International Journal of Engineering Research and Technology. ISSN 0974-3154, Volume 15, Number 2 (2022), pp. 119-129
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Design, Development and Evaluation of a Modified Improved Charcoal Cookstove for Space Heat and Power Generation

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Abstract

Wood fuel has sustainably been the major source of energy for millennia but with burgeoning human population and diminishing of forest cover, this vital resource has been pushed to the verge of becoming unsustainable. Improved cookstoves can alleviate this but they have faced low adoption rate as people do not perceive unsustainable wood fuel utilization as a threat to forest cover. These stoves have insulation which prevents space heating during cold seasons and this impedes their adoption in cold regions. These stoves can be integrated with features preferred by users so as to spur their adoption. This study aimed at modifying an improved charcoal cookstove by incorporation of thermoelectric generators for power generation, and modifying the stove to perform space heating for comfort during cold seasons. A maximum electric power of 1.99 W was realized. The power averaged 1.09 W and 1.52 W when simulating cooking without performing space heating, and when simultaneously simulating cooking and performing space heating, respectively. The stove was able to raise the room temperature by 5.2 ºC compared to 2.6 ºC achieved by the unmodified stove. Incorporation of thermoelectric generators into improved cookstoves not only improves the value of the stoves, but also solves an equally challenging need of provision of clean lighting to rural households.

Key words: Improved cookstove, Consumer acceptance, Thermoelectric generators, Space heating

I. INTRODUCTION

Approximately 2.7 billion people which is equivalent to 40% of the world population rely on low efficiency traditional cookstoves for their cooking [1]. The low efficiency in traditional cookstoves leads to unsustainable utilization of scarce wood fuel resources leading to deforestation [2]. Improved cookstoves (ICS) can alleviate this as they exhibit higher efficiency and consume lesser fuel compared to traditional stoves. For example, the efficiency of the Kenya Ceramic Jiko (KCJ) lies between 30% and 40% compared to traditional stoves which lie between 5% and 15% [3,4]. In 2013, World Vision introduced ICS in Ethiopia and found that the stoves reduced fuelwood consumption by between 46.98% and 52.94%. Households' expense in purchase of fuelwood was minimized. The ICS fuel consumption in 6.5 days was equivalent to fuelwood consumed by traditional stoves in two days [5]. The use of improved cookstoves in different parts of Kenya reduces fuel collection frequency by half [6].

Adoption of improved cookstoves has been very low despite their fuel saving benefits. In 2010, 98.5% of households in Wundanyi, Mwatate and Voi districts of Kenya were aware of ICS but only 32% had adopted them [7]. Less than 27.3% of households in six municipalities of Ghana had improved cookstoves in 2015 [8]. Unless ICS are incorporated with features more valued by users even if the features are not related to alleviating health or environmental adverse impacts, it will be difficult for the stoves to be adopted and used in the long term [9]. This beckons for the stoves to be incorporated with features preferred by the users in order to spur their adoption.

The need for ICS is not likely to end soon. Approximately 780 million (85.2%) people in sub-sahara Africa use traditional biomass: fuelwood, charcoal and animal dung for their cooking and heating. More than 80% or 7.2 million households in Kenya depend on wood fuel or charcoal for their cooking [10]. This shows that a large number of people in Africa rely on biomass to meet their energy needs. Global electricity access rate stood at 87% in 2018 where as in Africa it was 43%. The access rate in rural Africa was 25% [11]. More than 500 million people in rural Africa use kerosene lamps and candle to light their homes [12]. The large number of people, mostly in rural Africa using biomass energy and without electricity present an opportunity to develop ICS capable of providing the two core energy streams.

Development of ICS has posed a challenge of residential space heating. These stoves are designed to minimize heat loss to the environment and thus they cannot substantially raise the ambient temperature in a rural kitchen. This impedes their adoption in rural households [13]. These stoves can be modified so as to perform residential space heating; a phenomenon which could improve their adoption rate. The modification should focus on retaining their energy conservation aspect so as not to do away with the core purpose of developing them. This means that the stoves should be modified in a way to only perform space heating during cold seasons.

Thermoelectric generators (TEGs) are regarded as green sources of energy as they utilize waste heat energy which could be dissipated to the environment and convert it to useful electrical energy [2]. For instance, they can convert waste heat from photovoltaic systems into electrical energy thus improving their efficiency [14,15]. They can also be incorporated into domestic cookstoves to improve efficiency and substantially reduce air pollution [16]. They can power a fan to increase air supply in the combustion chamber thereby increasing cooking temperatures and reducing emission of particulate matter. Excess electricity from TEGs can be used to power an LED lamp, radio, charge a mobile phone among other needs in a household [17]. Adoption of LED lamps would enable people access cleaner sources of lighting, and ditch kerosene lamps and candles which contribute to indoor air pollution and incur cost of purchasing kerosene [18]. TEGs can be integrated into cookstoves to convert waste heat into electric power, and improve the value of the cookstoves.

This study delved to integrate TEGs into an improved charcoal cookstove, and to modify the stove to perform space heating. This was deemed necessary to encourage adoption of improved cookstoves as the power from the TEGs would enable users to use LED lights to illuminate their kitchens. The TEG power would also enable them to charge their mobile phones at home and save the time and money they spend to charge the phones elsewhere. The modified cookstoves would also bring comfort during cold seasons by warming the fireplaces, a common practice in many African settings. Adoption of more improved cookstoves would translate to conservation of forests through sustainable utilization of wood fuel.

II. Theoretical background

Design of ICS traces back to 1950s where it started with technological attempts to improve the design of biomass powered cookstoves. In the 1970s during the oil crisis, ICS programs were considered as a solution to fuelwood crisis and were thought to curb deforestation and desertification. This marked the beginning of development of ICS. Several ICS programs were promoted in developing countries but failed as they didn't meet the needs of people. The people deemed unsustainable consumption of wood fuel was not a threat to their livelihood [9].

The performance of a new cookstove is determined by comparing with that of a reference stove using Eqs. 1 and 4 [19].

$$H = Q_{Sens} + Q_{Lat} \tag{1}$$

$$Q_{Sens} = m_w * c_w * \left(T_f - T_i\right) \tag{2}$$

$$Q_{Lat} = m_w * Lv_w \tag{3}$$

$$Heat\ difference\ (\%) = \frac{H_{New} - H_{Ref}}{H_{New}} * 100 \tag{4}$$

Where H is total heat liberated, Q_{Sens} is sensible heat, Q_{Lat} is latent heat, m_w is mass of water (kg), c_w is heat capacity of water (4.18 kJ/kg.°C), T_f is final temperature of water, T_i is initial temperature of water, Lv_w is latent heat of vaporization of water (2257 kJ/kg), H_{New} is total heat from the modified stove, and H_{Ref} is total heat from the improved stove.

TEGs are devices that employ the Seebeck effect to directly convert heat energy into electrical energy. They consist of a set of thermocouples which are connected thermally in parallel and electrically in series, and are sandwiched between two parallel ceramic plates. The two ceramic plates should be at different temperatures so as to generate power in accordance with Seebeck effect [20]. Seebeck effect occurs when thermal gradient along a conductor induces a voltage. The effect results from heat provoking motion of electrons and holes along the conductor hence generating electric power [21].

Equations governing rate of heat input and output in a thermocouple are obtained by energy balances between the hot and cold-sides.

$$Q_{In} = 2\alpha I T_h + \frac{2KA}{l}(\Delta T) - \frac{1}{2} I^2 \frac{2\rho l}{A} \tag{5}$$

$$Q_{Out} = 2\alpha I T_c + \frac{2KA}{l}(\Delta T) + \frac{1}{2} I^2 \frac{2\rho l}{A} \tag{6}$$

Where Q is rate of heat, α Seebeck coefficient, I electric current, T_h temperature of hot-side, K thermal conductivity, A cross-sectional area of thermo-elements, l length of thermo-elements, ΔT temperature difference between hot and cold-side, and ρ electrical resistance. The power produced per thermocouple is obtained by power balance between the hot-side and the cold-side, and this helps to model the TEG characteristics.

$$P = Q_{In} - Q_{Out} \tag{7}$$

$$P = 2(\alpha I \Delta T - I^2 \frac{\rho l}{A}) \tag{8}$$

Where P is the electric power. Factor 2 is used because thermal conductivity, electrical and Seebeck coefficient of both legs (n and p) are assumed to be the same [17]. The highest voltage (open circuit voltage) is produced when the TEG ends are open and is expressed in eq. 9.

$$V_{oc} = \left(\alpha_p - \alpha_n\right)(T_h - T_c) = 2\alpha\Delta T \tag{9}$$

Where V_{Oc} is open circuit voltage, α_p and α_n are Seebeck coefficients of p-type leg and n-type leg, respectively. The electrical current is expressed as:

$$I = \frac{V}{R} = \frac{\alpha A \Delta T}{\rho l (1 + \frac{R_l}{R})} \tag{10}$$

Where R_l is external load resistance and R is internal load resistance.

$$V_{mv}(Maximum\ voltage) = \frac{V_{oc}}{2} = \alpha\Delta T \tag{11}$$

$$I_{sc}\ (Shortcircuit\ current) = \frac{\alpha A \Delta T}{\rho l} \tag{12}$$

$$I_{mc}(Maximum\ current) = \frac{\alpha A \Delta T}{2\rho l} \tag{13}$$

Maximum power is obtained when the internal load resistance matches the external load resistance [17].

$$P_{max}(Maximum\ power) = \frac{\alpha^2 A \Delta T^2}{2\rho l} \tag{14}$$

The efficiency of a TEG is expressed as the ratio of electrical energy output to the heat energy input [22].

$$\eta = \frac{P_{Electrical\ output}}{Q_{Heat\ input}} \tag{15}$$

Where η is efficiency. The performance of a thermo-element is influenced by its figure of merit, *Z*, which is given by eq. 17 [17].

$$ZT = \frac{\alpha^2 T}{k\rho} = \frac{\alpha^2 T\sigma}{k} \tag{16}$$

$$Z = \frac{\alpha^2}{k\rho} = \frac{\alpha^2 \sigma}{k} \tag{17}$$

Where T and σ refer to absolute temperature and electrical conductivity, respectively. Thermal conductance (K) and electrical resistance (R) of a TEG are expressed in eqs. 18 and 19 [23].

$$K = k_p \frac{A_p}{l_p} + k_n \frac{A_n}{l_n} \tag{18}$$

$$R = \rho_p \frac{l_p}{A_p} + \rho_n \frac{l_n}{A_n} \tag{19}$$

Where k_p is thermal conductivity of p-type leg, A_p cross-sectional area of p-type thermoelement, l_p length of p-type leg, k_n thermal conductivity n-type leg, A_n cross-sectional area of n-type leg, l_n length of n-type thermoelement, ρ_p electrical resistivity of p-type thermoelement and ρ_n electrical resistivity of n-type leg.

The efficiency of a TEG is limited by the Carnot efficiency like all heat engines. Increase in temperature gradient results in increase in efficiency. The efficiency is estimated by eq. 20. If the *Z* is infinite, then the efficiency will be equal to the Carnot efficiency [24].

$$\eta_{max} = 1 - \frac{T_c}{T_h} . \frac{\sqrt{1 - z\bar{T}} - 1}{\sqrt{1 + z\bar{T}} + \frac{T_c}{T_h}} \tag{20}$$

Where η_{max} is maximum efficiency and $\bar{T}$ is average temperature between hot and cold-sides. In order to obtain a maximum figure of merit, the semiconductor legs geometry design should fulfill eq. 21 [20].

$$\frac{k_n}{\rho_p \rho_n \, k_p} = \frac{l_n^2 \, A_p^2}{l_p^2 \, A_n^2} \tag{21}$$

So as to minimize manufacturing costs, the semiconductor thermo-elements are made of doped alloys in order to exhibit similar thermoelectric properties, thus, $\alpha_p = -\alpha_n$, $\rho_n = \rho_p$ and $k_n = k_p$. They are also manufactured with similar geometry where: $l_n = l_p$ and $A_p = A_n$ [20]. The performance of a TEG can be improved by increasing the magnitude of Seebeck coefficient, increasing electrical conductivity of thermo-elements and reducing their thermal conductivity [25]. The efficiency is directly proportional to temperature gradient between the hot and cold-sides and can be improved by lowering cold-side temperature by use of a heat sink. Forced water convection is the best heat sink, followed by forced air convection, natural water convection and natural air convection [17].

TEGs could be incorporated into cookstoves to convert waste heat into useful electric power. Some researchers have attempted to explore ways of integrating TEGs into different kinds of cookstoves with intent to either improve efficiency or provide some electric power for basic household use. Mahdi et al. (2018) investigated integrating kerosene-fueled stove used for space heating with three TEGs of 40 mm by 40 mm. The TEGs were intended to utilize waste heat from the stove to generate electricity. The cold-sides of the TEGs were cooled by a thirty-litre water storage tank. They achieved a maximum temperature gradient of 205 ºC where the hot-side was at a temperature of 250 ºC. The average electric power generated by the TEGs was 12.2 W and the maximum never exceeded 19 W. The power was considered enough to light an LED lamp and charge a mobile device.

Champier et al. [26] investigated the feasibility of integrating four TEG modules into an improved biomass fired stove. They achieved cold side temperature of 65 ºC with water as a heat sink and 117 ºC with a cooling fan. The electric power generated at a temperature difference of 160 ºC was 7 W, enough to power a small fan, light a small LED lamp and charge a battery. They stated that even if the TEG conversion efficiency is low, the fan increases air supply in the combustion chamber leading to efficient use of fuel and cleaner burning. They concluded that water heat exchangers are better than air heat exchangers as the temperature of water never exceeds 100 ºC in atmospheric pressure.

Zheng et al. [27] tested the performance of a TEG integrated into a stove used for space heating. They used a fan which consumed 3.18 W to cool the cold-side of the TEG. They achieved a maximum electric power of 14.79 W at a temperature gradient of 148 ºC. The average power was of 11.43 W.

O'shaughnessy et al. [28] retrofitted a TEG into Chiteteze Mbaula cookstove (ICS used in Malawi) and tested its ability to generate electricity and store enough for evening lighting and phone charging in Balaka district of Malawi. They modified the side walls of the stove to accommodate a TEG of 40 mm by 40 mm. The TEG was clamped between two 50 mm by 50 mm copper plates each of 3 mm thick. Holes were drilled into the plates to accommodate thermocouples. The copper plate on the hot-side was attached to another copper plate welded with three copper rods of 8 mm diameter. The rods protruded into the Centre of the cookstove to deliver heat to the TEG through conduction. The TEG also received some heat by radiation from fire. They stored the power generated in a 3.3 V lithium-iron phosphate battery. The cold-side of the TEG was cooled by a fan rated 2 W. They obtained a maximum electric power of 5.9 W and stored about 3 Wh in their battery during one-hour long burn. They concluded that a three-hour long cooking period could generate electrical energy of 9 Wh and 8 Wh would be stored in a battery. This energy was considered enough to charge a mobile phone, light an LED lamp and power a radio on a daily basis.

Montecuccu et al. [29] tested the feasibility of TEGs integrated into a solid-fuel stove to charge lead-acid battery rated 12 V and 12 Ah. The cold-sides of the TEGs were cooled by water which was intended for household use after gaining heat. They used four TEGs of 40 mm by 40 mm and attached them on an aluminum heat exchanger. The heat exchanger was placed atop the stove and had fins protruding into interior of the stove to improve heat capture. They used Maximum Power Point Tracking (MPPT) converter to charge the battery. The system generated a maximum electrical power of over 40 W at a temperature gradient of 250 ºC. The average electrical power was 27 W over a period of one hour.

Other researchers have attempted to find ways of performing space heating using biomass. For instance, Molefe and Simate investigated the capability of poultry litter to serve as fuel in performing space heating. They achieved a room temperature rise of 4.2 ºC in relation to ambient temperature at a distance of 90 cm from the stove [30].

Preceding researches have showed that TEGs incorporated into cookstoves can generate electric power to at least light an LED lamp. Several research studies have been conducted on designing improved charcoal cookstoves to conserve energy, but apparently none has ever delved to modify the stoves to be able to perform space heating to bring comfort during cold seasons and test their convenience for generating electricity. Developing an ICS capable of performing space heating and generating electricity could encourage adoption of the stoves and this could aid in curbing deforestation and perhaps reverse the ecological foot print.

III. METHODOLOGY

III.I. Stove design and fabrication

In this study, two improved charcoal cookstoves were redesigned by retrofitting them with TEGs for power generation, and one of the stoves fitted with a perforated rolled steel sheet to enhance the stove's space heating capability. The TEGs on either stove were respectively fitted with thermal silicone paste and thermal graphite sheets as thermal interface materials (TIMs).

The stoves were designed on freeCAD platform. The dimensions of the stoves were based on the standard size KCJ. The modified stove was designed illustrating the position of the TEGs. The perforated rolled 19 gauge steel sheet for enhancing space heating was then designed. The rolled steel sheet with perforation was to be placed atop the modified stove to test the performance of the stove in space heating.

Three identical KCJ cookstoves were sourced from local suppliers. Two of the stoves were modified and the other used as a reference during performance test. Fabrication of the modified charcoal cookstoves started with drawing the outlines of the stoves' walls to be removed in order to allow integration of the TEGs. Parts of walls of the stoves, which consisted of ceramic liner and a steel sheet, were removed guided by the drawn outlines. The removal left a gap of 130 mm in length and a height of 50 mm on each stove. Removal of the ceramic liners allowed heat liberated during fuel combustion to reach the hot-side of the TEGs as the ceramic liner serves as a thermal insulator. For the one stove, three TEGs were attached to a steel sheet of 19-gauge measuring 140 mm by 55 mm using a silicone thermal paste as TIM. Another set of three TEGs were attached to a similar steel sheet, but with a re-used thermal graphite sheet as TIM. The cold-sides of the TEGs were attached to finned aluminum heat sinks of 40 mm x 40 mm. The steel sheets were then to be fitted in the gaps left after removing the walls of the stoves with an overlap of 5 mm on either side.

The TEGs and the steel sheets were first thoroughly cleaned to remove dirt which could hinder heat transfer. Thermal silicone paste was then applied on the hot-sides of three TEGs and spread into a very thin layer to enhance its thermal conduction. The TEGs were then firmly attached to the steel sheets to remove any air gaps as air exhibits poor thermal conductivity. Thermal silicone paste was then applied on cold-side of the TEGs, spread into a very thin layer and three finned aluminum heat sinks firmly attached to them. The heat sinks, TEGs and the steel sheet were then tightly clamped together using annealed steel wires of 1 mm in diameter to maintain equal pressure throughout the experiment. The steel sheet with the TEGs and the heat sinks was welded onto the open slot on the stove wall. For the thermal graphite, the same process was repeated for the second stove. Charcoal was then burnt in the stove till it got exhausted. This ensured that the graphite sheet was used. The welded steel sheet was then removed and the graphite sheet retrieved. The re-used thermal graphite sheet was then firmly attached to the hot-sides and cold-sides of another set of three TEGs. The hot-sides of the TEGs were attached to a similar 19 gauge steel sheet as with silicone paste, and the cold-sides to aluminum heat sinks as well. The assembly was firmly wrapped together with annealed steel wire, and welded to the second stove in a similar manner to the first case.

To enhance ability of the stove to offer better space heating, a rolled steel sheet with perforations was fabricated from rectangular 19 gauge mild steel sheet measuring 753 mm by 60 mm. Perforation holes of 10 mm in diameter and spaced at a distance of 30 mm were made on the steel sheet before rolling it. The rolled steel sheet measured 240 mm in diameter and a height of 60 mm. The rolled steel sheet was to be placed atop the stove having thermal silicone paste as TIM when performing space heating.

III.II. Performance evaluation procedures

A comparative performance test of the modified stoves having thermal silicone paste and reused thermal graphite sheet as TIMs was conducted against a similar reference unmodified stove. The TEGs in each stove were connected together in series. A shunt resistor of 15 Ohms (Ω) was connected in series with the TEGs to aid in recording the output current as a voltage signal on a data logger. A thermocouple was attached on the metal sheet between the first and the second TEG to record hot-side temperature of the TEGs in each stove. Another thermocouple was attached at the interface between the middle TEG and the aluminum heat sink to record the cold-side temperature of the TEGs. The thermocouples were then connected to the data logger.

For water-cooled experiments, cotton wool was attached to the finned aluminum heat sinks and pushed into the fins. The wool was spread to cover the heat sinks. Metal strips were used to hold the wool in place. Water weighing 0.7 litters was poured onto the cotton wool to help in lowering the cold-side temperature of the heat sinks in order to increase temperature gradient across the TEGs. Additional thermocouples were inserted in the cooking pots to record water temperature during the tests and also connected to the data logger. The thermocouples were held on brims of the pots using battery clips in order to ensure they were suspended around 2 cm from the bottom of the pots. This prevented them from recording wrong water temperatures. The data logger was set to record data at two seconds intervals.

Test on space heating was performed in a room measuring 2.7 m by 3.6 m. A thread was tied horizontally across the room and above the stove at a height of 1.25 m to hold the thermocouples in place. Four thermocouples were attached on the thread at distances of 0.3 m, 0.5 m, 1 m and 1.5 m away from the edge of the cookstove being tested. The thermocouple distances were randomly chosen to assess change in room temperature at different distances but informed by typical kitchen dimensions. All the four thermocouples were connected to the data logger to record change in the room temperature as the fuel in the cookstove burnt up. When testing capability of the modified stove to perform space heating, the perforated steel sheet was placed on top of the stove having thermal silicone paste as TIM. This study employed Adapted Water Boiling Test (AWBT) in judging performance of the modified charcoal cookstove. The method was chosen as it is simple, is less prone to errors, takes into account local cooking methods, and it is accessible to local organizations unlike the recommended international Water Boiling Test Method. The AWBT recommends the test to be repeated three times for more accurate results [19].

In the first experiment, the modified stove with silicone paste as TIM was tested first against the reference stove. Gel fire starter of 78 g was weighed and spread uniformly in the grate of each stove. Charcoal of 580 g was weighed and also put in the grate of each stove. Two pots of water of 1200 g each were weighed and put aside. The fire starter was lit and when the charcoal began burning, the pots with water were put on the stoves and the data logger turned on to record data. The experiment was terminated when the water temperature dropped below 3 °C as recommended in the AWBT [19]. Water remaining in the pots was weighed and recorded. The experiment was repeated thrice. The other stove with reused thermal graphite sheet as TIM was also tested against the reference stove using the same experiment.

During space heating experiment, the stove having thermal silicone paste as TIM was tested against the reference stove. Each stove was tested independently to assess its capability in raising the room temperature. The stove with thermal silicone paste was tested first. Weighing of the fire starter, charcoal and water was done as stated previously. The fire starter was spread in the grate of the stove and charcoal added. The fire starter was lit and the rolled steel sheet put atop the stove. When the charcoal started burning, the pot with water was put on the stove. The data logger was turned on to record the data. The room was closed to minimize heat loss to the outside environment. The experiment was repeated thrice. Test on the reference stove was conducted using the same procedure, but without the rolled steel sheet atop.

III.III. Experimental setup

The experimental rig was set up on a bench. Fig. 1 shows the block diagram of the experimental system. Both stoves (labeled B and C) are placed two meters apart, and the data logger (labeled F) placed in the middle. Two identical pots (each labeled A) with water are placed on each stove. The TEGs are labeled D. The shunt resistor is labeled E. Thermocouples to record TEG hot-side and cold-side temperatures are labeled G and H, respectively. I and J are sensors to record TEG voltage and current, respectively. Thermocouples to record water temperatures are labeled K. Fig. 2 shows the experimental set up to test capability of the modified stove to heat water while generating power.

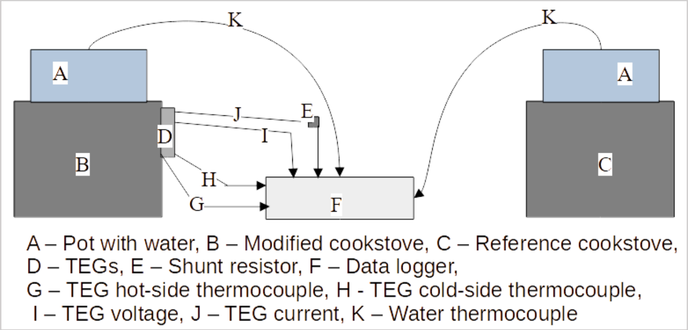

Figure 1: Schematic of the experimental system

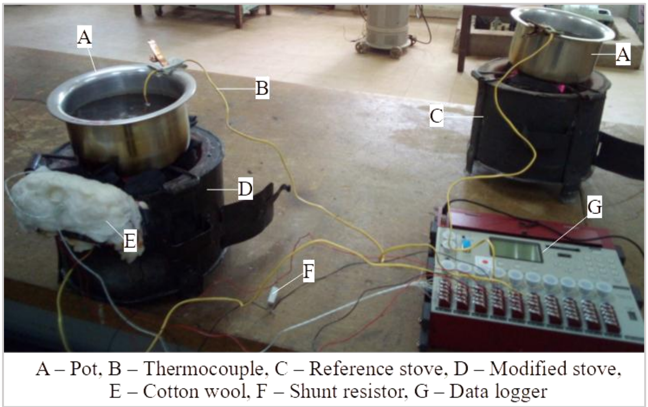

Figure 2: Experimental setup to test capability of the modified stove to heat water while generating power

The experimental setup to test performance of the modified stove having thermal silicone paste as TIM simulated its real life application in cooking while generating power, and simultaneously cooking and performing space heating while generating electric power for basic rural household use.

III.IV. Study materials and equipment

Thermal silicone paste with an operating temperature range of -60°C and 200 °C, and thermal conductivity of 0.671 W/mK was used as a TIM for one stove. Thermal graphite sheet with a thermal conductivity of 700 W/mK and temperature resistance of between -50°C to 400 °C was used as a TIM for the other stove. Its thickness was of 0.07mm. The study used nine TEP1-142T300 TEGs of 40 mm x 40 mm, selected based on the criterion that they can withstand a high temperature of 300 °C and can generate electric power of up to 3.9 W at temperature gradient of 100 °C which was enough for the study. Nine finned aluminum heat sinks of 40 mm x 40 mm and a height of 20 mm were also used in this study. Fig. 3 shows the materials used in TEG integration.

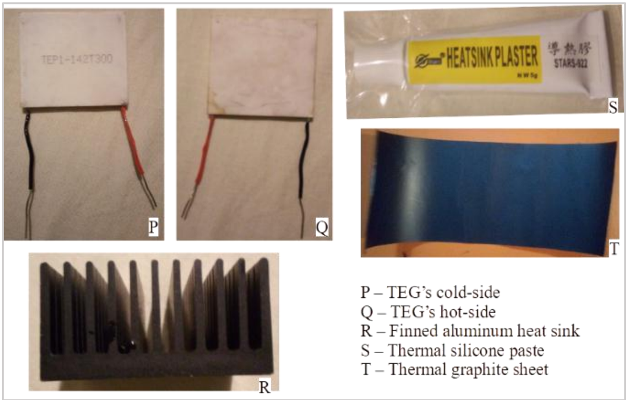

Figure 3: TEGs, finned aluminum heat sink, thermal silicone paste and thermal graphite sheet used in fabricating the modified charcoal cookstoves

The study used a 9-channel TDS-150 data logger which could record data at short intervals of 2 s. A digital weighing scale of maximum 3 kg and an accuracy of 0.02 g was used to weigh charcoal, fuel gel, pot and water samples. K-type thermocouples bearing a wide range of temperatures of 270 °C and 1260 °C with a standard accuracy of +/- 2.2 °C or +/- 75% were used for the measurement of temperatures.

IV. RESULTS AND DISCUSSION

IV.I. Stove design and fabrication

The design of the modified improved cookstove accommodated both the TEGs and the perforation for space heating, as shown in Fig. 4.

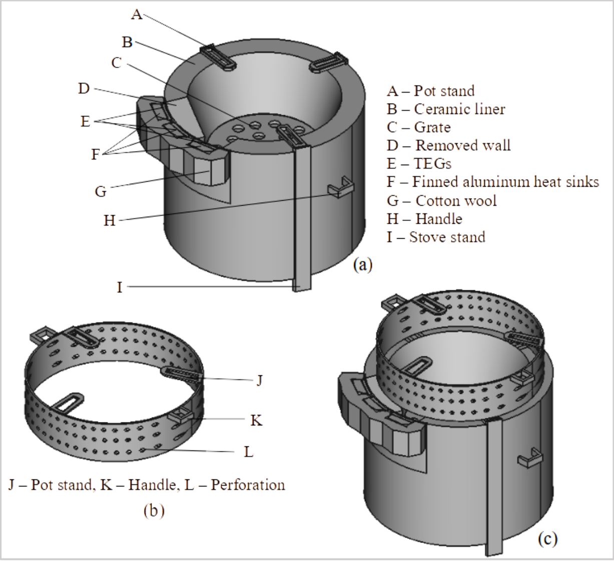

Figure 4: The modified KCJ cookstove, (a) provision for the TEG, (b) perforated rolled metal sheet, and (c) modified stove with TEG and perforated rolled metal sheet atop (illustration of the modified stove during space heating)

Fig. 5a shows the three sourced cookstoves from the local suppliers while 5b and 5c show the stoves after TEG incorporation. Fig. 5d shows the perforated rolled steel sheet for enhancing space heating.

Figure 5: (a) KCJ cookstoves before modifications, (b) cookstove with thermal silicone paste as TIM, (c) cookstove with re-used thermal graphite sheet as TIM, (d) Perforated rolled steel sheet, and (e) Modified KCJ and perforated rolled metal sheet for facilitating space heating atop

IV.II. Performance evaluation

The experimental data on power generation, water heating and indoor space heating was obtained, collated and analyzed. The electric power generated by the TEGs using the two TIMs was compared. Results on the TEG power generation, rise in room temperature and impact on cooking performance of the new stove were analyzed to establish its suitability.

IV.II.I. TEG power generation under two TIMs with natural air convection as heat sink

Table 1 summarizes the temperature gradient achieved and power generated when the cold-side was cooled by natural air convection for the two TIMs.

Table 1. Temperature gradient and generated electrical power for thermal silicone paste and re-used thermal graphite sheet under natural air convection

	Silicone paste	Re-used graphite sheet
Maximum temperature gradient (°C)	29.7	15.0
Average temperature gradient (°C)	21.0	8.7
Standard deviation of temperature gradient (°C)	8.3	2.3
Maximum voltage (V)	1.23	1.06
Average voltage (V)	0.80	0.72
Standard deviation of voltage (V)	0.28	0.23
Maximum current (A)	0.08	0.07
Average current (A)	0.05	0.05
Standard deviation of current (A)	0.02	0.02
Maximum power (W)	0.10	0.08
Average power (W)	0.05	0.04
Standard deviation of power (W)	0.03	0.02

When the finned aluminum heat sinks were cooled by natural air convection, the maximum power generated was 0.10 W. From Table 1, the stove reusing thermal graphite sheet as a TIM showed a lower power output compared to the one using thermal silicone paste. Its power generation averaged 0.04 W while the other using silicone paste averaged 0.05 W. This could be attributed to better thermal conductivity of thermal silicone paste compared to re-used thermal graphite sheet. This could have arisen from the thermal graphite sheet getting dirt and wriggling when transferring to new TEGs. Fig. 6 shows the variation in the power generated with time when testing capability of the stove in heating water without performing space heating

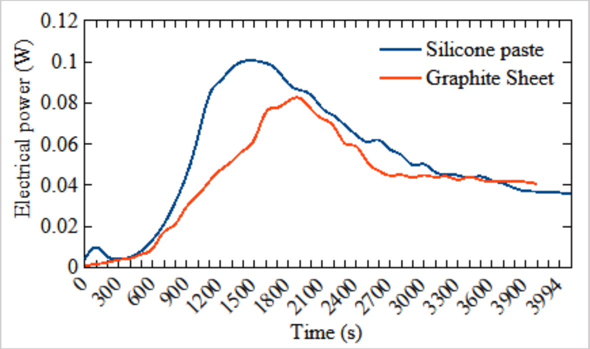

Figure 6: Variation in power generated with time when heating water without performing space heating

From Fig. 6, the power generated from both stoves rose to a maximum value as the experiment progresses and then dropped gradually up to the termination of the experiment. This is attributed to the combustion of charcoal releasing heat up to a maximum value and then the heat released reducing due to exhaustion of the charcoal up to termination of the experiment.

Other studies have tested natural air convection as heat sink. Lertsatitthanakorn [31] achieved a maximum power of 2.4 W at a temperature difference of 150 °C. He used the wall of the stove to attach the hot-side of the TEGs and a rectangular fin as heat sink. Nuwayhid et al. [32] used flower fins heat sink and aluminum plate on hot-side of the TEG. They generated power of 4.2 W when the cold-side was at 123 °C and the hot-side at 275 °C. Those studies show that natural air convection can serve as heat sink to generated power for lighting 1 W LED lamp and charge a mobile phone, even though such high yields were not realized in this study. Failure to realize this may have been attributed to using rectangular pin-type heat sink instead of flower fins heat sink, and a steel sheet as hot-side plate instead of aluminum sheet. Flower fins heat sink performs better than pin-type fin heat sink [2]. Using annealed steel wires to clamp TEGs instead of bolts could have led to slightly lower pressure and this could have also contributed to the low power output.

IV.II.II. TEG power generation under the two TIMs with cotton wool soaked in water as heat sink

Table 2 summarizes the power generated and temperature gradient achieved under water-cooled conditions. Fig. 7 shows the variation in power generated with time when cotton wool soaked in water serves as heat sink.

When the cold-sides of the TEGs were cooled by cotton wool soaked in water, a maximum power of 1.99 W was generated. This was realized from the stove using thermal silicone paste as TIM, and when simultaneously heating water and performing space heating. As shown in Fig. 7, the power output was low in the initial stages of the experiment. The power increased up to a maximum value as the experiment progressed and then dropped gradually until the termination of the experiment. The stove having thermal silicone paste as TIM maintained higher power output throughout the experiment compared to the stove having re-used thermal graphite sheet as TIM. The average temperature gradient lied between 35.7 °C and 47.5 °C for re-used thermal graphite sheet and silicone paste TIMs, respectively.

The stove having thermal silicone paste as TIM achieved an average power of 1.09 W compared to power of 0.30 W from the stove reusing thermal graphite sheet as TIM, when heating water without performing space heating. When simultaneously heating water and performing space heating, the stove having thermal silicone paste as TIM achieved an average power output of 1.52 W compared to average power of 0.50 W from the stove with re-used thermal graphite sheet as TIM. This is attributed to better performance of the thermal silicone paste as a TIM compared to re-used thermal graphite sheet. The reason for generating more power when simultaneously heating water and performing space heating than when heating water without performing space heating could be due to the perforated rolled steel sheet increasing air supply in the combustion chamber as ample air supply improves combustion thus liberating more heat [33].

Table 2. Temperature gradient and the generated electric power for thermal silicone paste and re-used thermal graphite sheet as TIMs, under water-soaked cotton wool. Letters A and B denote performance when heating water without performing space heating, and when simultaneously heating water and performing space heating, respectively

	Silicone paste		Re-used graphite sheet	
	A	B	A	B
Maximum temperature gradient (°C)	57.2	62.9	70.1	84.3
Average temperature gradient (°C)	43.7	47.5	45.5	35.7
Standard deviation of temperature gradient (°C)	11.6	12.0	10.9	11.1
Maximum voltage (V)	4.68	5.46	2.56	3.32
Average voltage (V)	3.96	4.71	2.09	2.71
Standard deviation of voltage (V)	0.83	0.81	0.33	0.45
Maximum current (A)	0.31	0.36	0.17	0.22
Average current (A)	0.26	0.31	0.14	0.18
Standard deviation of current (A)	0.06	0.05	0.02	0.03
Maximum power (W)	1.46	1.99	0.43	0.73
Average power (W)	1.09	1.52	0.30	0.50
Standard deviation of power (W)	0.38	0.43	0.08	0.14

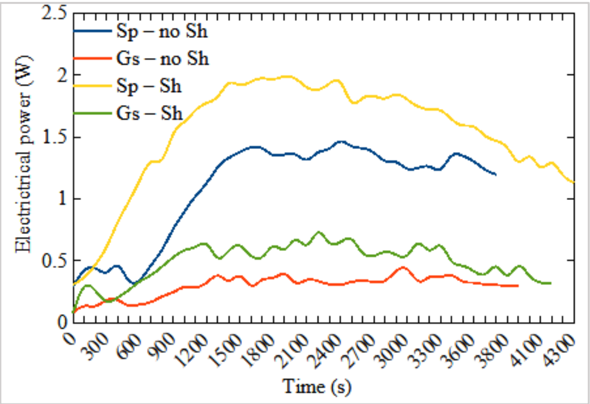

Figure 7: Variation in power generated with time when cotton wool soaked in water serves as heat sink. Sp – no Sh and Gs – no Sh denote the stove with silicone paste and the stove with graphite sheet without performing space heating, respectively. Sp – Sh and Gs - Sh denote the stove with silicone paste and the stove with reused thermal graphite sheet when performing space heating, respectively

During the tests, cold-side temperature of the TEGs ranged between 96.1 °C and 99 °C. This shows that firmly covering the finned aluminum heat sink with cotton wool soaked in water provides a good heat sink as it was observed that the cold-side temperature did not exceed 100 °C [26].

It is also observed that the power generated is not commensurate with temperature gradient. For instance, the average temperature gradient of the stove having graphite sheet as TIM is 35.7 °C corresponding to average power of 0.73 W when simultaneously heating water and performing space heating, while the average temperature gradient of the same stove is 45.5 °C corresponding to average power of 0.43 W when heating water without performing space heating, for the water-cooled experiment. This could be attributed to uneven heat distribution on hot-side of the TEGs. Unburnt charcoal blocks heat from reaching the TEGs and thus some sides of the TEGs will receive lower amounts of heat compared to the others. The thermocouple on hot-side of the TEGs recorded high temperatures if it was not blocked by unburnt coals and recorded low temperature if it was blocked.

Other studies have used vaporizing water to lower the cold-side temperature of TEGs. Nuwayhid and Hamade [34] used thermosyphonic heat pipe as heat sink and achieved power of 3.4 W. The cold-side temperature was at 130 °C while the hot-side at 215 °C. The cold-side temperature in this study was below 100 °C. This shows that cotton wool soaked in water is a better heat sink compared to heat pipes. This could be due to lack of pressure build up which causes water temperature in heat pipes to increase.

From the study, using cotton wool soaked in water as a heat sink substantially increased the generated power compared to using natural air convection as a heat sink. For instance, the stove having thermal silicone paste as TIM generated average power of 0.05 W when using natural air convection as heat sink, and power of 1.09

W when using water soaked in cotton wool as heat sink without space heating.

Table 3 summarizes the useful heat energy generated by the stoves to heat water. It compares the performance between the reference stove, and the modified stove having thermal silicone paste as TIM.

Table 3. Useful heat generated and stoves performance comparison. Letters A and B denote performance when heating water without performing space heating, and when simultaneously heating water and performing space heating, respectively

	Stove	Evaporated water (kg)	Temperature difference (°C)	Total heat (Latent+Sensible) (kJ)	Heat difference (kJ)	Heat difference (%)
Test A	Reference	0.8084	72.33	2187.458	3.419	0.156
	Modified	0.8098	72.40	2190.877		
Test B	Reference	0.8370	73.37	2257.191	125.239	5.257
	Modified	0.8916	73.77	2382.430		

Fig. 8 show variation in water temperature with time. Fig. 8 (a) shows when heating water without performing space heating, and Fig. 8 (b) when simultaneously heating water and performing space heating.

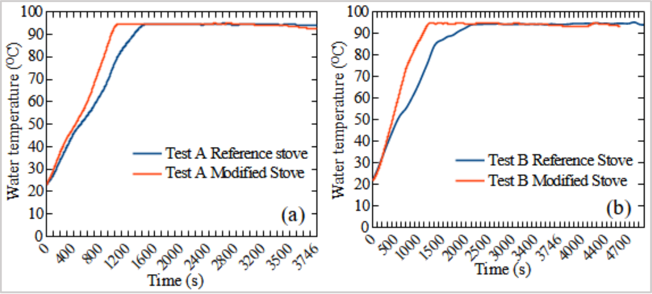

Figure 8: Variation in water temperature with time. (a) when heating water without performing space heating, and (b) when simultaneously heating water and performing space heating

The performance of the stoves was evaluated using Eqs. 1 and 4. When comparing the performance in heating water without space heating, the study showed an increased performance of 0.2%. Test on simultaneous heating of water and space heating showed increased performance of 5.3%.

Table 3 and Fig. 8 indicate that modifying an improved charcoal cookstove to cook while generating electric power, and to generate power while simultaneously cooking and performing space heating has no significant impact on its performance. This is because the difference did not exceed 10% which is recommended in the Adopted Water Boiling Test method [19]. The modified stove showed improved performance particularly when simultaneously heating water and performing space heating. This is attributed to improved air supply in the combustion chamber as ample air supply improves combustion thus liberating more heat [33]. Fig. 8 shows that the modified stove took twenty-two minutes to reach boiling point when heating water without performing space heating and twenty minutes when simultaneously heating water and performing space heating. From Figs. 8 (a) and 8 (b), water temperature of the reference stove lagged behind the water temperature of the modified stove. This shows that the modified stove liberated more heat than the reference stove. The water temperature in both stoves plateaus after reaching the boiling point, as latent heat of vaporization is absorbed for phase change from liquid to gaseous state.

IV.II.III. Room temperature distribution

Fig. 9 compares the room temperature rise recorded by the thermocouples at distances of 0.3 m, 0.5 m, 1 m and 1.5 m, respectively between the stoves.

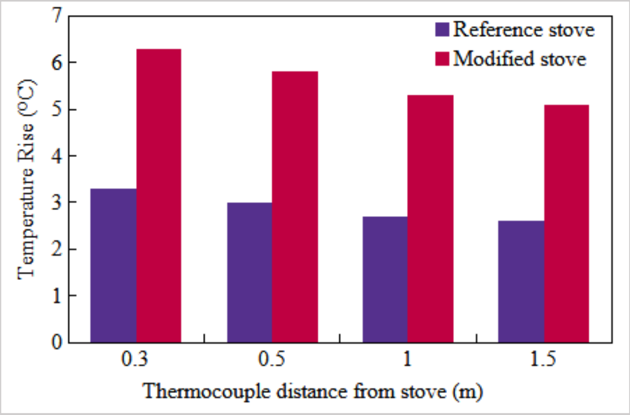

Figure 9: Rise in room temperature when comparing the capability of the stoves in space heating

Results from the three experiments conducted to test the performance of the stoves in raising room temperature were used to calculate the average room temperature rise. The modified stove recorded temperature rise of 6.3 °C, 5.8 °C, 5.3 °C and 5.1 °C at distances of 0.3 m, 0.5 m, 1 m and 1.5 m, respectively. The reference stove recorded temperature rise of 3.3 °C 3 °C, 2.7 °C and 2.6 °C at the same distances, respectively.

Fig. 9 shows that the perforated rolled steel sheet enhanced the ability of the stove to perform space heating. This is because the room temperature rise resulting from the modified stove was higher compared to the reference stove, in all cases. In the findings of a previous study, Dida et al. [35] reported that the average size of kitchens in rural western Kenya was 5.6 m^2. This size is within the radius of 1.5 m. This implies that the stove would dissipate sufficient thermal energy to provide warmth in kitchens during cold seasons. In a normal living room, it is expected that the modified stove would raise the ambient temperature more than the reference stove. This modification may significantly increase acceptance of the modified improved cookstove by users.

V. CONCLUSION

From the experiments conducted, the study established that it is possible to integrate TEGs into an improved charcoal cookstove to generate electric power to meet basic rural household needs of charging a mobile phone, powering a small radio and lighting an LED lamp in a normal cooking duration without significant impact on its efficiency. This is because the average power generated of 1.09 W and 1.52 W for the two experiments is considered enough to charge a mobile phone, power a small radio and light an LED lamp with the help of a DC – DC converter to stabilize the voltage. The study also found out that modifying the improved cookstove by addition of a rolled perforated metal sheet can raise the room temperature of a kitchen especially during cold seasons without significantly negating its ability to cook. These added features are deemed to endear the modified stoves to users thus improving their uptake.

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