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Laboratory Testing and Investigation of TEG Cookstoves and Study of its Performance**

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ARTICLE INFO

Article history:
Received 15 July 2022
Received in revised form
10 November 2022
Accepted 19 November 2022

Keywords:
Cookstove
Efficiency
ISO protocol
Modified combustion efficiency
Water boiling test

ABSTRACT

Laboratory testing of TEG cookstove is conducted with eucalyptus fuelwood following the testing protocols WBT 4.2.3 and ISO 19867-1 to evaluate the performance of the stove and CO and CO_2 emissions were measured to obtain the values of modified combustion efficiency. The performance results were analysed in terms of thermal efficiency, firepower, turndown ratio and specific energy consumption. It was found that the thermal efficiency conducted by WBT 2.2.3 resulted in the range 15-24% while ISO protocol testing was 18.23%. The experimental results found the least fuel burning rate, efficiency, and firepower during the cold start phase of the experiment. The duration of the simmering phase was nearly 2-3 times more than the duration of the hot-start phase while the turndown ratio was in the range of 0.8 to 1.5 which concluded that higher specific fuel consumption and lower thermal efficiency was a consequence of higher power output, or an inability to turn down the stove power. Higher value of MCE was calculated during simmering phase compared to high power tests due to availability of sufficient air to combust the gases in the combustion chamber.

1. INTRODUCTION

In low-income or developing countries, solid biomass is predominantly considered the prime source for cooking energy even today. This makes up around 2.6 billion of the global population living without access to clean cooking [1]. Global initiatives for clean cooking such as Clean Cooking Alliance (CCA) has reported that more than 400 million has gained access to clean cooking since its inception and contributed to reduction in emissions, empowered women and reduced potential economic losses in terms of billions [2]. However, during the Covid-19 pandemic, a study by (International Energy Agency) IEA reported that many households may be forced to push back to using inefficient cookstoves and fuels due to an increase in poverty levels. A case study by Shupler *et al*. [3], conducted in Nairobi during the Covid-19 lockdown period, found reduction in the family income among 95% of the surveyed household, which led to 15% of the households going back to kerosene fuel and nearly 13% of households back to collection of freely available fuelwood to perform their cooking task.

Cooking is a task which is undertaken on a daily basis between 2-3 times at different hour of the day. To meet the energy demand of daily cooking especially among the low-income countries, biomass continues to serve as the prime energy source. It has been reported in the world energy outlook 2020 that many developing economies of the world are observing a stagnant or sluggish transition from use of traditional solid biomass cooking fuel to cleaner cooking fuels and clean biomass energy alternatives [1]. The use of solid biomass fuel in inefficient cooking stoves, has been reported to be common for around 80% of the households in Sub-Saharan Africa and is responsible for around 4 million of global pre-mature deaths every year due to indoor air pollution resulting from high levels of $PM_{2.5}$, CO, SO_X, NO_2 [4]–[6].

The Sustainable Development Scenario's target by IEA to achieve clean cooking access by 2030 would only be possible by improving combustion efficiency, reduction of GHG emissions and reduced dependence on biomass for cooking. If SDG's target to achieve 50% of access to clean cooking by electric cookstoves and LPG is achieved, this would reduce almost 160Mt of CO_2-eq of methane and over 20 Mt CO_2-eq of N_2O emissions [1]. It has been estimated by the International Energy Agency that 1.8 billion people in 2040 will still rely on biomass to meet their energy demands, especially in developing countries and poor region. Therefore, achievement of the SDG target by biomass-based cooking technology still holds promising scope with users of over 32.5% global population using it as their prime source of cooking fuel, space heating and lighting.

The traditional use of raw biomass, such as wood, animal dung and agricultural waste, without any pre-treatment, in open fires or inefficient stoves, can produce large amounts of pollutants due to incomplete

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**This paper was presented at the *ICUE 2022 International Conference on Energy, Environment, and Climate Change* held at Pattaya City, Thailand from 26-28 October 2022.

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combustion. The residential biomass combustion contributes about 25% and 18%, to the total worldwide CO and NO_X emissions respectively [7]. In recent years, designers of household cookstoves have focused on improving efficiency and reducing emissions to mitigate health impacts associated with the use of solid biomass fuel However, ongoing research has revealed that greater emission reductions are needed to substantially reduce health risks. Some have suggested that a transition to affordable liquid or gaseous cooking fuels would be necessary to completely eliminate these health impacts [8]. However, even if a transition to liquid or gaseous fuels is ultimately necessary, such a transition would take many years to accomplish given the size and geographic distribution of the affected population. Consequently, a substantial fraction of the global population is expected to continue cooking with solid biomass fuel for the foreseeable future [9]. Next is the factor of reliability. Cooking as an activity is undertaken daily, between 2-3 times a day, usually on schedule. The reality of the present-day on-demand supply of LPG, especially in remote locations, is still not that well established. Therefore, while LPG is an aspirational fuel, it is biomass that keeps food on the table, day after day [10].

Cookstove intervention studies have been motivated by a need to improve assessment capabilities and accelerate the development of improved cookstoves (ICS). With over 2 billion daily users, biomass cookstoves have a significant impact on air quality and on global climate change. ICS targets to mitigate 1) health risks to cookstove users, 2) climate change, 3) deforestation, and 4) glacial retreat. Hence designing ICS requires testing methods with appropriate performance metrics that can define and identify improvements in cookstoves. To that end, several testing protocols have been developed including the recently established ISO 19867-1 laboratory testing standard, (a testing sequence for emissions and performance, safety, and durability of cookstoves used primarily for cooking or water heating), the water boiling test (WBT) and its derivatives, as well as the controlled cooking test (CCT) and the kitchen performance test (KPT) [11].

1.1 TEG Cookstove

Most of the traditional cookstoves has low efficiency ranging from 8-10%, because of energy lost and burning of excessive fuelwood. The traditional cookstoves also lose a considerable 10-15% amount of heat input to the stove body which contribute to the heat wasted [12]. To utilize the waste heat in the stove body, thermoelectric generator technology has been introduce as an appropriate technology intervention due to its no moving parts, longer operation cycle life, makes no noise and less maintenance [13], [14]. The principle behind thermoelectric generator (TEG) is to convert waste heat as heat source into electricity, which is regarded as a green technology since the input energy utilizing the waste heat from the fuel burning in cookstove, and the output of the TEG module is electricity which is an essential utility. Hence, it is of high importance due to its power generating feature and making the cookstove economically viable. To increase the thermal efficiency of the stove and reduce the emissions, studies have shown that stove harnessing with fan is a better option than a natural draft cook stoves. These stoves are known as forced draft cook stove. The power supply needed for running a fan can be provided by the power generated from TEG. Additional benefit provided is the utility of electricity for night-time illumination and mobile battery charging, which can reduce the level of dependence on reliable power source which is common in typical rural areas.

In this paper, the performance evaluation of a thermoelectric generator cookstove has been done under laboratory testing protocol to evaluate cookstove performance and emissions. Laboratory protocols such as Water Boiling Test (WBT) and ISO 19867-1 laboratory testing standard which has been adopted for comparison of various technical aspects of stove design and pre-field evaluations of performance prior to conducting of expensive field trials[15], [16].

2. METHODOLOGY

The standard cookstove testing protocols were used to calculate the performance parameters such as such as energy and exergy efficiencies, power output, *etc.* The laboratory ambient temperature was maintained at 25 ±5°C during the testing phase and the fuelwood was prepared as per cookstove testing protocols. Digital temperature sensors were used for measuring the temperature of water, flame and cookstove body, *etc.* Thermal imager Testo 868 was used for the measurement of pot, outer body of cookstove and ambient temperature.

As per the available literature, the performance parameters of the cookstove model were evaluated and Eucalyptus was selected as fuel for the study. The woody biomass used in the present study were selected because of their abundant availability in the study region, meaning they are generally used in most rural areas of the state of Uttarakhand (India) and is widely used for cooking and heating applications.

Following instruments were used while conducting experiments on the cookstoves: Electronic weighing scale (Make: iGene Labserve) of 30 kg capacity, digital temperature indicator, Thermocouple k-type shielded, two aluminium vessels each of 5 l capacity, pairs of tongs, temperature-resistant hand gloves, metallic tray *etc.*

The equipment used during the test procedure were a hood on which the cookstove was kept to monitor the emissions, with instrument Q-TRAK, 7575 of TSI, IAQ monitor for CO and CO_2, bomb calorimeter to find the calorific value of fuel. The laboratory test setup for cookstove testing is shown in Figure 1. In view of the requirements, the hood appropriately collected the emissions from the stoves being tested with the fluid flow influencing the fuel combustion process in the stove. Apart from allowing air to be drawn in the front opening, it also ensured adequate suction so that no emissions escaped the hood. To attain ratio of the average mass flow rate of diluted gas in duct to the average fuel burn rate, dilution ratio in range of 150:1 for domestic use, was maintained by ensuring an appropriate duct velocity. Hence the performance testing was carried out in such a way that the dilution ratio would fall in the range of 150:1 by adjusting the duct velocity in a fixed duct diameter. The final design of the hood and the ducting is in Figure 1. The gas temperature and the flow velocity in the duct were continuously monitored.

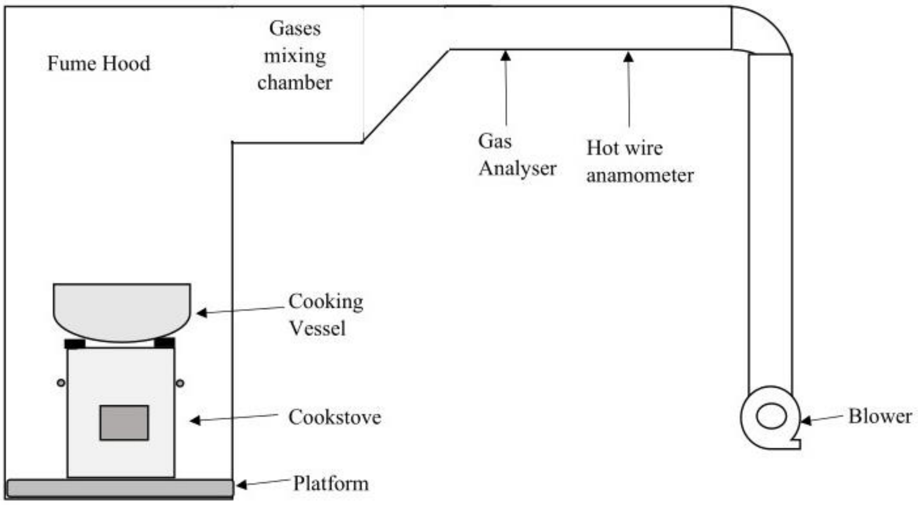


Fig. 1. Laboratory test setup for performing cooking test.

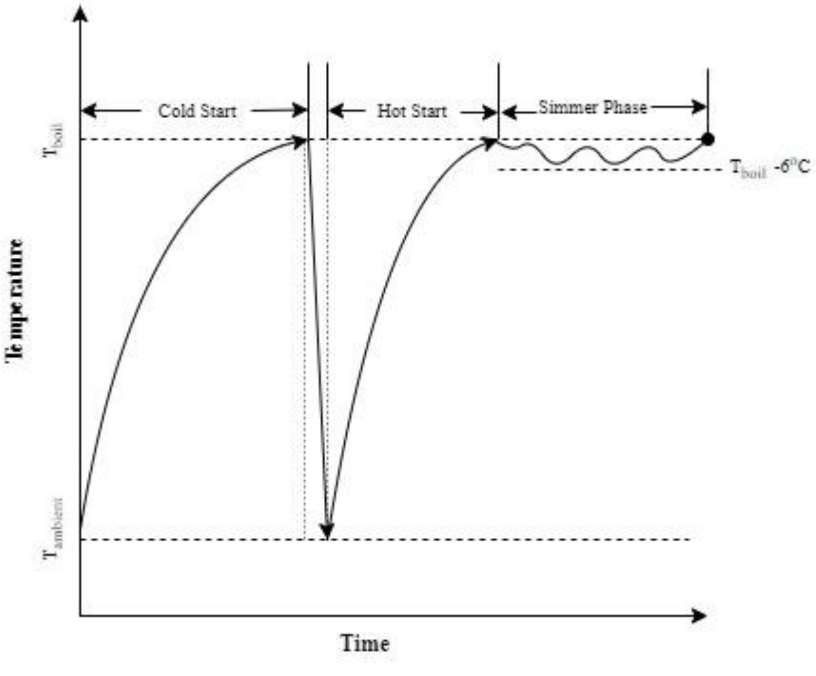


Fig. 2. Standard test sequence of a WBT.

2.1 *Water Boiling Test (WBT) Testing Protocol*

The Water Boiling Test was conducted to assess stove performance in a controlled manner, by trained technicians hence it is less similar to the cooking performed by locals. The WBT consists of three phases: cold-start high-power phase, hot-start high-power phase and simmer phase that immediately follow each other. These are discussed below and test sequence is shown graphically in Figure 2. The entire WBT should be conducted at least three times for each stove, which constitutes a WBT test set.

a. Thermal efficiency (h_c): it is the ratio of work done by heating and evaporating water to the energy consumed by burning fuel. It is an estimate of the total energy produced by the fire that is used to heat the water in the pot. It is calculated by formula in Equation 1.

$$h_c = \frac{(M_{water} x C_{water} x \Delta t) + (M_{evap} x \Delta h_{water})}{f_{cd} x\ LHV} \qquad (1)$$

Where, f_{cd} is the equivalent dry fuel consumed; Δh_{water} is the specific enthalpy of vaporization of water; M_{water} is the mass of water; M_{evap} is the mass of water evaporated; Δt is the heat gain of water from ambient to boiling point, C_{water} is the specific heat of water and LHV is the lower heater value of dry fuel.

b. Burning rate (r_{cb}): It is a measure of the rate of fuel consumption while bringing water to a boil. It is calculated by dividing the equivalent dry fuel consumed by the time of the test in Equation 2.

$$r_{cb} = \frac{f_{cd}}{\Delta t} \tag{2}$$

c. Specific fuel consumption (SC_c): Specific consumption can be defined for any number of cooking tasks and should be considered "the fuel required to produce a unit output". In the case of the cold-start high-power WBT, it is a measure of the amount of wood required to produce one liter (or kilo) of boiling water starting with cold stove. It is calculated by Equation 3:

$$SC_c = \frac{f_{cd}}{M_{fuelwood}} \tag{3}$$

d. Firepower (FP_c): It is the energy consumed to boil the water divided by the time taken to boil. It tells the average power output of the stove (in Watts) during the high-power test Equation 4.

$$FP_c = \frac{f_{cd} x LHV}{\Delta t x 60} \tag{4}$$

e. Fuel consumed: The fuel consumed is the mass of wood used to bring the water to a boil, measured by taking the difference of the pre-weighed bundle of wood and the wood remaining at the end of the test phase

f. Time to boil: The time to boil pot is the difference between start and finish times of boiling pot

g. Fuel burning rate: Burning rate is a measure of the rate of fuel consumption while bringing water to a boil. It is calculated by dividing the equivalent dry fuel consumed by the time of the test.

h. Effective mass of water boiled: The effective mass of water boiled is the water remaining at end of the test. It is a measure of the amount of water heated to boiling. It is calculated by simple subtraction of final weight of pot and water minus the weight of the pot.

2.3 ISO 19867-1 Protocol

The ISO standard test sequence characterizes performance of cookstove systems with international comparability for cookstoves tested at three power levels low, medium, and high as well as stoves designed for operation at only one power level and results at each power level be reported separately. The standard test sequence allows for both comparing cookstove systems of different types and comparing the same cookstove system at different facilities. The sequence of ISO cookstove testing protocol for one power is shown in Figure 3.

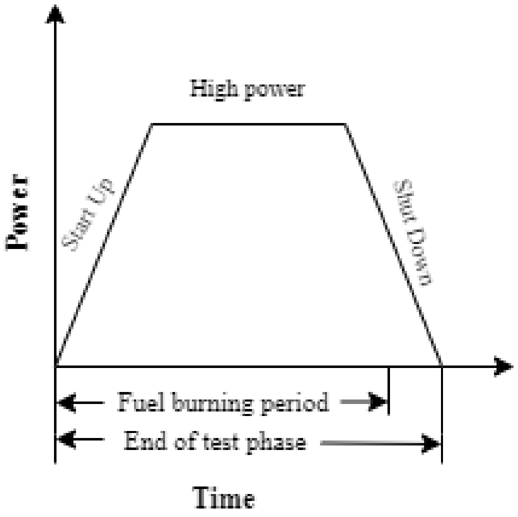


Fig. 3. Standard ISO test sequence for cookstoves in one power level.

a. The useful energy delivered (Q_1) shall be calculated using Equation 5

$$Q_1 = C_P X G_1 (T_2 - T_1) + (G_1 - G_2) \gamma) \tag{5}$$

Where Q_1 is the useful energy delivered, kJ; C_p is the isobaric mass-specific approximate heat capacity of water between 20°C and 100°C: 4,18 $kJ \cdot kg^{-1} \cdot K^{-1}$; G_1 is the initial mass of water in the cooking vessel, kg; G_2 is the final mass of water in the cooking vessel, kg; T_1 is the initial temperature of water in the cooking vessel, °C; T_2 is the temperature of the local boiling point or the highest temperature attained of the water in the cooking vessel, °C; γ is the latent heat of water vaporization at the local boiling point, kJ/kg.

b. Thermal efficiency (ψ_c) is the ratio of useful energy delivered to the contents of the cooking vessel to the fuel energy used. Cooking thermal efficiency with energy credit for remaining char shall be calculated using Equation 6.

$$\psi_C = \frac{Q_1}{BQ_{net.af} - CQ_{net.char}} X 100\% \tag{6}$$

Where Ψ_c is the cooking thermal efficiency with energy credit for remaining char, %; Q_1 is the useful energy delivered, kJ; B is the mass of the fuel fed, kg; $Q_{net.af}$ is the lower heating value of fuel, as fired, kJ/kg; C is the mass of the remaining char, kg; $Q_{net.char}$ is the lower heating value of remaining char, kJ/kg.

c. Cooking power is the average rate of energy delivered to the contents of a cooking vessel over any chosen period during the course of a cooking sequence or other task. It shall be calculated using Equation 7

$$P_C = \frac{Q_1}{(t_3 - t_1)} \tag{7}$$

Where Pc is the cooking power, kW; Q_1 is the useful energy delivered, kJ; t_3 is the final time at end of a test phase, s; t_1 is the initial time at beginning of a test phase, s.

d. Fuel burning rate is the rate at which test fuel is consumed in a cookstove (g/min)

e. The mass of fuel consumed is the mass of unburned fuel fed minus mass of residual fuel during a defined burn sequence

f. Char mass productivity, if char is present is calculated by Equation 8;

$$\mathrm{m_{char}} = \frac{\mathrm{C}}{\mathrm{B}} \mathrm{X}\ 100\% \tag{8}$$

Where, m_{char} is the char mass productivity, %; C is the mass of the remaining char, kg; B is the mass of the fuel fed, kg.

g. Char energy productivity is the energy productivity of the produced biochar. If char is present, it can calculated by Equation 9

$$\mathrm{E_{char}} = \frac{\mathrm{CQ_{net.char}}}{\mathrm{BQ_{net.af}}} \mathrm{X}\ 100\% \tag{9}$$

Where E_{char} is the char energy productivity, %; C is the mass of the remaining char, kg; $Q_{net.af}$ is the lower heating value of fuel, as fired, kJ/kg; B is the mass of the fuel fed, kg; $Q_{net.char}$ is the lower heating value of remaining char, kJ/kg.

h. The time taken to boil is the difference between start and finish boiling times. It can be calculated as given in Equation 10.

$$\Delta t_c = t_{c,f} - t_{c,i} \tag{10}$$

Where, Δt_c is the time to boil pot, $t_{c,I}$ is the time when boiling initially started and $t_{c,f}$ is the time when boiling ends.

i. The effective mass of water boiled is the water remaining at end of the test. It is a measure of the amount of water heated to boiling. It is calculated by simple subtraction of final weight of pot and water minus the weight of the pot. Digital temperature sensors were used for measuring the temperature of water, flame and cookstove body, *etc.* Thermal imager Testo 868 was used for the measurement of pot, outer body of cookstove and ambient temperature.

2.3 Modified Combustion Efficiency

MCE is defined as the proportion of total carbon emitted by a fire released as CO_2. It is the ratio of excess mole fraction of CO_2 and sum of CO_2 and CO excess mole fraction, and often used as an indicator of the combustion efficiency [7], [17], which was calculated using Equation 11.

$$MCE = \frac{CO_2}{CO + CO_2} \tag{11}$$

3. RESULTS AND DISCUSSION

The TEG cookstove comprises of heat source known as hot plates, is made of stainless steel with 5 probes. They are attached to the hot side of the TEG module where the biomass burning takes place in the combustion chamber of cookstove. The temperature readings were taken with the help of K-type thermocouple attached to a digital metre and Thermal imager Testo 868. The K-type thermocouples are thin wires placed at vital points where temperature was measured.

The thermal efficiency was calculated using WBT 4.2.3 standard protocol, ISO 19867-1:2018. A digital weight balance was used to measure the amount of water and wood spent during the laboratory experiment. The accuracy of the digital weight balance equipment used in the experiments was 5g. Additional performance parameters of the cook stoves like fuel burning rate, fire-power, specific fuel consumption, specific energy consumption and turndown ratio were determined. Table 1 shows the characterization of selected fuelwood in the current study.

Table 1. Eucalyptus fuelwood characterization.

Ultimate analysis	Fuelwood (Eucalyptus)	Proximate analysis	Fuelwood (Eucalyptus)
C	49.685	Volatile matter	78.79%
H	6.805	Fixed carbon	21.04%
N	0.229	Moisture	10%
O	43.281	Ash	0.41%
		LHV_{th}	19.40 kJ/kg

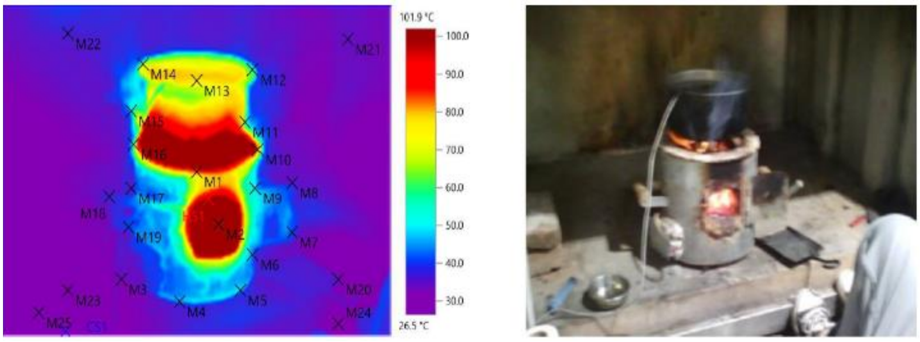


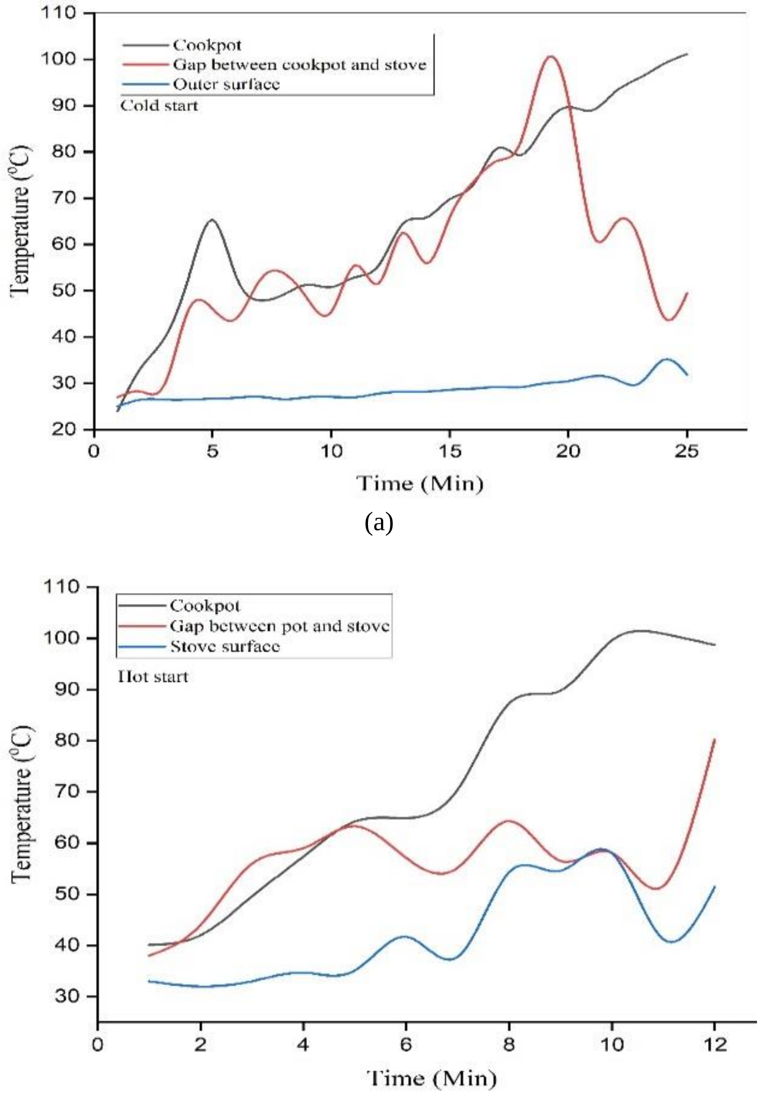
Fig. 4. Temperature profile while performing test.

3.1 Analysis of Cookstove Thermal Profile

The cookstove thermal profile imaging was by Thermal imager Testo 868, is evident in Figure 4. It is clear from Figure 4 that minimal heat loss took place at the cookstove outer wall, and the maximum temperature was reported at the two locations: the gap between pot bottom and pot stand, and fuel inlet. The surface temperature decreased towards the bottom of the stove was recorded to about 35-40°C. Additionally, heat transfer to the environment found that the difference between maximum temperature and air temperature on the floor surface ΔT was ≤ 45, on the wall surface ΔT was ≤ 60, metallic handle temperature ΔT was ≤ 20 and non-handle temperature ΔT was ≤ 32 which were best ratings with a score of four [18].

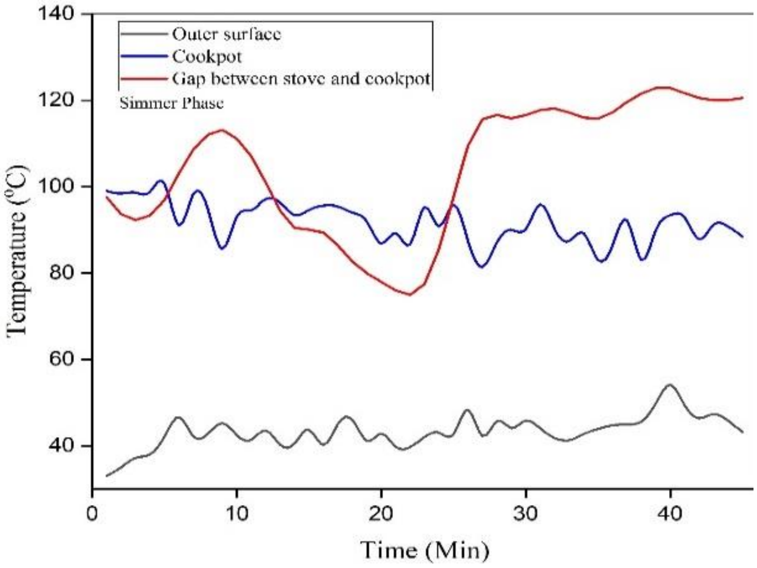
Water boiling test was performed to evaluate the TEG cookstove performance on the parameters such as thermal efficiency, burning rate, specific fuel consumption, firepower and turn down ratio [19]. The conduction heat transfer in the cookstove were measured using k-type thermocouples at three points *i.e.*, at the gap between the cookpot and the stove, outer surface of cookstove and temperature in the pot while performing WBT. Figure 5 shows the graph at all three stages of testing. It is evident from Figure 5 that readings taken corresponded to the results obtained from the thermal image (Figure 4). Likewise, minimum heat loss from the cookstove outer surface wall and maximum temperature at the gap between the pot bottom and the pot stand and fuel inlet was observed.

The experimental results of cold start test, hot start test and simmer phase are shown in Table 2. The thermal efficiency was instrumental to understand the heat transfer from the fuelwood to the cooking pot while burning rate, specific fuel consumption of high and low power and turn-down ratio helped in the identification of differences in performance between a cold started and hot started stove.



(a)

(b)



(c)

Fig. 5. Thermocouple readings of surface temperature during WBT a) cold start, b) hot start and c) simmer phase.

Table 2. Performance of TEG cookstove testing by WBT.

Parameters	WBT protocol results		
	CS	HS	SP
Thermal efficiency	17 - 18	17 - 19	15 - 19
Fuelwood used (kg)	0.51 – 0.57	0.45 – 0.46	0.53 – 0.62
Duration (min)	35 - 43	14 - 20	45
Fuel burning rate (g/min)	11 - 13	22 - 30	11 – 12.5
SFC (g/l)	191 - 245	112 - 149	260 - 344
Firepower kW	2.43 – 3.41	3.13 – 6.36	3.3 – 4.25
Turndown ratio	0.73 – 1.02	0.73 – 1.02	0.73 -1.02

From Table 2 when Eucalyptus was used as the combustion fuel, the average thermal efficiency of the TEG stove was 18.72%. The temperature of the water was continuously monitored using thermometer during all the three phases of WBT and results are reported in Figure 5. The average time taken to boil 2 l of water was 50 min for TEG stove during cold start condition. However, during the hot start, TEG stove required about 19 min to boil 2 liters of water. Eventually, the temperature of the water was maintained between 95-97°C for 45 min during the simmering phase for TEG stove as suggested by WBT 4.2.3.

Burning rate of TEG cookstove as reported in Table 2, was observed to increase from the cold start phase to the hot start phase indicating that ignition of fire was difficult at beginning because the forced draft fan had not been initiated. In terms of fuel burning rate (FBR), testing at high-power phases (cold and hot start) resulted in comparatively higher output than low power (simmering phase). Although the FBR during the low power phase was less when compared to the high-power phases, the duration of the simmering phase was much longer than the high-power phases (45 min). Therefore, the total energy consumed during the simmering phase was much higher than the high-power phases.

Additionally, the study also found a considerable variation in the burning rate during cold start and hot start, but in simmering phase, was almost constant for all replicated tests. The reason was due to the regulated air supply into the combustion chamber as the forced draft was activated when temperature difference was created continuously during the simmering phase which resulted in better combustion [20]. In an attempt to achieve stoichiometric condition without changing the air flow rates, the study found that proper supply of secondary air by TEG powered forced draft fan led to the higher burning rate and firepower, this was evident in readings as shown in Table 2.

Specific fuel consumption of TEG cook stove during high power (cold start and hot start) and low power (simmer) are shown in Table 2. The average SFC of TEG cook stove was 218 g/L during cold start, 130.5 g/L during hot start and 302 g/L during simmer phase. Thus, during high power phase, lower amount of fuel was consumed than in low power phase. Since the combustion chamber was half loaded in simmer phase and the inner surface of hot combustion chamber accounted for better SFC. Meanwhile, this led to the increase in specific fuel consumption and higher efficiency and low fire power. The value for fire-power was found to have a positive correlation with fuel burning rate. From Table 2, it was evident that the TEG cook stove delivered higher firepower in high power than low power phase.

Turndown ratio (TDR) is a measure of the range of firepower control capacity for the TEG cookstove during real cooking conditions [19]. TDR showed how well a stove could provide a range of firepower which for improved cookstoves were in the range 1.3 to 3.9 [19], [21]. The higher value of TDR has been identified to provide a higher ratio of high power to low power, and could indicate a greater range of stove power control [21]. The period of the simmering phase was nearly 2-3 times more than the duration of the hot-start phase while turndown ratio was in the range 0.8 to 1.5. Hence it was concluded that higher specific fuel consumption and lower thermal efficiency was a consequence of higher power output, or an inability to 'turn down' the stove power.

The specific energy consumption of the developed cook stove was evaluated by observing the amount of fuel consumed during the three phases of WBT 4.2.3. It was observed from Table 2 that high specific fuel consumption occured during simmering phase due to constant energy supply needed to maintain the temperature of the water between 95- 97°C. Hence the total energy consumed during the high-power phases were low when compared to the low power. Consequently due to constant power delivery during the simmer phase for 2-3 times longer duration than cold start and hot start.

3.2 *Cookstove Testing by ISO Protocol*

Output of ISO protocol cookstove testing obtained results which are shown in Table 3. The average efficiency obtained was 18.23% which corresponded to the efficiency obtained from WBT, the average value of cooking power was 34.64 kW with char mass productivity of 13.26%, char energy productivity of 21.20% and average time taken to boil was 26.75 min.

Table 3. Performance of TEG cookstove by ISO protocol.

Efficiency (%)	Cooking power (kW)	Char mass production (%)	Char energy production (%)	Time to boil (min)
18.23	34.64	13.26	21.20	26.75

3.3 *Comparison of Modified Combustion Efficiency*

MCE provides a general indication of how completely a fuel is being combusted. There is a consistent trend reported trend that controlled laboratory testing produces higher MCEs compared to field tests, with the median for each stove type higher when measured in the laboratory [22]. The MCE was calculated by taking reading from three different phases of WBT (cold start, hot start and simmering phase) and ISO protocol cooking test and comparison was drawn against thermal efficiency of the cookstove performance as shown in Figures 6 and 7.

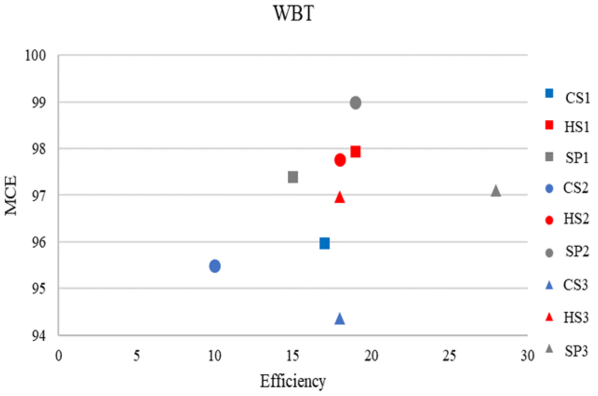


Fig. 6. Comparison of MCE against thermal efficiency at cold start, hot start and simmering phase.

From the graph it was evident that when the fire was dominated by flaming combustion, the modified combustion efficiency was high, meaning that the emissions were dominated by CO_2. The modified combustion efficiency decreased as smoldering combustion and emissions of CO become more dominant. Flaming combustion is generally associated with MCE values greater than 0.9 and smoldering combustion with values below 0.9 [17], [23]. Laboratory test results during simmering tests found consistency with the results reported in the past [24] with a higher MCE compared to high power tests because the combustion chamber tends to be overloaded restricting airflow when trying to boil large volumes of water, but during simmering, air flow into the combustion chamber was sufficient to combust the available gases.

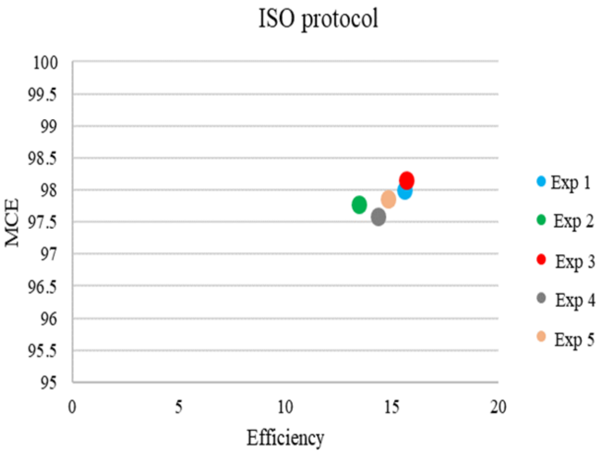


Fig. 7. Comparison of MCE against thermal efficiency from Cookstove test ISO protocol.

4. CONCLUSION

This study conducted the laboratory test of cookstove using WBT and ISO protocol on TEG cookstove to investigate the thermal efficiency, firepower, specific fuel consumption, turndown ratio and specific energy consumption by using popular fuelwood Eucalyptus. The results from the study found that minimum of heat is being lost from the cookstove outer wall and the maximum temperature reported at the location between bottom of the pot and pot stand, and the test conducted for heat transfer to the environment found that the temperature difference on the floor surface, wall surface, metallic handle temperature and non-handle temperature was best ratings with a score of four. The ISO and WBT testing protocols resulted in average thermal efficiency of 18.72% and in the range 15-24%, respectively after conducting 6 replicated tests while ISO protocol testing corresponded to 18.23% which correspond to the efficiency obtained from WBT. The results from fuel burning rate, specific fuel consumed, firepower and total energy consumed found that due to the time taken to initiate TEG fan in the cookstove, the experimental results found least fuel burning rate, efficiency and firepower at the cold start phase of the experiment. The period of the simmering phase was nearly 2-3 times more than the duration of the hot-start phase while turndown ratio was in the range 0.8 to 1.5. Hence it was concluded that higher specific fuel consumption and lower thermal efficiency was a consequence of higher power output, or an inability to ‘turn down’ the stove power.

The study also found high modified combustion efficiency when emissions were dominated by CO_2. As combustion efficiency decreased, CO become more dominant due to smoldering combustion. Consequently, during simmering tests a higher MCE was reported compared to high power tests because at the combustion chamber, air flow into the combustion chamber was sufficient to combust the available gases.

ACKNOWLEDGMENT

The authors acknowledge the Centre for Rural Development and Technology for supporting in the experimental work.

NOMENCLATURE

h_c = Thermal efficiency
f_{cd} = Equivalent dry fuel consumed
Δh_{water} = Specific enthalpy of vaporization of water
M_{water} = Mass of water
M_{evap} = Mass of water evaporated
Δt = Heat gain of water from ambient to boiling point
C_{water} = Specific heat of water
LHV = Lower heater value of dry fuel
r_{cb} = Burning rate
SC_c = Specific fuel consumption
FP_c = Firepower
Ψ_c = Cooking thermal efficiency with energy credit for remaining char, %
Q_1 = Useful energy delivered, kJ
B = Mass of the fuel fed, kg
$Q_{net.af}$ = Lower heating value of fuel, as fired, kJ/kg
C = Mass of the remaining char, kg
$Q_{net.char}$ = Lower heating value of remaining char, kJ/kg
Pc = Cooking power, kW
Q_1 = Useful energy delivered, kJ
t_3 = Final time at end of a test phase, s
t_1 = Initial time at beginning of a test phase, s
m_{char} = Char mass productivity, %
E_{char} = Char energy productivity
Δt_c = Time to boil pot
$t_{c,I}$ = Time when boiling initially started
$t_{c,f}$ = Time when boiling ends

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