Comparison on Experimental Result and Mathematical Model of the Performance for Two Pot Raised Mud Improved Cookstove

Hari Bahadur Darlami[1*], Bhakta Bahadur Ale[1],Govind Raj Pokharel[2]

[1]Tribhuvan University, Institute of Engineering,Pulchwok Campus, Lalitpur, Nepal
[2]TribhuvanUniversity, Institute of Engineering,Thapathali Campus, Kathmandu, Nepal
Corresponding Email:haridarlami@ioe.edu.np*

Abstract: Biomass cookstove is one of the most fuel consuming device among the most developing countries. Large number of people are using biomass fuels for cooking and space heating. Two pot raised mud Improved Cookstove (ICS) is one of the most promoted cookstoves in the context of Nepal. The goal of this study is to determine the thermal efficiency of cookstove experimentally and compare with model value and also determine distribution of heat after combustion of fuel. Experimental results have been compared with mathematical model which has been developed in MATLAB. In mathematical model combustion, transient heat transfer and flue flow formulae have been used. Experimental results have been compared with mathematical model to validate the model. Optimum thermal efficiency for existing cookstove has been found 18% at firepower 4.45 kW, i.e., 1.2kg/h feeding rate for the existing cook stove. Model analysis shows heat absorbed by wood for pyrolysis 5.29%, moisture evaporation 1.49%, the door 3.89%, heat loss in wall l4.22%, heat gain by pot 22.58%, heat gain by pot 22.58%, incomplete combustion 4.36% and heat lost through flue gas 48.1% by pot for optimum dimension cookstove. Thermal efficiency in experimental result has been found lesser than model analysis in significant value which indicates there is possibility to increase performance of cookstove with proper finishing of inner surface.

Keywords: Firepower, chimney, insulation, mathematical modeling

1. Introduction

Renewable energy one of the most emerging trend in the context of Nepal. Its optimum energy use can help for the fulfillment of present energy need and cope for environment aspect also. Biomass is one of the widely available renewable energy resources which is using for cooking and space heating purpose since long time. In the context of Nepal, 60.9% people are using fuelwood for cooking purpose [1]. Use of improved cookstove by improving thermal efficiency and combustion performance can reduce adverse effects on human health, reduce energy consumption and contribute to environmental aspects [2]. Fuelwood consumption and subsequent environmental pollution can be reduced by improving the thermal efficiency of cookstove and through optimum use of biomass fuel [3].Till date around 1.3 million improved cookstove disseminated and about 2 million (ICS) people are still using traditional cookstove.

Firepower influence the thermal efficiency cookstove and optimum value has been found at certain firepower range [4, 5,6].

Height and diameter of chimney influence for the optimum performance [7] . Variation of chimney height affects the performance of cookstove [8]. Chimney controls the mass flow rate of air into the combustion chamber [9]. Chimney with high suction (excess chimney height) leads to quenching of flame. On the other hand, chimney with low suction (not sufficient chimney height) leads to less excess air and incomplete combustion [10].

Insulation layer in the combustion chamber reduces the heat transfer to walls of cookstove. This results in high combustion chamber temperature which increases combustion efficiency and ultimately thermal efficiency [11]. A heavy cookstove such as mud brick absorbs 30-40% of heat during the cooking period [12].

These cookstoves have the ability to get carbon credits not only because of their contribution to climate-change mitigation but also they can yield major co-benefits in terms of energy access for the poor people. Besides, they may result in improved rural health, environmental, agricultural and economic benefits [13].

Modeling efforts were first done by Wood burning Stove Group at Eindhoven University in 1980s. De Lepeleire et al. in 1981 used combustion stoichiometry to determine combustion chamber and primary/secondary inlets dimensions for a given firepower and excess air for enclosed type stove [14].

Heat produced after combustion of fuelwood divids for pyrolysis of fuelwood, evaporation of moisture, losses from door, wall temperature raise, incomplete combustion, losses with flue gas as exit and heat gain by pot. [15].

In 1993, Sharma compiled basic design principles for a cookstove including combustion, fluid flow and heat transfer [7].

Most of the people are using traditional cookstove and lagging for the use of efficient cookstove. This affecting environmentally, socially and economically. So, thermal efficiency test of cookstove experimentally and its comparison with model value keeps importance for promotion of efficient cookstove in the context of Nepal.

Objective of this paper is to determine the thermal efficiency of cookstove experimentally and compare with model value and also determine distribution of heat after combustion of fuel.

2. Materials and Methods

This includes fabrication of cookstove, its performance test includes thermal efficiency and emission test experimentally. Experimental results has been compared with model which has been prepared in MATLAB.

2.1 Fabrication/construction of cookstove

Two pot raised mud ICS of size 82×40×28cm has been fabricated by using solid bricks, supporting structure parts and additives. Mud used for the fabrication of brick was composedof 5/8 fraction clay or local mud, 2/8 fraction rice husk or saw dust and 1/8 fraction cow or buffalo dung parts by volume.

2.2 Performance test of cookstove

For the analysis of cookstove parameters, experiment has been performed at Stove Lab of Pulchowk Campus, Institute of Engineering, Tribhuvan University and Renewable Energy Test Station Lab, Khumaltar Lalitpur.

Thermal efficiency of cookstove has been calculated by using "Power Test". Maintaining constant power during WBT is difficult and power variation result in data with high standard deviation and variance. The stove power varies according to supplying fuelwood to stove, it also depends on the steadiness of wood feeding. As a remedy this problem, power test was used. While most of the procedures are similar to cold start of WBT, some aspects are considered differently. First of all, the test has been conducted for one hour and secondly, constant fuel feeding rate has been maintained. The amount of wood to be supplied is divided in different batches of equal weight and is fed to stove at constant time intervals. All other protocols for testing were of Water Boiling Test 4.2.3. version [16]. Exploring stove performance at both high and low power output gives some indication of how a stove performs in a range of cooking conditions [17]. For the calculation of thermal efficiency of cookstove, excel sheet provided by Global Alliance for clean cookstove has been used.

Thermal efficiency test of cookstove has been obtained by changing one parameter with keeping other parameters in reference condition.

During performance test, main dimensional parameters such as combustion firepower, chimney height and material of cookstove

2.3 Mathematical model formulation

In cooskstove most of the phenomenon include drying, pyrolysis, combustion, turbulence, heat sink, conductive, convective and radiative heat transfer [18] .

The cookstove model has been primarily divided into three zones as shown in Figure 1. The main processes occurring inside a cookstove has been studied with the help of combustion theory, flue flow model and heat transfer process. Combustion is assumed to occur only in zone 1, heat transfer in all three zones and flue flow due to buoyancy force (caused by pressure difference; due to temperature difference in all three zones) is analyzed and further integrated to study the two pot enclosed type cookstove.

The flowchart shows the flow of program and calculation procedure. The work targeted to develop an easy tool for performance prediction of cookstove on parameter variation. The flowchart of mathematical model has been developed to solve the unknown. MATLAB has been used to solve the mathematical equations. MATLAB has an advantage over other coding software to solve engineering problems. MATLAB is capable of handling complex calculations involved, thus MATLAB was chosen for the purpose. Thus the model can be varied for input parameters to calculate important cookstove performance parameters. The iteration ends for convergence of temperature less than 0.1^{o}C and program generally converges for 8 to 20 iterations for different conditions. The transient problem asks for greater amount of time to be solved inside those loops. The program terminates with insignificant amount of error in approximation.

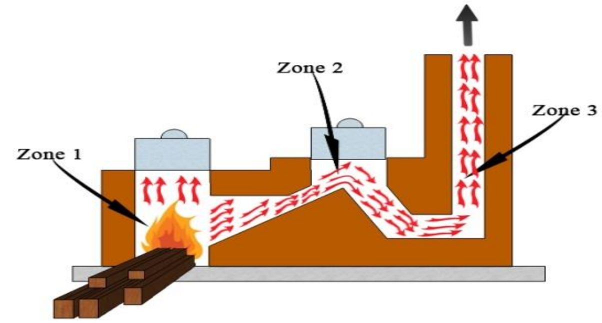

Figure 1 Schematic drawing of cookstove showing different zones

The cookstove model incorporated two pot enclosed type cookstove with chimney which is shown in Figure 1. In this type of stove, fire is enclosed in the combustion chamber, hence protected from outside air. The pot1 corresponding to the combustion chamber, only comes in contact with flame, and pot2 is heated through the flue traveling from the combustion chamber. The main aim of this type of construction is to cook food in the pot1 and keep the food warm in the second pot. Figure 1 shows the schematic diagram of flue flow path and different zones. The dark color indicates the surrounding wall of the stove. The arrow shows the flue flow path. Zone 1 is first combustion chamber which includes burning of fuelwood and heat transfer to the pot1 and wall1. Heat from fuelwood is directly transferred to pot1 through flame, which is denoted by upward arrow in Zone1. Second chamber including pot2 is depicted as Zone 2. In Zone 2 the heat source is flue from Zone 1. The heat is then taken by pot2, and wall2 and the remaining heat is carried by flue 3 through the chimney. The flue coming out of the chimney is shown by a black upward arrow, heat carried by which is lost in the atmosphere.

1. Calculation of mass flow rate of species from volatile combustion ($\dot{m}_{j,\,vol}$)

$$\dot{m}_{j,vol} = (\text{mass fraction})_j \times \dot{m}_{fu}$$

Where j represents individual species like CO, CO_2, H_2, H_2O and C_7H_{16}

$\dot{m}_{fu}$ = fuel feeding rate

⇩

2. Calculation of mass flow rate of char ($\dot{m}_{char}$)

$$\dot{m}_{char} = (1 - x_{vol})(1 - f) \times \dot{m}_{fu}$$

Where x_{vol} = 0.8 and f is moisture content

⇩

3. Calculation of mass flow rate of additional species ($\dot{m}_{j,\,add}$)

$$\dot{m}_{CO\,add} = \dot{m}_{char}\left(2\left(1-\frac{1}{\emptyset}\right)\frac{M_{CO}}{M_{char}}\right)$$

$$\dot{m}_{CO2,\,add} = \dot{m}_{char} \times \left(\left(\frac{2}{\Phi} - 1\right)\frac{M_{CO2}}{M_{char}}\right)$$

$$\dot{m}_{O2,\,add} = -\,\dot{m}_{char} \times \left(\frac{1}{\Phi}\,\frac{M_{O2}}{M_{char}}\right)$$

$$\dot{m}_{H2O,\,add} = -\,\dot{m}_{fu} \times \left(\frac{18\,x\,l}{M_{wo}}\right)$$

Where Φ represents stoichiometric air required for complete combustion

⇩

4. Calculation of heat released by volatile combustion ($\dot{Q}_{vol}$)

$$\dot{Q}_{vol} = \sum R_{j,\,net} \times \Delta V_{zone1b} \times \Delta H_{f,j}$$

Where $\Delta H_{f,j}$ is heat of formation which is corrected for temperature

⇩

5. Calculation of species concentration of bed ($\omega_{j,bed}$)

$$\omega_{j,bed} = \frac{\dot{m}_{air} \times \omega_{j\,air} + \dot{m}_{j\,vol} + \dot{m}_{j\,add}}{\dot{m}_{flue}}$$

⇩

6. Calculation of species concentration exiting from zone1($\omega_{j,\,exit}$)

$$\omega_{j,exit} = \frac{\dot{m}_{flue} \times \omega_{j\,bed} + R_{j\,net} \times M_j \times \Delta V_{zone1}}{\dot{m}_{flue}}$$

where ΔV_{zone1} is volume of zone 1 and M_j is molecular weight of species j

⇩

7. Calculation of species concentration of zone 1($\omega_{j,z1}$)

$$\omega_{j,z1} = 0.8\,\omega_{j,bed} + 0.2\,\omega_{j,exit}$$

⇩

8. Calculation of Temperature of wood (T_{wo}) solving iteratively

$$\frac{\dot{m}_{fu}(1-f)}{A_{wo}} = \frac{\rho_\rho D_{wo}}{8}\left(0.4x_{vol}exp\left(\frac{-E_{vol}}{RT_{vol}}\right) + 0.6(1-x_{vol})v_{char}exp\left(\frac{-E_{char}}{RT_{char}}\right)\right)$$

Where $T_{vol} = T_{wo} - 50$ and $T_{char} = T_{wo} + 50$ and

A_{wo}, ρ_{wo}, D_{wo} represents surface area, density and diameter of wood respectively

⇩

9. Calculation of heat required by wood ($\dot{Q}_{wo}$)

$$\dot{Q}_{wo} = \dot{m}_{fu} \big(C_{wo}(673-T_{amb}) + L_{wo} + C_{p\,vol}\,(T_{wo} - 673)\big) + \dot{m}_{fu} f \{C_{p\,water}\,(T_{boil} - T_{amb}) + L_{water})$$

10. Calculation of H_{flmax}

$$H_{flmax} = 0.2\,\dot{Q}_{vol}^{0.4}$$

Where H_{flmax} is maximum height of flame, which is used to calculate the flame temperature

11. Calculation of different resistance for electrical analogy of heat transfer from char to wall, door, pot1, wood, flue.

12. Start of transient analysis
Timestep = 1 to number of timesteps

13. Calculation of E_{b0} and J_1 solving

$$J_1.\left(\frac{1}{R_{01}}\right) + E_{b0}.\left(-\frac{1}{R_{01}} - \frac{1}{R_{02}+Z_2} - \frac{1}{R_{04}}\right) = -\frac{E_{b2}}{R_{02}+Z_2} - \frac{E_{b4}}{R_{04}}$$

and

$$\dot{Q}_{char} = \frac{J_1 - E_{b5}}{R_{15}} + \frac{E_{b0} - E_{b2}}{R_{o2} + Z_2} + \frac{E_{b0} - E_{b4}}{R_{04} + Z_4} + \dot{Q}_{wo}$$

Where E_{b2}, E_{b4}, and E_{b5} are emissive power of pot1, wall of combustion chamber and door respectively.

14. Calculation of Emissive power of char (E_{b1})

$$J_1.\left(-\frac{1}{Z_1} - \frac{1}{R_{01}} - \frac{1}{R_{15}}\right) + E_{b0}.\frac{1}{R_{01}} = -\frac{E_{b1}}{Z_1} - \frac{E_{b5}}{R_{15}} + \dot{Q}_{wo}$$

15. Calculation of different heat transfer from char ($\dot{Q}_{char\text{-}door}$, $\dot{Q}_{char\text{-}wall1}$, $\dot{Q}_{char\text{-}pot1}$, $\dot{Q}_{char\text{-}wood}$) using

$$\dot{Q}_{char\text{-}door} = \frac{J_1 - E_{b5}}{R_{15}}$$

$$\dot{Q}_{char\text{-}pot1} = \frac{E_{b0} - E_{b2}}{R_{o2} + Z_2}$$

$$\dot{Q}_{char\text{-}wall} = \frac{E_{b0} - E_{b4}}{R_{04} + Z_4}$$

$$\dot{Q}_{char\text{-}wood} = \dot{Q}_{wo}$$

16. Calculation of Temperature of zone1(T_1) solving iteratively following equations

$$\dot{Q}_{vol\text{-}pot1} = \sigma A_{pot1}\,(\varepsilon_{flue} T_{flame}^4 - \alpha_{pot1} T_{pot1}^4) + h_1 A_{pott1}\,(T_{flame} - T_{pot1})$$

$$\dot{Q}_{pot1\text{-}loss} = A_{pot1\,side} \times h_o \times (T_{pot1side} - T_{amb})$$

$$\dot{Q}_{vol\text{-}wall1} = \sigma A_{wall1}\,(\varepsilon_{g1} T_1^4 - \alpha_{g1} T_{iwall1}^4) + h_{1side} A_{wall1}\,(T_1 - T_{iwall1})$$

$$\dot{Q}_{flue} = \dot{m}_{fu} \times (1 + AFRs) \times C_{p1} \times (T_{flame} - T_{amb}) + (\dot{m}_{flue} - \dot{m}_{fu}(1 + AFRs)) \times C_{p1} \times (T_1 - T_{amb}) \times$$

$$\dot{Q}_{vol} = \dot{Q}_{vol\text{-}wall1} + \dot{Q}_{vol\text{-}pot1} + \dot{Q}_{flue}$$

Where i represents inner temperature and h_{1side} represents convective heat transfer towards side for zone1

Then $\dot{Q}_{pot1\text{-}loss}$, $\dot{Q}_{vol\text{-}pot1}$, $\dot{Q}_{vol\text{-}wall1}$ are calculated.

17. Calculation of specific heat of species j($C_{p,j}$) using

$$C_{p,j} = R(A + BT + CT^2 + DT^{-2})$$

Where j represents different species, R is universal gas constant and A, B, C, D are constants whose value are mentioned in Table A4 Then specific heat of zone 1($C_{p,z1}$) is calculated using

$$C_{p,z1} = \sum (w_{j,z1} x C_{p,j})$$

18. Calculation of temperature of each node for timestepi ($T^i_{m,wall1}$) using

$$T_n^{i+1} = T_{n-1}^i + \frac{\Delta x}{k}\,\frac{Q_{wall}^i}{A}$$

$$T_o^{i+1} = T_1^i - \frac{h_o \Delta x}{k}\,(T_o^i - T_{amb})$$

$$T_m^{i+1} = \frac{1}{2}\,(T_{m+1}^i + T_{m-1}^i)$$

Where m = 1 to n, is the number of nodes in which wall1 is divided, Δx and Δt denotes spatial step size and time step size respectively, and i represents the timestep

19. Calculation of Temperature of pot1 at timestep i+1 (T^{i+1}_{pot1}) using

$$Q_{pot}^i - Q_{pot\_loss}^i = (m_{water} C_{p,water} + m_{pot} C_{pot})\,(T_{pot}^{i+1} - T_{pot}^i)$$

Where i represents timestep

20. Calculation of Temperature of zone 2 (T_2) solving iteratively following equations

$$\dot{Q}_{pot2} = \dot{Q}_{rad} + \dot{Q}_{conv} = \sigma A_{pot2}\,(\varepsilon_{flue2} T_2^4 - \alpha_{wall2} T_{pot2}^4) + h_2 A_{pot2}\,(T_2 - T_{pot2})$$

$$\dot{Q}_{lue2\text{-}wall2} = \sigma A_{wall2} (\varepsilon_{flue2} T_2{}^4 - \alpha_{wall2} T_{iwall2}{}^4) + h_{2side} A_{wall2} (T_2 - T_{iwall2})$$

$$m_{flue} \times C_{p2} \times (T_1 - T_2) = \dot{Q}_{flue2\text{-}pot2} + \dot{Q}_{flue2\text{-}wall2}$$

21. Steps 17-19 are repeated for zone2.

22. Calculation of Temperature of zone 3 (T_3) solving following equations iteratively

$$\dot{Q}_{flue2\text{-}chim} = \dot{Q}_{rad} + \dot{Q}_{conv} = \sigma A_{chim} (\varepsilon_{flue2} T_3{}^4 - \alpha_{chim} Ti_{chim}{}^4) + h_3 A_{chim} (T_3 - Ti_{chim})$$

$$\dot{Q}_{flue2\text{-}chim} = \dot{m}_{flue} \times C_{p3} \times (T_2 - T_3)$$

23. Calculation of Heat lost by flue gases to atmosphere($\dot{Q}_{loss}$) using

$$\dot{Q}_{flue2} = \dot{Q}_{flue3\text{-}chim} + \dot{Q}_{loss}$$

24. Steps 17 and 18 are repeated for zone3

25. Steps 13-24 are repeated for each time steps (Transient loop)

26. Calculation of mass flow rate of air($\dot{m}_{air}$)solving iteratively following equations

$$P_3 - P_0 = \frac{-1 + K_{ent}}{2\rho_{amb}} \left(\frac{\dot{m}_{air}}{A_{door} A_r} \right)^2 + \frac{K_{bend1} + K_{exp1}}{2\rho_{z1}} \left(\frac{\dot{m}_{flue}}{A_{pot1}} \right)^2 + \frac{K_{cont1} + K_{bend2}}{2\rho_{z2}} \left(\frac{\dot{m}_{flue}}{A_{hole}} \right)^2 + \frac{K_{bend3} + K_{exp2} + \frac{fH_{chim}}{D_{chim}} + 1}{2\rho_{z3}} \left(\frac{\dot{m}_{flue}}{A_{chim}} \right)^2$$

$$P_3 - P_0 = (\rho_{amb} - \rho_{z3}) \times g \times (H_{chim} - D_{wo})$$

27.Check (T_{test}-T_1) > 0
If 'YES' then repeat steps 1-26
If 'NO' then exit the loop

Figure 2 Flow diagram of mathematical model

3. Results and Discussion

Mathematical model has been developed in MATLAB by using combustion, heat transfer and fluid flow equations. Thermal efficiency has been obtained by changing various parameters experimentally which has been compared with model analysis.

3.1 Thermal efficiency comparison with parametric variation

3.1.1 Variation of firepower

Experimental result of thermal efficiency of the cookstove with variation of firepower has been compared with model shown in Figure 3. Model trend is higher than experimental trend upto certain level than model trend has been found below the experimental trend. At higher firepower, there is lack of sufficient draft through chimney but in practical case, exhaust gas will follow the air fuel opening path. So, thermal efficiency of cookstove in experimental analysis at higher firepower has found more than model analysis.

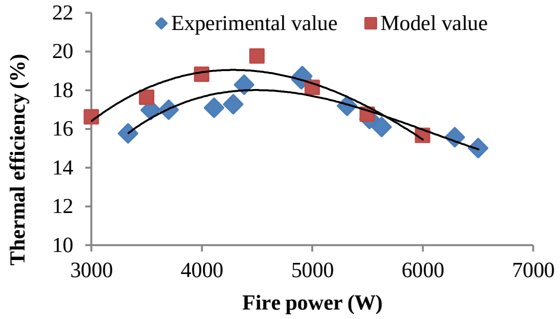

Figure 3 Comparison of thermal efficiency at different firepower between experimental and model value

Thermal efficiency versus firepower power characteristics has also been found in the shape of a shallow inverted bowl which has been found by Sangen as well as Sutal for less than 4kW cookstove [5,19, 20].

3.1.2 Variation of chimney height

Shape of the thermal efficiency of the cookstove with different chimney height for experimental analysis and model analysis has been found similar. The model trend has been found higher than experimental trend. This is due to high roughness factor in the internal surface of chimney. High roughness factor causes more frictional loss on the flow of flue gas and results less draft and insufficient air for combustion of air.

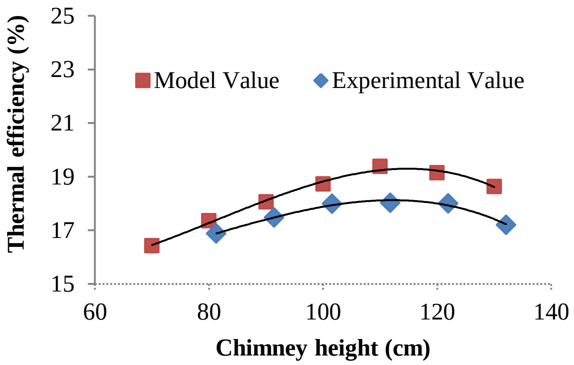

Figure 4 Comparison of thermal efficiency at different chimney height between experimental and model value

Sharma 1993 mentioned the role of chimney for the efficiency improvement. For smaller chimney height, the draft creation is low which results insufficient supply of air for the combustion process. For higher chimney height, suction draft increases and excess air also increases. This results in higher heat loss through flue gas and reduction of temperature of combustion chamber. All of these ultimately affect the thermal efficiency of cookstove [7].

3.1.3 Variation of material of cookstove

Experimental and model result of the thermal efficiency of cookstove has been compared at optimum feeding rate for the used material of mud and insulating at the combustion chamber. Thermal efficiency of cookstove in experimental value has been found lower than model value shown in Figure 5.

In case of mud cookstove, thermal efficiency has been found 17.99% in experimental analysis and 21.86% in model analysis.

In case of cookstove with insulation in inner surface, thermal efficiency has been found 20.21% in experimental analysis and 22.45% in model analysis. In model analysis, analysis has been done for full insulating material used in the cookstove but in practical case, insulating material has been used for inner lining only. Therefore, experimental value is lower than model value.

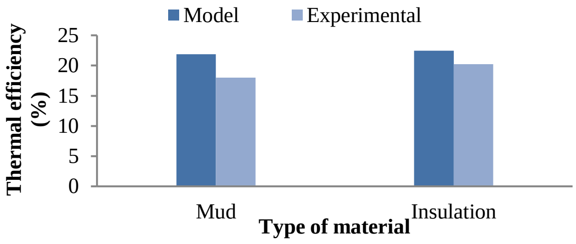

Figure 5 Comparison of thermal efficiency at different material between experimental value and model data

Thermal efficiency of cookstove with insulating layer has been increased from 18% to 20.21%; i.e., by 2.21%. This is due to decrease of thermal conductivity of cookstove material, increased reflectivity which results in increase of combustion chamber temperature [21].

3.2 Model analysis

3.2.1 Heat flow for mud cookstove

Heat produced during combustion process has been distributed to different components. Heat flow analysis for initial mud cookstove at firepower 4.445kW has been obtained. Heat flow into different components such as heat absorbed by wood for pyrolysis 5.29%, moisture evaporation 1.49%, the door 3.89%, and heat loss in wall l4.22%, heat gain by pot 21.86%, incomplete combustion 4.36% and heat lost through flue gas 48.89% is shown in Figure 6.

Model analysis shows that 48.49% heat has been lost through the flue gas. So, heat can recovered from flue gas through second pot hole with the creation of turbulence on the flow path of flue gas. About 5% has been lost due to incomplete combustion, so provision of secondary air supply and increase of combustion chamber temperature can reduce incomplete combustion.

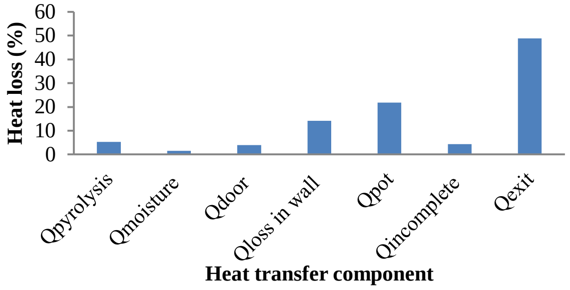

Figure 6 Model heat transfer analysis through different components

Heat loss through the wall has been found around 14% which can be reduced with the use of insulating material in the combustion chamber. Model results shows that heat loss from flue gas has been found 48.89%. In 2010, Zube has found that waste from flue gas has been found 44.9% energy losses from flue gas. [23]. The cause of lower waste due to use of better cookstove material.

3.2.2 Variation of cookstove material

Cookstove material with different density, thermal conductivity, specific heat capacity affects on temperature of combustion chamber, heat storage and heat loss from wall of the cookstove. Materials having higher thermal mass would store huge amount of energy. Thus four different materials has been used with properties enlisted in Table 1.

Table 1 Properties of different cookstove materials

Materials	Density (kg/m³)	Conductivity (W/mK)	Specific heat capacity (J/kgK)	Remarks
Mud and additives	1995	0.6	1251	Measured Value
Insulating material	1553	0.45	1175	Measured Value
Firebrick	1030	0.41	1050	Tabulated value
Vermiculite	90	0.064	960	Tabulated value

The effect of decreasing heat transfer to wall can be seen as increased heat transfer to pot, thus increasing the thermal efficiency. Whereas firebrick and vermiculate has higher thermal efficiency due less amount of heat lost through stove material. The effect can be seen in Figure 7.

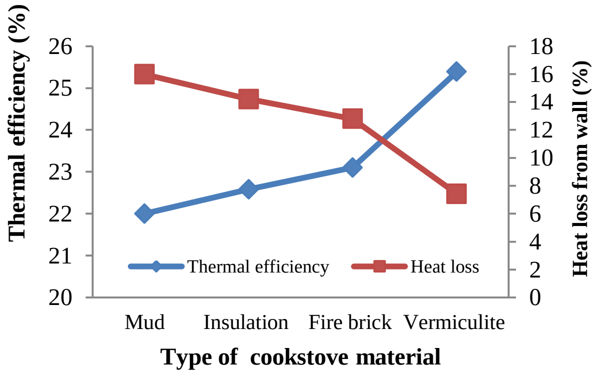

Figure 7 Thermal efficiency and heat loss from different stove materials

Use of better insulating material increase temperature of combustion and reduce conduction heat loss through the wall of cookstove [5].

3.2.3 Variation first pot hole diameter for different cookstove material

Variation of first pot hole diameter affects the thermal efficiency of cookstove. With the increase of first pot hole diameter, thermal efficiency of the cookstove increases. From social view point, larger diameter cookstove may not be suitable because size of small pot cannot be used. Thermal efficiency trend with increase of diameter of first pot hole has been found identical for mud stove, insulating stove, firebrick stove and vermiculite stove. Highest efficiency trend in vermiculite and lowest for mud cookstove as shown in Figure 8.

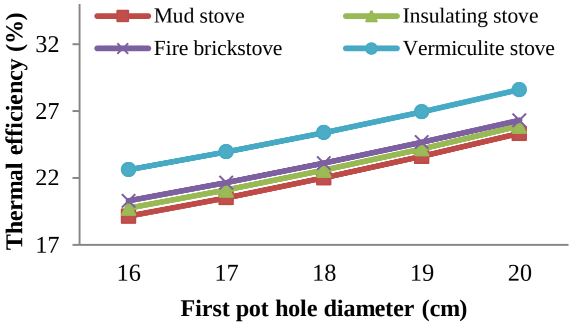

Figure 8 Thermal efficiency with variation of first pot hole diameter and use of different cookstove materials

Heat loss through the wall with increase of diameter of first pot hole of the cookstove has been decreased. Heat loss decease trend with increase of diameter of first pot hole has been found identical for mud stove, insulating stove, firebrick stove and vermiculite stove. Lowest heat loss trend has been found for vermiculite and highest for mud cookstove as shown in Figure 9. Other reason for the decrease in the heat loss may be due to the decrease in wall thickness, i.e., the thermal mass of the wall decreases. Smaller thickness of wall with considerable thickness increase the thermal efficiency of the cookstove.

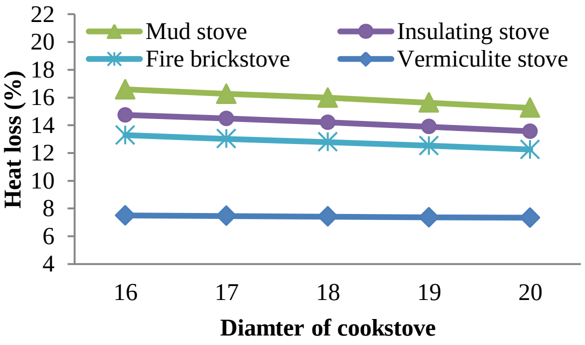

Figure 9 Heat loss through wall with change of first pot hole diameter and use of different cookstove materials

Increase of first pot hole increase the shape factor from bed to pot which results more convection and radiation heat transfer to the pot [24].

3.2.4 Variation of diameter of chimney hole

With the increase in the size of chimney hole, the area for flow of air increases. So, the choking of air decreases and the air can flow properly with more smoothness. The fluid flow property of no slip condition at the side of the wall can be applied. That's why the flow is improved and the excess air inlet has been increased. But the chimney height is kept constant at 101cm so it must have maximum capacity because the creation of draft is due to the stack effect (or to be more elaborative, pressure difference due to momentum balance) and the excess air saturates around 7.5cm chimney diameter shown in Figure 10.

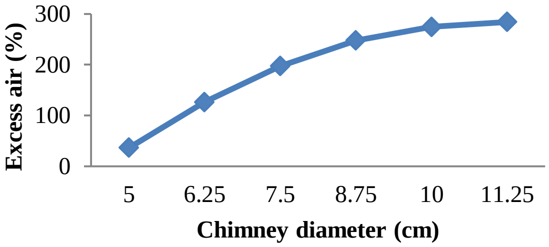

Figure 10 Variation of excess air with chimney diameter

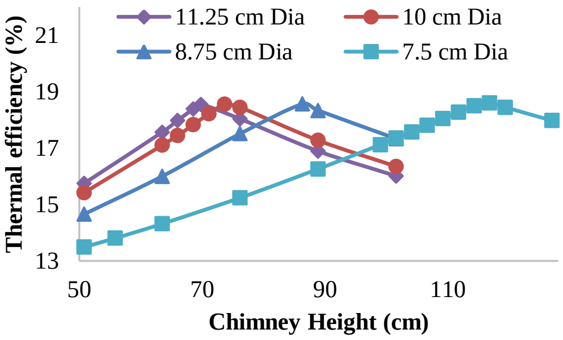

Figure 11 Variation of efficiency with coupled chimney height and diameter for mud cookstove

Figure 11 indicates the variation of efficiency with coupled chimney height and diameter. As seen from above analysis, the chimney height and chimney diameter are dependent parameter. So, they have been coupled together and analyzed with thermal efficiency. Considering all others parameters constant, there exists in finite data sets of chimney height and diameter yielding constant maximum efficiency of 18.6%. The figure shows four sets of chimney height and diameter {(116cm, 7.5cm), (86cm, 8.75cm), (73cm, 10cm) and (70cm, 11.25cm)} for which maximum thermal efficiency is 18.6%. All these data points can be surface fitted to obtain an empirical relation predicting overall efficiency.

4. Conclusions

Following are the conclusion from the study

- Optimum thermal efficiency for existing cookstove has been found 18% at firepower 4.45 kW, i.e., 1.2kg/h feeding rate for the existing cook stove.
- At optimum chimney height 113cm thermal efficiency has been found 18.16%.
- Thermal efficiency comparison in experimental and model value with use of mud has been found 17.99% and 21.86% respectively. While, with the use of insulation material corresponding value have been found 20.21% and 22.45% respectively.
- Model analysis shows heat absorbed by wood for pyrolysis 5.29%, moisture evaporation 1.49%, the door 3.89%, heat loss in wall l4.22%, heat gain by pot 22.58%, heat gain by pot 22.58%, incomplete combustion 4.36% and heat lost through flue gas 48.1% by pot for optimum dimension cookstove
- Model analysis shows that chimney height and diameter are dependent and coupled for maximum thermal efficiency 18.6% as (116cm, 7.5cm), (86cm, 8.75cm), (73cm,10) and (70cm,11.25).
- With increase of first pot hole diameter, thermal efficiency of cookstove can be increased.

Acknowledgement

The authors gratefully acknowledge the support from Department of Mechanical Engineering, Pulchowk Campus, Institute of Engineering, Tribhuvan University. Special thanks go to members of Renewable Energy Test Station, Khumaltar, Lalitpur for their continuous support. Finally, we would like to thank the editor and all reviewers for their helpful and incisive comments.

References

[1] C. Bureau and O. F. Statistics, "Annual household survey 2015/16," vol. 16, 2016.

[2] K. Smith, "Health,energy, and green house-gas impacts of biomass combustion in household stoves.Energy Sustainable Development 1994;1(4):239.," 1994.

[3] M. Sedighi and H. Salarian, "A comprehensive review of technical aspects of biomass cookstoves," *Renew. Sustain. Energy Rev.*, vol. 70, no. November 2016, pp. 656–665, 2017, doi: 10.1016/j.rser.2016.11.175.

[4] J. B. Kandpal and D. H. Khas, "Air Pollution From Biomass Combustion in Domestic Cookstove," *Renew. Energy*, vol. 1481, no. 5, pp. 545–549, 1994, [Online]. Available: http://www.sciencedirect.com/science/article/pii/096014819490216X?np=y.

[5] K. B. Sutar, S. Kohli, M. R. Ravi, and A. Ray, "Biomass cookstoves: A review of technical aspects," *Renew. Sustain. Energy Rev.*, vol. 41, pp. 1128–1166, 2015,

doi: 10.1016/j.rser.2014.09.003.

[6] K. K. Prasad, E. Sangen, and P. Visser, "Woodburning Cookstoves," vol. 17, J. P. Hartnett and T. F. B. T.-A. in H. T. Irvine, Eds. Elsevier, 1985, pp. 159–317.

[7] S. K. Sharma, "Improved Solid Biomass Burning Cookstoves: a Development Manual," no. 44, Asia Regional Cookstove Programme and Energy Research Centre of Panjab University, Chandigarh, 1993, p. 125.

[8] H. B. Dralami, G. R. Pokharel, and B. B. Ale, "Performance Test of Modified Mud Improved Cook Stove," *IOE Gratuate Conf.*, 2014.

[9] J. Prapas, M. E. Baumgardner, A. J. Marchese, B. Willson, and M. DeFoort, "Influence of chimneys on combustion characteristics of buoyantly driven biomass stoves," *Energy Sustain. Dev.*, vol. 23, pp. 286–293, 2014, doi: 10.1016/j.esd.2014.08.007.

[10] J. Agenbroad, M. DeFoort, A. Kirkpatrick, and C. Kreutzer, "A simplified model for understanding natural convection driven biomass cooking stoves-Part 1: Setup and baseline validation," *Energy Sustain. Dev.*, vol. 15, no. 2, pp. 160–168, 2011, doi: 10.1016/j.esd.2011.04.004.

[11] J. K. Kumar R, Lokras SS, "Development, analysis and dissemination of a three pan cook stove. Bangalore: Indian Institute of Science.," 1990.

[12] S. W. Claus J, "A comparison of the performance of three woodstoves, Proc Indian Acad Sci (Eng Sci) 1982;. 6(1):343–59.," 1982.

[13] J. Gill, "Improved stoves in developing countries. A critique," *Energy Policy*, vol. 15, no. 2, pp. 135–144, 1987, doi: 10.1016/0301-4215(87)90121-2.

[14] G. De Lepeleire and K. Prasad, "A woodstove compendium Citation for published version (APA)," 1981. www.tue.nl/taverne (accessed May 25, 2019).

[15] S. F. Baldwin, "Biomass Stoves: Engineering Design, Development, and Dissemmination," 1987. Accessed: May 25, 2019. [Online]. Available: http://blog.newdawnengineering.com/website/library/Papers+Articles/Biomass Stoves, Engineering Design, Development and Dissemination, Samuel Baldwin 1987.pdf.

[16] PCIA & Global Alliance, "The Water Boiling Test Version 4.1.2; Cookstove Emissions and Efficiency in a Controlled Laboratory Setting," *Glob. Alliances Clear. cookstoves*, vol. 2, no. January 2013, p. 52, 2013, [Online]. Available: http://www.aprovecho.org/lab/pubs/testing.

[17] R. Bailis *et al.*, "Performance testing for monitoring improved biomass stove interventions: experiences of the Household Energy and Health Project This paper is one of six describing work done as part of the Household Energy and Health (HEH) Project," *Energy Sustain. Dev.*, vol. 11, no. 2, pp. 57–70, 2007, doi: 10.1016/S0973-0826(08)60400-7.

[18] M. P. Kshirsagar and V. R. Kalamkar, "A mathematical tool for predicting thermal performance of natural draft biomass cookstoves and identification of a new operational parameter," *Energy*, vol. 93, pp. 188–201, 2015, doi: 10.1016/j.energy.2015.09.015.

[19] E. Sangen, "A survey of test results on wood stoves. Technical aspects of woodburningcook stoves. Netherlands: Eindhoven University of Technology;," pp. 199–259, 1983.

[20] J. B. Kandpal and R. C. Maheshwari, "Combustion of Biomass Fuels in 2 Cookstoves for Their Conservation," *Energy Convers. Manag.*, vol. 36, no. 10, pp. 1015–1021, 1995.

[21] G. De Lepeleire, "Heat transfer and cooking woodstove modelling," *Proc. Indian Acad. Sci.*, vol. 6, no. 1, pp. 35–46, 1983.

[22] C. M. De Lepeleire G, *Heat transfer and cooking woodstove modeling. ProcIndian AcadSci (EngSci);6(1):35–46.* 1983.

[23] D. J. Zube, "THESIS HEAT TRANSFER EFFICIENCY OF BIOMASS COOKSTOVES Submitted by," 2010.

[24] M. A. Herwijn, "Eindhoven University of Technology An experimental investigation into the heat transfer from a wood-fire to a pan Herwijn , A . J . M . An experimental investigation into the heat transfer from R-632-A by A . J . M . Herwijn Final thesis for the Departmen," 1984.