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Design and analysis of novel biomass stove

V.S. Shaisundaram [a,*], M. Chandrasekaran [b], S. Sujith [c], K.J. Praveen Kumar [c], Mohanraj Shanmugam [d]

[a] *Department of Automobile Engineering, Vels Institute of Science and Technology and Advanced Studies (VISTAS), Chennai, India*
[b] *Department of Mechanical Engineering, Vels Institute of Science and Technology and Advanced Studies (VISTAS), Chennai, India*
[c] *Engineering and Industrial Services, Tata Consultancy Services, Chennai, India*
[d] *Department of Materials Engineering and Nanotechnology Politecnico di Milano, Milan, Italy*

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ABSTRACT

In this paper, discussing in detail on how the thermal efficiency of the cooking stove fuelled by firewood can be increased to achieve maximum efficiency. For this purpose, a biomass stove is fabricated and tested domestically for regular household chores. Unlike regular biomass stoves, a number of design optimizations were made while fabrication to achieve the end goal. Biomass energizes are still being used by large number of populations in remote areas around the globe where the access to LPG gas stoves is limited because of location proximity and economy. Its simplistic design makes it unsuitable to perform any controlled test because they are known to display lots of variability in their performance. So, the other objective of this paper is to comprehend and characterize range of process involved inside the biomass stove and put forth a thorough analysis on all the variables to better configure for future use.

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1. Introduction

The conventional stoves used in household are usually made with bricks placed one above the other with mud enclosing the entire setup in a rectangular cross section over which cooking utensils are placed. The stove has a small opening at one side of the building block to accommodate firewood. Due to this straightforward design, much of the energy earned from burning wood is spent inefficiently (the conventional Chulha's has just around 5%-10% efficiency) and eventually resulting in more firewood consumption.

Number of researchers has proposed numerous cutting-edge comprehensions on the thermodynamics of a biomass stove to an extent where a number of accords were available to study its functions and principle. Dr. Larry Winiarski has spent over thirty years of his career working on the ignition and wood consuming stoves and he has helped manufacturers around the globe to come up with breakthrough in ignition stoves that is common in every household these days. Dr. Winiarski, who works at Technical Director of the Aprovecho Research Center, has contributed to this field of study since 1976. Group of researchers, Dr. Krishna Prasad and including Dr. Dwindle Verhaart and Dr. Piet Visser from Eindhoven University has worked on biomass stoves for over 10 years and written a book completely dedicated to biomass stoves. Dr. Sam Baldwin from West Africa has also contributed his part through his book Biomass Cook Stoves: Engineering Design, Development and Dissemination (1987).

Yuanbo et al. in his research paper on fire wood stove explained the necessity and demands of developing a modern highly efficient biomass stove fuelled by wood. For his research paper he used a water boiling test device on a composite built (NG-II) biomass stove to achieve maximum efficiency (25–30%). [1] Shankar B. Kausley, Aniruddha, B. Pandit et al. in their work has investigated varying factors causing the potential decline in efficiency in domestic stove. They conducted their experiment both in an ideal indoor environment and unstable outdoor space to analyse the factors in detail. Their objective was to calculate the extreme flame temperature in both the conditions. Notably, the result of their work has been used to design a geometrically balanced gas stove and to smart regulate the fuel inlet. One such example is the use of suction ignition inside the stove to propagate maximum fire temperature. [2]

Joshua Agen broad, Morgan Deffort, Cory Kreutzer *et al.* for their research paper they have fabricated a biomass stove based on natural convection principle to obtain upper limit in both efficient combustion and fire power. [3]. C.L. Orange, M. Defoot, B. Willson

* Corresponding author.

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et al. in their paper the authors had explained the complex combustion process occurring in liquid, solid and gas phases simultaneously. It was found that close to 200 parameters were found to control the combustion process in gaseous phase. Local temperature in wood has significantly limited the combustion process due to the presence of moisture before vaporization. Moisture is also found to reduce the adiabatic flame temperature and increase the amount of air required for complete combustions. [4] Christian L'Orange, John Volckens, Morgan De Fort *et al.* in their work discussed above the effect of pot temperature and convention heat on the walls of the stove.[5–8] Emission is found to be significantly dependent on the temperature of the stove wall. This test was performed with hot as well as cold pot and they produced different emission rates and also the condition of stove baseline with its size parameter is found to disrupt the emission rate. Thermophoresis were observed on the walls because of changing combustion temperature resulting in particle emissions. Their work also shows an increase in oxidation of stove with increase in temperature. [9–14]. So after carefully studying various literature review, the improved design has a look similar to conventional stove but it is equipped with grate and chimney. The thermal efficiency of this sort of stoves can achieve up to (25–30%).

2. Theoretical analysis

An analysis of parameters is required for the fabrication of a new bio mass stove. Feeding properties and design of the stove are considered for the theoretical analysis. Burning wood produces fire of 90 percent efficiency. A discharged heat energy of up to 40% from burning is utilized in the pot. Increase in efficiency of heat transfer to pot has a significant effect. Increased efficiency of combustion plays no role in reducing the fuel consumption. In order to lessen smoke and harmful derivatives, Ignition should be enhanced. To reduce fuel intake, increased heat exchange is vital [15–19]. The pot is not great conductor of heat since it is a degraded heat exchanger. The process should have a fire control level as it is significant in fuel reduction and decreased emission and the energy flow into pot can be higher. These parameters can be altered in building a stove. Fireplace addition to heating stove is a good way to maintain heat. In order to ensure good quality air, a cleaner stove is used for the process. Harmful emission is removed by chimney which ensure pollutant free environment. Air pollutants will be at higher level when cleaner burning stoves are used without a chimney. In open areas, Unvented stove usage is preferable. In order to lessen pollution levels, practices such as making vents in rooftop, open windows and stacks directed down to earth over the fire. With such practices, a cleaner burning stove is also operated and chimney [6] is fitted to all wood stoves if possible. [20–21]

3. Design of biomass stove

3.1. The height and the diameter of the chimney

3.1.1. Height of the chimney

Ca = Mass density of air outside chimney
Cg = Average mass density of hot gas.
Ca = 353×(1/tq)
= 353×(1/273 + 30)
=1.1650Kg/m^3
Cg = 353×(1/tq)
Cg = 353×(1/273 + 400)
= 0.5245 Kg/m^3
Density of air = 1.165 $\frac{kg}{m^3}$
Density = $\frac{mass}{Volume}$
1.165 = M$_a$ /4.7
Ma = 6.84 Kg
10$\frac{N}{m2}$= (1.165–0.5243) × 9.81 × H
H = 0.6283
30$\frac{N}{m2}$ = (1.165–0.5243) × 9.81 × H
H = 2.09 m.
Therefore, total height of the stove including the chimney = 2 m.

3.1.2. Diameter of the chimney

$$H1 = H\left\{\left[\left(\frac{ma}{ma+1}+1\right)\right]x\left(\frac{tg}{ta-1}\right)\right\}$$
$$= 0.6238\left\{\left[\left(\frac{6.84}{7.84}+1\right)\right]x\left(\frac{673}{303-1}\right)\right\}$$
H1 = 0.6636 m
C = $\sqrt{2gH1}$
=$\sqrt{2x9.81 \text{ x } 0.6636}$
C = 3.608 m/s
D = 1.128 $\frac{\sqrt{mg}xc}{Cg}$
Mass of hot gases = ma + 1
Mass of air = ma
mg = $\frac{total\ mass\ of\ hot\ gases}{Time}$
mg = $\frac{6.84+1}{3600}$
mg = 2.17 × 10^{-3} kg
D = 0.0381264 m.
Therefore, the diameter of the chimney = 0.0381264 m.

3.2. The height and diameter of the stove

The total Height of the stove from bottom of the stove to top of the chimney = 2 m
Therefore the height of the stove from grate to combustion chamber = 0.34 m
In a stove with no chimney, heat release rate is 20 Wt/cm^2 of grate area.
The heat release rate of the stove = 4000 wt
$\frac{4000}{20}$ = 200 cm^2
200 cm^2 = $\frac{\pi}{4}$d^2
= 16 cm
Therefore, the diameter of the stove = 16 cm
= 0.16 m.

3.3. Draft modeling of the biomass stove

3.4. Overall specification of the stove

4. Description of the stove

Its arduous to meet cooking needs daily as the price of the fossil fuel increases steadily. There is a huge demand for fossil fuel as it is being depleted constantly by people consumption. Considering all difficulties, for domestic application, a new designed Biomass stove is fabricated. Fig. 1 shows Drafting of the Biomass Stove and Table 1 shows Overall specification of the Stove in mm. As a result of which, People can use this stove thereby reducing the consumption fossil fuels. While designing the stove, stove efficiency is taken care (Tables 2–6).

4.1. Features incorporated in the stove

The main features of the biomass stoves to be fabricated includes the following

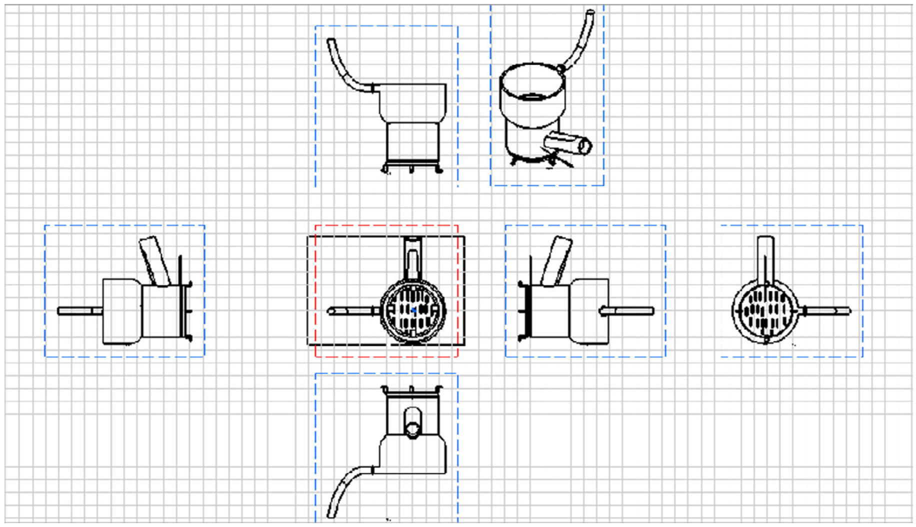

Fig. 1. Drafting of the Biomass Stove.

Table 1
Proximate analysis of wood in % basis.

Volatile content	87
Char	1.32
Ash content	1
Moisture content	10

Table 2
Ultimate analysis of wood in % basis.

C	49.05
H	6.5
O	43
N	0.4
Ash	0.6

Table 3
Oxygen required for combustion of 100 kg of wood.

Molecules Volumes	O2 Required for combustion
C = 4.125 mol	4.125 mol/vol
	$C + O_2 \rightarrow CO_2$
for H = 3.25–2.6874 = 0.5626 mol	$\frac{0.5626}{2} = 0.2813 \frac{mol}{vol}$
O = 0.000	$2H_2 + O_2 \rightarrow 2H_2O$
N = 0.01428 mol	=4.4063 mol / vol / 100 kg of wood

Table 4
Products of combustion total heat absorbed / produced.

Heat of combustion Kcal/kg	Heat absorbed/produced Kcal/kg
C = 8137.5	8137.05 (49.5)/100 = 4028.66.
H = 2890.5	(2890.5*1.25)/100 = 325.24
Total	4028.66 + 325.44 = 4353.30

- Pre-heated air supply
- Insulation of stove
- Wood pieces
- Chimney
- Grate
- Wood pre heating

Table 5
Overall specification of the Stove in mm.

Contents	Dimensions (mm)
Height of the Chimney	1000
Diameter of the Chimney	40
Height of the Stove	340
Diameter of the Stove	160

Table 6
Water temperature at regular time period.

S.no	Time in minutes	Temp of water in Celsius
1	0	25
2	11	30
3	15	40
4	19	47
5	26	48
6	32	51
7	40	59
8	45	69
9	50	74
10	55	86
11	65	93
12	70	99

Fig. 2 shows the fabricated Biomass Stove. The challenge is designing a new biomass stove. Depletion of conventional cooking fuels like petroleum products and its increased price leads to alternate fuel usage for daily domestic purposes. Considering these factors, a new designed biomass stove is fabricated. Few new features are incorporated in this stove. These features can be altered based on people convenience. Further improvement in design can lead to less expenditure and also results good performance. Following measures are taken care to improve the features. At first, Collection of literatures and design proposal by calculations for new biomass stove design. Initially, Chimney and size of biomass stove are determined. Height of stove is determined by calculation the dimensions. Next step is to calculate the diameter of stove and chimney. Once the stove dimensions are known, design calculation is made. A thorough research is made on all existing stove, after which a new design is made and new features are included. These new additions will improve the stove performance. Designing of the stoves is carried out with modelling software called Autocad. After the deign process, Selection of material is done. Research is

Fig. 2. Fabricated Biomass Stove.

performed to select optimum material for the stove for the design made. After this, Fabrication work is to be carried out. Finally the efficiency of stove is tested and determined. To increase stove performance, Optimization is done. The parameters for optimization are based on fuel feed rating. rate of air supply and vessel shape. After knowing all these factors, the eventual results are formulated.

5. Calculation of efficiency

5.1. Water boiling test

This is a modified version of Water boiling test which is derived from cooking process to determine the efficiency of transfer of energy from fuel to cooking stove. This method can be applied on most of stoves. Fig. 3 shows boiling of water in biomass stove. This approach is meant to be fabrication method of stove in better place and for variety of cooking application. [8]

5.2. Procedures for doing water boiling test

- Efficiency of stove is calculated by water boiling test
- Aluminium material is used for fabrication of pot

Fig. 3. Boiling of water in biomass stove.

- Water boiling test employs water as basic need
- Open top pot with no lid is used for closing the vessel
- Stove Feeding is through dry wood
- The performance test is carried out by regular temperature checks at time intervals. The test is carried out for 1 h.
- Both before and after the test, mass of the pot of water is noted
- Mass of fuel is also noted before and after the test.
- Observed readings are tabulated and Efficiency is determined

5.3. Calculation of efficiency

Thermal efficiency $h_h = [4.186(T1_{hf} - T1_{hi})(P1_{hi} - P1_{hf}) + 2260 w_{hv}]/f_{hd}$. LHV

$T1_{hf}$ = Temperature of water after test = 99 °c

$T1_{hi}$ = Initial temperature of water = 25 °c

$P1_{hi}$ = Mass of pot of water = 2000 g

$P1_{hf}$ = Mass of pot of water = 700 g

$w_{hv} = P1_{hi} - P1_{hf}$ = 2000–700 = 1300 g

LHV = Lower heating value of wood = 20,000 kJ/kg

f_{hd} = Equivalent dry wood consumed

$= [f_{hm}(LHV(1\text{-}MC) - MC(4.186(T_b\text{-}T_a) + 2257)) - C_h .LHV_{char}]/LHV$

MC = moisture content of a wood = 15% = 0.15

$f_{hm} = f_{hi} - f_{hf}$ = 1000 – 300 = 700 g,

where, f_{hi} = mass of fuel before test = 1000 g

f_{hf} = mass of fuel after test = 300 g

T_b = Local boiling point temperature = 100 °C

T_a = Ambient temperature = 30 °C

C_h = amount of char remaining after test = 200 g

LHV_{char} = lower heating value of charcoal = 30,000 kJ/kg

So,

$f_{hd} = [700(20000(1-0.15) - 0.15(4.186(100-30) + 2257)) - 200*30000]/20000$

= 431.72 g

Therefore,

Efficiency $h_h = [4.186(99-25)(2000-700) + 2260(1300)]/431.72*20,000$

= 0.386 = 38.6%

6. Conclusion

4KW biomass stove is designed. The complete detailed drafting is done using CATIA software. If any optimization is made to increase the efficiency of stove, the same will be performed and efficiency of the biomass stove will be determined.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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