Experimental investigations and thermal analysis of a natural draft improved biomass cookstove with different air conditions

Kinnari Modi¹ and Darshit S Upadhyay¹*

¹Mechanical Engineering Department, Institute of Technology, Nirma University, Ahmedabad-382481, Gujarat, India
*Corresponding Author: darshitupadhyay@yahoo.com; darshit.upadhyay@nirmauni.ac.in

Abstract. Traditional biomass cookstoves (TCS) are very popular among rural areas and street vendors especially in developing and underdeveloped nations due to their conventional process and simple construction. However, this direct combustion technique is not suitable due to poor efficiency and harmful gaseous-particular emission. Improved biomass cookstoves (ICS) have the potential to overcome the health and environmental problems that are common in the case of TCS. In the present study, investigations were carried out on 3.5 kWth ICS based on gasification design with four different air conditions. The opening to the closing ratio of primary to secondary air vents are taken at 50/50, 50/100, 60/100, and 80/100, respectively for the experiments. Performance of TCS and different ICS cases were compared in terms of burning rate, specific fuel consumption, firepower, useful firepower, thermal efficiency, total particulate matter, and gaseous emissions (CO, CO₂, O₂, NOₓ, CC, HC). Apart from that, thermal analysis such as mass balance, energy balance, and exergy efficiency was also calculated. 50/100 opening to the closing ratio of primary to secondary air offers the better performance in terms of higher thermal efficiency and lower gaseous and particulate emission is the major conclusion from this study.

Keywords: Traditional biomass cookstove, improved biomass cookstove, performance, emission, water boiling test, efficiency.

1. Introduction

A huge number of people in the world still depend on traditional (or conventional) biomass cookstove (the bricks/stone stove). It is not limited to rural area people, as people in urban areas are also used the traditional stove (especially homeless people and street vendors) in most of the underdeveloped and developing countries [1]. It is due to the fact that these stoves are inexpensive and simplest design. Apart from that, these types of cookstoves are easily operated [2]. The combustion efficiency of these stoves is very less. Moreover, these stoves generate a large amount of smoke, particulate matter, and other harmful gases. Due to the same reason, traditional cookstoves are not suitable for human health as well as environmental aspects [3]. These hazardous effects resulted in respiratory diseases, adverse
pregnancy outcomes, lung cancer, cardiovascular disease (CVD), and asthma. Worldwide annual death of household air pollution is estimating at 3.1 million deaths per year [4]. It includes 1.6 million premature deaths, and 0.9 million children die less than five years of age worldwide as per the World Health Organization (WHO) [5]. To overcome these problems, use improved biomass cookstove is essential nowadays.

The improved biomass cookstoves are made of different materials and designs. The gasification-based natural-draft and forced-draft cookstoves are some of the popular options among researchers. These cookstoves are having two types of air supply i.e., primary holes – to generate producer gas (generally CO + H2) and then secondary holes - to combust producer gas (generally CO2 + H2O). The top-lit updraft micro biomass gasifier-based cookstoves have primary holes and secondary holes at the bottom part and the upper part for air supply, respectively. the holes are partly or fully closed or opened depending on the needed heating rate to be supplied or controlled which is according to the combustion process [6].

The study of airflow variation in primary to secondary ratio is important due to changes in stoichiometric mixture. The energy and exergy analysis of an improved biomass cookstove was carried out with sheesham and eucalyptus (1 kg to 5 kg). The variation of exergy and energy efficiency was found in the range of 25.83%–30.53% and 3.83%–5.01%, respectively [2][6]. carried out a water boiling test for five different airflow rate values. They concluded that 9.07 Nm3 h−1 and 24.3 Nm3 h−1 airflow rates provide the highest (64 min) and lowest (50 min) operation time, respectively[7]. performed the experimental study on improved biomass cookstove with woody fuel and different insulating materials. They claimed that the stove with glass wool insulation offers lesser CO emission (29.36 ppm) & PM 10 emissions (3.64 mg) and higher thermal efficiency (32.66%) as compared to the stove with Plaster of Paris[8]. performed a comparative experimental study on gasifier cookstove for four different solid fuels. They observed low CO emission for all feedstock for the lower airflow rate. For the literature survey, it is observed that a limited study with different primary to secondary air ratios was carried out on a gasifier-based cookstove.

In this study, experimentation on traditional cookstove and 3.5 kWth improved biomass cookstove was carried out with different primary to secondary air ratios. Cookstove performance was evaluated by burning rate, specific fuel consumption, thermal efficiency, emissions, and particulate matter. Moreover, thermal analyses such as mass & energy balance, exergy efficiency were also carried out.

2. Experimental

2.1. Material

Wood was selected as a primary food for the experimentation purpose due to its abundant and inexpensive nature especially in the rural area. In the world, most of the cookstoves are operated by wood only. Teak wood was collected from the nearby furniture factory. It was cut and sized before utilizing it in a cookstove. Leco AC-350 Bomb Calorimeter [Test method: IS 1350 (part II)-1970] was used to measure the heating value of the wood. Heating value and ultimate analysis were expressed on a dry basis whereas proximate analysis was carried out on a wet basis. Proximate [Test method: IS 1350 (part I)-1984] and ultimate analysis of the wood is mentioned in Table 1.

| Properties of feedstock | Wood |
|-------------------------|------|
| Bulk Density (kg m⁻³)   | 413  |
| Physical Properties     |      |
| Particle Size (mm)      | 25×25×5 |
| Heating Value (MJ kg⁻¹)| 16.82|
| Carbon                  | 45.8 |
Hydrogen & 6.3 & \\
Ultimate analysis & Nitrogen & 0.4 & \\
 & Sulphur & 0.002 & \\
 & Oxygen$^a$ & 40.79 & \\
Proximate analysis & Fixed Carbon$^a$ & 5.92 & \\
 & Volatile matter & 82.84 & \\
 & Ash & 4.55 & \\
 & Moisture & 6.69 & \\

$^a$by Difference

2.2. Experimental set-up

3.5 kWth top-lit updraft micro biomass gasifier-based cookstove is designed as per the stoichiometric calculation. It is prepared by mild steel 3 mm thick sheet. Grate and ashpit are added to collect char and ash particles after the combustion process of the feedstock. A number of Primary holes (20 mm) & secondary holes (25.4 mm) and total height were kept 8, 12, and 365 mm, respectively. The shape of the combustion chamber is kept cylindrical whereas the shape of the ashpit is kept rectangular. For the experimentation, two aluminum pots (18L capacity) were used to heat the water. CAD model of biomass cookstove is shown in Figure 1.

2.2.1. Methodology. The experiments were performed on the improved biomass cookstove based on the gasification principle (at atmospheric pressure). Before starting the experiments, the setup is cleaned properly, and then after sized biomass is fed to the reactor. The feedstock is heated by the torch and combustion was taking place. The experiments were carried out three times with the same condition to check the repeatability of the results. To check the performance of the cookstove, three major tests (Water boiling for calculating thermal efficiency, emission, and particulate matter) were carried out.

For the water boiling test, two pots were filled with 18 kg water as per the Bureau of Indian Standards (BIS)[2]. There were two phases in the experiment. In the first phase, an aluminum pot was filled with 18 kg of water and 850 gm of teak wood was filled in the combustion chamber. The initial temperature of the water was measured at the beginning of the experiment along with time. The temperature of the water was constantly monitored at the interval of 5 min until it reaches 95°C with the help of the laboratory thermometer[6]. When 850 gm wood was partially burnt, then again add the remaining wood (350 gm). When the temperature of the water reaches 95°C then pot 1 was replaced by pot 2. The same process was repeated till the utilization of all the fuel in the chamber [2].

An emission test was carried out with five gas analyzer (i3Sys make, EPM 1601 model). Without interfering in any process of combustion in a cookstove, the flue gases were collected in a hood. In

Figure 1. CAD model of ICS.
order to take a sample of flue gases, this analyzer was fitted to the hood [9]. By this procedure, HC, NOx, O2, CO, CC, CO2, CO, and NOx were measured relatively in ppm or %.[10] Total Particulate Matter (TPM) was measured as per the guideline of the Ministry of New and Renewable Energy (MNRE), Govt. of India [10][11]. Axiva make glass fiber filters (25 mm diameter, 2.5-micron) were used to measure TPM through the gravimetric method. For suction of the flue gas from the hood to the TPM arrangement, a vacuum pump was used[12]. At the center axis of a duct nozzle, anemometer mounting was placed. Testing of water boiling, gaseous and particulate emission was carried out along with simultaneously during the experimental run. A flow rate of the gas and air was measured with an Amprobe TMA-21HW Hotwire anemometer with a data logger. The temperature of the combustion zone was measured by K (Chromel-Alumel) type thermocouple.

Experiments were carried out on traditional cookstove and improved cookstove with four different primary to secondary air ratios. For creating different conditions, few air vents are kept open and close. The opening to the closing ratio of primary to secondary air vents is maintained at 50/50, 50/100, 60/100, and 80/100, respectively. Example: 80/100 means 80% primary vent open and 100% secondary vent open. The exact mass flow can be found from mass balance Table 2.

2.2.2. Important Parameters and Thermal Analysis. Important parameters of a cookstove performance such as burning rate, firepower, specific fuel consumption (SFC), power output rating are defined as per their definitions available in the literature [2][10]. Mass, energy, and exergy analysis are carried out as per the authors’ previous work [13][14][15][16]

- Burning rate
  \[
  \text{Burning Rate} = \frac{\text{Equivalent mass of biomass consumed in kg}}{\text{Time of test in hour}} \quad (1)
  \]

- Firepower
  \[
  \text{Firepower} = \frac{\text{Equivalent mass of biomass consumed in kg \times CV}}{\text{Time of test in hour \times 3600}} \quad (2)
  \]

- Specific fuel Consumption
  \[
  \text{Specific Fuel Consumption} = \frac{\text{Burning Rate}}{\text{Firepower}} \quad (3)
  \]

- Thermal Efficiency
  \[
  \eta = \frac{(m \times cp \times \Delta T)_{\text{water}} + (\Delta m \times \lambda) + (m \times cp \times \Delta T)_{\text{pot}}}{(m \times cv)_{\text{wood}}} \quad (4)
  \]

- Useful firepower
  \[
  \text{Useful firepower} = \text{firepower} \times \eta \quad (5)
  \]

**Mass balance**

Mass balance was carried out by considering the output mass from a cookstove and input mass to a cookstove. The total input mass of a cookstove consists of air (primary and secondary), fuel while the total output mass of a cookstove consists of gas, char, PM, water, and ash. In the mass balance, the inconsistency finds by mass balance closure. It is defined by the ratio of the total mass output to the input mass. It should close to one proposed the mass balance is accurate.

Mass balance is done by the following equation.

\[
M_{\text{fuel}} + M_{\text{air-p}} + M_{\text{air-s}} = M_{\text{gas}} + M_{\text{char}} + M_{\text{PM}} + M_{\text{ash}} + M_{\text{water}} \quad (6)
\]

M fuel was calculated by weighing machine, Mair and Mgas were converted from respected volumes measured by hot-wire anemometer. M char and M ash were calculated by weighing machine. In fact, both were collected from the same ashpit. However, based on the ash content available in the
fuel, ash and char content could be calculated separately. M PM is a mass flow rate of total particulate matter. Mwater was calculated by psychometric chart by considering DBT and WBT observation[15].

Energy balance
Energy balance was carried out by considering output energy from flue gas (utilized or unutilized) and input energy especially from feedstock [17]. The energy balance equation is expressed as:

\[
E_{fuel} + E_{air} = E_{gas} + E_{char} + E_{pot} + E_{ash} + E_{water} + E_{losses}
\] (7)

The energy available from fuel and air was calculated by:

\[
E_{fuel} = m_{fuel} \cdot CV_{fuel}
\] (8)

\[
E_{air} = m_{air} \cdot Cp_{air} \left( T_{air} - T_{ref} \right)
\] (9)

Similarly, energy from char, water, gas, pot and ash were calculated.

Exergy analysis
Exergy efficiency (or second-law efficiency) computes the effectiveness of a system relative to its performance in reversible conditions. It can also be described as the ratio of the useful work output of the system to the reversible work output for work-consuming systems. It is normally ambient temp and atmospheric pressure [2].

Exergy Efficiency (\(\varphi\)) is expressed as,

\[
\text{Exergy efficiency} (\varphi) = \frac{\text{Exergy output}}{\text{Exergy input}}
\] (10)

Exergy input is calculated based on the following equation:

\[
Ex_i = m_{wd} \cdot cv \left( 1 - \frac{T_a}{T_{fuel}} \right)^n c
\] (11)

Exergy output is calculated based on the following equation:

\[
Ex_o = mw \cdot cpw \cdot \left( T_{fw} - Tiw \right) \left( 1 - \frac{T_a}{T_{fw}} \right) + mpot \cdot cp \cdot pot \cdot \left( 1 - \frac{T_a}{T_{fp}} \right)
\] (12)

3. Results and Discussion

3.1. Effects on Useful firepower and firepower

Figure 2 represents the effect of firepower and useful firepower with different airflow. It was observed that TCS has maximum firepower among selected cases, however, the useful firepower of TCS is very less. It is because most of the energy liberated from TCS was not utilized properly and went to the atmosphere. Firepower is depending on the burning rate and rate of oxygen involved in the reaction. Due to the same 50/50 ratio has lower firepower and 80/100 ratio with ICS has higher firepower, comparatively. Useful firepower is depending on efficiency as well as firepower. Due to the same, it is observed that 50/100 ratio has the highest useful firepower compared to other cases due to higher thermal efficiency.
3.2. Effects on burning rate and specific fuel consumption

SFC and burning rate are expressed in Figure 3. More air is involved in the reaction when vents are open to large extents. This process leads to a higher rate of combustion. Due to the same, TCS has a higher burning rate (excess air) whereas ICS with a 50/50 ratio has a lower burning rate. SFC is depending on the thermal efficiency of the system. Therefore, 50/100 ratio has a lower SFC compared to other cases. It is obvious fact that the SFC of TCS is extremely high due to the uncontrolled combustion process.

3.3. Effects on Thermal Efficiency and Exergy Efficiency

Figure 4 presents the effects on thermal efficiency and exergy efficiency of the biomass cookstove. Thermal efficiency and exergy efficiency were observed in the range of 32.34% - 40.54% and 7.79% - 7.95%, respectively for ICS. For TCS, thermal efficiency was observed only 15.64% and exergy...
efficiency was observed only 3.93%. It was observed that good quality producer gas may be generated for 50/100 ratio leads to a higher temperature at the secondary air inlet.

![Figure 4. Effects on Thermal efficiency and exergy efficiency.](image)

3.4. Effects on PM and Combustion temperature
Effects on PM and combustion temperature at different airflow are illustrated in Figure 5. Combustion temperatures of TCS and ICS (all cases) were observed in the range between 415ºC to 596ºC. Temperature with TCS was found lower due to improper combustion process. Due to improper combustion, a higher amount of HC and CO was observed in the flue gas for TCS. Due to the same, combustion efficiency was found lower for TCS as compared to ICS. 50/100 and 60/100 ratios offered good combustion temperature comparatively. Particulate emission was found lower as an increment of temperature. It is due to the fact that the vent of the primary holes was placed above the ashpit. Due to the same, fewer particles were carried along with producer gas in the cookstove. Moreover, at a higher temperature, cracking of coarse particles may have resulted in fine particles.

![Figure 5. Effects on PM and combustion temperature.](image)
3.5. Effects on Emission gas
Gaseous emissions such as CO, HC, O\textsubscript{2}, CC, NO\textsubscript{x}, CO\textsubscript{2} are shown in Figure 6. Emissions have a direct relation to combustion characteristics. From figure 6 it is observed that TCS has higher CO and HC contents. These data reveal that combustion products of TCS have the potential to generate more energy. However, due to the unavailability of a sophisticated system, the same components were thrown into the atmosphere. ICS with 50/100 ratio has minimum O\textsubscript{2} and CO\textsubscript{2} compounds. It is because producer gas was combusted properly with secondary air in the combustion chamber.

![Figure 6. Effects on gaseous emission.](image)

3.6. Mass balance
Table 2 shows a mass balance of different airflow for biomass cookstove. MBC was found in the range of 0.96 to 0.99. 50/50 ratio with ICS has a lower mass of gas. It is due to the lower secondary air providence compared to other cases.

| Different Airflow (%) | Input Masses (kg h\textsuperscript{-1}) | Output Masses (kg h\textsuperscript{-1}) | MBC (%) |
|-----------------------|----------------------------------------|----------------------------------------|---------|
|                       | Mfuel | Mair-p | Mair-s | Mgas | Mchar | Mash | MPM | Mwater |         |
| 50/50                 | 1.041 | 1.039  | 2.01   | 3.80 | 0.015 | 0.062 | 0.000022 | 0.085 | 0.968 |
| 50/100                | 1.178 | 0.831  | 4.02   | 5.69 | 0.020 | 0.054 | 0.000013 | 0.094 | 0.971 |
| 60/100                | 1.200 | 1.039  | 4.02   | 5.94 | 0.018 | 0.060 | 0.00001 | 0.113 | 0.980 |
| 80/100                | 1.241 | 1.662  | 4.02   | 6.62 | 0.021 | 0.064 | 0.00002 | 0.144 | 0.990 |

3.7. Energy balance
Energy balance was carried out and shown in Table 3. EBC was found in the range of 0.83-0.90. The reason behind lower EBC may be due to the following reasons: 1. No heat loss was considered (pot and reactor), 2. Combustion efficiency was not considered in Efuel, and 3. Unaccounted losses.
### Table 3. Energy balance of different air flow conditions.

| Different Airflow (%) | Input Masses (kJ h⁻¹) | Output Masses (kJ h⁻¹) | EBC (%) |
|-----------------------|-----------------------|------------------------|---------|
|                       | Efuel | Eair | Egas | Echar | Eash | Ewater+pot |         |
| 50/50                 | 20184 | 30.64 | 4772.04 | 267.77 | 2.71 | 12530.41 | 0.86    |
| 50/100                | 21462.3 | 48.75 | 4245.42 | 334.72 | 2.53 | 14704.09 | 0.83    |
| 60/100                | 20184 | 50.84 | 4614.62 | 301.24 | 2.62 | 13419.37 | 0.90    |
| 80/100                | 20184 | 57.10 | 5040.57 | 351.45 | 2.71 | 12616.32 | 0.88    |

### 4. Conclusions

Experiments were carried out with wood feedstock on TCS and ICS with different air conditions. The opening to the closing ratio of primary to secondary air vents was taken at 50/50, 50/100, 60/100, and 80/100, respectively. Following are the major conclusions from this study.

1. TCS has poor thermal efficiency (15.64%) and higher gaseous and particulate emission (>550 mg Nm⁻³). Even the combustion temperature of TCS is very less compared to ICS in all cases.

2. Burning rate and SFC are found in the range of 1.1 kg h⁻¹ to 1.24 kg h⁻¹ and 0.52 kg kWh⁻¹ to 0.66 kg kWh⁻¹ for different cases of ICS.

3. Firepower is found higher for 80/100 ratio (5.79 kW) whereas useful firepower is found higher for 50/100 ratio (2.21 kW).

4. 50/100 ratio has obtained maximum combustion temperature (596 ºC) and minimum PM as compared to other selected cases.

5. The thermal efficiency of ICS with 50/100 ratio is found maximum (40.54%). In fact, all ICS air conditions offer good thermal efficiencies in the range of 32.34% to 40.54%.

6. ICS with 50/100 ratio offers better output (better thermal efficiency and lower gaseous – particulate emission) compared to other selected conditions. It is due to the generation of good quality producer gas and achieved better stoichiometry during the combustion process.

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### Abbreviations

- m: Mass
- Cp: Specific heat
- ΔT: Difference between initial and final temperature
- Δm: Mass of water evaporation
- λ: Latent heat of water evaporation
- η: Thermal efficiency
- ηc: Combustion efficiency
- T_ref: Reference temperature
- Mwd: Mass of wood
- Mw: Mass of water
- Mpot: Mass of pot
- Cp_w: Specific heat of water
- Cp_pot: Specific heat of pot
- Ta: Ambient temperature
- Tfuel: Temperature of burning fuel
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\[ T_{fw} \] Final temperature of water
\[ T_{iw} \] Initial temperature of water
\[ T_{fp} \] Final temperature of pot
\[ T_{ip} \] Initial temperature of pot
\[ M_{air-p} \] Mass of primary air
\[ M_{air-S} \] Mass of secondary air