Design and Development of Household Gasifier Cooking Stoves: Natural Versus Forced Draft

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Abstract. In recent years, there has been renewed interest on renewable biomass based energies. This is due to the growing environmental stringent regulation, energy security concern and spiraling price of fossil fuel. More than 80% of the Ethiopian population who reside in the rural depend on biomass energy for their cooking and lighting. Traditionally, food cooking and *Injera* baking are carried out using an open fire/three stone/system in the rural areas. Despite the substantial effort made by Ethiopian government to disseminate improved biomass cooking stove technologies such as *Mirt, Lakech, Tikikil*, and *Gonzie*, the end of pipe technological use strategy is very minimal. In this study rigorous natural and forced draft gasifiers stove design were performed based on energy consumption load for cooking and solid waste management purposes. Standard water boiling test (WBT) and controlled cooking test (CCT) were used to determine the performance of the stove. The WBT showed that the gasifier stove had thermal efficiency of 22.7% and 25% for natural draft and forced draft respectively. Moreover, the CCT indicated that the performance of the gasifier stove were 84% and 72% for natural draft and forced draft as compared to the traditional open fire three stone stove. The burning time using 0.8 kg of fuel was 65 min and 40 min for natural and forced draft gasifier stoves respectively.

Keywords: Gasifier stove · Natural and forced draft · WBT and CCT

1 Introduction

1.1 Background

Now a day there are a huge interests in the developing countries to utilize renewable energy resources so as to reduce, fuel price, energy security and global warming concerns associated with fossil fuels [1]. Among those renewable energies, biomass is the oldest source of energy and currently accounts for about 15% of the world's primary energy consumption and about 38% of the primary energy consumption in developing countries [1]. In particular, biomass energy accounts for more than 90% of the total rural energy supplies in Ethiopia. Abundant biomass is available throughout the world which

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can be converted into useful energy forms. Biomass is traditionally available in the form of solid state such as crops residues, forest waste, animal waste, municipal waste, food waste, and plant waste. Biomass is the general term which includes phyto-mass or plant biomass and zoo-mass or animal biomass/cattle excreta [2]. Biomass can be used for the production of power, chemicals, fuels and fertilizer [3].

At global scale more than 3 billion people (nearly half of world human) are deprived of access to modern energy alternatives. Most of these people live in developing countries and depend on traditional biomass resources to meet their basic energy need [4]. Traditional cook stoves consume too much fuel, leading to longer time for fuel collection and deforestation. Subsequent indoor air pollution also results in mortality due to acute respiratory infection and chronic obstructive pulmonary disease [5]. Ethiopia has aimed at shifting from use of high-cost and environmental polluting fossil fuels to cost-effective renewable energies that can be sourced from renewable resources such as biomass, hydro, and wind, geothermal and solar energies.

Major challenge in Ethiopia's energy sector is aligning national energy supply with socio-cultural and economic developmental needs. However, energy crisis in the country is reflected in its overreliance on indigenously sourced biomass fuel. As compared to other energy sources, biomass can be used for production of fuel with diverse and wider uses like cooking, lighting, heating, and power generation. Almost all of the rural societies of Ethiopia depend on biomass energy for their cooking and lighting. Furthermore there is lack of well elaborated study on strategies and efficient cooking technologies for biomass based energies in the country. In Ethiopia, a common type of cooking and unique mode of baking (*injera* baking) requires the bulk of domestic energy demand. Obviously, food cooking and *injera* baking are carried out using an open fire/three stone/system in every households. As it is known this technique is inefficient and resource wasteful. To address this problem, many efforts have been and are being made by the government and non-government organizations since the early 1990s. The development of '*Mirt' Injera* stove, '*Lakech'* charcoal stove, *tikikil* and currently '*Gonzie*' biomass *injera* and pot stove are some of the results of these efforts in the country. Now a day, *mirt* stove is being widely promoted throughout the country due to the fact that it can achieve fuel saving efficiency up to 50% as compared to the open fire system. It can also improve the kitchen environment by reducing indoor air pollution and other problems such as burn and exposure to excessive heat [4, 6].

The dominant utilization of traditional fuels coupled with use of technologies of low efficiency contributes to the environmental degradation and prevalence of health problems due to indoor air pollution. Direct burning of biomass significantly contributes to CO_2 as well as black carbon emissions, which intensify greenhouse gas in the atmosphere. When there is a complete combustion of biomass, the resultant products are carbon dioxide and water vapor, which are not harmful at all, whereas incomplete combustion releases health damaging pollutants (CO, N_2O, and CH4) and GHG [7]. Traditional biomass stoves are very inconvenient for utilization. They are difficult to ignite and produce a lot of smoke, especially during the start-up time. The existing cooking technologies such as open fire three stone, *mirt, gonze, tikikil* and *lakech* stoves are direct combustion technology and hence they have less thermal efficiency. Moreover, these combustion cooking technologies pollute the environment by emitting carbon dioxide and other gases. Therefore, the development of improved cook stoves has been employed to improve indoor air quality in developing countries like Ethiopia whose populations depend primarily on biomass fuels. Overuse of these fuels depletes resources and degrades local environments, multiplies the time needed to collect fuel, and creates indoor air pollution that threatens the wellbeing of the members of households [8].

Biomass can be converted into heat and power by adopting appropriate conversion technologies. Digestion, gasification, incineration and combustion are some of the available processes for the conversion of biomass into useful energy forms [9]. However, due to its thermo-chemical conversion efficiencies, less area per unit output and the compatibility of the gas for all combustion engines and utilization of gas for cooking purpose, gasification is comparatively effective conversion alternative amongst the other biomass conversion technologies. Biomass gasifier cook stoves are based on an improved combustion technology, which is different from other common "improved" stoves, like rocket stoves and other rocket-type wood stoves [5]. Gasification is a process that converts carbonaceous materials into carbon monoxide, hydrogen, carbon dioxide, and methane. This is achieved by reacting the material at high temperatures (>700 °C) and a limited amount of oxygen and/or steam. The resulting gas mixture is called syngas or producer gas and is itself a fuel. In terms of volume, syngas of wood gasification contains approximately 15–21% H_2, 10–20% CO, 11–13% CO_2 and 1–5% of CH_4, plus N [10]. All of these gases are combustible except nitrogen which is not combustible. The general reaction for biomass gasification is: Biomass + air (or H_2O) → CO, CO_2, H_2O, H_2, CH_4 and N + tars + particulates.

Reports indicated that fuel moisture content, particle size and air fuel ratio have great impact on the performance of gasifier cooking stove [5].

The aims of this study are (1) to investigate appropriate design parameter such as reactor diameter, height, air fuel ratio, amount of fuel that fit the household energy demand; (2) to determine the temperature distribution and performance of gasifier cooking stove; (3) to compare the performance of the gasifier stove with the existing cooking stove.

2 Materials and Methods

2.1 Materials

Solid waste biomass feed stocks such as rice husk; coffee husk and saw dust were collected and analyzed for their particle size in the range of 0.5 mm and 2.4 mm. Sheet metal used for manufacturing gasifier stove with thickness of 1.6 mm was purchased from suppliers. Fan/blower with power rate of 30 W were purchased from local market for supplying of air to the gasifier. Pipes, fittings, and valves, different types of steel bars, cooking utensils such as *mitad* and pan were obtained from local supplier.

2.2 Methods

The complete household level gasifier stoves were manufactured in pilot scale and the following procedures were implemented. First, preliminary design loads were determined. Moreover, based on the load different parts of gasifier stoves were designed using appropriate software and then according to the design, the natural and forced draft gasifier stoves were manufactured by consulting appropriate manufacturing enterprises. After this, different types of feed stocks were burned. Finally, the pilot scale gasifier stoves performance were characterized for their efficiency, fuel consumption, burning time, heating value. The design parameters were determined using Belonio [11] methodologies.

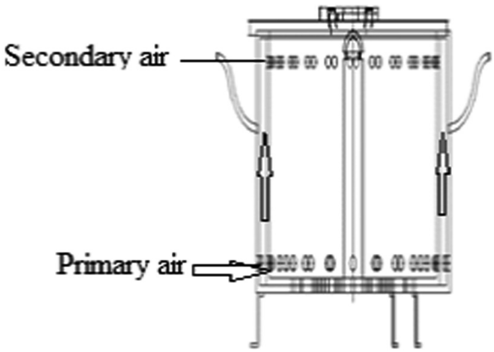

Fig. 1. Schematic sketch of the gasifier cooking stove

The natural and forced-draft gasifier stove tested in this study has two metal walls without thermal insulation material between the walls (Fig. 1). In this gasification process primary and secondary air is taken in at the bottom and the top respectively, and the gas started to burn at the top of the burner. The biomass moves counter to the gas flow and passes successively through drying, pyrolization, reduction, and hearth zones. The temperature distribution of the gasifier stove were measured using K-type thermocouple. The updraft gasifier could be designed to work under a natural and forced draft. For this study cooking energy load and size of gasifier stove for every household in Ethiopia, was investigated based on rice food cooking by taking 2 kg of rice within 20 min cooking time.

Design Parameters: All the appropriate gasifier stove design parameters of the gasifier stove were determined as follow.

Energy Needed. This is the amount of heat that needs to be supplied by the stove which can be determined based on the amount of food to be cooked and/or water to be boiled in a household and their corresponding specific energy. The amount of energy needed to cook this food was determined using Eq. 1.

$$\mathrm{Qn} = \frac{\mathrm{Mf} * \mathrm{Es}}{\mathrm{T}} \quad (1)$$

Where Qn - Energy needed (Kcal/h), Mf - Mass of rice to be cooked (Kg), T - Cooking time (h). Es - Specific energy of rice (330.43 kcal/Kg) [11].

Energy Input or Fuel Consumption rate (FCR). This is the amount of energy needed in terms of fuel to be fed into the stove. This was computed using Eq. 2.

$$\mathrm{FCR} = \frac{Qn}{\mathrm{Hvf} * \eta\mathrm{g}} \quad (2)$$

Where, FCR - fuel consumption rate (kg/h), Qn - heat energy needed (Kcal/h), HVf - heating value of fuel (Kcal/kg) and ηg - gasifier stove efficiency (22–25%).

Reactor Diameter. This refers to the size of the reactor in terms of the diameter of the cross-section of the cylinder where woods are being burned. This is a function of the amount of the fuel consumed per unit time (FCR) to the specific gasification rate (SGR) of wood and it is determined using Eq. 3.

$$\mathrm{D} = \left(\frac{1.27\,FCR}{SGR}\right)^{0.5} \quad (3)$$

Where, D - Diameter of reactor (m), FCR - fuel consumption rate (kg/h) and SGR - specific gasification rate of biomass material (50–210 kg/m^2-h). The specific gasification rate of different biomass materials are in the range of 40–210 kg/m^2-h [9]. For this study, the specific gasification rate and density of the fuel were selected as 43 kg/m^2-h and 129 kg/m^3 respectively.

Time to Consume Wood. This is the total time required to completely gasify the wood inside the reactor. This can be computed using Eq. 4.

$$\mathrm{T} = \frac{\rho * \mathrm{Vr}}{\mathrm{FCR}} \quad (4)$$

Where, T - Time required consuming the wood (h), Vr - volume of the reactor (m^3), ρ - Wood density (kg/m^3) and FCR is rate of consumption of wood (kg/h).

Height of the Reactor. This is the total distance from the top and the bottom end of the reactor and determines how long the stove would be operated in one loading of fuel. The height of the reactor can be computed using Eq. 5.

$$\mathrm{H} = \frac{\mathrm{SGR} * \mathrm{T}}{\rho} \quad (5)$$

Where, H - Length of the reactor, (m), SGR-specific gasification rate of wood, (kg/m^2-h), T - Time required consuming wood (h) and ρ - Wood density (kg/m^3).

Amount of Air Needed for Gasification. This is the rate of flow of air needed to gasify biomass. This is very important in determining the size of the fan or of the blower needed for the reactor in gasifying wood. This can be computed using Eq. 6.

$$AFR = \frac{\varepsilon * FCR * SA}{\rho a} \quad (6)$$

Where, AFR - air flow rate (m^3/h), ε - Equivalence ratio of wood, mostly in the range of 0.1–0.38, FCR - rate of consumption of wood (kg/h), SA - stoichiometric air of wood, 6.1 kg air per kg wood and ρa - air density (1.25 kg/m^3). The equivalent ratio of wood biomass is in the range of 0.1–0.38 and stoichiometric of air is also about 6.1 kg air per kg of wood biomass [11]. To determine air flow rate 0.3 equivalent ratio of wood (saw dust) fuel was taken.

Superficial Air Velocity. This is the speed of the air flow in the fuel bed. The velocity of air in the bed of woods will cause channel formation, which may greatly affect gasification and depends on the diameter of the reactor (D) and the airflow rate (AFR). This can be computed using Eq. 7.

$$Vs = \frac{4\,AFR}{\Pi * (D)^2} \quad (7)$$

Where, Vs - Superficial air velocity (m/s), AFR - air flow rate (m^3/h) and D - Diameter of reactor (m).

Resistance to Airflow. This is the amount of resistance exerted by the fuel and by the char inside the reactor during gasification. This is important in determining whether a fan or a blower is needed for the reactor. The height of the fuel column (Hf) and the specific resistance (Sr) of wood (saw dust) will give enough information for the total resistance needed for the fan or the blower. This can be computed using Eq. 8.

$$Rf = Hf * Sr \quad (8)$$

Where, Rf - resistance of fuel (cm of H_2O), Hf - height of the reactor (m) and Sr - specific resistance, which is 0.65 cm of water/m of fuel.

Characterization of the Gasifier Stove

Ultimate Analysis: The elemental compositions of fuel wood were obtained from the database PHYLLIS2 [12].

Proximate Analysis: the sample was milled and sieved to a particle size of 400 μm. To this end moisture content, volatile material, ash and fixed carbon were analyzed according to international standard ASTM D 1762-84.

Moisture Content-after drying the crucible in the muffle, two grams of the sieved sample was put in the crucible and then dried in the oven at 105 °C for two hours. The weight was recorded until constant mass was obtained. Then the moisture content was determined using Eq. 9.

$$\mathrm{Mc} = \frac{Wi - Wf}{\mathrm{Wi}} * 100 \quad (9)$$

Where, Mc - moisture content (%), Wi - initial mass of the sample before drying (g) and Wf - final mass of the sample after dried (g).

Volatile Material: the value of the volatile material was determine by placing the sample weight that was obtained after subjected to 105 °C in the crucible with cap and then putting it in the muffle at 950 °C. Finally the volatile material was determined using Eq. 10.

$$\mathrm{Vm} = \frac{Ws - Wv}{\mathrm{Ws}} * 100 \quad (10)$$

Where, Vm - volatile material (%), Ws - Weight of the sample after subjected to 105 °C (g) and Wv - weight of the sample after subjected to 950 °C (g).

Ash Content: the sample mass was put in the crucible without cap and then this sample mass was put in the muffle furnace at 750 °C for six hours to reach the total incineration of the sample. The ash content was determined using Eq. 11.

$$\mathrm{A} = \frac{\mathrm{Pa}}{\mathrm{Ps}} * 100 \quad (11)$$

Where, A - ash content (%), Pa - Weight of the ash (g) and Ps - weight of the sample after subjected to 950 °C (g).

Fixed Carbon: to determine the fixed carbon in content dry base, volatile material and ash content were subtracted to 100 [13] as shown in Eq. 12.

$$Fc = 100 - (Vm + A) \quad (12)$$

Calorific Value: the calorific value was analyzed using the bomb calorie meter.

Performance of Gasifier Stove

Water Boiling Test (WBT): The percentage of thermal efficiency is the ratio of mass of product in the cook pot, heat capacity and temperature change plus the evaporated water mass and latent heat of evaporation versus fuel mass and fuel energy. First of all the fuel and pot to be used in the test were separately weighed. And then the pot was partially filled up with two liter of water and weighed again. To this end the initial temperature of water was recorded before the stove was ignited to initiate heating of the pot. Moreover, boiling temperature of water was recorded. When the burning of the fuel was completed, the weight of water left on the pot was recorded and the thermal efficiency was determined using Eq. 13.

$$\eta = \frac{\text{Mn} * \text{Cp} * (Tb - To) + \text{Me} * \text{L}}{\text{Mf} * \text{Hv}} \tag{13}$$

Where, Ƞ - Thermal efficiency (%), Mn - mass of water in the pan (kg), Cp - specific heat of water (kj/kg/^{o}C), To - starting temperature of the water (^{o}C) and Tb - boiling temperature of the water (^{o}C), Me - mass of water evaporated (kg), L - latent heat of evaporation (kj/kg), Mf - weight of fuel burnt (0.8 kg) and Hv - heating value of the fuel (kj/kg).

Charcoal Yield: At the end of the gasification process the charcoal weight was recorded and the charcoal yield was determined using Eq. 14.

$$\text{Yield} = \frac{\text{Charcoal weight}}{\text{Feed stock weight}} * 100 \tag{14}$$

Controlled Cooking Test (CCT): The controlled cooking test is an intermediate test between simple water boiling test and the kitchen performance test. It is used to compare the fuel consumed, residual charcoal content and the time spent in cooking a meal on different stoves. In this test, locally available saw dust fuel was used for the cooking. Locally well-known food, *shiro wot*, was selected as cooking meal. All the tests were determined based the VITA [14] methodology in order to compare the fuel saving efficiency of the new technology with the traditional three stone stove. The test was repeated three times for each stove type. Different measurements also included to determine the moisture content of fuel wood, ambient temperature, time needed to cook the dish, time needed to light the fire, initial and final meal mass, initial and final fuel wood mass and the residual charcoal content. For this test, the initial meal and fuel mass were 2.46 kg and 0.8 kg respectively.

3 Results and Discussions

The designed prototype gasifier stove is shown in Fig. 2. The gasifier stove has the gas burner and the pot support on the top. Moreover, this biomass-fired gasifier stove consists of the reaction chamber, primary and secondary air inlet and three legs which support the gasifier stoves. To minimize the heat losses, the gasifier stoves have air gap as an insulation material between the outer and inner diameter of the reactors. In the case of forced draft gasifier stove, 24 V DC supply fan was used to supply primary and secondary airs for the gasifier stove.

3.1 Design Parameters

All the calculated size of natural and forced draft gasifier stove design parameters are summarized in Table 1. As it can be observed in Table 1, the optimal energy demand to cook the food, rice, was 1982.58 kcal/h. The appropriate size of the natural and forced draft gasifier stove diameter and height were 0.29 m and 0.36 mm respectively based on the energy demand and cooking time.

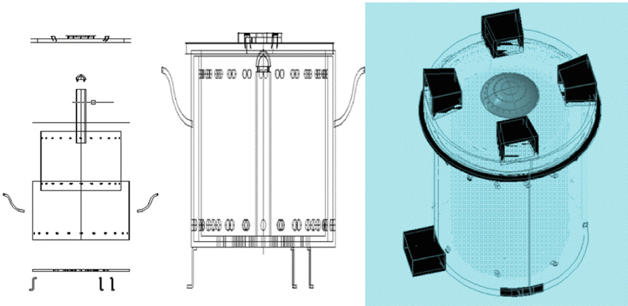

Fig. 2. Designed prototype gasifier stove

Table 1. Design parameters

Parameters	Unit	Natural gasifier stove	Forced gasifier stove
Energy needed	Kcal/h	1982.58	1982.58
Fuel consumption rate	Kg/h	2.33	2.8
Reactor diameter	m	0.29	0.29
Height of the reactor	m	0.36	0.36
Burning time	h	1.086	0.67
Gasification air flow rate	M^3/h	-	3.4
Superficial air velocity	M/s	-	1.77
Resistance to air flow	Cm of H_2O	-	0.234

The amount of air needed for forced draft gasification was 3.4 m^3/h. However, it was visualized that as the amount of air increased, more smoke was released which indicated gasification process was shifted to combustion process. It was also observed from the design size that the superficial air velocity of the forced draft gasification process was 1.77 m/s. Parikh et al. [15] reported that when the superficial air velocity increases, the fuel/air equivalence ratio significantly reduced. In the other way higher air superficial velocity also led to higher fuel consumption rate and consequently there is higher gasification temperature. If the superficial air velocity increases beyond the limit, the velocity of the gas phase increase and it has a convective cooling effect resulting extinction of the process.

Effect of Particle Size on Bio-Char Yield: Selection of natural and forced draft gasification process depends on the nature of the biomass particle size.

In Fig. 3, it was observed that as the particle size of the biomass became small, char yields reduced which signified that of the heat and mass transfer were more effective since the ratio of surface area/volume was increased resulting increase of gas yield and gas heating values. However, as the biomass particle size became very fine and powdered, it was difficult for the movement of air and in this case driving force, like fan, was used to circulate the primary air [16].

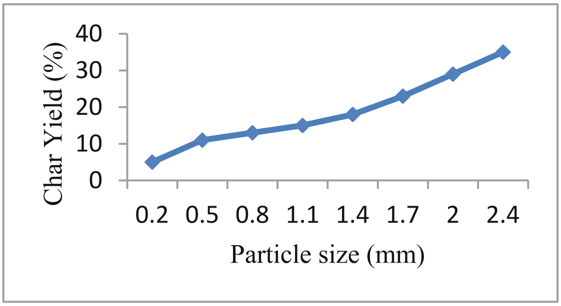

Fig. 3. Effect of particle size on char yield

3.2 Characterization of the Gasifier Stove

Fuel Feedstock Characterization: Different proximate and ultimate analyses were conducted on sawdust and coffee husk. The results of the proximate, ultimate and calorific value analysis carried out on the sawdust and coffee husk are presented in Table 2. The percentage moisture content of sawdust and coffee husk were 10% and 9.9% as shown in Table 2. From the proximate analysis it can be observed that sawdust has higher volatile content than coffee husk. The two feed stocks which have been considered in this study have low moisture and ash contents. The low ash content signified that it reduced problems associated with residual disposal, equipment cleaning and other operational aspects [17]. The result revealed that the moisture contents can be easily reduced by sun drying and the feed stocks have significant biomass energy potentials for gasification process in Ethiopia. Moreover, the ultimate analysis indicated that the percentage of hydrogen, nitrogen, and Sulphur were to some extent similar for the two feed stocks. From this ultimate analysis it was observed that the two feed stocks were relatively rich in carbon and oxygen composition contents.

Table 2. Proximate, ultimate and calorific values of sawdust and coffee husk (dry base)

Element	Proximate analysis		Element	Ultimate analysis	
	Sawdust	Coffee husk		Sawdust	Coffee husk
Moisture content (wt%)	10	9.9	C (%)	47.54	42.1
Volatile material (wt%)	78.30	64.6	H (%)	5.8	4.6
Fixed carbon (wt%)	18.9	31.3	N (%)	0.61	1.53
Ash content (wt%)	2.80	4.1	S (%)	0.00	0.10
HHV (MJ/Kg)	15.59	14.58	O (%)	43.23	47.57

3.3 Performance of Gasifier Stove

Water Boiling Test (WBT): The water boiling test was conducted as shown in Fig. 4. The performance of the natural and forced draft gasifier stoves have been carried out as per the standard water boiling test method (WBT). WBT only measure the heat transfer efficiency rather than the actual efficiency. The gasifier stove thermal efficiency of the fire was evaluated during the high power phase (cooking period). The gasifier stoves were ignited from top and gave combustible gas and a blue flame was established within 6 min of ignition. In this performance test, 0.8 kg of sawdust biomass fuel was used. It has been observed that the stove burnt continuously for about 65 min and 40 min in the natural and forced draft gasifier stove respectively for this amount of fuel.

Fig. 4. Testing of manufactured gasifier stove

The performance parameters of the gasifier stove were presented in Table 3. As it can be seen in Table 3, the thermal efficiency of natural and forced draft gasifier stove were 22.7% and 25% respectively and it is almost similar to the studies reported by Panwar and Rathore [18]. The charcoal contents were 33.3% for natural gasifier stove and 28% for forced gasifier stove.

Table 3. Thermal efficiency determination of gasifier stoves through WBT

Parameter	Unit	Natural draft	Forced draft
Fuel per batch	Kg	1.2	1.2
Time to start up	Min	24	2
Initial water mass	kg	2	2
Mass of water evaporated	kg	1.6	1.9
Time to boil water	Min	16	10
Initial temperature	°C	25	25
Boiling temperature	°C	98	98

(*continued*)

Table 3. (*continued*)

Parameter	Unit	Natural draft	Forced draft
Burning time	Min	65	40
Latent heat of evaporation	kj/kg	2258	2258
Specific heat of water	Kj/kg.°C	4.19	4.19
Maximum stove body temperature	°C	254	260
Maximum flame temperature	°C	700	850
Char yield	%	33.3	28
Thermal efficiency	%	22.7	25

Temperature Distribution: The temperature distribution of natural and forced draft gasifier stoves were plotted in Figs. 5 and 6 respectively. These temperatures were obtained by inserting five thermocouples in the oxidation, reduction, pyrolysis, drying and syngas zones. From this study the highest temperature records were found to be 700 °C and 850 °C in the oxidation zone of the gasifier for the natural and forced draft gasifier stoves respectively. Moreover, the highest temperature was recorded in the forced draft gasifier stove due to the high mass flow rate. The temperature profile were decreased in the order of oxidation, reduction, pyrolysis, drying and syngas of the gasifier reactor chamber as shown in Figs. 5 and 6. From these figures, it can be observed that in the syngas, drying and pyrolysis zones it took a longer time to reach high temperature level than the reduction and oxidation zones.

Ojolo et al. [19] explained that the gasifier has high thermal inertia in the syngas, drying and pyrolysis zones and hence temperature will not be raised to a high level until the thermal inertia is overcome. On the other hand, the thermal inertia helped the gasifierstove to keep a steady temperature level after the whole temperature was raised.

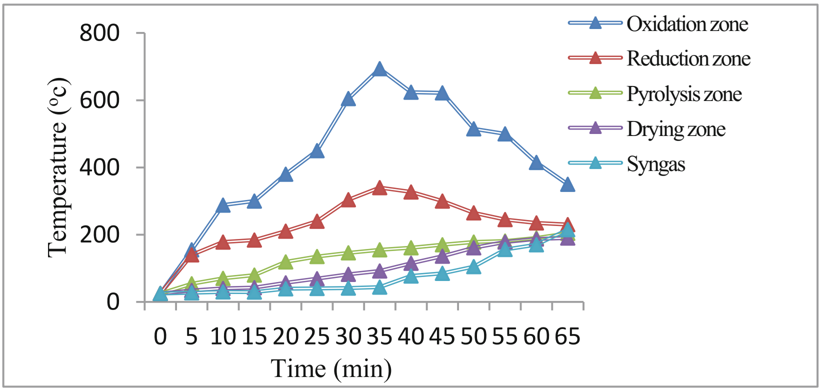

Fig. 5. Temperature distribution in natural gasifier stove

As it can be seen in Figs. 5 and 6, the highest temperature in oxidation zone is due to the combustion of volatile materials in the biomass. As time was gone the char content increased and this char was converted to syngas by endothermic reaction and the temperature was increased gradually and then declined when the char content decreased.

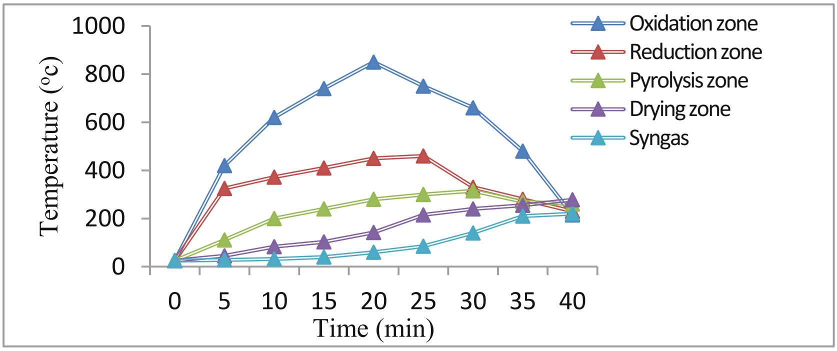

Fig. 6. Temperature distribution in forced gasifier

Water Boiling Test: The water boiling test was conducted by using WBT protocol. The test water was boiled within 10 min of time in the forced gasifier stove and it took about 15 min for the natural gasifier stove. Beyond 20 min, the boiling points were become constant for both gasifier stoves as shown in Fig. 7.

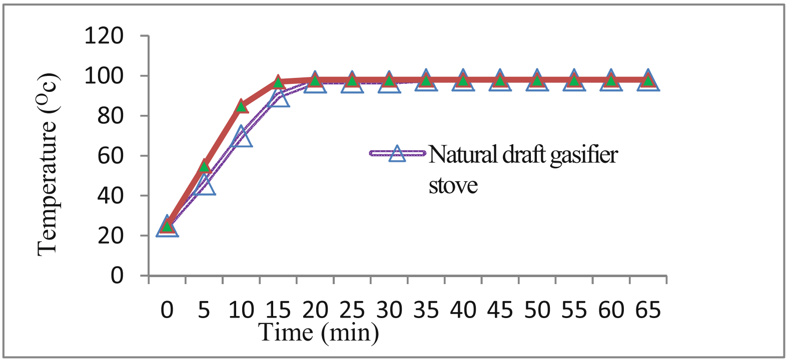

Fig. 7. Boiling water temperature profile

Fuel Consumption: The fuel consumption of natural and forced draft gasifier stove were plotted in Fig. 8. As shown in Fig. 8, it was observed that biomass fuel rapidly consumed in the forced gasifier stove as compared to the natural draft gasifier stove. The slope of the curve gives the mass loss rate of the gasifier stoves.

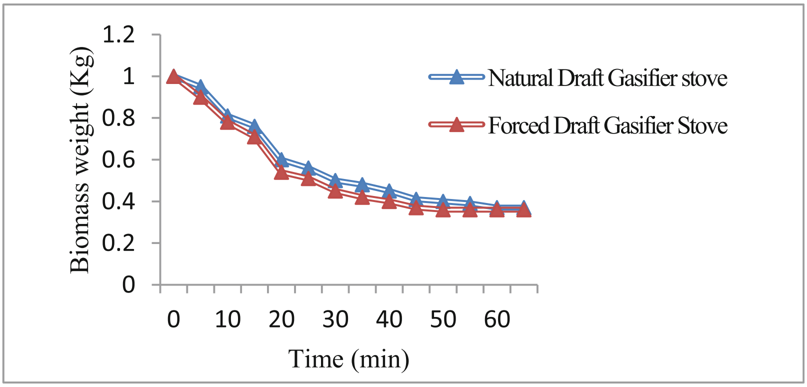

Fig. 8. Burning rate of fuel mass

Controlled Cooking Test (CCT): It is the test of efficacy to evaluate cook stove performance in a controlled environment, using locally available biomass fuels, pots and prevailing cooking practices in the community. This test determines the quantity of fuel used, while the real cook process using a common meal on the stove. It measures the fuel saving efficiency of the stove compared with three stone stove. The fuel saving

Table 4. Comparison of natural draft gasifier and three stone stoves by CCT

Sn.	Test parameters	Units	Test numbers				
			Test 1	Test 2	Test 3	Mean	St Dev
1	**Stove 1: Three stone stove**						
	Total weight of food cooked	g	2,460	2,464	2,468	2,464	4
	Weight of char remaining	g	170	171	172	171	1
	Saw dust consumed	g	221	202	227	217	13
	Specific fuel consumption	$g_{\text{-fuel}}/kg_{\text{-food}}$	90	82	92	88	5
	Total cooking time	min	28	30	29	29	1
2	**Stove 2: Gasifier stove**						
	Total weight of food cooked	g	1,560	1,564	1,572	1,565	6
	Weight of char remaining	g	160	161	162	161	1
	Saw dust consumed	g	24	27	17	23	5
	Specific fuel consumption	$g_{\text{-fuel}}/kg_{\text{-food}}$	15	17	11	14	3
	Total cooking time	min	18	20	19	19	1
3	**Comparison of Stove 1 and Stove 2**		**% difference**		**T-test**	**Sig @ 95%?**	
	Specific fuel consumption	$g_{\text{-fuel}}/kg_{\text{-food}}$	**84%**		**20.62**	**YES**	
	Total cooking time	**min**	**34%**		**12.25**	**YES**	

Table 5. Comparison of forced draft gasifier and three stone stoves by CCT

Sn.	Test parameters	Units	Test numbers				
			Test 1	Test 2	Test 3	Mean	St Dev
1	**Stove 1: Three stone stove**						
	Total weight of food cooked	g	2,460	2,464	2,468	2,464	4
	Weight of char remaining	g	170	171	172	171	1
	Saw dust consumed	g	221	202	227	217	13
	Specific fuel consumption	g_{-fuel}/ kg_{-food}	90	82	92	88	5
	Total cooking time	min	28	30	29	29	1
2	**Stove 2: Gasifier stove**						
	Total weight of food cooked	g	1,560	1,816	1,824	1,733	150
	Weight of char remaining	g	160	126	124	137	20
	Saw dust consumed	g	9	87	36	44	40
	Specific fuel consumption	g/kg	6	48	20	25	21
	Total cooking time	min	18	16	17	17	1
3	**Comparison of Stove 1 and Stove 2**		**% difference**		**T-test**	**Sig @ 95%?**	
	Specific fuel consumption	**g/kg**	**72%**		**4.98**	**YES**	
	Total cooking time	**min**	**41%**		**14.70**	**YES**	

comparison of natural draft gasifier and three stone stoves are portrayed in Table 4. As it can be seen in Table 4, the fuel and time saving efficiency of natural draft gasifier stove were 84% and 34% respectively when compared to the three stone stoves. The three stone stoves consumed more fuel than the natural draft gasifier stoves. It was also observed that the fuel and time saving efficiencies of forced draft gasifier stove were 72% and 41% respectively as compared to the three stone stoves as shown in Table 5.

Table 6. Comparison of gasifier stove with existing stoves in terms of efficiency

Sn.	Stove type	Thermal efficiency (%)	Fuel saving efficiency (%)
1	**Conventional stove (existing stove)**		
	Three stone	5–10	-
	Lakech	19–21	25
	Mirt	16–21	40–50
	Gonze	23	42–54
	Tikikil	28	50
2	**New innovation stove (gasifier stove)**		
	Natural draft gasifier	22	84
	Forced draft gasifier	25.7	72

The comparison showed that the natural draft gasifier stove was more efficient than the forced draft gasifier stove in terms of fuel saving efficiency. However, it has less efficiency in terms of cooking time.

Comparison of Existing Stoves with the Gasifier Stoves: The fuels saving efficiency of the conventional stove in Ethiopia are shown in Table 6. As it can be seen from this table, the fuel saving efficiency of the current cooking technologies such as *lakech, gonze, mirte, and tikikil* range between 25–50% as compared to the open fire three stone stoves [20]. The new innovation, gasifier stoves, fuel saving efficiencies were in the range of 72–84% which were more efficient than the existing cooking technologies. Moreover, the thermal efficiency of the gasifier stoves was higher than the three stone, *lakech* and *mirt* stoves efficiency. But it had a similar tendency to *tikiki*l (rocket) and *gonze* stove efficiencies.

4 Conclusions

A laboratory scale updraft natural and forced draft gasifier stoves were rigorously designed and fabricated and evaluated its performance. Solid waste biomass such as saw dust, coffee husk, rice husk and wood were used as feed stock. The performance of the gasifier stove was determined using standard WBT and CCT methods using saw dust as feedstock. The height and diameter of the designed gasifier stove were 0.36 m and 0.29 m respectively. The thermal efficiency of the natural and forced draft gasifier stoves were 22.7% and 25% respectively. Moreover, the fuel saving efficiency were 84% and 72% for natural and forced draft gasifier stove respectively which were higher than the conventional stove (mirt, gonze, lakech, tikikil) efficiency that are ranged between 25–50%.The highest oxidation temperature of natural and forced draft gasifier stoves were 700 °C and 850 °C respectively. The char yields were 33.3% for natural and 28% for forced draft gasifier stove. The burning time of biomass was 65 min for natural and 40 min for forced draft gasifier stoves which can be enough for full cooking process in the household in Ethiopia. Rigorous mathematical model is under way to elucidate the interplay of hydrodynamics with mass and heat transfer for the gasification process.

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