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A combined heat and power system for solid-fuel stoves using thermoelectric generators

Andrea Montecucco[a]*, Jonathan Siviter[a], Andrew R. Knox[a]

[a] School of Engineering, University of Glasgow, Glasgow, G12 8LT, UK

Abstract

Solid-fuel stoves are used in developing countries, remote locations, and in general more commonly due to convenient fuel cost. The possibility of using the stove heat to heat water and produce electricity represents an added benefit.
This work presents an application of thermoelectric generators to a solid-fuel stove to concurrently charge a lead-acid battery and transfer heat to water for heating or household use. The feasibility of the proposed CHP system is demonstrated for a common solid-fuel stove. This system produces an average of 600 W_{th} and 27 W_{el} during a 2-h long experiment, in which the TEG efficiency is around 5% and the MPPT efficiency of the power converters used is demonstrated.

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Keywords: thermoelectric generator; TEGs; stove; CHP; heating

1. Introduction

A thermoelectric generator (TEG) is a robust and reliable solid-state device that converts part of the heat flowing through it into dc current when a temperature difference is maintained across it. The most commonly used commercial TEG devices use Bismuth Telluride (Bi_2Te_3) as thermoelectric material, and they can work up to a maximum of 300˚C.

Bass and Killander [1] presented a prototype thermoelectric generator for a wood-burning stove, simply placed on the top of it. It produced up to 10 W from a 75x75 mm^2 TEG with cooling provided by a 2 W fan blowing air over the heat sink. Nuwayhid [2] proposed a similar system cooled by air convection, producing up to 4.2 W from a single 56x56 mm^2 TEG. Rinalde *et al.* [3] developed a prototype TEG system for firewood stoves, producing 12.3 W from a temperature difference of 200˚C with two TEGs, but they reported problems of non-uniform contact pressure. Champier [4] presented a TEG system for

* Corresponding author. *Tel.*: +44-141-330-2180. *E-mail address:* andrea.montecucco@glasgow.ac.uk.

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stoves that was tested in the lab with a gas heater producing a maximum of 9.5 W from a 56x56 mm^2 device. The authors highlighted the influence made on heat transfer by mechanical pressure and thermal contact resistances. O'Shaughnessy [5], Kinsella *et al.* [6] proposed a TEG system for portable biomass cook-stoves that uses commercially-available parts to produce up to 5.9 W from a 40x40 mm^2 TEG and an average of 3 Wh of energy stored in a 3.3 V *lithium-iron phosphate* battery.

The main aim of all the aforementioned systems applying TEGs to stoves is to produce electrical power and they rely on inefficient natural or forced air convection for the cooling of the TEG's cold side. Min and Rowe [7] provided an alternative solution to overcome the low efficiency drawback: combining generation of heat and power into a "symbiotic" system, in which the heat released to the cold side is used to pre-heat water, thus effectively creating a combined heat and power (CHP) system. The overall efficiency of the symbiotic system is equal to that of a conventional heating system, but with the advantage that both electricity and heat are produced. A similar symbiotic system was developed by Vieira and Mota [8]. Chen *et al.* [9] examined the feasible deployment of TEGs in various CHP plants, analyzing efficiency improvements, technical drawbacks and economic benefits.

This work presents a TEG system comprising of a heat exchanger that fits into a solid-fuel stove, four 40x40 mm^2 TEGs with individual water-cooling blocks and by a small DC pump that circulates water to and from a 60-L water tank into the cooling blocks. This system is designed to absorb part of the heat produced by a common stove, burning coal, wood or charcoal and to direct it through the TEGs to circulating household water in such a way that the water is heated up while the TEGs produce electrical energy. This is effectively a CHP system.

The following section presents the proposed system, Section 3 shows the performance of this system during a typical two-hour burning time and Section 4 contains a discussion about the experimental results before the Conclusions.

2. Description of the system

The block diagram of the experimental rig is shown on the left of Fig. 1. Four TEG devices are positioned on top of an Aluminium heat exchanger, milled from a single block, that covers the top opening of the stove and has fins protruding inside it to improve the capture of heat. Four cold blocks are placed on top of the TEGs and a dc pump circulates 60 L of water through them to and from a water tank with header tank on top. The water tank is insulated, while all the piping connections are not. The product code of TEGs used is GM250-241-10-12 produced by *European Thermodynamics Ltd* [10]. Graphite-based thermal grease is used on both sides of the TEGs to minimise thermal contact resistance.

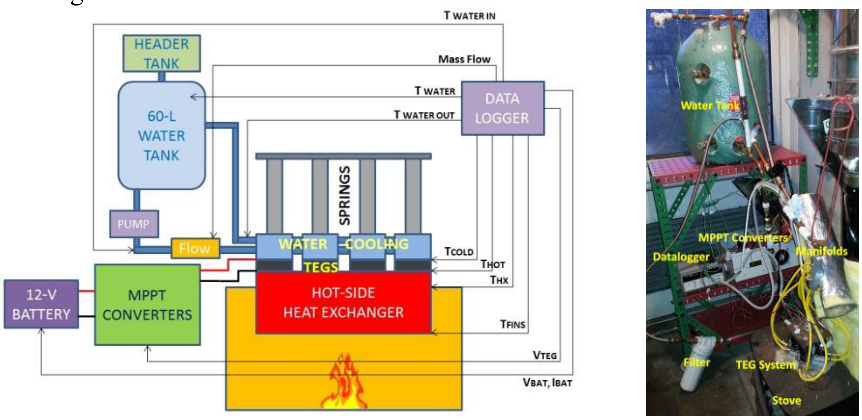

Fig. 1. Diagram (left) and picture (right) of the experimental system.

The whole system is mechanically clamped by a single M20 nut acting via a thrust bearing, and one 1000 lb/inch spring per TEG ensures even distribution of the force onto each fixture. A 24-V dc pump circulates water from a 60-L water tank to the flow and return manifolds distributing water to the cold blocks. The pump consumes $8W_{el}$ when set at 4.5 L/min (measured by a Hall-effect in-line flow sensor). Thermocouples are used to measure the temperatures on the cold sides of the TEGs, on the TEG side of the hot-side heat exchanger, and at the top and bottom of the fins inside the stove. The temperatures of the water inside the tank and at the inlet and outlet manifolds are also measured. A glass fibre gasket is used to ensure that no combustion gases escape from the stove and to isolate the fixture from the stove's exhaust pipe.

Two Buck-Boost MPPT converters, described in [11], are used to maximise the power produced by the TEGs and to interface them to a 12-V 12-Ah lead-acid battery. Each converter is connected to two TEGs, which in turn are connected in parallel. The voltage at the input of the MPPT converters, *i.e.* the TEGs output, the battery voltage and the battery current are measured. All sensors are connected to an *Agilent* datalogger to record the data through a program in *Agilent* VEE Pro.

A picture of the complete system is shown on the right of Fig. 1.

3. Experimental results

The stove was initially loaded with a significant amount of charcoal and fired. The results presented in this paper omit the first 16 minutes and are obtained during two hours of consecutive burning. During this experiment some solid fuel has been added approximately after 83 min, 107 min and 120 min.

Fig. 2 shows on the left the temperatures established at the bottom (T_{Fins}) and top (T_{HX}) of the fins (inside the stove), on the hot (T_{HOT}) and cold ($T_{COLD\ avg}$) side of the TEGs, inside the water tank ($T_{Water\ tank}$), and the temperature difference across the TEGs. The four thermocouples directly in contact with the TEGs cold sides measured almost identical values. Only one thermocouple was used to measure T_{HOT}, hence a precise measurement of the TEGs hot-side temperatures is not available. Nevertheless, the thickness of the heat exchanger and its high thermal conductivity provide good temperature uniformity, hence T_{HOT} approximates the values of the temperatures on the hot sides of the TEGs.

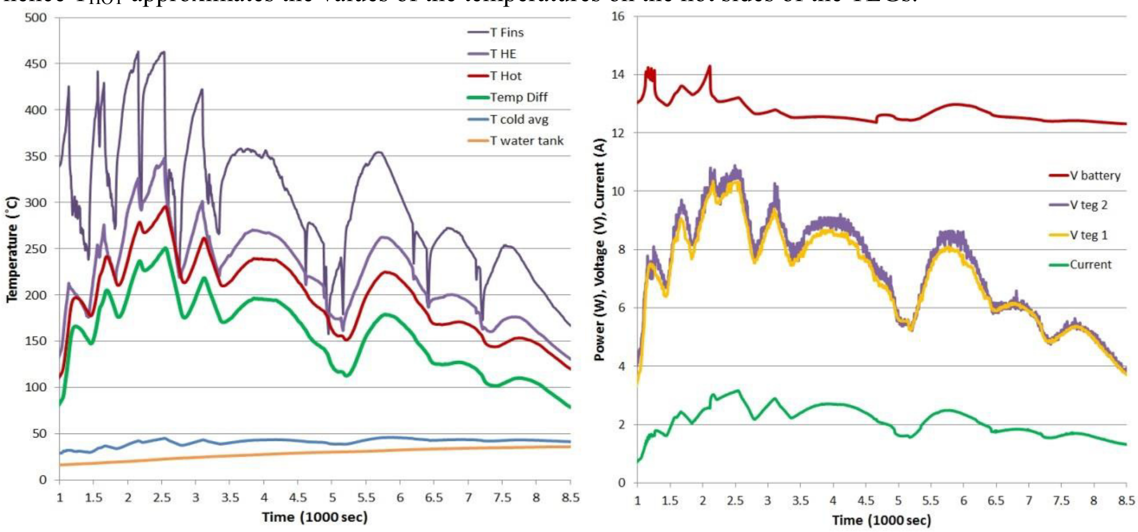

Fig. 2. Temperatures distribution (left) and electrical measurements (right) during the experiment.

T_{HOT} reaches almost 300˚C after 40 min. To prevent excessive temperature on the TEG hot side the window of the stove has been sometimes opened, easily noticeable by sudden drops of T_{Fins}. The large thermal mass of the stove heat exchanger limits this temperature swing on the TEG side.

The temperature difference across the TEGs varies considerably during the experiment, although the MPPT converters ensure operation at the maximum power point. The TEG operating voltages, V_{TEG1} and V_{TEG2}, are reported in Fig. 2, together with the battery voltage and current. $V_{battery}$ varies because some power resistors are periodically connected to prevent full charge of the battery.

The thermal power transferred to the water can be calculated from the temperature difference between the water in the outlet manifold, $T_{Water\ OUT}$, and that in the inlet manifold, $T_{Water\ IN}$, as shown in Eq. (1).

$$P_{Water} = \dot{m}C_{P,v}(T_{Water\ OUT} - T_{Water\ IN}) \tag{1}$$

where $\dot{m}$ is the flow rate in [L/s] and $C_{P,v}$ is the isobaric volumetric heat capacity in [J/LK]. P_{Water} and the electrical power generated by the TEGs ($P_{OUT} = V_B I_B$) allow calculating the thermal-to-electrical efficiency of the TEG system as shown in Eq. (2).

$$\eta = \frac{P_{OUT}}{P_{Water} + P_{OUT}} \tag{2}$$

Fig. 3 plots P_{OUT}, P_{Water} and η.

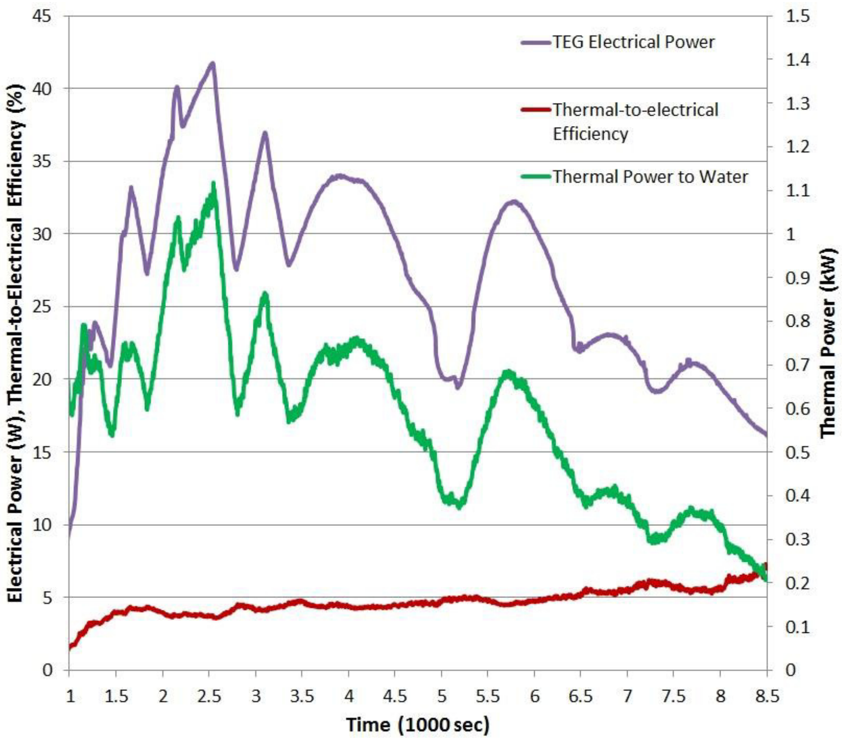

Fig. 3. P_{OUT} and η (left y-axis) and P_{Water} (right y-axis) during the experiment.

4. Discussion of results

This work proposes a CHP system that offers superior performance compared to other similar systems for stoves presented in literature and described in the Introduction. As shown in Fig. 4 the total electrical power produced by four 40x40 mm^2 TEGs and transferred to the battery (therefore including losses in the MPPT electronics) exceeds 40 W at the maximum temperature difference of 250˚C. This agrees with the performance listed in the TEG datasheet [10], thereby also validating the MPPT efficiency of the power converters used [11]. The average electrical power output during the considered period of time is 27 W, which is more than enough to drive the dc pump (8 W) and two high-power USB devices (2 A each).

The two MPPT converters were working at slightly different operating points (purple and orange lines in the plot on the right of Fig. 3). This could be due to small effects of thermal mismatch due to uneven mechanical conditions or to temperature variability [12] on the four TEGs due to their position on the stove, *e.g.*, the TEG closer to the stove door could sit at lower temperature.

The obtained thermal-to-electrical efficiency is between 4 and 5 %. Potential issues of excessive temperatures on the TEG hot side could occur if the stove is loaded with a significant quantity of fuel. A possible solution is represented by cascading two TEGs, one for high temperatures and one for low temperatures. Future work will address this issue.

Fig. 2 shows that the temperature of the water in the tank (orange line in left plot of Fig. 3) has been raised by 20˚C by an average thermal power of 582 W transferred through the TEGs. This is a convenient outcome because it can off-load the fuel consumption in the boiler use or transfer the heat produced by the stove to other parts of the house, passing through radiators or the under-floor heating system.

5. Conclusions

This experiment demonstrated the technical feasibility of the proposed CHP system for a common solid-fuel stove. This system both exchanges heat from the stove to circulating water for heating or normal household use, and it provides electrical power for the required pump and additional electrical equipment. Almost 600 W_{th} and 27 W_{el} are produced on average during a 2-h long burning experiment. The TEG efficiency is around 5% and the MPPT converters prove to constantly set the correct maximum power point at the TEGs output.

Future work will focus on the simulation of this experiment with the dynamic model presented in [13] and in the improvement of this technology with the aim to lower its cost.

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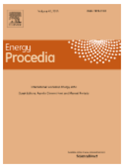

Biography

Dr Andrea Montecucco received his Ph.D. degree (2014) from the University of Glasgow, UK, where he is now a research associate. He has authored more than ten articles and holds one International patent. His research interests include testing and simulation of thermoelectric systems and MPPT converters for TEGs and PV.