, whether they consist of a single ring wick or a group of small wicks gathered in a ring.

After the introduction of a motor-driven oil burner in 1880, which blew air into the flame by means of a propeller driven by clockwork, had proved to be unsatisfactory, natural draught was applied to suck air into the flame by means of a glass chimney, resulting in a more vivid combustion and a higher temperature. According to the research of Stepanoff(1906) it proved to be a most important point to establish a suitable distribution of air for the inside of the hollow wick as compared with the outside of the flame. The application of a large glass chimney and a hollow wick, which creates a premixed flame, is nowadays still used in a kerosene lamp, the Aladin Lamp. The kerosene wick stove is known since 1916 (Romp 1937). In today's kerosene wick roomheaters, like Zibro Kamin and Elegance, and kerosene wick stoves, like Pet Stove and Thomas Cup, natural draft is created by tall combustion chambers in which the air is drawn through the perforated combustion chamber walls.

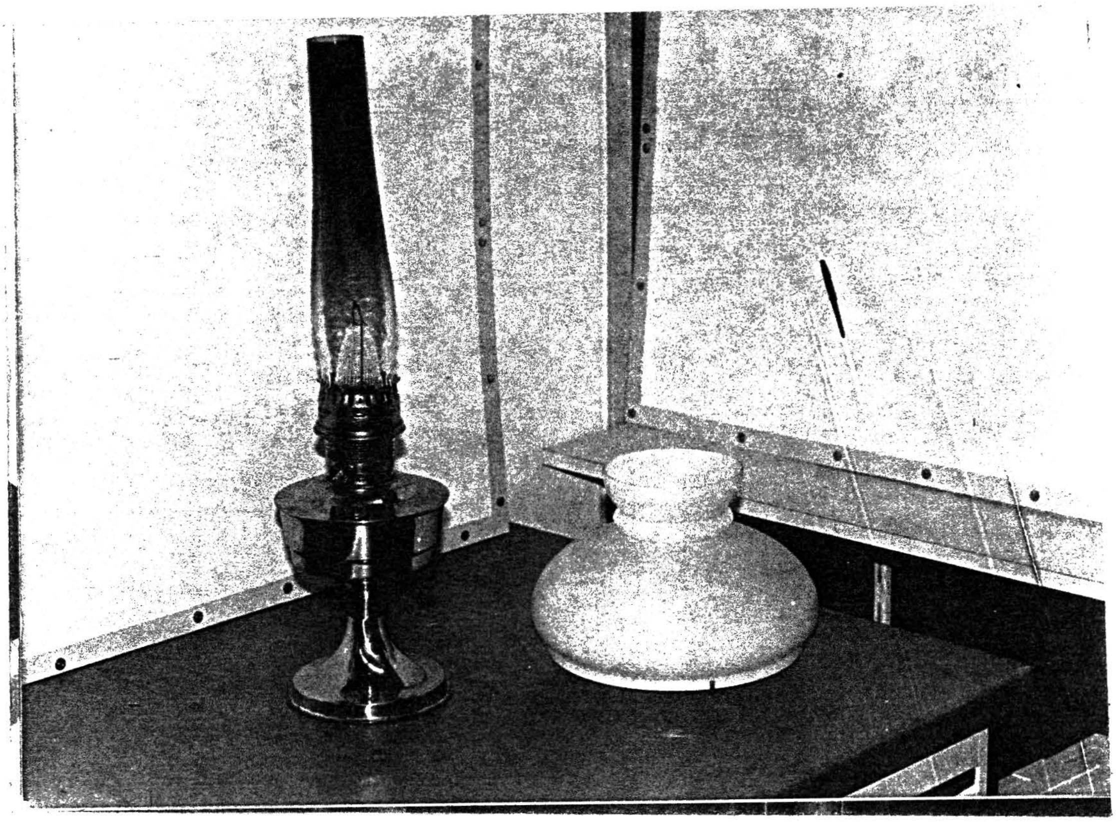


figure 3.1
The Aladin Lamp,
a kerosene burner whose function is to give light.

3.3 Principle of Operation of Kerosene Stoves

In general, kerosene burners for domestic use can be classified into two main categories:

(1) vapour jet burners;

(2) wick burners.

The wick burners can again be subdivided into open wick burners and range wick burners. This study and report is concerned with the latter. Range wick burners were developed to increase the power output of wick burners, while keeping the combustion clean. The principle of the construction is as follows (Prasad, 1983):

> A number of wicks is fixed in a holder such that they can move up and down. Moving up and down causes them to emerge into an annular space, the combustion zone, formed by two thin-walled concentric perforated steel shells, the flame holders. The distance between the inner- and outer flame holder is a little more than the thickness of the wicks, usually around 12 mm. The height of the cylindrical flame holders is about 10 cm.
>
> To start the stove, the wicks are turned up and set alight. The draft created by the flames draws ambient air through the small holes in the flame holders into the annular space. At these small holes tiny blue flames can be observed. If the wicks are being turned up to a sufficient height, the top level of the flames gradually rises, eventually filling the whole annular space and emerging from the open top in a stable blue flame. Raising the wicks even more will make the upper part of the blue flame become yellow, which is an indication of cracking of the kerosene in the flame (Spalding, 1955).
> The cracking of kerosene is mostly accompanied by the production of soot. Soot reduces the heat transfer from the flame to the pan and is therefore undesirable.
>
> The heat generated by the reaction of air and kerosene vapour will, after some time, make the flame holders glow red hot. To keep that heat from radiating away, the burner is

usually provided with an outer cover, the wind shield.

In figure 3.2 a range wick burner is described.

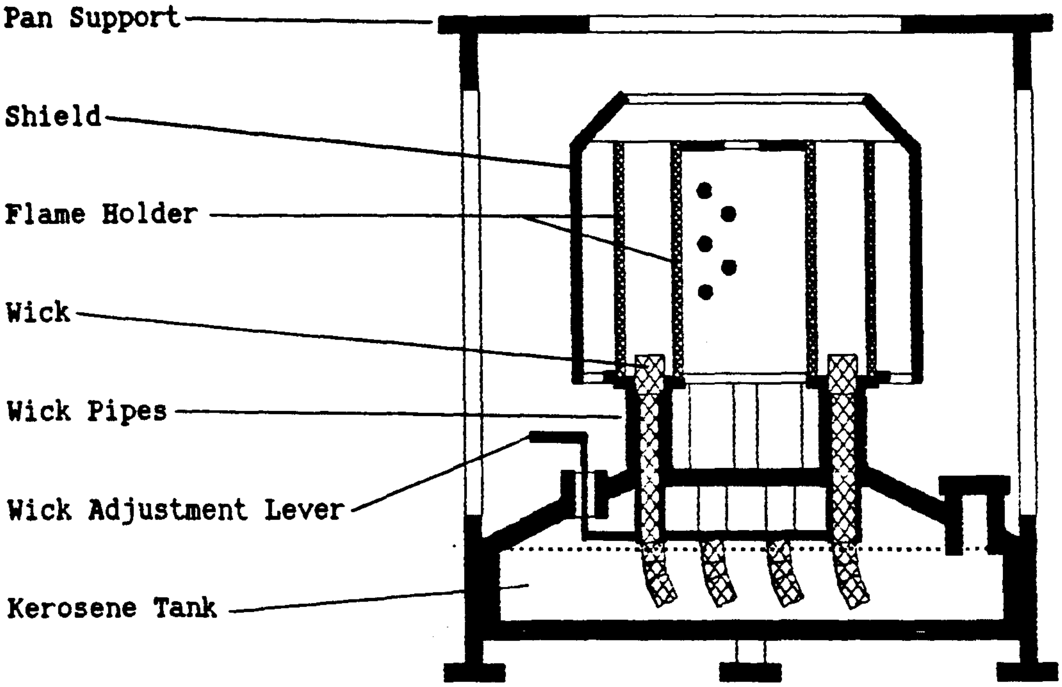


figure 3.2
A kerosene wick stove with pan support
of the multi wick type range burner.

3.4. Results of Previous Work

Literature on kerosene wick burners today is scarce. Books from the past, like Stepanoff's 'Grundlagen der Lampentheorie' of 1906 and the book of Romp 'Oil Burning' of 1937, are the major information sources on kerosene wick burning in this study. In the Energy Department Paper No.26 (World Bank, 1985) a number of kerosene stoves is described. The measurement methods described in this report, regarding maximum power output, minimum power output, blue flame maximum power output and heat transfer efficiency, are adopted in this study; they are described in chapter 5. The results in the World Bank report, specific for kerosene wick burners, are summarized in table 3.1.

table 3.1
Summary of results of World Bank report on kerosene stoves
(World Bank, 1985)

brand name	Pmax (kW)	Pmin (kW)	dp (cm)	dw (cm)	pan dia (cm)	Eff. (%)
Ashok	2.0	0.6	9.0	2.3	18	48
Nutan	1.1	0.2	9.0	0.0	14	44
Divyajyoti	1.2	0.1	8.7	5.5	16	24
Hock	1.8	0.4	10.0	4.5	18	43
Swan 14	1.3	0.3	9.3	3.9	14	39
Swan 20	2.0	0.5	12.0	4.7	18	41
Lark	1.4	0.3	8.6	4.0	16	41

dp = wick pitch diameter
dw = distance pan bottom - burner head top
Pmax = the blue flame maximum power
Eff. = the efficiency of the heat transfer from the flame to a pan with water

Reports of field studies on energy in Third World countries of P. Bussmann and H. Stiles 'Stoves for Cape Verde' (1988) and W.F. Sulilatu's 'Evaluation of Wood Stoves, Gas and Kerosene Stoves in Burkina Faso' (1988) give extra results on kerosene stoves tested under field conditions. The Cape Verde results show a disappointing behaviour of the Pet Stove and Thomas Cup 36. The Burkina Faso results are in table 3.2.

table 3.2
Summary of the Burkina Faso results on Thomas Cup 36
with different pan sizes
(Sulilatu, 1988)

pan dia. (cm)	Pmax (kW)	Pmin (kW)	dp in (cm)	dp out (cm)	dw (cm)	Eff. (%)
20	5.01	0.73	9.0	15.5	4.3	31
24	5.13	0.67	,,	,,	,,	33

dp in = wick pitch of the inner ring with 12 wicks
dp out = wick pitch of the outer ring with 24 wicks
dw = distance pan bottom - burner head top
Pmax = the blue flame maximum power
Eff. = the efficiency of the heat transfer from the flame to a pan with water

A consultancy mission for the Industry and Energy Department of the World Bank by E. Sangen to Indonesia 'Kerosene and LPG stoves in Indonesia' (1988) is the last known study on kerosene wick stoves at the moment of writing this report. Some of the important conclusions are:

(a) kerosene stoves show a wide range of efficiencies (33 to 51%) without bias towards factory or artisanally produced wick stoves;

(b) it was clearly shown that the high efficiencies were obtained with stoves constructed compactly (relative to pan diameter).

The results of E.Sangen are in table 3.3.

An overall conclusion from these reports is that the efficiency is a function of the pan size, the distance between pan bottom and burner head, and the burner head width. An efficiency measurement should always include these data.

table 3.3
Kerosene stoves built and tested in Indonesia
(Sangen, 1988)

brand name	Pmax (kW)	Pmin (kW)	dp (cm)	dw (cm)	pan dia (cm)	Eff. (%)
Butterfly-10	1.8	0.5	8.5	3.3	24	51
Dua Saudara	1.9	0.4	10.5	4.2	24	42
Rantai	1.6	0.8	11.7	2.4	22	33
Tiga Gelang	2.1	1.6	11.8	4.4	24	42
Wheel Brand	2.0	1.6	8.5	2.9	24	46
Bandung small	1.0	0.3	7.3	1.8	20	49
Mangga Biru 1B	3.2	1.2	14.0	5.7	28	38
Pasar Minggu 2A	1.6	1.2	11.0	8.7	22	44
Sinar Matahari	1.5	1.2	9.4	3.5	22	45
Butterfly round	2.0	1.0	8.4	3.2	24	37
Toyo Fuji	1.9	1.9	10.9	3.9	24	50

dp = wick pitch
dw = distance pan bottom - burner head top
Pmax = the blue flame maximum power
Eff. = the efficiency of the heat transfer from the flame to a pan with water

4. Combustion Theory

4.1 Chemical Reaction

The burning of hydrocarbons in free air is a complex and difficult phenomena. For the burning of a simple hydrocarbon like methane , CH_4, up to 90 reaction steps are possible (Lamers, 1985). Describing a chemical reaction system in detail is only possible on computers with enormous calculation power. Fortunately most details are less important. One can simplify the burning of a hydrocarbon to the reaction:

$$\text{fuel} + \text{oxidant} \rightarrow \text{product} \qquad (4\text{-}1)$$

Fuel and oxygen combine in stoichiometric ratios according to:

$$1 \text{ kg of fuel} + s \text{ kg of } O_2 \rightarrow (1 + s) \text{ kg product} \qquad (4\text{-}2)$$

where s is the stoichiometric oxygen to fuel ratio.

The next section is about the burning of alcohol and kerosene.

4.2 Complete Combustion of Kerosene and Alcohol

Kerosene is actually a mixture of hydrocarbons with one main component. This component is the hydrocarbon $C_{10}H_{22}$. For the experiments it is presumed that kerosene consists only of $C_{10}H_{22}$. The complete combustion reaction of kerosene is given by:

$$2\ C_{10}H_{22} + 31\ O_2 \rightarrow 20\ CO_2 + 22\ H_2O \qquad (4\text{-}3)$$

It is presumed that the used alcohol is 100 % pure C_2H_5OH. The complete combustion reaction of alcohol is given by:

$$C_2H_5OH + 3\ O_2 \rightarrow 2\ CO_2 + 3\ H_2O \qquad (4\text{-}4)$$

There are now several questions of interest one can find an answer to. Two of these questions are:

- What is the stoichiometric ratio for kerosene and air at s.t.p.?
- What is the stoichiometric ratio for alcohol and air at s.t.p.?

For convenience only average values are used to answer the question:

1 mole at s.t.p has a volume of 22.4 l.
1 mole of $C_{10}H_{22}$ has a mass of 142 g.
1 mole of C_2H_5OH has a mass of 46 g.
1 mole of O_2 has a mass of 32 g.
Volumetric composition of air at s.t.p.: O_2 20 % and N_2 80 %.
Mass fractions of air at s.t.p.: O_2 23 % and N_2 77 %.

To burn one mole of $C_{10}H_{22}$ at s.t.p. completely, one needs (31/2)*32 g = 496 g of oxygen or (496/23)*100 g = 2157 g of air.

To burn one mole C_2H_5OH at s.t.p. completely, one needs 3*32 g = 96 g of oxygen or (96/23)*100 g =417 g of air.

The stoichiometric ratio of air to alcohol is (417/46) = 9.1

The stoichiometric ratio of air to kerosene is (2157/142) = 15.2

4.3 Different Types of Combustion

The Bunsen burner operates with two visibly different flames. The two flame types are a noisy stable blue flame and a quiet flickering yellow fame. The first one is a premixed flame and the second one is a diffusion flame (Fristrom, 1965). Both flames have distinct zones where the reaction takes place. The yellowness of the diffusion flame can be explained by reference to figure 4.1. Fuel approaches the reaction zone from one side, oxygen from the other. There is thus a region on the fuel side of the reaction zone in which gas with an appreciable proportion of fuel, but no oxygen, is maintained at a high temperature. Under these conditions there is a tendency for hydrocarbon molecules to crack and polymerize, forming on the one hand lighter molecules and on the other hand particles of carbon or tarry matter. The latter, being very hot, radiate the characteristic bright yellow light. This light often makes it difficult to observe the blue emission, characteristic of the reaction zone itself (Spalding, 1955).

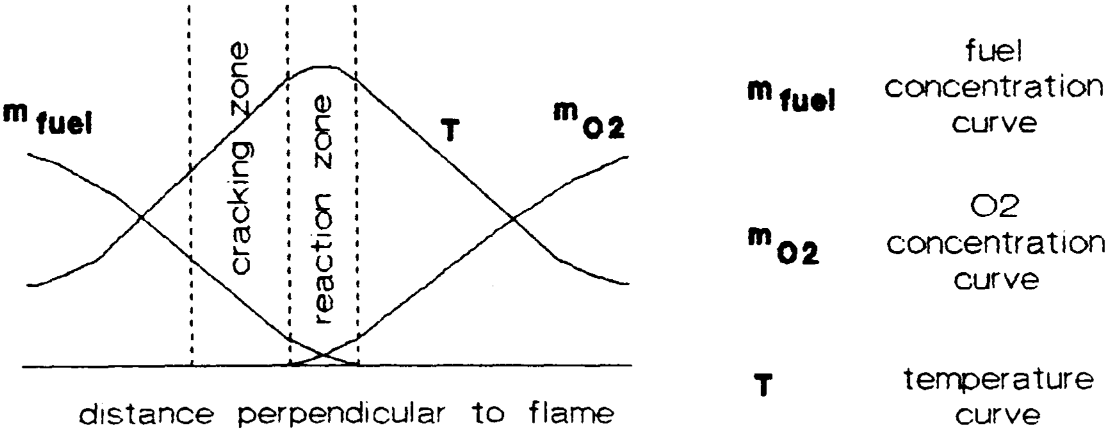


figure 4.1
Temperature and concentration profile of a diffusion flame (Spalding, 1955)

For the blue premixed flame the position and the extension of the reaction zone depends on the flow velocity of the fuel vapour - air mixture and the flame velocity. The flame velocity is directed to the highest fuel concentration. In this case the distinct blue reaction zone resembles a standing shock wave. The position of the reaction zone is where the flow velocity equals the flame velocity (Glassmann, 1977). These flames can also occur with yellow tops if the temperature of the surroundings where the reaction takes place, becomes too hot.

Romp speaks in his work of two types of combustion: the aldehydeous combustion and the carbonic combustion (Romp, 1937). This splitting of the combustion process is based on two theories (Chambers, 1983):

(1) The hydroxylation theory. Based on the idea that when a

hydrocarbon is oxidized, there is a natural tendency for its hydrogen atoms to be successively converted into OH groups, thus producing hydroxylated molecules with consequent heat evolution.

(2) The thermal dissociation theory. The dissociation of certain molecules under the infuence of heat.

According to Romp, there is a race between thermal dissociation and hydroxylation. If the conditions favour hydroxylation, there will be no soot. If, however, conditions favour cracking, the heat from the combustion of part of the hydrocarbon decomposes or cracks the remainder. In accordance with the theory mentioned above, a blue flame burning with a diffusion flame is possible if the temperature of the fuel stays low enough to avoid cracking. A method to achieve this is called the reversed flame principle. This principle is based on the fact that the temperature inside the flame is the highest. If a jet of air is fed into an environment of combustible gas or vapour, the jet of air is most intensely heated which, favours "clean" chemical reactions with the hydrocarbons (Prasad, 1983). It is on this principle most of the existing kerosene stoves are based. In figure 4.2 the reverse flame principle is demonstrated.

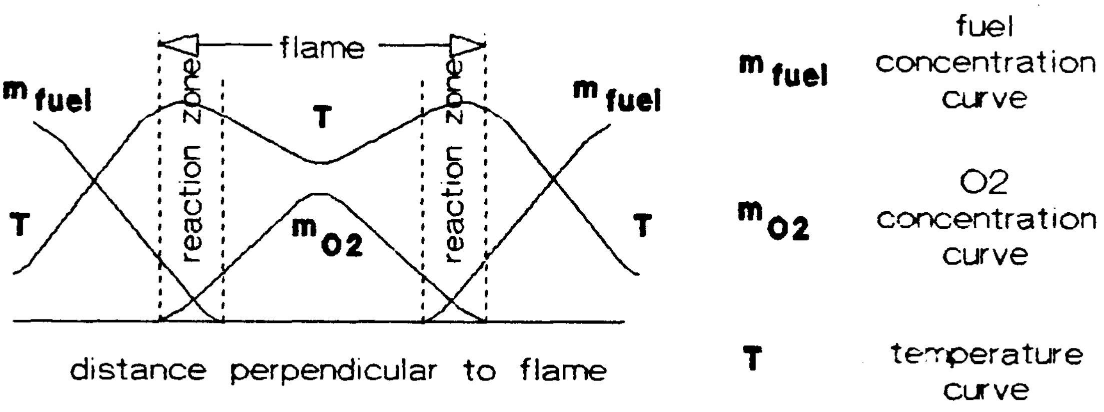


figure 4.2
The reverse flame principle

The range burner mentioned and described in the first part of this work, is a burner which works on the reverse flame principle. With this type of burner the air is sucked by natural draft into the holes of the perforated shells, the flame holders, which form the combustion chamber. The combustion chamber is filled with fuel vapour evolved by evaporation at the wicks. Thus every little hole will form a small perfectly blue flame of air burning in hydrocarbon gas in accordance with the aldehydeous combustion process; these flames make the shells red hot.

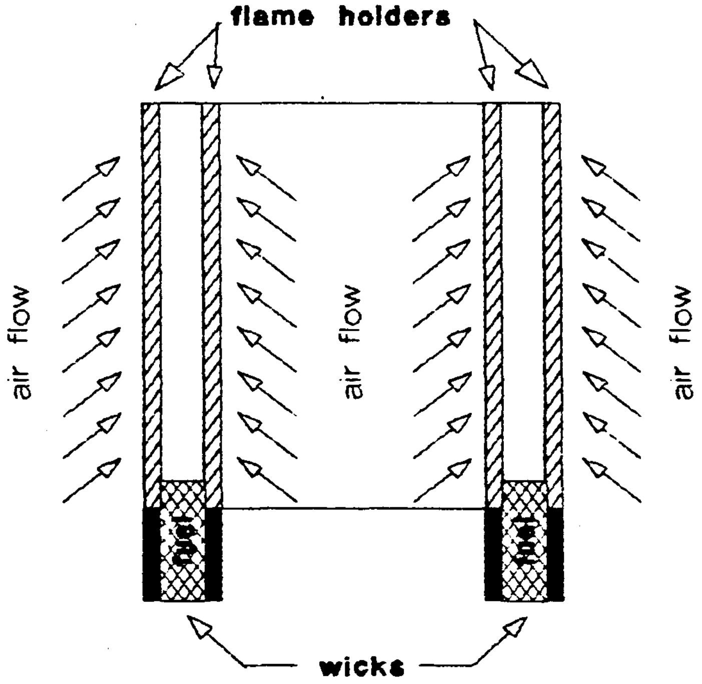


figure 4.3
The range burner principle

4.4 Flame Length Theory

Bussmann et. al. introduced a theory for open fire with the aim that an insight into the processes that are involved with open fires, will lead at least to first guesses on the rules governing the dimensioning of combustion spaces in woodburning stoves. This theory is used in this chapter to see if it can also be fitted for open single wick fuel burning. It is not the aim of this chapter to reproduce the theory and its setup completely, only general lines on which the theory is built are given. For a detailed description see Bussmann et. al. 1983. The theory is initially set up for open woodfires which have two types of combustible products: charcoal and volatiles. The fuels used at the open single wick fuel burning are kerosene and alcohol, which in a manner of speaking consist of 100% volatiles. The theory as it is given in this chapter also speaks of volatiles and charcoal, but it has the convenience that one can choose the mass fraction of each.

4.5 The Flame Length Model

The problem of the rising gas column above the fuelbed is considered to be a turbulent free convection problem. The fundamental equations of mass, momentum and energy make up the basis of the model. In arriving at these equations the following assumptions are made:

(1) The volatiles leaving the fuelbed and the air that is entrained in the convection column, behave like ideal gases; the gas properties of the volatiles and air are the same.

(2) The convection column has reached a steady state.

(3) The driving force is the buoyancy; pressure gradients are neglected. The pressure differences in the vertical direction, due to the hydrodynamic pressure gradient, are of no significance for this situation. The radial pressure

difference is neglected because the transverse accelerations are small relative to those in the vertical direction.

(4) Turbulent flow is fully developed and thus molecular transfer mechanisms are neglected relative to turbulent processes.

(5) Radiant heat losses from the flames need not be taken into account.

These assumptions will simplify the fundamental equations and after some manipulations will introduce a set of integrated equations.

4.6 Boundary and other Conditions

Before the integrated equations lead to solutions, some more assumptions have to be made. They concern firstly the shape of the velocity and temperature profile, which are asumed to have a top-hat shape. Thus if b represents the plume radius then for

$$\begin{aligned} r < b &\rightarrow T = T(z),\ u = U(z) \\ r > b &\rightarrow T = T_a\ \ ,\ u = 0 \end{aligned} \qquad (4\text{-}6)$$

where r and z are cylindrical coordinates,

T_a is the ambient temperature,

u and U(z) are velocities in z-direction.

Secondly it is assumed that the way in which air is entrained can be described by the entrainment assumption for strong buoyant flames

$$r\, v_{z,\infty} = \alpha \left[\frac{\rho}{\rho_a}\right]^{\frac{1}{2}} u\, b \qquad (4\text{-}7)$$

where $v_{z,\infty}$ is the velocity in $r \rightarrow \infty$ at height z,

ρ_a is the ambient density and,

α is the entrainment constant.

Thirdly it is assumed that volatiles burn instantaneously with entrained air and that the air quantity is the stoichiometric amount plus excess amount.

4.7 The Computer Programme

All the assumptions mentioned above form a solvable set of equations and boundary conditions. The solution involves a set of physical constants which have to be given. The original computer programme was written in a nowadays unused computer language and was therefore rewritten in Fortran 77. This version of the computer programme was specially written for use on a small personal computer. When one runs this programme, it will ask the user several questions. The programme will give a set of physical constants and their computer values, default values, and asks the user if he or she wants to change them. In tables 4.1 the physical constants for a wood fire and their default values are presented. In the appendix the computer programme, the setup on a floppy disk , a print out of the screen communication, and a print out of a result as presented by the computer, is given. The physical constants presented in table 4.1, are explained in the next section.

table 4.1
The default values of physical constants for a wood fire

1	The combustion value of fuel is:	.1870E+08	J/kg
2	The gravitational accel. is:	10.00	m/s^2
3	The entrainment constant is:	.080	(-)
4	The excess air factor is:	1.80	(-)
5	The stoich. air to fuel ratio is:	5.10	(-)
6	The ambient temperature is:	293.	K
7	The temp. of the fuel bed is:	1100.	K
8	The ambient density of air is:	1.25	kg/m^3
9	The spec. heat coeff. of air is:	1000.	K kg/J
10	The fuel bed area is:	226.980	cm^2
11	The combustion value of chaorcoal	.3300E+08	J/kg
12	The mass frac. of volatiles is:	.8000	(-)
14	The power of the fire is:	6000.00	W

4.8 The Physical Constants of a Fire

the combustion value

the amount of energy in J that is released by the burning of 1 kg of fuel. Some examples;

for kerosene: 0.435E+08 J/kg   for alcohol: 0.200E+08 J/kg
for white fir: 0.187E+08 J/kg   for charcoal: 0.330E+08 J/kg

the gravitational acceleration

acceleration with which a body would fall freely under the action of gravity in a vacuum. Usually $g = 9.8$ m/s

the entrainment constant

a constant which determines how much air is entrained into a jet or plume. This empirical constant can have values between 0.057 for round jets near the source to 0.082 for round plumes far from the source (Steward, 1970).

the excess air factor

the proportion of air that has to be supplied, in excess of what is theoretically required for complete combustion of a fuel, because of the imperfect conditions under which combustion takes place in practice.

the stoichiometric air to fuel ratio

the ratio of the theoretical amount of air in kg to the amount of fuel that can be burned with this amount of air completely.
Some examples;
for kerosene: 15.2   for alcohol: 9.1

the temperature of the fuel bed

for a wood fire this is the temperature of the charcoal bed. For a gas or liquid fuel fire this is the temperature of the mouth of the nozzle of a gas jet or the temperature of the wick top.

the fuel bed area

for a wood fire this is the charcoal bed size. For a liquid or gas fire this is the cross section of the nozzle or wick top.

the mass fraction of volatiles

the fraction of wood which is not burned as charcoal, but as volatiles. For most wood species 0.8.

5. Six different Types of Range Burners

5.1 Introduction

In this work six different designs of kerosene wick burners are tested and compared: the Pet stove, the Thomas Cup 24, the Thomas Cup 36, which are stoves; the Elegance K786, the Zibro Kamin RCA68, which are roomheaters; and the Aladin Lamp, which is a lamp. There were several goals:

(a) getting familiar with the available experimental equipment;

(b) getting familiar with the different stove designs and working characteristics of the stoves, and the measuring methods for the different experiments;

(c) An extra goal was to gain some ideas to improve the wick stove, regarding power output, efficiency, combustion quality and safety.

table 5.1
Six different kerosene burners and their origin

brand name	Country of manufacturing	type of burner
Pet Stove	The Netherlands	multi wick stove
Thomas Cup 24	Indonesia	multi wick stove
Thomas Cup 36	Indonesia	multi wick stove
Elegance	Taiwan	ring wick room heater
Zibro Kamin	Japan	ring wick room heater
Aladin Lamp	Brasil	ring wick lamp

All six burners use natural draft to get air into the combustion area. Three burners, the Pet Stove and both Thomas Cups, are constructed with multiple small wicks, which are placed in a ring, while the other three have a large annular ring wick: the Zibro Kamin, the Elegance and the Aladin Lamp. Except for the Aladin Lamp, which has a large glass chimney, the burners get their natural draft through the tall combustion chambers. In all six burners the wick area exposed in the combustion area, can be increased or decreased by means of a control lever, resulting in an increase or decrease of the power output of the burner. Table 5.1 lists some of the characteristics of the six burners. The next sections contain more detailed descriptions.

The existence of a power output control lever for all the six burners, made it possible to measure three different powers, each with its own different function:

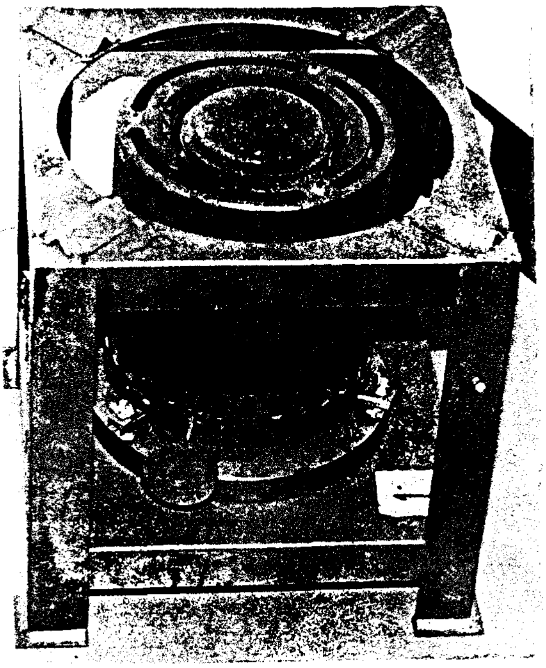
(1) The minimum power is the lowest power at which the burner still burns.

(2) The maximum power is the largest power a wick burner can achieve through its controls. The burner in this case often produces yellow flames, frequently accompanied by soot.

(3) The blue flame maximum power is the maximum power at which no yellow flames occur. In this case there is no soot.

The available laboratory equipment made it possible to measure the minimum and maximum power output of the burners, the heat transfer efficiency towards a pan during a boiling test with a stove, the CO/CO_2 ratio of the flue gases, and the temperature of the kerosene in the kerosene tank. Due to their construction, it was not possible to do the heat transfer efficiency measurements with the Zibro Kamin and the Aladin Lamp; also the Zibro Kamin has a closed kerosene tank, which made tank temperature measurement impossible. Although in principle the Elegance is a roomheater, it can easily be changed into a cookstove. For convenience the maximum power, minimum power and efficiencies are already given with the stove descriptions in the next sections, whereas the measurement method is described in chapter 7.

5.2 Pet Stove



Name	:Pet Stove
Manufacturer/country	:The Netherlands
Weight (empty)	:4.5 (kg)
Tank capacity	:2.2 (kg)
Material/finish	:Steel
Wick material	:Cotton
Fuel level indicator	:None
Type	:See figure 5.1

Overall dimensions (round)	$d * h$	:190 * 300	(mm)
Number of wicks	n_w	:21	
Wick travel		:35	(mm)
Wick diameter	d_w	:6	(mm)
Wick pitch circle	d_p	:112.5	(mm)
Wick pipes length	l_w	:50	(mm)
Flame holder (inside)	$d_i * h_i$	:100 * 140	(mm) [1]
(outside)	$d_o * h_o$	:125 * 140	(mm) [1]
Flame holder holes (inside)	d_a	:1.3	(mm)
diameter (outside)	d_a	:1.3	(mm)
Flame holder holes (inside)	$a * b$	:10 * 10	(mm)
pattern (outside)	$a * b$	:10 * 10	(mm)
Central hole diameter	d_c	:10	(mm)
Inside air holes (number)	n_v	:1	
(diameter)	d_v	:94	(mm) [2]
Outside air holes (number)	n_u	:31	
(diameter)	d_u	:10	(mm)
Shields (number)	n_s	:1	
(diameter * height)	$d_s * h_s$	:185 * 190	(mm) [3]
Minimum power	P_{min}	:1.6	(kW)
Maximum power	P_{max}	:5.1	(kW)
Nominal power	P_{nom}	:3.0	(kW)
Efficiency (- evap. water)	η	:50.4	(%)
Efficiency (+ evap. water)	η	:54.1	(%)

[1] The lower 20 mm of the combustion chamber walls are not perforated.

[2] Inside the inner flame holder a radiation shield is attached with a diameter of 80 mm. The actual inner air hole is a gap with a diameter of 20 mm.

[3] Between the shield and the outer flame holder there is a gap; this annular gap can be closed by a control mechanism.

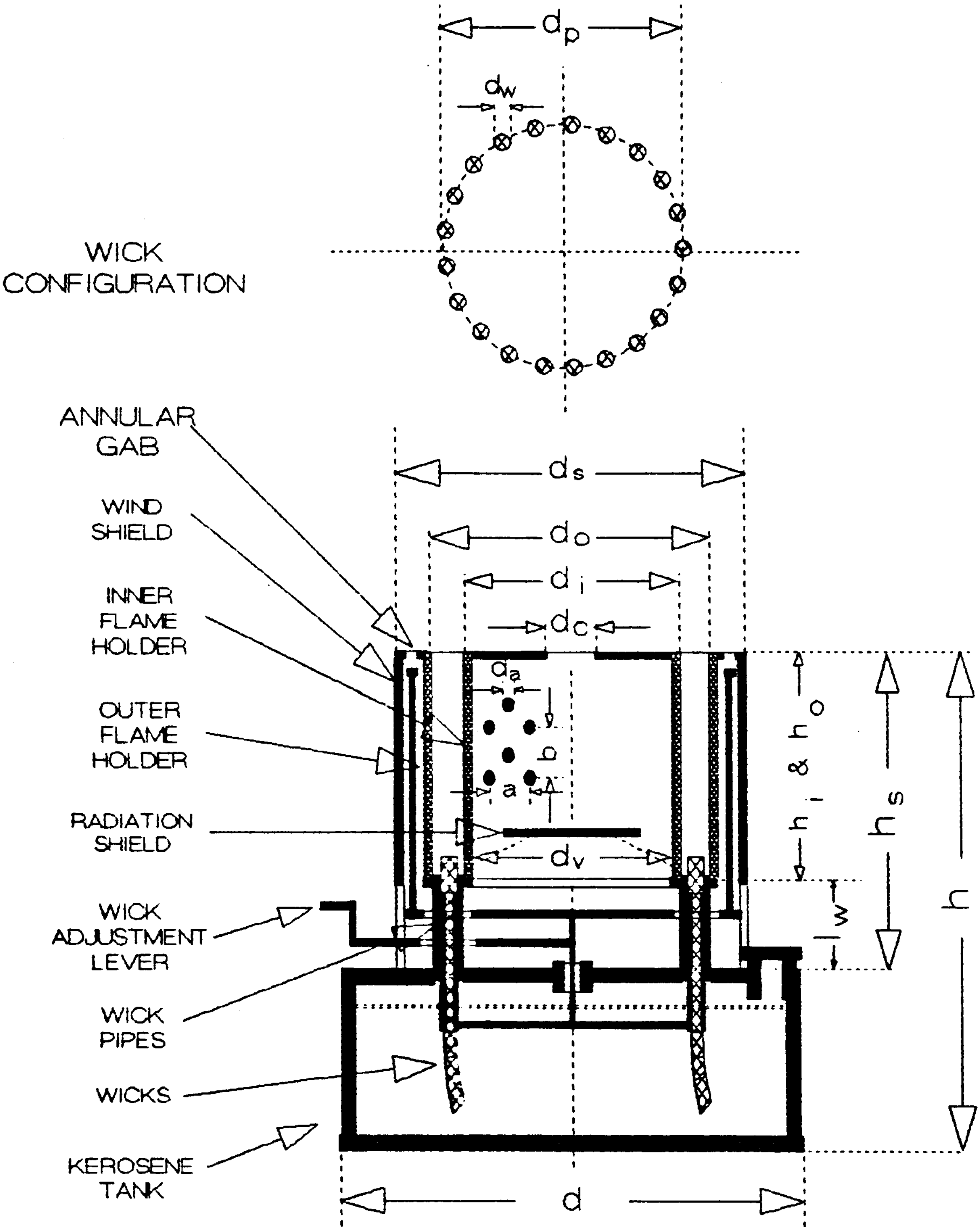
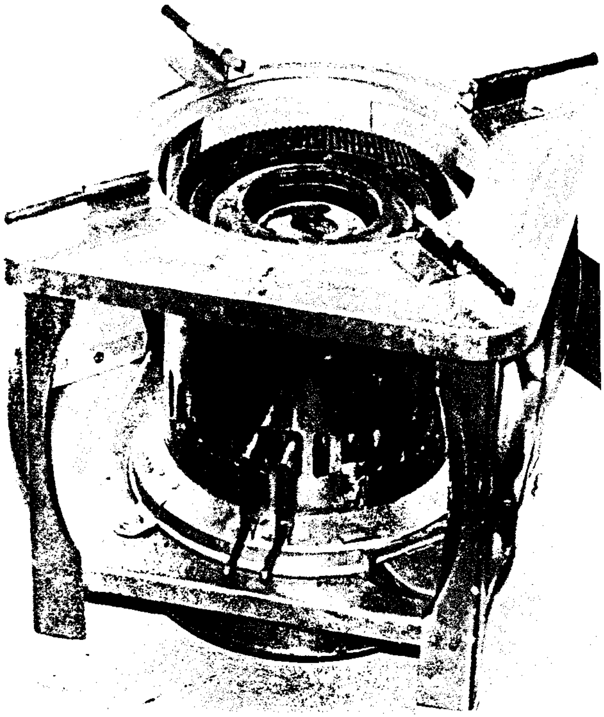


figure 5.1
The Pet Stove without frame

5.3 Thomas Cup 36



Name :Thomas Cup 36
Manufacturer/country :Indonesia
Weight (empty) :
Tank capacity :3.25 (kg)
Wick material :cotton
Fuel level indicator :None
Material/finish :Steel
Type :See figure 5.2

Overall dimensions (round)	$d * h$	:210 * 330	(mm)
Number of wicks	n_w	:36	

		inner	outer	[1]
Wick diameter	d_w	:6	:6	(mm)
Wick travel		:30	:30	(mm)
Wick pitch circle	d_p	:90	:155	(mm)
Wick pipes length	l_w	:70	:70	(mm)
Flame holder (inside)	$d_i * h_i$	: 80 * 110	:140 * 110	(mm)
(outside)	$d_o * h_o$	:100 * 100	:170 * 110	(mm)
Flame holder holes (inside)	d_a	:1.3	:1.3	(mm)
diameter (outside)	d_a	:1.3	:1.3	(mm)
Flame holder (inside)	$a * b$	:11 * 10	:11 * 10	(mm)
holes pattern (outside)	$a * b$	:11 * 10	:11 * 10	(mm)

Central hole diameter	d_c	:15	(mm)
Outside air holes (number)	n	:32	
(diameter)	d_u	:20	(mm)
Shields (number)	n_s	:1	
(diameter * height)	$d_s * h_s$	:220 * 210	(mm)
Shield top diameter	d_t	:180	(mm)
Minimum power	P_{min}	:0.9 [2]	(kW)
Maximum power	P_{max}	:7.2	(kW)
Nominal power	P_{nom}	:4.8	(kW)
Efficiency (- evap. water)	η	:48.4	(%)
(+ evap. water)	η	:54.3	(%)

---

[1] In this stove there are two rings with wicks; the outer ring contains 24 wicks and the inner ring 12 wicks.

[2] (Sulilatu 1988).

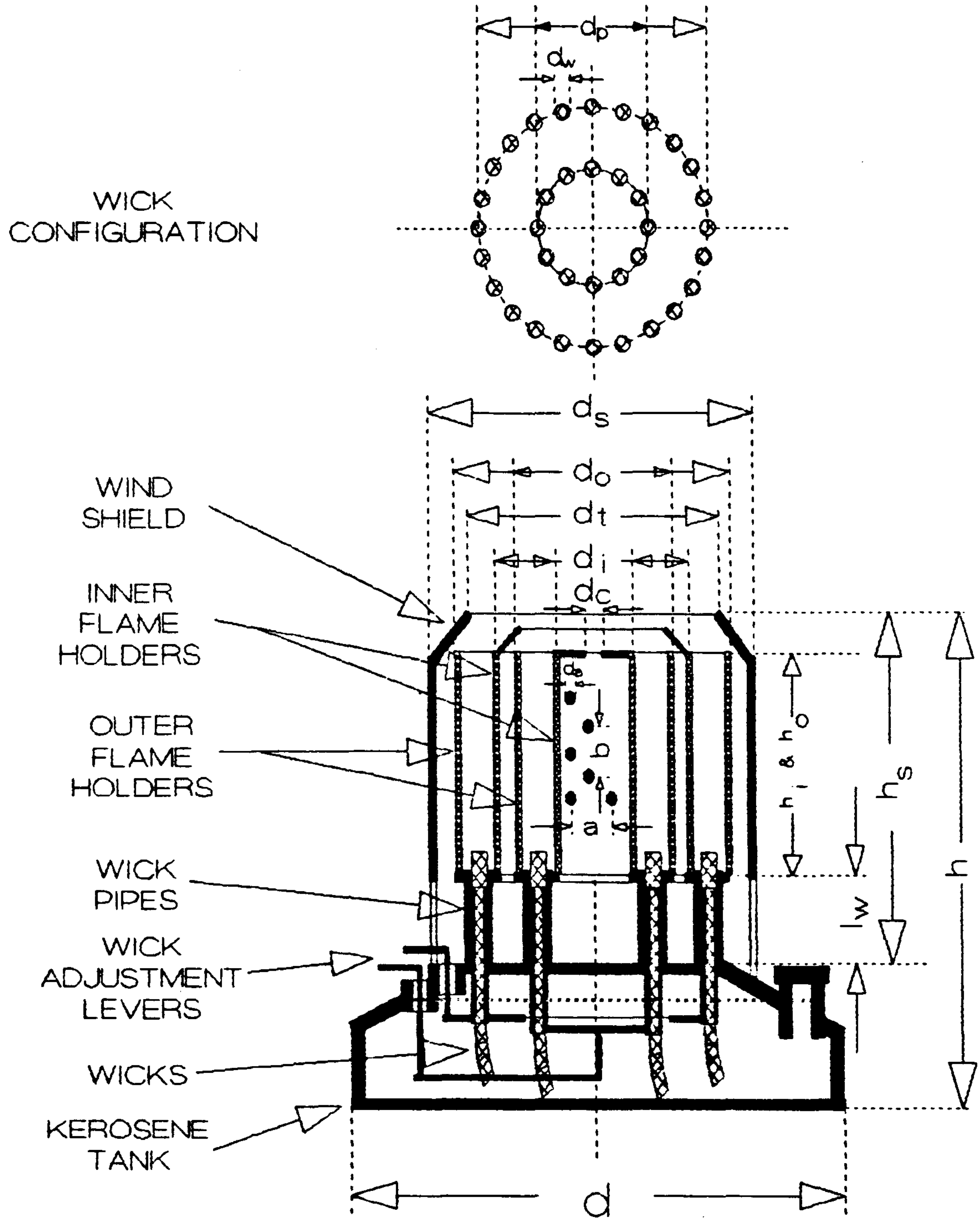
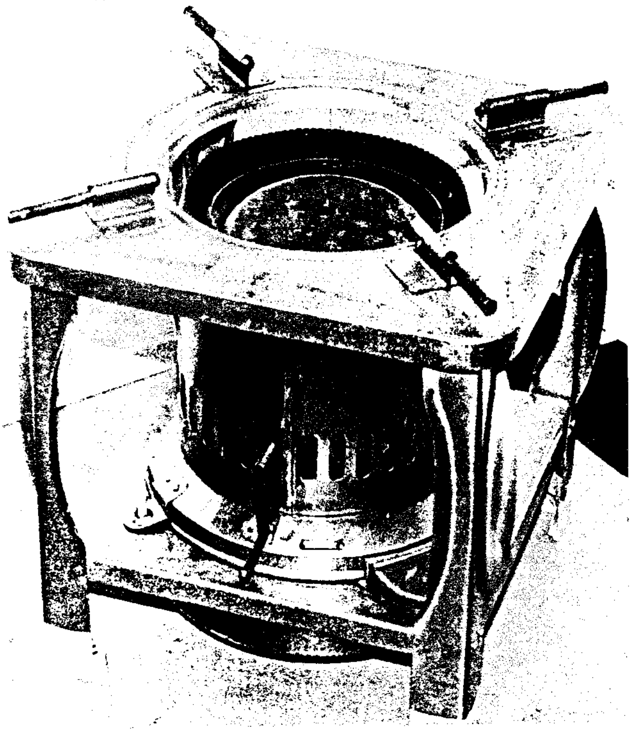


figure 5.2
The Thomas Cup 36 without frame

5.4 Thomas Cup 24



Name :Thomas Cup 24
Manufacturer/country :Indonesia
Weight (empty) : (kg)
Tank capacity :3.25 (kg)
Material/finish :Steel
Wick material :Cotton
Fuel level indicator :None
Type :See figure 5.3

Overall dimensions (round)	$d * h$	:210 * 310	(mm)
Number of wicks	n_w	:24	
Wick diameter	d_w	:6	(mm)
Wick pitch circle	d_p	:155	(mm)
Wick pipes length	l_w	:70	(mm)
Flame holder (inside)	$d_i * h_i$	:140 * 115	(mm)
(outside)	$d_o * h_o$	:170 * 115	(mm)
Flame holder holes (inside)	d_a	:1.3	(mm)
diameter (outside)	d_a	:1.3	(mm)
Flame holder holes (inside)	$a * b$	:11 * 10	(mm)
pattern (outside)	$a * b$	:11 * 10	(mm)
Central hole diameter	d_c	:15	(mm)
Inside air holes (number)	n_v	:1	
(diameter)	d_v	:133	(mm)
Outside air holes (number)	n_u	:32	
(diameter)	d_u	:20	(mm)
Shields (number)	n_s	:1	
(diameter * height)	$d_s * h_s$	:220 * 210	(mm)
Shield top diameter	d_t	:180	(mm)
Minimum power	P_{min}	:2.0	(kW)
Maximum power	P_{max}	:5.4	(kW)
Nominal power	P_{nom}	:3.1	(kW)
Efficiency (- evap. water)	η	:46.3	(%)
(+ evap. water)	η	:52.2	(%)

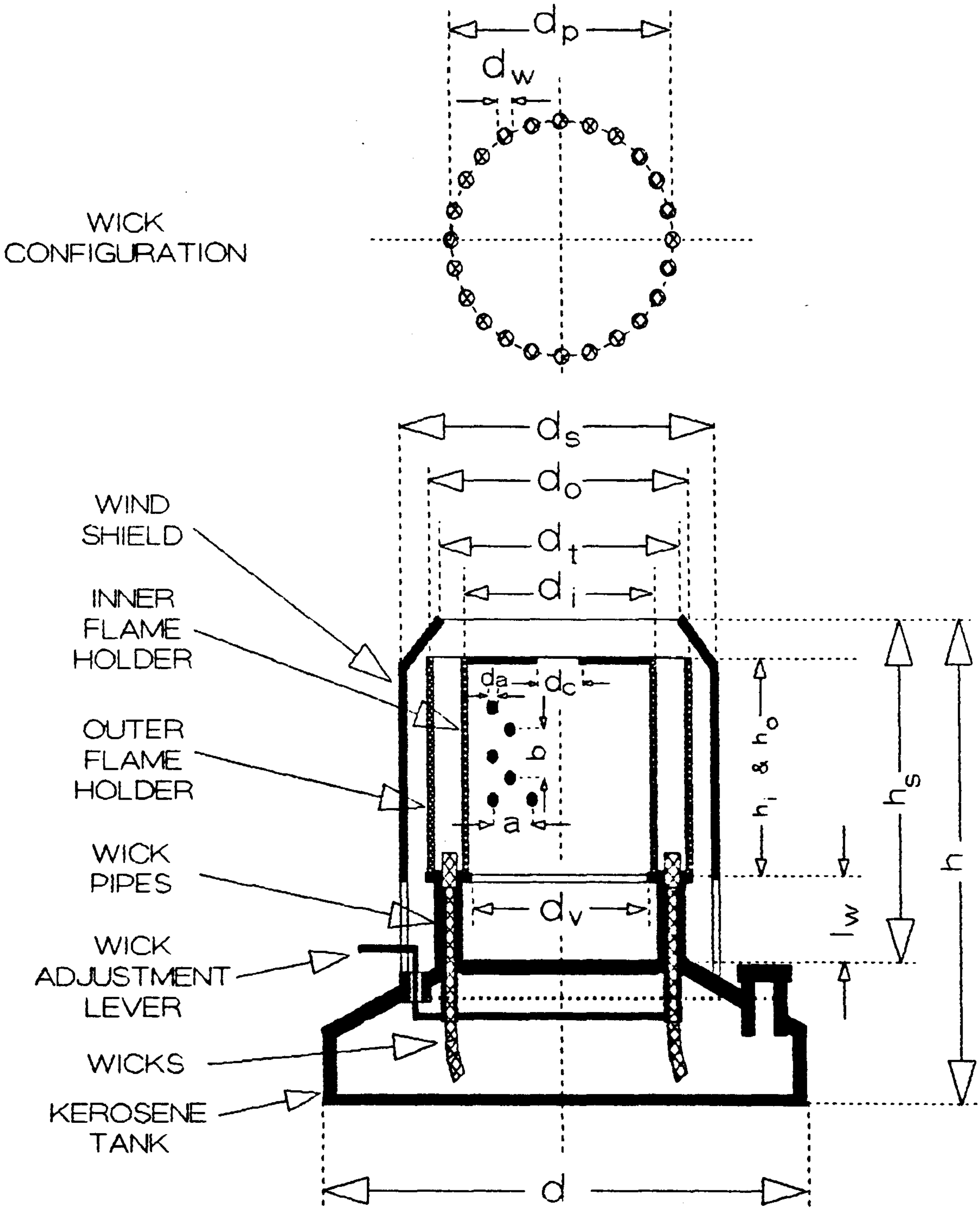
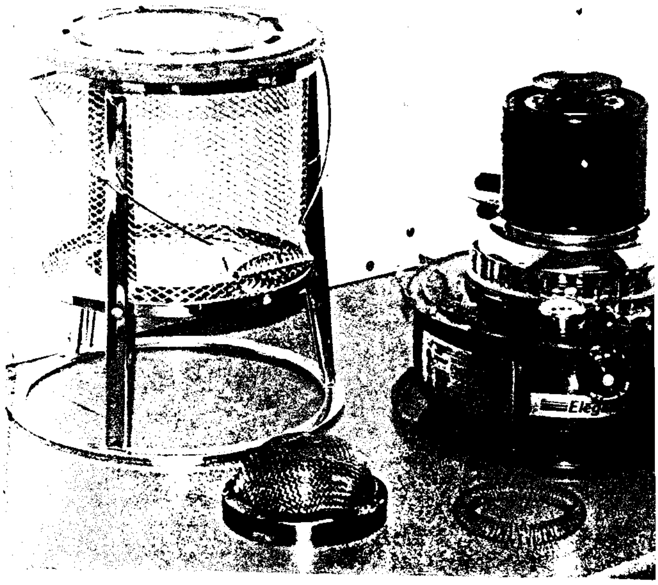


figure 5.3
The Thomas Cup 24 without frame

5.5 Elegance K786



Name :Elegance K786
Manufacturer/country :Taiwan
Weight (empty) :5.5 (kg)
Tank capacity :4.0 (kg)
Material/finish :Steel/painted
Wick material :Glassfiber
Fuel Level indicator :Yes
Type :See figure 5.4

Overall dimensions (round)	d * h	:299 * 300	(mm)
Number of wicks	n_w	:1	
Wick travel		:	(mm)
Wick width	d_w	:6	(mm)
Wick pitch circle	d_p	:99	(mm)
Flame holder (inside)	d_i * h_i	: 85 * 100	(mm)
(outside)	d_o * h_o	:110 * 105	(mm)
Flame holder holes (inside)	d_a	:1.4	(mm)
diameter (outside)	d_a	:1.4	(mm)
Flame holder holes (inside)	a * b	:6 * 11	(mm)
pattern (outside)	a * b	:6 * 11	(mm)
Central hole diameter	d_c	:	(mm) [1]
Inside air holes (number)	n_v	:1	
(diameter)	d_v	:77	(mm)
Outside air holes (number)	n_u	:	
(diameter)	d_u	:	(mm)
Shields (number)	n_s	:1	
(diameter * height)	d_s * h_s	:130 * 110	(mm)
Shield top diameter	d_t	:130	(mm)
Minimum power	P_{min}	:1.6	(kW)
Maximum power	P_{max}	:3.2	(kW)
Nominal power	P_{nom}	:2.6	(kW)
Efficiency (- evap. water)	η	:51.8	(%)
(+ evap. water)	η	:55.7	(%)

[1] There is no central hole on the top of the inner flame holder, but there is a number of small holes near the edge of the combustion chamber. On the top there is an extra shield, which forces the flames outwards.

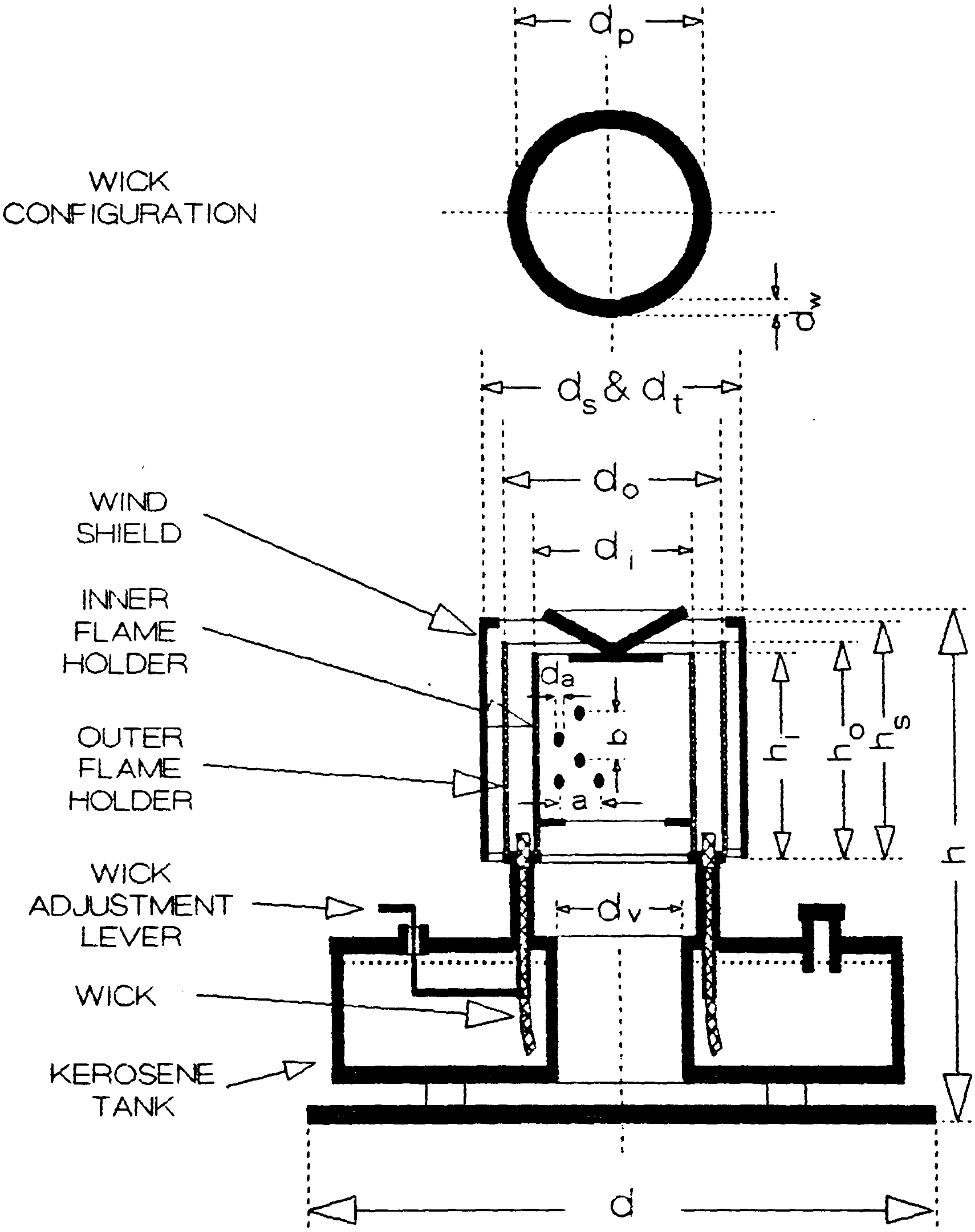
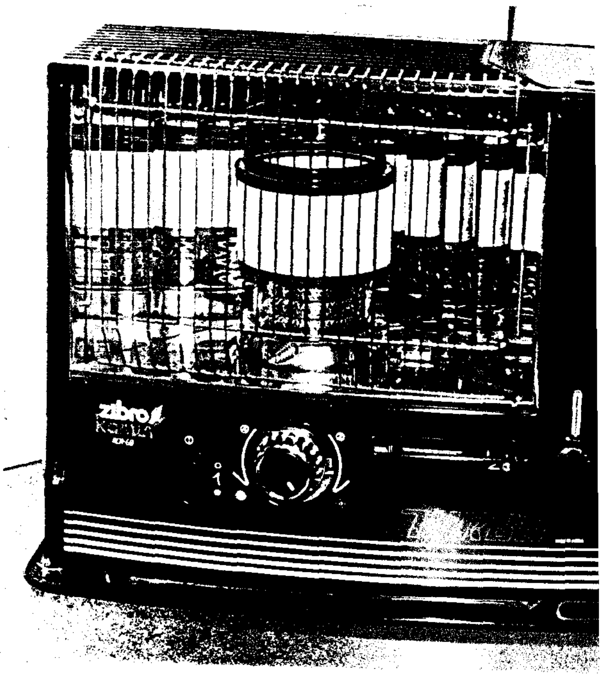


figure 5.4
The Elegance K786

5.6 Zibro Kamin RCA68



Name :Zibro Kamin RCA68
Manufacturer/country :Japan
Weight (empty) : (kg)
Tank capacity :4.0 (kg)
Material/finish :Steel/painted
Wick material :Glassfiber
Fuel level indicator :Yes
Type :See figure 5.5

Overall dimensions (square)	$l * w * h$	:480 * 220 *420	(mm)	
Number of wicks	n_w	:1		
Wick width	d_w	:6	(mm)	
Wick pitch circle	d_p	:68	(mm)	
Wick pipes length	l_w	:	(mm)	
Flame holder (inside)	$d_i * h_i$	:56.7 * 79	(mm)	[1]
(outside)	$d_o * h_o$	:80 * 92.5	(mm)	
Flame holder holes (inside)	d_a	:	(mm)	[2]
diameter (outside)	d_a	:	(mm)	[3]
Flame holder holes (inside)	$a * b$	:	(mm)	[2]
pattern (outside)	$a * b$	:	(mm)	[3]
Central hole diameter	d_c	:	(mm)	[1]
Inside air holes (number)	n_v	:		
(diameter)	d_v	:	(mm)	
Outside air holes (number)	n_u	:		
(diameter)	d_u	:	(mm)	
Shields (number)	n_s	:1		
(diameter * height)	$d_s * h_s$	:100 * 60	(mm)	
Shield top diameter	d_t	:	(mm)	
Minimum power	P_{min}	:	(kW)	
Maximum power	P_{max}	:1.6	(kW)	
Nominal power	P_{nom}	:1.6	(kW)	
Efficiency (- evap. water)	η	:	(%)	
(+ evap. water)	η	:	(%)	

[1] On the top of the inner flame holder there is an extra construction which, according to the manufacturer, functions as a turbo combustion in three steps. The construction is patented by Zibro Kamin.

[2] There are three different sets of holes, divided in a lower-, a middle- and, an upper part; the diameters are respectively 1.4, 2.0, and 2.4 mm.

[3] There are two different sets of holes, divided in an upper- and a lower part; the diameters are respectively 1.4 and 3.5 mm.

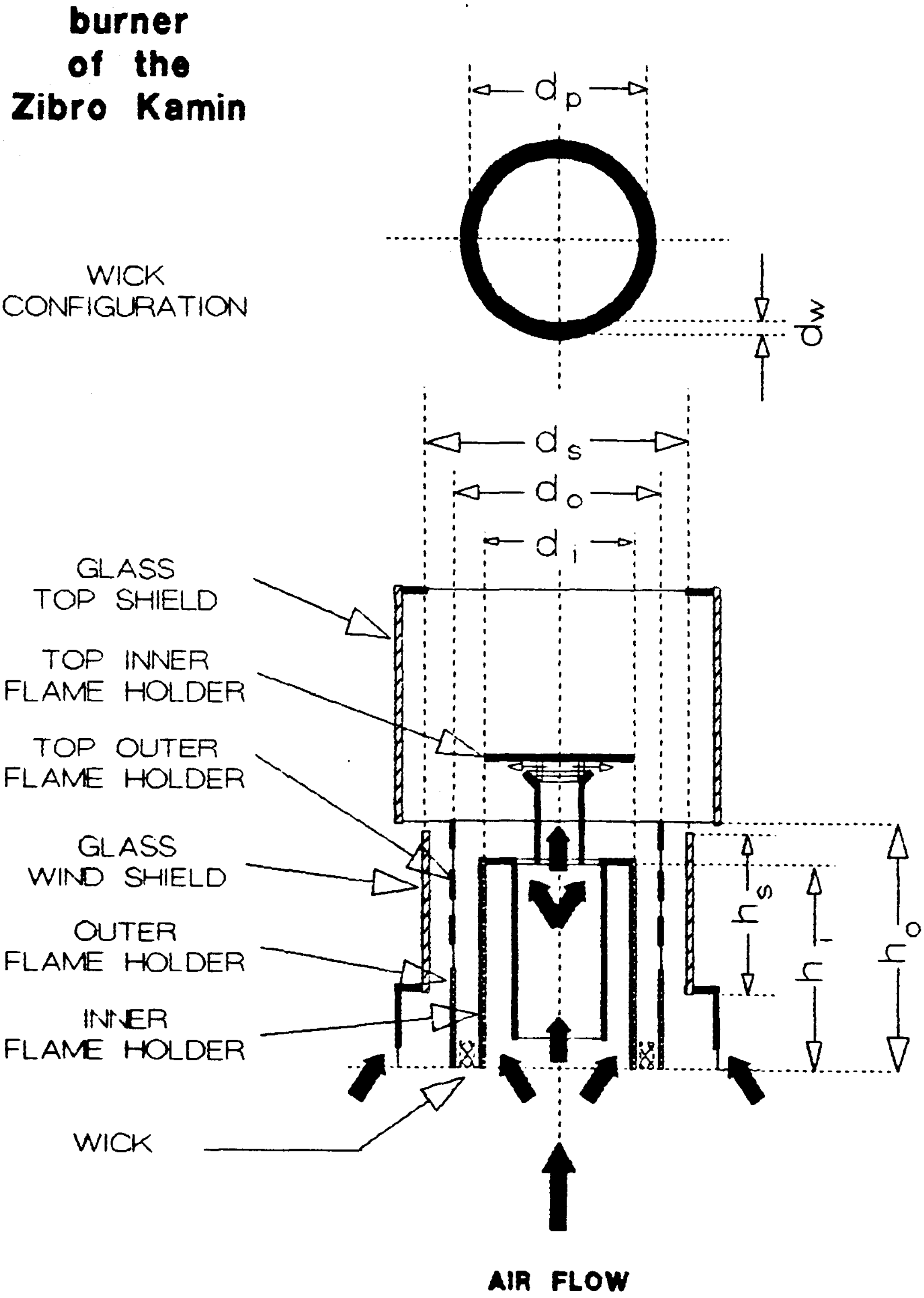
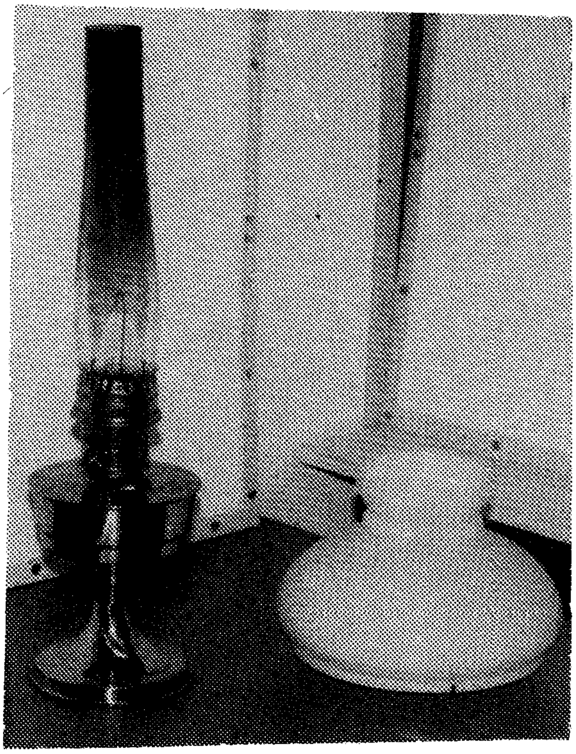


figure 5.5
The Zibro Kamin RCA68 Burner



5.7 Aladin Lamp

Name :Aladin Lamp
Manufacturer/country :Brasil
Weight (empty) : (kg)
Tank capacity :1.0 (kg)
Material/finish :Steel/polished
Wick material :Cotton
Fuel level indicator :None
Type :See figure 5.6

Overall dimensions (round)	$d * h$	:100 * 600	(mm)
Number of wicks	n_w	:1	
Wick diameter	d_w	:6	(mm)
Wick pitch circle	d_p	:26	(mm)
Wick pipes length	l_w	:	(mm)
Flame holder (inside)	$d_i * h_i$	:22.5 * 12.5	(mm)
(outside)	$d_o * h_o$	:35 * 7.5	(mm)
Flame holder holes (inside)	d_a	:1.3	(mm)
diameter (outside)	d_a	:1.3	(mm)
Flame holder holes (inside)	$a * b$	:	(mm)
pattern (outside)	$a * b$	:	(mm)
Central hole diameter	d_c	:	(mm)
Inside air holes (number)	n_v	:1	
(diameter)	d_v	:20	(mm)
Outside air holes (number)	n_u	:	
(diameter)	d_u	:	(mm)
Shields (number)	n_s	:	
(diameter * height)	$d_s * h_s$	:	(mm)
Shield top diameter	d_t	:	(mm)
Minimum power	P_{min}	:	(kW)
Maximum power	P_{max}	:1.1	(kW)
Nominal power	P_{nom}	:0.7	(kW)
Efficiency (- evap. water)	η	:	(%)
(+ evap. water)	η	:	(%)

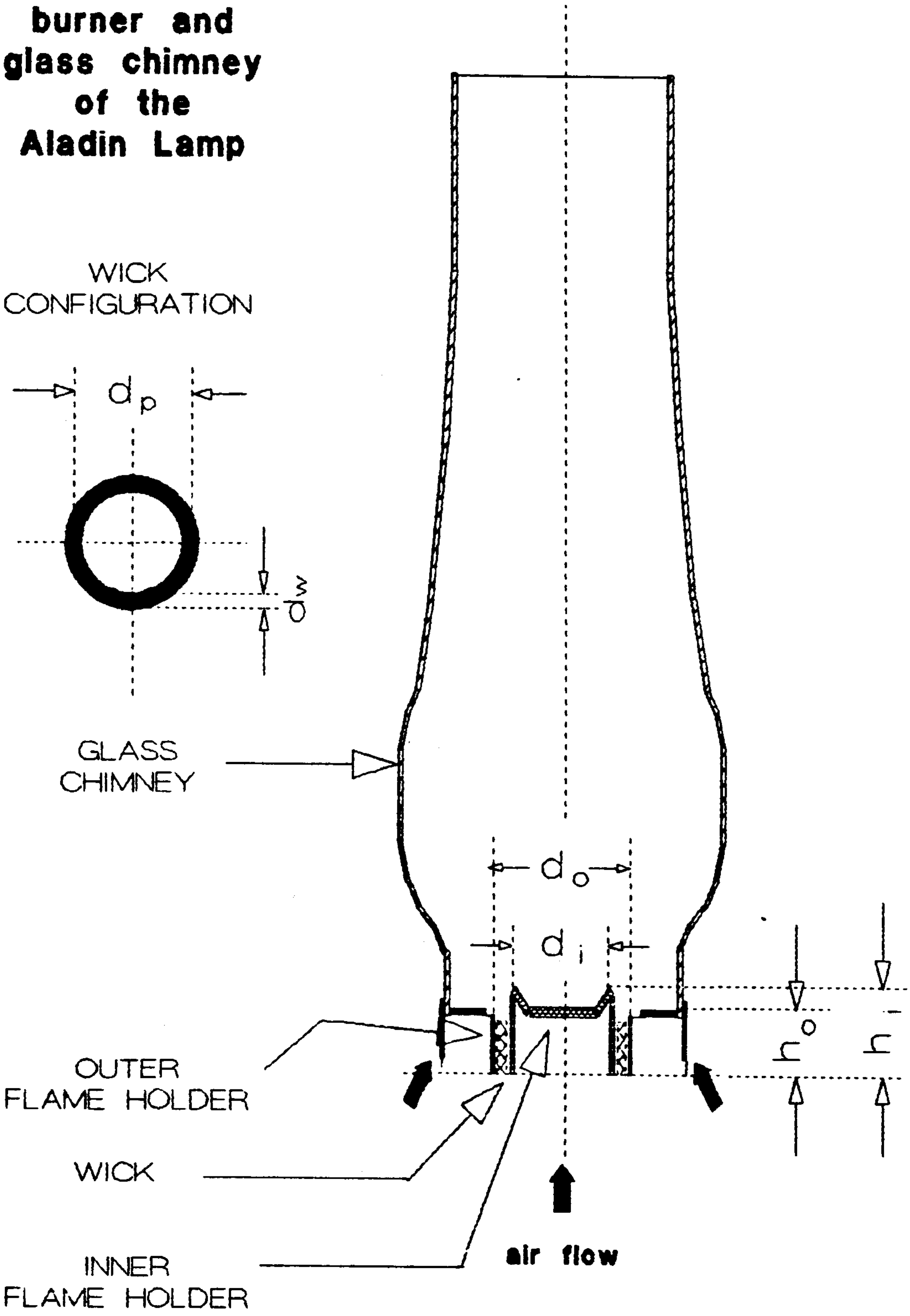


figure 5.6
The Aladin Lamp

6. Single Wick Setups

6.1 Free Single Wick Fuel Burning

The first experiments on a single wick are the measurements of the mass rate, the CO/CO_2 ratio and the flame length of a single wick with different wick lengths. The wick's setup for these measurements is shown in figure 6.1. In all the experiments it consists of two wicks which do not influence each other; the mass rate of one wick is too small to measure it with the mass balance used. Earlier experiments showed that the mass rate of a wick is constant in time when the distance of the fuel level in the fuel tank is constant (Kriesels, 1988). All the experiments start with a same distance between the fuel level and the wick support top. Due to the very limited mass rate of the two wicks it is reasonable to assume that this distance is constant in time.

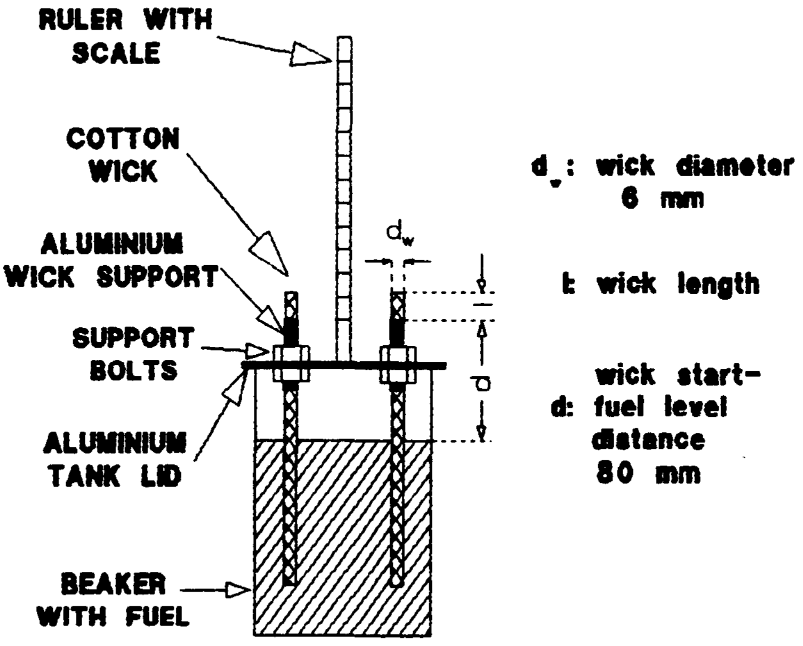
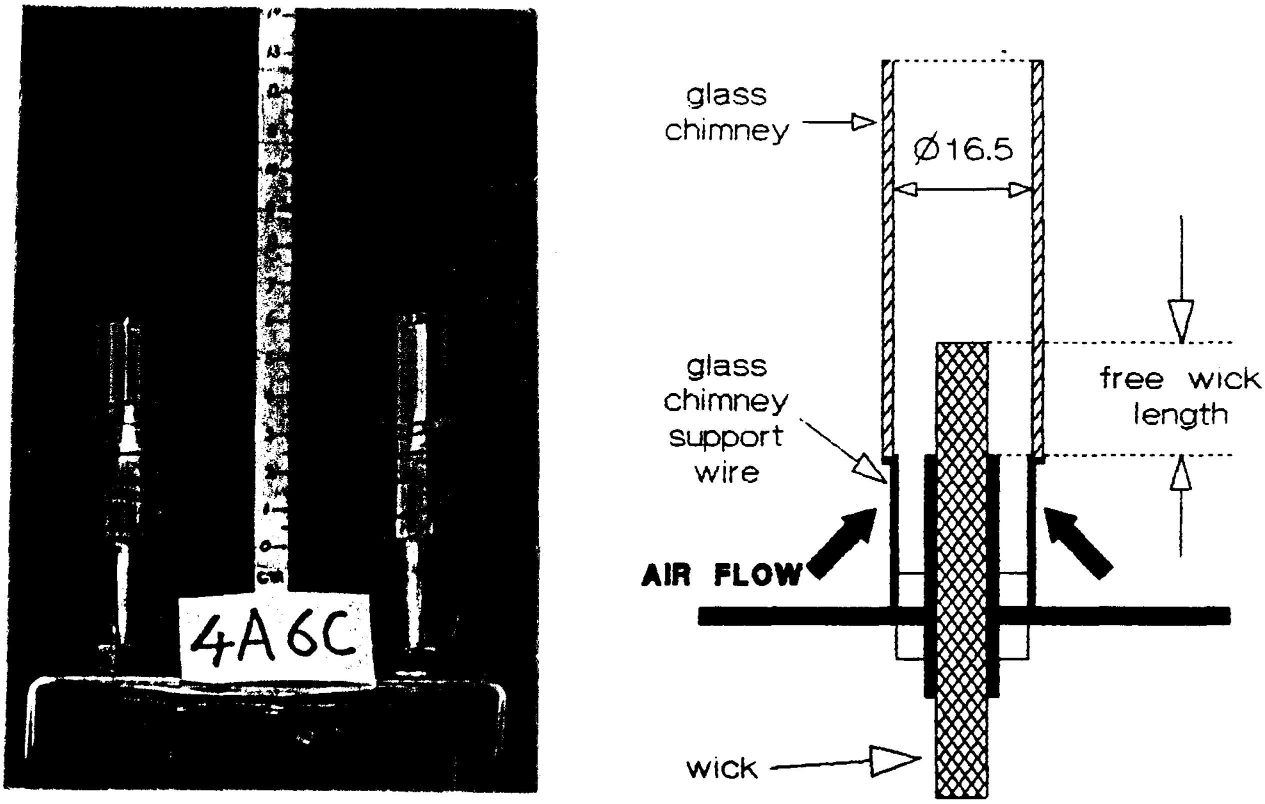


figure 6.1
A beaker with two wicks and a ruler to measure flame length

6.2 Glass Chimney Setup

The glass chimney experiments are done to measure the influence of draft on the mass rate and the quality of the combustion. For these experiments a number of differently sized glass tubes were made. The diameters of all the tubes are indentical; the length of the tubes differ from 1 cm to 14 cm in steps of 1 cm. To carry out the experiments a supporting device, consisting of small metal wires to avoid the influence on the air flow, was constructed. The glass chimney bottom is at the same level as the wick support top, and the air enters the chimney by the annular gap between the wick and the chimney. Figure 6.2.a shows an example of an alcohol flame on a wick with a 4 mm length and a chimney of 6 cm. Figure 6.2.b gives the general lay out of the wick - glass chimney configuration.



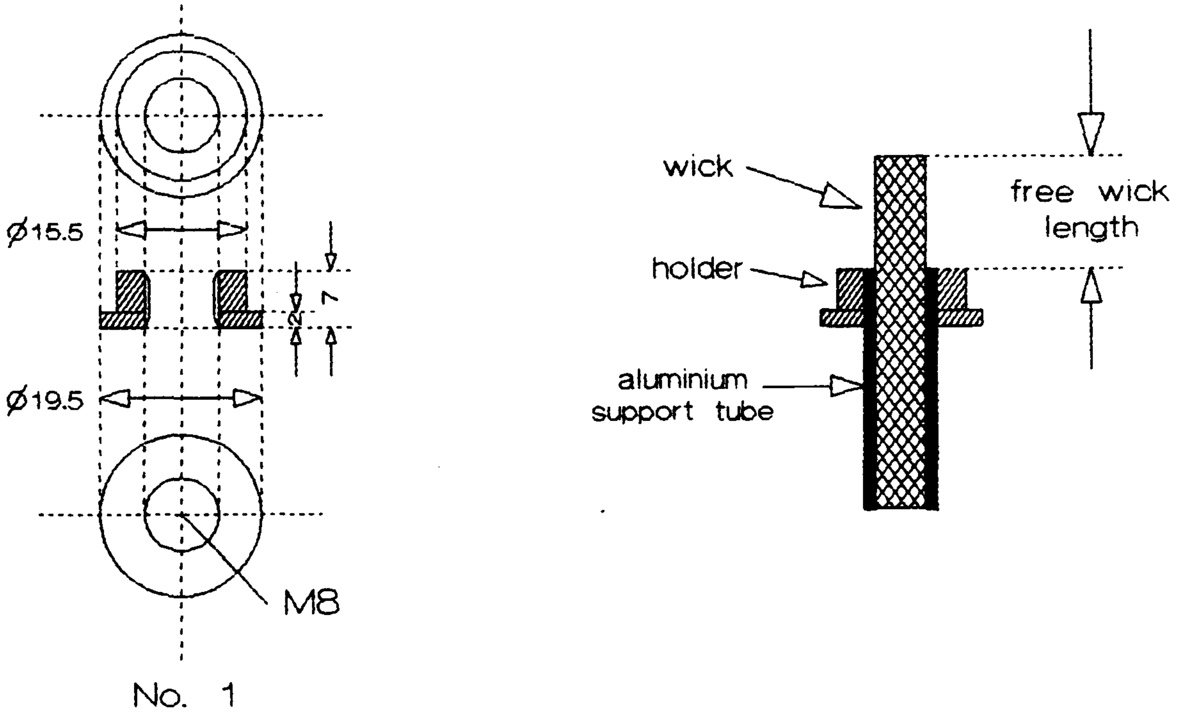
a. picture of glass chimney experiment

figure 6.2

b. general setup glass chimney - wick

6.3 The Massive Holder Effect

This experiment is done to see the influence of a massive metal object near the wick support top on the mass rate and the quality of the combustion. In the configuration as described in figure 6.1, the wick is supported by a small aluminium tube with screw-threads, before it makes contact with the free air. Because this tube is in direct contact with the air, it stays relatively cool, thus hardly influencing the evaporation of fuel. A massive metal object on the aluminium top is heated up by the wick flame, it gives this heat back to the aluminium top and indirectly to the wick, thus influencing the fuel evaporation rate. The massive metal object is a holder for supporting small metal tubes. The holder is screwed on the top of the aluminium tube such that the top of the holder is on a level with the start of the wick. In figure 6.3.a a drawing of the holder is given. In figure 6.3.b the general lay out of the holder with the wick is given.



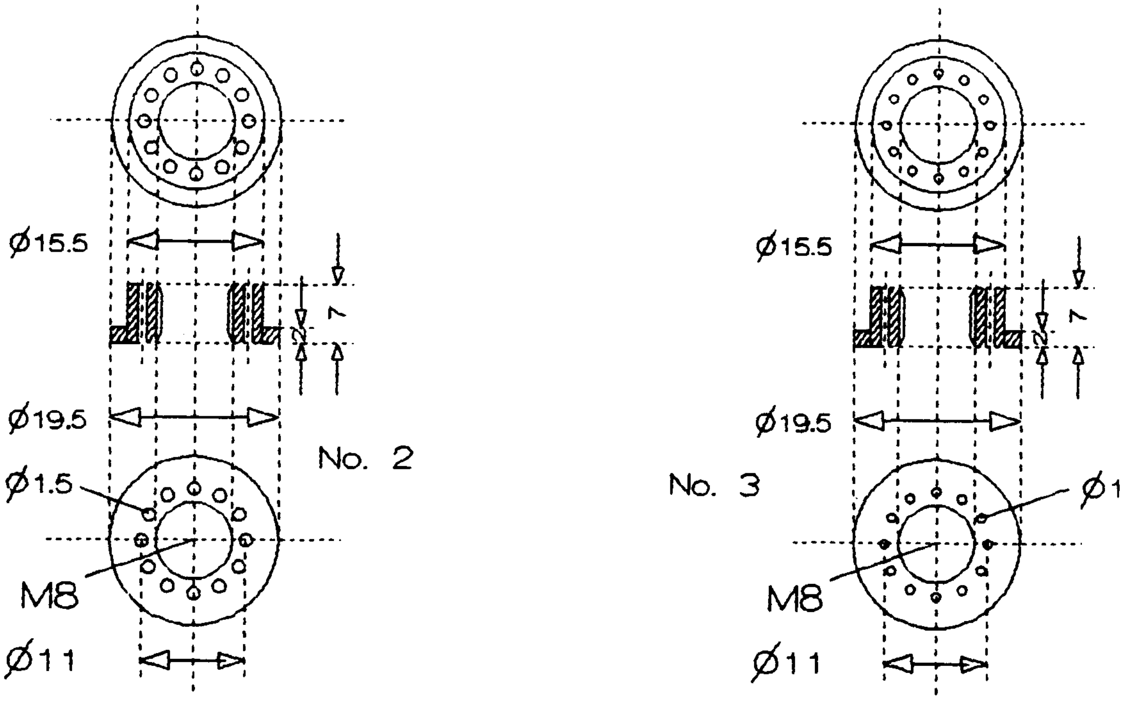
a.
drawing of the holder

figure 6.3

b.
setup of holder with wick

6.4 Different Holders and Chimneys

A kerosene range burner consists of wicks at the bottom of the combustion chamber, and the combustion chamber itself is perforated with air holes. A similar approach is possible with a single wick: a wick at the bottom is connected to a metal tube with air holes. To achieve this construction, a holder has to be attached near the wick top to hold the metal tube. Of these holders five types were designed, each with a different configuration. The drawings of holder No. 1 are already given in figure 6.3.a. The drawings of the other four holders are given in figure 6.4.a, b, c, and d. Besides the five holders, four different types of chimneys were constructed. The drawings of these chimneys are in figures 6.5, 6, 7, and 8. They are named after the burner which shows an identical air hole configuration. Figure 6.6 gives an example of how a holder and a chimney fit together.



a.
flat holder with 12 air holes of 1.5 mm diameter

figure 6.4

b.
flat holder with 12 air holes of 1 mm diameter

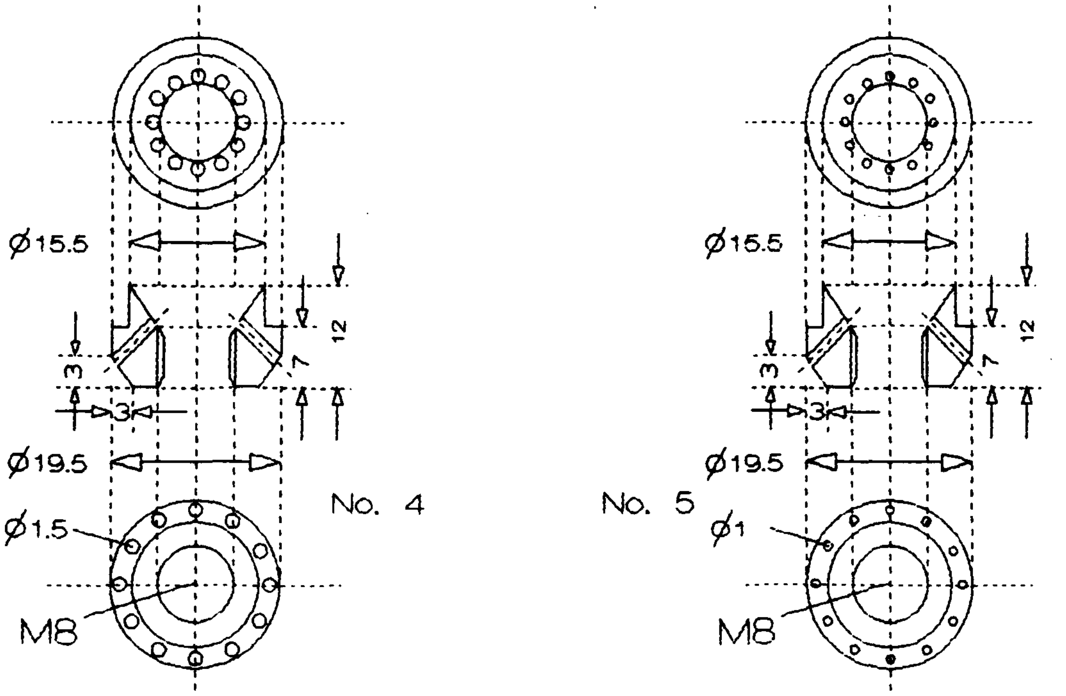


figure 6.4

c.
angled holder with 12 air holes of 1.5 mm diameter

d.
angled holder with 12 air holes of 1 mm diameter

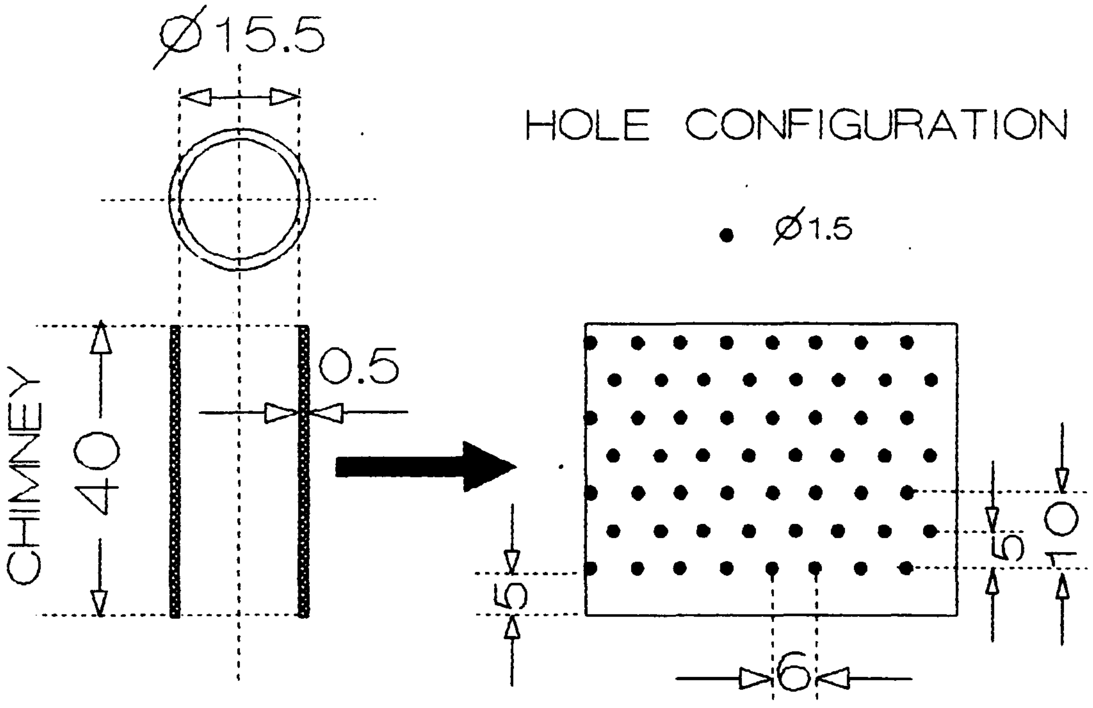


figure 6.5
Taiwan stove chimney small

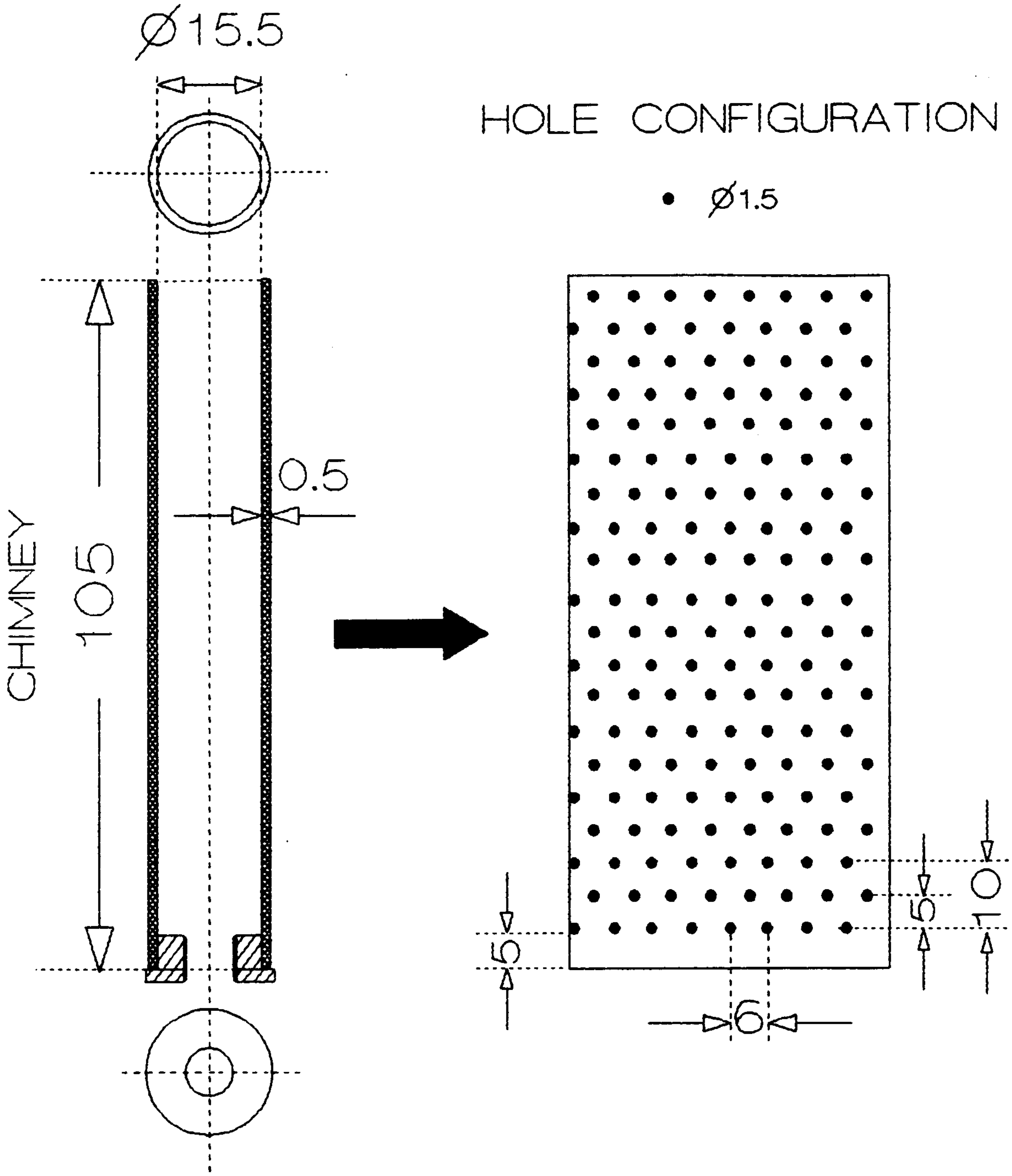


figure 6.6
Taiwan Stove chimney large, fitted to holder no.1

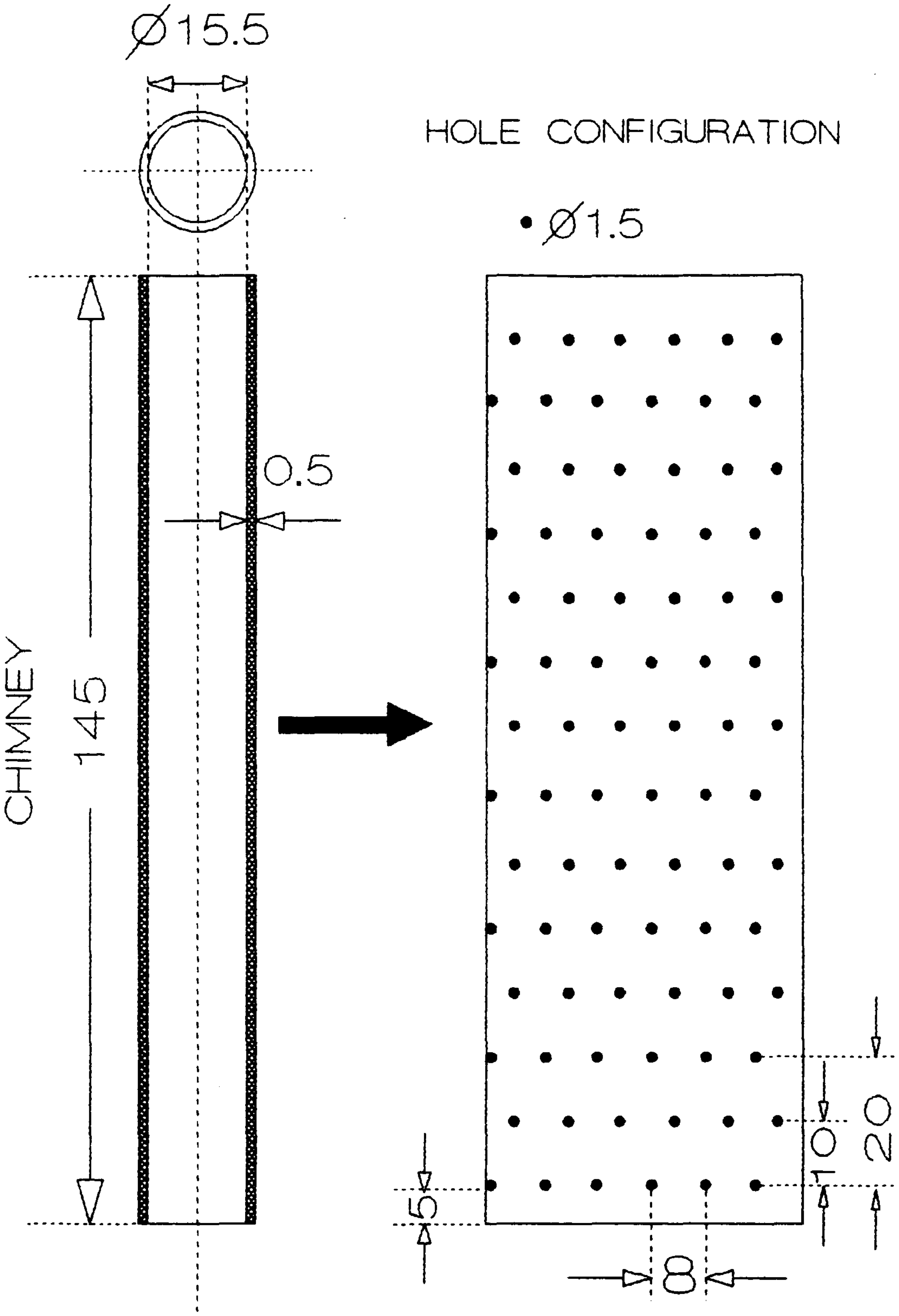


figure 6.7
Pet Stove Chimney

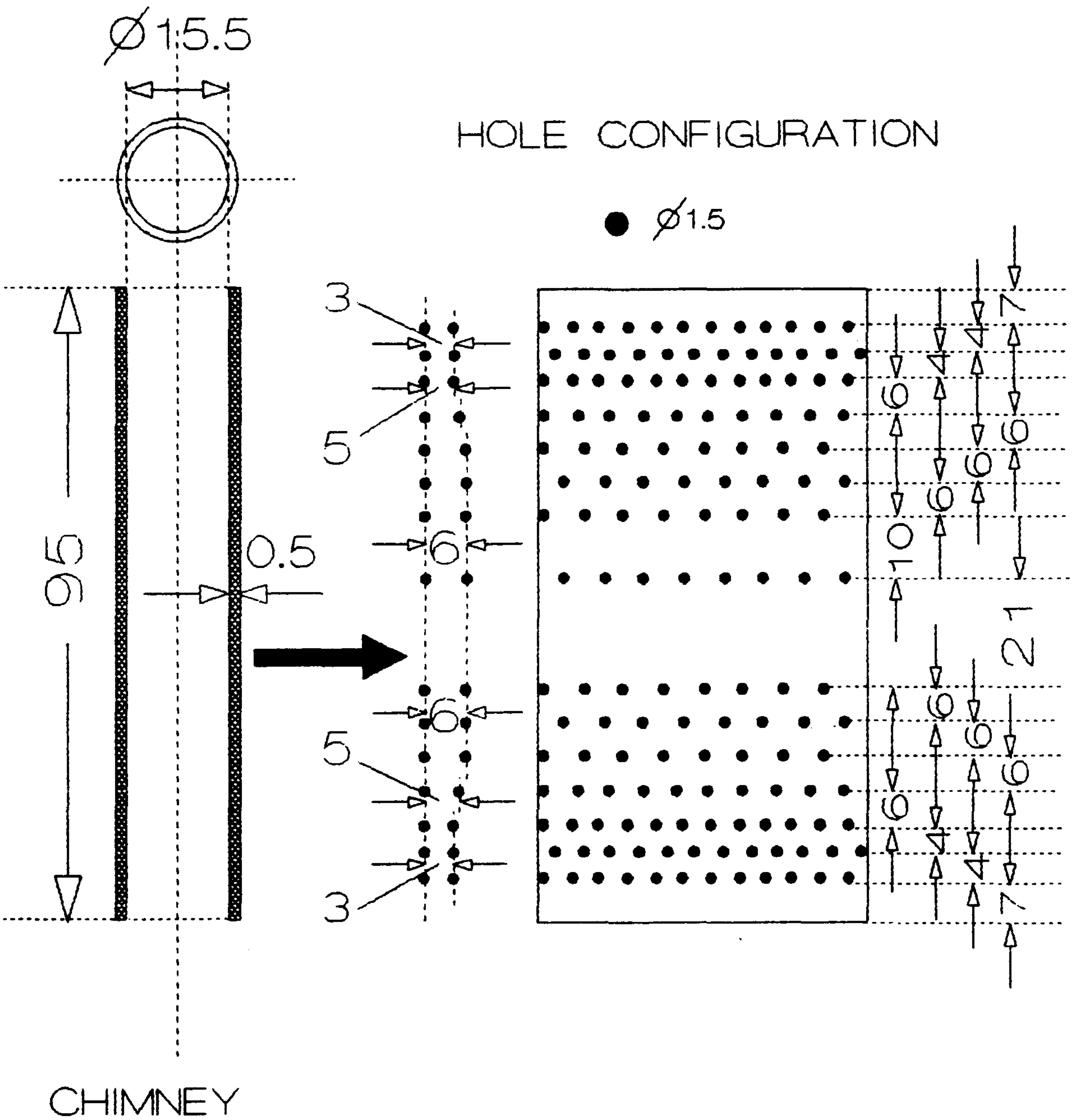


figure 6.8
Experimental Chimney

The five holders and the four chimneys give a total of 20 combinations which can be investigated. The experimental chimney is actually constructed after experiments with the other four chimneys were done and the results were available. The three chimneys with the five holders give a total of 15 experiments.

The air holes in the metal tubes are drilled from the outside inward, thus leaving burrs in the inside of the metal tube. An experiment was carried out to investigate the influence of these burrs on the mass rate and quality of the combustion. First the experiment was carried out with the Taiwan Stove Chimney with burrs inside, and then the burrs were removed and the mass rate and quality of the combustion were measured again.

It is known that for a stove the minimum power also influences the fuel economy. With the Taiwan Stove Chimney without burrs, minimum power experiments were carried out. The free wick length for these experiments was chosen at 0 mm.

7 Experimental Setup

A total of four different experiments were done: a mass rate experiment, an efficiency test by means of the water boiling method, a gas analysis of the Pet Stove, and a flame length measurement.

7.1 Mass Rate

The mass rate of a burner is measured by means of a mass balance on which the burner rests. The mass balance records the mass loss due to the fuel consumption as a function of time. The mass loss as a function of time gives the mass rate of the burner. In figure 7.1 the experimental setup of the mass rate measurement is given. In the setup the computer controlled datalogger samples, at fixed intervals of time, the output of mass balance and thermocouples.

For complete combustion the power output of the burner is defined as the mass rate multiplied by the lower calorific value of the fuel:

$$P = B * \frac{\Delta m}{\Delta t} \tag{7-1}$$

where P = the power output of the burner, W,

Δt = a time interval, s,

Δm = the mass loss in time interval Δt, kg,

B = the lower calorific value of the fuel, J kg^{-1}

for alcohol $B = 2.003 * 10^7$ J kg^{-1} and

for kerosene $B = 4.353 * 10^7$ J kg^{-1} (World Bank 1985).

The tests are described in the following section.

7.2 Three Types of Power Outputs

As is mentioned in chapter 5.1 the wick setting of the range burners can be changed by a control lever. When the stove or burner is lit, the wicks are in their highest position inside the combustion chamber. After a preheating phase of approximately 10 minutes, the stove will burn with large yellow flames. The maximal wick length inside the combustion chamber is prearranged by the experimentator such that yellow flame power output will always occur. The power output measured by this type of flame is called the yellow flame maximum power output. The blue flame maximum power output is obtained by lowering the wicks until the yellow flame just tends to turn blue. By lowering the wicks even more, the blue flame becomes yellow and the blue flame minimum power is reached.

The advantage of the yellow flame power output is that from every stove the maximum wick length is known, such is not the case with the blue flame maximum power measurement, where the wick length depends on the moment where the flames turn from blue to yellow. With the maximum wick length and the yellow flame maximum power output the wick efficiency is found. The wick efficiency (W_e) is defined as the yellow flame power output (P_y) divided by the free area (A_f) of the wick inside the combustion chamber:

$$W_e = \frac{P_y}{A_f} \tag{7-1}$$

The wick efficiency is in units of Watts per square meter.

The free area of the wick depends on the diameter of the wick and the length of this wick in the combustion chamber. There are two kinds of burners used in the experiments:

(1) burners consisting of a number of single wicks;

(2) burners where the wick is an annular ring.

The total free area (A_f) of a multi single wick burner is calculated by:

$$A_f = n\ (\tfrac{1}{4}\pi d^2 + \pi dl) \tag{7-2}$$

where A_f = the free area, m^2

n = the number of wicks,
d = the diameter of a single wick, m
l = the wick length inside the combustion chamber, m.

The total free area (A_f) of an annular ring wick stove is given by:

$$A_f = \tfrac{1}{4}\pi o^2 - \tfrac{1}{4}\pi i^2 + \pi i l + \pi o l \tag{7-3}$$

where A_f = the free area, m^2
o = the outside diameter of the ring wick, m
i = the inside diameter of the ring wick, m
l = the wick length inside the combustion chamber, m.

7.3 The Boiling Test or Heat Transfer Efficiency Test

Due to the specific construction of the different types of burners this test involves only the Pet Stove, the Thomas Cups 24 and 36, and the Elegance K786. The heat transfer efficiency is measured by means of the water boiling method. This method involves the measuring of the power output of the stove, the time it takes to heat a pan with a known quantity of water from room temperature to 100 °C, and the water evaporated out of the pan during the heating process. The pan with water hangs above the stove, without resting on the stove, with a fixed distance between the top of the burner and the bottom of the pan. The pan bottom - burner top distance is kept at 2 cm. The stove burns with blue flame maximum power output. Everytime the water in the pan starts boiling, the pan is taken from the stove and replaced by a similar pan with water at room temperature. To measure the water loss by evaporation the heated pan is, immediately after it is taken from the stove, placed on a second mass balance. In total five pans were used, each containing 5 kg of water. The pans were of the Sahelian type no. 3, which is a round bottom pan with a diameter of 24 cm. A short preheating phase was taken into account before the first pan was put above the stove. The fifth pan was kept on boiling for twenty minutes before the evaporated water amount was measured. All the experiments were carried out with a lid on the pan. The experimental setup of this test is drawn in figure 7.1.

From the experiment described above two types of efficiencies can be calculated: the efficiency with water evaporation and the efficiency without water evaporation. The equation to calculate the efficiency with water evaporation is:

$$\eta = \frac{m_w (T_b - T_i) c_p + m_e H}{m_f B} * 100 \% \qquad (7\text{-}5)$$

where η = heat transfer efficiency, %
T_b = boiling temperature of water, 100 °C
T_i = initial temperature of water, °C
m_w = initial mass of water, kg
c_p = specific heat of water, 4.186 kJ kg^{-1}
H = latent heat of evaporation of water, 2257 kJ kg^{-1}
m_e = mass of evaporated water, kg
m_f = fuel used in the test, kg
B = lower calorific value of the fuel, kJ kg^{-1}

To calculate the efficiency without water evaporation one can also use equation (7-5), by stating m_e = 0 kg.

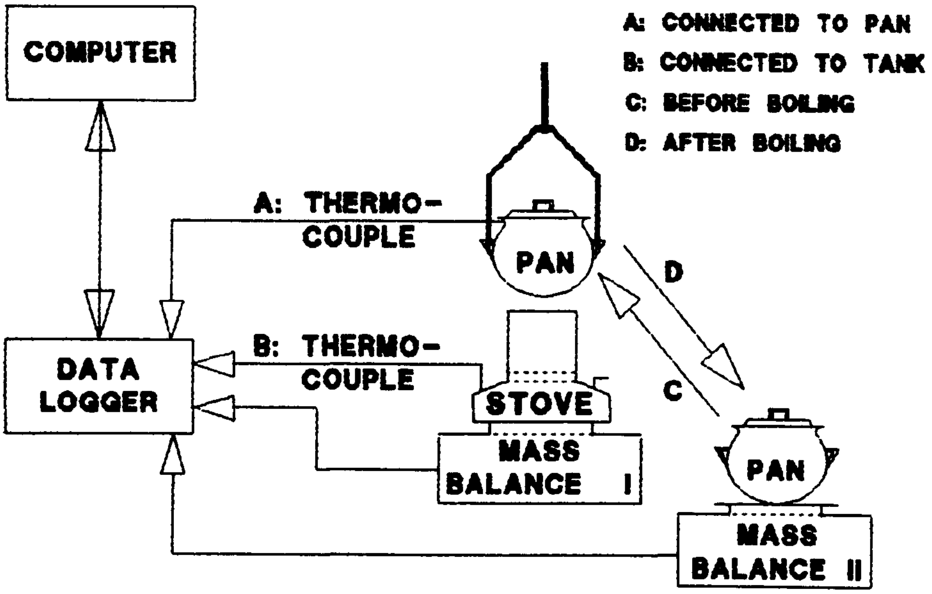


figure 7.1
Experimental set-up of the mass rate and heat transfer efficiency measurement

7.4 Gas Analysis of the Flue Gas

Due to the general construction of the burners and the laboratory equipment it is not possible to measure the pure flue gas. The flue gas sample was taken above the burner and is a mixture of flue gas and air. See figure 7.2 for the experimental lay out of the gas analysis. The sample is pumped through two filters and a water trap to the CO, CO_2 and O_2 meters. The meters are read by the computer controlled data logger at fixed time intervals.

Air is a mixture of different types of gases. For the contents of air see table 7.2.

table 7.2
Contents of dry atmospheric air
(Chambers, 1983)

constituent	content by vol. %	content by weight %
nitrogen	78.08	75.5
oxygen	20.95	23.1
argon	0.93	1.3
CO_2	0.03	0.05
rest	0.01	0.05
air	100	100

The unknown quantity of air in the flue gas sample makes it actually impossible to estimate the flue gas contents. The CO_2 concentration of the flue gas sample varies between 2 and 6 %, so the CO_2 content of air can be neglected. This assumption makes it possible to estimate the CO/CO_2 ratio of the flue gas. The CO/CO_2 ratio is an indication for the virulence (Sulilatu, 1985) and for the release of the unburned hydrocarbons (Sangen, 1983).

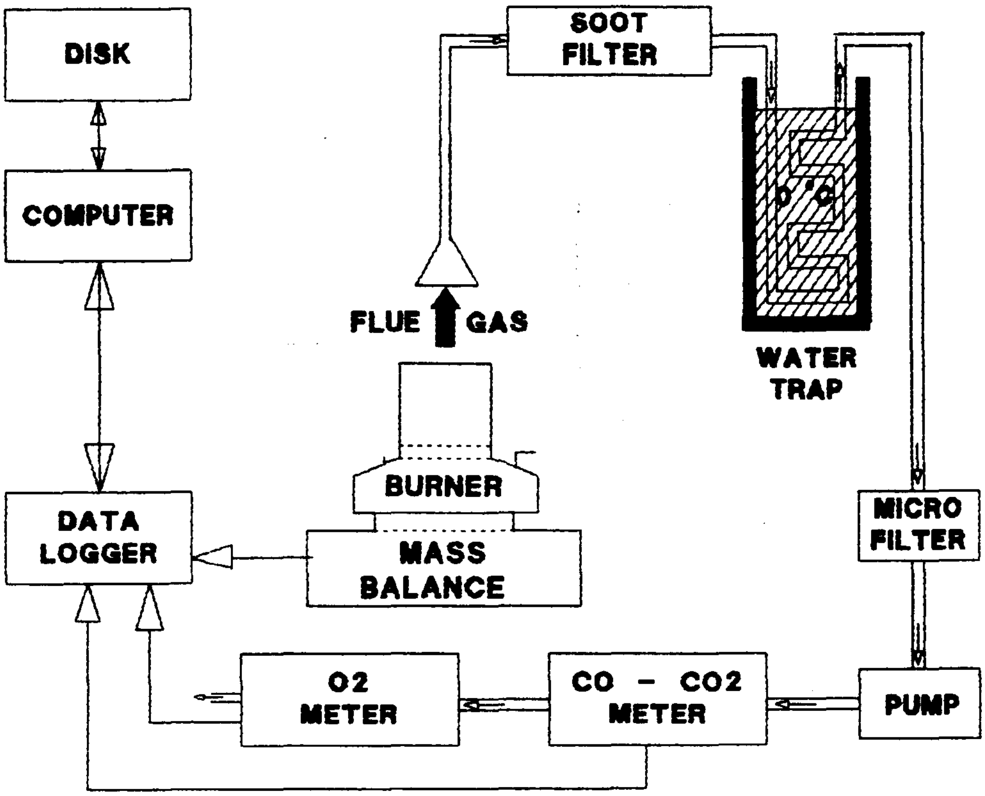
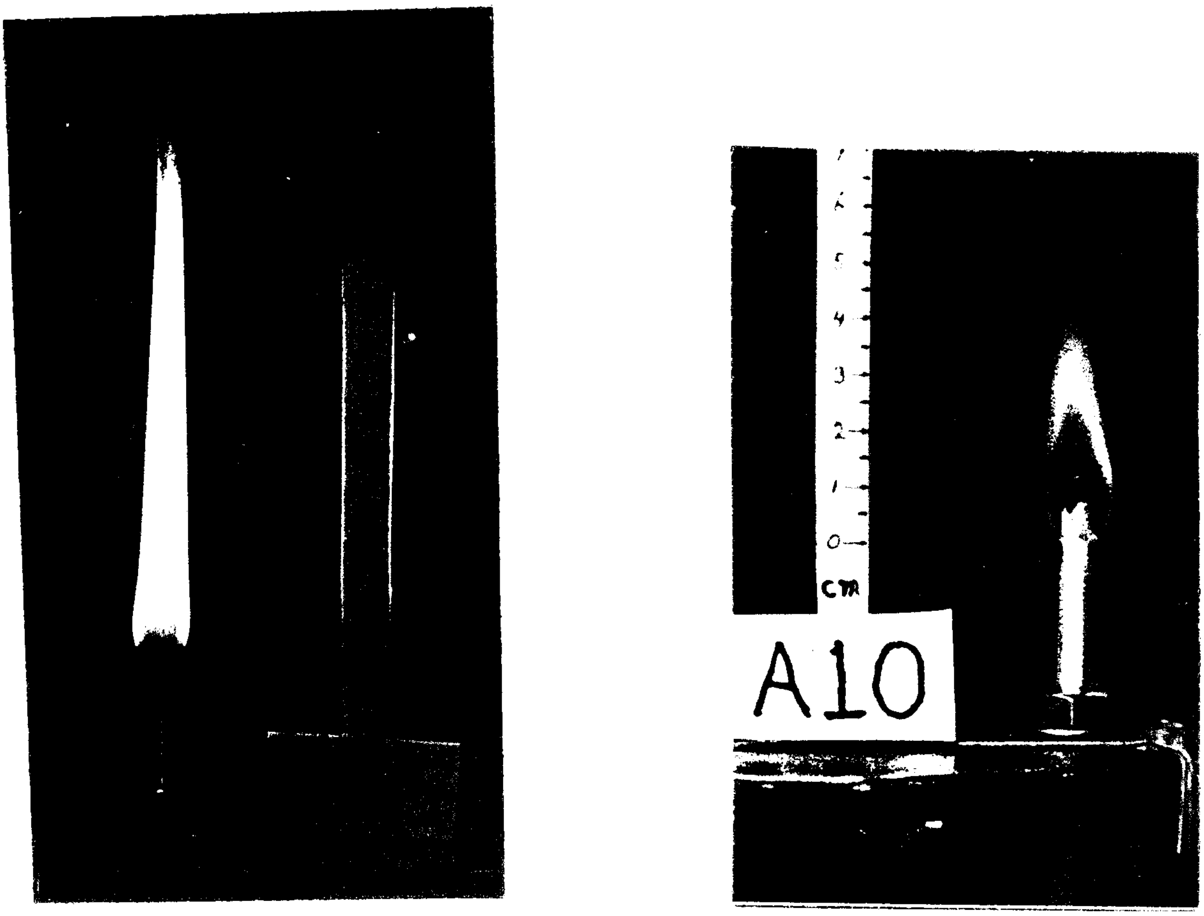


figure 7.2
Experimental setup of the gas analysis and
mass rate measurement on a kerosene wick burner

7.5 Flame Length Measurement Setup

The flame length is measured by taking a black and white photo of the flame and a ruler which is near the flame. The open kerosene diffusion flames have mostly a soot flow at the top of the flame. The soot flow at the top of the wick is very hot and radiates light. This phenomena makes it almost impossible to measure the real flame length. To solve this problem it is assumed that the flame radiates a brighter light than the soot column. The blackness of the kerosene flame photo is scanned by a computer controlled digital television camera. The part of the photo with the lowest blackness is assumed to be the flame. The flame length is measured from the end of the wick support tube to where the blackness suddenly increases. In figure 7.3 an alcohol flame photo and a kerosene flame photo are presented.



a.
kerosene flame

figure 7.3

b.
alcohol flame

8 Results

For convenience the results are presented in two sections; the first section is about kerosene stove and the second one is about single wick fuel burning.

8.1 Results of the Test of the Kerosene Burners

In this section the results collected during the testing of the kerosene burners are presented. The results are discussed with reference to design and operational characteristics. In table 8.1.1 a summary of the results is given.

table 8.1.1
Summary of the results

	Pet stove	Thomas Cup 24	Thomas Cup 36	Elegance K786	Aladin lamp	Zibro Kamin
min. power (kW)	1.6	2.0		1.6		
nom. power (kW)[a]	3.0	3.1	4.8	2.6	0.7	1.6
max. power (kW)[b]	4.9	5.4	7.2	3.2	1.1	1.6
temp. increase tank (K min.$^{-1}$)[c]	0.21	0.14	0.09	0.08		
power during boiling (kW)	2.7	4.4	5.6	2.4		
time for boil. (min. l^{-1})	4.2	2.8	2.3	4.6		
eff. -evap. water (%)[d]	50.4	46.3	48.4	51.8		
eff. +evap. water (%)[d]	54.1	52.2	54.3	55.7		
fuel used for boiling (g)	428	488	481	426		
wick efficiency (W cm^{-2})	58.0	56.0	49.0	45.0	60.0	58.0

[a] blue flame maximum power output.
[b] yellow flame maximum power output.
[c] temperature rise per minute during boiling test.
[d] heat transfer efficiency.
empty spaces: measurement not possible or carried out.

8.1.1 Maximum Power Output Test Results

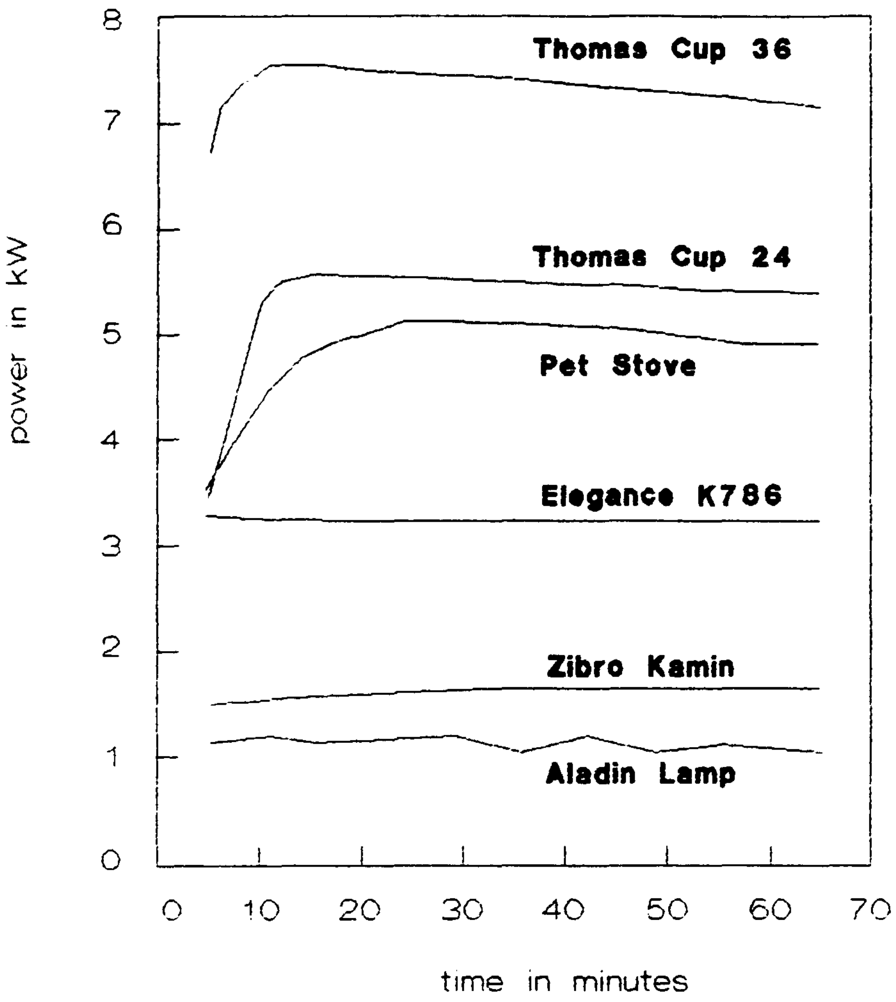


figure 8.1.1
Yellow flame maximum power output as a function of time of the six test burners.

In figure 8.1.1 the yellow flame maximum power output as a function of time is given. This power is dependent on the pre-arranged wick setting of the operator and is therefore arbitrary.

The small decrease of the power output of the Thomas Cups and the Pet Stove is due to the large fuel consumption, and consequently of the lowering of the fuel level in the fuel tank.

It turned out, after the experiment, that the wicks of both

Thomas Cups and the Pet Stove were burned quite distinctly. In the exstinguishing phase there were small yellow flames on the wicks, which is an indication that not only the fuel but also the wick material was burning. For the wick efficiency calculation the initial maximum wick length is taken, assuming that the wicks were burned only during the extinguishing phase. The values of wick diameter, wick length, number of wicks, and the free area of the wicks, are given in table 8.1.2.

table 8.1.2
Wick characteristics of the different burners

brand	number of wicks	wick length (mm)^x	type of burner	wick diameter (mm)	free area wicks (mm^2)^{xx}
Pet stove	21	20	single	6	8505
Thomas Cup 24	24	20	single	6	9720
Thomas Cup 36	36	20	single	6	14580
Elegance K786	1	10	ring	96 * 102	7153
Zibro Kamin	1	5	ring	65 * 71	2777
Aladin Lamp	1	10	ring	23 * 29	1780

^{x} maximum wick length inside combustion chamber.
^{xx} maximum free area inside the combustion chamber.

The maximum power output for the calculation of the wick efficiency is the power output of the burner after it has burned for one hour. The results of the maximum power output and the wick efficiency is given in table 8.1.3.

table 8.1.3
Wick efficiency and maximum power results

Brand	maximum free area (mm^2)	power at 1h (kW)	wick eff. (W cm^{-2})
Pet Stove	8505	4.90	58
Thomas Cup 24	9720	5.40	56
Thomas Cup 36	14580	7.21	49
Elegance	7153	3.22	45
Aladin Lamp	1780	1.06	60
Zibro Kamin	2777	1.61	58

In design four of the six stoves are nearly identical. Of these four stoves the Pet Stove and Thomas Cup 24 have a wick efficiency larger than 55 W cm^{-2}, that of the Elegance and Thomas Cup 36 is smaller than 50 W cm^{-2}. The main difference in design between the former and latter two is the structure of the burner head top; the Pet stove and the Thomas Cup have a nearly closed burner head top, while the Thomas Cup 36, with its two rings of wicks, and the Elegance have an open burner head top. It is reasonable to presume that a burner with a nearly closed burner head top has a larger air flow resistence than a burner with a nearly open top. It is the air flow near the wicks which cools the wicks and lowers the evaporation rate.

The Aladin Lamp and the Zibro Kamin, which in design structure differ from the others, have a nearly identical wick efficiency with the Pet Stove and Thomas Cup 24.

At this moment no final conclusions can be drawn towards influences on the wick efficiency; there are still too many parameters that need to be investigated. These parameters are given by the differently designed burners; some of them are:

a chimney to create draft,
the porosity of the flame holders,
the wick material, cotton or glass fiber,
the burner head top,
the wick support tube.

In the section on the single wick fuel burning, more information of the wick efficiency is given.

8.1.2 Minimum Power Output Test Results

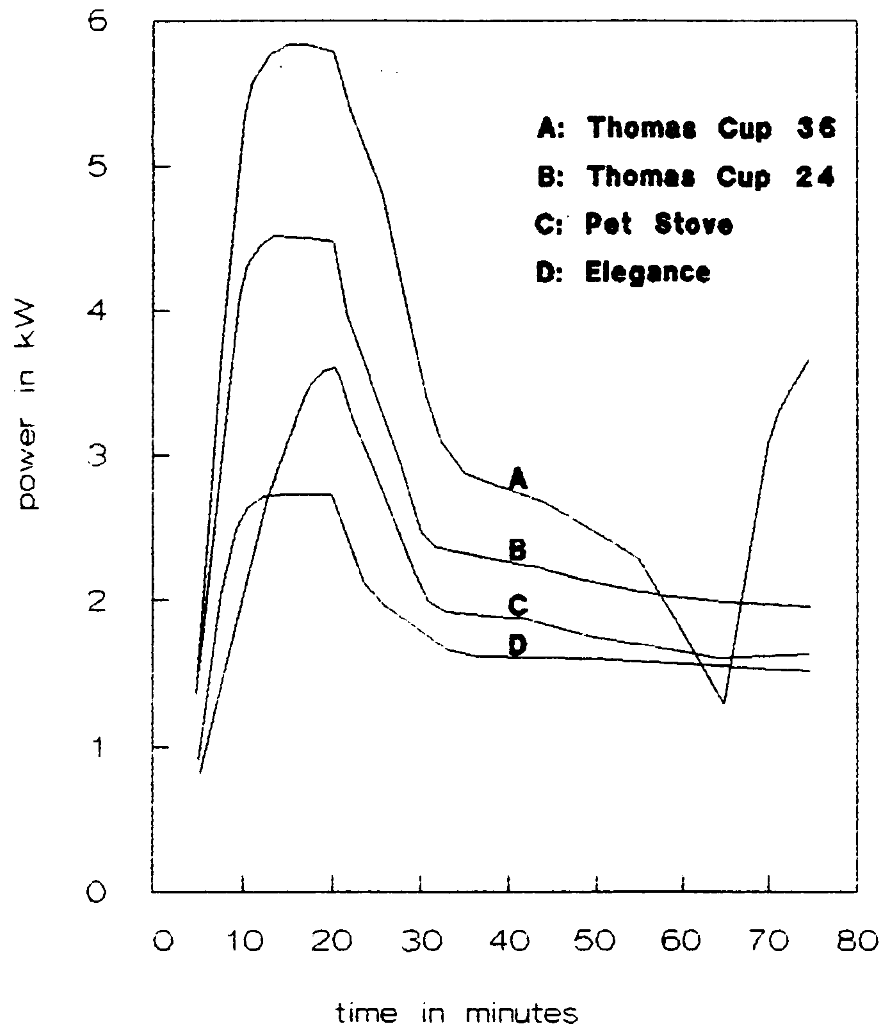


figure 8.1.2
Minimum power output as a function of time.
After 20 minutes of full power output burning of 4 test burners.

After twenty minutes of full power output burning the burners were turned down to minimum power output. It took approximately 10 minutes before a stable minimum power was reached. The test with the Thomas Cup 36 failed, there was no stable minimum power output. During the experiments all 36 wicks were used. Sulilatu used for this stove only the inner 12 wicks and reached a power of 0.9 kW (Sulilatu, 1988).

8.1.3 Blue Flame Maximum Power Output Results

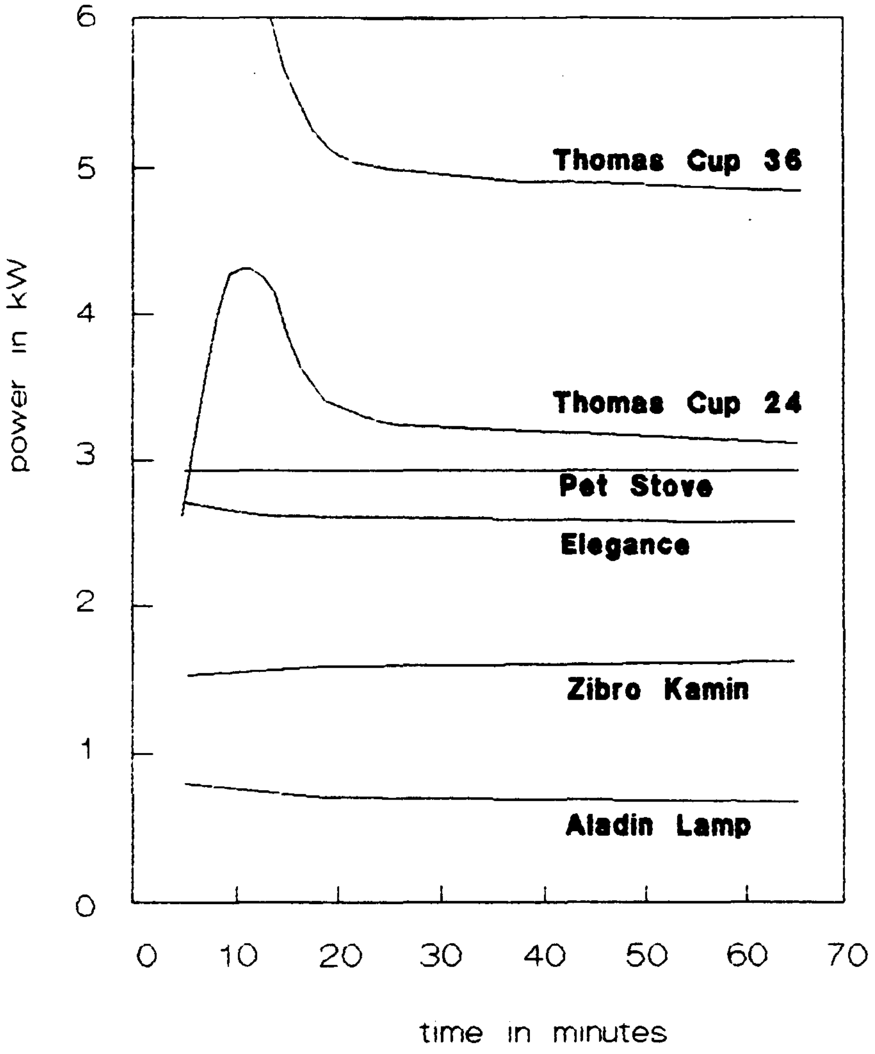


figure 8.1.3
Blue flame power output as a function of time.
The Thomas Cups were readjusted after 15 min.

The blue flame maximum power output of all the burners is quite stable in time. The small decrease of the power output is mainly due to the lowering of the fuel level in the tank during the operation.

8.1.4 Heat Transfer Efficiency Results

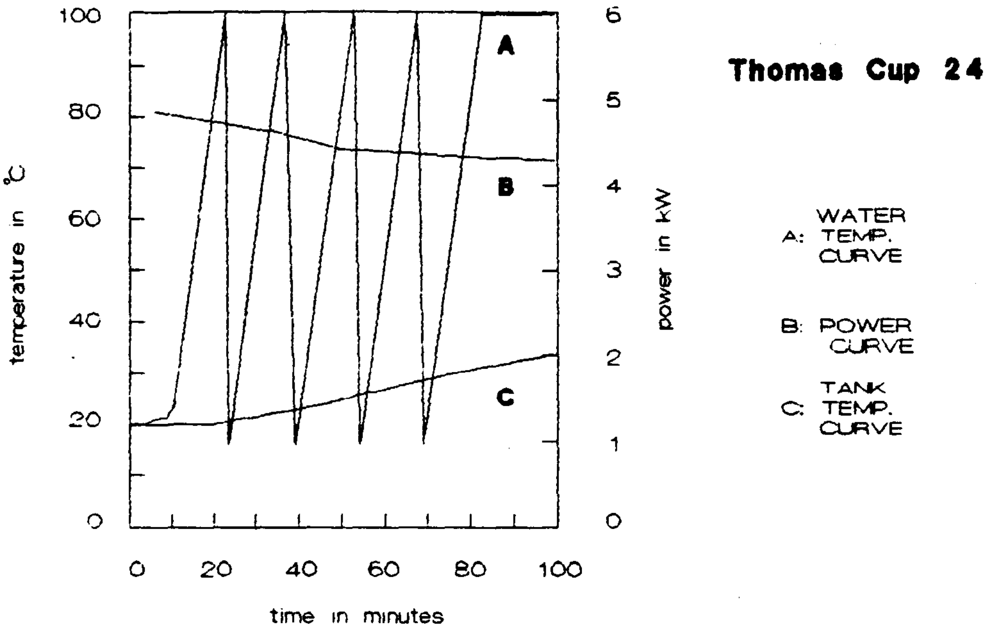


figure 8.1.4
Heat transfer test with the Thomas Cup 24
on five pans with 5 kg of water each

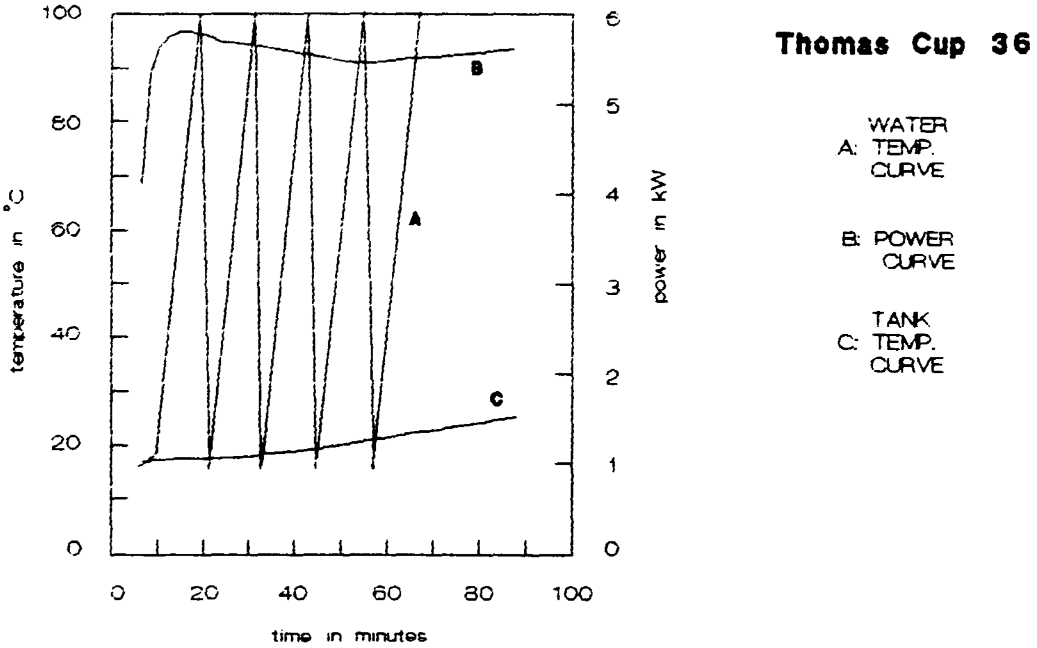


figure 8.1.5
Heat transfer test with the Thomas Cup 36
on five pans with 5 kg of water each

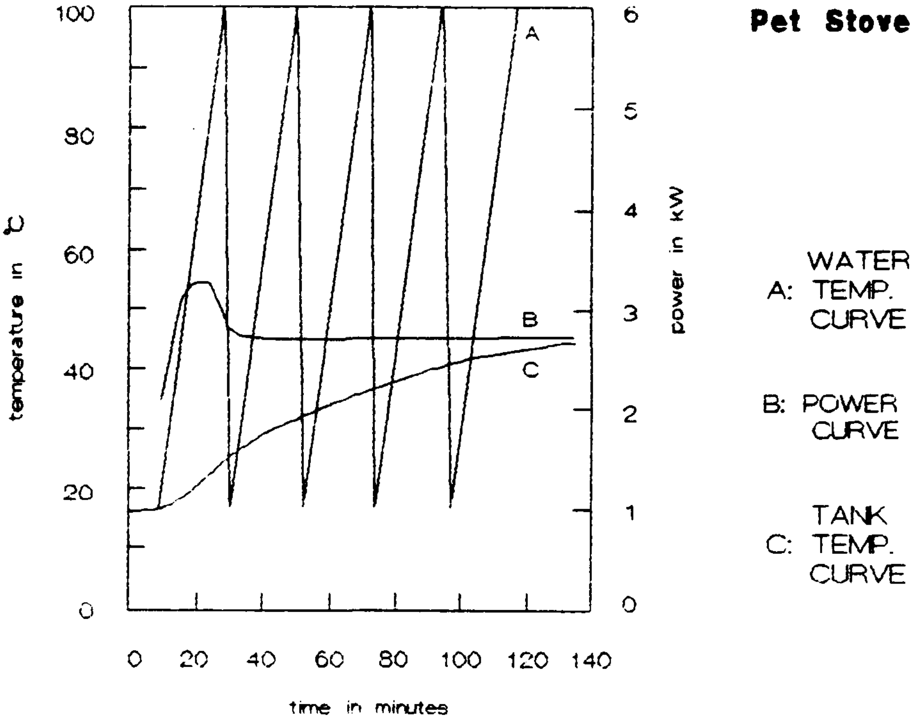


figure 8.1.6
Heat transfer test with the Pet Stove on five pans with 5 kg of water each

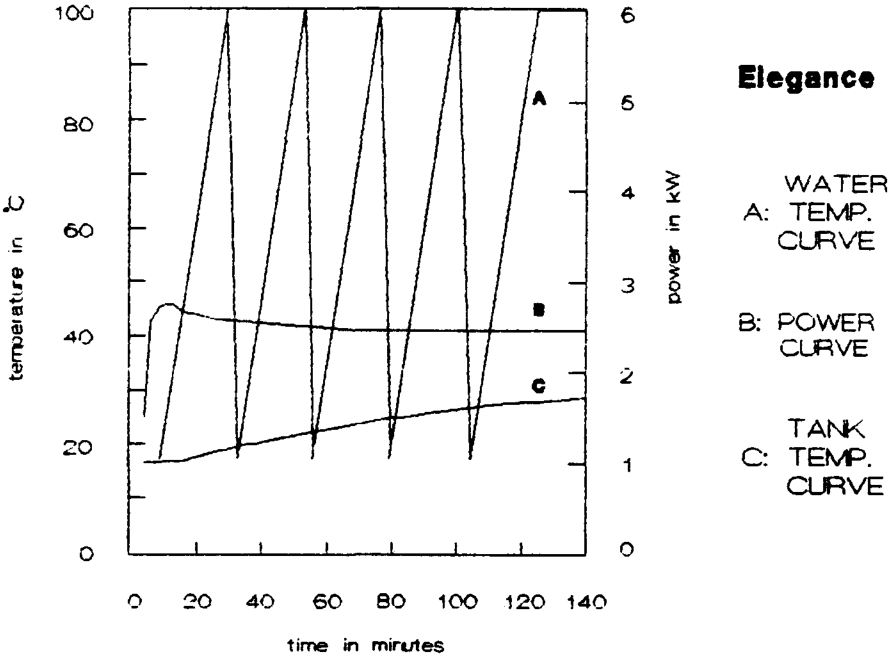


figure 8.1.7
Heat transfer test with the Elegance K786 on five pans with 5 kg of water each

As is mentioned in section 7.3, five pans filled with water were used. The time it takes for the water in the pan to start boiling and the amount of water evaporation was measured. These data are presented in tables 8.1.4 to 8.1.7. These tables contain all the relevant data to calculate the heat transfer efficiency, as well as the efficiency itself. For each type of burner the tests were similar. The power output, the fuel tank temperature and the temperature of the water in the pan are presented in figures 8.1.4 to 8.1.7.

table 8.1.4
Heat transfer efficiency test results of the
Thomas Cup 24

Pan No.	boil. time (s)	water evap. (g)	energy supplied (kJ)	energy to boil (kJ)	energy to evap (kJ)	eff. + evap (%)	eff. - evap (%)
1	830	129	3700	1680	291	53.3	45.4
2	830	99	3613	1680	99	52.7	46.5
3	830	79	3613	1680	79	51.4	46.5
4	860	104	3657	1680	104	52.4	45.9
5	790		3482	1680			46.1
5a		1142	5093		2576	50.6	
average heat transfer efficiency [x]						52.2[xx]	46.3

[x] without pan no.1 [xx] also without 5a

table 8.1.5
Heat transfer efficiency test results of the
Thomas Cup 36

Pan No.	boil. time (s)	water evap. (g)	energy supplied (kJ)	energy to boil (kJ)	energy to evap (kJ)	eff. + evap (%)	eff. - evap (%)
1	675	103	3744	1680	232	51.1	44.8
2	615	75	3439	1680	169	53.8	48.9
3	575	91	3395	1680	205	55.5	49.5
4	670	102	3569	1680	230	53.5	47.1
5	790		3657	1680			48.3
5a		1142	6791		3596	53.0	
average heat transfer efficiency [x]						54.3[xx]	48.4

[x] without pan no.1 [xx] also without 5a

table 8.1.6
Heat transfer efficiency test results of the Elegance

Pan No.	boil. time (s)	water evap. (g)	energy supplied (kJ)	energy to boil (kJ)	energy to evap (kJ)	eff. + evap (%)	eff. - evap (%)
1	1380	67	3569	1764	151	53.6	49.4
2	1330	42	3352	1764	95	55.5	52.6
3	1380	55	3395	1764	124	55.6	52.0
4	1390	61	3352	1743	138	56.1	52.0
5	1380		3439	1743			50.7
5a		692	3004		1561	51.9	
average heat transfer efficiency [x]						55.7[xx]	51.8

[x] without pan no.1

[xx] also without 5a

table 8.1.7
Heat transfer efficiency test results of the Pet Stove

Pan No.	boil. time (s)	water evap. (g)	energy supplied (kJ)	energy to boil (kJ)	energy to evap (kJ)	eff. + evap (%)	eff. - evap (%)
1	1170	52	3526	1743	117	52.8	49.4
2	1275	43	3439	1743	97	53.5	50.7
3	1275	55	3439	1743	124	54.3	50.7
4	1300	69	3482	1743	156	54.5	50.1
5	1270		3482	1743			50.1
5a		764	3221		1724	53.4	
average heat transfer efficiency [x]						54.1[xx]	50.4

[x] without pan no.1

[xx] also without 5a

All the average heat transfer efficiency values are calculated without the results of pan no.1. The heating of pan no.1 is clearly influenced by the preheating phase of the stove. In table 8.1.8 the average heat transfer efficiencies are presented with their standard deviation. The standard deviations show that the results are very accurate.

The differences between the heat transfer results without water evaporation are more pronounced than those with water evaporation. When one looks at the results with and without water evaporation, the difference for the Pet Stove and Elegance is approximately 4 % and for the Thomas Cups 6 % in favour of the efficiency with water evaporation. The actual boiling of water with the Thomas Cups was more violent than that with the Pet Stove and Elegance. It took some time before the pan with boiling water was taken of the burner. During this small period of time it is reasonable to assume that with the more powerful Thomas Cups more water vapour escaped.

table 8.1.8
Average heat transfer efficiency results

brand	efficiency with water evap. (%)	effiency. without water evap. (%)
Pet Stove	54.1 ± 0.5	50.4 ± 0.4
Thomas Cup 24	52.2 ± 0.7	46.3 ± 0.3
Thomas Cup 36	54.3 ± 1.1	48.3 ± 1.0
Elegance	55.7 ± 0.3	51.8 ± 0.8

The standard deviation of the heat transfer efficiency without water evaporation of the Elegance is strongly influenced by the different result of pan no.5.; without this result the average is 52.2 % and the standard deviation is 0.4 %.

8.1.5 Pet Stove Flue Gas Results

The flue gas analysis was concentrated on the CO/CO_2 ratio. This CO/CO_2 ratio was measured in combination with the power output of the Pet Stove. The results of this test are presented in figure 8.1.8. The power output and the CO/CO_2 ratio are presented as a function of time. The time axis is divided into five phases. The first phase represents the lighting of the stove and the preheating. The large CO/CO_2 ratio in this phase shows that there is a large production of unburned flue gas. The second phase is the blue flame maximum power output burning. This phase represents the actual operating of the stove for cooking tasks. The CO/CO_2 ratio is smaller than the standard value of 1.2 % for kerosene burners (Bussmann, 1988). The third phase is the yellow flame maximum power output burning. In this phase the CO/CO$_2$ ratio is also small. The fourth phase is the minimum power output burning. Due to a mechanical defect of the stove the power output could not be lowered more. The actual lowering of the wicks resulted in the increase of CO emission, which decreased when the stove burned in a stationary state with minimum power. The CO/CO$_2$ ratio in this phase was somewhat larger than the ratio in phases two and three, but still below the standard value. Finally the fifth phase represents the extinguishing of the fuel burning. The fire was extinguished suddenly and violently, the flames were blown out. Due to the heat of the stove at that moment there was a large evaporation of kerosene at the wicks and semi-combustion inside the combustion chamber, which resulted in an extremely large CO emission during a short period of time. The CO/CO$_2$ ratio grew to 120 %. This large ratio is also due to the decrease of CO$_2$ production in this phase.

Both the lighting and extinguishing of the stove produces CO, which is harmful to health and influences the taste of food negatively.

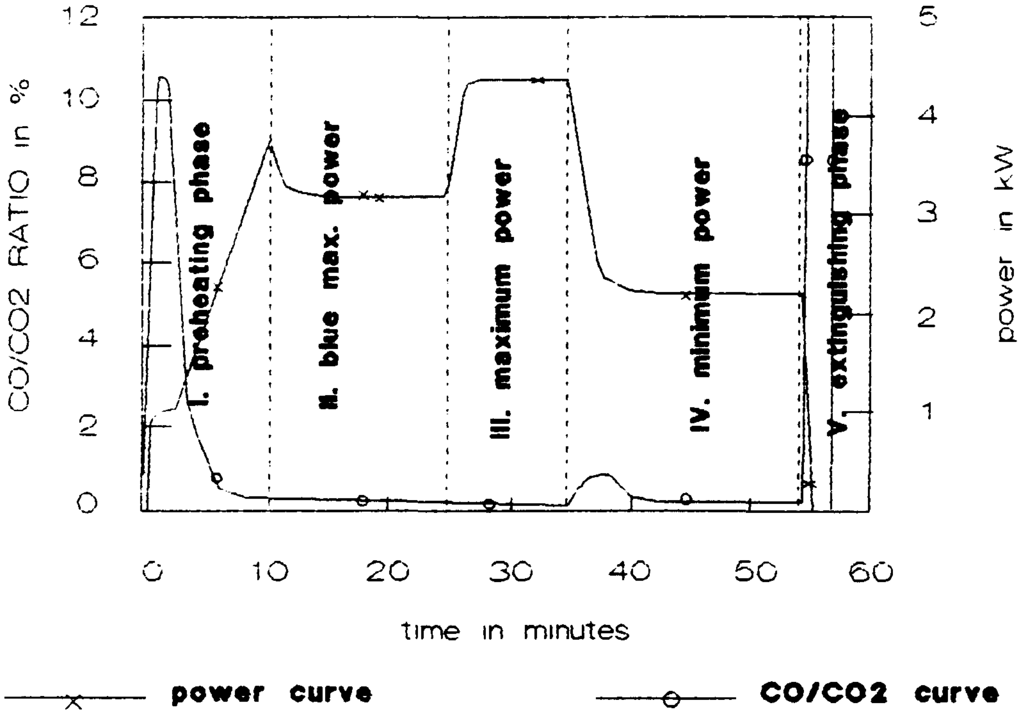


figure 8.1.8
CO/CO$_2$ ratio and power of the Pet Stove as a function of time

8.2 Results of the Single Wick Fuel Burning

In this chapter the results of the different experiments on single wick fuel burning are presented and discussed. In table 8.2.1 a summary of the results of the tests with alcohol is given. Alcohol is only used in the free burning tests and the glass chimney tests. In table 8.2.2 a summary of the results of the tests with kerosene is given. Kerosene is also used in the tests with the different holders and metal chimneys, but because these tests are somewhat different from the free burning and glass chimney tests, they are presented in a different table. The results of the different holder and metal chimney tests are presented in table 8.2.3. In the following sections the results are presented in more detail; they are presented in graphs and discussed in the context of the experimental approach and setup. The results of the flame length measurements are presented in tables 8.2.5 and 8.2.7. Most of the results are not given in tables, because especially the results of the CO/CO_2 ratio measurements as a function of time go up to a hundred data points. To present these data in tables would make this report become too extensive.

In table 8.2.0 the extreme values of the results of alcohol and kerosene are presented.

table 8.2.0
Extreme results of alcohol and kerosene for single wick

	alcohol	kerosene
maximum power output	108 W	266 W
minimum power output	22 W	24 W
maximum mass rate	5.3 mg s^{-1}	6.1 mg s^{-1}
minimum mass rate	1.08 mg s^{-1}	0.56 mg s^{-1}
maximum CO/CO_2 ratio	1.13 %	48.2 %
minimum CO/CO_2 ratio	0.00 %	0.11 %
maximum wick eff.	90.9 W cm^{-2}	420.9 W cm^{-2}
minimum wick eff.	45.2 W cm^{-2}	25.4 W cm^{-2}
maximum flame length	103 mm	103 mm
minimum flame length	11.9 mm	10 mm

table 8.2.1
Alcohol results

wick length (mm)	chimney (mm)	mass rate (mg/s)	power (W)	CO/CO$_2$ ratio (%)	wick eff. (W cm^{-2})
0.0		1.08	22	0.05 ±0.04	77.8
1.0		1.88	38	0.18 ±0.05	80.6
2.0		2.96	59	0.20 ±0.05	89.4
3.0		3.54	71	0.12 ±0.04	83.7
4.0		4.00	80	0.13 ±0.03	77.2
5.0		4.50	90	0.17 ±0.05	73.5
7.5		5.30	106	0.11 ±0.04	62.5
10.0		4.90	98	0.12 ±0.06	45.2
5.0	0	4.33	87	0.12 ±0.03	71.0
5.0	20	5.01	100	0.15 ±0.03	81.6
5.0	40	5.00	100	0.85 ±0.07	81.6
5.0	60	4.89	98	0.33 ±0.13	80.0
5.0	80	4.90	*	0.03 ±0.02	**
7.5	0	4.66	93	0.07 ±0.03	54.8
7.5	20	5.11	102	0.10 ±0.04	60.1
7.5	40	5.38	108	1.13 ±0.09	63.7
7.5	60	4.79	96	0.64 ±0.09	56.6
7.5	80	4.75	*	0.00 ±0.00	**
4.0	0	3.93	79	0.07 ±0.03	76.2
4.0	20	4.53	91	0.11 ±0.03	87.8
4.0	40	4.59	92	0.81 ±0.09	88.7
4.0	60	4.58	*	0.08 ±0.06	**
4.0	80	4.55	*	0.00 ±0.00	**
3.0	0	3.34	67	0.13 ±0.04	79.0
3.0	20	3.77	75	0.13 ±0.04	88.4
3.0	40	3.87	77	0.53 ±0.12	90.8
3.0	60	3.76	*	0.09 ±0.06	**
3.0	80	2.02	40	0.23 ±0.05	47.2
2.0	0	2.60	52	0.11 ±0.04	78.8
2.0	20	2.96	59	0.07 ±0.02	89.4
2.0	40	2.98	60	0.08 ±0.04	90.9
2.0	60	2.04	40	0.42 ±0.06	60.6

* There is a large unburned fuel vapour emission which makes it impossible to calculate the power output of these flames.
** The wick efficiency is related to the power output.

table 8.2.2
Kerosene results

wick length (mm)	chimney (mm)	mass rate (mg/s)	power (W)	CO/CO$_2$ ratio (%)	wick eff. (W cm^{-2})
0.0		0.56	24	0.40 ±0.05	84.9
1.0		1.69	74	0.62 ±0.04	157.0
2.0		2.39	104	0.63 ±0.04	157.6
3.0		2.96	129	0.74 ±0.04	152.1
4.0		3.72	162	0.78 ±0.05	156.3
5.0		4.20	183	0.84 ±0.07	149.4
7.5		5.30	231	0.98 ±0.15	136.2
10.0		6.10	266	1.06 ±0.14	122.7
10.0	0	3.40	148	1.30 ±0.48	69.3
10.0	20	4.10	178	0.77 ±0.03	82.1
10.0	40	4.04	176	1.13 ±0.24	81.2
10.0	60	3.98	*	16.50 ±1.60	**
10.0	80	1.27	55	0.23 ±0.03	25.4
7.5	0	4.76	207	1.23 ±0.19	122.0
7.5	20	5.20	226	0.93 ±0.09	133.2
7.5	40	5.19	226	0.83 ±0.11	133.2
7.5	60	3.70	161	3.57 ±2.10	94.9
7.5	80	1.85	80	0.47 ±0.08	47.2
5.0	0	4.34	189	1.27 ±0.10	154.3
5.0	20	5.20	226	1.07 ±0.06	184.5
5.0	40	3.68	*	12.00 ±2.00	**
5.0	60	1.32	57	0.27 ±0.06	46.5
5.0	80	1.20	52	0.38 ±0.04	52.0
4.0	0	3.47	151	2.24 ±0.55	145.7
4.0	20	4.70	205	1.13 ±0.10	197.7
4.0	40	3.99	174	1.24 ±1.08	167.8
4.0	60	1.86	81	0.32 ±0.06	78.1
4.0	80	1.26	55	0.27 ±0.04	53.1
3.0	0	3.11	135	3.08 ±0.06	159.2
3.0	20	3.60	157	1.21 ±0.13	185.1
3.0	40	3.48	*	8.04 ±1.84	**
3.0	60	2.40	104	0.99 ±0.70	122.6
3.0	80	1.13	49	0.45 ±0.05	57.8
5.0	0	4.14	180	1.24 ±0.10	146.9
5.0	10	4.67	203	1.01 ±0.05	165.7
5.0	20	4.77	208	1.02 ±0.11	169.8
5.0	30	4.82	210	1.03 ±0.12	171.4
5.0	40	4.88	212	0.80 ±0.07	173.0
5.0	50	5.03	219	2.60 ±2.40	178.7
5.0	60	4.86	*	11.83 ±2.70	**
5.0	70	3.25	141	0.64 ±0.05	115.1
5.0	80	1.38	60	0.21 ±0.04	49.0
5.0	90	1.28	56	0.28 ±0.06	45.7
5.0	100	1.28	56	0.27 ±0.03	45.7
5.0	140	1.22	53	0.40 ±0.05	43.3

table 8.2.3
Holder and chimney results with kerosene

wick (mm)	ho. No.	chim. type	rate (mg/s)	power (W)	wick eff. (W cm^{-2})	CO/CO_2 ratio (%)	top flame
5.0	1	Pet	1.22	*	**	40.00 ±1.00	no
10.0	1	Pet	1.65	*	**	48.20 ±1.30	no
15.0	1	Pet	3.15	*	**	46.20 ±0.70	no
15.0	1	Pet	3.18	138	44.4	0.41 ±0.06	yes
15.0	1	Pet	3.02	*	**	45.80 ±7.70	no
1.0	1		1.26	55	116.7	0.83 ±0.04	
2.0	1		2.10	91	137.9	0.81 ±0.04	
3.0	1		2.53	110	129.7	0.81 ±0.03	
4.0	1		3.21	140	135.0	0.80 ±0.04	
5.0	1		3.81	166	135.5	1.00 ±0.06	
7.5	1		5.12	223	131.5	1.14 ±0.06	
10.0	1		5.91	257	118.6	1.27 ±0.13	
0.0	2	Taiw.	2.17	94	332.5	1.52 ±0.21	no
2.5	2	Taiw.	2.75	120	159.2	5.15 ±0.49	y/n
5.0	2	Taiw.	3.48	151	123.2	1.99 ±1.54	y/n
7.5	2	Taiw.	4.24	185	109.1	0.64 ±0.11	yes
10.0	2	Taiw.	4.61	200	92.3	0.41 ±0.05	yes
0.0	2	Taiw#	2.67	116	410.3	4.71 ±0.60	no
2.5	2	Taiw#	3.15	137	181.7	4.71 ±0.31	no
5.0	2	Taiw#	3.83	166	135.5	0.97 ±0.24	yes
7.5	2	Taiw#	4.39	190	112.0	0.55 ±0.07	yes
10.0	2	Taiw#	4.97	216	99.6	0.50 ±0.07	yes
0.0	1	Exp.	3.77	*	**	20.70 ±0.42	no
2.5	1	Exp.	4.39	191	253.3	0.17 ±0.04	yes
5.0	1	Exp.	5.00	217	177.1	0.15 ±0.03	yes
7.5	1	Exp.	5.92	258	152.1	0.23 ±0.04	yes
10.0	1	Exp.	5.95	259	119.5	0.25 ±0.04	yes
0.0	1	Taiw#	1.82	78	275.9	0.30 ±0.03	no
0.0	2	Taiw#	2.57	119	420.9	3.96 ±0.85	no
0.0	3	Taiw#	1.80	78	275.9	0.15 ±0.06	no
0.0	4	Taiw#	1.08	47	166.2	0.20 ±0.03	no
0.0	5	Taiw#	0.82	35	123.8	0.11 ±0.03	no

The top flame is the flame on top of the metal chimney. It is not a reversed flame but a premixed flame.

The difference between the Taiw. chimney and the Taiw# chimney is that the former has burrs inside and the latter does not.

* The power output cannot be calculated. The CO/CO_2 ratio clearly indicates incomplete combustion.

** Wick efficiency and power output are related.

8.2.1 Free Single Wick Fuel Burning and Flame Length

In figures 8.2.1 and 8.2.2 the mass rate and the CO/CO_2 ratio of the flue gas is plotted against the free wick length.

For kerosene and alcohol the mass rates are nearly identical. It should be stated that the density of kerosene and alcohol is also nearly identical.

The mass rate increases progressively with increasing wick length, although this mass rate increase gradually becomes smaller. The part of the wick exposed to a high temperature is larger when the free wick length is large. Thus the wicks have more chance to be carbonized when their length is larger. The carbonization of the wick influences the mass rate through the wick negatively. This explains the diminishing increase of the mass rate.

In contradiction the flue gas quality of both liquids differs a lot. The CO/CO_2 ratio of the alcohol flue gas is almost always below 0.2 %. The CO/CO_2 ratio of the kerosene follows the mass rate curve of kerosene. The difference between the alcohol- and kerosene flue gas

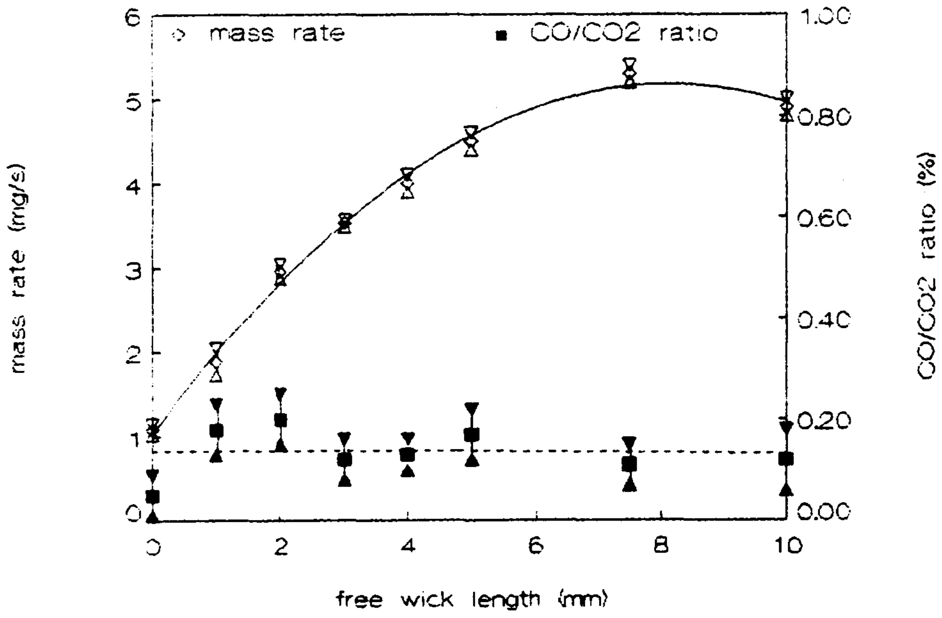


figure 8.2.1
Free burning of alcohol at wicks with different lengths

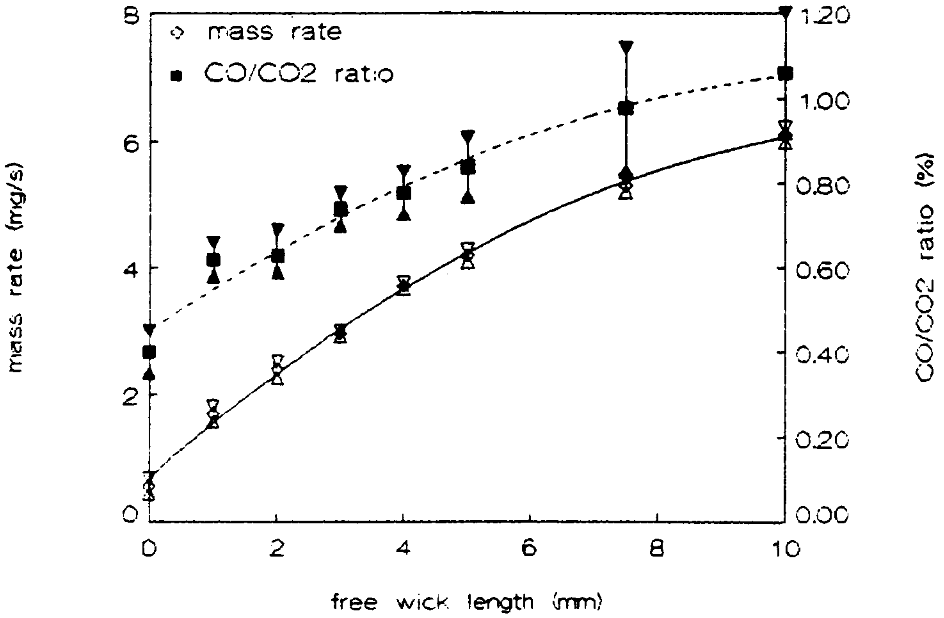


figure 8.2.2
Free burning of kerosene at wicks of different lengths

quality can be found in the difference of the chemical reaction steps in the burning of these fuels. It is beyond the scope of this work to explain these chemical reaction steps. It should be stated that probably the CO/CO_2 ratio curve of alcohol also follows the mass rate curve, but the equipment is not sensitive enough to measure the very small CO concentrations of the alcohol flue gas.

The measured flame lengths of alcohol and kerosene are presented in figures 8.2.3 and 8.2.4. The graphs of these figures have different scales on the axes because of plotting difficulties.

In the figures also the flame lengths, calculated according to the theory mentioned in chapter 4, are presented. There are two theoretically calculated curves for each graph. The solutions with the largest excess air factor have the largest flame length. For the alcohol flame the solutions, even with the lowest possible excess air factor, are larger than the measured flame lengths.

The alcohol and kerosene curve, with excess air factor 1, are nearly identical. The main differences between the two reactions can be found in the stoichiometric air to fuel ratio and in the wick top temperature; the former are 9.1 for alcohol and 15.2 for kerosene, the latter are the boiling temperature of alcohol, 351 K, and of kerosene, 435 K. It turns out that both differences have minor influence on the calculated flame length.

For alcohol and kerosene the measured flame length curve and the calculated one with excess air factor 1 intersect approximately at an identical point: a power output of ~ 140 W and a flame length of ~ 50 mm. For power outputs above 140 W the theory, when the excess air factor is 1, gives lower values for the flame length than the measured ones. For power outputs below 140 W the theory, even when the excess air factor is 1, gives larger values than the ones measured.

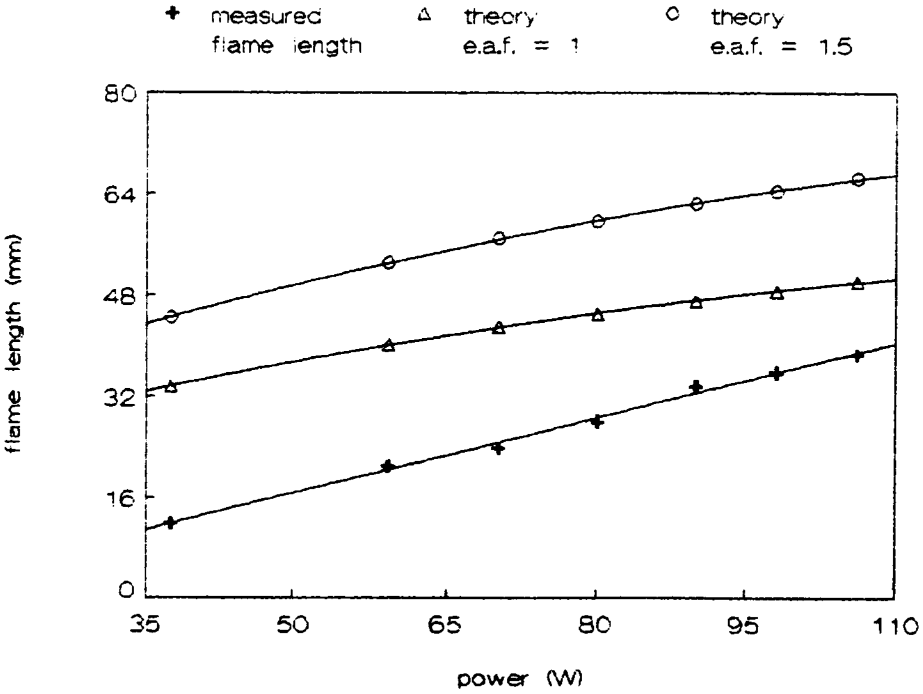


figure 8.2.3
Flame length of an alcohol flame at a wick.
Measured, and calculated with two different excess air factors.

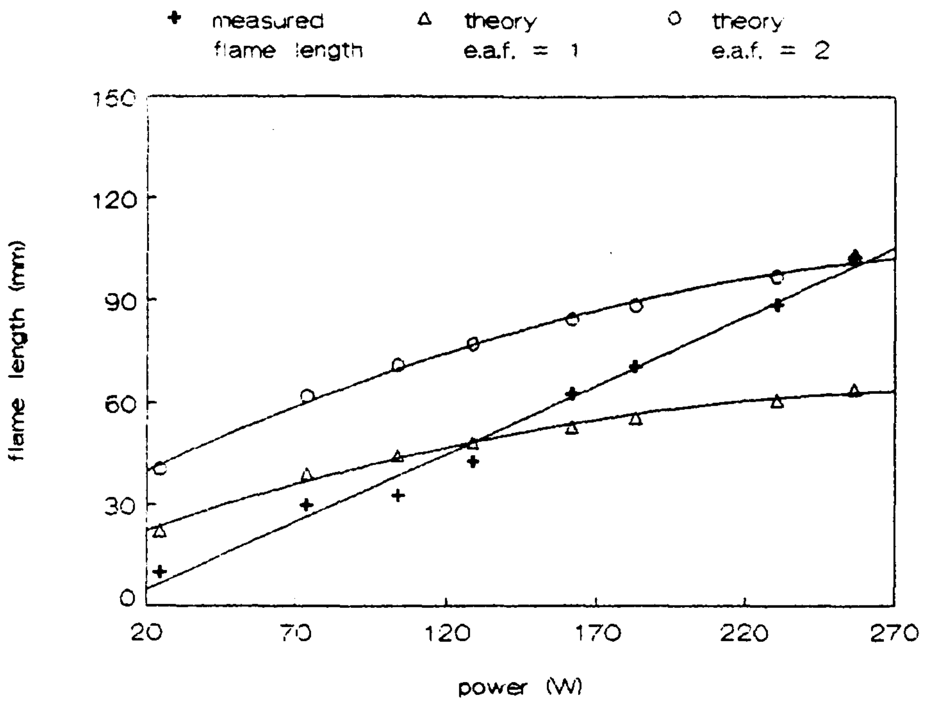


figure 8.2.4
Flame length of a kerosene flame at a wick.
Measured, and calculated with two different excess air factors.

The theory is based on a fully developed turbulent flow. In all cases the flames have a typical laminar character. The pictures presented in figures 7.3 show stable laminar flames, thus the entrainment assumption should be valid for laminar conditions.

Tables 8.2.4 and 8.2.6 show examples of calculated flame length with the parameters which are also used for the calculation of the data of figures 8.2.3 and 8.2.4. Tables 8.2.5 and 8.2.7 contain the measured and theoretically calculated flame lengths.

table 8.2.4
Example of the parameters used for calculation of the alcohol flame length

```
The fuel is alcohol

 1 The combustion value of fuel is:      .2003E+08  J/kg
 2 The gravitational accel. is:         9.80        m/s^2
 3 The entrainment constant is:          .057       (-)
 4 The excess air factor is:            1.00        (-)
 5 The stoich. air to fuel ratio is:    9.10        (-)
 6 The ambient temperature is:        293.          K
 7 The temp. of the fuel bed is:      351.          K
 8 The ambient density of air is:       1.25        kg/m^3
 9 The spec. heat coeff. of air is:  1000.          K kg/J
10 The fuel bed area is:                 .283       cm^2
13 The power of the wick is:          106.16        W


No variable parameters


Froude number at fuel bed =  .3533
The combustion number    =   7.51
The velocity at fuel bed  =  .1795 m/s

The flame length of the fire with given parameters is   50.3 mm

Froude number at flame top =  1.386
The velocity at flame top  =  1.237 m/s
The width at flame top     =   .927  cm
```

table 8.2.5
Flame lengths for alcohol

power output (W)	measured flame length (mm)	theor. calc. flame length e.a.f.=1 (mm)	e.a.f.=1.5 (mm)
38	11.9	33.6	44.5
59	21.0	40.1	53.1
71	23.8	43.0	56.9
80	28.0	45.0	59.6
90	33.6	47.1	62.4
106	38.6	50.1	66.4
98	35.7	48.6	64.4

table 8.2.5
Example of the parameters used for calculation of the kerosene flame length

```
The fuel is kerosene

 1 The combustion value of fuel is:      .4353E+08  J/kg
 2 The gravitational accel. is:         9.80        m/s^2
 3 The entrainment constant is:          .057       (-)
 4 The excess air factor is:            1.00        (-)
 5 The stoich. air to fuel ratio is:   15.20        (-)
 6 The ambient temperature is:        293.          K
 7 The temp. of the fuel bed is:      525.          K
 8 The ambient density of air is:       1.25        kg/m^3
 9 The spec. heat coeff. of air is:  1000.          K kg/J
10 The fuel bed area is:                 .283       cm^2
13 The power of the wick is:          265.53        W


No variable parameters


Froude number at fuel bed =  .6083
The combustion number   =   9.77
The velocity at fuel bed  =  .3090 m/s

The flame length of the fire with given parameters is   64.2 mm

Froude number at flame top =  1.527
The velocity at flame top  =  1.595 m/s
The width at flame top     =  1.270  cm
```

table 8.2.7
Flame lengths for kerosene

power output (W)	measured flame length (mm)	theor. calc. flame length	
		e.a.f.=1 (mm)	e.a.f.=2 (mm)
24	10	22.3	40.3
74	30	39.1	62.1
104	33	44.7	71.1
129	43	48.6	77.3
162	63	53.1	84.6
183	71	55.7	88.6
231	89	60.9	97.0
266	103	64.2	102.4

8.2.2 Glass chimney test results

In figures 8.2.5 and 8.2.6 the mass rate and the CO/CO_2 ratio is presented as a function of the glass chimney length for 4 different free wick lengths.

The mass rate and the CO/CO_2 ratio of the four wick lengths are similar in shape. The mass rate is increased when a small glass chimney is used. The increase in draft, due to the small chimney, increases the mass rate by approximately 10 % compared to the mass rate without glass chimney. When a large chimney is used, especially for kerosene, the mass rate decreases dramatically. The draft created by a large chinmey decreases the temperature of the wick in such a way that the evaporation of fuel at the wick also decreases. The mass rate of alcohol with large glass chimneys does not decrease as much as for kerosene, because the boiling point of alcohol is much lower than the boiling point of kerosene. The alcohol flame in a large chimney is very small compared to the alcohol flame without chimney.

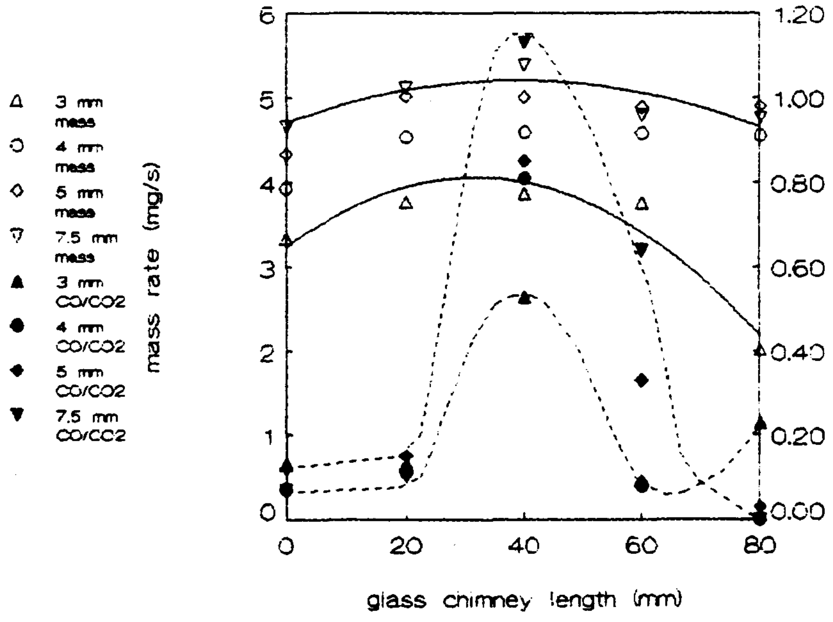


figure 8.2.5
Burning of alcohol in different glass chimneys at wicks with different lengths

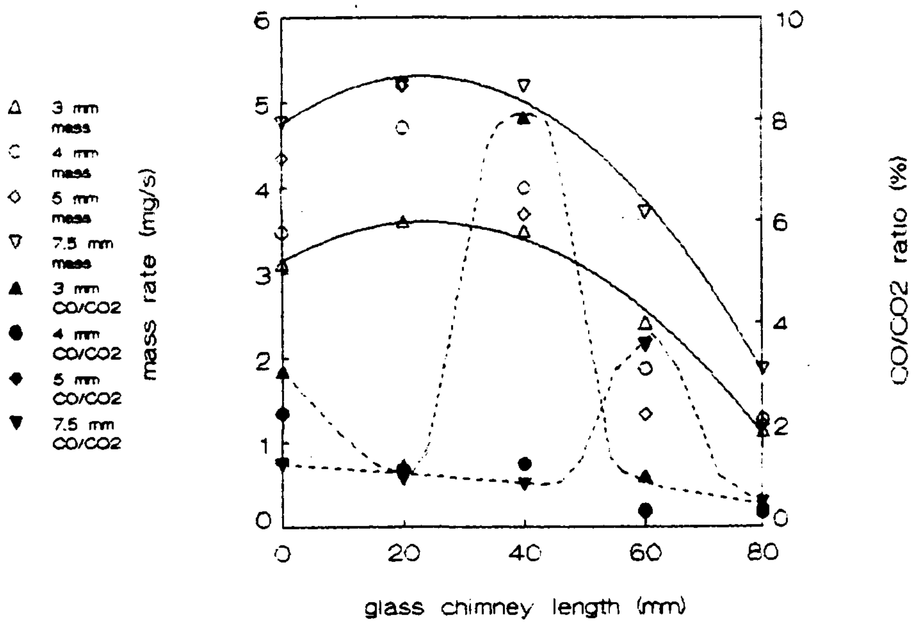


figure 8.2.6
Burning of kerosene in different glass chimneys at wicks with different lengths

The CO/CO$_2$ ratio of such flames is very low.

The CO/CO$_2$ ratio as a function of the glass chimney length has a similar form for both alcohol and kerosene. The CO/CO$_2$ curve stays more or less constant for small chimneys and is very low for large ones. When small chimneys are used most of the fuel is burned completely. The CO emission rises to very large values when the chimney length is increased more. The burning of fuel into carbon dioxide and water is a multi-step reaction which needs time. The velocity of the fuel vapour, due to the draft created by the chimney, is such that only part of the burning reaction takes place, which explains the large CO emission.

In figure 8.2.7 a more extensive survey of the mentioned phenomena is done on a 5 mm wick with kerosene as fuel. The CO/CO$_2$ curve and mass rate curve of this figure confirm what also has been presented in figures 8.2.5 and 8.2.6.

The mass rate increases with increasing chimney length and decreases when the chimney length is increased even more. The decrease of the mass rate takes place very suddenly; from 6 cm chimney to 8 cm chimney the mass rate decreases by approximately 70 %. For chimney lengths larger than 8 cm the mass rate remains more or less the same.

The CO/CO_2 ratio stays more or less constant with increasing chimney length, until the chimney length of 5 cm is reached. The CO/CO_2 ratio increases considerably with a chimney length of 5 cm. With a chimney of 6 cm the CO/CO_2 ratio is increased even more; the CO/CO_2 ratio is approximately 12 times as large as the ratio of a flame without a chimney. If the chimney length is now increased more, the CO/CO_2 ratio will decrease to a very low value and will stay more or less constant. In all three figures it can be seen that the largest CO/CO_2 ratio occurs with the chimney with lengths of 4, 5 and 6 cm.

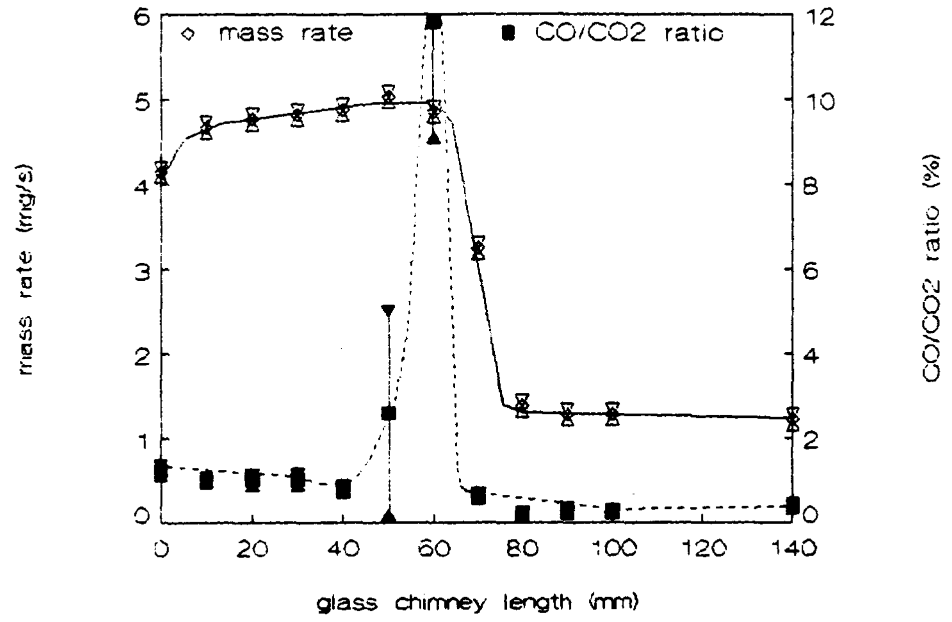


figure 8.2.7
Mass rate and CO/CO_2 ratio as a function
of glass chimney length while burning kerosene at wick
with a 5 mm free wick length

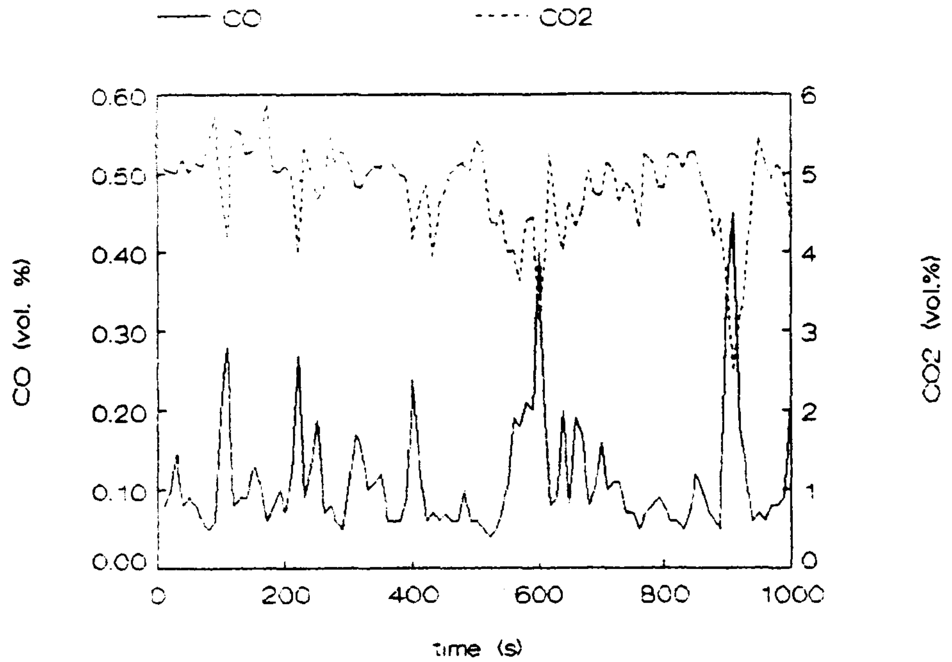
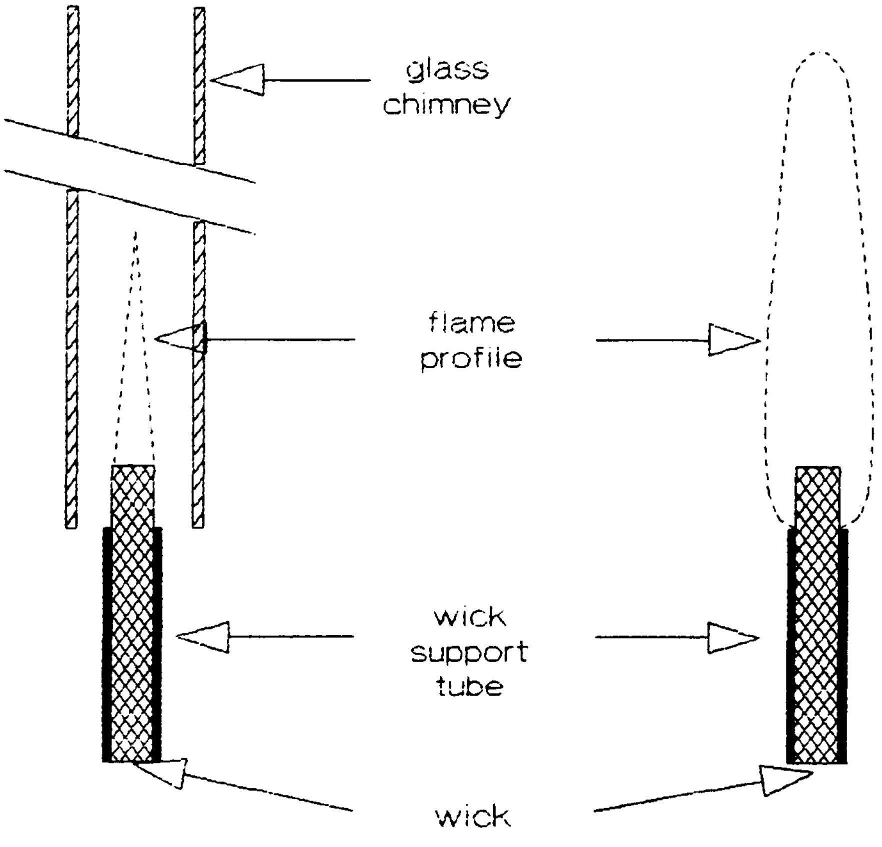


figure 8.2.8
Flue gas of the burning of kerosene in a 5 cm glass chimney at a wick with a free length of 5 mm

If one looks at the details of figure 8.2.7 one will see that the error bar of the CO/CO_2 ratio at 5 cm glass chimney is quite large. The CO/CO_2 ratio is the average value of all the CO/CO_2 ratios calculated by means of the measured CO and CO_2 concentration as a function of time. The standard deviation of all the CO/CO_2 ratios is the error of the average CO/CO_2 ratio. Thus the error bar at 5 cm wick length indicates a large variance in the CO/CO_2 ratios. In figure 8.2.8 the measured CO and CO_2 concentration is presented as a function of the measuring time. From this figure the quality of the combustion can be found; a large CO_2 concentration and a small CO concentration indicate a good combustion and the other way around a bad combustion. It is clear in this case that the combustion is not always good. The draft is not yet strong enough to blow the partly burned flue gases continuously out of the combustion zone, as is the case with the 6 cm chimney.

All the remarks regarding the decrease of the mass rate with increasing chimney length, do not explain why the mass rate drops so suddenly. It can be stated that the draft is a function of the chimney length; the draft increases when the chimney length increases. The chimney length increase is gradual and thus is the increase of draft.

The kerosene flame at large chimney lengths is a small non-sooting yellow flame, which is concentrated at the top of the free wick. In figure 8.2.9 a small sketch of this flame is drawn. From the sketch it can be seen that there is no flame at the edges of the free wick; this is in contrast with the kerosene flame photo of figure 7.3.



a.

figure 8.2.9
Kerosene flame sketch

b.

flame inside
large glass chimney

free flame

The decrease of the mass rate can be explained by the difference between the two flames. In case of the free burning, figure 7.3 and figure 8.2.9.b, the flow is not strong enough to blow away the flame at the edges of the wick. In case of the large glass chimney the flow is larger than the flame velocity, and so it blows away the flame at the edges of the wick. The air flow which blows aside the wick has the ambient temperature, which is far below the boiling temperature of kerosene, and thus reduces the evaporation of kerosene at the wick. The boiling temperature of alcohol is smaller than of kerosene; this explains why the decrease of mass rate is more evident with kerosene than with alcohol.

It is clear that the mass rate decreases when the draft becomes above a certain value, but all the remarks made above do not explain why this decrease takes place so suddenly. Although it can be seen from figures 8.2.5 and 8.2.6 that the decrease also takes place at different wick lengths, it is not sure that it will occur at the same chimney length.

The phenomenon of fuel evaporation at a wick is not as straightforward as it seems to be and clearly needs further investigation.

8.2.3 The Holder Effect

In figure 8.2.10 the mass rate and the flue gas quality are presented as a function of the free wick length. The result with and without a massive holder can be compared in this figure. For all free wick lengths the mass rate with holder is approximately 10 % larger than without holder. The higher temperature near the wick due to the holder has a positive effect on the mass rate.

The influence of a holder on the flue gas quality is substantial. The air flow to the combustion zone is obstructed by the holder and the quality of the combustion gets worse.

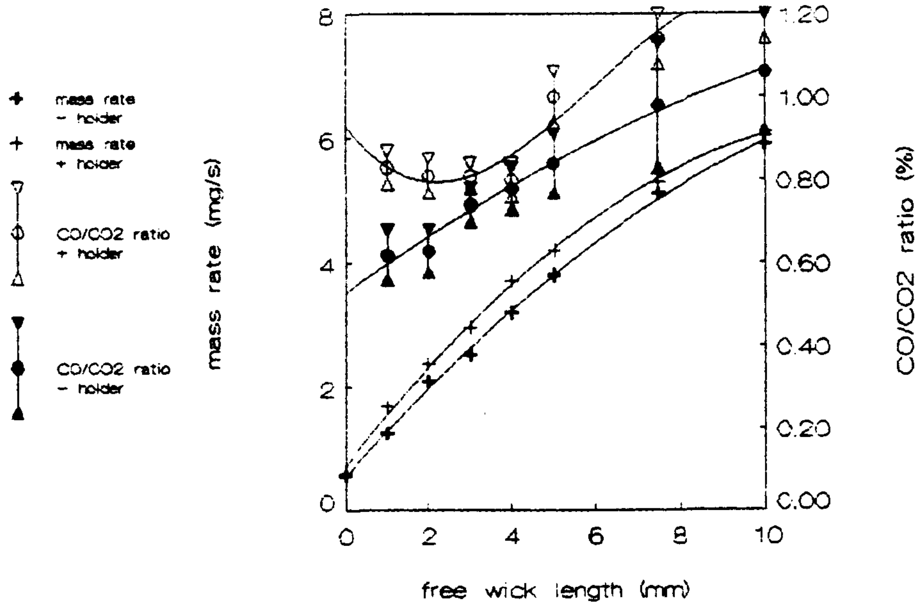


figure 8.2.10
Mass rate and flue gas quality as a function of wick length with and without holder

8.2.4 Holder No. 1 and Pet Stove Chimney

The results of the combination Pet Stove Chimney and Holder No.1 are already presented in table 8.2.3. They clearly show the influence of the existence or non-existence of the top flame on the combustion quality. The large values of the CO/CO_2 ratio clearly indicate the incompleteness of the combustion. At some of the air holes in the chimney the fuel vapour and oxygen have reacted only partially. At a number of air holes no small flames were observed. The top flame, when appearing, burns the partly reacted flue gas and the oxygen - fuel vapour mixture completely. In figure 8.2.11 the CO, CO_2 and O_2 concentrations, regarding the experiment with the 15 mm free wick length, are presented as a function of time. At t = 1340 the top flame was extinguished to determine the consequences of its disappearing. The increase of the O_2 concentration and decrease of the CO_2 concentration show that a large part of the fuel vapour is not burned at all and the increase of CO shows that the part that is burned has not reacted completely.

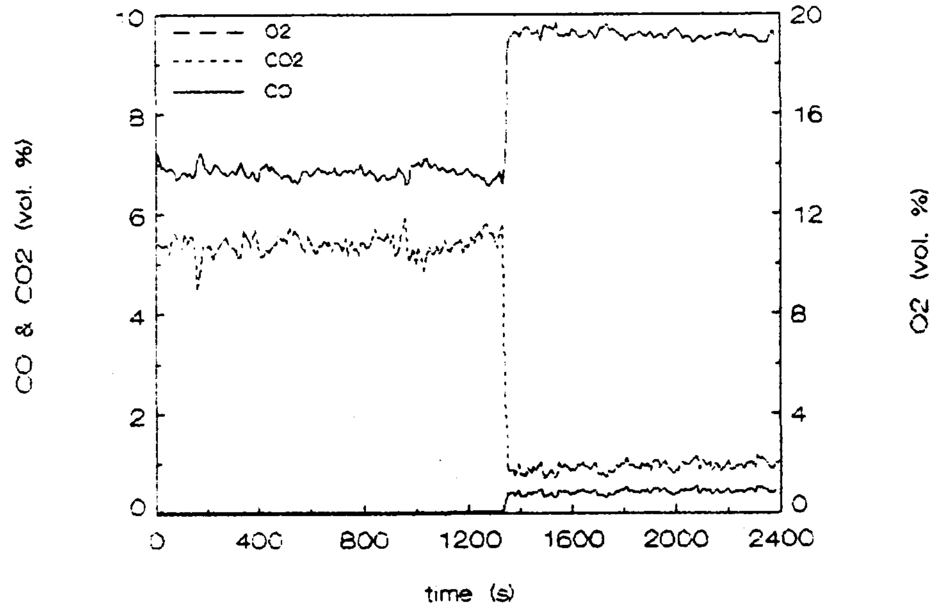


figure 8.2.11
Contents of flue gas of the combination
holder no.1 - Pet Stove chimney at 15 mm free wick length

8.2.5 A Survey of Different Holder-Chimney Configurations

The results of the survey analysis of different chimney - holder configurations are presented in table 8.2.8. The flue gas quality for the combination Taiwan Stove chimney - holder no. 2 is the best of all the tested combinations. Nearly all the combinations with holder no. 2 show a better flue gas quality than the combination with other holders. The large air flow through the holes in holder no. 2 clearly makes the combustion of better quality. The flue gas quality of the combinations with the Taiwan Small Stove chimney is also very low, but these flames soot. The chimney is obviously too small to burn the fuel premixed with the air. The flames of these chimneys are nearly similar to the free wick flames of section 8.2.1. The results clearly show that an ideal chimney should not be too large, like the Pet Stove chimney, nor too small, like the Taiwan Small chimney. The ideal chimney should have a concentration of air holes near the wick, like the situation with holder no. 2.

table 8.2.8
Survey results of the fuel burning at a
10 mm wick with different holder - chimney combinations

chimney	holder	top flame	soot	CO/CO_2 ratio
Pet Stove	No.1	blown away	no	> 5 %
Pet Stove	No.2	unstable	no	~ 5 %
Pet Stove	No.3	blown away	no	> 5 %
Pet Stove	No.4	blown away	no	> 5 %
Pet Stove	No.5	blown away	no	> 5 %
Taiwan	No.1	unstable	no	~ 1 %
Taiwan	No.2	large, blue	no	< 1 %
Taiwan	No.3	unstable	no	~ 1 %
Taiwan	No.4	tiny, blue	no	~ 5 %
Taiwan	No.5	tiny, blue	no	~ 5 %
Taiwan Small	No.1	large, unstable	yes	< 1 %
Taiwan Small	No.2	large, unstable	yes	< 1 %
Taiwan Small	No.3	large, unstable	yes	< 1 %
Taiwan Small	No.4	large, unstable	yes	< 1 %
Taiwan Small	No.5	large, unstable	yes	< 1 %

8.2.6 Taiwan Chimney with and without Burrs

In figure 8.2.12 the mass rate and CO/CO_2 ratio of the combination Taiwan chimney - holder no.2, with and without burrs, are presented as a function of the free wick length. Only for 0 mm free wick length the CO/CO_2 ratios of both differ from each other. The mass rate of the experiment with burrs at 0 mm free wick length is low enough to allow the air - fuel vapour mixture to be burned nearly completely inside the chimney, whereas the mass rate of the experiment without burrs is too large. The mass rate of the experiment without burrs is larger than that with burrs. The difference in percentage of the mass rate for small free wick lengths is approximately 10 %, while for large free wick lengths it is decreased to approximately 5 %.

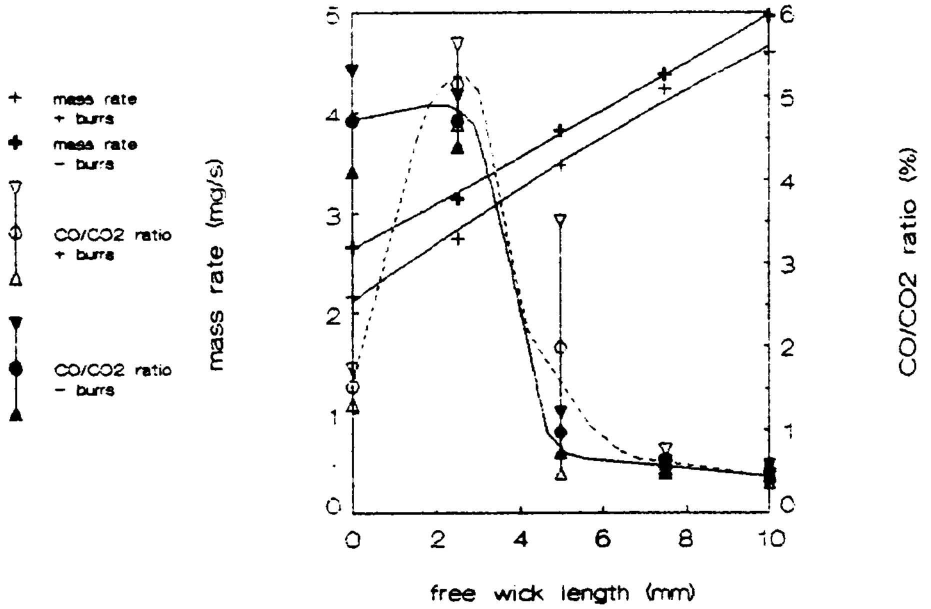


figure 8.2.12
Mass rate and CO/CO_2 ratio
as a function of the free wick length
for the Taiwan Stove chimney - holder no.2 combination

8.2.7 The Experimental Chimney - Holder No.1 Combination

The Experimental chimney - holder no.1 combination proved to be a very good combination for free wick lengths larger than 2 mm and smaller than 7.5 mm. The mass rate for these wick lengths is large, and the quality of the combustion, except for small wick lengths, is good. In figure 8.2.13 the mass rate and the CO/CO_2 ratio are presented as a function of the free wick length. The quality of the combustion for free wick lengths smaller than 2.5 mm is very bad; the CO/CO_2 ratio for 0 mm free wick length is 20 %. The flames at the free wick lengths larger than 7 mm produce soot and are therefore of lesser quality. Remarkable for this combination is that the mass rate, and under clean combustion conditions the power output, is very large regarding the small free wick lengths.

The burrs inside the chimney are also removed.

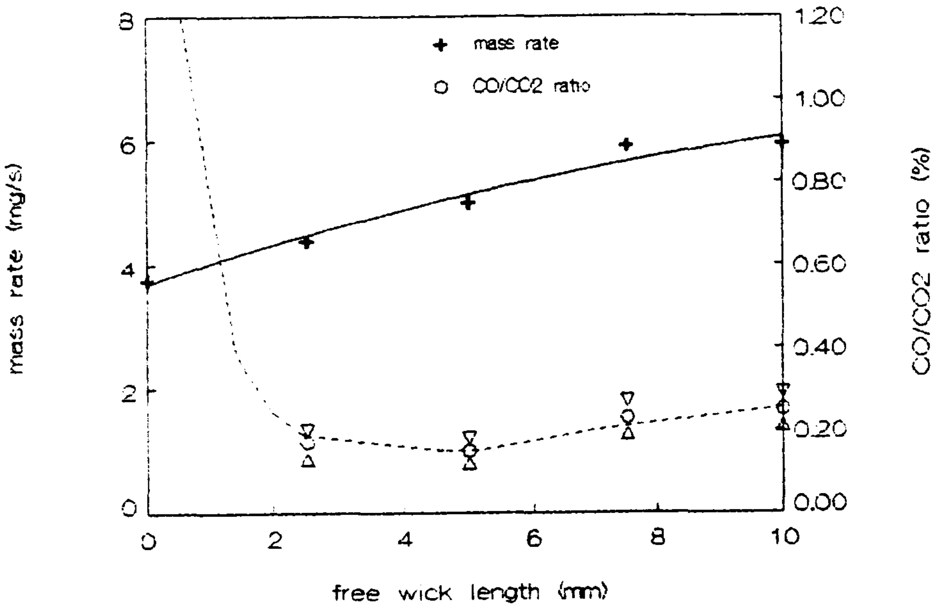


figure 8.2.13
Mass rate and CO/CO_2 ratio as
a function of the free wick length
for the Experimental chimney - holder No.1 combination

8.2.8 Minimum Mass Rate Experiment Results

Until now all the results show a disappointing flue gas quality for the small free wick lengths. In figure 8.2.14 the mass rate and CO/CO_2 ratio of the Taiwan Chimney, without burrs and with different holders, are presented in a bar chart. It can be seen from this figure that the combination with holder no. 2 has the largest CO/CO_2 ratio and thus the poorest flue gas quality. In contrast with this result it is this combination which has the best flue gas quality for large wick lengths. The mass rate of this combination is also the largest.

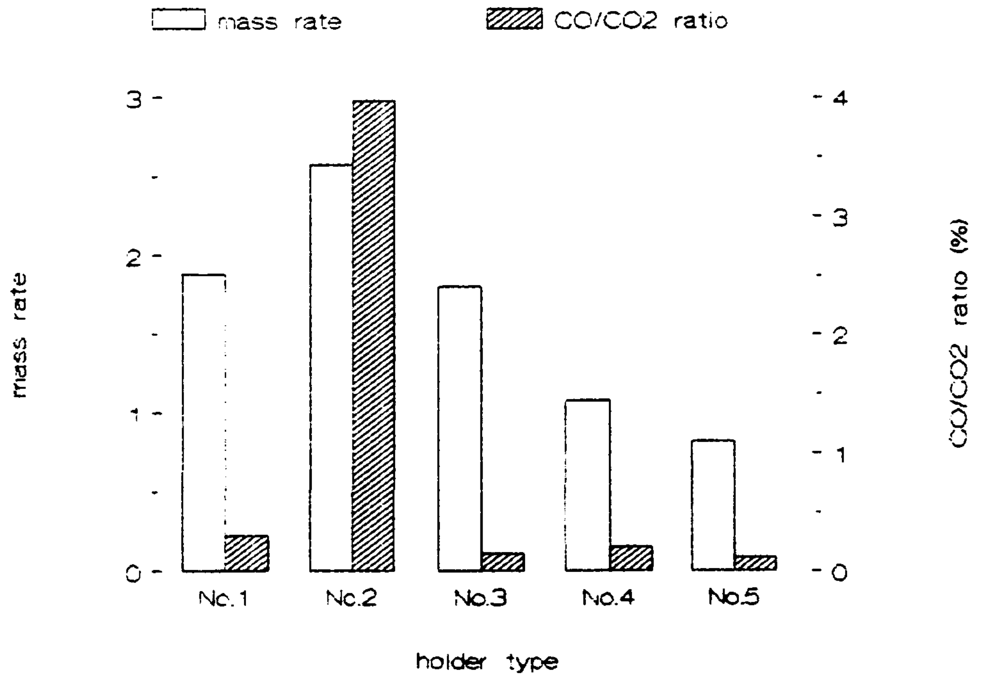


figure 8.2.14
Mass rate and CO/CO_2 ratio of
different holder - Taiwan stove chimney combinations

9 Conclusion and Recommendations

9.1 Kerosene Burners

Six burners were tested during this study:

(1) the Thomas Cup 24, a stove with 24 wicks;
(2) the Pet Stove, a stove with 21 wicks;
(3) the Thomas Cup 36, a stove with two independently operated sets of wicks, one of 12 wicks and the other of 24 wicks;
(4) the Elegance K786, an annular ring wick room heater;
(5) the Zibro Kamin, an annular ring wick room heater;
(6) the Aladin Lamp, an annular ring wick lamp.

Only four of the six burners can be compared with each other. They are the Thomas Cups, the Pet Stove and the Elegance K786. The Zibro Kamin is designed to function as a room heater. This is not only evident from the general appearance of the design, but also from the design of the burner head. The Aladin Lamp is even more different from the rest. This burner uses a tall chimney, to create the draft which draws air into the combustion zone.

Remarkable is that the mass rate of kerosene per unit of wick area, defined as the wick efficiency, is nearly identical for the Aladin Lamp, Zibro Kamin, Pet Stove and Thomas Cup 24: approximately 60 W cm^{-2}. Both the Thomas Cup 36 and the Elegance K786 have a low wick efficiency, because in these stoves the cooling air flow near the wicks is probably quite large. The flow resistence of this air flow is small because of the large air holes in the top of the burners.

The blue flame maximum power output of the burners is the maximum power output, without producing soot and with only a blue flame. This power output has its function for the actual cooking task.

Testing this output was also possible with the Aladin Lamp and the Zibro Kamin. For all the burners the blue flame maximum power output burning is very stable in time.

The minimum power output of a stove is the lowest power at which a stove still burns stable and is used during the simmering phase of cooking. The minimum power output of the four stoves - both Thomas Cups, Pet Stove and Elegance K786 - was measured. In all cases, except for the Thomas Cup 36, the minimum power output is quite large compared to the blue flame maximum; it is only a factor 2 smaller. This factor is called the turn down ratio. The test with the Thomas Cup 36 - all 36 wicks were used - failed, because there was no stable minimum power. A turn down ratio of 5 with this stove is possible when one only uses the inner 12 wicks (Sulilatu, 1988).

If one divides the minimum power by the number of wicks, in case of the multi single wick stove, one will get a nearly identical minimum power output per wick for each stove. This is demonstrated in table 9.1.

table 9.1
Minimum power output per wick

brand	no. of wicks used	minimum power (kW)	minimum power per wick (W)
Thomas Cup 36	12	0.9	75
Thomas Cup 24	24	2.0	83
Pet Stove	21	1.6	76

It is as if there is a lowest minimum power per wick; this leads to the assumption: to get a very low minimum power one better reduce the number of wicks used.

The heat transfer efficiency tests were carried out with the water boiling method. From these tests two heat transfer efficiencies can be obtained: the efficiency with water evaporation and the efficiency without water evaporation.

E. Sangen (1988) presented a graph where he plotted the heat transfer efficiency as a function of the pan diameter - wick pitch ratio; a similar graph is given in figure 9.1. The results of E. Sangen's work are also presented in this graph. From this it is clearly seen that a more compact stove has a larger heat transfer efficiency than a stove with a large wick pitch. The disadvantage of the work of E. Sangen is that, in his efficiency measurements, he did not keep the pan bottom - burner head distance constant, which resulted in a larger variance in the results of this work. The results of the efficiencies without water evaporation are presented in figure 9.1.

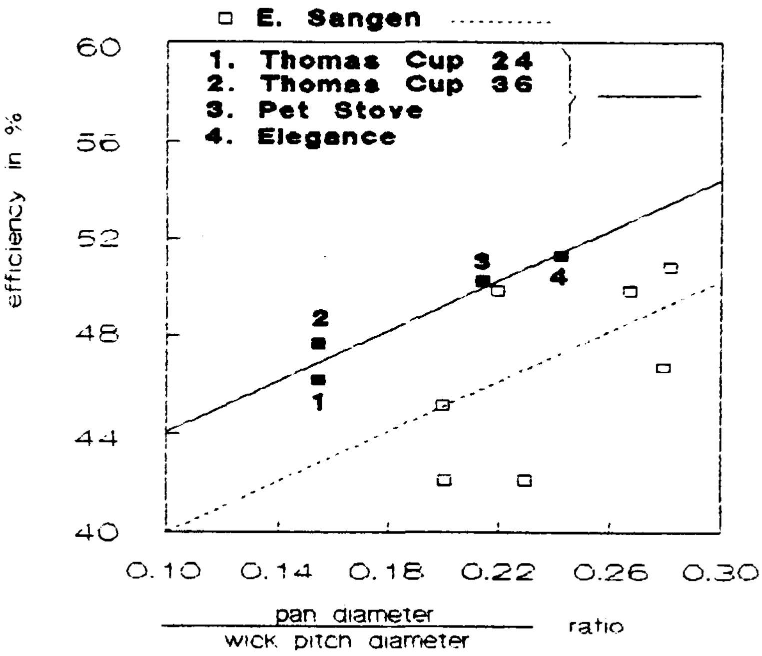


figure 9.1
Heat transfer efficiency as a function of pan diameter - wick pitch diameter

The flue gas of the Pet Stove has more CO in the preheating phase and the extinguishing phase than allowed by standard. The lowering of the power will increase the CO emission, although this emission is still below the standard. Except for the already mentioned preheating and extinguishing phase, the stove does not emit harmful quantities of CO.

9.2 Single Wicks

A number of experiments was carried out on different single wick configurations, in order to see the influence of temperature and draft on the mass rate and combustion quality. The theoretically calculated flame length of Bussmann et. al. is compared with the measured results.

The mass rate through a wick is a function of the free wick length. The mass rate increases with increasing free wick length, until the free wick length is so large that it is burned away partly; the mass rate will then decrease. The emission of CO follows an identical curve as the mass rate as a function of the free wick length. The flames at a free single wick are all laminar diffusion flames. The flame length is a function of the mass rate: the larger the mass rate, the larger the flame length. A large flame length means that a large part of the fuel is exposed to high temperatures. At high temperatures fuel without oxygen shows a tendency to crack and soot. The soot only reacts partially with oxygen, which accounts for the larger CO emission.

For power outputs below 140 W the flame length theory gives too large values, even if an excess air factor of 1 is chosen. Above 140 W the measured flame length values are between the theoretical curve with excess air factor 1 and the curve with excess air factor 2. The flame length theory assumes a fully turbulent flow, while all the flame length photos clearly show stable laminar flames; so the theory is not applicable for very small laminar fires.

An open glass chimney to create draft alongside a wick, has a large influence on the mass rate and the combustion quality. A very small glass chimney increases the mass rate with approximately 10 % and influences the combustion quality very much. A very tall open glass chimney reduces the mass rate with 70 % compared to the free wick burning, and the combustion quality is very good. This mass rate drop happens very suddenly. The reason why this happens needs further investigation. Before this phenomenon occurs, part of the flame is already blown away by the large draft in such a way that the combustion reaction has taken place only partly, which accounts for the large CO emission in this phase.

The relation between the mass rate and the power output is no longer valid when the combustion reaction only has taken place partly. A large draft in kerosene wick stoves is dangerous, because it can blow away partially reacted fuel gas, containing poisonous CO.

A large massive object, attached to the place where the wick enters the free air, increases the mass rate and influences the combustion quality compared to a wick without such an object. The large massive object is heated by the flame and gives this heat back to the wick. From a warm wick more fuel can be evaporated, thus increasing the mass rate. The object near the wick blocks part of the air flow, so the fuel vapour and the air are not mixed as is the case without the object; this influence works negatively on the combustion quality.

The mass rate through a wick with a very small free wick length can be increased substantially, by combining the massive holder with a chimney which creates a draft that transports the fuel vapour. The mass rate in such a combination at a 5 mm wick equals the mass rate at a 20 mm wick of a kerosene wick stove.

The wick efficiencies of single wicks vary from 25 to 420 W cm^{-2}, while those of the tested kerosene range burners vary from 45 to 60 W cm^{-2}. It seems that the wick efficiency in a stove has an upper limit far below that of the single wicks. A stove can be built more compact if larger wick efficiencies in a stove can be obtained.

Several chimney - holder combinations were constructed and tested. The combination with a large number of air holes near the wick, in the lower part of the chimney and at the end of the chimney, has the largest mass rate. The air holes in the bottom are the holes by which the air enters the chimney. The entrainment at the top through the air holes reduces the flow velocity and stabilizes the flame on top of the chimney. In the case of the chimney holder combination a flame on top of the chimney is essential for the completeness of the combustion. The combustion is complete when the top flame appears and is highly incomplete when it does not; the flue gas will then contain an enormous amount of CO.

The holder-chimney combinations show three types of combustion:

(1) the mass rate is low and the combustion is complete and takes place entirely inside the chimney;

(2) the mass rate is medium and the combustion reaction is partial and takes place inside the chimney;

(3) the mass rate is large and the combustion is complete and takes place partially inside the chimney and partially at the top of the chimney by the top flame.

Combustion type no.2 should always be avoided, because of its harmful CO emission.

9.3 Recommendations

It is clear from the heat transfer efficiency measurements that a compact stove has an effective heat transfer. Also, it is obvious from the maximum power output tests that a burner with many wicks has the largest maximum power. These burners can not be built compactly, because each wick needs a minimum area. A way of solving this problem is increase the mass rate through the wicks. At this moment no final conclusions regarding the designing and improving of stoves can be drawn. The single wick experiments prove that it is possible to increase the mass rate through a wick substantially, without influencing the flue gas quality negatively. There is still a large number of obscurities concerning the single wick fuel burning which needs further research.

As a final remark it should be stated that this work is not complete in itself, but only the start of more practical and theoretical work on kerosene stoves.

10. References

Bussmann, P., and Krishna Prasad, K. (1982).
Model Prediction of Temperature and Velocity Profiles in
Turbulent Diffusion Buoyant Flames, in
Proc. 8th IHTC, Hemisphere, Washington.

Bussmann, P., and Visser, P. (1986).
Stoves for the UNSO/NER/85/X02 Project,
Ministere des Mines et de l' Energie, Niamey.

Bussmann, P., Visser, P., and Sangen, E. (1987).
On the Designing of High Power Kerosene Stoves,
WSG, Eindhoven University of Technology, Eindhoven.

Bussmann, P., and Stiles, H. (1988).
Stoves for Cape Verde.
Biomass Technology Group, University of Twente, Enschede,
The Netherlands.

Bussmann, P. (1988).
Woodstoves, Theory and Applications in Developing Countries.
Dissertation, Eindhoven University of Technology, Eindhoven.

Collocott, T., and Dobson, A. (1983).
Dictionary of Science and Technology, Revised Edition.
W & R Chambers, Edinburgh, Scotland.

De Lepeleire, G., Krishna Prasad, K., Verhaart, P., and Visser, P. (1982).
A Woodstove Compendium,
WSG, Eindhoven University of Technology, Eindhoven.

Fristrom, R.M., and Westenberg, A.A. (1965)
Flame Structure.
McGraw-Hill Book Company, United States of America.

Glassmann, I.(1977)
Combustion.
Academic Press, New York

Kriesels, P. (1988)
Metingen aan een Laminaire Petroleum Vlam (in dutch).
Trainee report, Eindhoven University of Technology, Eindhoven.

Lamers, A. (1985)
Fysische modellen en numerieke methoden bij
stromingsproblemen (in dutch).
Lecture notes, Eindhoven University of Technology, Eindhoven.

Madon, G., and Matly, M. (1986).
Project UNSO/NER/85/XO2: Conversation et Substitution de l' Energie a l' Usage domestique.
Ministere des Mines et de l' Energie, Niamey.

Krishna Prasad, K., Sangen, E., Sielken, M., and Visser, P. (1983).
Test Results on Kerosene and Other Stoves.
WSG, Eindhoven University of Technolgy, Eindhoven.

Romp, H. (1937).
Oil Burning
Martinus Nijhoff, The Hague, The Netherlands.

Sangen, E.,and Krishna Prasad, K. (1983).
Technical Aspects of Woodburning Stoves.
WSG, Eindhoven University of Technology, Eindhoven.

Sangen, E. (1988).
Kerosene and LPG Stoves in Indonesia
Report of a consultant mission for the Industy and Energy Department of the World Bank, Jakarta, July 1988, Indonesia.

Spalding, D. (1955).
Some Fundamentals of Combustion.
Gas Turbine Series Volume 2
Butterworths Scientific Publications, London.

Steward, F. R., (1970)
Prediction of the Height of Turbulent Diffusion Flames.
Combustion Science and Technology, Volume 2.

Sulilatu, W. F. (1984).
Danger Signals to Human Health.
TNO, Apeldoorn, The Netherlands.

Sulilatu, W. F. (1988)
Evaluation of Wood Stoves, Gas and Kerosene Stoves in Burkina Faso.
TNO report, Apeldoorn, The Netherlands.

Stepanoff, A. J. (1896)
Grundlagen der Lampentheorie.
German translation of the original Russian work
Verlag von Ferdinand Enke, Stuttgart, (1906), Germany.

World Bank Energy Department.(1985)
Test Results on Kerosene and Other Stoves for Developing Countries.
Energy Department Paper No. 27, Washington D. C.

Appendix Requirements for Kerosene Stoves for the Sahel

In the Sahel, sustituting LPG or Kerosene for fuelwood and charcoal is an important way of reducing deforestation due to fuelwood consumption. However, no really practical stoves for kerosene are yet available. This note lists preferred requirements for such kerosene stoves; completeness was attempted but certainly not attained. The list sets high demands; it will certainly prove impossible to satisfy all conditions simultaneously. Designers could aim for the closest approach feasible, using the list as a 'check-list' of aspects to be included in the evaluation of the competing designs.

The requirements are formulated as if for one stove. It may be necessary to specify a set of several stoves of increasing sizes, but this can mean that some households would have to buy two stoves instead of one, thus increasing the effective price.

Usage and performance

- may be either a wick or a pressure-burner stove (each has its advantages and disadvantages)
- suitable for Sahelian round-bottomed pots of sizes 1 to 6. No accurate fitting of the stove to pot needed; in some areas flat-bottom pots are also used and should fit
- an advantage if also suitable for frying (flat or bowl-shaped pan)
- easy lighting, also in a wind: preferably no separate lighting fuel (such as petrol or spirits)
- maximum power sufficient for cooking meals in the largest pots
- low specific energy consumption at high power even in medium wind
- low fuel consumption when simmering (maintaining boiling)
- easy power regulation: turn-down ratio of 4 or preferably more
- no unintended extinguishing of the flames at low power, even in wind
- no very hot outer parts (danger of burns; children!)
- pots and pans can be put on/taken off without getting burned
- good quality combustion; no CO, smoke or smells
- clear indication when fuel is low
- easy filling with fuel, even when hot
- should stand stable on sand or uneven soil
- the pot/pan should stand firmly in/on the stove, especially if the food requires vigorous stirring as for tö
- only simple instructions for use
- errors in handling should not lead to danger
- lifetime at least several years with daily use; materials used should not age

Maintenance and servicing

- simple maintenance and cleaning by housewife, even in the unfavourable conditions of Sahelian households
- should withstand boiling-over of food without damage or need for servicing
- mechanical moving parts must move easily, both when hot or cold, even if dirty or poorly oiled or maintained; should not get out of adjustment
- tolerant of sand and dust, both outside and in the fuel
- tolerant of mechanical mishandling (dents, breakage) or being left unused for a long time (dirt and rust)
- infrequent replacement of consumable parts (such as wicks), preferably by the owner; minimum maintenance
- no loose parts or items that can be lost
- simple spare parts that any local retailer can sell or fit
- spare parts to use materials or items currently available (e.g. pump, seals for motor vehicles; standard wicks)
- maintenance by a dealer should not require complicated tools or training, no accurate adjustment needed
- exchangeability of parts between different models and sizes; no possibility of confusion of parts looking somewhat alike
- no possibility for wrong assembly

Manufacture

- as far as possible local manufacturer in one or more Sahelian countries
- type of manufacturer to correspond to manufacturing techniques and accuracy required
- if possible manufactured by local artisans of the informal sector
- a price that is not more than three times that of a traditional metal stove ("foyer malgache")
- no difficult manufacturing "know-how" that requires extensive training or special equipment
- most materials to be locally available or already normally imported; use of local raw materials (like clay or recuperated metal) is an advantage
- any special parts (e.g. wicks, jets) may if necessary be imported
- support by a multinational may be an advantage, but monopolistic supply is too vulnerable; second sourcing required

I would be grateful for comments and suggested improvements to the list.

20 september 1988

dr. ir. Eric T. Ferguson
van Dormaalstraat 15,
5624 KH Eindhoven
The Netherlands
tel. +31 40 432878

Thomas Cup 36 blue flame power measurements. New wicks.
24/feb/1988 15:00 - 16:30

1-The first measurement was five minutes after the stove was lit.
2-The first three measurements are influenced by wick readjustment.

time (min)	temp. tank (°C)	fuel used (g)	power 5min. (kW)
0	23.4	0	
5	23.7	41	5.95
10	23.6	79	5.51
15	24.0	114	5.08
20	24.5	148	4.93
25	25.0	181	4.79
30	25.6	214	4.79
35	26.3	248	4.93
40	27.0	282	4.93
45	27.8	315	4.79
50	28.6	349	4.93
55	29.4	382	4.79
60	30.2	415	4.79
65	31.0	449	4.93

Thomas Cup 24 blue flame power measurements. New wicks.
24/feb/1988 11:00 - 12:15

1-The first measurement was five minutes after the stove was lit.
2-The first three measurements are influenced by wick readjustment.

time (min)	temp. tank (°C)	fuel used (g)	power 5min. (kW)
0	16.7	0	
5	16.8	18	2.61
10	23.6	79	5.51
15	24.0	114	5.08
20	24.5	148	4.93
25	25.0	181	4.79
30	25.6	214	4.79
35	26.3	248	4.93
40	27.0	282	4.93
45	27.8	315	4.79
50	28.6	349	4.93
55	29.4	382	4.79
60	30.2	415	4.79
65	31.0	449	4.93

Pet Stove blue flame power measurements.
24/feb/1988 10:30 - 12:00

1-The first measurement was five minutes after the stove was lit.
2-The first three measurements are influenced by wick readjustment.

time (min)	temp. tank (°C)	fuel used (g)	power 5min. (kW)
0	19.4	0	
5	22.3	20	2.93
10	24.9	40	2.86
15	27.3	60	2.95
20	29.3	80	2.95
25	31.2	100	2.95
30	32.9	121	2.96
35	34.5	142	2.95
40	35.9	162	2.95
45	37.3	182	2.93
50	38.7	202	2.95
55	40.0	223	2.93
60	41.4	243	2.92
65	42.8	263	2.95

Elegance blue flame power measurements.
29/feb/1988 10:30 - 12:00

1-The first measurement was five minutes after the stove was lit.
2-The first three measurements are influenced by wick readjustment.

time (min)	temp. tank (°C)	fuel used (g)	power 5min. (kW)
0	18.0	0	
5	19.2	18	2.63
10	19.8	36	2.55
15	20.6	53	2.54
20	21.4	70	2.55
25	22.3	88	2.54
30	23.1	106	2.55
35	23.8	124	2.55
40	24.5	141	2.55
45	25.3	159	2.55
50	25.9	176	2.57
55	26.5	194	2.54
60	27.0	212	2.57
65	27.5	229	2.55

Appendix Blue flame power measurement

Zibro Kamin blue flame power measurements.
29/feb/1988 13:00 - 15:00

1-The first measurement was five minutes after the stove was lit.
2-The first three measurements are influenced by wick readjustment

time (min)	temp. tank (^{0}C)	fuel used (g)	power 5min. (kW)
0		0.0	
5		10.3	1.49
10		20.8	1.52
15		31.9	1.61
20		42.8	1.58
25		54.1	1.64
30		65.5	1.65
35		76.7	1.63
40		87.7	1.60
45		98.8	1.61
50		109.9	1.61
55		121.1	1.63
60		132.2	1.61
65		143.3	1.61

Aladin Lamp blue flame power measurements.
29/feb/1988 13:30 - 15:00

1-The first measurement was five minutes after the stove was lit.
2-The first three measurements are influenced by wick readjustment.

time (min)	temp. tank (^{0}C)	fuel used (g)	power 5min. (kW)
0	20.5	0.0	
5	21.2	6.0	0.87
10	21.9	11.4	0.78
15	22.4	17.5	0.89
20	22.9	22.3	0.70
25	23.2	27.1	0.70
30	23.3	31.9	0.70
35	23.5	36.1	0.61
40	23.7	41.0	0.71
45	23.9	45.2	0.61
50	24.1	50.0	0.70
55	24.2	54.2	0.61
60	24.4	59.0	0.70
65	24.5	63.3	0.62

Appendix **Mimimum power measurement**

Thomas Cup 24 mimimum power. 16/mar/1988 13:15 - 14:45

1-The first twenty minutes the burner was put on maximum.

time (min.)	temp. tank (^{0}C)	fuel used (g)	power 5min. (kW)
0	19.7	0.0	
5	19.7	12.6	1.83
10	19.9	47.5	5.06
15	20.3	77.8	4.40
20	20.9	105.4	4.00
25	21.8	128.6	3.37
30	23.1	145.4	2.44
35	24.7	161.6	2.35
40	26.3	176.8	2.21
45	28.1	192.1	2.22
50	29.9	206.9	2.15
55	31.6	220.7	2.00
60	33.3	234.5	2.00
65	34.8	248.0	1.96
70	36.2	261.6	1.97
75	37.5	275.0	1.94

Thomas Cup 36 mimimum power. 16/mar/1988 13:15 - 14:45

1-The first twenty minutes the burner was put on maximum.

time (min.)	temp. tank (^{0}C)	fuel used (g)	power 5min. (kW)
0	19.8	0.0	
5	19.7	9.3	1.35
10	19.7	51.0	6.05
15	19.9	89.3	5.56
20	20.2	127.1	5.48
25	20.9	160.9	4.90
30	21.8	182.0	3.06
35	22.9	201.2	2.79
40	24.1	220.0	2.73
45	25.4	238.0	2.61
50	26.7	254.6	2.41
55	28.1	270.3	2.28
60	29.5	282.6	1.78
65	30.7	291.4	1.28
70	31.5	312.8	3.11
75	32.4	338.4	3.71

Mimimum power measurement

Elegance mimimum power. 16/mar/1988 15:15 - 16:45

1-The first twenty minutes the burner was put on maximum.

time (min.)	temp. tank (⁰C)	fuel used (g)	power 5min. (kW)
0	20.3	0.0	
5	20.3	6.0	0.87
10	20.5	23.0	2.47
15	21.1	40.7	2.57
20	22.0	58.7	2.61
25	23.1	72.8	2.05
30	24.5	85.5	1.84
35	25.7	96.9	1.65
40	26.9	107.8	1.58
45	28.0	119.0	1.63
50	29.2	130.3	1.64
55	30.3	141.7	1.65
60	31.1	152.4	1.55
65	32.1	162.9	1.52
70	33.0	173.7	1.57
75	33.8	184.2	1.52

Pet Stove mimimum power. 16/mar/1988 15:15 - 16:45

1-The first twenty minutes the burner was put on maximum.

time (min.)	temp. tank (⁰C)	fuel used (g)	power 5min. (kW)
0	21.4	0.0	
5	21.5	5.5	0.80
10	21.9	19.8	2.07
15	23.4	41.8	3.19
20	25.8	67.8	3.77
25	28.6	87.8	2.90
30	32.2	100.1	1.78
35	35.6	113.4	1.93
40	39.1	126.7	1.93
45	42.8	139.2	1.81
50	46.8	151.0	1.71
55	50.5	162.4	1.65
60	54.1	173.3	1.58
65	57.0	183.9	1.54
70	59.7	194.8	1.58
75	62.3	206.0	1.63

Thomas Cup 36 maximum power. 01/mar/1988 14:30 - 16:00

1-The first measurement was 5 min.after the stove was lit.

time (min.)	temp. tank (°C)	fuel used (g)	power 5min. (kW)
0	21.6	0.0	
5	21.6	48.0	6.96
10	21.7	100.1	7.56
15	21.9	152.2	7.56
20	22.5	203.9	7.50
25	23.1	255.5	7.49
30	23.9	307.0	7.47
35	24.6	358.2	7.43
40	25.3	409.0	7.37
45	26.0	459.6	7.34
50	26.7	510.0	7.31
55	27.4	560.1	7.27
60	28.2	609.8	7.21
65	28.9	659.2	7.17

Thomas Cup 24 maximum power. 01/mar/1988 14:30 - 16:00

1-The first measurement was 5 min.after the stove was lit.

time (min.)	temp. tank (°C)	fuel used (g)	power 5min. (kW)
0	21.8	0.0	
5	21.9	23.8	3.45
10	22.1	60.3	5.30
15	22.4	98.6	5.56
20	22.9	136.7	5.53
25	23.7	175.1	5.57
30	24.5	213.0	5.50
35	25.5	250.8	5.48
40	26.5	288.5	5.47
45	27.5	326.3	5.48
50	28.5	363.6	5.41
55	29.6	400.7	5.38
60	30.6	437.9	5.40
65	31.6	475.2	5.41

Elegance maximum power. 02/mar/1988 10:30 - 12:00

1-The first measurement was 5 min.after the stove was lit.

time (min.)	temp. tank (^0C)	fuel used (g)	power 5min. (kW)
0	22.2	0.0	
5	23.6	22.7	3.29
10	24.8	44.8	3.21
15	25.8	66.9	3.21
20	26.0	89.2	3.24
25	27.0	111.3	3.21
30	27.9	133.6	3.24
35	28.7	155.8	3.22
40	29.4	178.1	3.24
45	30.1	200.3	3.22
50	30.8	222.5	3.22
55	31.3	244.8	3.24
60	31.9	267.0	3.22
65	32.4	289.1	3.21

Pet Stove maximum power. 02/mar/1988 10:30 - 12:00

1-The first measurement was 5 min.after the stove was lit.

time (min.)	temp. tank (^0C)	fuel used (g)	power 5min. (kW)
0	21.8	0.0	
5	21.9	25.0	3.63
10	22.2	55.4	4.41
15	22.7	88.7	4.83
20	23.3	123.3	5.02
25	24.1	158.6	5.12
30	25.1	194.0	5.14
35	26.1	229.1	5.09
40	27.2	264.3	5.11
45	28.3	299.2	5.06
50	29.4	333.9	5.03
55	30.5	367.8	4.92
60	31.6	401.6	4.90
65	32.8	435.4	4.90

Appendix Yellow flame maximum power

Aladin Lamp maximum power. 02/mar/1988 10:30 - 12:00

1-The first measurement was 5 min.after the stove was lit.

time (min.)	temp. tank (^{0}C)	fuel used (g)	power 5min. (kW)
0	23.8	0.0	
5	24.0	7.8	1.13
10	24.2	16.3	1.23
15	24.4	24.1	1.13
20	24.7	31.9	1.13
25	25.0	39.8	1.15
30	25.3	48.2	1.22
35	25.6	55.4	1.04
40	25.8	63.3	1.15
45	26.1	71.1	1.13
50	26.3	78.3	1.04
55	26.5	86.1	1.13
60	26.7	93.4	1.06
65	26.9	100.6	1.04

Zibro Kamin maximum power 29/feb/1988 13:00 - 15:00

1-The first measurement was five minutes after the stove was lit.

time (min)	temp. tank (^{0}C)	fuel used (g)	power 5min. (kW)
0		0.0	
5		10.3	1.49
10		20.8	1.52
15		31.9	1.61
20		42.8	1.58
25		54.1	1.64
30		65.5	1.65
35		76.7	1.63
40		87.7	1.60
45		98.8	1.61
50		109.9	1.61
55		121.1	1.63
60		132.2	1.61
65		143.3	1.61

Appendix **Boiling measurements results**

Elegance efficiency test 10/mar/1988 14:15 - 16:45

time (min.)	temp. tank (°C)	temp. water (°C)	fuel used (g)	power 3min. (kW)
0	16.7	16.9	0.0	
3	16.8	17.4	0.3	0.07
6	16.8	32.1	10.8	2.54
9	16.9	16.0	22.6	2.85
12	17.1	29.3	34.0	2.76
15	17.2	41.9	45.2	2.71
18	17.5	53.9	55.9	2.59
21	17.8	65.7	66.6	2.59
24	18.1	76.9	77.2	2.56
27	18.4	86.9	87.8	2.56
30	18.8	95.3	98.4	2.56
33	19.3	17.8	108.9	2.54
36	19.6	30.6	119.3	2.52
39	20.1	42.2	129.8	2.54
42	20.5	54.4	140.1	2.49
45	20.9	67.0	150.5	2.52
48	21.2	77.1	160.8	2.49
51	21.6	87.3	171.2	2.52
54	22.0	97.8	181.6	2.52
57	22.3	24.5	191.8	2.47
60	22.7	36.4	201.9	2.44
63	23.0	48.0	212.0	2.44
66	23.3	59.5	222.1	2.44
69	23.6	70.4	232.2	2.44
72	23.9	80.7	242.3	2.44
75	24.2	91.0	252.2	2.39
78	24.5	98.8	262.5	2.49
81	24.8	26.0	272.6	2.44
84	25.0	37.0	282.7	2.44
87	25.3	48.4	292.8	2.44
90	25.5	59.8	302.5	2.35
93	25.7	70.0	312.8	2.49
96	25.9	80.6	322.8	2.42
99	26.1	90.0	332.8	2.42
102	26.4	98.9	342.8	2.42
105	26.5	22.3	352.9	2.44
108	26.7	34.1	363.3	2.52
111	26.9	45.8	373.6	2.49
114	27.1	57.6	384.0	2.52
117	27.3	68.6	394.3	2.49
120	27.4	79.1	404.5	2.47
123	27.6	88.9	414.8	2.49
126	27.8	98.3	425.1	2.49
129	27.9	100.1	435.4	2.49

Thomas Cup 36 efficiency test 09/mar/1988 10:30 - 12:15

time (min.)	temp. tank (°C)	temp. water (°C)	fuel used (g)	power 3min. (kW)
0	17.2	16.0	0.0	
3	17.2	16.4		
6	17.2	18.6	16.7	4.04
9	17.2	20.6	40.6	5.78
12	17.3	43.4	63.8	5.61
15	17.3	67.8	87.3	5.68
18	17.4	89.4	110.7	5.66
21	17.4	17.2	134.2	5.68
24	17.6	43.6	157.1	5.54
27	17.8	67.4	179.7	5.47
30	18.0	90.8	202.3	5.47
33	18.3	20.9	225.1	5.51
36	18.6	48.0	247.8	5.49
39	18.9	70.6	270.2	5.42
42	19.3	93.9	293.2	5.56
45	19.6	23.3	190.3	
48	20.0	47.8	337.8	
51	20.4	71.5	359.7	5.30
54	20.7	92.9	381.7	5.32
57	21.1	13.9	404.1	5.42
60	21.5	49.0	427.8	5.73
63	21.8	71.5	451.1	5.63
66	22.2	94.1	474.5	5.66
69	22.6	100.1	497.8	5.63
72	23.0	100.2	521.1	5.63
75	23.3	100.1	544.3	5.61
78	23.7	100.1	567.6	5.63
81	24.0	100.1	590.7	5.59
84	24.4	100.0	613.8	5.59
87	24.7	100.1	637.0	5.61

Pet Stove efficiency test 15/mar/1988 13:15 - 15:45

time (min.)	temp. tank (°C)	temp. water (°C)	fuel used (g)	power 3min. (kW)
0	16.4	16.3	0.0	
3	16.4	16.3	1.6	0.39
6	16.5	18.2	6.8	1.26
9	16.7	23.5	15.4	2.08
12	17.4	28.1	26.3	2.64
15	18.6	40.8	39.0	3.07
18	20.3	55.0	52.6	3.29
21	21.9	71.2	67.0	3.48
24	22.4	84.3	79.8	3.10
27	23.9	94.0	91.1	2.73
30	25.2	17.2	102.3	2.71
33	26.4	31.1	113.7	2.76
36	27.5	43.8	124.8	2.68
39	28.5	56.5	136.0	2.71
42	29.4	68.8	147.0	2.66
45	30.2	80.1	158.2	2.71
48	31.0	91.3	169.2	2.66
51	31.7	99.3	180.4	2.71
54	32.5	26.6	191.5	2.68
57	33.2	38.3	202.6	2.68
60	33.9	51.5	213.9	2.73
63	34.4	63.4	225.0	2.68
66	35.1	75.1	236.2	2.71
69	35.8	85.9	247.4	2.71
72	36.4	96.5	258.6	2.71
75	37.0	23.6	269.7	2.68
78	37.5	38.0	281.0	2.73
81	38.1	48.5	292.1	2.68
84	38.6	59.8	303.1	2.66
87	39.1	72.1	314.2	2.68
90	39.7	83.4	325.3	2.68
93	40.1	93.9	336.3	2.66
96	40.6	19.5	347.5	2.71
99	41.0	28.8	358.8	2.73
102	41.6	41.0	370.2	2.76
105	41.9	53.1	381.5	2.73
108	42.2	65.1	392.8	2.73
111	42.5	76.5	404.1	2.73
114	42.7	88.0	415.4	2.73
117	43.0	97.8	426.7	2.73
120	43.3	99.3	438.1	2.76
123	43.5	99.3	449.3	2.71
126	43.7	99.3	460.7	2.76

Appendix Boiling measurements results

Thomas Cup 24 efficiency test 02/mar/1988 10:30 - 12:00

time (min.)	temp. tank (^{0}C)	temp. water (^{0}C)	fuel used (g)	power 3min. (kW)
0	19.6	19.7	0.0	
3	19.6	20.1	1.4	0.34
6	19.7	24.4	21.5	4.86
9	19.7	24.2	41.3	4.79
12	19.8	34.4	59.9	4.50
15	19.9	54.4	79.8	4.81
18	20.0	73.8	99.3	4.72
21	20.2	91.8	119.0	4.76
24	20.5	15.3	135.8	4.06
27	20.9	40.2	157.2	5.18
30	21.4	59.0	174.8	4.26
33	21.8	76.6	192.6	4.30
36	22.5	91.9	210.5	4.33
39	22.8	30.8	228.4	4.33
42	23.4	34.2	246.6	4.40
45	24.0	53.5	264.9	4.43
48	24.6	72.6	283.5	4.50
51	25.1	89.5	301.0	4.23
54	25.7	16.2	318.6	4.26
57	26.3	34.1	336.1	4.23
60	26.9	53.5	354.3	4.40
63	27.4	71.9	371.7	4.21
66	28.0	88.1	389.2	4.23
69	28.5	29.0	407.0	4.30
72	29.1	36.9	425.2	4.40
75	29.6	55.4	443.2	4.35
78	30.1	73.4	460.9	4.28
81	30.6	90.2	478.7	4.30
84	31.1	100.0	496.4	4.28
87	31.5	100.0	514.3	4.33
90	32.0	100.0	531.7	4.21
93	32.5	100.0	549.1	4.21
96	32.9	100.0	566.5	4.21
99	33.3	100.0	583.6	4.14

Appendix Computer programme for the input of data for the calculation of flame heights.

```
C  FORTRAN77
C
C  This programme contains data for the flame height calculation
C  according to the method of Paul Bussmann et. al. 1982
C
      REAL X,XOUD,XVLAM,B,BOA(20),B2,F,FO,F2,V,M,MOUD,P,P2,U,UO,G
      REAL ALFA,LANDA,NU,NS,RO1,PGRA(20),RPR,SGR,QW,QC,QV,CP,U2
      REAL T,TO,TA,RO,RO2,ROO,ROA,RRO,RROO,RROA,RRO2,PGR1,BO,AREA
      REAL VLAMGRENS,ONDER,BOVEN,MU,PI,JJ,HLP1,HLP2,HLP3,HLP4
      REAL POW(99),RADI(99),VLBODEM,PITLA(20),BO2,PGR,PITL,FLUC(100)
      REAL AA1,BB2,CC2,DD2,EE2,FF2,BO1,VAL1(14),LOW,UPP,DESTEP
      INTEGER N,I,J,L,FIRST,I2,J2,YORN,NUM1,VAL2(14),LQWD,PORM
      INTEGER NUM2,LUSTEP,MSTEP,YORN1,YORN2
      EXTERNAL IMP,IMPJ,IMP2,IMP3
      CHARACTER ALIST(18),EXTEND(5),LIST(16),DISK(1)
      CHARACTER*14 ANAME
      CHARACTER*70 EERSTE
      CHARACTER*70 TWEEDE
      CHARACTER LIST1(70),LIST2(70)
      DATA EXTEND/'.','P','R','N',':'/
C
  911 DO 1 J2=1,24
  001 WRITE(*,'()')
      WRITE (*,53)
  053 FORMAT(1X,'Give the name of the disk on which you want the ',
     *'data'/' (A, B, or C)')
      READ (*,54) DISK
  054 FORMAT(1A)
  050 WRITE (*,10)
  010 FORMAT (1X,'Give only name of data file (maximum 8',1X,
     #'characters)'/,1X,'12345678')
      READ (*,20) LIST
  020 FORMAT (16A)
      DO 040 I=16,1,-1
      LAST=I
      IF (LIST(I).NE.' ') GOTO 030
  040 CONTINUE
      GOTO 50
  030 CONTINUE
      IF (LAST.GT.8) LAST=8
      DO 70 I=1,LAST
      FIRST=I
      IF (LIST(I).NE.' ') GOTO 60
  070 CONTINUE
  060 CONTINUE
      DO 080 I=1,4
```

```
      LAST = LAST+1
      LIST(LAST)=EXTEND(I)
 080  CONTINUE
      DO 090 I=1,LAST
      ALIST(I+2)=LIST(I)
 090  CONTINUE
      FIRST=FIRST+2
      ALIST(FIRST-1)=EXTEND(5)
      ALIST(FIRST-2)=DISK(1)
      FIRST=FIRST-2
      WRITE(ANAME,'(14A)')(ALIST(I),I=FIRST,LAST+2)
      WRITE (*,100)ANAME
 100  FORMAT(////,1X,'The data will be stored on: ',A14,////)
      OPEN (6,FILE='NUMBER',STATUS='NEW',FORM='FORMATTED')
      WRITE (6,313)ANAME
 313  FORMAT(A14)
C
      WRITE(*,987)
 987  FORMAT(1X,/,1X,'Which fuel do you use'/,
     *' Wood = 1  Liquid fuel = 0')
      READ(*,988) LQWD
 988  FORMAT(I1)
      PI = 4.*ATAN(1.)
      VAL1(1)=1.87E7
      VAL1(2)=10.
      VAL1(3)=0.08
      VAL1(4)=1.8
      VAL1(5)=5.1
      VAL1(6)=293.
      VAL1(7)=1100.
      VAL1(8)=1.25
      VAL1(9)=1.E3
      VAL1(10)=0.085*0.085*PI*10000
      VAL1(11)=3.3E7
      VAL1(12)=0.8
      VAL1(13)=1.
      VAL1(14)=6000.
C
 701  DO 091 J2=1,24
 091  WRITE(*,'()')
      WRITE (*,410) VAL1(1)
 410  FORMAT(1X,' 1 The combustion value of fuel is:',E15.4,'  J/kg')
      WRITE (*,420) VAL1(2)
 420  FORMAT(1X,' 2 The gravitational accel. is: ',F12.2,8X,'m/s^2')
      WRITE (*,430) VAL1(3)
 430  FORMAT(1X,' 3 The entrainment constant is:',F14.3,7X,'(-)')
      WRITE (*,440) VAL1(4)
 440  FORMAT(1X,' 4 The excess air factor is:',F16.2,8X,'(-)')
      WRITE (*,450) VAL1(5)
 450  FORMAT(1X,' 5 The stoich. air to fuel ratio is:',F8.2,8X,'(-)')
      WRITE (*,460) VAL1(6)
 460  FORMAT(1X,' 6 The ambient temperature is:',F12.0,10X,'K')
```

```
      WRITE (*,470) VAL1(7)
  470 FORMAT(1X,' 7 The temp. of the fuel bed is:',F10.0,10X,'K')
      WRITE (*,480) VAL1(8)
  480 FORMAT(1X,' 8 The ambient density of air is:',F11.2,8X,'kg/m^3')
      WRITE (*,490) VAL1(9)
  490 FORMAT(1X,' 9 The spec. heat coef. of air is:',F8.0,10X,'K kg/J')
      WRITE (*,492) VAL1(10)
  492 FORMAT(1X,'10 The fuel bed area is:          ',F8.3,7X,'cm^2')
      IF (LQWD.EQ.1) THEN
      WRITE (*,495) VAL1(11)
  495 FORMAT(1X,'11 The combustion value of charcoal:',E14.4,'  J/kg')
      WRITE (*,497) VAL1(12)
  497 FORMAT(1X,'12 The mass frac. of volatiles is:',F12.4,6X,'(-)')
      WRITE (*,498) VAL1(14)
  498 FORMAT(1X,'14 The power of the fire is:    ',F12.2,8X,'W')
      ELSE
      VAL1(12)=1.
      WRITE (*,491) VAL1(13)
  491 FORMAT(1X,'13 The mass rate of one wick is:  ',F12.4,6X,'mg/s')
      ENDIF
C
      WRITE (*,600)
  600 FORMAT(/,1X,'How many of these values you want to change?  (xx)')
      READ (*,601) NUM1
  601 FORMAT(I2)
      IF (NUM1.EQ.0) GOTO 700
      DO 610 I=1,NUM1
      WRITE (*,620) I
  620 FORMAT(/,1X,'Which ',I2,' th number you want to change?   (x)')
      READ (*,630) VAL2(I)
  630 FORMAT(I2)
  610 CONTINUE
      DO 640 I=1,NUM1
      IF (VAL2(I).EQ.1) THEN
      WRITE (*,410) VAL1(1)
      WRITE (*,649)
  649 FORMAT(1X,'Give the value you want it to be:   (x.xxxEyy)'/)
      READ (*,651) VAL1(1)
  651 FORMAT(E15.4)
      GOTO 640
      ENDIF
      IF (VAL2(I).EQ.2) THEN
      WRITE (*,420) VAL1(2)
      WRITE (*,650)
      READ (*,652) VAL1(2)
      GOTO 640
      ENDIF
      IF (VAL2(I).EQ.3) THEN
      WRITE (*,430) VAL1(3)
      WRITE (*,650)
      READ (*,652) VAL1(3)
      GOTO 640
```

```
      ENDIF
      IF (VAL2(I).EQ.4) THEN
      WRITE (*,440) VAL1(4)
      WRITE (*,650)
      READ (*,652) VAL1(4)
      GOTO 640
      ENDIF
      IF (VAL2(I).EQ.5) THEN
      WRITE (*,450) VAL1(5)
      WRITE (*,650)
      READ (*,652) VAL1(5)
      GOTO 640
      ENDIF
      IF (VAL2(I).EQ.6) THEN
      WRITE (*,460) VAL1(6)
      WRITE (*,650)
      READ (*,652) VAL1(6)
      GOTO 640
      ENDIF
      IF (VAL2(I).EQ.7) THEN
      WRITE (*,470) VAL1(7)
      WRITE (*,650)
      READ (*,652) VAL1(7)
      GOTO 640
      ENDIF
      IF (VAL2(I).EQ.8) THEN
      WRITE (*,480) VAL1(8)
      WRITE (*,650)
      READ (*,652) VAL1(8)
      GOTO 640
      ENDIF
      IF (VAL2(I).EQ.9) THEN
      WRITE (*,490) VAL1(9)
      WRITE (*,650)
      READ (*,652) VAL1(9)
      GOTO 640
      ENDIF
      IF (VAL2(I).EQ.10) THEN
      WRITE (*,492) VAL1(10)
      WRITE (*,650)
      READ (*,652) VAL1(10)
      GOTO 640
      ENDIF
      IF (VAL2(I).EQ.11) THEN
      WRITE (*,495) VAL1(11)
      WRITE (*,749)
  749 FORMAT(1X,'Give the value you want it to be:   (x.xxxEyy)'/)
      READ (*,751) VAL1(11)
  751 FORMAT(E15.4)
      GOTO 640
      ENDIF
      IF (VAL2(I).EQ.12) THEN
```

```
    WRITE (*,497) VAL1(11)
    WRITE (*,650)
    READ (*,652) VAL1(11)
    GOTO 640
    ENDIF
    IF (VAL2(I).EQ.13) THEN
    WRITE (*,491) VAL1(13)
    WRITE (*,650)
    READ (*,652) VAL1(13)
    GOTO 640
    ENDIF
    IF (VAL2(I).EQ.14) THEN
    WRITE (*,498) VAL1(14)
    WRITE (*,650)
    READ (*,652) VAL1(14)
    GOTO 640
    ENDIF
650 FORMAT(1X,'Give the value you want it to be:   (xxxx.yyyyy)')
652 FORMAT(F16.8)
640 CONTINUE
    GOTO 701
    LUSTEP=1
700 WRITE (*,611)
611 FORMAT(/,1X,'Which value do you want to let fluctuate (xx)',/,
   *' If you give 0 there will be no fluctuation!',/,' Remark: ',
   *' the power or mass rate can be varied randomly')
    READ (*,612) NUM2
612 FORMAT(I2)
    IF (NUM2.EQ.0) GOTO 811
704 IF (NUM2.EQ.1.OR.NUM2.EQ.11)THEN
    WRITE (*,812)
812 FORMAT(/,1X,'Give lower boundary, upper boundary and number',
   *' of steps.'/'  (x.xxxEyy,a.aaaEbb,cc)')
    READ (*,813) LOW,UPP,LUSTEP
813 FORMAT(2E15.4,I2)
    ELSE
    WRITE (*,814)
814 FORMAT(/,1X,'Give lower boundary, upper boundary and number',
   *1X,'of steps.'/'  (xxx.xxx,aaa.aaa,cc)')
    READ (*,843) LOW,UPP,LUSTEP
843 FORMAT(2F15.6,I2)
    ENDIF
    WRITE(*,761)
761 FORMAT(1X,'Is this correct?  Yes = 1  or  No = 0')
    READ(*,702) YORN
702 FORMAT(I2)
    IF (YORN.EQ.0) GOTO 704
    DESTEP=(UPP-LOW)/(LUSTEP-1)
    IF (NUM2.EQ.13.OR.NUM2.EQ.14)THEN
    MSTEP=1
    GOTO 851
    ENDIF
```

```
811 WRITE(*,847)
847 FORMAT(1X,'Do you want random power(wood) or mass rate(liquid)',
   *' input'/' Yes = 1   No = 0')
    READ(*,849) YORN1
849 FORMAT(I2)
    MSTEP=1
    IF (YORN1.EQ.0) GOTO 851
    WRITE(*,853)
853 FORMAT(1X,'How many power or mass rates do you want to give?')
    READ(*,855) MSTEP
855 FORMAT(I2)
    DO 791 I=1,MSTEP
    WRITE(*,792) I
792 FORMAT(1X,'Give the ',I2,'th power in Watts(wood) or mass rate',
   *' in mg/s(liquid)'/' and the width in cm of the fire',
   *' (aaa.aaa,bbb.bbb)')
    READ(*,793)POW(I),RADI(I)
793 FORMAT(2F12.6)
791 CONTINUE
741 WRITE(*,771)
771 FORMAT(//,1X,'Number     power-mass rate       width',/,
   *'              (Watts-mg/s)         (cm)')
    DO 722 I=1,MSTEP
    WRITE(*,723)I,POW(I),RADI(I)
723 FORMAT(4X,I2,5X,F14.4,8X,F6.3)
722 CONTINUE
    WRITE(*,731)
731 FORMAT(/,1X,'Are these correct?  Yes = 1  or  No = 0')
    READ(*,732) YORN
732 FORMAT(I2)
    IF (YORN.EQ.0) THEN
    WRITE(*,733)
733 FORMAT(/,1X,'Which one is wrong? Give the number!')
    READ (*,734) YORN2
734 FORMAT(I2)
    WRITE(*,738)
738 FORMAT(//,1X,'Number     power-mass rate       width',/,
   *'              (Watts-mg/s)          (cm)')
    WRITE(*,735)YORN2,POW(YORN2),RADI(YORN2)
735 FORMAT(4X,I2,5X,F14.4,8X,F6.3)
    WRITE(*,736)
736 FORMAT(1X,'Give the correct values  first power-mass rate',
   *' and than the width')
    READ (*,737)POW(YORN2),RADI(YORN2)
737 FORMAT(2F14.4)
    GOTO 741
    ENDIF
851 IF (YORN1.EQ.0) MSTEP=1
    IF (NUM2.EQ.0) LUSTEP=1
    IF (LQWD.EQ.1) THEN
    WRITE(6,960) 1
960 FORMAT(I2)
```

```
      ELSE
      WRITE(6,961) 0
  961 FORMAT(I2)
      ENDIF
      WRITE(6,962) MSTEP*LUSTEP
  962 FORMAT(I3)
      WRITE(6,971) NUM2,YORN1
  971 FORMAT(2I2)
      DO 819 J=1,MSTEP
      IF (YORN1.EQ.0) GOTO 921
      VAL1(10)=RADI(J)*RADI(J)*PI/4.
      IF (LQWD.EQ.1)THEN
      VAL1(14)=POW(J)
      ELSE
      VAL1(13)=POW(J)
      ENDIF
  921 DO 815 I=1,LUSTEP
      IF (NUM2.EQ.0) GOTO 922
      VAL1(NUM2) = LOW+(I-1)*DESTEP
  922 QW =VAL1(1)
      G = VAL1(2)
      ALFA = VAL1(3)
      LANDA = VAL1(4)
      NS = VAL1(5)
      TA = VAL1(6)
      TO = VAL1(7)
      ROA = VAL1(8)
      CP = VAL1(9)
      BO = 2*SQRT(VAL1(10)/PI)
      QC = VAL1(11)
      NU = VAL1(12)
      QV = (QW-(1.-NU)*QC)/NU
      IF (LQWD.EQ.1) THEN
      PGR = VAL1(14)
      ELSE
      PGR = VAL1(13)*QW/1000./1000.
      ENDIF
      WRITE(6,310) QW
  310 FORMAT(E15.4)
      WRITE(6,320) G
  320 FORMAT(F12.2)
      WRITE(6,330) ALFA
  330 FORMAT(F14.3)
      WRITE(6,340) LANDA
  340 FORMAT(F16.2)
      WRITE(6,350) NS
  350 FORMAT(F8.2)
      WRITE(6,360) TA
  360 FORMAT(F12.0)
      WRITE(6,370) TO
  370 FORMAT(F10.0)
      WRITE(6,380) ROA
```

```
380 FORMAT(F11.2)
    WRITE(6,390) CP
390 FORMAT(F7.0)
    WRITE(6,392) BO*BO*PI/4.
392 FORMAT(F8.3)
    IF (LQWD.EQ.1) THEN
    WRITE(6,395) QC
395 FORMAT(E15.4)
    WRITE(6,397) NU
397 FORMAT(F12.4)
    ENDIF
    WRITE(6,398) PGR
398 FORMAT(F12.2)
815 CONTINUE
819 CONTINUE
    STOP
    END
```

Appendix Computer programme for the calculation of flame heights.

```
C  FORTRAN77
C
C  This programme calculates the flame height according to the
C  method of Paul Bussmann et. al. 1982
C
      REAL X,XOUD,XVLAM,B,BOA(20),B2,F,FO,F2,V,M,MOUD,P,P2,U,UO,G
      REAL ALFA,LANDA,NU,NS,RO1,PGRA(20),RPR,SGR,QW,QC,QV,CP,U2
      REAL T,TO,TA,RO,RO2,ROO,ROA,RRO,RROO,RROA,RRO2,PGR1,BO,AREA
      REAL VLAMGRENS,ONDER,BOVEN,MU,PI,JJ,HLP1,HLP2,HLP3,HLP4
      REAL POW(99),RADI(99),VLBODEM,PITLA(20),BO2,PGR,PITL,FLUC(100)
      REAL IMP,IMPJ,IMP2,IMP3
      REAL AA1,BB2,CC2,DD2,EE2,FF2,BO1,VAL1(14),LOW,UPP,DESTEP
      INTEGER N,I,J,L,FIRST,I2,J2,YORN,NUM1,VAL2(14),LQWD,PORM
      INTEGER NUM2,LUSTEP,MSTEP,YORN1
      EXTERNAL IMP,IMPJ,IMP2,IMP3
      CHARACTER ALIST(18),EXTEND(5),LIST(16),DISK(1)
      CHARACTER*14 ANAME
      CHARACTER*70 EERSTE
      CHARACTER*70 TWEEDE
      CHARACTER LIST1(70),LIST2(70)
      DATA EXTEND/'.','P','R','N',':'/
      OPEN (6,FILE='NUMBER',STATUS='OLD',FORM='FORMATTED')
      PI=4.*ATAN(1.)
C
      READ(6,312)ANAME
  312 FORMAT(A14)
      OPEN (7,FILE=ANAME,STATUS='NEW',FORM='FORMATTED')
C
      READ(6,963)LQWD
  963 FORMAT(I2)
      READ(6,962) MSTEP
  962 FORMAT(I3)
C
      READ(6,971)NUM2,YORN1
  971 FORMAT(2I2)
      DO 815 J=1,MSTEP
C
      READ (6,410) VAL1(1)
  410 FORMAT(E15.4)
      READ (6,420) VAL1(2)
  420 FORMAT(F12.2)
      READ (6,430) VAL1(3)
  430 FORMAT(F14.3)
      READ (6,440) VAL1(4)
  440 FORMAT(F16.2)
      READ (6,450) VAL1(5)
```

```
  450 FORMAT(F8.2)
      READ (6,460) VAL1(6)
  460 FORMAT(F12.0)
      READ (6,470) VAL1(7)
  470 FORMAT(F10.0)
      READ (6,480) VAL1(8)
  480 FORMAT(F11.2)
      READ (6,490) VAL1(9)
  490 FORMAT(F7.0)
      READ (6,492) VAL1(10)
  492 FORMAT(F8.3)
      IF (LQWD.EQ.1) THEN
      READ (6,495) VAL1(11)
  495 FORMAT(E15.4)
      READ (6,497) VAL1(12)
  497 FORMAT(F12.4)
      READ (6,498) VAL1(14)
  498 FORMAT(F12.2)
      ELSE
      VAL1(12)=1.
      READ (6,491) VAL1(13)
  491 FORMAT(F12.2)
      ENDIF
C
      IF (J.EQ.1) THEN
      IF (LQWD.EQ.1) THEN
      WRITE(7,960)
  960 FORMAT(/,1X,'The fuel is wood'/)
      ELSE
      WRITE(7,961)
  961 FORMAT(/,1X,'The fuel is liquid'/)
      ENDIF
      WRITE (7,401) VAL1(1)
  401 FORMAT(1X,' 1 The combustion value of fuel is:',E15.4,'  J/kg')
      WRITE (7,402) VAL1(2)
  402 FORMAT(1X,' 2 The gravitational accel. is: ',F12.2,8X,'m/s^2')
      WRITE (7,403) VAL1(3)
  403 FORMAT(1X,' 3 The entrainment constant is:',F14.3,7X,'(-)')
      WRITE (7,404) VAL1(4)
  404 FORMAT(1X,' 4 The excess air factor is:',F16.2,8X,'(-)')
      WRITE (7,405) VAL1(5)
  405 FORMAT(1X,' 5 The stoich. air to fuel ratio is:',F8.2,8X,'(-)')
      WRITE (7,406) VAL1(6)
  406 FORMAT(1X,' 6 The ambient temperature is:',F12.0,10X,'K')
      WRITE (7,407) VAL1(7)
  407 FORMAT(1X,' 7 The temp. of the fuel bed is:',F10.0,10X,'K')
      WRITE (7,408) VAL1(8)
  408 FORMAT(1X,' 8 The ambient density of air is:',F11.2,8X,'kg/m^3')
      WRITE (7,409) VAL1(9)
  409 FORMAT(1X,' 9 The spec. heat coef. of air is:',F8.0,10X,'K kg/J')
      WRITE (7,412) VAL1(10)
  412 FORMAT(1X,'10 The fuel bed area is:           ',F8.3,7X,'cm^2')
```

```
      IF (LQWD.EQ.1) THEN
      WRITE (7,415) VAL1(11)
  415 FORMAT(1X,'11 The combustion value of charcoal:',E14.4,'  J/kg')
      WRITE (7,417) VAL1(12)
  417 FORMAT(1X,'12 The mass frac. of volatiles is:',F12.4,6X,'(-)')
      WRITE (7,418) VAL1(14)
  418 FORMAT(1X,'14 The power of the fire is:',5X,F11.2,8X,'W'//)
      ELSE
      VAL1(12)=1.
      WRITE (7,419) VAL1(13)
  419 FORMAT(1X,'13 The power of the wick is:',5X,F11.2,6X,'  W'//)
      ENDIF
      ENDIF
      IF (YORN1.EQ.0.AND.NUM2.EQ.0) THEN
      WRITE (7,521)
  521 FORMAT(1X,'No variable parameters '//)
      ENDIF
      IF (YORN1.EQ.0.AND.NUM2.NE.0) THEN
      IF (NUM2.EQ.1.OR.NUM2.EQ.11)THEN
      WRITE (7,522)NUM2,VAL1(NUM2)
  522 FORMAT(1X,'The changed parameter is number ',I2,/,
     *16X,' and the value is now ',E15.4,' J/kg'//)
      ELSE
      WRITE (7,523)NUM2,VAL1(NUM2)
  523 FORMAT(1X,'The changed parameter is number ',I2,/,
     *16X,' and the value is now ',F15.4,//)
      ENDIF
      ENDIF
      IF (YORN1.NE.0.AND.NUM2.EQ.0)THEN
      IF (LQWD.EQ.1) THEN
      WRITE (7,524)VAL1(10),VAL1(14)
      ELSE
      WRITE (7,524)VAL1(10),VAL1(13)
      ENDIF
  524 FORMAT(1X,'The area is ',F11.5,' cm^2  and the power is ',
     *F12.2,' Watts'//)
      ENDIF
      IF (YORN1.NE.0.AND.NUM2.NE.0) THEN
      IF (NUM2.EQ.1.OR.NUM2.EQ.11) THEN
      WRITE (7,525)NUM2,VAL1(NUM2)
  525 FORMAT(1X,'The changed parameter is number ',I2,/,
     *16X,' and the value is now ',E15.4,' J/kg'//)
      ELSE
      WRITE (7,526)NUM2,VAL1(NUM2)
  526 FORMAT(1X,'The changed parameter is number ',I2,/,
     *16X,' and the value is now ',F15.4,/)
      ENDIF
      IF (LQWD.EQ.1) THEN
      WRITE (7,527)VAL1(10),VAL1(14)
      ELSE
      WRITE (7,527)VAL1(10),VAL1(13)
      ENDIF
```

```
  527 FORMAT(1X,'The area is ',F11.5,' cm^2  and the power is '
     *,F12.2,' Watts'//)
      ENDIF
      QW =VAL1(1)
      G = VAL1(2)
      ALFA = VAL1(3)
      LANDA = VAL1(4)
      NS = VAL1(5)
      TA = VAL1(6)
      TO = VAL1(7)
      ROA = VAL1(8)
      CP = VAL1(9)
      BO = SQRT(VAL1(10)/PI)/100
      QC = VAL1(11)
      NU = VAL1(12)
      QV = (QW-(1.-NU)*QC)/NU
      IF (LQWD.EQ.1) THEN
      PGR = VAL1(14)
      ELSE
      PGR = VAL1(13)
      ENDIF
C  ROO is the density of the gas at the fuel bed
      ROO = ROA*TA/TO
C  RROA is the dimensionless density
      RROA = ROA/ROA
      RROO = ROO/ROA
C  UO is the velocity of the gas leaving the fuel bed
      UO = (NS*(1.-NU)+1.)*PGR/QW/ROO/PI/BO/BO
C  FO is the Froude number
      FO = SQRT(2.*ALFA)*UO/SQRT(G*BO)
C  V is the combustion number
      V = QV/LANDA/NS/CP/TA
      N = 0
      XVLAM = 0.
      F = FO
      WRITE(7,801)F,V,UO
  801 FORMAT(1X,'Froude number at fuel bed = ',F6.4,/,
     *1X,'The combustion number   = ',F6.2,/,
     *1x,'The velocity at fuel bed  = ',F6.4,' m/s'/)
      IF (V.EQ.0) THEN
      F2 =FO
      B2 = BO
      U2 = UO
      RO2 = ROO
      ENDIF
      IF (V.NE.0) THEN
      VLAMGRENS = RROO*F*(NS*LANDA+1.)/(NS*LANDA*(1.-NU)+1.)
      VLBODEM = RROO*F
      DO 151 J2=1,25
  151 WRITE(*,'()')
      WRITE (*,150)J,MSTEP
  150 FORMAT (////,1X,'Start ',I3,' th Simpson calculation of',I3,/)
```

```
     X = SIMPSOM(IMPJ,JJ,VLBODEM,VLAMGRENS,100,V,RROO,F)
     DO 161 J2=1,25
 161 WRITE (*,'()')
     XVLAM = X*BO/2./ALFA
     WRITE (7,170) XVLAM*1000.
 170 FORMAT (1X,'The flame length of the fire with',
    *' given parameters is',2X,F5.1,' mm'/)
     M=VLAMGRENS
     RO2=M/((M-RROO*F)*(V+1)+F)*ROA
     RRO2=RO2/ROA
     U2=IMP(M,V,RROO,F)/M*UO/F
     B2=SQRT(M*M/IMP(M,V,RROO,F)/RRO2)*BO
     F2=SQRT(2*ALFA)*U2/SQRT(G*B2)
     WRITE(7,802)F2,U2,B2*100
 802 FORMAT(1X,'Froude number at flame top = ',F6.3,/,
    *1X,'The velocity at flame top  = ',F6.3,' m/s'/,
    *1X,'The width at flame top     = ',F6.3,'  cm'/)
     WRITE(7,096)
 096 FORMAT(1X,'----------------------------------------',
    *'-------------'//)
     ENDIF
 815 CONTINUE
     WRITE (*,100)ANAME,ANAME,ANAME
 100 FORMAT(////,1X,'The data is stored on: ',A14,////,1X,
    *'With the DOS command:'//' TYPE ',A14,//,' you will see the ',
    *'results on the screen'/' or  with DOS command:'//' COPY ',A14,
    *' PRN'//' on the printer'////)
     STOP
     END
C
C Function IMP
C The dimensionless momentum flow rate in z-direction
     REAL FUNCTION IMP(IM,IV,IRROO,IF)
     REAL IV,IM,IRROO,IF,HELP1,HELP2,HELP3,HELP4
     IMP = ((5./6.*IV*(IM**3.-(IRROO*IF)**3.)-
    # 5./4.*IRROO*IF*(IV-(1.-IRROO)/IRROO)*(IM**2.-(IRROO*IF)**2.)+
    # (IRROO*IF*IF)**(5./2.))**2.)**0.2
     RETURN
     END
C
C Function IMP2
C The dimensionless momentum flow rate in z-direction
     REAL FUNCTION IMP2(IM,IV,IRRO2,IF)
     REAL IV,IM,IRRO2,IF,HELP2,HELP3,HELP4
     IMP2 = (5./4.*IRRO2*IF*(1.-IRRO2)/IRRO2*(IM**2.-(IRRO2*IF)**2.)+
    # (IRRO2*IF*IF)**(5./2.))**(2./5.)
     RETURN
     END
C
```

```
C  Function IMP3
C  The dimensionless momentum flow rate in z-direction
      REAL FUNCTION IMP3(IJJ,IM2,IRRO,IF)
      REAL IM2,IJJ,IRRO,IF,HELP2,HELP3
      IMP3 = (5./4.*IRRO*IF*(1.-IRRO)/IRRO*(IJJ**2.-(IRRO*IF)**2.)+
     # (IRRO*IF*IF)**(5./2.))**(2./5.)
      RETURN
      END
C
C  SIMPSOM
C  Simpson integration calculation
C  SFX  function that is to be integrated
C  SX variable
C  SXO lowerboundary of the integral
C  SXB upperboundary  of the integral
C  SN numer of steps
      REAL FUNCTION SIMPSOM(SFX,SX,SXO,SXB,SN,SA,SB,SC)
      REAL SFX,SX,SXO,SXB,STEP,SUM,SCOUNT,SA,SB,SC
      INTEGER SN
      STEP = (SXB-SXO)/SN/2.
      SUM = SFX(SXB,SA,SB,SC)+SFX(SXO,SA,SB,SC)
      SCOUNT = 0
      DO 310 I = 1,SN-1
      SCOUNT = SCOUNT+SFX(SXO+2.*I*STEP,SA,SB,SC)
      WRITE (*,305) I,SN*2
  305 FORMAT('+ ready 'I4' of 'I4)
  310 CONTINUE
      SUM = SUM+2.*SCOUNT
      SCOUNT = 0
      DO 320 I = 1,SN-1
      SCOUNT = SCOUNT+SFX(SXO+(2.*I-1.)*STEP,SA,SB,SC)
      WRITE (*,315) I+SN,SN*2
  315 FORMAT('+ ready 'I4' of 'I4)
  320 CONTINUE
      SIMPSOM = STEP*(SUM+4.*SCOUNT)/3.
      RETURN
      END
C
C  Functie IMPJ
C  The dimensionless momentum 1/sqrt(flow rate) in z-direction
      REAL FUNCTION IMPJ(IJJ,IV,IRROO,IF)
      REAL IV,IJJ,IRROO,IF
      IMPJ = SQRT((1./(5./6.*IV*(IJJ**3.-(IRROO*IF)**3.)-
     # 5./4.*IRROO*IF*(IV-(1.-IRROO)/IRROO)*(IJJ**2.-(IRROO*IF)**2.)+
     # (IRROO*IF*IF)**(5./2.)))**(2./5.))
      RETURN
      END
```

Appendix — Setup of the computer programme on floppy disk

The computer programme is split up into two independent fortran progammes which communicate with each other. For the user the total of the two programmes looks as one single programme. The programme that communicates with the user is the programme for the input of data for the calculation of the flame heights. The second programme is the programme that calculates the flame heights. In an MS/PC DOS surrounding the programmes on a floppy disk look like:

```
FLAMEA    BAT           145   14-01-89       15:38
INPUT     FOR         11008   14-01-89       15:40
INPUT     OBJ         15812   14-01-89       15:42
INPUT     EXE         56900   14-01-89       15:44
OUTPUT    FOR          9856   14-01-89       15:55
OUTPUT    OBJ         15650   14-01-89       15:57
OUTPUT    EXE         57764   14-01-89       15:59
NUMBER                  179   14-01-89       16:05
FLAMEB    BAT           145   14-01-89       15:39
```

The programmes called INPUT communicate with the user and store the physical constants and number of calculations to be done in a temporary file called NUMBER. The programmes called OUTPUT read the data of the temporary file NUMBER and use this data to calculate the Froude number at the fuel bed, the Froude number at the flame top and the flame height.

The files called FLAMEA and FLAMEB are batch files by which the two programmes are combined to one programme. The file FLAME*.BAT (* = A or B) looks like:

```
*:\
INPUT
OUTPUT
```

One can start the programme on a PC with the command 'a:flamea' if the disk with the programmes is in drive a, or with 'b:flameb' if the disk is in drive b.

This section represents what will happen if one gives the command 'flame'. All the output that appears on the screen is boxed, every remark that is not on the screen starts with the % sign and is not in the box. The example is carried out on a Philips PC with two floppy disk drives. The disk with the programmes is in drive a and a second disk is in drive b for the data storage.

```
a:flame
```

% starting of the programme, given by user.

```
Give the name of the disk on which you want the data
(A, B, or C)
```

```
b
```

% given by user, the data will now be stored on the disk in drive b.

```
Give the name of data file (maximum 8 characters)
12345678
```

```
example
```

% given by user, name of the file in which the data is stored on the disk in b.

```
The data will be stored on: b:example.PRN

Which fuel do you use
Wood = 1  Liquid = 0
```

% Wood consists of two combustible parts; charcoal and volatiles. Liquid fuel is presumed to consist of 100 % volatiles. If you choose wood by giving '1' the physical constants will contain the combustion value of charcoal, the mass fraction of the volatiles and the power of the fire. If you choose liquid fuel by giving '0' the programme will make the mass fraction of volatiles to be 1 and will give the mass rate of the liquid fire.

```
1
```

% the user's choice is wood.

```
 1 The combustion value of fuel is:      .1870E+08  J/kg
 2 The gravitational accel. is:        10.00        m/s^2
 3 The entrainment constant is:          .080       (-)
 4 The excess air factor is:            1.80        (-)
 5 The stoich. air to fuel ratio is:    5.10        (-)
 6 The ambient temperature is:        293.          K
 7 The temp. of the fuel bed is:     1100.          K
 8 The ambient density of air is:       1.25        kg/m^3
 9 The spec. heat coeff. of air is:  1000.          K kg/J
10 The fuel bed area is:              226.980       cm^2
11 The combustion value of charcaol:     .3300E+08  J/kg
12 The mass frac. of volatiles is:       .8000      (-)
14 The power of the fire is:         6000.00        W

How many of these values you want to change?  (xx)
```

% In total in this example 13 physical constants can be changed. The number the user can give varies from 0, no changes, to 13, change all. If the user answers this question with for example '3' the computer will ask to give the number of the first physical constant that has to be changed. After the user's answer the computer will give the physical constant with its default value and asks to give the value the user wants it to be. The programme also gives an example of the type of value the user has to give. For example the configuration (aaa.bbb) means: give a real number with three numbers behind the decimal point. For convenient purposes these numbers behind the decimal point can be neglected if they are all zero, but the decimal point always has to be included in a real number. For example if you want to change the ambient temperature in 300 K you have to give 300. to the computer. The computer will give physical constants until the value of the numbers you wanted to be changed, is reached. After this the computer again gives all the physical constants and again asks you how many you want to change. If you do not want to change any, give '0'.

```
0
```

% the user's choice is not to change any of the physical constants.

```
Which value do you want to let fluctuate (xx)
If you give 0 there will be no fluctuation!
Remark: the power or mass rate can be varied randomly
```

% This part is specially designed if one wants to investigate the influence on the flame height of one of the above mentioned physical constants. If you answer this question with the number of the constant you want to fluctuate, the computer will ask you to give the lower boundary, upper boundary and the number of steps for this value. The number of steps represent the number of flame height calculations the computer has to do, so the lowest value of this number is 2. Again be careful with real numbers.

```
0
```

% given by user, so no fluctuations.

```
Do you want random power(wood) or mass rate(liquid) input
Yes = 1   No = 0
```

% Different experiments can have different power outputs in case of a wood fire, or different mass rates in case of a liquid fire, even if the experimentator keeps all the physical properties constant. For a wood fire the charging rate determines the power output and for a wick stove the wick length inside determines the mass rate. So this part of the programme is designed to cope with this problem. If you answer the question with 'yes' the programme will ask you the number of power or mass rates you want to give. After this question the computer asks you step by step to give the power or mass rates. Be careful with real numbers; do not forget the decimal point. After you have given all the power or mass rates the computer will show you the values you gave and asks you if they are correct. Incorrect values can be changed by giving the number of these values. After you have corrected the mistakes the computer will ask you again if the values are correct. If you answer this question with 'no' the data input programme INPUT is finished and the calculation programme OUTPUT will start.

```
Stop - Programme terminated
```

% INPUT programme is finished

% The programme OUTPUT will start with the following counter indicator, whose only purpose is to give the user an indication of the calculations already done and the calculations still to be done.

```
Start   1 th Simpson calculation of  1
 ready   xxx of 200
```

% In this example the programme tells the user that it is busy with the first Simpson calculation of a total of one. The Simpson calculation in this programme uses 200 steps to come to an answer; the programme tells you how many of these 200 are already finished.

% After all the Simpson calculation are finished the computer tells you where the data is stored and how to get it.

```
The data is stored on:  b:example.PRN


With the DOS command:
TYPE b:example.PRN
you will see the results on the screen
or  with DOS command:
COPY b:example.PRN  PRN
on the printer

Stop - Programme terminated
```

% For this example the data looks like:

```
The fuel is wood

 1 The spec. heat of the fuel is:        .1870E+08  J/kg
 2 The gravitational accel. is:        10.00        m/s^2
 3 The entrainment constant is:          .080       (-)
 4 The excess air factor is:            1.80        (-)
 5 The stoich. air to fuel ratio is:    5.10        (-)
 6 The ambient temperature is:        293.          K
 7 The temp. of the fuel bed is:     1100.          K
 8 The ambient density of air is:       1.25        kg/m^3
 9 The spec. heat coeff. of air is:  1000.          K kg/J
10 The fuel bed area is:              226.980       cm^2
11 The spec. heat of charcoal is:        .3300E+08  J/kg
12 The mass frac. of volatiles is:       .8000      (-)
14 The power of the fire is:         6000.00        W

 No variable parameters

Froude number at fuel bed =  .0372
The combustion number    =  5.62
The velocity at fuel bed  =  .0858 m/s

The flame length of the fire with given parameters is  121.0 mm

Froude number at flame top =  1.232
The velocity at flame top  =  1.988 m/s
The width at flame top     =  4.166  cm
```