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Investigation of CTARA wood-burning stove. Part I. Experimental investigation

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Abstract. This paper describes experimental investigation of a single pot wood-burning stove developed at CTARA. The stove incorporates features such as a converging combustion space, a grate, preheated secondary air and a swirling-device. Using chipped wood and a large diameter vessel (30 cm), efficiencies in excess of 40% have been measured. An electric stove, having a geometry similar to that of the wood-burning stove, has also been experimented with to obtain magnitudes of heat transfer coefficient at the vessel bottom, to estimate relative contributions of convection and radiation heat transfer to the vessel bottom, to study the effect of flame to grate heat release ratios and to study the effect of depth of insertion of the vessel into the stove. Finally, a 3-pot mud stove used in the Konkan region is investigated and it is shown that provision of a grate improves the efficiency of the stove.

Keywords. Wood-burning stove; swirling-device; efficiency; heat transfer coefficient.

1. Introduction

1.1 *The context*

Wood has been man's primary source of energy for most of his existence. Even today, nearly two billion people, mostly in the third world use wood for energy (space heating, water heating and cooking). Several studies have shown that fuel wood for cooking accounts for nearly 60 to 80% of the total energy consumption in rural areas. Typical fuel wood consumption for cooking amounts to nearly 1 to 1½ tons (Gupta 1979; Date 1986) per family per year. Hidden behind such consumption is the drudgery of 600 to 900 human hours typically expended by women in fetching firewood (Date 1986). Also to be noted is the financial burden on a semi-urban poor household for acquiring fuel-wood which can be estimated at

A list of symbols is given at the end of the paper.

between Rs.500 to 800 per annum. Use of firewood in cooking also contributes to the denudation of forests although this contribution is very small, since mostly twigs and branches are used in cooking (Reddy & Reddy 1985). The more important environmental aspect is concerned with inhaling of smoke during firewood cooking by women (Smith *et al* 1983), although smoke is often preferred from the point of view of preservation of thatched roofs.

There is need for developing inexpensive liquid and gaseous fuels which are based on locally available resources. Production of biogas from cowdung or from other organic matter and of ethanol from certain kinds of biomass offers such possibilities. Direct use of solar energy is yet another possibility. For the foreseeable future, however, it appears that firewood will continue to be the main source of energy for cooking. Besides, there are already indications that a complete switch-over to alternative fuels is likely to result in an inequitous distribution of the fuel itself.

Considerations such as the above have led to development of newer designs of cook-stoves. Since traditional stoves have often been found to have thermal efficiencies varying between 8 and 15%, considerable scope exists for reduction in fuelwood consumption through improvement in efficiency of stoves. Newer designs must however be evolved keeping in mind cooking practices and the manner in which the stoves are produced.

The Centre for Technology Alternatives for Rural Areas (CTARA) is committed to development of technologies suited to the developmental priorities of the Karjat Tribal Block in the Raigad district of Maharashtra. The energy consumption pattern (Date 1986) for a village in the block has clearly demonstrated the need for improving and developing wood-burning cookstoves. Table 1 shows the data on cooking practice presently followed in the block.

1.2 *Scope and purpose*

Several recent publications (DeLepeleire *et al* 1981; Clarke 1982, 1985; Smith *et al* 1986) deal with information on wood-burning stove designs and with aspects related to

Table 1. Traditional cooking practice in Karjat Tribal Block. Average cooking time/meal = 1 h.

Type of stove	Three-stone	C-type	E-type	Two-pot	Three-pot
Family size	5	4	7	6	12
One meal					
Rice (kg)	1·5	1·0	2·0	1·5	3·0
Dal (g)	100	200	250	200	350
Firewood (kg)					
per meal	3·5	2·75	3·0	2·0	2·5
per day	10·0	8·0	7·5	6·5	8·4
Area of pot seat (cm^2)	225	344	730	344	480
Fuel entry area (cm^2)	188	260	488	225	188
Pot diameter (cm)					
Rice	19	25	25	21	25
Dal	19	19	18	18	18
Estimated efficiency (%)	3·65	6·2	8·16	9·57	14·0

their dissemination. Although sketches of the designs are provided, various dimensions, so critical to performance, are not. Often efficiency values are quoted without specifying all the operating parameters and experimental procedures followed. This makes it difficult to adopt the design without careful experimentation and/or theoretical analysis. The theoretical developments appear to be deliberately weak (although sensibly curtailed from fuller logical developments) suggesting the complexities involved in such an effort for assisting the design work. Nonetheless these developments coupled with experimental findings do assist in development of rules which can be used for a preliminary design of a new wood-burning stove (Duraiswamy 1985).

Having noted the foregoing, CTARA proposed a stove design (see § 2) and defined the scope of work as:

(i) parametric investigation of the CTARA wood-burning stove through experimental investigation;
(ii) development of a theoretical model to predict the performance of the stove;
(iii) testing a stove model with electric heating (rather than wood) to verify trends obtained in (i) and to provide information needed for (ii).

2. Experimental investigation

2.1 *Measurement of efficiency*

For a cooking task performed over a period (t^*), the efficiency (η) is defined as

$$\eta = (H_a/t^*)/(H_r/t^*) = H_a/H_r. \quad (1)$$

For experimental determination of the efficiency of stoves, the value of t^* is 1 to 2 h.

The quantity of heat released over a period (t^*) is given by

$$H_r = M_{wo}\, Ca_{wo} - M_{char}\, Ca_{char}. \quad (2)$$

Wood is charged intermittently in stoves. As such M_{wo} is the weight of wood used over the entire time period t^*.

The calorific value of wood is typically determined in a bomb-calorimeter. However, in the present work, its value is derived from an assumed chemical formula for wood. The "chemical formula" for a typical variety of dry wood may be taken as (Tillman *et al* 1981)

$$C_{4\cdot42}H_{6\cdot1}O_{2\cdot42}N_{0\cdot01}\ (+\text{ash}). \quad (3)$$

In different wood species, the H/C ratio typically varies between 1·35 and 1·4.

Assuming complete combustion of wood, it can be shown that

$$Ca_{wo} = 4{\cdot}18\,\{\,Y(1-0{\cdot}01f) - 5{\cdot}832\,[f + 54{\cdot}53(1-0{\cdot}01f)]\}, \quad (4)$$

where the value of Y varies between 4500 and 4700 in different types of wood.

In the laboratory, water-heating (rather than cooking) tests are usually performed. For cooking tasks involving boiling, however, it has been shown (Popali *et al* 1979) that the energy required for cooking is very nearly equal to the increase in the sensible heat of the same amount of water.

When water is heated in a vessel, the heat absorbed is given by:

$$H_a = m_{wi}\, Cp_w(T_{wf} - T_{wi}) + m_{we}\,\{\lambda + Cp_w(100 - T_{wf})\}. \quad (5)$$

From (2), (4) and (5), it can be seen that calculation of efficiency requires measurement of the following eight quantities:

$$t^*, M_{wo}, M_{char}, f, m_{wi}, m_{wf}, T_{wi} \text{ and } T_{wf}.$$

2.2 *Experimental procedure*

Although the above calculations appear quite simple, there are various ways in which an experiment may be performed. There is no standard procedure specified in the literature as it relates to instrumentation to be used, sizing of wood, wood species, size of the vessel, material of the vessel, quantity of water in the vessel etc. All these factors can have a significant effect on the value of efficiency measured. As such it is necessary to specify the exact procedure followed in every test.

Two procedures (A and B) were adopted; procedure B being different from procedure A only in some aspects as discussed below.

Procedure A: (1) Specify t^* – Except for some preliminary half-hour tests, all tests were carried out over a one-hour period.

(2) Specify power input (*Pkw*) to the stove – Usually the power input in all our work was between 2 and 5 kW. Specification of *Pkw*, predetermines M_{wo} as

$$M_{wo} = Pkw \times t^* \times 3600/Ca_{wo}. \tag{6}$$

(3) Specify charging frequency – M_{wo} kg of wood are separated out and then split into bunches of 20 to 30 g each. Typically each bunch was charged into the stove after every 10 to 20 min. For large power input, the frequency was reduced to 6 to 7 min.

The first charge typically consists of very small pieces of wood to facilitate quick establishment of fire.

(4) Initial weight of water – In all tests aluminium vessels were used. Their dimensions will be mentioned later when data are presented.

Typically 10 l of water were taken. We found it easier to measure the volume of water rather than its weight. Thus

$$m_{wi} = V_{wi}/v_i. \tag{7}$$

Measuring jars (1- or 2-litre capacity) were used to measure the volume of water. The temperature T_{wi} was measured by a mercury-in-glass thermometer.

(5) Measurement of f – For each lot of wood moisture content f was measured once in two weeks. The method adopted was as follows: Typically $100 \pm 0{\cdot}005$ g of wood (W_i) in 2 cm × 1 cm × 15 cm strips were taken and dried in a furnace maintained at a temperature of 90°C. The strips were weighed after every 24 h. The weight (W_f) of the strips was found to be constant after two or three such cycles. f was then calculated as

$$f = [(W_i - W_f)/W_i] \times 100. \tag{8}$$

(6) Start-up procedure – The tests were typically begun by noting initial temperature of water T_{wi} and ambient temperature T_∞. The vessel was filled completely with V_{wi} amount of water, placed on the stove and covered with a lid.

The initial charge of wood was placed on the grate of the stove. The wood was lit by inserting a burning kerosene swab below the grate. As soon the wood caught fire, the swab was removed.

(7) Intermediate procedure – Wood was fed into the stove at the predetermined charging rate. The temperature of water in the vessel was measured every 15 min. Also, towards the end of the test, the exhaust gas and flame temperatures were measured, although these were not found to be very reliable.

(8) Ending procedure – At the end of the period t^*, the water temperature T_{wf} was noted. The quantity of water in the vessel was estimated by siphoning out the water from the vessel into the measuring jars. The final weight of water was thus estimated as

$$m_{wf} = V_{wf}/v_f. \tag{9}$$

Immediately after noting T_{wf}, but before commencing measurement of V_{wf}, the fire is quenched by throwing water on it. The charcoal pieces are removed from the grate and are allowed to dry for a day. The dry charcoal is then weighed (M_{char}). Often, it is found that the pieces of wood are not completely converted to charcoal but that there is wood at the core. In such cases, intelligent correction to charcoal weight is applied.

(9) Efficiency calculation – The efficiency is calculated according to (1). Thus,

$$\eta = \frac{4{\cdot}18\,(T_{wf} - T_{wi})\dfrac{V_{wi}}{v_i} + \left(-\dfrac{V_{wi}}{v_i} - \dfrac{V_{wf}}{v_f}\right)[2257 + 4{\cdot}18\,(100 - T_{wf})]}{M_{wo}\,Ca_{wo} - M_{char} \times 30{,}500} \tag{10}$$

where Ca_{wo} is estimated from (4), with $Y = 4500$ in all our experiments.

(10) Error analysis – The range of errors associated with measurement of various quantities is given below.

$$dV_{wi} = dV_{wf} = \pm 50 \text{ ml};\ dT_{wi} = dT_{wf} = 0{\cdot}1°\text{C};$$
$$dM_{wo} = dM_{char} = \pm 0{\cdot}005 \text{ kg}.$$

Given below are the readings for a typical experimental run:

$$V_{wi} = 10 \text{ l};\ V_{wf} = 9{\cdot}9 \text{ l};$$
$$T_{wi} = 30°\text{C}\ (v_i = 1{\cdot}0043 \times 10^{-3} \text{ m}^3/\text{kg});$$
$$T_{wf} = 90°\text{C}\ (v_f = 1{\cdot}03585 \times 10^{-3} \text{ m}^3/\text{kg});$$
$$M_{wo} = 600 \text{ g},\ M_{char} = 20 \text{ g};\ f = 10{\cdot}0\ (Ca_{wo} = 15603{\cdot}9 \text{ kJ/kg}).$$

The data gives:

$$\eta = (2497{\cdot}2 + 919{\cdot}2)/(8752{\cdot}34) = 0{\cdot}39034,$$

where the first term in the numerator signifies sensible heat gain whereas the second term gives the heat absorbed in evaporating water. The above calculations clearly demonstrate the relative magnitude of the terms involved.
Noting that

$$d\eta/\eta = dH_a/H_a + dH_r/H_r,$$

where the right hand side is evaluated from (10); it can be shown that for the particular case considered

$$\frac{d\eta}{\eta}=\frac{225{\cdot}42}{3116{\cdot}4}+\frac{228{\cdot}4}{8752{\cdot}34}=0{\cdot}0659+0{\cdot}027=0{\cdot}0929.$$

Thus, the maximum experimental error can be expected to be of the order of 10%. In fact this error estimate is on the higher side since the error assumed in the volume measurement of water is deliberately larger corresponding to the least count of the scale on the jars used for measurement. The actual error in measurements of η is thus expected to be less than $\pm 10\%$.

Procedure B: This procedure differs slightly from procedure A in steps 6 and 7 as follows.

(6) Start-up procedure – Here the initial water volume taken is about two-thirds of the volume of the vessel rather than filling it up to its maximum capacity.

(7) Intermediate procedure – In procedure A, the lid is kept closed throughout the period of the test. In procedure B, the lid is removed as soon as the bulk water temperature reaches 90°C.

2.3 *The basic design of the* CTARA *stove*

Figure 1 shows the geometry of the stove. The clay stove body consists of a cylinder of inner diameter D_{gr} (also grate diameter) and height H_t. The grate is placed at a height H_{gr} from the bottom. On top of the grate is placed a clay cone (with a cut-out to match the feed port) with bottom diameter equal to D_{gr} and throat diameter D_{th}. The height of the throat from bottom is H_{th} and the cone height is $(H_{th}-H_{gr})$. Placed on top of the cone is a metal (GI 18 gauge) cylinder of diameter D_c. The pan of diameter D_p and height H_p is separated from the stove through a distance H_g.

The stove has semicircular primary port openings at the bottom with port diameter D_{pr}. The secondary air openings at the top have diameter D_s. The GI cylinder has further openings of diameter D_{sec}. The wood feed entry port is of diameter D_{ent}.

The main dimensions of the basic design are as follows (all dimensions in millimetres):

$H_t=330$;	$D_{gr}=220$;
$H_{gr}=75$;	$D_{th}=80$;
$H_{th}=235$;	$D_{pr}=55$ (6 ports);
$H_g=20$;	$D_{sec}=10$ (24 holes, two rows);
	$D_c=150$;
	$D_s=40$ (8 ports);
	$D_{ent}=100$.

In DeLepeleire *et al* (1981) two tentative recommendations are made for the sizing of stoves. These recommendations relate to the combustion volume of the stove above the grate and the grate surface area. The combustion volume recommended is 0·6 l/kW power input and the grate surface is to be determined according to 10 to

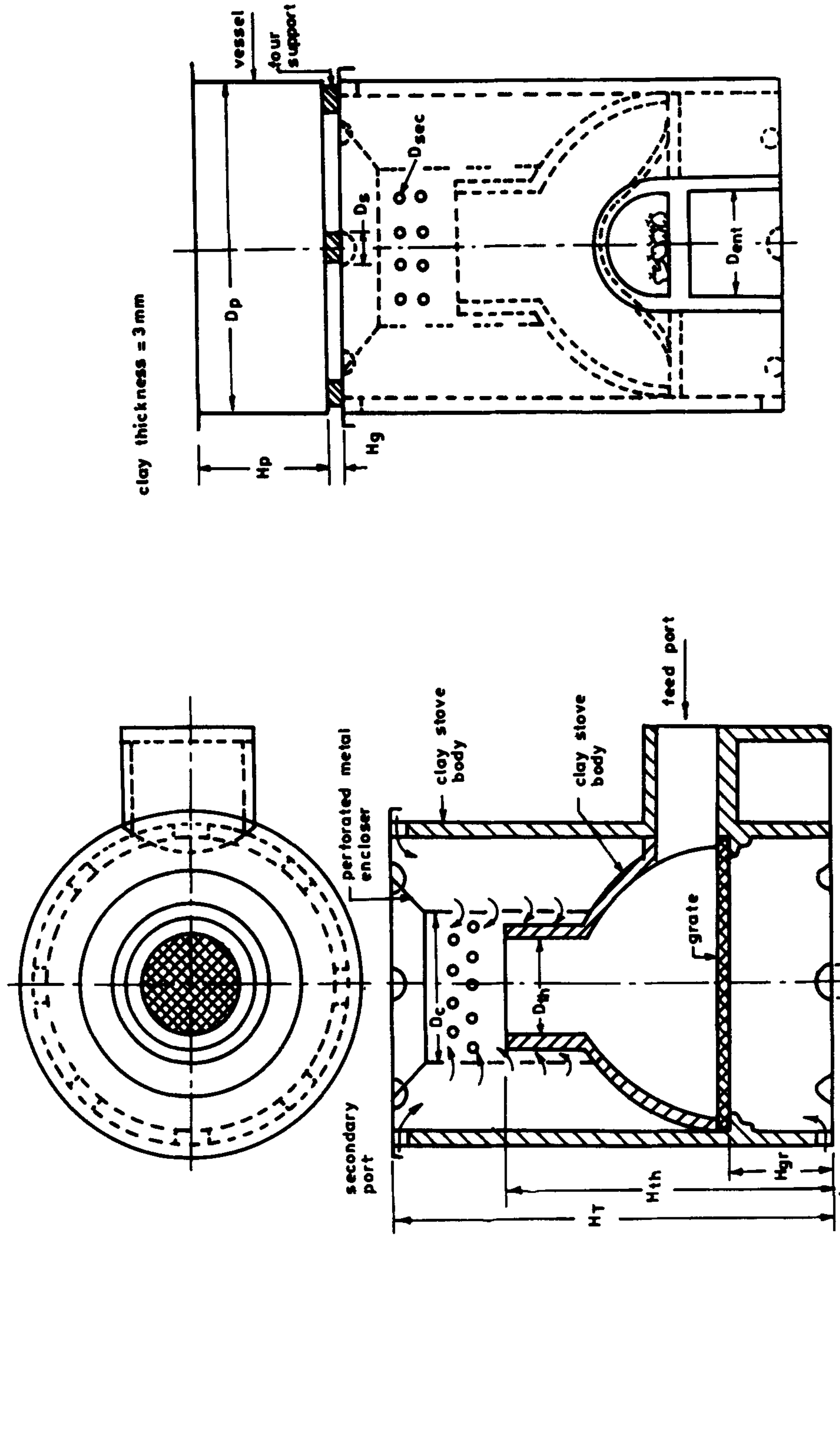

Figure 1. The CTARA stove-basic design.

15 W/cm^2 of grate area. In the basic design the grate area is 380 cm^2 and the combustion volume 2·8 l. Thus the stove power input can be about 5 kW.

Combustion air is drawn in through the primary ports at the bottom, through the feed port and through the secondary ports at the top. Secondary air passes through the perforations in the metal cylinder and mixes with the combusting materials. In the space between the stove body and the metal cylinder, the secondary air is expected to be preheated; thus reducing the heat losses from the stove.

2.4 *Pilot tests*

In order to familiarize ourselves with the testing procedure we carried out some pilot tests of half-hour duration each with various types and sizes of wood. In all tests an aluminum pan of 31 cm dia was used. Also the GI metal cylinder did not have any perforations. As such the secondary air drawn into the metal enclosure (through the gap between the metal cylinder and the clay enclosure) was negligibly small.

The main conclusions drawn from the pilot tests were:

(i) About 50 to 80 g of small chipped wood are essential for starting the fire within 60 to 90 s. The most convenient way of starting the fire is to use a kerosene swab (steel rod wound with asbestos rope and dipped in kerosene). The flaming swab is inserted below the grate on which the chipped wood is placed. Once the chips catch fire, the swab is removed.

(ii) Wood species like pangara, soft furniture wood etc. give rise to a large amount of smoke and are difficult to burn while species such as mango, subabul and other jungle woods are easier to burn.

(iii) Woods ranging from small chips (2 × 0·5 × 12 cm^3) to large branches (5 cm dia, 60 cm length) can be used for sustained burning.

(iv) For ensuring repeatability, at least three tests are essential. Tests showing more than ±3% variation about the mean value should be discarded.

(v) The stove was demonstrated to some people in the Karjat tribal block. They were asked to use their normal fuel wood (4 to 6 cm dia). The people appreciated the kerosene stove-like concentrated flame emerging from the stove and appeared enthusiastic about receiving the stove. Since the usual cooking period is about 1 h, all future tests were to be performed for this period.

(vi) We decided to use small chipped wood for all future tests as this is convenient from the point of view of accurate weighing of wood fed in and char left over. Specifications of the wood samples used are given below.

Sample	*Type*	*Density* (kg/m^3)	*Moisture content* (f)	*Size* (cm^3)
A	Jungle	893	15·4	2 × 2 × 18
B	Mango	700	13·4	2 × 2 × 18
C	Jungle	893	13·8	2 × 2 × 18
D	Jungle	853	12·8	2 × 2 × 18
E	Subabul	not measured	11·02	3 × 3 × 18

Table 2. Effect of perforations on the metallic cylinder.
Procedure: A $D_p = 31$ cm
Wood sample: A $V_{wi} = 10$ l

Power (kW)	M_{wo} (g)	M_{char} (g)	T_{∞} (°C)	T_{wi} (°C)	T_{wf} (°C)	V_e (ml)	η (%)
2·19	535	22	29	29·5	60	140	26·38
2·23	540	31	29·5	30·0	61	80	25·30
2·68	650	20	27	29	73	50	26·38
2·76	670	15	29·5	29	74	100	26·80

2.5 *Parametric investigations*

In order to bring about improvement in the efficiency of the stove, several parameters of the basic design were varied. The results obtained are presented below.

2.5a *Perforation of the metallic cylinder*: Since the pilot tests were performed with non-perforated cylinders, later tests were performed with 24 holes (1 cm dia) in the metallic cylinder. This was expected to facilitate the passage of secondary air. The results are presented in table 2. It is seen that the efficiency is almost independent of the power.

The notable change brought about by the use of perforations was that the burning of wood was established quickly and there was drastic reduction in smoke density because of mixing of secondary air.

2.5b *Effect of power input*: Adopting the repeatability constraint mentioned in the previous section, tests were performed with different power inputs as shown in table 3. The efficiency variation is small with power input. However, since η is maximum at 2·5 kW, it was decided that all future tests would be performed around this value.

2.5c *Reduction in cylinder diameter*: It was found that the flames emerging from the throat flared too quickly and did not hit the pan bottom directly. It was therefore decided to reduce the metallic cylinder diameter, so that $D_c = D_{th}$. (Results obtained are shown in table 4.) The flames were now found to hit the pan directly and improvement in efficiency was also observed.

2.5d *Inclining the horizontal part of the metal cylinder*: In the basic design, the top part of the metal cylinder was horizontal. Now that it was possible for flames to hit the vessel directly by reducing D_c to D_{th} (§ 2·5c), it was felt that the top horizontal part could be given an incline so that the flames would touch a larger part of the

Table 3. Effect of power.
Procedure: A $D_p = 31$ cm
Wood sample: A $V_{wi} = 10$ l

kW	1·86	2·50	3·00	4·45
η(%)	25·25	26·25	24·20	23·00

Table 4. Effect of reduction in D_c (i.e. making $D_c = D_{th}$).
Procedure: A $D_p = 31$ cm
Wood sample: A $V_{wi} = 10$ l

Power	M_{wo}	M_{char}	T_∞	T_{wi}	T_{wf}	V_e	η (%)
2·76	670	40	29·5	31·5	73	80	27·42
2·80	680	20	34	32	79	90	28·9
3·62	880	30	31	35	89	200	28·31

Units of measurement of all parameters as in table 2.

vessel. The horizontal part was thus given an incline of 15° (to the horizontal). The results are shown in table 5. As the flames hit a greater part of the vessel and as the residence time of hot gases is somewhat increased, the efficiency is found to increase as compared to the earlier figures.

2.5e *Tangential entry of secondary air*: It was felt that if the residence time of hot gases was further increased a further improvement in efficiency could be obtained. Hence, a new metal cylinder with an inclinded top was made. But instead of drilling round holes in it, 10 triangular vents (2 cm side) were punched such that one side of the triangle remained attached to the main cylinder body. The cut portions were bent inwards forcing the secondary air to enter tangentially into the metallic cylinder, thus imparting swirl to the hot gases. The results obtained are presented in table 6.

Imparting a swirl to the hot gases below the vessel afforded a dramatic improvement in efficiency.

2.5f *Imparting swirl to hot gases*: Encouraged by the results in § 2·5e, it was decided to impart a swirl to the hot gases more positively. Four types of swirling devices were thus inserted in the throat of the clay enclosure to study their effect on efficiency and smoke. The devices are shown in figure 2.

Figure 2a shows the two-blade swirler made out of GI sheet. The blade was mounted on a vertical rod which was brazed to a horizontal rod. The latter was

Table 5. Effect of inclined top metal cylinder.
Procedure: A $D_p = 31$ cm
Sample: A $V_{wi} = 10$ l

Power	M_{wo}	M_{char}	T_∞	T_{wi}	T_{wf}	V_e	η (%)
2·27	550	15	29	29·5	72	60	31·14
2·72	660	20	29·5	30	83	70	32·50

Units of measurement of all parameters as in table 2.

Table 6. Effect of tangential entry of secondary air.
Procedure: A $D_p = 31$ cm
Wood sample: A $V_{wi} = 10$ l

Power	M_{wo}	M_{char}	T	T_{wi}	T_{wf}	V_e	η (%)
2·59	630	20	30	31	91·2	90	39·11
2·65	690	20	27	28·6	88·0	80	37·21

Units of measurement of all parameters as in table 2.

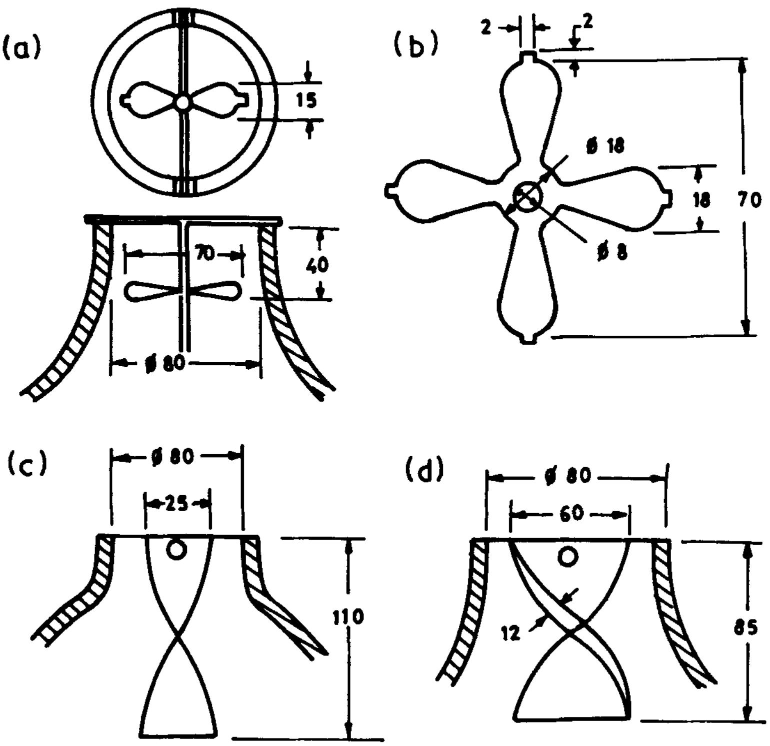

Figure 2. Swirling devices. (**a**) Two-bladed swirler; (**b**) four-bladed swirler; (**c**) metallic twisted-tape; (**d**) clay twisted-tape.

rested on the top of the clay enclosure. Figure 2b shows a four-bladed swirler which was similarly positioned. Figure 2c shows a narrow 2·5 cm metallic twisted tape which was hung from a horizontal rod resting on top of the clay enclosure. Figure 2d shows a wider (6·5 cm) clay and 'bamboocrete' (bamboo coated with concrete) twisted tape similarly mounted.

The clay twisted tape was hand-moulded from pottery clay mixed with *gobar* (cow-dung) (50%). After sun-drying for one week, it was baked in the furnace for 12 h at 250°C. The 'bamboocrete' twisted-tape was made as follows.

A rectangular mat of bamboo was first woven. It was then twisted and held on to a rod passing through its centre. The twisted mat was quoted with fine sand concrete and allowed to cure for one week.

The results obtained with four types of swirlers are shown in table 7.

It is thus seen that when the 4-blade GI swirler and 6·0 cm clay twisted-tape are used, efficiencies in excess of 42% are achieved. This suggests that the strong swirl imparted to hot gases improves the efficiency considerably.

The swirlers however increase the smoke density to some extent particularly during the starting-up period. The clay twisted tape provided the least amount of smoke.

The 'bamboocrete' twisted-tape proved to be a failure. Apart from imparting the largest amount of smoke, the concrete is found to crumble after repeated use, exposing the bamboo inside which burns out.

2.5g *Reducing air inlet areas*: It was not possible to measure air-fuel ratios in the

Table 7. Effect of swirlers.
Procedure: A $D_p = 31$ cm
Wood sample: B $V_{wi} = 10$ l

Swirler	Power	M_{wo}	M_{char}	T_∞	T_{wi}	T_{wf}	V_e	η (%)
2-blade	2·51	610	35	30·2	27·5	80	60	39·81
	2·51	610	25	29	27·5	85	80	38·57
4-blade	2·56	620	70	29·9	26·5	83	50	43·18
	2·55	610	80	27·6	26·6	81	60	45·19
	2·43	590	50	30·5	28	85	50	42·44
2·5 cm twisted-tape	2·082	505	35	30·5	25·9	70	40	36·93
	2·515	610	80	32	26	70	50	36·20
6·0 cm clay twisted-tape	2·68	650	90	26·2	24·3	82	100	46·70
	2·68	650	70	28	25	83	70	42·12
6·0 cm 'bamboocrete' twisted-tape	2·68	650	70	28	25	73	10	33·00

Units of measurement of all parameters as in table 2.

tests conducted. As such it was decided to examine the effects of closing the primary ports, the feed port and secondary ports, in turn, on the efficiency. Tests were conducted with the 4-bladed swirler. The results are shown in table 8.

It is seen that closing of any of the ports lowers the efficiency of the stove. When the primary ports were closed, it was found that initiation and sustenance of the fire was difficult and it was necessary to frequently blow on the embers. When the secondary port was closed, there was an increase in smoke density particularly at the beginning. When the feed port was closed, the wood did not burn with sufficiently high intensity and often the flames did not touch the bottom of the vessel.

2.5h *Effect of wood-type and size*: In order to study the effect of wood-type and size, various tests were conducted (table 9).

Table 8. Effect of closing air-inlet ports. (4-bladed swirler used.)
Procedure: A $D_p = 31$ cm
Wood sample: C $V_{wi} = 10$ l

Ports closed	Power	M_{wo}	M_{char}	T_∞	T_{wi}	T_{wf}	V_e	η (%)
Primary	2·38	595	30	27·6	28·9	76·6	90	34·56
Secondary	2·48	620	50	30·1	29·1	76·8	110	35·24
Feed	2·08	520	20	29·5	27·7	72	70	37·0

Units of measurement of all parameters as in table 2.

Table 9. Effect of wood-type and size (4-bladed swirler).
Procedure: A $D_p = 31$ cm
$V_{wi} = 10$ l

Wood-type	Wood-size (cm³)	Power (kw)	f (%)	η (%)
Jungle	$5 \times 5 \times 60$	3·85	11·0	37·28
Jungle	$2 \times 2 \times 18$	2·8	12·0	41·12
Subabul	$2·5 \times 2·5 \times 10$	2·6	11·00	37·40

The results presented in table 9 are averages of three tests in each case. The results show that a larger diameter of wood reduces the efficiency. Also different varieties of wood with similar dimensions and at similar power levels exhibit different efficiency values.

2.5i *Effect of pan diameter and testing procedure*: So far all tests were performed with a pan diameter of 31 cm. Also the tests were performed with procedure A in which the lid was kept closed throughout the experiment. Here tests were repeated with procedure B (see § 2.2) for $D_p = 31$ cm in which the pan was filled to two-thirds capacity and the lid was opened as soon as the bulk water temperature reached 90°C. Tests using procedure B were then repeated with other pan diameters. The results are shown in table 10.

The first result (for $D_p = 31$ cm) shows that procedure B reduces the measured efficiency drastically as heat losses from the water increase. The effect of pan diameter is also significant. As the diameter is reduced (i.e. as the bottom surface area reduces), efficiency drops considerably. Note that because the pan is kept open in procedure B, the evaporation also increases.

2.6 *Conclusions on the CTARA stove*

(i) In the range 1·86 to 4·45 kW, the efficiency of the stove has been found to be independent of the power input; although maximum efficiency is obtained at around 2·5 kW.

(ii) Three modifications to the metal cylinder have resulted in an improvement in efficiency. These are

a) making $D_c = D_{th}$;
b) perforating the cylinder;
c) providing an incline to the horizontal part of the metal cylinder.

(iii) Imparting a swirl to the combustion products improves efficiency considerably. The methods used were

a) tangential entry of secondary air;
b) 2-bladed swirler;
c) 4-bladed swirler;
d) 2·5 cm vertical twisted-tape;
e) 6·0 cm clay twisted-tape.

Table 10. Effect of pan diameter. (4-bladed swirler.)
Procedure: B
Wood sample: D

D_p (cm)	V_{wi} (l)	M_{wo} (g)	M_{char} (g)	$T_{wf} - T_{wi}$ (°C)	V_e (ml)	η (%)
31	6	650	30	60	600	32·29
22	2·6	650	30	65	510	23·00
22	2·6	600	35	68	480	21·43
17	1·6	650	40	70	490	18·38
17	1·6	650	25	74	470	17·25

The 4-bladed swirler and the 6·0 cm clay twisted-tape have resulted in the maximum improvement in efficiency. The maximum efficiency measured with small-sized wood is 46%.

(iv) Preventing entry of air through any of the ports results in a reduction of efficiency of the stove.

(v) Large diameter wood (5 cm) gives lower efficiencies than smaller diameter chipped wood (2 cm). The species of wood used can also influence efficiency.

(vi) The most important parameter for stove efficiency is pan diameter. The smaller the pan diameter, the lower is the efficiency. This however, is an operating parameter.

(vii) Water boiling tests with procedure B (in which the lid is removed as soon as the water reaches 90°C) provide lower efficiency values than those obtained using procedure A (in which the pan is kept covered throughout). This again is an operating parameter.

(viii) The stove has not been tested by varying other geometric dimensions such as D_{gr}, H_{th} and H_t. Such tests may assist in optimising the stove further.

(ix) Some remarks on testing methods and the evaluation of efficiency are essential. In all tests, calorific value has been evaluated using a single formula, (4). Thus efficiency values are not necessarily very accurate. As the error analysis showed, the measured values have an uncertainty of $\pm 10\%$. Secondly, the method of charging, particularly, the timing of the last charge, has considerable effect on measured efficiency. The timing of the last charge determines the amount of charcoal left behind and thus affects the magnitude of the denominator in the efficiency calculations. In procedure A, where the lid is used throughout, the steam condenses on the lid and the condensate may fall back into the water thus reducing the estimated evaporation and indicating a lower efficiency than may actually be the case.

(x) The orders of magnitude of efficiency compare favourably with those measured with other single-pot stoves (Popali *et al* 1987). The only single-pot stove using the principle of swirling is reported by U Shrinivasa and H S Mukunda (private communication in 1986) where efficiencies between 40 and 46% have been reported. This stove however restricts itself to only chipped wood because swirl is imparted by providing a feed port which allows tangential entry of air. The present design inparts swirl internally by means of twisted-tape or a 4-bladed swirler allowing a radial feed port which enables use of large diameter wood. At present the feed port extends outwards and is covered at the top. This semicircular cover restricts the number of large pieces that can be fed into the stove. Hence, it is desirable to remove the covering of the feed port.

(xi) Experimentation with chulas is time-consuming and tedious. Design modifications are not easy to bring about. Hence, a theoretical model must be built to derive directions for all incremental changes to be imparted to the basic design.

2.7 *Testing of the traditional stove*

In the Karjat tribal block, a local manufacturer makes clay stoves with two, three and four pot holes. The stoves are without grates and have no bottom. Hence, wood is fired by placing it on the ground. We have tested a 3-pot stove

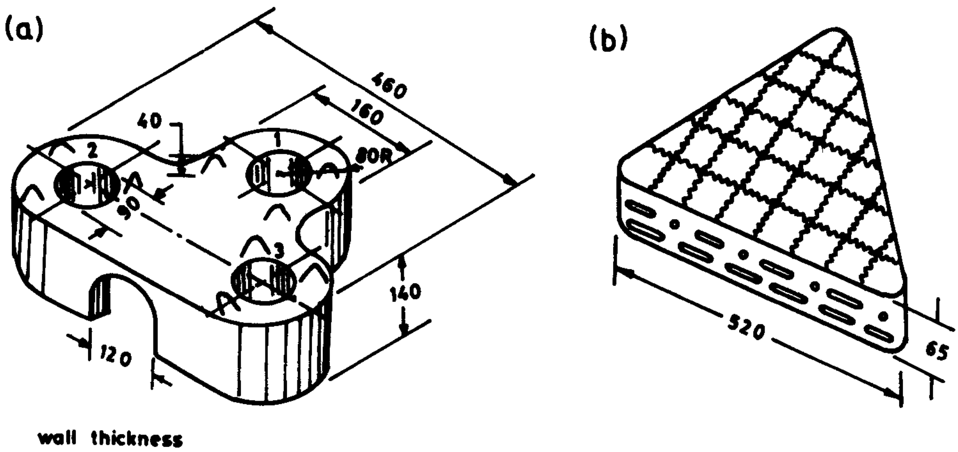

Figure 3. (**a**) Traditional cook-stove; (**b**) the grate.

manufactured by a potter in the Karjat tribal block. The dimensions of this stove are shown in figure 3a.

The tests were porformed with chipped wood ($2 \times 2 \times 18$ cm^3) as well as large wood ($5 \times 5 \times 30$ cm^3) pieces. Three vessels were used: a 22-centimetre vessel on hole 1, and 17-centimetre vessels on holes 2 and 3. Results obtained (using procedure B) are shown in table 11a. In each case, fire was started with chipped wood.

As was shown in table 1, the field test with large pieces of wood showed an estimated efficiency of 14%.

In the tests carried out it was found necessary to blow on the fire from time to time to sustain it.

In order to improve efficiency and provide more uniform heat to all vessels a simple modification was made. The stove was placed on a 6 cm high triangular stand with a wire-mesh grate (see figure 3b). The stove when fired showed that flames were equally well-directed to all the three pots and because of sufficient air suction from below the grate the smoke reduced considerably. Also, the fire did not require any blowing-on for its sustenance. The average result of 3 tests is presented in table 11b. The efficiency increases to 23%.

Table 11a. Tests using a traditional stove.

Wood pieces	M_{wo}	M_{char}	T_{wi}	T_{wf_1}	T_{wf_2}	T_{wf_3}	V_e	η
Small	710	40	26·8	97·5	67·8	45	400	16·8
Large	800	25	27·0	99	70	60	370	14·8

Table 11b. Traditional stove on addition of stand and grate.

Wood pieces	M_{wo}	M_{char}	T_{wi}	T_{wf_1}	T_{wf_2}	T_{wf_3}	V_e	η
Large	980	130	25·5	98	97·5	98	650	23

Units of measurement of all parameters as in table 2

2.8 *The electrically heated stove*

2.8a *The purpose*: The principal feason why the wood-burning stove never achieves a thermal steady state is that the wood is charged intermittently. Also the rate of burning of wood itself varies with time. Hence, the rate of heat release also varies with time. This unsteadiness poses two difficulties.

The vessel absorbs heat by two mechanisms i.e. convection and radiation. Their individual contributions can be determined only when the temperatures of the inner walls, the gases and the vessel bottom are measured. But these temperatures vary with time and unless these temperatures are continuously monitored with an elaborate measuring system, evaluation of convective and radiative contributions becomes difficult. The second difficulty associated with unsteadiness is the measurement of the air–fuel ratio. Since air intake is by the process of natural convection, the amount of air drawn in depends on temperatures inside the stove which vary with time.

In order to obviate this difficulty of unsteadiness an electrical analog of the wood stove system is considered here. Instead of burning wood, heat is supplied by means of electrical heater elements placed inside the stove. Wood, however, burns in two stages: as volatiles above the grate and as char at the wood surface. Hence, we have provided two heater elements: one at the grate surface to simulate char burning and the other in the enclosure above the grate to simulate volatile burning. Electrical input to both elements was monitored separately. Figure 4 shows the experimental arrangement. Figure 5 shows the heater elements. Complete details of the experimental set-up are available in Gopi (1986).

The objectives of the experiments were to measure

(a) efficiency

(b) radiative and convective components of the heat absorbed by the vessel;

(c) air flow rates for given power input; and

(d) The heat transfer coefficient at the vessel surface. The parameters varied were flame to grate heat release rates (Q_{fl}/Q_{gr}), the inlet area opening (A_i), the total input power ($Q_{in}=Q_{fl}+Q_{gr}$), and the depth of insertion of the vessel into the stove (h_d).

After achieving the steady state for each heat input, the temperatures at the walls and of the exhaust air were noted. From the theory of radiation heat transfer in enclosures, the radiation contribution to the vessel is evaluated knowing the enclosure wall temperatures. This radiation contribution was subtracted from the total heat absorbed in the water to deduce the convective contribution, from which the heat transfer coefficient is evaluated based on the mean temperature difference between the hot air temperature and the vessel temperature. Details of experimental procedure are given in Gopi (1986).

As will be seen from figure 4, the electrical stove is not an exact replica of the CTARA wood stove. For example, no secondary air is provided nor is the converging–diverging section similar to the CTARA wood stove. Also the vessel is inserted inside the stove in the electric stove which is not the case with the CTARA wood stove. The purpose was only to detect the major tendencies of the stove system.

2.8b *Experimental results*: Figure 6 shows the effect of input power on the efficiency and the heat transfer coefficient for $Q_{fl}/Q_{gr}=2{\cdot}0$ and $h_d=1{\cdot}5$ cm at three inlet area

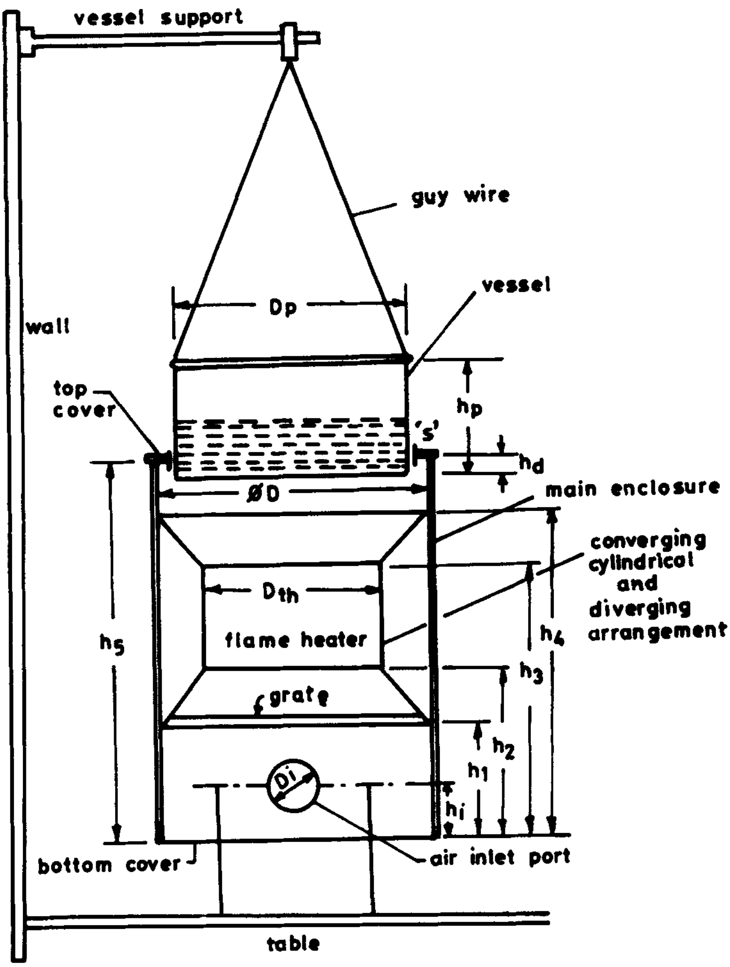

Figure 4. Experimental set-up of the electric stove.

openings (A_i). It is seen that as the A_i decreases, the efficiency decreases. The value of the efficiency shows a peak around 1200 W, but the variations with power are small as was found in the wood-burning stove. The heat transfer coefficient is affected by the area opening; it is smaller at smaller area openings. With power, the heat transfer coefficient remains almost constant at 40% opening but at higher openings it increases. The magnitudes of heat transfer coefficient are somewhat larger (25%) than those reported by Krishna Prasad & Bussman (1986). Over several parametric variations the heat transfer coefficient could be correlated as

$$\mathrm{Nu}_{D_{th}} = \alpha_{pf}\, D_{th}/K = 2{\cdot}733\ \mathrm{Re}_{D_{th}}^{0{\cdot}59} \tag{11}$$

All properties are evaluated at the throat temperature. From the theory of laminar boundary layers (Kays & Crawford 1974), it can be shown that for the stagnation point flow near the vessel bottom, the Nusselt number in terms of the throat dimension can be given by

$$\mathrm{Nu}_{D_{th}} = 1{\cdot}65\ \mathrm{Re}_{D_{th}}^{0{\cdot}5} \tag{12}$$

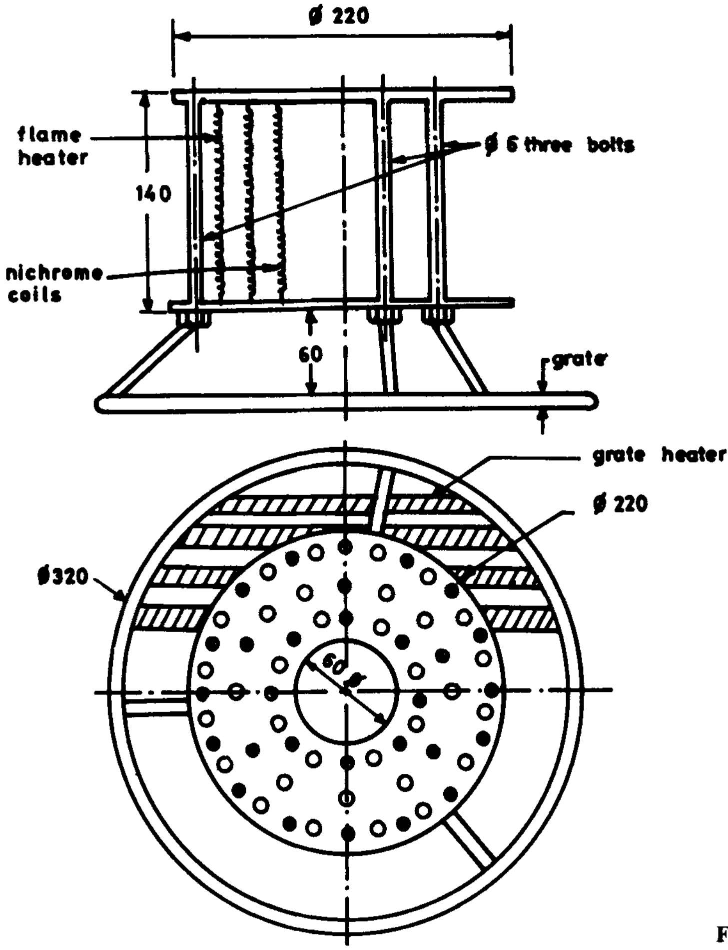

Figure 5. The heater unit.

The correlations are plotted in figure 7. The higher multiplier in (11) may be attributed to the streamline curvature that occurs due to flow expansion above the throat as well as the possibility of turbulence of the freestream outside the boundary layer at the vessel surface. The heat transfer coefficients measured by Krishna Prasad & Bussman (1986) lie between those predicted by (11), and (12). These results cannot however be plotted here because their stove did not have a throat above the grate.

Gopi (1986), also made measurements with a swirler at the throat with a cylindrical enclosure rather than an expanding cone on the downstream side. The measured heat transfer coefficients were 20% higher than those measured without the swirler in the new configuration.

Over the Reyholds number range found here, the air mass flow rate varies from approximately 6 kg/h to 14 kg/h; and the power input varies from 1 to 2·2 kW. For a typical wood species, the stoichiometric air–fuel ratio is approximately 6·5 kg of air/kg of wood or 1·4 kg/h of air/kW power input. Usually, the excess air factors are known to range from 2·5 to 4 (Krishna Prasad & Sangen 1983), yielding air flow rates of 3 to 6 kg/h per kW power input. The air flow rates measured in electric stoves compare favourably with those of the wood-burning stoves.

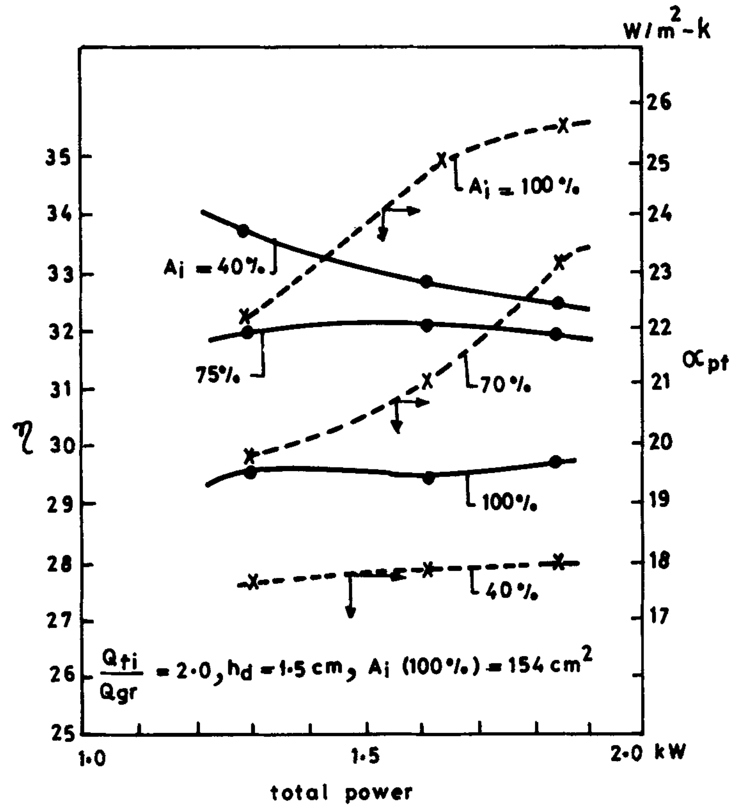

Figure 6. Effect of power and inlet area on the electric stove.

Figure 8 shows the effect of depth of insertion of the vessel into the stove. The negative value of h_d suggests that the vessel is kept above the stove. The efficiency is found to increase with the depth of insertion, but the heat transfer coefficient appears to be negligibly affected.

The parameter Q_{fl}/Q_{gr} is an important one. Typical wood is known to consist of 20 to 25% char (or fixed carbon) and 70 to 80% volatiles by weight. The calorific value of wood is approximately 4000 kcal/kg and that of char approximately 7300 kcal/kg. These values suggest that the value of the rate of heat released by the volatiles divided by that released by the char must be approximately 1·6. Keeping this in mind we have varied Q_{fl}/Q_{gr} between 1 and 2·5 to account for different species of hard and soft woods. The effect of Q_{fl}/Q_{gr} for const. Q_{in} is plotted in figure 9. The efficiency is found to increase with Q_{fl}/Q_{gr}, but the value of α_{pf} is relatively unaffected by the type of wood species. Figure 9 brings out the importance of standardising the wood species in the testing of wood-burning stoves. The effect of wood species used on efficiency was also observed in wood-burning stove tests.

In all the tests performed, the contribution of the radiative component as compared to that absorbed at the vessel surface was found to be between 10 and 28%. Thus the heat absorption process is predominantly convective. Any method which increases the residence time of the hot gases near the vessel (swirling or

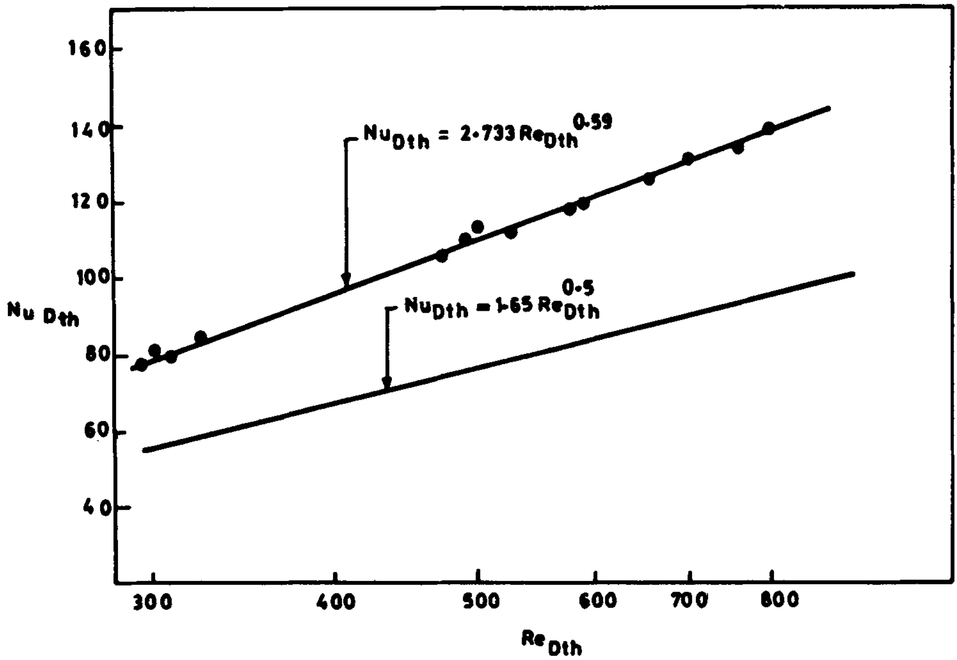

Figure 7. Correlation for $Nu_{D_{th}}$

inclined metal cylinder in the wood-burning stove for example) must therefore yield higher efficiences as was found in the CTARA stove.

3. Conclusions

Although electric stove tests do not exactly replicate those on wood-burning stoves,

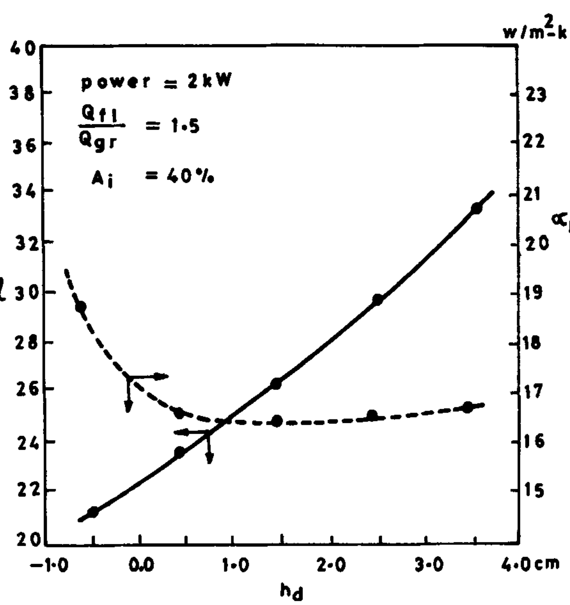

Figure 8. Effect of depth of insertion of the pan using the electric stove.

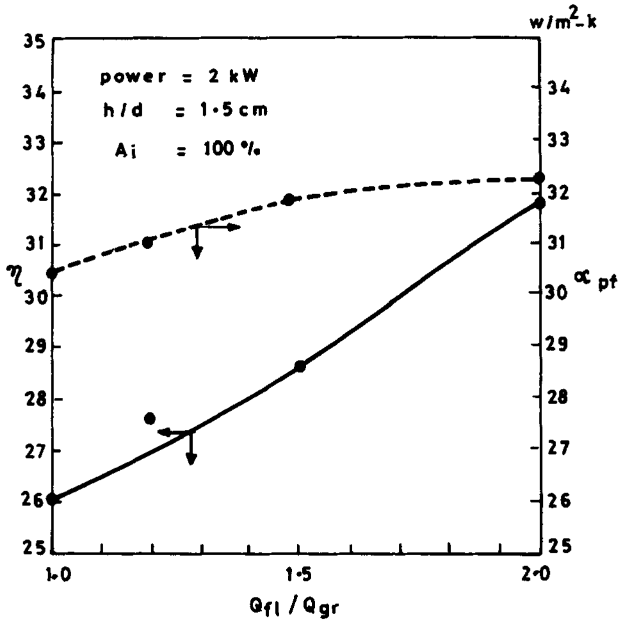

Figure 9. Effect of flame to grate heat release rates using the electric stove.

they have the advantage that a thermal steady state can be obtained The efficiency values measured are comparable to non-swirling efficiency values obtained in a wood-burning stove. Since the heat input in flaming combustion and char combustion can be easily controlled in electric stoves, the effect of wood species containing different char to volatile ratios can be easily simulated in electric stoves. Finally because of the achievement of the steady state, reliable values of heat transfer coefficient have been measured. Equation (11) gives the Nusselt number at the vessel surface in terms of Reynolds number evaluated at the throat. A more elaborate expression in terms of operating and geometric parameters is derived as follows

$$Nu_{D_{th}} = 524 \left[\frac{h_d}{D_{th}}\right]^{-0\cdot1956} \left[\frac{A_i}{A_{th}}\right]^{0\cdot4585} \left[\frac{Q_{fl}}{Q_{gr}}\right]^{-0\cdot1854} \left[\frac{Q_{in}}{\dot{m}_a Cp\,\Delta T_a}\right]^{-0\cdot487}$$

where $A_{th} = (\pi/4)\,D_{th}^2$; (13)

and $\Delta T_a = T_{exit} - T_\infty$.

Equation (13) is, however, particular to the configuration used. Nonetheless it brings out the relative effects of the operating parameter, such as the depth of insertion and the type of wood species used.

The electric stove has shown that the heat absorption process is chiefly convective and therefore swirling devices should yield higher efficiency stoves.

The experimental work presented here has shown how the secondary air assists in reducing the smoke and how positive swirling devices (such as the 4-blade swirler or twisted tape) assist in improving the efficiency of the CTARA stove. The tests carried out with the electric stove have supported the wood-burning stove results besides yielding three additional important results. These are (a) the heat absorption process at the vessel surface is chiefly convective, (b) the magnitude of heat transfer coefficient varies from 16 to 30 $W/m^2 K$, and (c) the flame to grate power (i.e. the ratio of char to volatiles in wood) has an important effect on efficiency.

The tests performed with the traditional stove have shown that mere provision of a stand and a grate not only achieves more uniform heating of all the pots of a 3-pot stove but improves efficiency by about 60%.

It is now appropriate to construct a theoretical model of the CTARA stove so as to optimise its design from the thermal efficiency point of view and to assist in designing a higher power stove. This is considered in Part II.

The authors would like to thank the staff of the Heat Transfer and Combustion and Instrumentation Laboratories for their cooperation and help.

List of symbols

A_i	inlet area opening;
Ca_{char}	calorific value of char (30,500 kJ/kg);
Ca_{wo}	lower calorific value of green wood (kJ/kg);
Cp_w	specific heat of water (4·18 kJ/kg K);
D_c	diameter of metal cylinder;
D_{ent}	diameter of wood feed entry port;
D_{gr}	grate diameter; inner diameter of cylindrical stove body; bottom diameter of clay cone;
D_p	diameter of pan;
D_{pr}	port diameter;
D_s	diameter of secondary air openings;
D_{sec}	diameter of openings on GI cylinder;
D_{th}	throat diameter of clay cone;
f	percentage moisture content of wood;
h_d	depth of insertion of vessel into stove;
H_a	heat absorbed by wood (kJ);
H_g	distance between stove and pan;
H_{gr}	height of grate from bottom;
H_r	heat released by burning wood (kJ);
H_t	height of stove body;
H_{th}	height of throat from the bottom;
$\dot{m}_a$	mass flow rate of air;
m_{wf}	final mass of water in the vessel (kg);
m_{wi}	initial mass of water in the vessel (kg);
M_{char}	weight of unburnt char left over at the end of period t^* (kg);
M_{we}	mass of water evaporated (i.e. $m_{wf} - m_{wi}$) (kg);
M_{wo}	total weight of green wood burnt (kg);
pkw	power input to the stove;
Q_{fl}	flame heat release rate;
Q_{gr}	grate heat release rate;
Q_{in}	total input power;

t^*	period of time;
T_{wf}	final temperature of water in pan (°C);
T_{wi}	initial temperature of water in pan (°C);
v_f	specific volume of water at temperature T_{wf};
v_i	specific volume of water at temperature T_{wi};
V_e	volume of water evaporated during experiments (ml);
V_{wf}	volume of water at T_{wf};
V_{wi}	total volume of water;
W_f	final weight of wood;
W_i	initial weight of wood;
Y	calorific value of dry wood;
α_{pf}	heat transfer coefficient between pan and flue gases;
η	efficiency;
λ	latent heat of water (2257 kJ/kg).

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