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Performance Evaluation of Domestic Rice Husk Gasifier Stove (Belonio Type) and Study on Modification of Design for using Different Biomass

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Abstract

This paper attempts to address the performance analysis of the updraft domestic gasifier stove (Belonio type) which is designed for rice husk and intended to modify for the different feedstocks. The feedstock namely rice husk, 50% biomass pellet and 50% rice husk, 50% rice husk and 50% wood chips were used for analysis. The stove performance was evaluated in terms of fuel consumption rate, water boiling test, gasification efficiency, flame temperature and temperature along the axis of the gasifier with response to regular time interval. The water boiling test reveals the high efficiency of 27.93% for wood chips mix, followed by pellet mix as 27.89% and rice husk as 26.97%. The fuel consumption rate was 1.71 kg/h for the case of pellet mix and wood chips mix whereas for rice husk as 1.2 kg/h. The fabricated stove have some drops its performance for rice husk as 20.02%, pellet and rice husk as 25.89% and wood chips and rice husk as 26.27%. So, two pot chamber is expected to exhibit better performance with better combustion and use of energy.

Keywords

gasifier – feedstocks – efficiency – fuel consumption rate – water boiling test

1. Introduction

Energy consumption and utilization pattern in Nepal differs from industrialized country. Energy is necessary requirement in everyday life. Its application ranges from cooking, local industries, food processing, warming of the body, and other more complex industrial and commercial applications. The commercial source of energy cannot fulfil the major population energy demand. Non -commercial sources of energy such as fire-wood and agricultural residues constitute the main source of energy in the rural areas of most part of Nepal. Keeping in view of problems related to availability, price of LPG; throughout the world, since few years an unprecedented energy consciousness has been developed and researchers are widely participated for the effective utilization of available resources and find the sustainable devices with sustainable materials. In Nepal biomass accounts for approximately 87.1% of the total energy use [1]. According to the economic survey of the fiscal year 2014/2015 the ratio of traditional, commercial and renewable energy consumption during the same period has been 77%, 20% and 3% respectively. Comparing to the fiscal year 2013/2014, dependency of Nepalese economy on traditional energy remained unchanged [2]. Based on the census June 22, 2011 population of Nepal stands to be 26,494,504 with population growth rate of 1.35 per annum. Similarly, total number of households in the country is 5,427,302 with 5,423,297 individual households and 4,005 institutional households (Barracks, Hostels, Monasteries etc). About two third of the total households (about 64%) use firewood as usual source of fuel for cooking followed by LPG (21.03%), cow dung (10.38%). Biogas and Kerosene is used for cooking by 2.43% and 1.03% of the total households respectively. Very few households (0.08%) use electricity as usual fuel for cooking. In urban areas, more than two third (67.68%) of the total households use LPG as their usual fuel for cooking [3]. On the fiscal year 2014/2015 supply of kerosene as a cooking fuel has been decreased by 0.2% and the LPG supply has been increased by 9.8%

[2]. But LPG seems to be ideal or temporary option which is dependent on the international supply, have led to periodic shortage, crisis, is not a sustainable and affordable fuel in the context of Nepal. About 80% of energy is utilized in residential sector for heating and cooking purposes which indicates that Nepal is not an industrialized country. So, it is evident that biomass is a dominant cooking fuel in the context of Nepal. This dependency is closely related to overall development of infrastructure and to the economic level in the society.

Biomass gasification, which is the conversion of solid fuels like wood and agricultural residues into a combustible gas mixture, is a fairly new technology in Nepal. The resulting gas is a producer gas which is a mixture of the combustible gas (H_2, CO, CH_4) and incombustible gases i.e. CO_2, N_2 [4]. The gasifier seems to be the best available technology tapping the highest amount of energy content in the biomass with higher efficiency alternative to Improved Cooking Stoves with direct combustion. In the gasification process air surplus rate should be less than 1 otherwise the thermal process will be transformed to combustion. The theoretical air requirement is described in following equation [5].

$$\text{Equivalence ratio, } \lambda = \frac{\text{Actual air}}{\text{Stiochiometric air}} \tag{1}$$

Different researchers found effective equivalence ratio for wood gasification in the range of 0.25 to 0.35. If equivalence ratio is below 0.20, it may give rise to incomplete gasification, excessive char formation and lower heating value of producer gas. For equivalence ratio above 0.4, it may result in excessive formation of complete combustion products in the expense of CO, CH_4 and H_2 of producer gas [6]. Thus, gasifier led to complete gasification with minimal emissions which is a major problem with solid fuel combustion.

There are two types of gasifier stove viz updraft gasifier and downdraft gasifier stove [7]. The stove discussed here is based on updraft type in which biomass flow and air flow is in opposite direction. It is expected to create numerous help to uplift clean cooking standard.

2. Objectives

The main objective of this paper is performance evaluation of the domestic rice husk gasifier stove (Belonio type) and study on modification of the design for different biomass while the specific objectives are:

1. To evaluate performance of the gasifier stove using different biomass materials.
2. To study the improvement in the existing gasifier stove for using different biomass materials.
3. To modify the stove using available material and technology and test using different feedstock.

3. Materials and Methods

The biomass samples namely rice husk, wood chips and biomass pellet were used as a feedstock for testing. The proportion of 100% rice husk, 50% rice husk and 50% pellet, 50% rice husk and 50% wood chips were made for observing the performance of the stove. Some piece of waste paper were used for igniting the fuel. The road map used in this study is shown below:

3.1 Proximate analysis

The PA analysis test were done following JIS 8812 standard method to evaluate the percentage of moisture content, ash content, volatile matter content, fixed carbon. The fuel samples for the PA analysis were prepared by grinding them in powder form. The fuel test were repeated three times to minimize experimental error and average value were noted down. The samples were weighted and recorded in a digital balance. The results of the proximate analysis are shown in figure 5.

3.1.1 Determination of Moisture Content

Samples after collection was placed in drying oven ability to maintain air tight to prevent gains or losses in moisture from the atmosphere. The crucible with approx. one gram samples were placed in the oven for about an hour at 107°C and cooled in the desiccators to the room temperature and reweighted. To reduce the possibility of errors, experiment was repeated three times and average value was determined. Thus, moisture content is determined as the loss in weight that occurs when the sample is dried in an oven. The following equation is used to determine the moisture content.

$$\%\text{MC} = \frac{W_i - W_f}{W_i - W_c} \times 100 \tag{2}$$

where,
W_i = initial weight of the sample plus crucible
W_f = weight of sample plus crucible after oven dry
W_c = weight of the empty cruicible

3.1.2 Determination of Ash Content

Ash is the inorganic solid residue left after the fuel is completely burned. Sample with approx. one gram in a cruicible porcelain was placed in the muffle furnance at about 815°C for about an hour. After removing from the furnance samples were cooled in the deciccators and weight was taken. Experiment was repeated for three samples and average value was noted down. The following formula is used to determine ash content.

$$\%\text{Ash} = \frac{W_b - W_c}{W_{od}} \tag{3}$$

where,
W_b = weight of the crucible and ash
W_c = weight of the empty cruicible
W_{od} = oven dry weight of the sample

3.1.3 Determination of Volatile Matter

The condensable and non condensable vapor released on heating of fuel is considered to be volatile matter whose amount is dependent on the rate of heating and temperature to which it is heated. Porcelain crucible with approx one gram sample was placed in the muffle furnance at about 900 °C for about 7 min after that it was allowed to cool in the deciccators and samples was reweighted. The experiment was repeated three times to minimize the experimental error.

3.1.4 Determination of Fixed Carbon

Fixed carbon is calculated as the summation of percentage of moisture, ash, volatile matter and is subtracted from 100%. The solid carbon in biomass remaining after devolatization process is represented as fixed carbon.

$$\%\text{FC} = 100\% - (\%\text{MC} - \%\text{AC} - \%\text{VM}) \tag{4}$$

where,
MC = Moisture Content
AC = Ash Content
VC = Volatile Matter Content

4. Determination of calorific value

The calorific values of the three different fuels were determined following IP-12 corresponding to 1359-1959 standard method, using calibrated Toshniwal Digital Bomb Calorimeter. The results of the calorific value of different fuels are shown in table 1. Since the fuel were mixed in the proportion so the calorific value for the mixed fuel were calculated by using the following empirical formula.

$$\text{CV} = \%P_1 \times CV_1 + \%P_2 \times CV_2 \tag{5}$$

where,
$\%P_1$ = percentage of first fuel
CV_1 = calorific value of first fuel
$\%P_2$ = percentage of second fuel
CV_2 = calorific value of second fuel

5. Performance test

The performance test of the gasifier stove was done for the following: Fuel consumption test, Water boiling test, Flame temperature test

5.1 Fuel consumption test

Biomass consumption is the amount of biomass consumed for the gasification process which is being considered for monitoring till its flame exist. The fuel consumption depends on the air flow rate and moisture present in the fuel. The test results is discussed in figure 6.

5.2 Flame temperature test

The k-type thermocouple was placed in the fire zone. The temperature was recorded in Fluke dual temperature data logger during the test. The probe was placed about 10cm above fire zone and in the centre of combustion chamber. In this test, maximum air supply was done to accomplish the good fire. The results of temperature change of gas flames is discussed in figure 7.

5.3 Water boiling test

The stove efficiency and the other parameters were obtained using the modified water boiling test version 4.2.2

[8]. The water was boiled in the aluminum pot without lid. The real time temperature of the water in the pot was noted automatically by a digital temperature recorder. To calculate the efficiency of the stove, the quantity of water evaporated after complete burning of the fuel was recorded. And together with left over charcoal and ash were also weighted. The test results is discussed in figure 8. Efficiency is calculated using the following formula.

$$\eta = \frac{M_{wi} \times C_{pw} \times (T_b - T_i) + M_{w,evap} \times L_e}{M_f \times CV_f - E_c \times M_c + blowerpower \times time} \quad (6)$$

where,
η = efficiency or Percentage of Heat Utilized (PHU)
M_{wi} = initial mass of water in the cooking vessel, kg
C_{pw} = specific heat of water, $kJ/kg°C$
T_b = temperature of the boiling water ,$°C$
T_i = initial temperature of the water ,$°C$
$M_{w,evap}$ = mass of evaporated water, kg
M_f = mass of fuel burned, kg
CV_f = calorific value of the fuel used, kJ/kg
E_c = heating value of the charcoal, kJ/kg
M_c = mass of charcoal, kg
L_e = latent heat of evaporation at 100 °C
and 10^5 Pascal = 2260 kJ/kg

6. Design modification

Problems identified based on the experimental evidence were the guide tool used to modify the existing design. During the combustion of the pellet as a fuel, due to high heat energy developed, the gasifier stove temperature raised high and the blower was burnt down. So to sort out this problem air supply duct was extended outward and the thickness of inner combustion chamber was increased to 6 mm along with the thickness of other components for the easeness of welding. On testing with the pellet with around 4.5 kg which operated for almost 2 hour but the blower was safe. During water boiling test smoke was observed which may be due to the result of gap between pot base and stove so slightly higher base stand was made. The thickness of the materials was based on the availability of materials in the market. Based on the problems faced on the existing stove, modification and fabrication of the stove and testing and analysis of the existing design is tried to be done.

6.1 First modification

Modification made for air supply duct by extending outside and pot stand holder.

6.2 Second modification: two pot system

First trial
During this test, problem was encountered that due to long distance between the combustion chamber and additional chamber, flame in the second chamber was low. Along with the smoke emission with particles of the wood was blown outside. The dust particle would be controlled by controlling the air flow rate or avoiding small particle size.

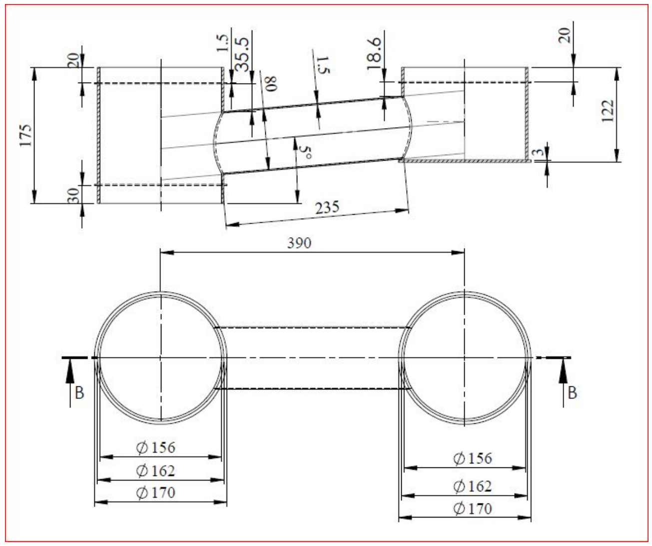

Figure 1: Dimension of the two chamber

Second trial
After the problems occurred from the first trial, fabrication of the prototype using the GI sheet was done. On testing, flame has reached in the secondary chamber. To sort out the problem in first trial, the distance between the two chambers were reduced by 120 mm and initial height of the two additional chambers were reduced.

Final setup
The final setup developed is shown in the figure 3. On this set up test, when the pot was placed in the combustion chamber due to the complete blockage of the main combustion chamber flame reached to the secondary chamber but after certain time the smoke was emitted. To sort out this, material of approx 10 mm thickness was welded in upper part of main combustion chamber. This

worked well with biomass pellet only with emission of smoke at initial stage only.

Figure 2: Prototype made of GI sheet

Figure 3: Final setup

7. Operation of the existing stove

The existing gasifier stove is cylindrical in shape whose weight is approx. 12.3 kg. It comprises of the different components which were as fuel combustion chamber, grate plate, primary air supply duct with fan, secondary air inlet chamber, and air a as a heat exchanger. The tested gasifier stove works on the principle of biomass gasification and is updraft gasifier.

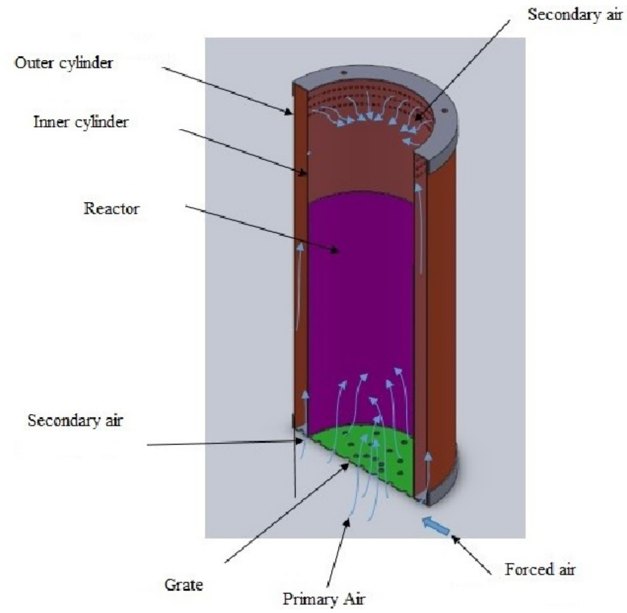

Figure 4: Schematic section of domestic gasifier stove

7.1 Combustion chamber

This chamber is the heart of the gasifier stove which is to sustain heat produced during the combustion period. This reactor consist of cylindrical shape with an external diameter of 148 mm, height of 280 mm and thickness 3 mm. In this chamber, primary air is supplied by using a fan placed at the side of the gasifier stove which passes through the grate and at the top of the combustion chamber 41 number of holes with a diameter of 2.5 mm is provided for the supply of secondary air.

7.2 Primary and secondary air inlet

The air is supplied through the grate at the lower portion of the combustion chamber. The hot gases produced from the partial combustion of the fuel is carried upwards towards the top of the combustion chamber. The heated air on combining with gases at upper portion achieve clean combustion. The fan speed can be adjusted to control the air entering in the combustion chamber which helps in addition to control the burning rate of the fuel and the temperature. The fan selected is axial flow fan with air flow rate of 181.44 m^3/h which consist of blades and the rotor contained with the housing.

7.3 Grate

A grate is pinned at the lower portion of the combustion chamber which is used to improve the combustion quality and burning rate by supplying adequate air supply uniformly.

7.4 Blower for air supply

At the one of the side of the gasifier, the blower is placed which can be operated by electricity or solar energy. Air flow speed measured by digital anemometer recorded the air flow speed at the inlet of the duct as 3.5-3.6 m/s. The duct is made square in cross section of 120 mm x 120 mm (internal dimension). This determined air speed is helpful to determine the air flow rate and gas flow rate.

8. Result and Analysis

8.1 Fuel analysis

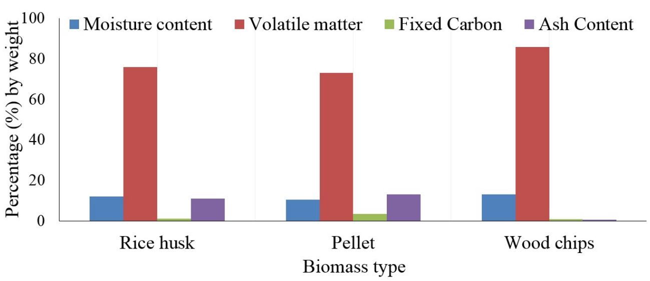

Figure 5: Proximate Analysis test results

Figure 5 shows the results of different fuels tested in the lab. The figure clearly depicts that wood chips seem better for high volatile matter (85.78%) and lower fixed carbon content (0.81%), which indicates that this fuel is highly reactive and has high carbon conversion efficiency. The volatile matter was 75.92% for rice husk and 73.12% for pellet respectively. Higher the volatile matter of the fuel, faster is the combustion hence the temperature of the flame as well as water seems to be higher [9]. The fixed carbon for the case of pellet (3.34%) is higher compared to rice husk (1.17%) so further solid combustion takes place in case of pellet. Thus, further combustion of pellets generated a significant amount of ash compared to other tested fuels. The use of pellet as a fuel had led to the formation of slag during the test.The highest ash content (13.17%) was found in pellet sample. Similarly, rice husk showed 11.01% and wood chips had lowest as 0.47% ash content respectively. The highest ash content in biomass has effect of disposal of ash from the gasifier system. The highest moisture content (12.92%) was found in wood chips sample while rice husk was 11.90%. Similarly, moisture content for the pellet was 10.36%, lowest compared to other two studied. The highest moisture content in the wood chips may be due to the climatic condition and may have absorb some moisture on storage. High moisture content has a effect on the calorific value of biomass fuels since some energy is lost for vaporizing the moisture in the fuel. So, to reduce moisture content in biomass they should be dried by natural means sunlight.

8.2 Calorific values

The results of the heating value of the tested fuels are shown in the table 1. The calorific value of the fuel were determined individually but during test different proportion were used, so equation 5 was used to evaluate the calorific value of mixed fuel which is needed to calculate the thermal efficiency during water boiling test.

Table 1: Calorific values of tested fuels

SN	Property/ sample	Unit	Rice husk	Pellet	Wood chips
1	CV, ar	MJ/kg	15.78	15.07	20.34
2	CV, db	MJ/kg	17.34	17.54	22.20

where,
CV, ar = Calorific value, as received
CV, db = Calorific value, dry basis

It seems that calorific value was higher for the woodchips fuel compared to others on basis of fuel as recieved. But when the fuel is dried, the fuel heating value has increased to 9.89% for rice husk, 16.39 % for biomass pellet and 9.13% for wood chips. This shows that by reducing the moisture content which is a non burnable component in biomass, its heating value can be increased.

8.3 Fuel consumption profile of different fuel

When the gasifier was run on rice husk only, it consumed around 1000g of fuel to give flame since its ignition which last for approx. 50 minute (approximately 1.2

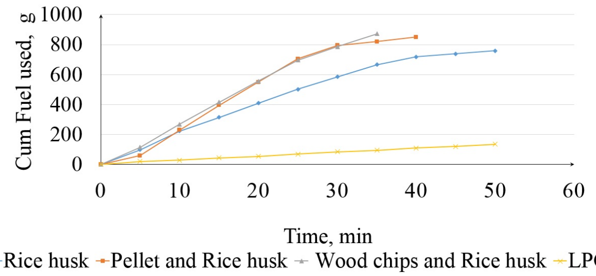

Figure 6: Fuel consumption of different fuel

kg/h). On the other hand when the gasifier was loaded with wood chips mixed with rice husk equally and pellet mixed with rice husk equally, fuel consumption was 1.71 kg/h and 1.71 kg/h respectively. The fuel consumption rate was higher for pellet mixed with rice husk and wood chips mixed with rice husk compared to rice husk only which may be due to non-uniform size and high density of fuel. Incase of biomass pellets further heat can be utilized by burning char. But the newly fabricated stove shows that fuel consumption is higher for all compared to previous tested fuels. It shows that around 1.33 kg/h for rice husk, 2 kg/h for biomass pellet mix with rice husk and 2 kg/h for wood chips mix with rice husk. The LPG fuel seems to be have consistent and lowest fuel consumption about 100 g for 50 minute tested time.

8.4 Flame temperature test

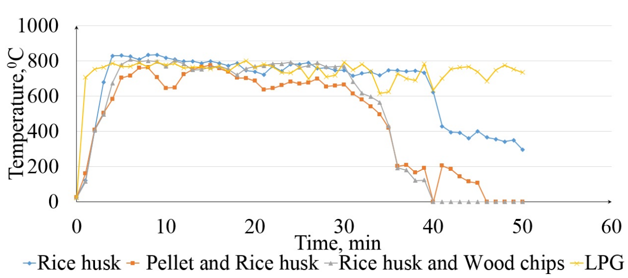

Figure 7: Flame temperature test

The figure 7 depicts the flame temperature profile on the use of different feedstock's as listed with respect to time. The flame was red yellowish in appearance and was consistent and was intense for the fuel used. The rice husk catches fire easily and have a uniform flame on the full supply of forced air from the downward direction. But in case of pellet and wood chips the moisture presence and density have slow down to catch fire. After it catches fire, the flame was very high compared to rice husk. But the flame was encountered fluctuating which shows that air supply was not smooth and regular and may be the effect of environmental air blow. Though the fuel was loaded at once, smoothness in the flame could not be found. In this test, maximum temperature of the flame observed was 834.43 °C, 774.47 °C, 808.17 °C for feedstock as rice husk, pellet mix with rice husk, wood chips mix with rice husk respectively. Most of the time, flame temperature last for the range of 600 – 800 °C for the three different feedstock's and the average operating time to gasify 1 kg of fuel was approximately 50 minutes for rice husk, 35 minutes for pellet and wood chips mix from the start of the ignition to completion of gasification. The change in color of the flame may be due to the moisture content and hydrocarbon in fuel being burnt in the fire zone. The flame temperature can be taken as the indication of the calorific value of the fuel and quantity of gas produced. The flame of the LPG gas seems consistent to the range of 700°C – 800°C compared to other tested fuels. The flame height in the case of pellet and wood chips seems large and seemed to be wastage during full air flow which had shown the path to modify for two pot gasifier stove.

8.5 Water boiling test

The efficiency of the stove was highest as 27.93% for the system operated with wood chips and rice husk mix as a fuel whereas 26.97% for rice husk only. Total ignition duration is approx. 53 minutes, 48 minutes and 40 minutes for rice husk, rice husk and pellet, rice husk and wood chips respectively. The boiling point was reached faster by the wood chips mixed with rice husk with in 16 minute which is clearly indicated by the inclined curve. All the fuels tested could not last for 45 minutes of simmering test. Compared to other tested fuels LPG takes about 32 minute for boiling 5L of water which has lowest inclined curve. There was little difference in the boiling time for the water incase of the newly fabricated stove. The efficiency of newly fabricated gasifier stove was 20.02% for rice husk, 25.89% for equal proportion mix of pellet and rice husk, 26.27% for equal proportion mix of rice husk and wood chips. Figure 8 below shows the average test results of different fuels.

8.6 Gasifier temperature profile

The fuel of average weight of 1 kg with monitored feedstock was fed in to the gasifier and the thermocouple

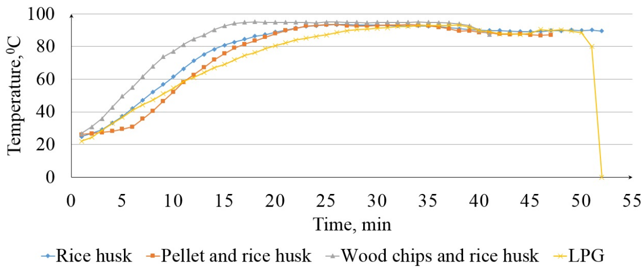

Figure 8: Water boiling test

probe was inserted into the reactor and placed such that probe touches the biomass. The thermocouple with continuous data acquisition system data logger was used to determine the axial temperature distribution of the gasifier. The K type thermocouple was placed at the middle position to the location from the grate. During the experiment it was found the wall temperature increase with increase in air flow rate. The thermocouple recorded the maximum temperature inside the reactor for the rice husk as 791.2 °C, pellet mix 734.7 °C and wood chips mix as 810.5 °C. Experimental evidences shows that the temperature rises fast inside the chamber at approx. 10 minute for the use of pellet mix, 20 minute for wood chips mix and for the rice husk seem to rise in temperature nearly at approx. 28 minute of start of the gasifier stove. In case of the pellet mixed with the rice husk the slag was formed which seems that the observed temperature was higher than ash fusion temperature resulted in to the clinker formation.

9. Conclusion

This study is undertaken with the objective of modification of the existing design on the belony gasifier stove. During the initial testing of the stove overall efficiency of the stove was higher. The modification of the design were entirely based on the experimentation. After the fabrication with first modification, efficiency was 20.02% for rice husk, 25.89% for equal proportion mix of pellet and rice husk, 26.27% for equal proportion mix of rice husk and wood chips. The last set up developed has emitted smoke when the main combustion chamber was completely covered by the base of a pot. So, after supplying the air at the top of the main combustion chamber it is expected to rise the efficiency with two pot system. The change made worked well with biomass pellets only but on mixing pellet with rice husk and simply rice husk, smoke was emitted. This results shows that biomass gasification with two pot system is indeed a promising technology with biomass pellets for better cooking environment.

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