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Wood Burning Cook Stoves

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ABSTRACT

The major domestic energy needs of people in the under-developed and developing countries are met by burning wood in cook stoves. The quest for energy conservation and its efficient use has motivated researchers the world over to look for improvements in wood burning cook stoves. Even a marginal increase in efficiency can contribute considerably to a total saving in energy consumption and therefore conservation.

Analysis of cooking using wood shows that better energy efficiency can be achieved by complete and controlled combustion of wood, maximum energy transfer to food cooked and reducing the energy losses. The various component design features that contribute to better utilisation of wood energy are discussed. These can be of use in emerging designs, or in the modifications to the existing designs. In addition to dealing with the sizing factors, the rating or performance testing of wood stoves is detailed, thus providing a basis for comparison of different stoves. Operational guidelines that contribute to increased efficiency during cooking are provided.

INTRODUCTION

Most of the debates and discussions on energy issues centre around the so called commercial forms of energy, namely, oil, coal and electricity. These discussions tend to lose sight of the fact that for the vast majority of the population living in the rural areas, the dimensions of the energy problems are altogether different. Though their dependence on commercial fuels has not been large, there is as acute an energy crisis in the rural areas as in the urban centres. On account of dwindling supplies of fuel wood and gradual commercialisation of even traditional fuels like firewood and cowdung cake, securing adequate energy supply at a cost which is affordable, has become more and more difficult.

Research and development work in the area of wood burning cook stoves has been receiving increased attention due to the fact that for the vast majority of people in the developing countries, these stoves continue to be the main energy conversion devices. Percentage of the total energy supplied by fuel wood for some of the countries is shown in brackets [1]: Nepal (95.8), Tanzania (96.0), India (30.3), Uganda (90.2), Brazil (59.1), Sri Lanka (69.1), U.S.S.R. (3.6), Sweden (3.0), West Germany (0.3), Canada (1.0), U.S.A. (0.4). This shows that most of the under-developed and developing countries are heavily dependent on wood as an energy source. Further break up of energy utilised task-wise shows that approximately 60-80% of the energy supplied by fuel wood is utilised for cooking and water heating domestic tasks [2]. Thus, the major energy conversion takes place in a large number of low powered, low efficiency cook stoves. The scenario is similar in most developing/under-developed countries.

The origin of wood stoves dates back to prehistoric times starting with the three stone open combustion fire. Evolution of this open fire has resulted in thousands of other cook stoves. However, open fire is still used by rural people with nomadic tendencies or those with no permanent shelter. Perhaps it fulfills many of their needs like cooking, providing warmth, drying out damp clothes, rodent control or even a source of light, etc., in addition to it being simple to construct and easy to operate. Any evolved stove for this class of people should fill as many of the open fire's uses and have as few of its drawbacks as possible. Settled populations generally use built-in cook stoves. Dimensioning of stoves, which hitherto had not received much attention, is recognized as a major factor affecting stove efficiency and therefore energy conservation.

FACTORS CONTROLLING ENERGY CONVERSION AND UTILIZATION IN COOK STOVES [3]

The objectives of improving cook stoves are:

(i) To increase the overall energy efficiency and reduce fuel consumption for a given task,
(ii) To provide for varying power output level so as to control the stove power depending on the task,
(iii) To minimise the problems of pollution and inconvenience caused by smoke, soot, radiation, etc., and
(iv) To increase stove durability and reduce the frequency of repairs.

The scope for improving the cook stoves can be seen by taking a look at the energy flow diagram (Fig. 1) for a wood burning cook stove. The energy diagram indicates that complete combustion of fuel, efficient heat transfer for cooking and minimization of heat losses are the basic requirements for improved energy utilisation. These aspects in the context of wood burning stoves are discussed in brief in order to provide directions in the design of stove components and also in the better utilisation of fuel wood.

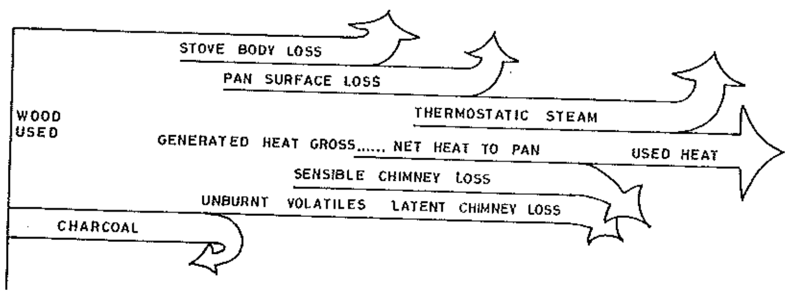

Fig. 1. Energy flow diagram in cook stoves.

Combustion

As in all combustion, there is an initial two-step heating phase when wood is combusted in stoves. The first step pyrolysis involves heating to a temperature where chemical decomposition commences liberating gaseous volatiles and thereby separating fixed carbon in a solid state. The size of wood pieces and the moisture content of wood are the main factors that determine the time taken for this initial heating phase of combustion. After this step, the combustion of wood takes two separate paths. One, the burning of gaseous volatiles which can take place in the complete volume of the combustion chamber, and the other, burning of solid residue, a process of surface combustion. For sustaining these two types of combustion, a high temperature (about 800°C) and a supply of oxygen at the right rates and at the right places is necessary. In the construction of wood stoves, provision should be made for a larger excess air intake than that calculated theoretically (stoichiometric air/fuel ratio), because some of the air passes through the fuel chamber/combustion chamber without contributing to combustion. If the fuel/air mixture is too rich (not enough oxygen) combustion is incomplete with not all carbon getting converted to carbon dioxide, on the other hand if the mixture is too lean, then the products of combustion get cooled, eventually quenching the flames. The ratio of quantity of air actually taken in to the stoichiometric quantity is called coefficient of excess air. The suggested excess air coefficient for wood stoves is between 1.5 to 2.0 [4]. This can be measured by the CO_2 content of the flue gases. Figure 2 shows the CO_2 content and excess air coefficient. When the CO_2 content diminishes, it may be concluded that excess air has increased and vice versa. If the surfaces of the combustion chamber get cooled at a faster rate than they receive heat from combustion flames, then the flames will get quenched. The three T's of ensuring good combustion are :

1. Temperature high enough to ignite the constituents.
2. Turbulance or good mixing of gases.
3. Time sufficient enough for combustion to be complete.

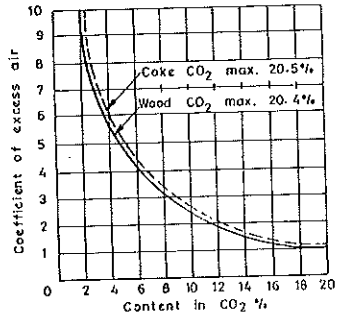

Fig. 2. Ratio between excess air and CO_2 content at complete combustion.

A simple means of judging good combustion is to observe the colour of smoke it gives off. If it is not transparent, it means that part of the fuel is not being consumed and is escaping in the form of unburnt products. Since the purpose of burning fuel in a stove is to have a controlled heat output rate, ways and means of providing controlled air for combustion in the form of primary and secondary air at the appropriate places in a combustion chamber become important. The theoretical temperature of combustion is determined not only by the calorific value of wood but also by excess air, too much excess air lowers gas temperature and hampers sustained combustion.

Heat Transfer and Fluid Flow

An average small-scale wood burning device is a naturally aspirated system involving combustion, heat transfer (conduction, convection and radiation) and fluid flow. The heat that is generated has to be transferred to the cooking vessel and to food. The heat is mainly transferred by convection and radiation to the vessel. The convective heat transfer is increased if the hot combustion gases lap the vessel and a forced vortex motion could be created. Vessel shape, size and its position in the combustion chamber would affect heat transfer. A longer gas path over the surface area of the pot will provide more residence time for heat transfer, and thus reduce the exhaust losses. Improved convection can be obtained by off-setting the flue tunnels giving rise to vortex or by the use of baffles and deflectors. The combustion volume could also be varied by positioning/sinking the pot in the stove. In an ideal pot position, the temperature of exit gases should approximately be the same as the pot surface temperature. The pot size and shape and its position in relation to the stove will not only be a factor that determines the gas flow pattern but also it will be a factor that goes to determine the shape factor for radiation heat transfer from flame to vessel. The radiation heat loss from flame to stove surface can be minimised by using suitably spaced shields that will in addition assist in stabilising combustion. The power output of the stove can be varied by regulating the wood feed rate. This is an operational parameter that depends on the cooking task and the person's experience and skill in maintaining a regulated power output.

DESIGN CONSIDERATIONS IN COOK STOVE COMPONENTS

For a fuel efficient stove design, knowledge of the above basic facts of combustion, heat transfer and fluid flow processes involved has to be translated into guidelines for the design of its functional components. Components sizing and incorporation or otherwise, therefore becomes important to obtain improved energy utilization in stoves. Components basic to emerging designs are: 1) Fire box and vessel mountings, 2) Grate, 3) Baffles, 4) Dampers, 5) Chimney, 6) Shields, and 7) Vessel size, shape and material. Factors useful in sizing each of the above components are detailed below.

Fire Box or Combustion Chamber and Vessel Mounting

This is the space in which initial combustion takes place and the fuel is burned. Some stoves also contain a secondary fire box where many of the gases produced by the initial combustion are burned. The height (distance between the floor of stove or grate if grate is used as the bottom of the pot) is one of the important parameters that affect the over-all efficiency of energy conversion. If the height of the combustion chamber is too low, incomplete combustion with condensation of volatiles, choking and smoke production results. If the combustion chamber is too high, the flames mix with the surrounding sheets of air and lower the temperature, with the consequent lowering of convective and radiative components of heat to the pot. Hence, the combustion chamber must have an optimum height for different burning rates.

Jayaraman and Bhatt [5] have recommended combustion chamber heights for various burning rates in single-pan grated stoves with vessel mounts (Table 1). Joseph and Loose [6] have suggested a combustion chamber height in the range 160-200 mm for two-pan non-grated stoves with vessel mounts. They have also suggested a combustion chamber of height in the range 150-180 mm for non-grated stoves in general.

Table 1. Optimum heights of combustion chambers and vessel mounts.

Sl No.	Fuel burning rate, kg/hr	Optimum height of vessel mounts, mm	Optimum height of combustion chamber, mm
1	0.5	30	65
2	0.8	40	88
3	1.4	50	110
4	2	60	140
5	3	65	160
6	5	70	180
7	10	75	210

The vessel mounting arrangements adopted must take into consideration the twin aspects of holding the vessel load in a stable manner as well as venting out the exhaust gases. In stoves with vessel mounts these need to be optimized. The height of the vessel mounts is determined by the volume of the flue gases handled, which in turn is dependent on the fuel burning rate. When the height of the vessel mounts is too great, the radiation loss from the sides of the flame increases. Also, the effective flame temperature of gases in contact with the vessel decreases because of variation in temperature with height of the chamber. On the other hand, if the vessel mount height is reduced too much, smoke and soot from the condensation of volatiles result. There is also flame licking on vessel sides causing severe radiation loss. A vessel mount height of 30 mm has been recommended by Jayaraman and Bhatt [5] for a chamber of 180-200 mm diameter. Various vessel mount heights suggested are given in Table 1 [5].

In stoves where the vessel is immersed in the combustion chamber, the combustion chamber shielding is extended upwards to cover the pot partially. Three ceramic blocks are placed radially at three locations 120° apart on the grate or combustion bed and the vessel is placed on them. The vessel is so immersed into the combustion chamber that the gap between the vessel wall and the shield is about 20 mm all round. The exhaust gases pass through the annular space between the vessel and the shielding. The advantage of this system is that it not only reduces the radiation losses but also increases the area of heat transfer between the vessel and the stove. The disadvantages are that only certain cylindrical vessels can be placed on the stove and the entire vessel sides become sooty.

Every stove needs an opening for feeding the fuel logs, but this opening causes convective and radiative losses and therefore should not be large. With regard to fuel feed openings there are two main stove types:

(1) Horizontal or inclined fuel axis stoves with or without a door.

(2) Vertical fuel axis stoves. These have the following advantages over horizontal fuel axis stoves:

- (a) there is no need for fuel adjustment as it is gravity fed,
- (b) they can burn wet wood with up to 32% moisture [5] because of elimination of radiation losses through the fuel feed opening and consequently higher combustion temperatures, and
- (c) wood chips fueled stoves, in which the chips are placed on the grate and lighted.

The pot is placed following good kindling. For refeed, the pot is lifted and chips replenished.

Air is aspirated into the fire box through an air inlet and then passed through the fuel by the draft created. An efficient stove should have an adjustable opening to allow the cook to control the rate of burning and thus to control the temperature.

Grate

Experiments have shown that use of a grate definitely improves the efficiency, presumably providing better access for air and thus improving the rate of combustion. It is suggested [6] that if a grate is used, the walls of the combustion chamber must slope in toward the grate and that the area of the grate open to the passage of air must be approximately 25 to 30% of the total grate area. The air and combustion gas flow pattern is significantly affected by the use of a grate. The use of a grate is a very old concept and there are many advantages. When a grate is used in the main combustion chamber, it has the following effects:

(i) In most stoves the combustion chamber is too high (140-190 mm). Introduction of a grate 40 mm above the ground level reduces the height to 100-150 mm. Thus, in the same old structure, the efficiency of heat transmission to the vessel can be increased.
(ii) When a grate is placed, an air gap between the floor and the heat source (burning logs) is created. This acts as a thermal resistance to downward heat flow.
(iii) The grate removes ash from the combustion zone, but retains embers.
(iv) The combustion rate increases compared to non-grated stoves.
(v) The flame becomes steady and does not waver. This reduces the side-ward losses to the chamber walls.
(vi) Symmetric air flow results, because air enters uniformly from all sides.
(vii) Charcoal formation is minimised.
(viii) CO concentration in flue gases is reduced.
(ix) Escape of unburnt volatiles from wood is minimised.When there is no grate, the hot bed of charcoal minimises the combustion chamber volume and also releases volatiles from the fresh logs so fast that they escape unburnt.
(x) Flame stability increases and the number of blowings per operation is reduced considerably.

In spite of all these advantages certain agencies like Intermediate Technology Development Group (ITDG) and also some rural development organisations prefer not to have grates, because in certain areas, cooking involves baking operations or heating of food directly on the cinders.

Types of grates generally used are:

(i) Cast iron grates.
(ii) Mild steel sheet grates.
(iii) Two sheets of expanded metal and weld mesh tied together by thin metal wires.
(iv) Mild steel rod grates. Mild steel rods are sharpened at both ends like sharpening pencil on either side. Two iron strips with holes are made. The rods are placed in between these two and hammered.
(v) Mild steel strips. A grate is made from these strips by placing them parallel or inclined at 60° to the horizontal and welded to side-plates.
(vi) Clay ceramic plate with holes.

Cast iron grates are best suited for clay stoves. Rod grates are suitable for brick stoves. Mesh or steel grates are useful for metallic stoves. Ceramic grates are the cheapest, while the cast iron ones are the longest lasting.

Baffles

The baffle is an obstruction to flue gases and gives direction to the flow. Baffles can be either in the form of a rectangular wall or a spherical mound constructed inside the subsidiary pot openings. A baffle or a series of baffles prevents direct escape of hot gases, allowing them to burn more completely. Also, a carefully placed baffle redirects the flow of hot gases around the pot, thereby facilitating better heat transfer. If baffles are placed at the exit of the combustion chamber, they redirect the flame and the flame lashes back onto the surface of wood, as well as under the pot surfaces. This results in quick heating of the pot and helps in cooking the food faster.

If baffles are placed in the flue, they will keep the hot gases near the second and third pots. More heat is transferred to the pots, thereby hastening the cooking. ITDG has done tests which show that baffles can decrease wood consumption by 50% when placed correctly.

According to Joseph [6] when a baffle is placed under the second pot, the distance between the base of the pot and the top of the baffle should be approximately 20 mm to obtain maximum heat transfer. If the distance is too great , heat transfer to the pots is reduced considerably and if it is too little, the gases may not be able to overcome the flow gradient and they get choked. A distance in the range 35-75 mm has been recommended.

Dampers

A damper is a movable plate which controls the draft or flow of exhaust gases. It can be made of metal or blocks of clay or stone. If sheet metal is used it will be especially hot to touch when cooking is being done, so a handle of poor conductivity should be provided. Normally, one or more dampers are used to control the flow of air. Placement and operation of the dampers depend on the design and construction material of the stove. If only one damper is used or needed, it should be placed at the mouth of the air inlet. A second damper can be placed near the chimney, just before it bends upwards. A very large stove may require additional dampers to prevent the hot gases from reaching unused areas of the stove. Dampers usually have uniaxial movement. Dampers used at the fuel door serve to minimise the radiation losses from the combustion chamber.

Chimney

The chimney is a passage way through which gases and smoke leave the fire. Its function is to draw vapour and smoke out of the kitchen and create a pressure difference so that air is drawn into the fire box. Chimneys can be made from clay pipes, sheet metal, cast iron, masonry, concrete pipes, bamboo, ferromud and so on. Brick or clay pipes have a longer life compared to sheet metal chimneys. Ferromud chimneys can be made from chicken mesh plastered with clay to form a strong structure. They could be significantly cheaper than either metal or clay chimney pipes.

Chimney diameter is ascertained on the basis of the quantity and velocity of the flue gases. The height is designed from the point of view of draft requirements. The bigger the stove, the greater should be the size of the chimney. If the chimney is not big enough, the stove will not be able to draw in sufficient air to operate at maximum efficiency. Too big a chimney will however increase the heat losses. It is advisable not to have a diameter greater that 150 mm as cold air could flow back down the chimney. The height could be from 2 to 2.5 m. The top end should be about 0.75 m above the highest point of the roof. This is desired both for fire safety as well as for preventing down drafts.

In addition to smoke venting, chimneys induce draft and increase the fuel burning rate. It is reported [5] that for every square metre of grate area, a stove without chimney can burn only 20-30 kg/hr of wood, while, if a chimney is used, combustion rates as high as 100 kg/hr can be obtained. Chimney stoves can have higher or lower overall efficiency in comparison with the traditional stove. With the introduction of a chimney, both the fuel burning rate and the air to fuel ratio increase. This increases the rate of production of hot combustion gases when a stove has a chimney. Attempts must be made to extract the heat of the flue gases in an efficient manner by having set-ups that collect more heat per unit of wood burnt than the version without a chimney. If this criterion is not satisfied, the efficiency of a chimney stove will be poorer than that of a traditional stove.

Slanted chimneys and other unnecessary resistances in the flow passages increase fuel consumption. The following precautions must be taken when installing a chimney.

(i) The chimney must not be constructed exactly at roof level, but about 300 mm above it. It must also not be constructed by the side of a wall. In these two situations, the wind causes back draft and the flue gases are forced through the fuel feed openings, thereby extinguishing the fire.

(ii) It must not end inside a thatched roof just below the thatching.

Blowers produce forced air flow and increase the combustion rate. While passive elements like chimneys produce a burning rate of 100 kg/hr m^2 of grate area, the use of a blower increases this to 200 kg/hr m^2 when logs are used and to 300 kg/hr m^2 when chips are used. Blowers could either be hand operated or power operated resulting in (a) forced draft type when air is blown before the combustion zone, and (b) induced draft when flue gases are drawn out after the combustion zone. Draft can be diagonal, up, down or cross type. Blowers are generally suggested for hotels, where fast combustion and wide load variations are to be met [7].

Shields

The function of any stove is to transfer the maximum possible heat produced from the wood to the load. When the fuel burning zone in the combustion chamber is exposed to the environment, heat is radiated out. When it is shielded, the shield only conducts heat away. The combined radiative and convective loss is about 250 times the conduction loss, when the conducting material is clay. Therefore, shielding is essential for any efficient stove. Shielding systems are based on the use of large thermal resistances to minimize the side-ward heat loss. Low thermal conductivity materials like air, asbestos, plaster, mica, cement, hollow bricks, clay, etc. provide good shielding. Usually a multiple resistance system with air as one of the resistances give a high conductive resistance. But heavy shielding does not improve the efficiency for the following reasons:

(a) When the stove wall thickness increases, the conductive resistance increases, but the heat is taken away in another form as capacitance heat of the thermal mass. Thus thick walls absorb more heat than that which they resist through conduction.

(b) When the air gaps (used as conductive resistances) are too big, they produce convective currents and offset the gains of the low conductive transfer. Also, there is substantial heat by-pass from the connected portions of the stove.

(c) Total suppression of heat losses to the sides lowers the overall efficiency. This is probably due to loss of heat through stack gas.

There are two ways of tapping flue gas heat: (a) provision of a water jacket around the combustion chamber, and (b) provision of a water jacket around the flue gas connection. The hot water is then tapped and used for bathing. The main advantage of these systems is that the overall efficiency increases. The disadvantages are : sealing problems, corrosion, and marked fall in the power output to the main load. Hence, in spite of increase in system efficiency, firewood consumption may increase. Also, on many occasions the hot water or steam produced may not find immediate use.

Vessel Size, Shape and Material

The heat from the combustion gases gets transferred to the food via the vessel. The heat transfer to the bottom of the vessel is by conduction, convection and radiation, and therefore the factors affecting heat flow will be, surface area for conduction, the thermal conductivity of vessel bottom and radiation configuration factor between the flame and the vessel bottom. High thermal conductivity with large surface area would be desirable. Also from the convection point of view attached flow over a longer path permitting more residence time for gases would be desirable. This can be obtained with a round bottomed vessel with copper bottom as is used in some cooking vessels. The surface area to the volume of the vessel should be large. The flow pattern over the sides of the vessel should be attached flow and short circuiting of the combustion gases should be minimised as it could be the case with detached and deflected flows from vessel surfaces. Attached, preferably vortex and turbulent flows result in higher convective heat transfer to vessel. Stirring of fluid enhances heat transfer from vessel to food. These aspects of heat transfer and fluid flow should be the guiding factors in the selection and use of proper sized and shaped vessels in order to get better heat utilisation.

Details of some of the representative improved cook stoves are provided in Appendix I.

ESTIMATION OF VARIOUS ENERGY LOSSES [12]

Quantitative estimates of various energy losses that occur in cook stoves would be valuable in identifying the areas of weakness of the stove and an eventual rectification in design. To establish the cooking efficiency, important questions to be answered are how the energy is utilised and how losses occur during the cooking cycle. The various energy losses are estimated based primarily on simple measurements. These measurements are made periodically during the simulated cooking test. In the calculations of energy losses, measurements are averaged over the entire burning cycle, assuming that the wood consumption does not vary throughout the cycle. Due to this simplification, the energy loss estimates are only approximate. Various energy losses from the stove are listed below.

(i) The energy loss from the pot and pot cover through radiation and convection.
(ii) Sensible heat loss contained in the combustion products released from the stove.
(iii) Sensible heat loss in the excess air.
(iv) Heating and evaporation of moisture in the fuel.
(v) Evaporation of water originating from hydrogen in the fuel.
(vi) Heat losses from the stove body.
(vii) Heat loss through the incomplete combustion in the form of carbon monoxide.
(viii) Heat loss from the charcoal residue at the conclusion of the cooking.

Pot Surface Losses

Energy losses from the pot and cover are by convection and radiation to the ambient. The convection heat losses from the vessel is estimated from the formula:

$$Q_{vc} = U_v \, A_v \, (T_v - T_a) \, t \tag{1}$$

where Q_{vc} = Convection losses from the vessel surface, Kcal
A_v = Surface area of the vessel, m^2
T_v = Temperature of the vessel, °C
T_a = Ambient temperature, °C
U_v = Overall heat transfer coefficient, Kcal/m^2 hr °C
t = Duration of combustion, hrs.

U_v is determined by measuring the heating rate dT/dt and temperature difference $(T_v - T_a)$. dT/dt is estimated from the heating and cooling graph of the vessel and then U_v is calculated as:

$$U_v = \left(\frac{dT}{dt}\right) \times \left(\frac{\rho_{H_2O}}{A_v}\right) \times \left(\frac{V_{H_2O}\, C_{H_2O}}{T_v - T_a}\right) \tag{2}$$

where ρ_{H_2O}, V_{H_2O}, C_{H_2O}, are the density, volume and specific heat of water respectively.

The heat losses due to radiation from the vessel surface are calculated from the formula:

$$Q_{vr} = \varepsilon \sigma A_v (T_v^4 - T_a^4)\, t \tag{3}$$

where T_v = Temperature of vessel surface, °K
T_a = Ambient temperature, °K
Q_{vr} = Heat losses due to radiation from the vessel surface, Kcal
σ = Stefan Boltzman constant = 4.9×10^{-8} Kcal/m^2 hr $°K^4$
ε = Emissivity of the pot material
t = Duration of combustion, hrs
A_v = Surface area of the vessel, m^2.

Stove Body Surface Losses

Energy loss through the stove body by convection, radiation and conduction to the ambient is:

$$Q_{sc} = U_s A_s \, (T_s - T_a)\, t \tag{4}$$

where Q_{sc} = Convection losses from the stove surface, Kcal
A_s = Surface area of the stove body, m^2
T_s = Stove body temperature, °C
T_a = Ambient temperature, °C
t = Duration of combustion, hrs
U_s = Overall heat transfer coefficient, Kcal/m^2 hr °C.

U_s is determined by measuring the heating rate dT/dt and temperature difference $(T_s - T_a)$. dT/dt is measured from the heating and cooling graph of the stove body and U_s is calculated as:

$$U_s = \left(\frac{dT}{dt}\right) \times \left(\frac{\rho_{air}}{A_s}\right) \times \left(\frac{V_{air}\ C_{air}}{(T_s - T_a) A_s}\right) \tag{5}$$

Where ρ_{air}, V_{air} and C_{air} are density, volume and specific heat of air respectively. Heat loss due to radiation from the stove body surface is calculated from the formula:

$$Q_{sr} = \varepsilon \sigma A_s (T_s^4 - T_a^4)\, t \tag{6}$$

where Q_{sr} = Radiation loss from the stove body surface, Kcal
σ = Stefan Boltzman constant, 4.9 x 10^{-8} Kcal/m^2 hr °K^4
ε = Emissivity of the stove body material
t = Duration of combustion in hours.

Heat loss due to conduction from the stove body to the floor is found by :

$$Q_{cd} = 2k\ A_{cd} (T_f - T_a) \left(\frac{t}{\pi \alpha}\right)^{1/2} \tag{7}$$

where, Q_{cd} = Heat losses due to conduction from stove body, Kcal
A_{cd} = Contact area between stove and floor, m^2
k = Thermal conductivity of the stove body material, Kcal/m hr °C
T_f = Floor temperature, °C
α = Thermal diffusivity of the stove material, m^2/hr
t = Duration of combustion, hrs.

Sensible Heat Loss through the Combustion Products

Thermal energy loss from the combustion products when they are released from the stove is given by :

$$Q_{cp} = W_{fw} (1 - F_m)\, Q_i (\Delta H_i) \tag{8}$$

where Q_{cp} = Thermal energy losses from the combustion products, Kcal
W_{fw} = Amount of fuel wood burnt, kg
Q_i = Average quantity of combustion products, kg per kg of dry wood
F_m = Fraction of moisture in the wood
ΔH_i = Difference in the enthalpy for the products between the average temperature at the point of release and ambient, Kcal/kg.

The quantity of products of combustion are calculated assuming that the elemental composition of the dry wood is 52 per cent carbon, 41 per cent oxygen, 6 per cent hydrogen and 1 per cent ash by weight. Also it is assumed that all of the oxygen present in the wood reacts during the combustion and that the fuel is completely converted to CO_2, CO and H_2O. Using these assumptions overall combustion reaction per kg of dry wood is :

[43.3 moles of C + 30.0 moles of H_2 + (X + 12.81) moles of O_2 + 3.76 X moles of N_2]
= [43.3Y (1-Z) moles of CO_2 + 43.3 (1-Y) (1-Z) moles of CO + 30.0 moles of H_2O
+ 3.76 X moles of N_2] (9)

where X is the number of moles of atmospheric oxygen used in combustion and is given by :

$$X = 21.65\,(Y - Z - YZ) + 23.85 \quad (10)$$

and Y is the fraction of reacting carbon converted to CO_2 and is given by:

$$Y = F_{CO_2}(F_{CO_2} + F_{CO})^{-1} \quad (11)$$

where F_{CO_2} and F_{CO} are the fractions of CO_2 and CO respectively in the dry combustion products released from the stove. Z is the fraction of the carbon in the fuel remaining as charcoal residue after the completion of cooking and is given by :

$$Z = W_{cr}\;[0.52\,W_{fw}\,(1 - F_m)]^{-1} \quad (12)$$

where W_{cr} = weight of the charcoal reclaimed, kg.

The CO_2 and CO percentages in the combustion gases are measured using an Orsat analyser.

Sensible Heat in the Excess Air

The energy loss Q_{ca} due to heating of the excess air drawn into the stove is given by:

$$Q_{ca} = W_{fw}\;(1 - F_m)\,Q_a\;\Delta H_a \quad (13)$$

where Q_a = average number of moles of excess air per unit of dry wood
ΔH_a = the difference in the enthalpy content of the air between the average temperature at the assumed point of release and ambient, Kcal

and

$$Q_a = 4.76\,F_{O_2}(1 - 4.76\,F_{O_2})^{-1}\;Q_{cp} \quad (14)$$

where F_{O_2} = the fraction of oxygen in the dry combustion products released from the stove
Q_{cp} = the quantity of the dry combustion products CO_2, CO and N_2 per unit of dry wood.

F_{O_2} is measured using an Orsat analyser.

Heating and Evaporation of the Moisture in the Fuel

Energy loss Q_{cm} due to heating the moisture in the fuel to its boiling point, evaporating and heating water vapour to the average temperature at which the gases are released from the stove is given by:

$$Q_{cm} = W_{fw}\,F_m\,[C_{H_2O}\;(T_c - T_a) + L\,\Delta H_2O] \quad (15)$$

where, ΔH_2O = difference in the enthalpy content of water vapour between the average temperature at the assumed point of release and the boiling temperature T_c

Q_{H_2O} = specific heat of the water, Kcal/kg °C

L = Latent heat of water, Kcal/kg.

Evaporation of Water Originating from Hydrogen in the Fuel

The heat loss due to the evaporation of water originating from hydrogen in the fuel is given by Q_{H_2}:

$$Q_{H_2} = W_{fw}\,(1 - F_m)\; Q_{H_2O}\, L$$

where Q_{H_2O} = the quantity of water per unit of dry wood, which is based on the assumed combustion stoichiometry and the molecular weight of water.

Using loss calculations a heat balance sheet could be drawn for the stove which will enable identification of the strength and weakness of the stove.

TESTING THE PERFORMANCE OF WOOD BURNING STOVES

The stoves constructed/fabricated have to be tested and rated so that their performance can be compared. This requires the concept of efficiency of stoves. Also desirable would be an accepted standard method of testing. Different researchers have reported different testing methodologies. Provisional International Standards [8,9,10,11] list in detail three tests labelled as Water Boiling Test (WBT), Controlled Cooking Test (CCT) and Kitchen Performance Test (KPT). It is also agreed that a distinction should be made between testing done for local use only and testing where results are intended to be transmitted to other places. The Water Boiling Test is generally used for comparing the performances of different stoves.

The testing of stoves is of importance for the following reasons:

(a) It permits a better understanding of the process of combustion, heat utilisation and recuperation possibilities.

(b) It renders possibility to determine the functioning of the individual components in stoves, and to isolate weaknesses with a view to improving the overall performance.

(c) It gives an opportunity to observe the reactions of the users and to asses the acceptability of the stoves.

(d) It provides stove makers with valuable information for further design modifications.

(e) It also provide a basis for comparing different stoves.

There now seem to be a fairly general consensus on the testing of stoves, although more discussion and investigation is needed on some of the difficult questions such as the criteria for comparing different models [3]. A stove which is considered satisfactory under one set of circumstances may prove inadequate under others. Experience has shown that nothing can replace field tests, conducted over a period of time with the participation and involvement of local communities. The aim of properly conducted field tests should be to establish the average, as opposed to exceptional performance of the stoves and to, as far as possible, seek out areas for possible improvements.

Concepts of Efficiency [8]

There are many different ways of looking at stove performance and of measuring stove efficiency. A widely used method compares the energy that goes into the stove with the energy that comes out, to determine Percentage of Heat Utilized (PHU). A broader concept of efficiency accounts for energy losses in evaporation. Once food or water reaches the boiling point, it does not absorb more heat, only excess heat is produced. A stove that is regulated to maintain the temperature for boiling without creating excess heat is in that respect, more efficient. This section will review some different ways of measuring efficiency.

Energy Losses

Figure 1 is an energy flow diagram for a wood burning cook stove. Useful heat is absorbed in the food, but heat losses are associated with:

- incomplete combustion of wood,
- heat loss from the stove body to the environment,
- heat loss from the pot surfaces (including lids),
- heat loss through the chimney, and
- thermostatic steam escaping from the pot due to excessive stove power.

Partial Efficiencies

Different partial efficiencies can be suggested. For example, combustion efficiency (η_c), heat transfer efficiency (η_t), pot efficiency (η_p) and control efficiency (η_r) can be given as:

$$\eta_c = \frac{\text{heat generated by combustion}}{\text{energy potential in fuel wood}}$$

$$\eta_t = \frac{\text{gross heat input to the pot}}{\text{heat generated by combustion}}$$

$$\eta_p = \frac{\text{net heat input to pot}}{\text{gross heat input to the pot}} = \frac{\text{gross heat} - \text{surface losses}}{\text{gross heat input to the pot}}$$

$$\eta_r = \frac{\text{heat absorbed by the food}}{\text{net heat input to the pot}}$$

These efficiencies can be associated with stoves operated in predictable or well-defined ways, such as at a single power level, or in defined cooking patterns.

Overall Stove Efficiency

An overall stove efficiency η_o is often used. It is a product of the first three partial efficiencies described above.

$$\eta_o = \frac{\text{net heat input to pot}}{\text{energy potential in fuelwood}} = \eta_c\,\eta_t\,\eta_p$$

A cooking efficiency η_k can be defined as:

$$\eta_k = \frac{\text{heat absorbed by the food}}{\text{energy potential in fuel wood}}$$

The cooking efficiency η_k accounts for all the heat losses.

Thus: $$\eta_k = \eta_o\ \eta_r = \eta_c\ \eta_t\ \eta_p\ \eta_r$$

Specific Consumption

Alternatively, stove performance can be expressed by specific fuel consumption figures, *SC*, instead of efficiencies. For example at the cooking efficiency level,

$$SC = \frac{\text{mass of consumed fuelwood}}{\text{mass of cooked food}}$$

There is a link with the cooking efficiency, as

$$\eta_k = \frac{\text{heat absorbed in cooked food}}{\text{energy potential in fuel wood}}$$

$$\eta_k = \frac{(\text{mass of cooked food})\ C_p\ \Delta T}{(\text{mass of consumed wood}) \times \text{heating value}}$$

Thus: $$\eta_k = \frac{1}{SC}\left[\frac{(C_p\ \Delta T)}{\text{heating value}}\right]$$

where C_p represents the specific heat of the food, and ΔT the temperature change (from ambient temperature to boiling temperature). Therefore

$$SC = \frac{1}{\eta_k}\left[\frac{(C_p\ \Delta T)}{\text{heating value}}\right]$$

Expected General Tendencies of Various Efficiencies

The combustion efficiency might be relatively high at high stove power output (Fig. 3). However, in general, a wood-stove has a limited power range $(p_{max} - p_{min})$ or flexibility $(p_{max} - p_{min})$. Below the power level p_{min}, stable combustion cannot be maintained and thus the combustion efficiency disappears.

The heat transfer efficiency (Fig.4) is expected to increase slightly when the stove power is reduced. This is a well-known tendency in any heat exchanger.

The pot efficiency (Fig.5) can be written as $\eta_p = (1 - \text{pot loss/gross heat input})$. With a given pot temperature, pot losses are expected to be constant, therefore, pot efficiency will decrease when the power is reduced. It goes down to zero when the gross heat input to the pot equals the pot losses.

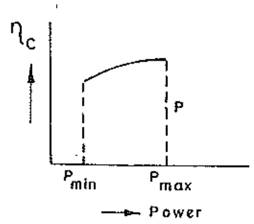

Fig. 3. Combustion efficiency.

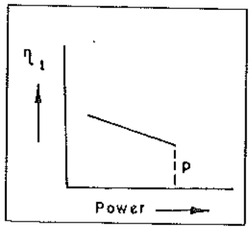

Fig. 4. Heat transfer efficiency.

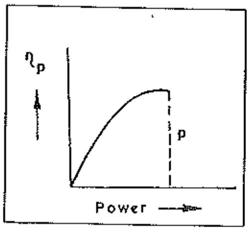

Fig. 5. Pot efficiency.

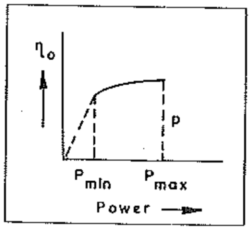

Fig. 6. Overall stove efficiency.

Finally, the control efficiency, is close to one as long as the water is not boiling. It drops too close to zero when steam is generated, as little heat is further absorbed in the food.

From the preceding it can be seen that overall stove efficiency (Fig. 6) is zero when the pot is maintained at simmering without producing steam. If the stove cannot operate at this low power level, the cooking efficiency, not the stove efficiency, is zero.

WATER BOILING TEST

Water Boiling Tests (WBT) are short, simple simulations of standard cooking procedures. They measure the fuel consumed and time required for a quick comparison of the performance of different stoves or the performance of the same stove under different operating conditions to quantify an expected stove performance. WBTs are carried out by stove designers, researchers, and field workers. Water Boiling Tests use water to simulate food, the standard quantity is two-thirds the full pan capacity. The test includes high power and low power phases. The high power phase involves heating the standard quantity of water from the ambient temperature to boiling as rapidly as possible and keeping it boiling at the same high power for 15 minutes. The low power phase follows and the power is reduced to the lowest level needed to keep the water within 2°C of boiling over a one hour period. WBTs should be repeated at least four times, and the results averaged. Test results are expressed in terms of wood consumption and time required.

Efficiencies in Water Boiling Tests

The overall stove efficiency can be measured in Water Boiling Tests by using the stove at high power, or by using it at a controlled power level where steam generation simulates absorbed heat. A power efficiency plot can be drawn, with power limits, $(p_{max} - p_{min})$. Alternatively, it can be an averaged value for one test period simulating the cooking period.

Cooking efficiency can be measured in a similar way. Note that in this case the steam generation is a loss. At simmering power levels the cooking efficiency is close to zero. The cooking efficiency concept therefore has been applied to a cycle that included both the heating up period and simmering. In this case, however, the cooking efficiency drops as simmering times increase.

A better approach to this problem is to switch to specific consumption concepts with *SC* given as:

$$SC = \frac{C_p \, \Delta T}{\eta_k \text{ heating value}}$$

When the cooking efficiency goes to zero during simmering, the *SC* figure will not go to infinity (which is meaningless). The reason for this is that the temperature change is also equal to zero.

For practical reasons a Water Boiling Test report should give not only the specific consumption, but the power limits and evaporation as well. This will make it easier to predict cooking test results from simple Water Boiling Tests.

Cooking efficiencies can more realistically be checked in Controlled Cooking Tests. Again, the concept should be applied to the entire cooking cycle. However, in Controlled Cooking Tests, the specific consumption concept is widely preferred.

Alternatively, for the complete test period of one test overall efficiency can also be calculated as $\eta_o = X/Y$, where X = [Σ (mass of each pot x sp. heat of each pot x temp. rise of each pot from ambient) +Σ (initial mass of water in each pot x sp. heat of water x temp. rise of water from initial temperature to boiling water temp. in each pot) − Σ (mass of water evaporated from each pot x latent heat of water)], and Y = [(mass of wood consumed x lower calorific value) − (mass of charcoal left x calorific value of charcoal)].

It is important to know how to interpret the results of the WBT, and to remember that a low specific consumption indicates a high efficiency. As efficiency declines, *SC* rises. It is possible to use WBT results to judge the suitability of a stove for various cooking tasks. For example, for high power cooking (rapid frying and boiling), a stove with the greatest high power efficiency might be best, for simmering, however, the best stove might be the one that shows low *SC* for both high and low power.

CONCLUDING SUGGESTIONS

Efficient use of wood as an energy source for cooking is emphasized. Even a marginal increase in cooking efficiency will be valuable. Emerging stove designs may be based on scientific factors enumerated earlier, though the local economic factors may override some of these. Further, the following operational guidelines would contribute to increased cooking efficiency.

- Make sure that the cooking pot sits snugly on to the cooking stove.
- Keep the damper closed as much as possible.
- Use small pieces of wood.
- Keep the fire small and cook slowly.
- Keep covers on the pots.
- Use metal pots and when possible pressure cookers.
- Keep the doors and windows closed in cold climate.

- Remove charcoal and wood when the cooking is finished and extinguish them with water.
- Close damper after cooking to keep the stove warm.
- Clean chimney pipes regularly for fuel efficiency and safety.

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APPENDIX - I

DETAILS OF SOME IMPROVED COOK STOVES [12, 13]

As noted in the Introduction, a large number of stove designs have emerged of late. Very few of the representative ones which have accounted for some of the design aspects enumerated earlier are presented here. It may be noted that though their energy utilisation for cooking is better than many early models, these are not necessarily the best.

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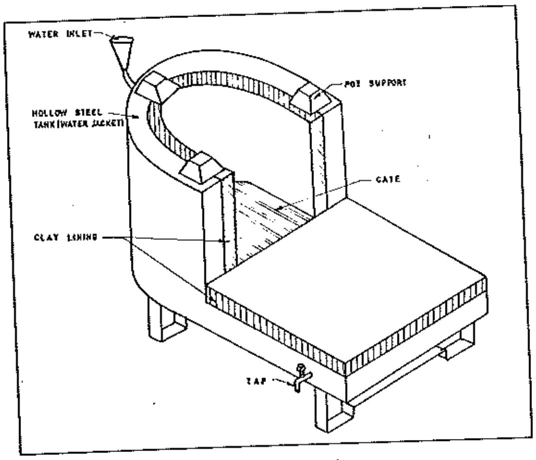
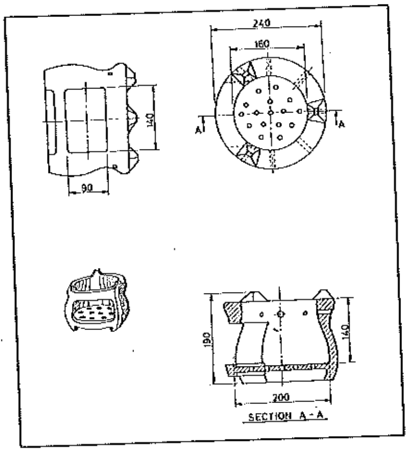
Economical Chula

It is a single pan water jacketed stove for absorbing heat from the stove body. Grate improves air circulation on the fuel bed. Overall dimension of the stove is approximately 750 mm x 1800 mm x 900 mm height. Thermal efficiency is approximately equal to 14%. Disadvantages of this stove are that it is not smoke free, heat losses can occur through front side and the construction is complicated by water jacket.



Economical chula.



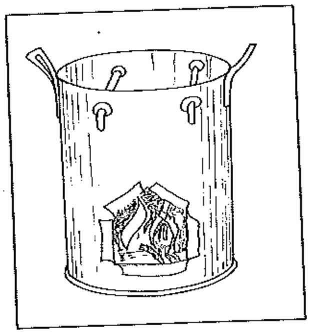
New keren stove.

New Keren

A portable ceramic stove which can accommodate one pot of spherical or cylindrical shape. This pot can have a diameter of 0.24m. It will burn long wood pieces and it has no chimney, no dampers, no baffles. It has grate and a provision for secondary air. It weighs 3 kg and can be refuelled without lifting the pan. Water boiling test has shown that the average wood consumption is 1.15 kg/h r[3].

Economical Wood Burning Stove

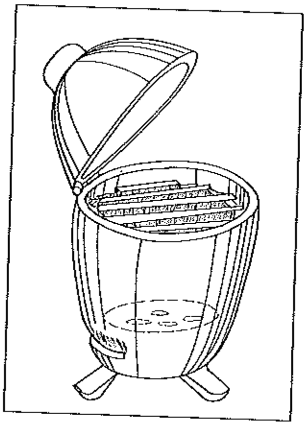
It is a portable metal stove, which can accomodate one pot of cylindrical or spherical shape. It will burn long wood pieces and it has no chimney, no damper, no baffles, no grate and no provision for secondary air. The stove is made of a paint can or a small oil drum. It weighs 2 kg and it conserves 50% of the fuel wood compared to the open fire.



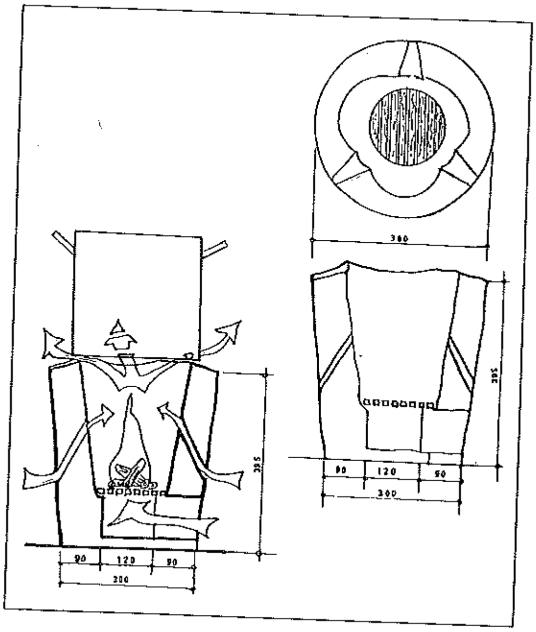
Economical wood burning stove.

Kamado Cooker

It is a portable ceramic stove which can accommodate one pot of cylindrical or spherical shape. It will burn short wood pieces or charcoal. It has no chimney. It has a damper for combustion gases and a damper for combustion air and a metal grate, but no provision for secondary air. It can be used as a small oven. It weighs 10 kg with a potential fuel saving of 50% compared to the open fire.



Kamado cooker.



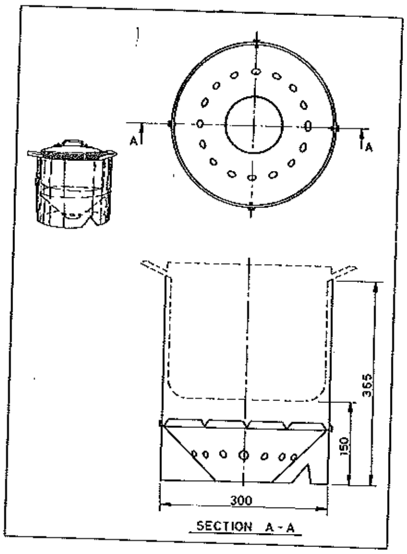
Bucket stove.

Bucket Stove

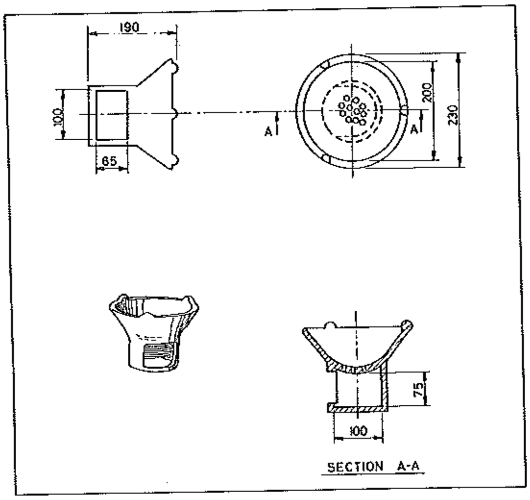
An old metal bucket is used as basic mould. First, an opening is made in the bucket for the ash chamber and then six holes are cut at grate level, for the admission of secondary air. On the top of the stove, three small mounds are provided on which the cooking pot will sit. Its efficiency is not high but may be improved by the use of round bottomed pots which enters the fire box. These will give better results than flat bottomed pots placed on top of the stove. The principal advantages of the bucket stove are its low cost, mobility and ease of manufacture.

De-Lepeleire Stove

It is a portable metal stove which can accommodate one pot of cylindrical shape. This pot can have a diameter of 0.25 m. It will burn short wood pieces and it has no chimney, no dampers, no baffles, a grate and no provision for secondary air. Stove weighs 8 kg and refuelling is made through the pot hole when the pan is removed. It shows a high efficiency of about 20 to 30%.



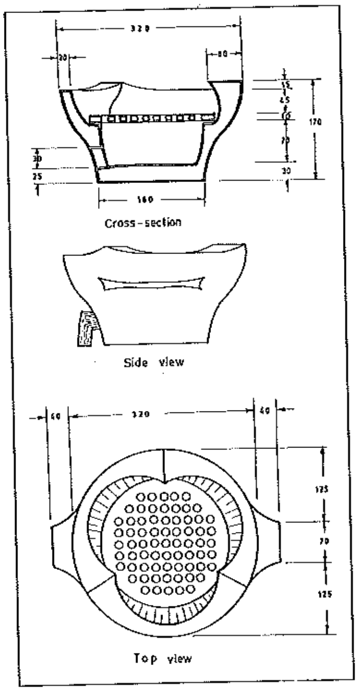
De-lepeleire stove.



Indonesian stove.

Indonesian Stove

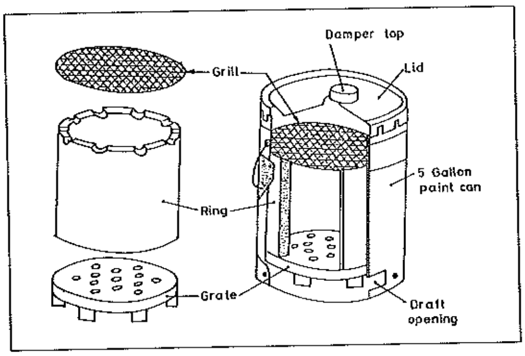
It is a portable ceramic stove which can accommodate one pot of cylindrical or spherical shape. This pot can have a diameter of 0.25 m and it has no chimney, no dampers, no baffles, a grate and no provision for secondary air. This stove weighs 3 kg and for refuelling, the pan must be lifted from the stove. It has a high efficiency of about 35%.



Clay Jiko stove.

Clay Jiko Stove

The Clay Jiko Stove is very common in many parts of the world. It is baked in small wood fired kiln. It is useful and low priced. Several tests have been conducted with this type of stove which has displayed good resistance to thermic shock. It has not yet been possible to determine longevity of the stove under condition of intensive use. It is mainly used as a charcoal burning stove. It has an efficiency of about 23%.



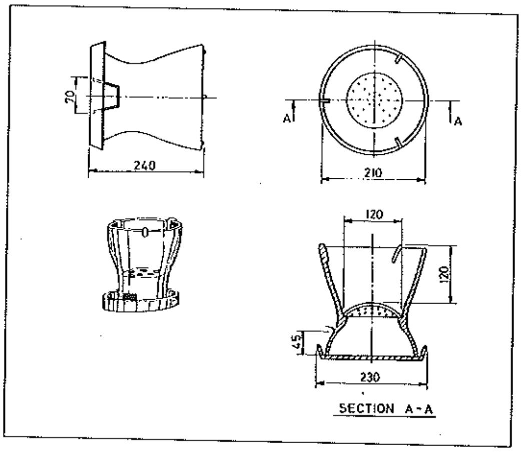
Kamado demonstration cooker.

Kamado Demonstration Cooker

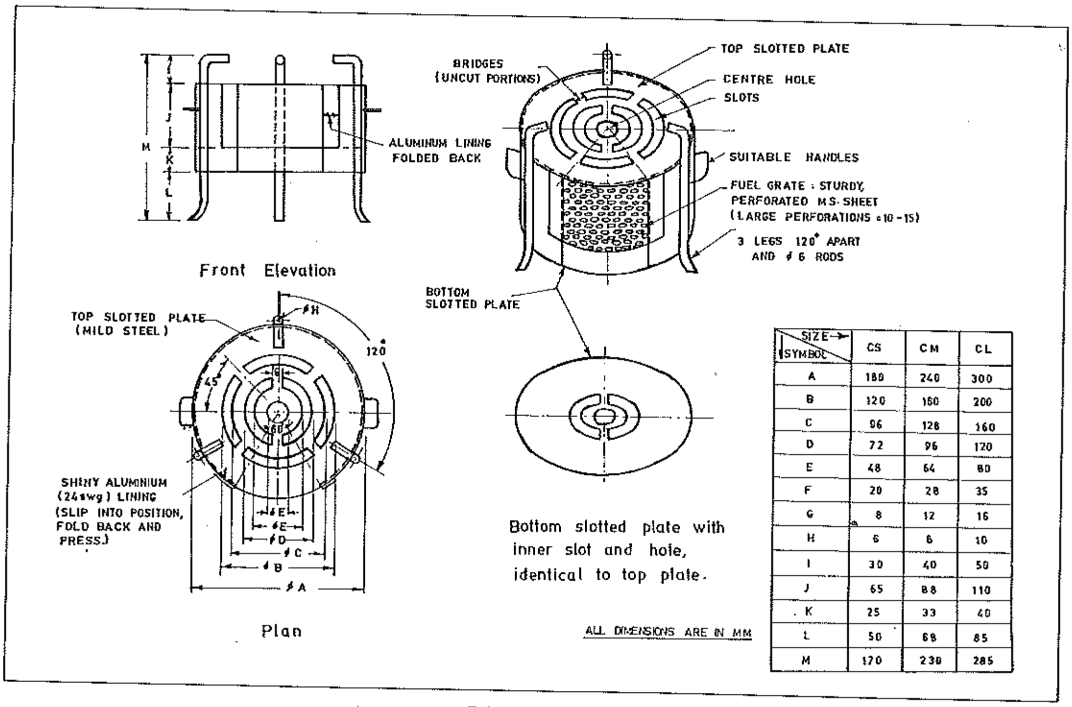
This stove was developed at the Georgia Institute of Technology, USA, as a modification of the Kamado Cooker used in Japan. This stove can be used with wood or coal as fuel. Design features considered are ceramic grate with holes for air circulation, damper for draft control, metal grill for seating cooking vessel, and provision of holes on the lid and base of the can for air vent. In this, heat utilisation is greater because of double walled construction and enclosed cooking.

Da Silva Stove

It is a portable ceramic stove, which can accommodate one pot of cylindrical or spherical shape. The pot can have a diameter of 0.25 m. It has no chimney, no damper, no baffles, a grate and no provision for secondary air. It weighs 4 kg. Refuelling is made by lifting the pot from the stove. Water boiling tests have shown a high efficiency of about 35%.



Da Silva stove.



SIZE → / ↓ SYMBOL	CS	CM	CL
A	180	240	300
B	120	160	200
C	96	128	160
D	72	96	120
E	48	64	80
F	20	28	35
G	8	12	16
H	6	8	10
I	30	40	50
J	65	88	110
K	25	33	40
L	50	68	85
M	170	230	285

Priyagni stove.

Priyagni Stove

Central Power Research Institute, Bangalore, has developed a high efficiency wood burning stove in three sizes for use in rural domestic cooking. It is simple in design and needs minimum material for its construction. The stove has been scientifically designed to obtain a correct proportion of air to mix with the fuel to yield a less smoky, less luminous, steady and well directed flame. It has an efficiency of up to 30%. An aluminium sheet lining is also provided in the chamber to reflect heat, thus reducing the wall radiation losses.

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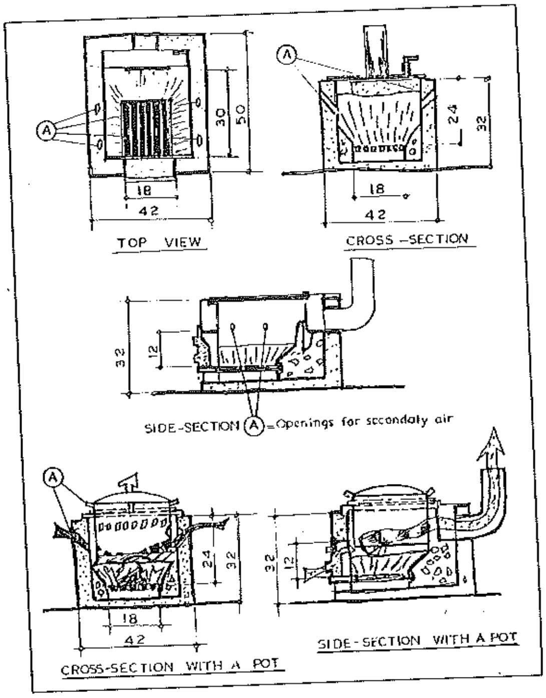


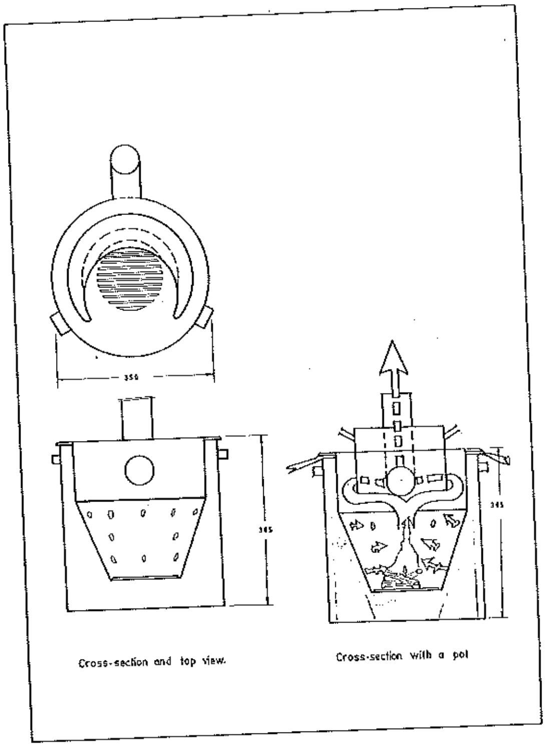
Rural stove.

Rural Stove

The rural stove is suitable for a small family, which does not need the facility of cooking with two pots at the same time. Optimal fuel efficiency is achieved through a carefully designed fire box, the provision of preheated primary and secondary air, the use of a baffle to slow down the exit of gases and the use of a damper to regulate draught. Tests give good results which satisfy the user.

Polish Stove

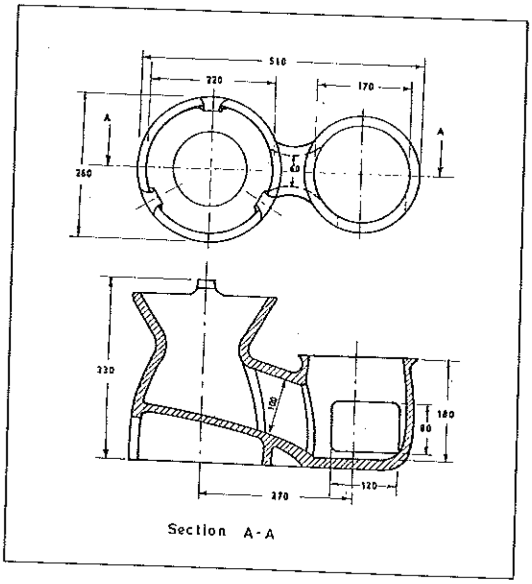
The stove takes the form of a cylinder, with double walls, welded to a round metal sheet base and enclosed from above by a metal ring. An inner structure is then lowered inside the double walls. This consists of an open cone fire box, into which holes are drilled to allow for the admission of secondary air. In operation, the flames and gases first heat the base of the pot. They are prevented by a crescent shaped platform from leaving the stove directly, and are forced to flow around the sides of the pot before departing via a chimney. In this way the heating surface of the pot is increased while the cooling surface in diminished. It has a high efficiency.



Polish stove.

Micuta Jiko

It is a portable metal stove which can accommodate one pot of cylindrical or spherical shape. This pot can have a diameter of 0.2 m. It will burn short wood. It has a chimney, no damper, no grate, a baffle and no provision for secondary air. The stove is completely made of sheet steel and weighs 20 kg. The water boiling test showed a very high efficiency.



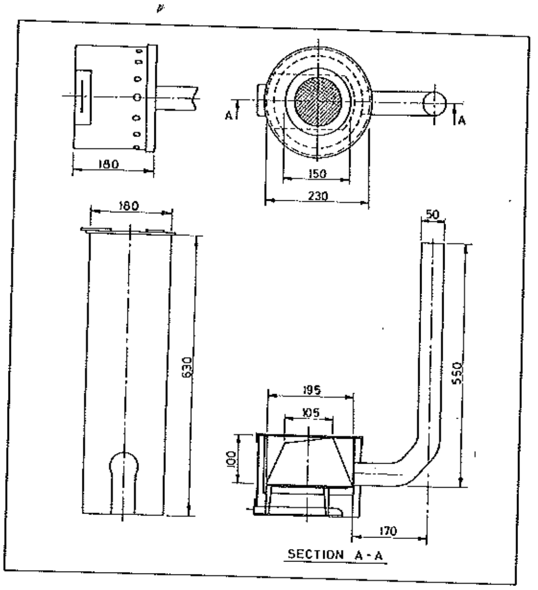
TERI-ITDG stove.

TERI-ITDG Stove

It is a portable ceramic stove which can accommodate two pots of cylindrical or spherical shape. These pots can have diameters of 0.23 and 0.30 m. On the second pot hole smaller pots also can be used with a minimum diameter of 0.15 m. It has no chimney, no damper, no baffles, no grate and no provision for secondary air. It weighs 12 kg and refuelling is made without lifting the pan. Water boiling tests have shown good efficiency.

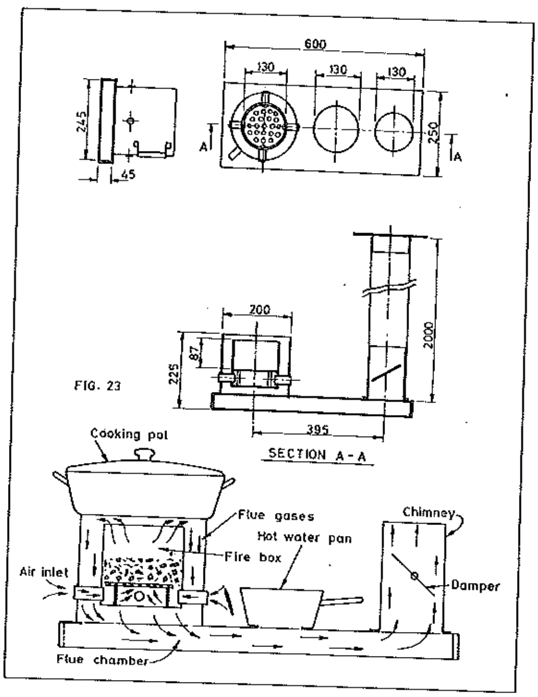
Family Cooker

This stove was developed at the Department of Appropriate Technology, Eindhoven University of Technology. The design won an international award. The design features of the



Micuta Jiko.

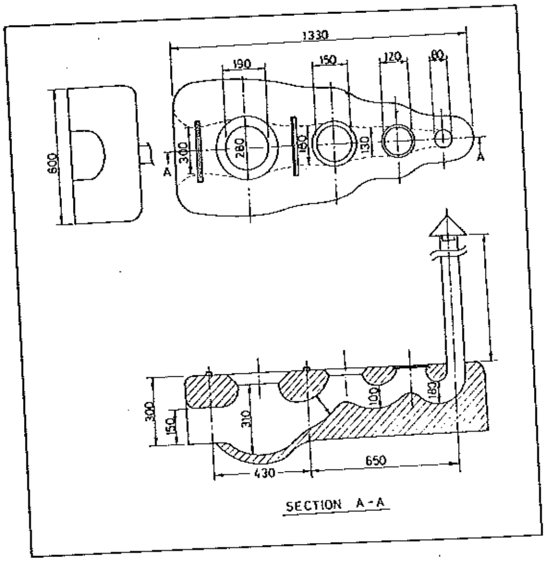
stove are cylindrical housing with concentric fire box, one pot hole for warming located on flue chamber, grate for burning chamber, damper in chimney for draught control and chimney for smoke outlet. It saves 75% of the fuel compared to an open fire and can be fully dismantled.



The family cooker.

Lorena Guitar Stove

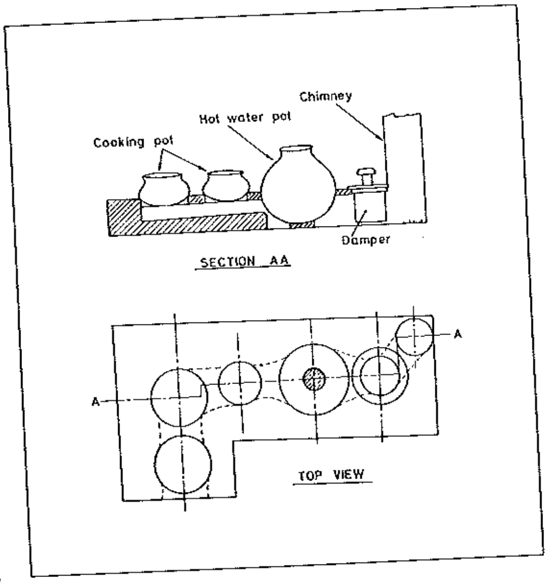
This stove built of mud, takes three spherical pots of 0.25, 0.20 and 0.16 m diameter. It burns short wood pieces and has a chimney, air and flue gas dampers, no grate, baffles or secondary air provision. It weighs 200 kg and is refuelled with pans in place. Water boiling test showed good efficiency and fuel wood saving of 50% compared with the traditional open fire.



Lorena guitar stove.

Herl Chula

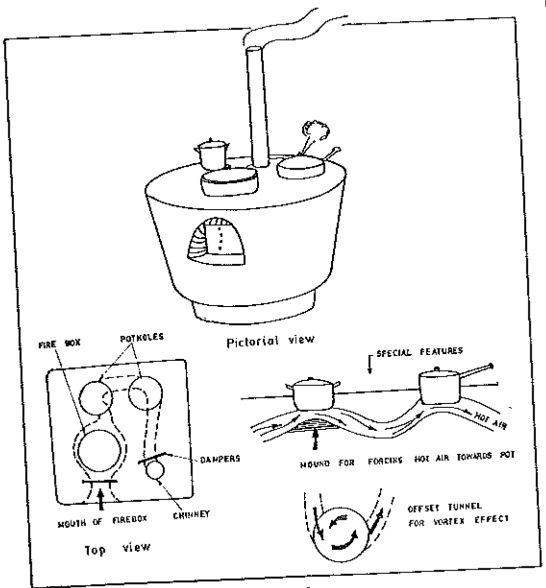
This stove was developed at Hyderabad Engineering Research Laboratory. The design features of this stove are an 'L' shaped duct with three pot holes for cooking and one for heating water. Adjustable damper between last pot and chimney for combustion control and chimney for smoke outlet.



Herl chula.

Lorena Mud Stove

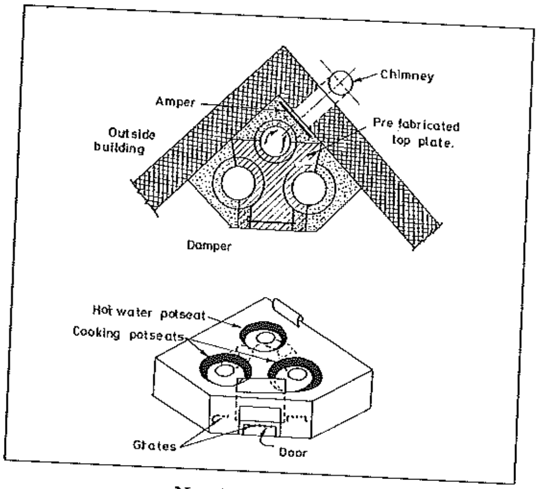
This stove wad developed as a part of the Appropriate Technology Project of Volunteers in Asia in Guatemala in 1976. The design features are : three to five holes, one directly over the fire box and others heated by flue gases, risers at the bottom of the pot holes to force hot air towards pot, offset tunnels to create vortex effect and improving convection, two dampers, one connecting at the mouth of the fire box and the second between last pot hole and chimney for smoke outlet. Advantages of the stove are: it burns smoke free, it has multiple cooking stations. Dampers help in controlling the combustion and ability to cook in a standing position.



Lorena mud stove.

New Nepali Chula

It was developed at the Research Centre for Applied Science and Technology, Khatmandu, Nepal. The design features are : three pot seats (two for cooking, one for heating water), two adjustable dampers for controlling the combustion, a grate for burning fuel and a chimney is provided outside the dwelling and connected by flue passage with the last pot hole. The advantages of this stove are : it burns smokeless, gives uniform heat to two cooking pots, and gives hot water as a by-product.



New Nepali Chula.