

Investigation of local materials on the durability of energy generating biomass cook stove for rural settlers

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Abstract

Energy demands in rural communities of developing countries are relatively low. The objective of this work is to provide a smart energy generation from available local materials. Biomass cook stoves are used in most rural communities in developing countries. Its durability and mode of pollution dispersion remains a major challenge. In this research, biomass cook stove was constructed using different local materials. The heat sink sources that were used are steel, copper, iron and low grade steel. Two focuses of the research were the compatibility of the local materials to the thermoelectric (TE) module and its influence on the corrosion of its heat sink. The design specification of the biomass cookstove was to limit environmental pollution and control airflow to the biomass fuel. It was observed that the thermal effect on the heat sink has great influence on the thermoelectric module. The challenge of recurrent results in past research was resolved by the introduction of image analyzer to examine the thermal corrosion on the heat sink. The challenges facing the durability of the improved biomass cook-stove were highlighted in the study for further study.

Keywords: Biomass; Cook Stove; Heat Sink; Design; Heat; Thermal Analysis; Energy.

1. Introduction

The purpose of working on the modernize cook-stove is to provide a clean, safer, more fuel efficient way to generate energy for domestic usage. These feats can be achieved by initiating a forced airflow into the stove's combustion chamber using low powered fan. Logically, increased airflow improves the combustion efficiency of fuel, leading to higher burn temperatures achieved with lower usage of fuel [1]. Furthermore, less ash and smoke is emitted as a way of abating pollution. The physical structure of biomass cook stove is transforming to a complex system [2] that could be used to generate minimal voltages for recharging handset, laptops, lamps e.t.c. One of its advantages is controlling air pollution and heat associated with biomass cook stove. The pollution caused by the traditional cookstove has led to high concentration of particulates in the atmosphere [3] and the emergence of diseases [4]. Its new added electrical functionality is appropriate, affordable and achievable to meet the energy needs of rural dwellers/inhabitants. In rural settlement, fuel source includes crop residues, grass, roots and animal dung.

In 2012, International Working Agreement (IWA) provided a framework for rating cookstoves using four major indicators i.e. efficiency, total emissions, indoor emissions and safety [5]. This study postulates another indicator - durability. The durability of the modern biomass cook stove is somewhat questionable because of the material composition of the typical cookstove. The main disadvantage of a non-durable cook stove is its pollution to the immediate environment in form of greenhouse gases e.g. black carbon [6]. Indoor air pollution was reported to cause respiratory illness [7].

The second disadvantage of non-durable biomass cook stove is its inability to preserve the lifespan of the thermoelectric generator (TEG) due to uneven/differential heat supply. Hence, it is very important to consider durability of the biomass cook stove (BC).

The key component that determines the durability of the modern BC is the heat sink. The heat sink transfers heat energy from the heat source to the TEG. The principle guiding TEG operations are explained using the 1D-Fourier's law of heat conduction and Newton's law of cooling. The TEG uses the heat of the combustion chamber to generate electricity. The power that is generated is used to power air circulation (i.e. fan) which makes more oxygen available for combustion i.e. increasing the combustion efficiency and decreasing the amount of harmful emissions. These days, high efficiency fans are made with brushless DC motors and have a voltage boosting circuit, which allows the fan to run at higher speed. Air flow also cools the other side of the TEG. This activity increases the efficiency of the thermoelectric generators and maximizes the temperature difference across the thickness of the TEG. Advanced biomass cookstoves now have fan draft gasifiers to improve upon the efficiency of BC. Most homes in Africa have adopted the modern cookstove. In recent times BC sales grew roughly from 4 million in 2011 to 8 million by the end of 2013 [8]. Rysankova et al. [9] projected 35–200% annual sales growth of BC in the future. Hence, the market base for BC in rural and urban settlements of developing countries is promising. The commercial prospects of biomass cookstove in developing countries can be expressed in Table 1.

Table 1: Commercial Prospects of Biomass Cook Stove

Types of biomass stove	Fuel Consumption (Kg/hr)	Power Consumption (kWh)	Year of production	cost	Ref
Continuous Feeding Cookstove	3.5-6	0.03	2003	\$156	[10]
Jwala Briquette Stove	3.5 - 4	110	2009	\$187	[11]
Prime Stove	0.3 - 2	6,000	2010	\$24	[12]
Greenway Smart Stove Biomass cookstove	0.3 - 2	2000	2011	\$23	[13]

Champier et al. [14] worked on thermoelectric power generation from biomass cook stoves with emphasis on the best thermoelectric (TE) module. The best TE module was Bismuth Telluride with a maximum power output of 6 W. However, O'Shaughnessy et al. [15] developed same model which lasted 3 months. Hence, the question on durability is a very cogent challenge if the power generating cookstove must be adopted for commercial purposes. In this paper, an improved BC was used to generate electricity for home use. The main emphasis was on durability. Durability in the light of this paper includes an efficient model to convert the waste heat energy of the biomass stove to electrical energy using thermoelectric generator. This research can be used to determine the feasibility of using biomass cook stove for cooking and powering homes in rural areas.

2. Materials and method

The heat sinks adopted in this study were two samples of different types of hybrid aluminium steel (whose properties are shown in Table 2 below) and one sample of chrome nickel steel. The measuring device includes: digital thermometer, digital multimeter, and image analyzer. The physical quantities measured were temperature, voltage, heat and power. The image analyzer is made-up of six components i.e. image input, image memory and display, gray and binary image processing and analyzing, data process, system control interface, and data or image output. The image analyzer diagrams (Figures 3, 5 and 7) were adopted to show the structural changes that occur in the heat sink. In this study, we propose that the defaults in the structure of the heat sink can compromise the efficiency of the TEG. Manual logger was used to record the temperature and voltage at every 10 seconds. The action was sustained to capture the energy exchanges that are associated with the start-up operation. Differential temperature is very high at this stage. In this experiment, it led to the damage of several TEG samples. Hence, our focus was on the impact of start-up operations on the TEG. The design, construction and experimentation were discussed in this section. The type of biomass used for this experiment is wood charcoal. Its local and biological names are 'Afara' and 'Terminalia superba'. Its average calorific value is 8.25 kCal/g. Its elemental and proximate analysis are reported by Ogunsawo et al. [16]. The export potential of the wood charcoal from Nigeria to Europe is documented in Food and Agriculture Organization of the United Nations [17].

3. Results and discussion

Table 2: Thermal Conductivities of Heat Sinks Used for the Study

Type	Component Of Heat Sink	Thermal Conductivity (W/(Mk))
1	Aluminum Oxide Slip Cast	11.1
2	Chrome Nickel Steel (18% Cr, 8 % Ni)	16.3
3	Aluminum Oxide 22% Porosity	2.3

The design of the cookstove is shown in Figures 1a-c. The biomass cook stove is multi-shaped to address salient physics of the component design as discussed in the introductory part. It generally consists of a combustion chamber (section A, Figure 1a), fan draft gasifiers (behind) heat harvesting/electrical sections (Figure 1c). The combustion chamber is designed to have space for the biomass fuel

e.g. firewood, crop residues, grass, roots and animal dung (unit E of Figure 1b). Perforated sheets were attached to the combustion chamber which leads to another chamber (see arrow in Figure 1c) that contains anti-pollution devices i.e. electrostatic precipitators (wet and dry types), fabric filters, wet scrubbers and cyclones (unit C of Figure 1a). The air from the fan (black arrow at section B, Figure 1a) flows across the biomass. The smoke is expected to shift in the opposite direction (red arrow at section C, Figure 1a). The fan draft gasifiers section is made-up of the fan and gasifiers within a streamlined chamber to encourage maximum heat flow towards the pot and heat harvesting unit (see arrow in Figures 1d-g). The heat harvesting/electrical section is made up of the thermoelectric generator (new thermoelectric power generator Peltier module TEG 40*40mm high temperature), circuit and the heat sink (Figure 1h and i). Hence, the major sections of the stove includes: A is the gas chamber, B is the air inflow window, C is the anti-pollution device, D is perforated base for the exit of ash, E is the biomass inlet widow and F is the ash tray, G is the TEG.

The basic formulars for estimating the heat energy, as well as the power generation were

$$H = mc\Delta T \quad (1)$$

where c is specific heat capacity of the heat sink, m is the mass of the heat sink, ΔT is the temperature gradient. Also the rate at which heat is transferred by conduction to the heat sink can be written as

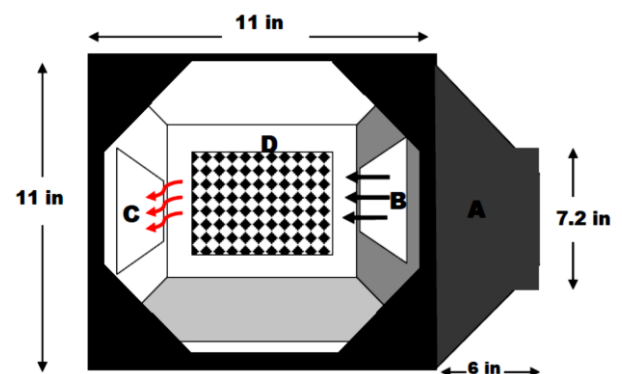
$$\dot{H} = cA \frac{dT}{dx} \quad (2)$$

where A is the cross-sectional area of the heat sink, T is the temperature gradient. The power generated was calculated using the equation below

$$P = \frac{H}{t} \quad (3)$$

where t is the time taken for the heat to transfer.

The feed-rate adopted for this experimentation was a single batch feeding. This concept minimizes error since feeding rate of fuels affect the efficiency of fuel burning stoves [18]. Readers interested to see the operational errors in analyzing cook stove should consult Ref [18]. The thermoelectric generator's hot side heat sink and the cold side heat sink was meant to produce approximately 14.6 volts and 0.6 Amps DC. However, under differential heating it had a maximum open voltage of 1.5 volts (see Figures 2, 4 and 6).

**Fig. 1:** A) Front View of the Cook Stove.

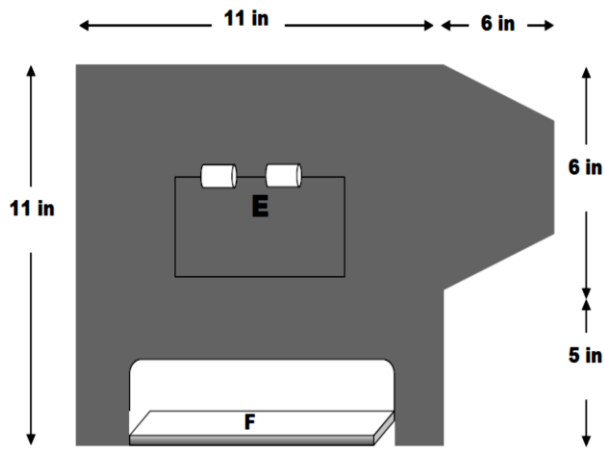


Fig. 1: B) Side View of the Cook Stove.

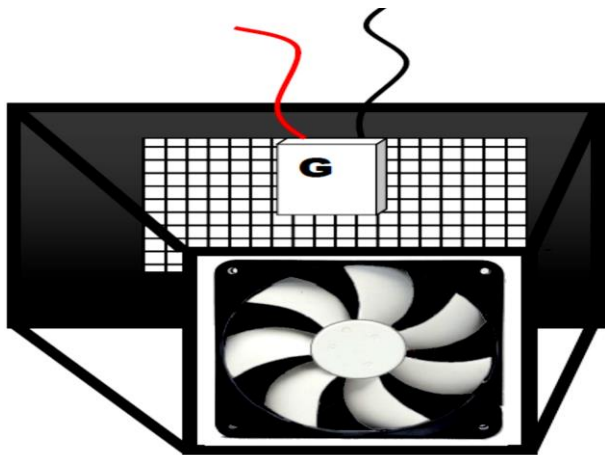
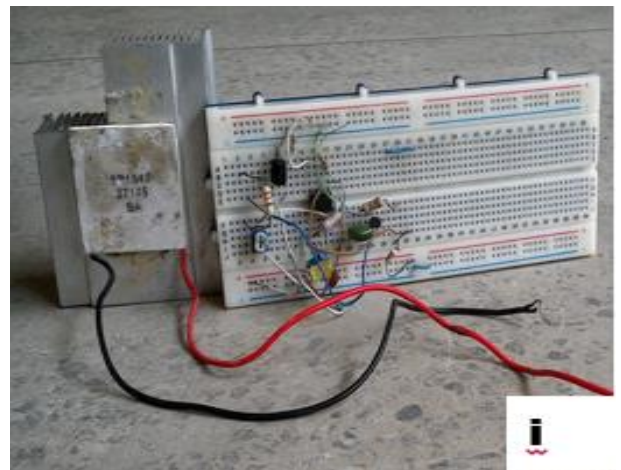
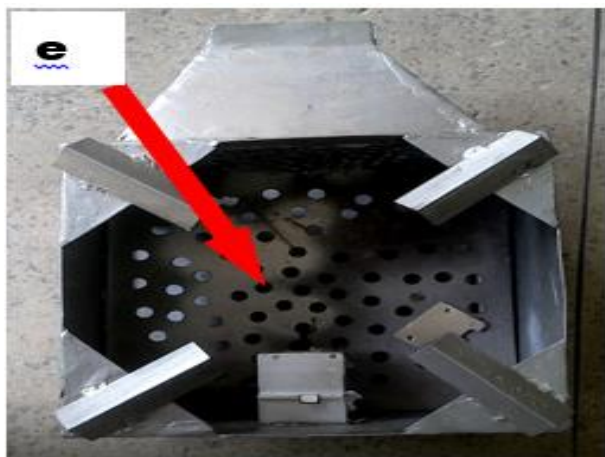
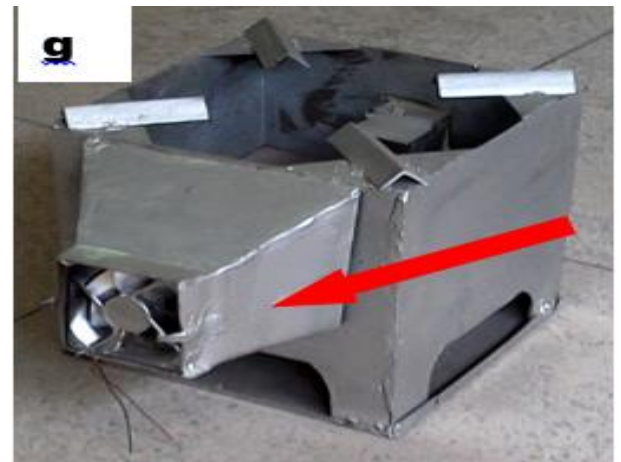
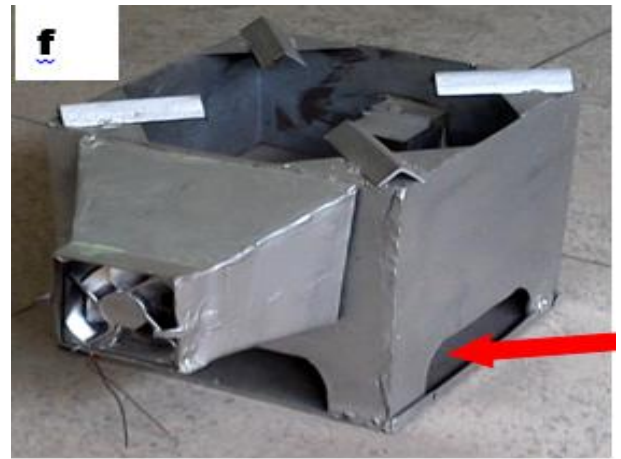


Fig. 1: C) Wind Chamber of the Cook Stove.



In this section, both the qualitative and quantitative results were obtained from the construction of the biomass cook stove. Also, the results of the Image Analysers were presented. It was stated in the previous section, the objective of this paper is to design a BC to produce electricity for home use in rural areas with emphasis on durability. The varying differences of temperature and voltage were measured. From the measured quantity, the heat and power generated from each heat sinks used for the construction of the cook stove was calculated. Results obtained from 'heat sink 1' are shown in Figures 2a-d. It was observed in Figure 2a that heat increases in a nearly parabolic way as time. The undulations of the graphs are evidences of differential heating which is proportional to the component and structure of the heat sink.

It was also observed that the rate of heat generation between 300s - 600s was more stable than the previous heat generation below 300s. Figure 2d was the theoretical calculation of expected power generated (in Watt) from the heat energy produced within the system. However, in reality, the experimental power generated from the TEG is less than 1W. Hence, there is an evidence of massive energy loss via the heat sink.

The focus shifted to knowing the causes of heat loss in the heat sink. A critical look on the results from the image analyzer further enlightened the reasons for the observations made (Figures 3a and b). The structure of the heat sink before and after heating was examined. The results from the image analyzer show the effect of temperature on the expansion of the natural faults of the heat sink (red line in Figure 3b). The heat-time graph (Figure 2a) agrees with established experiments [19]

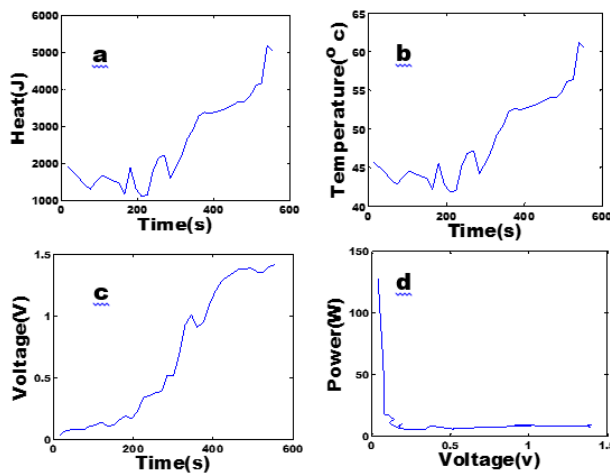


Fig. 2: A) Thermal Analysis of Heat vs Time (2b) Thermal Analysis of Temperature vs Time (2c) Thermal Analysis of Voltage vs Time (2d) Thermal Analysis of Power vs Voltage.

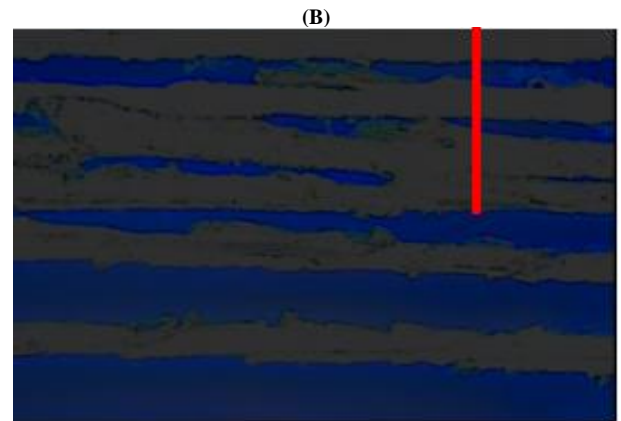
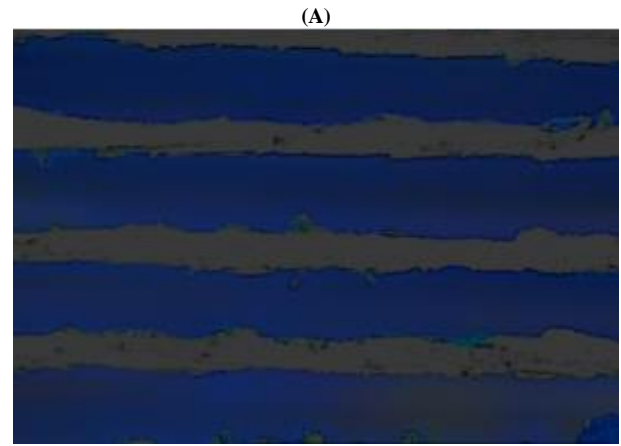
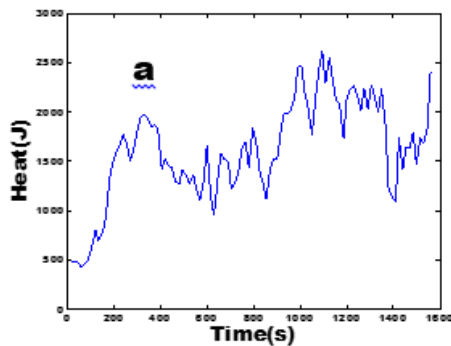
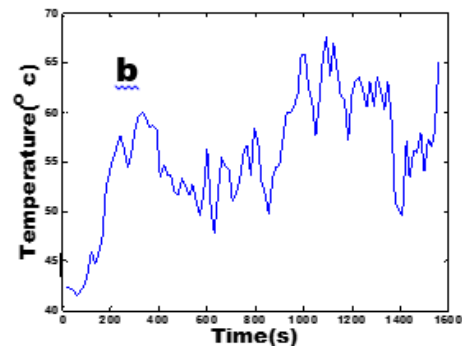


Fig. 3: A) Before Heating The Heat Sink (3b): After Heating the Heat Sink.

Most steel comprise of metals that was added to tune-up its properties, like strength, corrosion resistance, or ease of fabrication [20], hence, it is expected that the application of heat would alter the configurations of the loosely-bond steel. Chitty and Foster [21] used computer modeling to study the impact of thermal response on steel structures that had undergone heating. Steel configurations is a challenge until date [22].

The temperature dynamics (Figure 2b) follows almost the same pattern as shown in Figure 2a. The dip shown in the graph varies between 10 – 200 s and can be attributed to poor combustion. The differential temperature effect at 550 s led to the damage of the TEG.



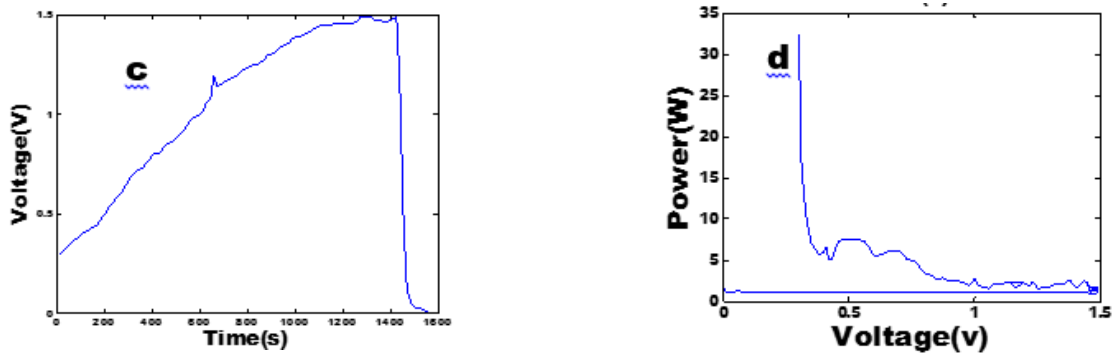


Fig. 4: A) Thermal Analysis of Heat vs Time (4b) Thermal Analysis of Temperature vs Time (4c) Thermal Analysis of Voltage vs Time (4d) Thermal Analysis of Power vs Voltage.

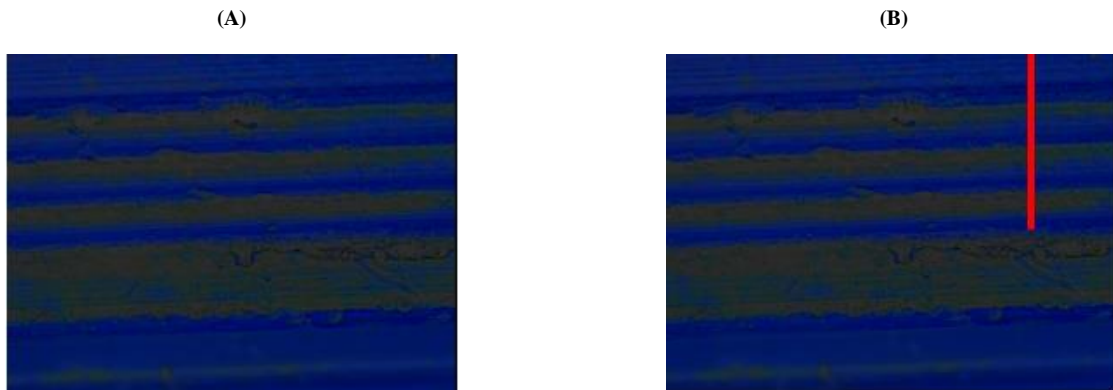
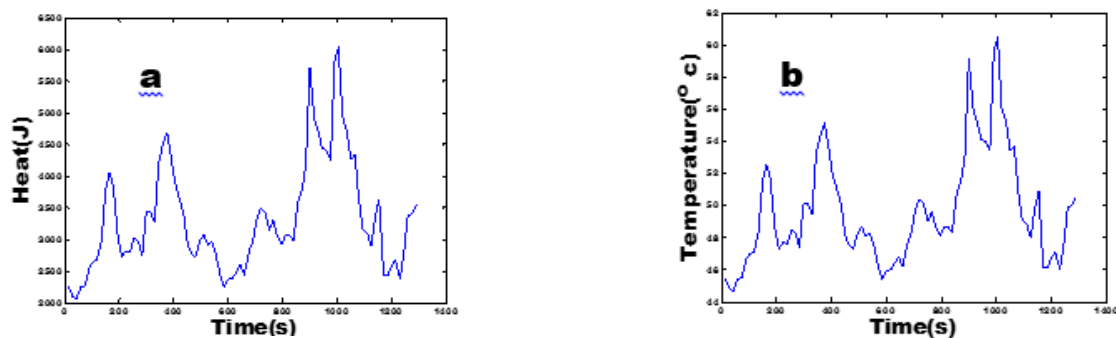


Fig. 5: A) Before Heating the Heat Sink (5b): after Heating the Heat Sink.

At this point, the TEG stopped functioning due to uneven heating from the refuel of biomass (charcoal) at the 190th sec. The voltage increased with temperature (Figure 2c) which leads to a positive parabolic relation with maximum power of 132 W (Figure 2d). The rate of change of heat for 'heat sink 2' (Figure 4a) after the initial increase from 0 – 200 s is highly unpredictable because of the undulating heat energy. However, the undulation was within an average of 1400 J. The temperature output shows the same pattern as heat energy (Figure 4b). The dips in the graph at 600 s, 900 s, 1100 s, and 1400 s are due to poor combustion. The irregularity of the heating led to an irregularity in the temperature. There was a very sharp drop in voltage from 1600s due to the malfunctioning of the TEG caused by an uneven heating. Hence, uneven heating is common for the biomass cookstove. Uneven heating led to the destruction of another TEG. For example, the sharp drop of voltage at 1480 s (Figure 4c). The resultant effect on the expected power output is reduced to about 32 W (Figure 4d). These results enabled a further probe on the structure of the heat

sink before and after heating (Figure 5 a and b). The results from the image analyzer show there is no significant effect of temperature on the expansion of the natural faults of the heat sink 2 (red line in Figure 5b). The rate of change of heat in the 'heat sink 3' (Figure 6a) after the initial increase from 0 – 180 s was highly unpredictable unlike the 'heat sink 2' because of the undulating heat energy. However, the undulation was within an average of 2200 J. The temperature output shows the same pattern as heat energy (Figure 6b). The dips in the graph were attributed to poor combustion. The irregularity of the heating led to an irregularity in the temperature. There was a very sharp drop in voltage from 1600s due to the malfunctioning of the TEG caused by an uneven heating. The drop of voltage was not distinctively noticeable as heat sink 2 (Figure 6c). The resultant effect on the power was found to be above 150 W (Figure 6d). The structure of the heat sink before and after heating was examined (Figure 7 a and b).



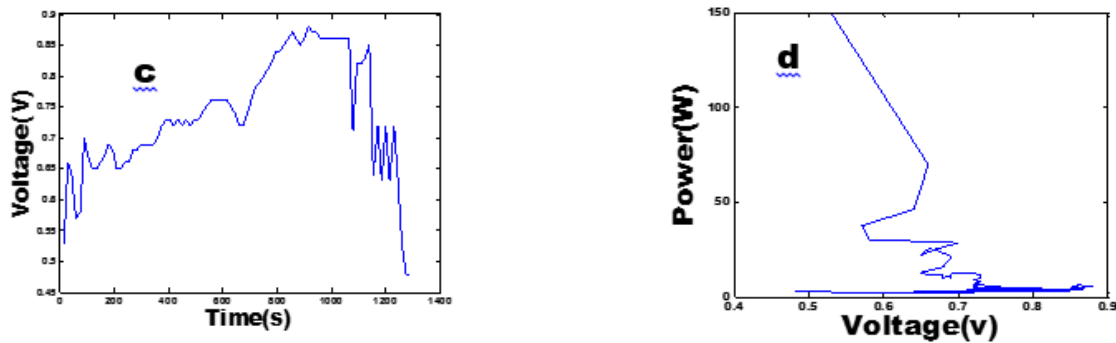


Fig. 6: a) Thermal analysis of Heat vs Time (6b) Thermal analysis of Temperature vs Time (6c) Thermal analysis of Voltage vs Time (6d) Thermal analysis of Power vs Voltage.

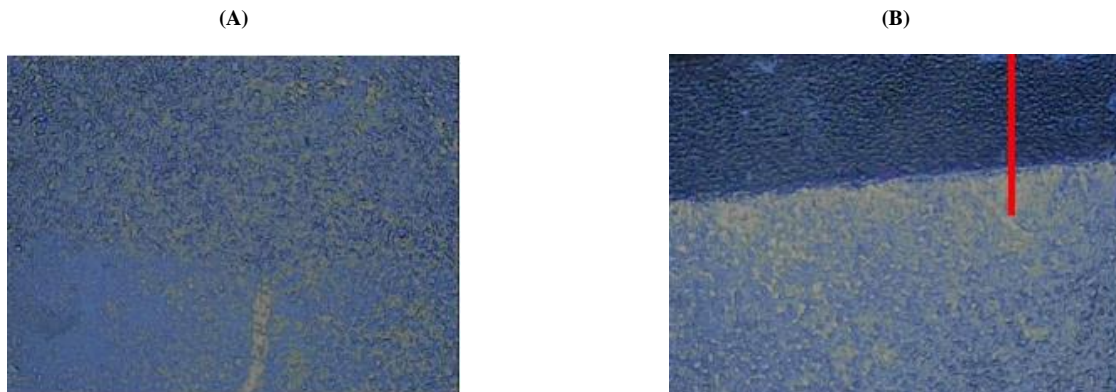


Fig. 7: A Before Heating the Heat Sink (7b): after Heating the Heat Sink.

The results from the image analyzer show a significant impact of temperature on the expansion of the natural faults on the heat sink 2 (red line in Figure 7b). From the initial results shown via the image analyzer, it can be inferred that thermal energy widens the fractures in the heat sink. Hence, the durability of the modern biomass cookstove is hinged on hybrid aluminium steel that are characterized by faults that enhance high functionality of the TEG. However, the main challenge was the uneven heating that ensued as a result of the biomass fuel consumption in fire. The power – voltage graph for the three heat sinks showed a unique feature which negates the usual features [23] and scientific interpretation [24].

4. Conclusion

Clean burning, efficient cook stoves drastically reduce the fuel usage and the harmful emissions. In this study, it was observed that clean burning may be characterized into even and uneven burning. Uneven burning leads to the destruction of the TEG. Hence, the durability of the biomass cookstove depends on the heat distribution of the heat sink and TEG. The heat sink fracture can be widen due to thermal energy. These observations could foster high production of energy if the TEG technology is improved to be more rugged. It was observed that locally available materials possessed high energy loss which led to the damage of several TEG and a low voltage to run the electric fan attached to the BC. Hence, the durability of the modern biomass cookstove is hinged on hybrid aluminium steel that naturally have faults that enhance high functionality of the TEG.

Using the aluminium hybrid steel, it was observed that the natural faults enhance the production of energy that could possibly be used to power-on the BC fan and rechargeable devices. Also, the cookstove design would dramatically improve the lives of rural dwellers as they spend less money on fuel and are exposed to lower concentrations of smoke. In the future, thermoelectric generation technology should be improved upon to foster its sustainability under uneven heating.

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