Optimization and Development of Solid Biomass Burning Cookstoves

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Abstract

In India, the rural population mostly uses biomass feedstock as a fuel for cooking and heating purposes. They conventionally use traditional three stone chulhas (cookstove) and modified Indian traditional chulhas. These chulhas not only emit pollutants like CO_2, CO, particulate etc due to incomplete and inefficient combustion but also have low thermal efficiency (less than 15%). Our present work provides detailed experimental studies and heating methodologies on different designs of chulhas, which are commercially available in the market. Modifications in the existing designs were also carried out to possibly increase the thermal efficiency. We carried out experiments on two kinds of chulhas, batch (packed bed) and continuous (continuous feeding) operation mode. Effect of variations in fuel size (voidage) for packed bed combustion, secondary air's quantity and its locations of introduction and radiation losses through fuel entry opening (continuous feeding) were studied individually. Also, a near complete energy balance for chulha has been carried out to asses the causes of heat losses and the reason for the observed reduced thermal efficiencies. It was found that increasing voidage of packed bed increases the devolatization rate and hence the combustion for which the secondary air is many a times not sufficient. This results in incomplete combustion of the volatiles due to which the thermal efficiency reduces and smoke is emitted. Allowance for the secondary air aids in combustion of volatiles and improves thermal efficiency approximately by 4 %. We found that by optimizing opening width (fuel side opening) of chulha which reduces radiation losses through fuel opening in case of continuous chulhas, results in an improvement in the thermal efficiency by around 4-2%.

Keywords: Cookstove, solid biomass fuel, secondary air, thermal efficiency, energy balance.

Introduction

Most of the India's population uses biomass as fuel for cooking and heating purposes. Biomass contributes over a third of primary energy in India. Biomass fuels are predominantly used in rural households for cooking and water heating, as well as by traditional and artisan industries. Biomass delivers most energy for the domestic use (rural - 90% and urban - 40%) in India [5]. Wood as a fuel contributes 56 percent of total biomass energy [9]. In rural areas limited availability of cash income, combined with freely available biomass resources, lead people to continue to rely on biomass for cooking. A main problem with the traditional biomass use is the social costs associated with excessive pollution. The incomplete combustion of biomass in traditional stoves releases pollutants like carbon monoxide, methane, nitrogen oxides, undesirable particulate matter etc. These pollutants cause considerable damage to health, especially of women and children who are exposed to indoor pollution for long duration [8],[6]. Another associated problem is energy inefficiency. Modern programmes initiated by various Governments aims to overcome these problems. The Indian Government also has started programmes to make improved chulhas (cookstoves). The Indian Government in 1950 launched National Programme on Improved stove. Over 25.9 lakh improved stoves have been distributed during 1997-98 [10]. The efficiency of an improved stove ranges from 15 to 25 percent as against an efficiency of only 5-10 percent found in the conventional stoves [3],[4].

Principle of combustion

Three mains process is occurring in stove are combustion, heat transfer and fluid flow. By controlling these processes, thermally efficient stoves can be designed. The combustion process is dependent on the physico-chemical properties of the fuel (size, shape, density, moisture content, fixed carbon content, volatile matter, etc.), quantity and mode of air supply (primary and secondary air) and the conditions of the surroundings (temperature, wind, humidity, etc) [1],[2].

Combustion of wood takes place in the following sequence [7].

- Drying
- Pyrolysis
- Combustion of volatiles
- Char oxidation

Material

Our present work provides detailed experimental studies on different designs of stoves, which are commercially available in a market. Modifications in the existence designs were carried out to increase thermal efficiency. Basically these stoves are classified into two types, Natural draft and Forced draft. In natural draft stoves air gets sucked due to buoyancy of hot flue gasses which is caused by density difference between cold and hot air. In forced draft, air is supplied by using centrifugal fan and its velocity and the flowrate can be varied. For packed bed combustion in stoves air has to be supplied by using a fan and in case of continuous feeding (natural draft) there is no need to use a fan to supply air as the pressure drop experienced by the flowing air in this case is low. We carried out experiments with Oorja Stove (forced draft) (www.firstenergy.in), Envirofit stove (natural draft) (www.envirofit.org) and Siporex stove (natural stove).

Oorja stove

This stove consists of concentric cylinders, inner cylinder is a combustion chamber and annulus is to convey secondary air. In this stove air is supplied using an electrically drivers fan and its speed can be change using a voltage regulator. In this stove manufacturer has provided two modes for fan speed i.e slow mode and fast mode, of which we experimented using the slow mode. As shown in the figure.1 air gets distributed as primary air and secondary air. Primary air is fed to combustion chamber at the bottom and secondary air goes in the annulus. Secondary air enters in combustion chamber through holes provided at the top. The location of these holes is 2 cm from top. These are 16 numbers of holes each diameter is 2mm. In this stove, fuelin form of pellets is randomly stacked in the combustion chamber.

Envirofit stove

This stove is made of porous ceramic combustion chamber and has metal cladding and it was natural draft. It is of cylindrical shape having cylindrical cavity which is a combustion chamber of diameter 10 cm and a height of 22 cm as shown in figure.2. It has an opening of 10×15 cm at the bottom for continuous feeding of fuel. To improve the thermal efficiency, a provision was made for the introduction of secondary air in the stove by hanging a metal cylinder of diameter 8 cm in the cavity of stove from top having a shoulder to support. The annulus thus formed had close end at top. The secondary air flows through the annulus and gets heated and enters the combustion chamber through holes drilled on metal cylinder similar to Oorja stoves. We drilled 16 holes and varied their diameter and location from top.

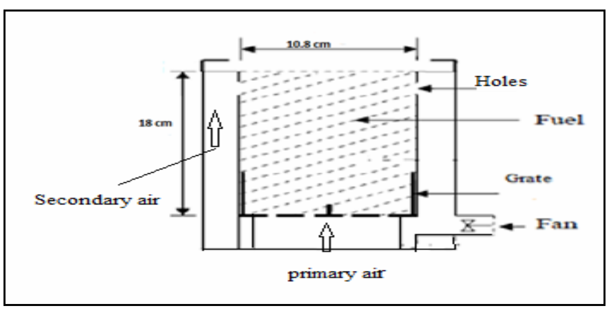

Figure.1 schematic of Oorja stove.

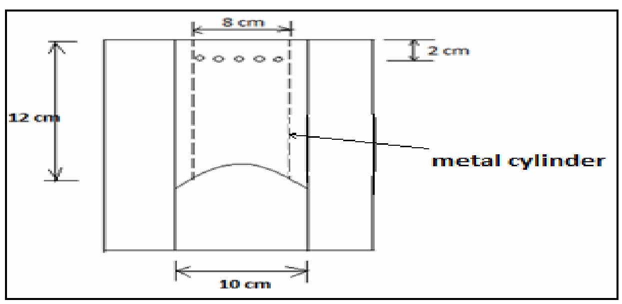

Figure.2 schematic of modified Envirofit stove

Siporex stove

This stove is made using Siporex blocks which have good insulation property and it is again natural draft stove similar in design to envirofit stove. We varied opening width (fuel side opening) of stove and studied its effects on radiation losses. Siporex was chosen as it can be worked upon very easily.

Experimental details and general procedure

Experiments were conducted using wood pellets and wood sticks. The results of above experiments were analysed by calculating burn rate, delivered heat flux, and thermal efficiency (useful heat efficiency) as defined below.

Experimental Procedure

- Asbestos sheets were placed on the platform of the electronic weighing machine to protect it from heating, and then stove was placed above it as shown in figure.3.
- Fuel was fed to the stove continuously or stacked in the combustion chamber.
- After establishing flame, a pot (29 cm diameter) containing 6 kg of water was placed on the top.
- K-type thermocouples were inserted at different locations (axial and radial) inside the pot to measure temperature of water.
- Few grams of sawdust and wood shavings were used along with approximately 2 g of kerosene for initial ignition of fuel bed.
- Fuel was ignited at the top.
- The burn rate was monitored continuously by noting down the change in the weight of fuel.
- After the temperature of water in the pot reaches 90^0C experiment is stop. The water temperature was restricted to 90 ^{0}C to limit the evaporation losses.

The following terms are used in the analysis of results.

Average burn rate = $\frac{wright\ of\ fuel\ consumed}{time}$, (gm/min) (1)

Average Flux = $\frac{average\ burn\ rate \times calorific\ value\ of\ fuel}{base\ area\ of\ pot}$, (kcal/hr m^2) (2)

Thermal efficiency = $\frac{Wtw \times Cpw \times (Twf - Twi) + Wtls \times \lambda}{Mfuel \times calorific\ value\ of\ fuel}, \times 100$, % (3)

Energy balance calculations and setup

During combustion process in the stove, majority of the heat losses are due to flue gases, thermal inertia of stove and radiation. We did steady state experiment to account the energy.

Setup

The entire stove, the pot and weighing balance are enclosed in a barrel with inlet port for air and fuel. An exit port is provided for the escape of flue gases. Flue gas velocity at the exit port was measured by using duct anemometer as shown in Figure 4. Seven thermocouples were used to measured temperature (T1-T7). (T1) thermocouple is placed inside the stove near the bottom grate to measure temperature of the flame which is assumed same as the inner temperature of stove, (T2-T3) are placed on outer wall of stove (average of it is reported as temperature of outer wall of stove), (T4) is placed in the pot and reports changing water temperature, (T5) is placed 6cm below the exit port and it reports the temperature of the flue gases and (T6-T7) are placed on the outer wall of barrel (average of it is reported as temperature of outer wall of barrel).

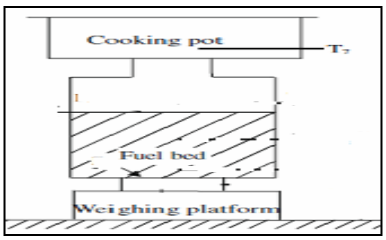

Figure.3 schematic of experimental setup

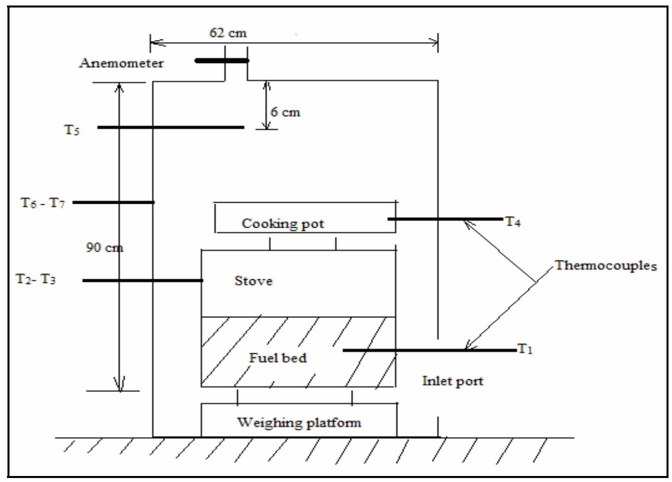

Figure.4 schematic of experimental setup for energy balance

Energy balance calculations

Table 1 & 2 provides the data regarding energy balance calculations. E is the source energy supplied by the burning of the wood sticks in stove.

$$E = M_{fuel} \times Q_{fuel} \text{ (kcal)} \quad (4)$$

Table 1 Data for energy balance calculation

C_{pw} (kcal/kg ^{0}C)	$C_{p\ barrel}$ (kcal/kg ^{0}C)	$C_{p\ stove}$ (kcal/kg ^{0}C)	$C_{p\ flue}$ (kcal/kg ^{0}C)	e	M_{fuel} (kg)	T_{wf}	T_{wi}	T_{bf}
1	0.12	229.66	0.243	0.51	328	100	30	30

Table 2 Data for energy balance calculation.

T_{bi} (^{0}C)	T_f (^{0}C)	Average velocity of flue gas V_f (m/sec)	M_{barrel} (kg)	M_{stove} (kg)	Temperature of stove (^{0}C)		Wt_w (kg)	Wt_{ls}(kg)	λ (kcal)
					Inner wall	Outer wall			
68	104	1.94	18.5	5.2	650	40	6	112	540

Thermal Efficiency of Stove

Thermal efficiency is the useful heat efficiency, it accounts the heat energy received by pot. Expression for thermal efficiency is given in equation (3).

Wood energy losses by Flue Gases

Flue gases formed as a result of combustion carry a fraction of the heat supplied. We measured the velocity of the flue gases using duct anemometer. We calculate density of the flue gas by using ideal gas law and then calculate mass flow rate of flue gasses.

Heat loss by flue gases = $m_{flue} \times Cp_{flue} \times (T_f - T_R)$, (kcal/s) (5)

Process is carried for some duration time t-min

Therefore heat loss by flue gas $Q_{flue} = m_{flue} \times Cp_{flue} \times (T_f - T_R) \times t \times 60$, (kcal) (6)

Flue gases also heated the barrel, so energy gained by the barrel is due to heat of the flue gasses.

Heat gained by Barrel Qbarrel = $M_{barrel} \times Cp_{barrel} \times (T - T_R)$, (kcal) (7)

Therefore Total Heat loss by fuel gas $Q_{tflue} = Q_{flue} + Q_{barrel}$, (kcal) (8)

% Heat losses by Flue gas $= \frac{Qtflue}{E} \times 100$, % (9)

Wood energy loss by thermal inertia of stove

The fraction of the source heat which is utilised by the stove to heat itself is known as thermal inertia of stove. To calculate thermal inertia we use ΔT_{LMTD}- Log Mean of the inner and outer wall temperatures.

$$\Delta T_{LMTD} = \frac{T_{si} - T_{so}}{\ln\left(\frac{T_{si}}{T_{so}}\right)}, (^0C) \quad (10)$$

energy used the by thermal inertia $Q_{st} = M_{stove} \times Cp_{stove}\, \Delta T_{LMTD}$, (kcal) (11)

% energy used by thermal inertia = $\frac{Q_{st}}{E} \times 100$, % (12)

Wood energy losses due to radiation

Heat loss due to radiation occurs through the opening for the fuel feed. This loss was considered to be the major radiation loss encountered in the operation of stove.

Heat loss by radiation $Q_r = e \times \sigma \times (T^4_c - T^4_{atm}) \times Ac/s$,(W) (13)

$e=0.51$, $\sigma=5.61\times10^{-8}$ (W/ m^2 K^4)

Ac/s Opening for fuel = 15×15 cm^2

Process is carried for some duration t-min

$Q_r = (e \times \sigma \times (T^4_c - T^4_{atm}) \times Ac/s \times t \times 60)/4.18$, (kcal) (14)

% heat loss by radiation= $\frac{Qr}{E} \times 100$ % (15)

Total Heat energy balance

From eq (3), (9), (12) and (15) we get total % energy accounted.

Results and discussion

Effect of variation of voidage.

Experiments are performed on Oorja stove. The size of the fuel (wood pellets) were varied to get the variation in the voidage. Table no.3 compares the experiments carried out with different voidages and it was found that increasing voidage of packed bed increases the devolatilization rate and hence the combustion for which the secondary air is not sufficient resulting into smoke. This results in incomplete combustion of the volatiles due to which the thermal efficiency reduces.

Increase in the devolatization rate is due to the following reasons. With higher voidage, air velocity through packed bed is more as compared to a packed bed having low voidage, so residence time for the volatiles will be low in a packed bed having higher voidage which results in incomplete combustion. Another reason for an increase in the devolatization rate is the radiative heat transfer to the particles in the bed through the voids which heats the particle beneath. So with higher voidage beds heat flux will increase and so does the devolatization rate.

Effect of Secondary air and its location

These experiments were performed on envirofit stove and wood sticks were used as a fuel. Table No.4 compares the experiments performed by varying the locations and the diameter of holes used for the introduction of the secondary air. It was found that allowance for the secondary air aids in the combustion of the volatiles. Locations of holes were varied for better mixing of secondary air and the volatiles. We found that shifting down the location of holes from top provides better mixing and gives better thermal efficiency, but it also found that beyond a certain height there is a drop in thermal efficiency, in this case pressure by the flame front is more and thus it resists the allowance of secondary air through the holes restricting the introduction of the secondary air.

Variation of width size (fuel feed side opening).

Siporex blocks were used to construct stoves of different configurations and the size of the fuel side feed opening was varied. It was found that by reducing the width the radiation losses can be reduced and thermal efficiency can be improved. Table 3 compares the experiments performed on Siporex stove.

Table 3 Comparison of experiments performed by varying voidage.

Exp no	Fuel fed (gm)	Voidage %	Thermal efficiency %	Average Burnrate (gm/min)	Average Flux (kcal/hr m^2)	Duration (min)
1	200	71	26.89	14.28	51896.19	14
2	300	57	35.04	13.04	47389.8	24

Table 4 Comparison of experiments performed by varying secondary air locations

Experiment no	Diameter of holes (mm)	Location of holes from top (cm)	Thermal efficiency %	Average Burnrate (gm/min)	Flux (kcal/hr m^2)	Duration (Min)
1	2	2	30.44	16.33	59346.28	20
2	2	2	32	12.28	44619.4	28
3	4	4	34.38	14.31	52005.22	19
4	4	6	28	11.7	42511.96	29

Table 5 Comparison of experiments performed by varying width of the fuel fed side opening

Exp no	Diameter of combustion chamber (cm)	Opening cross sectional area (cm^2)	Thermal efficiency %	Average Burnrate (gm/min)	Flux (kcal/hr m^2)	Duration (min)
1	15	10×11	23.24	16.6	60327.51	20
2	10	8×8	32.11	12.08	43900.98	23

Conclusion from energy balance.

A near complete energy balance for stove has been carried out to assess the locations of heat losses and the reason for the observed thermal efficiencies.

Figure 5 provides details of heat losses in combustion process. We were able to account 95% of wood energy of which 36% is utilized as useful efficiencies, 24% is losses due to flue gasses, 20% is losses due to thermal inertia and 15% is due to radiation. We can reduce energy losses due to thermal inertia and radiation by optimizing weight of stove and fuel feed side opening respectively.

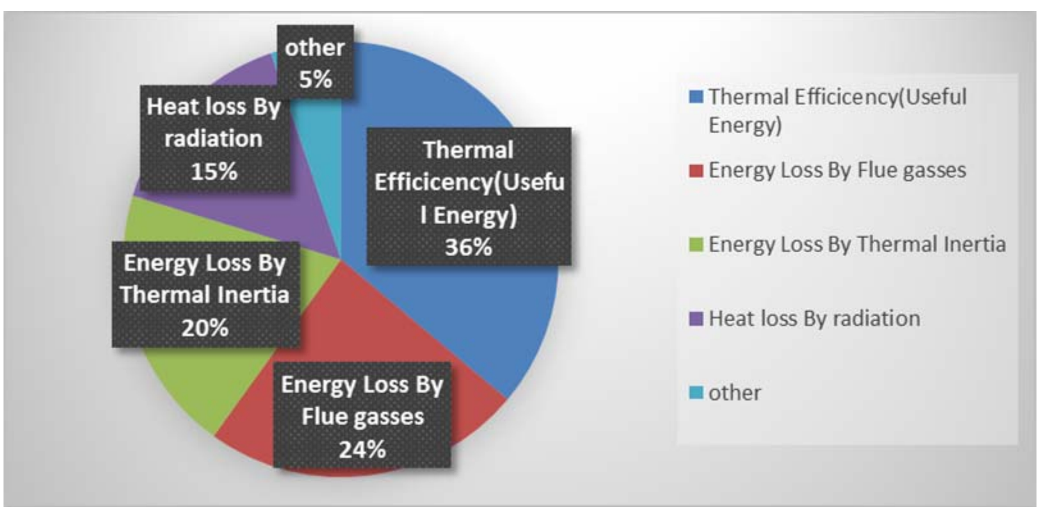

Figure No.5 Pie Diagram for conclusion of energy balance of wood energ

Conclusion

In the above experiments it is observed that the thermal efficiency in range 30-34% it had burnrate in range of 12-14 (gm/min) and thus flux 44000 – 52000 (kcal/ hr m^2) thus burnrate is a controlling parameter for improvement of thermal efficiency and burnrate depends upon bed voidage, air supply and geometry of stove. Thus by optimizing voidage, allowance for the secondary air and by optimizing opening width (fuel side opening) of chulha which reduces radiation losses through fuel opening in case of continuous chulhas, results in an improvement in the thermal efficiency.

Nomenclature

Ac/s_{duct} cross sectional area of duct anemometer
$C_{p\ w}$ specific heat of water (kcal/kg ^{0}C)
$C_{p\ barrel}$ specific heat of barrel (mild steel) (kcal/kg ^{0}C)
$C_{p\ flue}$ specific heat of flue (kcal/kg ^{0}C)
$C_{p\ stove}$ specific heat of stove (ceramic) (Envirofit) (kcal/kg ^{0}C)
E energy of the source (kcal)
e emissivity
M_{flue} mass flowrate of flue gas (kg/sec)
M_{barrel} mass of barrel (mild steel) (kg)
M_{stove} mass of stove (Envirofit) (kg)
M_{fuel} mass of fuel consumed (kg)
P atmospheric pressure (kPa)
Q_{fuel} calorific value of fuel (kcal)
Q_{flue} heat loss due to flue gases (kcal)
Q_{barrel} heat gained by barrel (kcal)
Q_r heat loss due to radiation (kcal)
Q_{ts} thermal inertia of stove (Envirofit) (kcal)
Q_{tflue} total heat loss due to fuel gas (kcal)
q volumetric flowrate of flue gases (m^3/sec)
T_{wf} final temperature of water (^{0}C)
T_{wi} initial temperature of water (^{0}C)
T_{flue} temperature of flue gases (^{0}C)
T_{bi} initial temperature of barrel (^{0}C)
T_R reference temperature for flue gases (^{0}C)
T_{bf} final temperature of barrel (^{0}C)
T_{si} temperature of inner wall of stove (^{0}C)
T_{so} temperature of outer wall of stove (^{0}C)
ΔT_{LMTD} mean temperature attained by stove (Envirofit) (^{0}C)
T_f flame temperature (^{0}C)
T_{atm} atmospheric temperature (^{0}C)
V_f average velocity of flue gases (m/sec)
Wt_w weight of water heated (kg)
Wt_{ls} weight of water loss (kg)
Greek letters
λ latent heat of evapouration for water (kcal/kg)
ρ density of flue gas (kg/m^3)
σ Stefan Boltzmann constant (W/ m^2 K^4)

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