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Electricity generation from a biomass cookstove with MPPT power management and passive liquid cooling

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ABSTRACT

An electrical power generator for use with biomass cooking stoves has been developed. The design is intended for users in developing countries who lack regular access to electricity. Electricity is generated based on the thermoelectric effect. A bespoke heat collector captures heat from the combustion chamber of the cooking stove and transfers it to a single thermoelectric generator (TEG) module. To maintain a sufficiently high temperature difference across the TEG, heat is dissipated using a passive single phase liquid thermosiphon system. This cooling system eliminates the requirement for mechanical components such as fans or pumps, which are unreliable and draw significant electrical power. In a controlled laboratory setting, a maximum power of 5.8 W has been produced from a single TEG installed into a low cost ceramic cooking stove currently disseminated in large numbers in Malawi, Africa. The TEG power is controlled using a maximum power point tracking (MPPT) conditioning circuit with an estimated efficiency of ~70%. The circuit provides a stable 5 V output via a USB connector for charging mobile phones, lights, power banks and other devices. Experiments have shown that the device is capable of performing for extended periods without significant reduction in performance. The magnitude of the power generated by this passive cooling system is observed to be comparable to that delivered by similar TEG-stove systems driven by active cooling. An average power generation of over 4 W was achieved which, including circuit efficiency, provided ~10 W·h of useful electrical energy over a 4 h burning interval, which is sufficient for charging low powered electrical appliances. Five prototypes fitted with data measurement and acquisition were deployed to families in rural Malawi in order to evaluate real-life performance of the technology. Initial field-trial results have advocated the viability of the TEG-stove technology for charging low powered electronic devices typically used in developing countries such as Malawi.

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Introduction

A thermoelectric generator, or TEG, is a solid state semi-conductor device which converts heat directly into electricity via the thermoelectric effect. The efficiency of thermoelectric devices is typically <7%, but the simple construction and absence of moving parts makes them extremely reliable in many circumstances. TEGs are versatile and can be found in a wide variety of space, automotive, military and domestic applications to name but a few (Elghool et al., 2017), and have risen in popularity due to their use in waste heat-to-power generation applications.

Research into the use of thermoelectric generators with cooking stoves has increased over the last thirty years. A comprehensive review of the development of stove-powered thermoelectric generators is provided in ref. (Gao, Huang, Li, Qu, & Zhang, 2016). To produce electricity

from a TEG, a temperature difference must be maintained between its heated and cooled faces. In the majority of cases involving stoves used in a domestic environment, heat is extracted from the fire primarily by conduction and radiation. This can be achieved by a protrusion into the fire (O'Shaughnessy, Deasy, Doyle, & Robinson, 2015a, 2015b; Raman, Ram, & Gupta, 2014; Stokes, Mantini, Chartier, & Rodes, 2012), or by attaching the TEG to a solid, hot boundary (Killander & Bass, 1996; Lertsatitthanakorn, 2007; Mastbergen, Willson, & Joshi, 2005; Nuwayhid, Rowe, & Min, 2003; Nuwayhid, Shihadeh, & Ghaddar, 2005). To cool the TEG, a wide variety of different cooling systems have been investigated. The cooling methods can be categorised based on the working fluid and on their dominant heat transfer mode.

A recent review by Gao et al. (2016) found that air-cooled forced convection is the most common and straightforward technique, where the cold heat sink of the thermoelectric generator is cooled by air provided by a fan. Fan-cooled systems can achieve low thermal resistances using a small number of components, and the air can also be routed to the combustion chamber to aid the combustion process. However, a moving part is required which can break down leading to total power

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generation system failure, and extra circuitry is required to control the operation of the fan, which is typically powered using some of the electricity generated by the TEG.

Forced convection air cooling systems have been employed by the authors in previous studies (O'Shaughnessy, Deasy, Doyle, & Robinson, 2014; O'Shaughnessy, Deasy, Kinsella, Doyle, & Robinson, 2013). In these examples a heat pipe heatsink normally used for CPU cooling was equipped with an adapted low power fan, driven by a portion of the power generated by the TEG. This proved effective in terms of TEG power production and fan power consumption and there was an excess of energy produced compared to what was used for phone and LED (light emitting diode) lantern charging. However, the overall cost and complexity of this technology demonstrator was too high for developing world technology and the power draw to run the fan was non-negligible. User feedback also indicated that the generator was bulky and cumbersome.

The authors adapted their design based on user feedback and developed a lower cost and smaller form factor generator, albeit one which produced less power than previous designs (O'Shaughnessy et al., 2015a). The design again used forced convection cooling and achieved adequate power generation initially, but failure eventually occurred due to a combination of low power generation and a depleted internal battery caused by simultaneously charging and discharging. This had the knock-on effect that the fan-fin cooling system operation was also compromised which led to slow fan speed and eventual melting of the fan casing and overheating of the TEG. Here, the simple yet functional charge control circuitry developed by Kinsella, O'Shaughnessy, Deasy, Duffy, and Robinson (2014) was not capable of coping with user in-field behaviour indicating that a 'smarter' circuit is required. Again, the power draw by the fan did consume a non-negligible amount of the limited electrical energy produced by the TEG.

The TEG power draw relating to fluid circulation become quite significant in forced liquid convection systems which typically use water as the working fluid. Much of the TEG-related research in this area has focused on cogeneration applications with domestic boilers, such as studies in refs. (Brazdil & Pospisil, 2013; Qiu & Hayden, 2011; Rowe et al., 1997). The advantages of such systems is that the pump and pipe network is typically already in place. For standalone power generation from cooking stoves, pumped liquid systems are much rarer. Goudarzi et al. (2013) used 21 TEGs in a 7×3 configuration, and liquid water was pumped at high flow rates through cooling blocks. Each TEG was capable of producing 16 W. At a maximum fuel consumption rate of 9 kg of wood per hour, an average power output of 7.9 W per TEG was achieved, which did not account for the ~5 W of power required by the pump. However, it appears that their system is open loop which means that a continuous supply of cold water is required to achieve the stated power output.

Passive cooling systems of TEG systems are desirable because they have no moving parts (pumps, fans etc.) which increases long term reliability and does not draw on the comparatively low power produced by a TEG system. Furthermore, they solve the paradoxical situation encountered whereby powered cooling systems must be active in order for the TEG to generate sufficient electricity to power them. To this end, some systems have employed natural convection with air as the coolant. However, the poor thermal properties of air result in the requirement of inappropriately large air-side heat sinks, which are generally low performance, cumbersome and expensive. For example, Nuwayhid et al. (2005) fitted a thermoelectric generator to the side of a domestic woodstove in rural Lebanon. The generator was driven using one or more thermoelectric modules. Cooling was achieved using a high performance fin type heat sink exposed to the surrounding air. Using a single module that was capable of producing over 16 W, the maximum steady state matched load power was determined to be only 4.2 W, with the difference being due to the high thermal resistance of the air-side heat sink. Nuwayhid and Hamade (2005) investigated the viability of a two phase thermosyphon, whereby the heat is transported

and spread evenly over a significant air-side surface area exposed to ambient air via condensation. The system included a HZ-20 module capable of 19 W of power generation. In their study Nuwayhid and Hamade achieved only 3.4 W of electrical power at matched load in a laboratory setting for the same reasons as Nuwayhid et al. (2005). Furthermore, the cooling system was disproportionately large and complicated to manufacture, making its viability questionable in the developing world context.

Natural convection systems using water have also been investigated. Water cooling systems have a lower thermal resistance than air due to the liquid's more favourable thermophysical properties. In some circumstances the systems are intended as cogeneration systems that simultaneously generate electric power and heat for domestic hot water use. This typically involves a large water reservoir in direct contact with the cold heat sink, such as in studies by Nuwayhid, Moukalled, AbuSaid, and Daaboul (2000) and Champier, Bedecarrats, Rivaletto, and Strub (2010), Champier et al. (2011). In ref. (Champier et al., 2010) the authors used up to four TEG modules, each capable of 10.5 W, but the maximum total power output was only 7 W at a temperature difference of 160 °C. In (Champier et al., 2011), a maximum 9.5 W was generated from a single TEG capable of producing 16.2 W. The authors stated that the difficulty is to find a solution which can be used in developing countries and not only in a laboratory.

Despite the various TEG cooling mechanisms studied, few studies consider a fully integrated TEG-stove system which must include some form of power control circuitry. A previous study by Kinsella et al. (2014), implemented in the aforementioned field trials (O'Shaughnessy et al., 2013, 2014, 2015a), showed that it is possible to achieve high circuit efficiencies without the use of maximum power point tracking (MPPT) by carefully matching the load resistance to the internal resistance of the particular thermoelectric module. In that study, a rechargeable lithium iron phosphate battery was used to store the power generated by a single TEG. However, this approach limits the range of applicable TEGs and batteries. Furthermore, reasonable efficiencies were only achievable with a TEG temperature difference of approximately 150 °C. At lower temperature differences the efficiency decreased significantly. Regardless of the simplicity of the approach, the rechargeable battery significantly increased the cost of the overall generator system and required significant training of end users to avoid misuse which could damage the battery. To address these issues, a new MPPT conditioning circuit was developed. MPPT provides the ability to generate maximum power from a TEG independent of the TEG temperature and the load resistance, effectively electrically decoupling the TEG from the load that is charging. It is noted that MPPT circuits require electrical power to operate at the compromise of system efficiency when a TEG internal resistance matches the effective resistance of the load. MPPT circuits more than make up for this by continually providing maximum power regardless of the load resistance associated with the charging electrical appliance.

Objectives

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The use of a single phase thermosyphon to cool TEGs for power generation in a developing world has not been studied extensively. Many studies that consider TEGs for use in stoves are laboratory based, and only a few actually integrate the TEG with the stove. Even fewer study the performance of the entire system including the stove, TEG, electrical circuitry, heat collector and cooling method. The principal objective of this work is to develop and test a fully integrated TEG-stove system, including a modified low cost stove, passive heating and cooling systems and MPPT circuitry. The design must be capable of producing sufficient voltage and electrical energy from normal cooking practices so that users can charge devices such as mobile phones, rechargeable batteries, LED lanterns and radios on a daily basis. The magnitude of the power generated by the passive system must be comparable to that delivered by similar TEG-stove systems driven by active cooling. Additionally,

the full system should be tested in a manner that is representative of how it will be used in the field. Furthermore, the system must be robust and low-cost as the targeted environment can be considered harsh and the end-users will be economically vulnerable.

Nomenclature

Symbol/acronym	Description	Unit
α_{eff}	Effective Seebeck co-efficient	V/K
Bi_2Te_3	Bismuth telluride	-
P_{elec}	Electrical power	W
R_L	Electrical resistance of load	Ω
R_{TEG}	Electrical resistance of TEG	Ω
ΔT_{TEG}	TEG temperature difference	K
V_{OC}	TEG open circuit voltage	V
V_{TEG}	TEG voltage	V
CPU	Central processing unit	-
DC	Direct current	-
LED	Light-emitting diode	-
MOSFET	Metal–oxide–semiconductor field-effect transistor	-
MPP	Maximum power point	-
MPPT	Maximum power point tracking	-
PIC	Programmable Interface Controller	-
RTD	Resistance temperature detector	-
SD	Secure digital	-
SEPIC	Single ended primary inductor convertor	-
TEG	Thermoelectric generator	-
USB	Universal serial bus	-

TEG theory and module parameters

The Seebeck effect is a phenomenon by which a voltage difference is produced between two dissimilar electrical conductors or semiconductors

in response to a temperature difference between them. TEGs operate based on this effect and a voltage is generated when the two faces of the TEG are at different temperatures.

As depicted in Fig. 1, TEGs are intended to be thermally oriented so that heat is supplied to the 'hot' face whilst simultaneously dissipated from the 'cold' face. A TEG therefore produces electrical power in response to a temperature differential across the module as heat is forced to flow between them. The electrical power output by the TEG also depends on the electrical load resistance, R_L (Fig. 1). A full description of TEG behaviour can be found in (Höglblom & Andersson, 2016; Hsu, Huang, Chu, Yu, & Yao, 2011; O'Shaughnessy et al., 2013; Rowe, 1978). It is easily shown that the power produced by the TEG, P_{elec} , is given as

$$P_{\text{elec}} = (\alpha_{\text{eff}} \Delta T_{\text{TEG}})^2 \frac{R_L}{(R_L + R_{\text{TEG}})^2} \quad (1)$$

where α_{eff} is the effective Seebeck coefficient, ΔT_{TEG} is the temperature difference across the TEG module and R_L and R_{TEG} are the resistances of the load and TEG respectively. From Eq. (1) it can be shown that the maximum power is produced at matched load, which gives justification for the requirement of MPPT circuitry in application.

The power generation system described in this study is designed for operation with a single 7.2 W nominal power TEG module, although it is suitable and scalable for use with larger, more powerful TEGs and/or multiple modules. The chosen TEG is the TEG1B-12610-5.1 module, supplied by TEGTEG. The specifications for the TEG used in this study are given in Table 1.

Fig. 1. Thermoelectric power generation.

t1.1 Table 1

t1.2 TEG specifications at a cold side temperature of 30 °C.

t1.3	Type	Bi ₂ Te ₃
t1.4	Max. hot side temperature	300 °C
t1.5	Dimensions	40 mm × 40 mm
t1.6	Open circuit voltage	7.2 V
t1.7	Internal resistance	1.8 Ω
t1.8	Matched load output voltage	3.6 V
t1.9	Matched load output current	2 A
t1.10	Matched load max. output power	7.2 W
t1.11	Heat flow through the module	~148 W

247 TEG-stove design overview

248 Although the design is intended to be adaptable to a variety of
 249 biomass-fed cooking stoves used in developing countries, for performance
 250 evaluation it was deemed appropriate to integrate the design into a mass
 251 produced low cost stove, and one which has been previously investigated
 252 by the current authors in Malawi, Africa (O'Shaughnessy et al., 2013, 2014,
 253 2015a, 2015b).

254 The cookstove

255 A modified *chitetezo mbaula* (translated as 'protection stove') is used
 256 in this investigation and is shown in Figs. 2 and 3. This is a clay stove
 257 with thick walls, handles for portability and a pot rest which can accom-
 258 modate different pot sizes. For this work, the stove has been modified to
 259 include an opening opposite to the firewood port for integration of the
 260 TEG system. A stove manufacturing facility was established in a rural
 261 village in the Thyolo district of Malawi to manufacture the stoves for

Fig. 2. Nsima (maize flour and water) preparation with a chitetezo mbaula cooking stove in Malawi.

this research. The manufacturing process takes places over several
 days, and is depicted in Fig. 3. The main processes are as follows:

- Day 1: dry earth is collected then soaked in water overnight to form a clay.
- Day 2: a paddle mould (cost ~100 USD) is used to manufacture the main shape of the stove after which details such as handles, pot stand and holes for firewood and the TEG generator are added. They are left to cure until dry.
- Day 3: wood is collected and the cured stoves are loaded into the kiln and covered with a layer of clay and the kiln is fired.
- Day 4: the stoves are unloaded.

The TEG system

The TEG-stove generator system involves four main components; the heat collector, the TEG module, the cooling system and the MPPT conditioning circuitry. The heat collector design is based on previous studies with the chitetezo mbaula (O'Shaughnessy et al., 2013, 2014, 2015a, 2015b). The collector comprises a 90 mm × 90 mm × 6 mm mild steel plate onto which three 12 mm diameter steel rods are welded. A spacer is attached to the bottom of the rods to ensure that they do not rest on the bottom of the combustion chamber. The purpose of the rods is to act as a grate, compelling the user to position the fuel on top of it thus allowing air to flow beneath and up through the fuel. This air is preheated by the coals so that when it reaches the fire it improves combustion (Bryden et al., 2005) and acts to reduce the build-up of charcoal, which can act to insulate the TEG from the heat source. The steel rods also conduct heat to the mounting plate onto which the hot side of the TEG module is fixed.

The TEG is fastened between the heat collector plate and a water-cooled aluminium heat sink, depicted in Fig. 4. As discussed in ref. (Deasy, Baudin, O'Shaughnessy, & Robinson, 2017) and depicted in Fig. 5, the water-cooled heat sink has been designed using computational fluid dynamics (CFD), whereby the geometric parameters are such that a sufficiently low thermal resistance is afforded with a buoyancy-driven single phase thermosiphon system. To this end, the aluminium heat sink has a finned area of 40 mm × 40 mm with 17 fins, 1.6 mm fin spacing, 9 mm fin height and a fin thickness of 0.7 mm. The finned area is positioned at the centre of a 2.4 mm thick base of dimensions 61 mm × 58 mm. The thermal resistance of the thermosiphon system ranged between 0.068 K/W and 0.099 K/W depending on the heat flux and the water temperature. This is considerably lower than what would be afforded by a passive air cooling system.

The heat sink is sealed within an aluminium manifold. The manifold is manufactured from a single block of aluminium of 30 mm thickness. A cavity of 44 mm × 44 mm cross-sectional area and a depth of 27 mm is machined into the solid. Two holes are drilled and tapped at an angle of 30° to the outer face to accommodate two G1/4 male to 12 mm ID hose fittings. This angle is chosen to allow the hole to intersect with the cavity and to prevent the formation of air pockets which were observed to form using horizontal connections. Pressure is applied to both sides of the TEG by four M5 clamping bolts supported by spring washers and nuts. The same torque (0.75 Nm) is applied to each bolt using a narrow range torque screwdriver. A sketch of the manifold and assembled generator is provided in Fig. 4.

The lower and upper barbed hose connections of the manifold are connected to separate flexible braided PVC hoses which also connect to a water reservoir with a maximum capacity of 9.5 l. The lower hose supplies the manifold with cold water from the bottom of the reservoir and is named the feed line. As heat is dissipated by the aluminium heat sink to the water, temperature gradients are established in the water inside the manifold. This in turn causes density gradients in the liquid and results in buoyancy-driven natural convection. The warmer water naturally moves toward the upper regions of the manifold and exits through the upper hose connection. The warm water is transported through the

Fig. 3. Photographs of the stove manufacturing sequence.

upper pipe, named the return line, and back to the reservoir. Simultaneously the warm liquid leaving the manifold is replaced by cold fluid from the feed line. Since the cooling mechanism does not require any mechanical devices to drive the flow, it may be considered passive and since it operates in a loop i.e. it is a single phase thermosiphon. One key advantage of passive cooling is that it does not require electrical energy to drive the fluid motion, thus negating the requirement for mechanical devices such as pumps, which are expensive and susceptible to failure, and they draw from the limited power generated by the TEG (O'Shaughnessy et al., 2013). Furthermore, since fans are not employed and are therefore not powered from the TEG, the cooling system will

continue to operate if there is a malfunction in the power control circuitry, unlike previous studies by the current authors (O'Shaughnessy et al., 2014). This decouples the power conditioning circuit from the cooling system operation and allows for troubleshooting, maintenance and long term reliability.

The positioning of the reservoir and the connections are important to the operation of the integrated passive cooling system. To establish the thermosiphon effect, the reservoir must be positioned at a location higher than the manifold, as shown in Fig. 5. Moreover, the location of the connection of the return line to the reservoir should be below the surface level of the water in the reservoir to avoid air entering the return

Fig. 4. The assembled unit.

line. The purpose of the reservoir is to act as a thermal store; i.e. to collect the thermal energy dissipated to the aluminium heat sink from the source. Previous in-field studies with this stove have indicated that the daily usage time for these stoves can vary greatly, and in many cases individual usage periods may be over 3 h in duration (O'Shaughnessy et al., 2014, 2015a, 2015b). The volume of water (9.5 l) in the reservoir is such that a significant amount of heat energy must be absorbed before the feed water experiences a considerable rise in temperature. In this way the temperature difference across the thermoelectric module can be maintained at reasonable levels for sustained periods, providing that the heat input and subsequent hot side temperature from the heat collector do not greatly exceed the recommended maximum levels for the TEG.

The reservoir is operated with an exposed surface, meaning some water is lost to the surroundings by evaporation. However, this also provides a path of low thermal resistance to the surroundings which is beneficial with regard to reducing the rate at which the reservoir temperature rises and is beneficial for maintaining a low cold side temperature of the TEG. For extended operation (>10 h (Deasy et al., 2017)), it may be necessary to replenish some of the liquid lost to evaporation so that the return line is always below the surface level of the water in the reservoir. This could also be mitigated by designing a reservoir to avoid such a problem. Of course, during extended operation the average

temperature of the reservoir will increase, and the user could choose to replace this warm water with colder water which will increase the power output from the TEG system. Alternatively, the user will have a source of warm water at the end of their meal preparation, which could be used for other domestic purposes such as washing or cleaning. In this situation the generator can be viewed as a cogeneration device.

Some of the design choices for the TEG-stove system in this study were influenced by the desire to use commonly available components such as hoses and buckets to act as reservoirs. The thermal performance of the thermosyphon system depends on many aspects such as the choice and geometry of the TEG module, the anticipated heat flow through the TEG, the design of the heat sink and cooling block and the volume and diameter of the reservoir. Thus, a general mathematical model for system performance is not possible. However, a detailed study on the effect of these parameters can be found in ref. (Deasy et al., 2017) which can be used as a design guideline.

MPPT conditioning circuitry

For the MPPT circuit depicted in Fig. 6, a single-ended primary-inductor converter (SEPIC) is employed to more efficiently avail of the potential power when the TEG and load resistances are not matched. A SEPIC allows the voltage at its output to be greater than, less than,

Fig. 5. Experimental setup.

Fig. 6. Charging a ZTE-brand mobile phone using the SEPIC circuit.

or equal to that at its input. When a SEPIC is employed with a TEG as a power source, it electrically decouples the load resistance from the TEG's internal resistance. Maximum power can be achieved across a range of input resistances. This enables the direct conversion of power to a user's device without the need for an intermediate battery. The use of a power converter also provides flexibility, with scope for changing both the input (TEG) and the load (appliance).

The output of the SEPIC is controlled by the duty cycle of its control N-MOSFET. Here, the duty cycle is generated and modulated by a PIC24F micro-controller which is also employed for a number of auxiliary functions, including mode selection, data acquisition and logging, and data time stamping.

A maximum power point tracking algorithm is created based on the open circuit voltage method. Maximum power is produced when the input voltage, V_{TEG} , is equal to half the open circuit voltage, V_{OC} . A disadvantage of this method is that it requires disconnecting the load from the input to measure the open circuit voltage. In this study, V_{OC} is measured every 10 s, with each measurement taking place 1.5 ms after the disconnection with the TEG.

The microcontroller constantly adjusts the duty cycle to maintain a stable voltage at the output of the circuit. If the input power is insufficient to achieve this target, the duty cycle is adjusted to maintain maximum output power. Maximum output power is determined by taking into account the MPP of the TEG as well as the efficiency of the circuit.

The input voltage is boosted by the SEPIC to a user-selectable output voltage (5 V or 4 V) at the USB connection. When boosting to a fixed output voltage, the efficiency of the power converter increases with increasing input voltage. The circuit contains a mode select button which changes the set point voltage at the USB port. The mode is represented by an LED which changes colour in response to the user pressing the mode select button:

- Blue LED – 5 V output for mobile phones
- Green LED – 4 V output for radios
- Red LED – data access mode

To facilitate the measurement and acquisition of data pertaining to generator performance during laboratory and field trials, input and output power measurements are recorded by the microcontroller and saved to an on-board microSD card. The card can be disconnected from the circuit if necessary, but the data can also be accessed via the mode button and USB connection, in which case the card appears as an external storage drive. For field trials, the end users are trained to operate the circuit during the initial stove deployment, work which is carried out by the United Purpose field staff.

System cost estimates

The circuit described above contains many elements that may be removed in a non-research environment, thus simplifying the circuit design and reducing the overall cost significantly. For this system, estimates are based on order volumes of 10,000 TEG-stove generators. The main cost component is the TEG module, quoted at \$8 per module from the supplier. The simplified circuit cost reduces substantially with volume too, with an estimate of \$4 per circuit. The metallic components, hoses and reservoir are estimated at \$5 per generator, the electrical housing at <\$2 per generator and the electrical cabling at <\$0.2 per generator. To make the TEG-stove system a viable alternative to other power generating technologies, a target cost of ~\$25 is envisaged.

Laboratory experiments

Whilst each of the components of the TEG-Stove system have been tested separately, it is still deemed necessary to evaluate the complete system performance under laboratory conditions.

Experimental setup

The generator system is installed into a modified chitetezo mbaula stove which was manufactured as described in The cookstove. The TEG-stove is investigated in a test centre in Ireland where a burn laboratory, depicted in Fig. 7, has been designed and commissioned. As the schematic shows, the TEG-stove is placed into a 1.0 m³ chamber with transparent doors on all sides. Each door enables user access to the stove and includes an air vent so that the stove can continue to burn fuel with the doors closed. The stove rests on a bed of fire bricks to insulate and prevent damage to the test facility. Above the stove is a fume hood

Fig. 7. Diagram of stove testing facility.

that has been designed to capture and monitor the exhaust emissions if required. The fume hood is connected to a ducting system with interior dampers to prevent back drafts. The ducting can also draw fresh air from outside the test facility if desired. Exterior to the facility, a variable-speed extractor fan is employed to draw the exhaust gases and other emissions through the ducting and out of the building. The speed of the extractor fan has been set to ensure that it does not affect the normal operation and performance of the stoves under test.

Experimental procedure

An experiment commences by filling the reservoir with 9.5 l of water at 20 °C. The manifold, feed and return lines are primed with water and checked for air pockets. A pot filled with water is placed on top of the stove to replicate practices observed in real life cooking scenarios. Wood from a single source is chopped into variable sizes whilst ensuring that three sticks can fit in the fuel entrance of the stove simultaneously, as per best practice for users of the chitetezo mbaula.

The fuel is ignited without accelerant and gradually burned, with infrequent stoking in order to emulate observations in earlier field trials. The initial fuel load is allowed to be reduced to charcoal before refuelling as this appears to be normal practice within the rural communities in Malawi. It has been observed over the course of numerous visits over different regions of Malawi that stove users frequently attend to other tasks (meal preparation, child minding, chores etc.) whilst cooking.

During a test, temperatures are recorded at 1 Hz at several locations in the stove and generator assembly. All thermocouple signals are acquired using National Instruments NI-DAQ9211 4-channel thermocouple data acquisition modules in conjunction with LabVIEW, and Type K, stainless steel, 1.5 mm diameter and 150 mm long grounded thermocouple probes. The temperatures in the region of the steel rods (i.e. the grate) and in the region of the flames are also recorded to give a qualitative measure of the heat source intensity. To enable the measurement of the approximate temperature difference across the TEG module during experiments, thermocouples are inserted into two 40 mm × 40 mm × 3 mm copper plates that are placed either side of the TEG. The temperature at the inlet and outlet of the reservoir and at one location in the reservoir is also measured to monitor the cooling system performance. All thermocouples were calibrated against a F100 RTD probe with uncertainties of ± 0.2 °C in the range 20–350 °C.

The TEG voltage, TEG current, load voltage and load current are recorded at 1 Hz using a National Instruments NI-DAQ9219 data acquisition module. To enable LabVIEW current measurements, a precision 0.03 Ω sense resistor is placed between the TEG and circuit input, and between the load and circuit output. These measurements are also recorded on-board the power control circuit. This dual measurement enables verification of important electrical data recorded by the circuit.

The circuit is connected via the USB port to a BK Precision 8540 Electronic Load set to control voltage mode. The circuit mode is set to 5 V output mode, as indicated by the blue LED. In many instances where devices such as mobiles phones are charged from a power-limited source, the charging voltage is actually lower than 5 V and is linked to the voltage of the internal battery of the particular device. This frequently occurs when charging from USB ports on PCs or laptops, where the current is limited to 500 mA. In these cases, the actual charging voltage can vary from 3.7 V to 5 V. For this reason, the electronic load was set to draw power from the circuit at a mid-range value of 4.5 V.

Results and discussion

Laboratory experiments

Several laboratory experiments have been performed with the TEG-stove system. Due to the stochastic nature of fuel burning, somewhat different results are obtained for each experiment though the general trends are adequately close to one another to have confidence in the

repeatability and efficacy of the measurements. The results presented in this section are provided as an example and relate to one particular experiment during which the TEG-stove was operated for approximately 5 h. Usage periods of this duration have been frequently measured in previous field trials (O'Shaughnessy et al., 2014). For this example and all other experiments, the fuel is allowed to burn to charcoal before the addition of more wood to the combustion chamber. In this example, fresh fuel is added at approximately 2.5 h.

Fig. 8 shows the temperature recorded on either side of the TEG module along with the associated temperature differential across it. Several important features are immediately apparent. After an initial increase immediately after the fire is ignited, the cold side temperature quickly rises to the region of 50 °C and remains quite constant. The hot side of the TEG module also rises quickly to 250 °C and subsequently fluctuates in accordance with the fluctuations in local temperature in the combustion chamber of the stove. These fluctuations can be naturally occurring, or may be attributed to the occasional stoking of the fuel. These fluctuations are responsible for those seen in the TEG temperature difference since the cold side temperature remains relatively stable throughout the test interval.

The aluminium heat sink is cooled by a supply of low temperature water as shown in Fig. 9. Although the return line water experiences an initial rapid rise in temperature once heat transfer through the heat sink is initiated, the thermal mass of the reservoir ensures that cool water is supplied for almost 1 h before any significant rise in feed water temperature, and this had the effect of moderating the return line temperature which plateaus as well. This phenomena is discussed in more detail in a previous study (Deasy et al., 2017). After this initial quasi-steady period, both feed line and return line temperatures begin to rise and again plateau after about 3 h as evaporation from the exposed free surface of the water reservoir, and to a lesser extent convection from the reservoir walls, transfers heat to the ambient. The return line temperature exhibits low magnitude fluctuation due to those of the TEG hot side temperature.

The electrical power generated by the TEG is plotted in Fig. 10 which also shows the power consumed by the electronic load and the circuit efficiency. The efficiency is calculated as the ratio of the measured power supplied to the electronic load to that generated by the TEG subsequent to the MPPT circuitry. The input power reflects the temperature difference across the TEG module, and displays an identical pattern to that seen in Fig. 8. Since the circuit efficiency is relatively constant, ~70% when the input power is above 1 W, the output and input power follow the same trend. A maximum power supply to the electronic load of 3.8 W was achieved, corresponding to a maximum power generation of approximately 5.8 W. The largest power output is obtained at the early stages of the burn associated with the time interval when the TEG temperature difference is greatest (see Fig. 8). Since the feed water temperature increases over time, an expected drop in output

Fig. 8. TEG temperatures during experiment.

Fig. 9. Water temperatures during test.

Fig. 11. Input and output voltage and current as measured by LabVIEW.

power is observed, though this drop is also linked to the general reduction in hot side temperature after 2.5 h as well.

From Fig. 10 it is noted that the delivered power is typically above 2.5 W. A large range of devices can be charged from a USB port at a nominal 5 V and a maximum current of 500 mA. Examples of such devices which have been observed by the authors in rural developing world communities are mobile phones, portable radios, LED lights and lanterns, portable battery packs, ultra-violet water sterilizers and portable fans.

Fig. 11 plots the input and output voltage and current throughout the duration of the test. The input voltage fluctuates with ΔT_{TEG} but the output voltage remains stable at the set point voltage for the electronic load.

In the context of the power output for charging low powered electronics appliances such as phones, LED lanterns and radios, it should be noted that this level exceeds that of a USB port on a laptop computer, which provides a maximum 2.5 W at 5 V.

The TEG continues to produce usable power until just over 4 h, at which point the input power is insufficient to maintain 5 V at the circuit output and the power control circuitry engages a sleep mode. Over the duration of the experiment, a total of 14.6 W·h is generated and 9.9 W·h is delivered to the electronic load, as shown in Fig. 12. This is the energy that would be available for device charging and is more than sufficient for general use of low powered devices (O'Shaughnessy et al., 2014, 2015b). Also shown in Fig. 12 is a comparison between the data measured on-board the circuit (which will subsequently be used for field trial generator performance evaluation) and that measured externally via the DAQ hardware and LabVIEW. The data shows excellent agreement, with the total power integrals agreeing to within 0.1% and 2.9% for the input and output power respectively. This demonstrates

that the on-board data logging capability can be used for reliable measurements in the field.

The production and delivery of approximately 10 W·h of power over the course of 4 h is sufficient power to charge most smart phones and larger LED lamps. This will more than meet the minimum daily needs of 5 W·h per day from normal usage of the stove. The output of 2.5 W on average is consistent with power level at which many devices charge. In this regard, the output of the TEG-stove system was deemed adequate for DC charging of low powered devices and was thus suitable for field trials.

Preliminary field testing

A total of five generators were produced, assembled and tested in TCD before being sent to Malawi. The completed generator unit and circuit were integrated with modified Malawi-made chitetezo mbaula by United Purpose field staff. The field staff were responsible for sourcing local water reservoirs (plastic buckets), attaching and positioning the fittings and hosing and sealing the generator into the stove with fresh clay. The completed TEG-Stoves, an example of which is shown in Fig. 13, were then distributed to five families in three separate areas for testing. Stove, circuit and reservoir operating instructions were provided to the users of the generators. USB phone cables and a portable power bank were also supplied with each generator.

The data was collected from the circuits after several days of operation along with user feedback. The operation of the TEG-Stove has not yet caused any negative technical issues or crossed any unforeseen social-cultural boundaries. The TEG-stoves usage hours are similar to those recorded in previous field trials (O'Shaughnessy et al., 2013, 2014, 2015b), with daily usage patterns of between 2 and 8 h.

Fig. 10. Power generated and supplied and circuit efficiency during test.

Fig. 12. Input and output power integrals as measured by the TEG circuit and LabVIEW.

Fig. 13. TEG-Stove in operation in Malawi.

crop-waste fuel which can result in a lower temperature difference across the TEG. The higher ambient temperature in Malawi also results in a higher average operating temperature which adversely affects power output (Deasy et al., 2017).

Fig. 14 also plots the open circuit voltage, which is clearly correlated to the power. In this example, the users operated the TEG stove for almost 3 h, most likely for the breakfast meal. Interestingly, the users did not choose to connect any device during the first ~40 min of operation, despite this being the period with the greatest available power. During this phase, the TEG is effectively in the open-circuit condition, except for the small amount of power required to run circuit features such as the LED and data logging. At approximately 07:09, a device is connected to the circuit and the on-board measurements are logged to the SD card. In this case, the user's device draws almost the maximum power available to it, at approximately 65–70% efficiency for the majority of the charge.

Conclusion

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This study describes the design, construction and testing of a complete TEG-stove system, with the target users being those in households in the developing world where electricity access for low powered electronic devices is problematic. The complete system involves the manufacture of a portable clay improved cookstove, a heat collector, TEG system, passive liquid cooled heat sink and MPPT circuitry. The laboratory trials resulted in a stable output of ~2.5 W at 5 V via a USB connection. The laboratory experiments also showed that the heat collector and cooling system can maintain the maximum temperature of the TEG to below the manufacturer's recommended threshold. Importantly, the simple and low cost single-phase thermosiphon cooling system can maintain the temperature of the cold side of a single TEG module at adequately low temperatures for sustained periods. Over the course of a five hour long laboratory-based experiment, the generator produced a maximum of 5.8 W, with a total energy output of 14.6 W·h. The magnitude of the power generated by this passive cooling system was observed to be comparable to that delivered by similar TEG-stove systems driven by active cooling. Using a specifically designed power control circuit with an efficiency of ~70%, the usable energy was ~10 W·h for charging. Thus, the laboratory trials showed that the system can be used to charge a variety of appliances that are powered by 5 V supplies such as mobile phones, LED lights, radios and rechargeable batteries and fields trials ensued.

Fig. 14 shows a daily power profile from a volunteer Malawian family using the prototype TEG-stove, and is very typical of the profiles measured across all stoves deployed in the field trial so far. The figure overlays the measured power generated by the TEG and the measured power consumed by the user's device. It must be noted that the power levels achieved in the field were lower when compared with laboratory experiments (cf. Fig. 10), which can be attributed to infrequent tending to the stove along with other factors such as using non-ideal wood or

Fig. 14. Measured TEG parameters during user operation of Stove B in the Thyolo field trial.

Prototypes were disseminated to 5 disparate volunteer households in the Thyolo district of Malawi, Africa. Preliminary field trial data shows promising results, with the generators being regularly used for charging and appearing to provide electrical energy when required. In-field power production is determined to be slightly below laboratory levels, which demonstrates that data measurement and collection is vital to the iterative design process. Even under-performing, the TEG-stove appears to provide adequate base-load electrical energy for the target demographic in Malawi. Future work will target improvement of performance by analysing the heat collection and cooling methods, based on the results obtained over a longer duration of the field trial.

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