Fabrication and Performance Evaluation of Small Scale Wood Gas Stove for House Hold Purpose Using Water Boiling Test Method

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DOI: 10.29322/IJSRP.9.11.2019.p9587
http://dx.doi.org/10.29322/IJSRP.9.11.2019.p9587

Abstract: A Double drum type inverted down draft gasifier was fabricated in Assela Agricultural Engineering Research Center Metal workshop. The water boiling test version 4.2.3 was used to evaluate thermal and stove characteristic performance indicators of the stoves. Performance result was compared with three stone traditional cook stove. High power and low power performance were compared and reported in this paper. During high power test wood gas stove performed better than three stone cooking method by all thermal performance indicators at tested significance level. While the traditional method numerically performed better than wood gas stove by stove character stick performance indicators though it was statically not significant. During low power test except thermal efficiency and turn down ratio where wood gas performed better than three stone cooking for all tested performance indicators were not significantly different.

Key words*:* inverted down draft gasifier, wood gas stove thermal performance indicators, stove characteristics indicators, high power test, and low power test.

1. INTRODUCTION

Wood gas is a syngas consisting of nitrogen, carbon mono oxide, hydrogen and traces of methane and other gases used as fuel. During the production process biomass or other carbon-containing materials are gasified within the oxygen-limited environment of a wood gas producer/wood gas generator. **Wood gas stove** is a gasification unit which converts solid biomass into wood gas or syngas through pyrolysis process. The process is preceded by pyrolysis, where the biomass is first converted to char, releasing methane and tar rich in polycyclic aromatic hydrocarbons[1].

The development of micro-gasification is relatively new in the cooking energy sector. Many stakeholders are not yet aware of the potentials and challenges of revolutionizing the way we make fire to cook food. A gasifier cook stove powered by *wood-gas* from dry solid biomass shows great promise for making an important contribution to the goal of reducing the negative health-effects of household air pollution from cooking[2].

There is growing concern about the negative health effects of smoke from open fires and rudimentary cook stoves operated with solid biomass or coal. In the last few decades, since indoor air pollution is understood as chronic health problem, many improved wood stoves have been developed and promoted to developing world by different organizations. Although, there is improvement in indoor air pollution problems, still there are gaps to be filled. There is an ardent quest to shift to cleaner fuels such as LPG or electricity for the sake of health. However, for billions of poorer households, this will not be a realistic scenario for years to come. We have to accept the fact that solid biomass will be the cooking fuel of choice for many of these households for the future decades. On account of their clean and efficient *combustion* of biomass, gasifiers do have the potential to bridge this gap and offer users the convenience of cooking with gas derived from the solid biomass fuels[2].

Gas cooking is advantageous compared to direct combustion improved cook stoves (ICS) by providing cleaner burning of solid biomass (considerable reduction of soot, black carbon and indoor / outdoor air pollution), fuel efficient due to more complete combustion (less total biomass consumption), use a variety of small-sized biomass residues (no need for stick-wood or charcoal) and easy lighting allows for cooking to commence within minutes[3].

Of the gasifiers available, an inverted (top burning) downdraft gasifier can be used for indoor cooking practice because it can be made in different sizes. The major advantage of the inverted downdraft gasifier is that the rate of gas production depends on the amount of primary air admitted to the bottom and it can be practiced indoor cooking purpose[9].

In Ethiopia, different organization made effort to avail improved gas stoves. Of these, BAERC energy team attempt to modify this technology for Injera baking purpose and the work is underway. And the initiation of this work was adapting double cylinder inverted down draft gasifier and evaluating its performance at local condition to use in household cooking.

2. MATERIALS AND METHODS

2.1 Materials

Materials and apparatus used for this experiment were:

- Wood Gas Stove- fabricated in AAERC work shop from different size and type mild steel materials purchased from local market
- Three stone cooking stove (TSCS)-locally prepared
- Stainless steel Cooking vessel-purchased from local market
- Timer
- Digital balance (7Kg, accuracy ±1 gram)
- Digital thermometer (accuracy ± 0.5)
- K-type thermocouple probe
- Oven
- hygrometer (air relative humidity)
- anemometer (to measure wind speed)
- Fuel wood
- Tape measure

2.2 Site Description

ISSN 2250-3153

The test was conducted in Asella AERC with the local atmospheric conditions of ambient temperature 20-26.6oc, Air pressure 75.7Pka, Relative humidity 35% and Altitude/elevation 2430m. The test was conducted in one side opened shade where air freely flow and protected from wind blow.

2.3 Description of Stoves

The inverted down draft (double) type of Wood gas stove was fabricated by Asella AERC workshop (***figure 1***). The outer cylinder both end opened and a ring of ventilation holes drilled around the whole of the bottom edge of the cylinder and support rods are run through the drum. These rods supports perforated sheet which forms grate. The inner cylinder both ends opened forms combustion chamber. This cylinder fits inside the outer cylinder. It rests on the perforated sheet or grate which is supported by rods. This cylinder has a ring of ventilation holes drilled around the upper end of the cylinder. The third cylinder which is only slightly smaller than the outer cylinder is cut down to make a cap for the inner cylinder. The cap is not tight-fitting (1cm less than outer cylinder diameter); it effectively closes off the top of the gap between the sides of inner cylinder and the sides of the outer cylinder. The cap has riser (to increase combustion efficiency of producer gas) and circular hole cut in it, and this hole is only slightly smaller than the diameter of the inner cylinder. It is supported by the upper lip of the combustion chamber but the hole is large enough so that it does not obstruct the flow of heat up through the top of the combustion chamber. The pot seat is supported by the cap.

Fuel wood charge is lit on the top, forming a layer of charcoal, the flaming pyrolysis is below charcoal layer and the unburned fuel is at the bottom on the grate. The primary air for the pyrolysis process is entered at bottom through holes drilled at the bottom of outer cylinder and move up forming gases in the flaming pyrolysis zone as shown in the ***figure 2***. The pyrolysis gas is combusted by secondary air entered from the top through clearance of top cover and holes drilled on the top of combustion chamber above the charcoal zone and part of primary air which flow through whole between inner and outer cylinders.

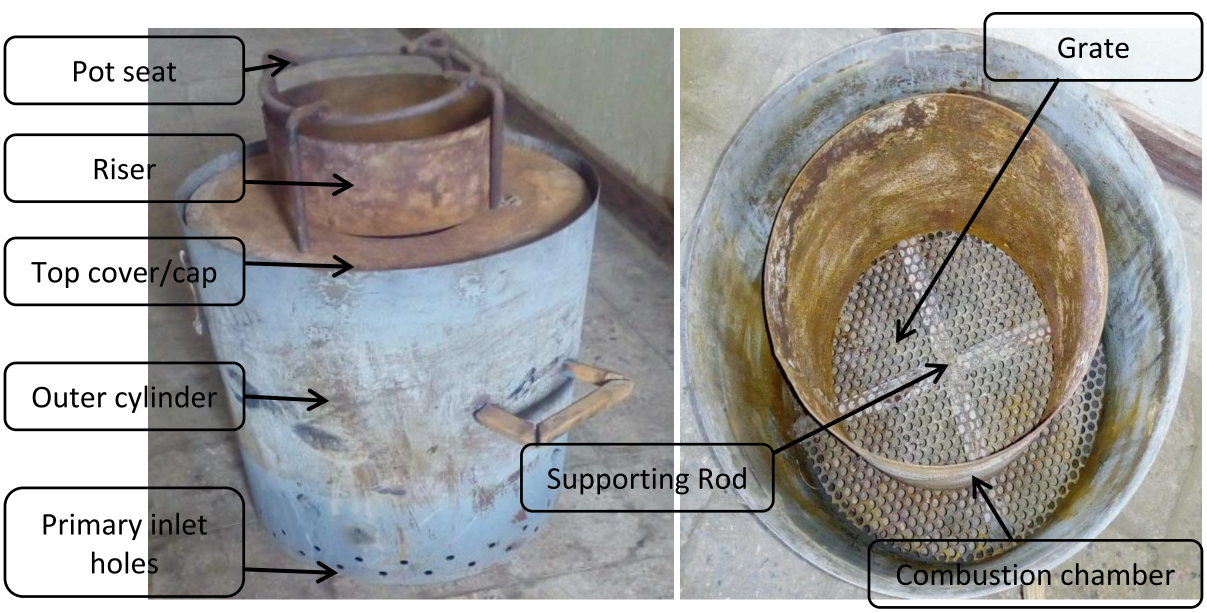

Figure 1: Photo of the fabricated stove showing different parts

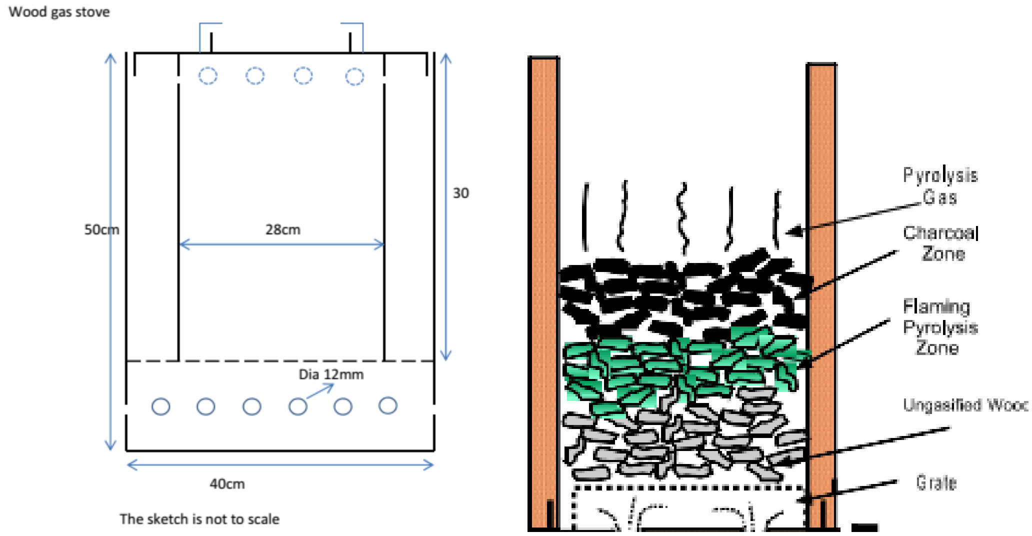

Figure 2: shows 2D schematic drawing (left) and Wood gas stove showing combustion process (right)

2.4 Fuel Characteristics

The wood used for the experiments was Eucalyptus (local names bargamo) obtained from the center as leftover of different activities, split and air-dried. Semi-cylindrical pieces of wood (2-4 cm in diameter and 25-30 cm in length) were used during each experiment.

The moisture content (11.67%) and the calorific value of fuel wood (4090cal/gram) were determined at the end of the entire series of experiments by using oven drying method and bomb calorimeter respectively.

2.5 Performance evaluation

The Water Boiling Test (WBT) is a simplified simulation of the cooking process. It is intended to measure how efficiently a stove uses fuel to heat water in a cooking pot and the quantity of emissions produced while cooking[4]. It measures the quantity of fuel consumed and time required for the simulated cooking and usually employed in investigating the performance of cook stoves under different operating conditions.

The standard WBT consists of three phases that immediately follow each other. The ***cold-start high-power phase***, we begun the test with the stove at room temperature and uses fuel from a pre-weighed bundle of fuel (5kg) to boil a measured quantity of water (5 Kg)in 7cm diameter stainless steel vessel. Then we replaced the boiled water with a fresh water of ambient-temperature to perform the second phase. The ***hot-start high-power phase*** was conducted after the first phase while stove and cooking vessel were still hot. Again, we used fuel from a pre-weighed bundle of fuel to boil measured quantity of water (5 Kg) in the vessel. Repeating the test with a hot stove helps to identify differences in performance between a stove when it is cold and when it is hot. The ***simmer phase*** provides the amount of fuel required to simmer a measured amount of water at just below boiling point for 45 minutes. This step simulates the long cooking of legumes or pulses common throughout much of the world. During this phase, pre-weighed amount of fuel was used to simmer the boiled water for 45 minutes.

As it is quick method of comparing the performance of cook stoves[4], we employed in evaluating the performance of the improved biomass cook stove and compared with the performance of the 3-stone traditional cook stove, which it intends to replace. For each stove, the three phases were repeated three times.

2.5.1 Determination of stove performance parameters

a. Moisture content of fuel (M): The moisture content of fuel wood used was determined by the weight loss of sample that was oven-dried at 100°C until the weight of the sample stabilized. The Sample of moist fuel was taken from the fuel wood prepared for the tests and oven dried as stated above. And moisture content was calculated by equation 1 and found 11.67%.

$$M(\%) = \frac{100(W_w - W_d)}{W_d} \quad (1)$$

Where: W_w-is weight of wet fuel sample, W_d-weight of dry fuel (after oven dried)

b. Fuel consumed (dry base): The amount of fuel wood used to bring water temperature from room temperature to boil [8]. And it **a**ccount for two factors: (1) the energy that was needed to remove the moisture in the fuel and (2) the amount of char remaining unburned. And given by:

$$\text{Mass of dry fuel} = \text{Fuel mass (wet)} * (1-M) \quad (2)$$

c. Burning rate: A measure of the average unit of wood burned per unit of time during the test. Between tests, compares how consistently the user was operating the stove. Between stoves, indicates how rapidly the stove consumes fuel. And it is given by:

$$\text{Burning rate} = \frac{\text{mass of fuel dry base}}{\text{time taken}} \quad (3)$$

d. Firepower (F_p): This is a ratio of the wood energy consumed by the stove per unit time. It is a useful measure of the stove's heat output, and an indicator of how consistently the operator ran the stove over multiple tests. And the firepower (Fp) is given by:

$$\text{Fp} = \frac{\text{mass of fuel dry base} * \text{LHV}}{\text{time taken}} \quad (4)$$

Where LHV- is lower heating value of the fuel

e. Turn-Down Ratio (TDR): Turn-Down ratio indicates how much the user adjusted the heat between high power and low power phases. A higher value indicates a higher ratio of high power to low power, and could signal a greater range of power control in the stove.

$$\text{TDR} = \frac{\text{cold start fuel consumed dry base} * \text{simmering time}}{\text{simmering fuel consumed dry} * \text{cold start time taken}} \quad (5)$$

f. Thermal efficiency (η_{th}): Thermal efficiency is a measure of the fraction of heat produced by the fuel that made it directly to the water in the pot. The remaining energy is lost to the environment. So a higher thermal efficiency indicates a greater ability to transfer the heat produced into the pot. While thermal efficiency is a well-known measure of stove performance, a better indicator may be specific consumption, especially during the low power phase of the WBT. This is because a stove that is very slow to boil may have a very good looking TE because a great deal of water was evaporated. However the fuel used per water remaining may be too high since so much water was evaporated and so much time was taken while bringing the pot to boil[4]. And determined using equation (6).

$$\eta_{th} = \frac{4.186 * \text{mass of water boiled} * \text{change in temp} + \text{LHW} * \text{mass of Vapor}}{\text{fuel consumed dry base} * \text{LHV}} \quad (6)$$

Where LHV-lower heating value of the fuel wood and LHW-is latent heat of vaporization of water.

g. Specific fuel consumption (SFC): This is a measure of the amount of fuel required to boil (or simmer) 1 liter of water. It is calculated by the equivalent dry fuel used minus the energy in the remaining charcoal, divided by the liters of water remaining at

ISSN 2250-3153

the end of the test. In this way, the fuel used to produce a useful liter of "food" and essentially the time taken to do so is accounted for and given by equation (7).

$$SFC = \frac{\text{fuel consumed dry base}}{\text{Volume of water boiled}} \quad (7)$$

h. ***Specific Energy Consumption (SEC)***- It is a measure of the amount of energy required to boil (or simmer) 1 liter of water and given by:

$$SEC = SFC * LHV \text{ of dry fuel} \quad (8)$$

i. **Temp-Corrected Specific Fuel Consumption (*$SC^T c$*)** – This corrects specific consumption to account for differences in initial water temperatures. This facilitates comparison of stoves tested on different days or in different environmental conditions. The correction is a simple factor that "normalizes" the temperature change observed in test conditions to a "standard" temperature change of 75 ºC (from 25 to 100)[4]. It is calculated in the following way:

$$SC_c^T = SC_c \cdot \frac{75}{T1_{cf} - T1_{ci}} \quad (9)$$

j. **Temp-Corrected Specific Energy Consumption (*$SE^T{}_c$*)** – Similar to the temperature corrected specific fuel consumption, this metric is a measure of the amount of fuel energy required to produce one liter (or kilo) of boiling water starting with cold stove. It is the temperature corrected specific fuel consumption multiplied by the energy content of the fuel[4]:

$$SE_c^T = SC_c^T \cdot \frac{LHV}{1000} \quad (10)$$

k. **The local boiling point** (**T_b**) of water is the point at which the temperature no longer rises, no matter how much heat is applied. The local boiling temperature is influenced by several factors including altitude, minor inaccuracies in the thermometer, and weather conditions. For these reasons, the local boiling temperature cannot be assumed to be 100^0 C. For a given altitude h (in meters), the boiling point of water may be estimated by the following formula [2]:

$$T_b = \left(100 - \frac{h}{300}\right)^\circ C \quad (11)$$

l. **Temperature Corrected Time to Boil** (Δt_c^T)– The time it took for the vessel to reach boiling temperature, corrected to reflect a temperature rise of 75 deg C from start to boil. This measure can be compared across tests and stoves to determine the "speed" of the stove at high power, often an important factor to cooks[4].

$$\Delta t_c^T = \Delta t_c \cdot \frac{75}{T1_{cf} - T1_{ci}} \quad (12)$$

Where $T1_{cf}$ and $T1_{ci}$ are initial and final water temperature of the test, Δt_c -time taken to boil water.

3. RESULT AND DISCUSSION

3.1 Visual observations

Initially, the flames come out of the top of the stove, but after a few minutes, the combustion changes. The wood is slowly converted to charcoal and the gas released by this process burns with higher flame height than the wood would give as well as burning for a much greater length of time. After a while, flames no longer come out of the top of the stove, they come out of the ring of holes around the base of the outer cylinder. The heat flowing out of the bottom gets diverted around the outside of the combustion chamber, flows upwards, is caught by the cap and fed back into the combustion chamber through the ring of holes at the top of the combustion chamber. The result attained was similar with [9].

3.2 Performance indicator parameters determined by the above equations

Both thermal and stove characteristics indicators discussed above under determination of performance parameter part of this paper is summarized and statically discussed below.

***Table 1*: Calculation result summary**

Description	**Cold start**		**Hot start**		**Simmering**	
	WGS	**TSCS**	**WGS**	**TSCS**	**WGS**	**TSCS**
Phase duration (min)	17	44	13.3	40	45	45
Burn rate (g/min)	35	45	23	32	41	49
Thermal efficiency (%)	23.5	11	28.7	14	21	13.4
Specific fuel consumption (g/lit)	117	212	107	203	815	533
Specific energy consumption (KJ/lit)	1998	3543	1827	3393	14171	9261
Fire power (kw)	10.2	7.4	11.7	7.4	11.8	11.3
Turn down ratio					0.9	0.66

Where WGS-is Wood Gas Stove and TSCS is three stone cooking stoves

***Table 2*: Mean comparison of cold start phase for WGS and TSCS**

Parameters	units	WGS			TSCS			Significance test		
		Mean	STD	COV	Mean	STD	COV	%mdf	t-critical	Significance at p<0.05
time to boil	min	17	1	0.059	44	1	0.023	61.36	27.79	**
Tcore- time to boil	min	16.79	1.29	0.077	42.31	0.96	0.023	60.31	19.52	**
fuel consumed (dry)	g	596	40.63	0.068	1119	21	0.019	46.74	9.99	**
Burning rate	g/min	35.19	4.09	0.116	25.44	0.81	0.032	27.7	2.15	ns
Ƞ (%)		23.5	0.01	0.038	10.8	0.005	0.045	54.25	11.13	**
SFC	g/liter	116.59	8.42	0.072	212	3.05	0.014	45.01	7.28	**
Temp corrected SFC	g/liter	114.97	5.54	0.048	203.9	2.93	0.014	43.61	12.056	**
Temp-corrected SEC	kJ/liter	1998.15	96.31	0.048	3543	50.94	0.014	43.6	12.06	**
Firepower	watts	10193.6	1183.8	0.116	7369	235.0	0.032	27.8	2.15	ns

From the mean comparison of cold start high power phase (table 2), the Wood Gas Stove performed significantly better than Three stone Cooking stove for most of performance indicators of stoves except for stove characteristic indicators (Burn rate and fire power) where the stoves performance was not significantly different at P<0.05.

***Table 3*: Mean comparison of hot start phase for WGS and TSCS**

Parameters	**units**	WGS			TSCS			Significance test		
		Mean	STD	COV	Mean	STD	COV	%mean diff	t-critical	Significance at p<0.05
time to boil	min	13.3	1.53	0.115	40.3	0.58	0.014	66.9	10.006	**
Tcore- time to boil	min	13.2	1.86	0.141	38.8	0.56	0.014	66	7.588	**
Fuel consumed (dry)	g	535	38	0.071	190.9	298.3	1.562	48	11.085	**
Burning rate	g/min	40.5	6.38	0.157	25.6	0.80	0.031	37	2.070	ns
Ƞ	%	28.5	0.02	0.065	14	0.003	0.018	51	4.671	**
SFC	g/liter	107	7.45	0.070	203	10.53	0.052	48	9.264	**
Temp corrected SFC	g/liter	105	6.33	0.060	195.2	10.13	0.052	46	8.438	**
Temp-corrected SEC	kJ/liter	1827	110	0.060	3393	176	0.055	46	8.438	**
Firepower	watts	11742	1848	0.157	7410	232.2	0.031	37	2.070	ns

From Table 3, during hot start high power test Wood Gas Stove (WGS) performs significantly better than Three stone Cooking stove (TSCS) for most of the performance indicators except for stove characteristic (Burn rate and fire power) where stoves performances were not significantly different at P<0.05.

***Table 4*: Mean comparisons during simmering test of the stoves**

Parameters	**units**	**WGS**			**TSCS**			**Significance Test**		
		Mean	STD	COV	Mean	STD	COV	%Mean diff	t-critical	Sign. at p<0.05
Fuel consumed (dry)	g	1769.8	189.17	0.107	1749	179.9	0.103	1.15	1.527	ns
Burning rate	g/min	39.33	4.21	0.107	38.9	4	0.103	1.15	1.529	ns
Ƞ	%	20.4	0.01	0.049	13.4	0.02	0.147	34.10	3.47	**
SFC	g/liter	814.8	202.27	0.248	532.9	59.5	0.112	34.60	1.326	ns
Temp-corrected SEC	kJ/liter	14161.3	3515.4	0.248	9261	1034.6	0.112	34.60	1.326	ns
Firepower	watts	11392	1218.3	0.107	11261	1157.8	0.103	1.15	1.529	ns
Turn down ratio	--	0.895	0.042	0.047	0.659	0.068	0.104	26.36	3.598	**

From Table 4, Most of the performance indicators of the stoves were not significantly different except for thermal efficiency and Turn Down Ratio where WGS performed significantly better than TSCS at $p<0.05$.

3.3 Comparisons of performance parameters

Both thermal performance and stove characteristic indicators were elaborated.

i. Phase duration (min)

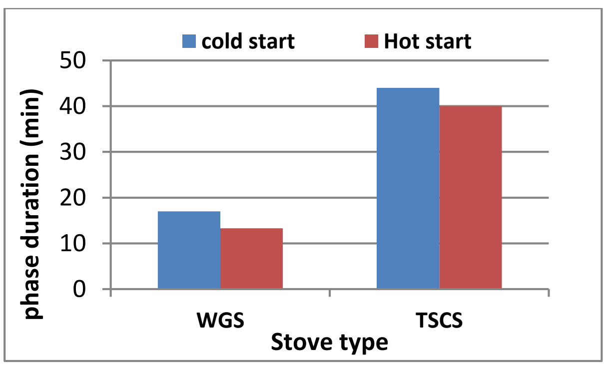

Figure 3: Phase duration comparison of WGS and TSCS

Least boiling time was recorded during high power hot start phase (13.3min and 40min) by WGS and TSCS respectively. The result obtained by the experiment was similar with [6, 7]. The boiling time reduction during high power hot start by the stoves were due to heat absorbed by stove body in this phase. Taking the mean of high power tests, the technology improved cooking time by 67.4%.

ii. Burning rate comparison

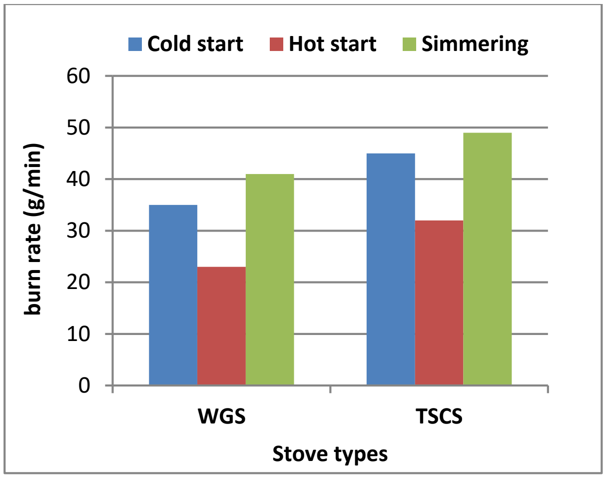

Figure 4: Burning rate comparison

Least burn rate was recorded during hot start by WGS (23g/min) and simmering test by TSCS (32g/min). Highest burn rate was recorded during simmering test by WGS (41g/min) and TSCS (49g/min). Comparing burn rate the WGS performs better than TSCS, but it was not significant at tested significance level as indicated in *Table 4*.

iii. Thermal efficiency comparison

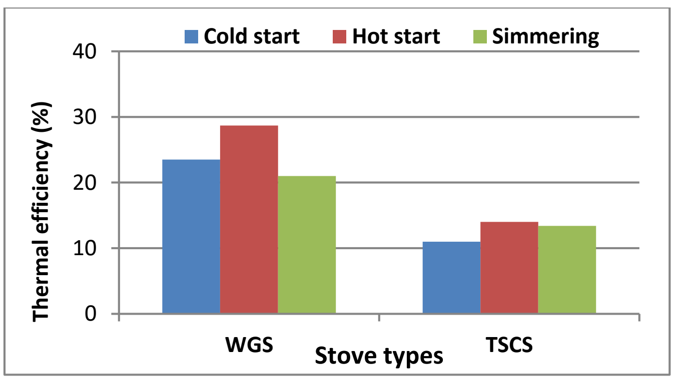

Figure 5: Shows how thermal efficiencies of the stoves compared

The highest thermal efficiency was recorded during hot start and simmering test by WGS and TSCS respectively. Least efficiency was recorded during simmering test and cold start test by WGS and TSCS respectively. The high power thermal efficiency were 26% and 12% for WGS and TSCS respectively and low power efficiency were 21% and 13.5% for WGS and TSCS respectively.

iv. Specific fuel consumption

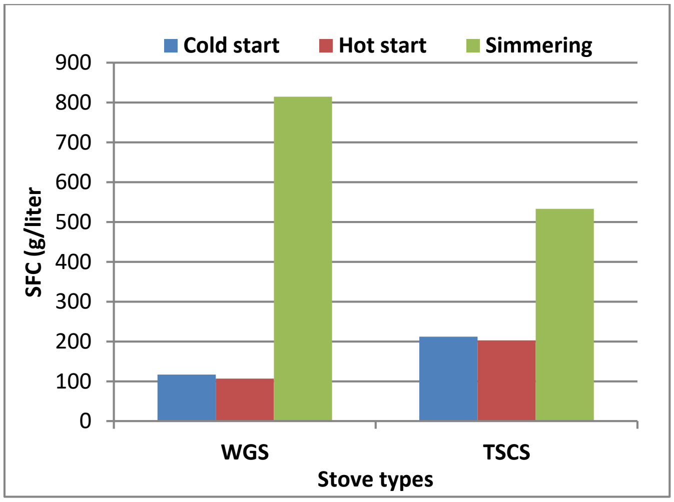

Figure 6: Shows the comparison of specific fuel consumptions

Specific fuel consumption is the measure of stove fuel consumption to boil a unit of water. Least sp. fuel consumption was recorded during hot start and cold start by WGS and TSCS respectively. As indicated, for high power test WGS recorded least SFC and low power test was recorded least SFC by TSCS. Comparing the two stoves during high power test WGS improved SFC by 46.5 while during lower power TSCS performs better than WGS.

v. Turn Down Ratio comparison

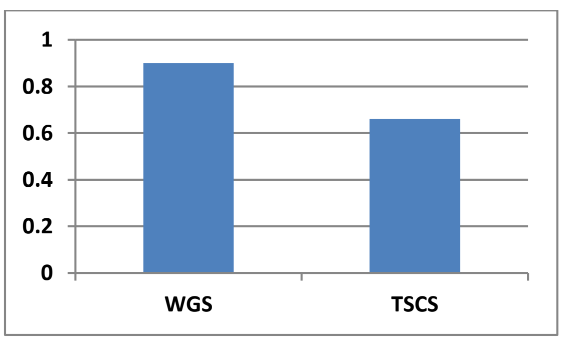

Figure 7: Compares the turn down ratio of the stoves

Comparing the mean Turn down ratio (TDR) of the stove Wood Gas Stove performed better than three stone cooking stove by 26%.

4. CONCLUSION AND RECOMMENDATION

4.1 Conclusion

The Wood Gas Stove improved the thermal efficiency by 54% during high power tests and 36% in low power test when compared with Traditional cooking stove (TSCS). It can contribute to indoor air pollution reduction and afforestation in developing countries. Comparing the mean the power controllability of the tested stove WGS performs better than TSCS by 26%. The stove performed better than TSCS for all performance indicators of thermal parameters. The technology performed better than traditional stove by most of thermal performance indicators except specific fuel consumption during low power test, it is important to promote to end users.

4.2 Recommendation

- Since the technology was performed better than traditional cooking by most of thermal indicators, it was recommended to be promoted and collect end users comment for further dissemination.
- Modifying the technology to decrease thermal mass so that it could be easily used in house hold cooking condition and applying insulation on the outer cylinder.
- The evaluation was under taken on hard wood, so it was recommended to further evaluate on different feedstock available in local area

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