Performance Optimization of Biomass-Fuelled Thermoelectric Cookstoves for Off-Grid Rural Electrification

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Abstract

With the growing need for clean, decentralised fuels of energy in remote and areas prone to disasters, new forms of biomass fuelled thermoelectric technologies have been expanded. A portable thermoelectric cookstove capable of generating electricity from biomass combustion is designed, developed, and optimized in this paper. Thermoelectric generators (TEGs), heat sinks and insulation are combined into the stove to improve thermal efficiency and power output. The system was subject to Key performance tests such as Water Boiling Test (WBT), Temperature Duration Test (TDT), and Power Output Test (POT) under different configurations and environmental conditions. Thermal dissipation and voltage consistency were superior for four heat sink geometries tested (vertical fins, pin-type, flower-type, and extended flower-type) and vertical fin results were obtained. A continuous 3 V–7 V DC was produced by the optimized cookstove to power 6 LED lights at once or communications devices including 'walkie-talkies'. The efficiency was greatly improved by the integration of a latent heat storage using phase change material (PCM) and thermal insulation using glass wool. The design is suitable for rural electrification in areas of the world exposed to natural disasters and with no dependable grid infrastructure.

1. Introduction

Due to the push for global energy equity and sustainability, devices for decentralized, low cost, environmentally friendly energy generation are greatly desired. It is usually the case that rural and disaster-prone areas lack access to reliable electricity leaving few options to integrate daily energy use with power generation. One such innovation in integrating traditional cooking with demand for modern power is biomass fired thermoelectric cookstove.

The See beck effect is used to use heat energy from combustion of biomass to produce electricity in a thermoelectric cookstove. The See beck effect is that of the generation of voltage across two dissimilar conductors or semiconductors when a temperature gradient is provided. This effect is tapped by optimised thermoelectric generators, one side of which is insulated to maintain a temperature differential between its hot side and its cooling side (which is in turn incarcerated to protect against loss) [1-6].

Biomass stoves are ubiquitous for cooking in traditional settings where they are found in rural areas. Yet, an energy inefficient characteristic and waste heat producers lie in these stoves. Because this unused heat represents a resource loss and because poor people face indoor air pollution, this heat is not only wasted, but it is also a risk to health. Thermoelectric cookstove proposed addresses both problems by converting wasted heat to electricity and improving fuel combustion efficiency and cut down environmental impacts. The concept of this work derived from the fact that a good deal of heat energy (in particular, that released during cooking with charcoal, coconut shells, wood, and honeycomb briquettes) is wasted. The thrust of this study is to recover and convert that heat into electricity to power such things as mobile devices, small LED lights or drive basic electronics that are required to sustain off grid communities [7-9].

Additionally, phase change materials (PCMs) are incorporated for the storage and delayed thermal dissipation of heat, prolonging of power output following extinction of the flame. In addition to reducing convective heat losses it further improves the cookstove's energy efficiency. Material selection, temperature thresholds as well as expected output power were used to determine the basis for the integration of the TEG modules into the stove. At medium temperature (up to 330–400 °C) range, Bi2Te3 based thermoelectric modules were selected with high performance. The system is intended to be small, lighter, simpler and more easily transportable systems as they are for outdoor fans, emergency response teams, and rural households [10-14]. In addition, the cold side of the TEGs were experimentally tested for different heat sink configurations to optimize the heat sink configuration. In the real world, vertical fins, pin-type fins and flower-type fins were all studied for heat dissipation as it is very important due to heat transfer. The objective was to find an optimal design for long term life without active cooling systems [12-16]. In this work, a thermoelectric biomass stove prototype is explored from a thermodynamic perspective in regard to its performance, energy generation potential, and real-world usability. This discusses the technical considerations in material selection, stove construction, and thermal optimization; however, electrical performance assessment is not discussed. Above all, the device is intended to combat energy poverty but it also reaches its potential as a scalable, environmentally friendly means to supply basic electricity needs.

2. Methodology

2.1 System Design and Architecture

In this study, we further developed the thermoelectric cookstove system that consists of a very carefully designed collection and set of synergistically integrated components (shedding light on some of what can be achieved), each critical to the energy conversion efficiency and overall system functionality in off grid or resource constrained environments.

The system is heart-based, as the combustion chamber is cylindrical design, of mild steel (MS) for structural integrity and high thermal conductivity. Dual function of ceramic block as retaining heat during combustion and reflecting and concentrating the heat towards the stove walls where thermoelectric modules are mounted in the inner lining.

Bismuth telluride (Bi_2Te_3) based thermoelectric modules are based on a material, which has a good thermoelectric performance at moderate temperature ranges. They are there in these modules installed to the outer wall of the combustion chamber absorbing both radiated as well as conducted heat from the combustion chamber. Heat sinks are attached to the cold side of each TEG in order to maintain the requisite temperature differential for effective power generation. The possibility of natural convection both in temperature and in subsonic flow was investigated for four types of heat sinks: vertical fins, a type of flower, extended flower type and pin type to identify the optimal heat sink configuration for dissipating heat.

Glass wool insulation also called quilt wool, will be wrapped around the stove body in order to prevent unwanted thermal losses. It minimizes convective heat transfer to the surrounding air, and thereby utilizes more of the energy in a thermoelectric conversion pathway. Moreover, around the heat exchange zones embeds paraffin-based phase change material (PCM). This PCM stores surplus heat during the peak combustion period and releases it slowly during the non-combustion period, thereby increasing power generation duration.

Then, the electrical output from the TEGs are connected to a DC circuit through a USB interface. The stove’s power allows it to power 1–6 LED bulbs (1–3 watts each), and even charge small electronic devices like mobile phones and power banks. The cookstove is a self- contained, practical solution for rural electrification due to its integration of heat recovery, energy storage, and direct power delivery.

2.2 Fabrication Process

Mild steel (MS) sheets were chosen for its strength and durability in addition to being thermally conductive in fabrication of the stove body. To promote thermal stability and improve the internal heat retention, the inner chamber was partially lined with a ceramic wall, which serves the function of an insulating layer and reflecting and concentrating the heat onto the TEGs. Strategically, these Bi_2Te_3 based TEGs were mounted on the outer surface of the combustion chamber at locations where they were determined to be the hottest zones as preliminarily mapped. Additional thermal conduction was achieved by placing the stove wall and the TEGs in an aluminium plate. A heat sink selected from different tested types was placed on the cold side (i.e. heat reject side) of each TEG to maintain temperature differential for efficient power generation under natural convection conditions. Voltage and power output were continuously monitored by use of a digital multimeter that was connected to appropriately matched load resistors. It was able to collect these data with precision under varying fuel conditions for performance comparisons and to optimize the thermoelectric component of the conversion system of the stove.

2.3 Experimental Setup

Thermoelectric cookstove was experimental evaluated under real world, ambient outdoor conditions in order to replicate typical usage scenarios. These three types of biomass fuels were tested in three separate test sessions, including a standardized fuel load of 250 grams per session, using charcoal, wood (dry branch) and honeycomb briquettes. In order to assess performance of the stove across the three different fuels, the three main metrics were measured. The first was the Water Boiling Test (WBT), by which 2 liters of water placed on top of the stove was reported to become boiled within allotted, and hence direct, indicators of heat transfer efficiency. The Temperature Duration Test (TDT) was the second metric and a measurement of how long the stove could have maintained cooking temperatures close to 400 degrees after being ignited, providing information about thermal retention and fuel combustion. Finally, the Power Output Test (POT) came to include electrical generation by measuring both the open circuit voltage and a matched voltage across a resistive load in order to calculate the power output of the thermoelectric modules. The digital multimeters were unwillingly used, and the tests recorded precisely and collectively gave a performance profile of the stove under different fuels types and conditions.

2.4 Heat Sink Evaluation

Four different heat sink configurations were tested under identical combustion and ambient environmental conditions in order to optimize the thermal management of the thermoelectric generator (TEG) system. The fins that were designed for natural heat dissipation included vertical fins, flower fins, extended flower fins and pin type fins, which all possessed specific geometry and surface area. The problem was to identify the configuration that would keep a sufficiently large temperature gradient across the TEG modules while at the same time removing a maximum amount of heat from the cold side. Each heat sink was evaluated on how well it retained voltage output over time, which was directly proportional to thermal gradient and, therefore, power generation efficiency. In addition, the thermal dissipation rate, mechanical design complexity, weight, and material cost were also included. Some heat sinks were bulkier or more expensive to manufacture, but better cooled. Eventually, the vertical fin design turned out to have been a good solution as it largely provided superior heat dissipation, mechanical simplicity and cost, and was suitable for integration into portable, off grid energy systems.

3. Results and Discussion (≈1200+ words)

3.1 Heat Sink Performance Evaluation

In optimizing the thermoelectric cookstove performance, the optimization of heat dissipation from the cold side of the thermoelectric generator (TEG) modules turned out to be one of the critical aspects. Since it is desirable to achieve high heat flow rates to high temperatures, four separate heat sink designs were experimentally evaluated: vertical fins, pin type fins, flower fins, and extended flower fins. The passive cooling through natural convection and radiation were provided through each design. Three parameters of the heat sinks were assessed, that is, maximum open circuit voltage (V_{oc}), time obtained to reach peak voltage, and voltage maintained for 20 minutes of operation.

The vertical fin heat sink was found as the most effective, achieving up to 6.2 V in just 8 minutes and then sustaining up to 5.4 V for 20 minutes as shown in Table 1. This is attributed to its ability to have larger surface area and have a linear geometry which enhanced the airflow pathways and helped remove the heat quickly. The least efficient of the fins was the pin-type, which being more compact and potentially cheaper suffered from only 5.4 V at peak and just

4.2 V after 20 mins due to its small surface area and less favourable air flow dynamics. In achieving a momentary voltage of 5.9 V, the flower fins were unable to maintain this output dropping instead to 4.5 V, which is possibly due to heat dispersion and airflow obstruction caused by the intricate design. Even though extended flower fins are slightly better than the standard flower type with a sustained voltage of 4.8 V, they did not reach the desired vehicle performance. The results clearly show that the geometry and orientation of the heat sink are critical for design and operation of efficient thermal gradient across TEG modules. Vertical fins tested among the others, however, provided the best of thermal efficiency, durability, and manufacturability, capitalizing them as the most appropriate for real world use in off grid thermoelectric systems [15-18].

Table 1: Open Circuit Voltage Comparison Across Heat Sink Types

Heat Sink Type	**Max Open Circuit Voltage (Voc)**	**Time to Peak Voltage**	**Sustained Voltage (20 mins)**
Vertical Fins	6.2 V	8 mins	5.4 V
Pin-Type Fins	5.4 V	6 mins	4.2 V
Flower Fins	5.9 V	10 mins	4.5 V
Extended Flower Fins	5.7 V	9 mins	4.8 V

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3.2 Power Output and Load Performance

The thermoelectric cookstove was evaluated under matched load conditions in order to determine the relationship between the temperature differential across the thermoelectric modules as a function of power output. Three different biomass fuels, all of mass approximately 250 grams (charcoal, dry branches, and honeycomb briquettes) were used to assess the performance of the stove. As shown in Table 2, power output and duration of electrical generation varied significantly with the fuel type.

Honeycomb briquettes had the best performance: maximum power output of 4.0 W and great viability of generating electricity for up to 150 minutes. A large unique maximum voltage of 7.0 volts was obtained over the greatest voltage range from 3.2 to 7.0 volts, indicating the stability and endurance of the combustion process. In this way, honeycomb briquettes have the dense composition and uniform structure that makes them burn more slowly and steadily than other fuel types. They are able to release a constant stream of heat, allowing the TEG modules sufficient temperature differential for long periods to maximize the electrical output.

Unlike charcoal, the power output produced from charcoal was only 3.0 W for 120 minutes, however it did require constant stoking and airflow adjustment to maintain combustion. Charcoal has very high calorific value and clean burning characteristics but it had a tendency to lose heat quickly and was sensitive to air supply which posed challenge to its overall efficiency in this setup.

Table 2: Power Output at Various Fuel Conditions

Fuel Type	**Mass (g)**	**Power Output (W)**	**Output Duration (min)**	**Voltage Range (V)**
Charcoal	250	3.0 W	120	3.5–6.2
Wood (dry branches)	250	2.2 W	90	3.0–5.8
Honeycomb Briquette	250	4.0 W	150	3.2–7.0

The lowest power output was at 2.2 W followed by a reduced output duration of 90 minutes as well as the power output for dry branches (specified in the method section). Natural wood presents an irregular shape and a varying density that also produces fluctuating combustion rates and a differing heat distribution. This causes a less stable temperature gradient across the TEGs and therefore reduces voltage stability and therefore power production.

The obtained results show that fuel selection is an important parameter in maximizing thermoelectric stove performance. The honeycomb briquettes provide a cleaner and longer burn with a more reliable energy source for electricity generation in off grid applications. Their features of consistent combustion characteristics reduce user's intervention and provide steady power output which are favourable for the practical application of their combustion systems in rural electrification scenario or that of emergency relief [18-22].

3.3 Effect of Insulation and PCM on Efficiency

The inclusion of appropriate amounts of glass wool insulation and paraffin-based phase change material (PCM) served as a key enhancement in the performance of the thermoelectric cookstove. The major challenges in thermoelectric energy conversion that were addressed via this design intervention were minimizing heat loss from thermoelectric generator (TEG) modules and increasing the temperature gradient in the TEG modules beyond active combustion occurs. Table 3 demonstrates quantitatively the effectiveness of this improvement in improving system thermal behavior by means of comparing the system with and without thermal management components.

If operated without insulation, the peak temperature of the stove was 310 °C and thermal efficiency was 5.86 %. In addition, the residual heat time (or duration of the fire, over which useful heat was still available for electricity generation) was limited to 15 minutes. However, in contrast to the ceramic chamber, the addition of glass wool around the ceramic chamber reduced convective heat losses of the ceramic chamber to the environment. Because it acts as a highly effective thermal barrier, glass wool retains that heat within the combustion zone and funnels it into the TEG modules.

The thermal inertia of paraffin-based PCM further amplified the system performance by integrating it. When the PCM is in active combustion, the PCM absorbs and stores excess heat.

Soon after combustion stops, this stored latent heat will be released gradually, allowing for a long duration temperature differential across the TEGs. Thermal efficiency improved to 9.23%, up some 57.5% from the 5.78% it achieved while obtaining a realization increase in the maximum operating temperature from 360°C to the one usually experienced at an ambient temperature of 80°C. Furthermore, the residual heat time was increased by more than a factor of two to 35 minutes to continue to produce power even without active fuel combustion.

This result validates the hypothesis that it is desirable to combine latent heat storage and thermal insulation in a thermoelectric system to optimize its effectiveness in intermittent use applications. Moreover, it improves the system in terms of the energy conversion capability and usability and reliability in real world applications where fuel availability or user supervision may not be consistent. The cookstove is more sustainable and dependable energy solution for off grid users due to its prolonged power output, especially valuable for lighting or charging devices during nighttime or post cook hours [22-27].

Table 3: Efficiency Comparison With and Without Insulation

Stove Configuration	Max Temperature (°C)	Thermal Efficiency (%)	Residual Heat Time (min)
Without Insulation	310	5.86	15
With Glass Wool + PCM	360	9.23	35

3.4 Water Boiling and Thermal Duration Tests

This was especially important as the Water Boiling Test (WBT) was critical as the manner by which the heat transfer performance and real-world cooking efficiency of the thermoelectric cookstove was evaluated. For this test, 250 grams of the three different biomass fuels — charcoal, wood and honeycomb briquettes – were first heated in 2 litres of water to simulate a typical cooking scenario. Figure 1: Temperature Curve for Water Boiling Test shows a presentation of the trends of heating of each fuel type during 14 minutes. It is clearly seen that sequence of data pertaining to rate of temperature rise and maximum temperature reached displays that the honeycomb briquettes give better combustion consistency and thermal output as compared to other fuels. One of the things which affected the performance was the presence or lack of wind shielding. Open to the outdoor ambient air with no shielding showed a significant impact of heat retention on the duration of boiling and on thermal efficiency. On the other hand, the wind shields placed around the pot decreased convective losses and hence improved its utility of heat. It took 11 to 14 minutes to boil water, and the shortest time to achieve this was when shielding and high-density fuels such as briquettes were used. Also, when slow burning fuels (honeycomb briquettes) are used it could last for up to 2.5 hours with the thermal duration being the period during which usable heat is supplied for cooking. Knowing that it's going to be available for such a long period of time is important for multi- phase cooking tasks as well as for maintaining that temperature differential needed to power the device through thermoelectric modules. These results highlight the significance of integrated stove design incorporating accessories such as wind shields that are not just mere extra accessories for purchase but essential components that dramatically enhance stove thermal and electrical performance. Therefore, it is expected that future stove prototypes should have integrated or attachable shielding mechanisms to allow maximum efficiency under different environmental conditions. In addition to demonstrating the importance of fuel selection and combustion control for maximizing power generation and cooking dual functions, the test confirms the usefulness of using candle oil for the operation of the dual function cookstove.

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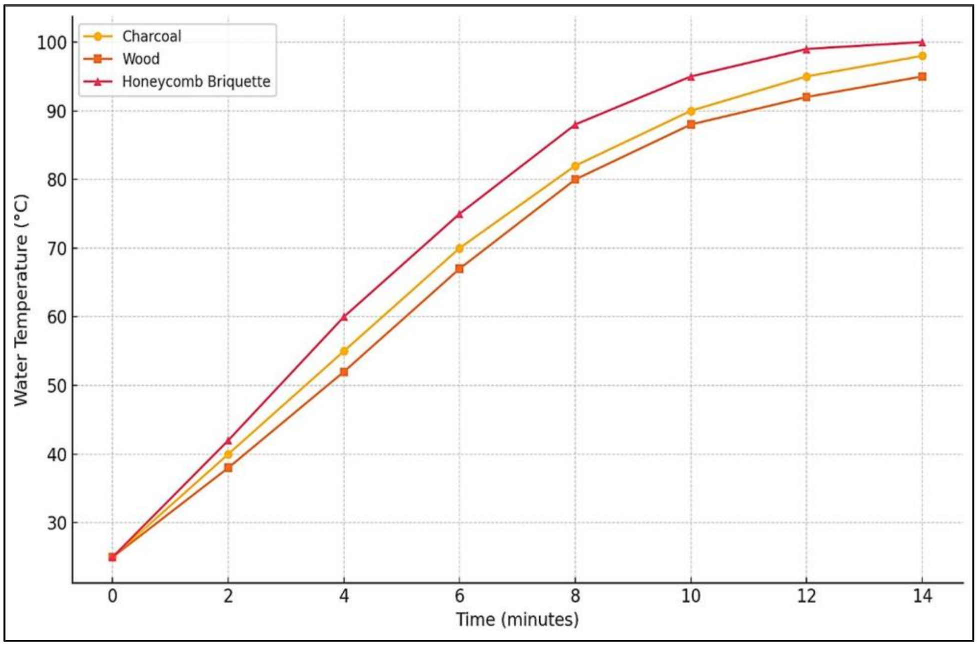

Figure 1: Temperature Curve for Water Boiling Test

3.5 Practical Usability and Application

Beyond just converting heat to electricity, the thermoelectric cookstove performed in the real world in a practical usable way. With up to 6 LED bulbs varying from 1 to 3 watts the product was able to run successfully with enough power to drive mobile phones and power banks through the included USB port. The above yield translates to being able to adequately light an area of up to 15 square metres, enough to simultaneously illuminate two to three small rooms. This performance of the stove makes it a highly functional and one that is self-sustaining, for households operating in off grid rural areas, where electricity is non-existent or at best is intermittent.

Furthermore, given its value in disaster relief situations after earthquakes, floods, cyclones or other disasters, wherinedical infrastructure is damaged or inaccessible, the stove can be very helpful. Its compact and lightweight construction as well as its modularity also boosts its practical use given the ease and speed with which it can be transported and deployed to emergency scenarios. In addition to its applications for campers, this device can also serve field researchers, trekkers, and outdoor enthusiasts because it allows for removing the need to carry any separate lighting or charging equipment. Adopted as a scalable energy solution for diverse user environments, this cookstove functions as a dual-purpose device as a cooking stovetop and a generator, with portability, is identical for all applications.

4. Conclusions

1 The vertical fin heat sink displayed the highest performance of the tested 4 configurations as it achieved a maximum open circuit voltage of 6.2 V and maintained a sustained voltage of 5.4 V for the first 20 mins giving proof to its enhanced thermal dissipation ability and an optimal support for TEG efficiency.
2 Paraffin-based PCM plus glass wool insulation increased maximum heat transfer temperature from 310°C to 360°C and improved thermal efficiency at 5.86% to 9.23% (57.5%) and extended residual heat availability from 15 to 35 minutes, providing electricity output past the time when fuel combustion ceases.
3 Charcoal and wood were found to be the least effective fuel and delivered the minimum power output of 1.3 W, the minimum voltage range of 1.7–3.0 V, and had the lowest duration of electricity production of only 91 minutes.
4 The stove reliably generated 3–7 V DC enough to power 1 to 6 LED bulbs (1–3 W each), charge mobile phones and power banks so that up to 15 m² (equivalent to 2–3 rooms in typical off grid households) were effectively illuminated.
5 The cookstove has a lightweight design and low fuel requirement of 250g per session that make the stove a cost effective and scalable solution for rural electrification, disaster relief operations and field-based energy access making it a good candidate for deployment in energy poor and disaster affected regions.

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