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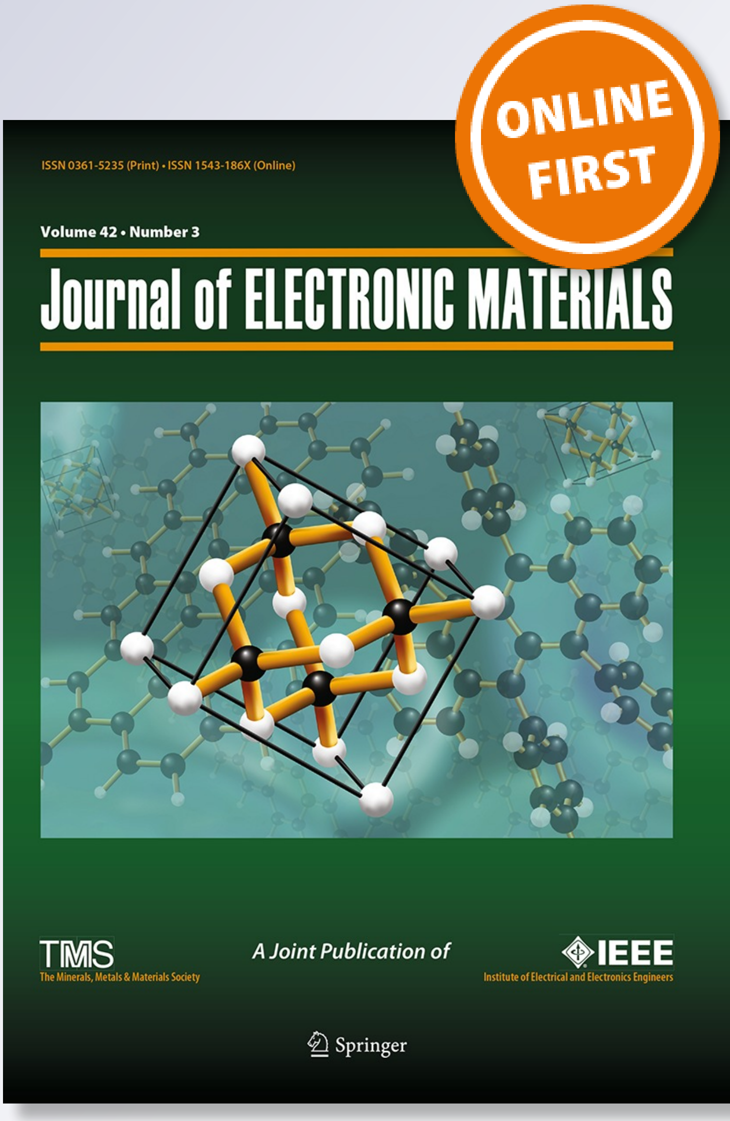

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Novel Heat Controller for Thermogenerators Working on Uncontrolled Stoves

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This paper describes the development of a thermogenerator designed for uncontrolled firewood household stoves. It was built on BiTe thermoelectric (TE) modules, and it uses a water pot as a cooling device that also serves as a hot water source. An original heat controller was developed; it has low thermal resistance (R) during low-power operation, but its R can be continuously increased according to the stove temperature so that the TE never overheats while its power generation is optimized.

Key words: Thermoelectricity, thermogenerator, heat flux controller, prototype development, household electrification

INTRODUCTION

Thermoelectric (TE) materials have been known for almost two centuries, although to date they have not been massively applied for electricity generation. However, in the last few years, TEs have been considered within the portfolio of new sustainable energies[1–4] due to the entrance onto the open market of independent manufacturers of BiTe modules from the USA such as Tellurex[5] and also Thermonamic from China.[6] Tellurex's TEs are priced at approximately 4000 USD/kW and Thermonamic's at 2500 USD/kW, both cheaper than photovoltaic (PV) panels. In addition, the possibility of using a household heating source (such as a firewood stove) burning for many hours a day allows TEs to obtain net capacity factors (calculated as the total amount of electricity generated annually divided by the product of the annual hours and the nominal power of the module) noticeably higher than PVs, thus potentially offering a less costly option.[7] Nevertheless and despite this favorable outlook, there are issues related to thermal behavior that must be solved in order for TEs to become a feasible technology, since commercial TEs available on the open market cannot withstand the temperatures of gas chimneys[8] or the tops of domestic firewood stoves.[2,8] Up to now, only conceptual prototypes have been proposed, but they do not resolve this major issue.[1,2,9–11]

The Hi-Z prototype[9] uses two TE modules attached to a hot gas chimney and cooled by dissipators with self-powered fans. This solution implies high consumption of about half of what the TEs generate.[10] However, worse than that, this design cannot manage the high temperature range of output gases, ranging from 150°C to 450°C.[8] Of course, it is possible to put a large thermal resistance between the chimney and the hot side of the TE so that it never overheats; however, in this case, the TE generation is greatly penalized when the stove is working at lower temperatures, which is what happens in most cases.

The above-described behavior is key to understanding the real potential of this application. Domestic stoves usually work within a wide range of temperatures, for example, reaching the maximum temperature once a week for baking, but working at much lower temperatures most of the time. Commonly, a stove works at medium temperature during the morning hours for cooking, and after that it is kept at a minimum temperature throughout the whole day except when cooking. This pattern is reinforced during the winter season with longer working hours and higher temperatures with much higher temperatures at night, since the stove is

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used for space heating as well. This pattern matches very well with the electricity demand of dwellers, which is a strength of this TE application, being almost the opposite to PV generation.

The fan-cooled dissipator is a compact design suitable for stove-top thermogenerators, as was proposed for Arctic homes.[8] The stove-top design has the advantage of using a less-variable heating source (maximum 280°C), but it has the drawback of wasting most of the heat used. Regarding the very low thermoelectric efficiency (4%) and scarcity of firewood resources, this is a major concern. Some "pot cooling" designs have been proposed, in which the water reservoir is used as a heat sink.[6,12] In this way, the fan energy consumption is eliminated and hot water, a useful byproduct, is obtained, achieving cogeneration efficiencies of about 90%. However, since thermal concerns have not yet been solved, these generators have only been proposed for working on preset butane burners.[5] This paper presents a new design for the thermogenerator of a pot cooling design suitable for working on uncontrolled heating sources such as firewood stoves. The innovation is related to a heat controller device developed for managing the variable heating flux.

PROTOTYPE DEVELOPMENT

This prototype was built on nine G1-54-0557 Tellurex modules mounted between two aluminum plates (the heating collector and dissipator) in a square assembly (0.2 m × 0.2 m) and held together with 12 screws (Fig. 1) used to ensure a homogeneous contact force. This thermopile is mounted on the tall lateral walls of the water pot; in this way, the fluid is directly on top of the dissipator plate. These TEs are connected electrically in three parallel lines so that in average operation a voltage suitable for charging lead–acid batteries is obtained. The tap water facilitates the exchange of hot and cold water in order to optimize the TE generation, as discussed in the next section (Fig. 2).

THERMAL MODELING

The thermal modeling was performed using a one-dimensional (1-D) model of thermal resistances connected in series between temperature nodes that describe each subsystem with a homogeneous temperature, as illustrated in Fig. 3. This hypothesis is valid when the thermal gradient inside each node is negligible in relation to the temperature drop across the thermal resistances. This model applies very well here, as has been demonstrated.[10] In this case the nodes are: (1) the stove top, T_{top}, (2) the heating collector plate, T_{h}, (3) the dissipator plate, T_{c}, and (4) the water bulk, T_{w}. The two inner nodes represent the TE hot side (T_{h}) and cold side (T_{c}), while the two outer nodes represent the boundary conditions. These nodes are interlinked by thermal resistances: (1–2) the heating resistance, R_{top}, (2–3) the TE resistance, R_{TE}, and (3–4) the resistance of

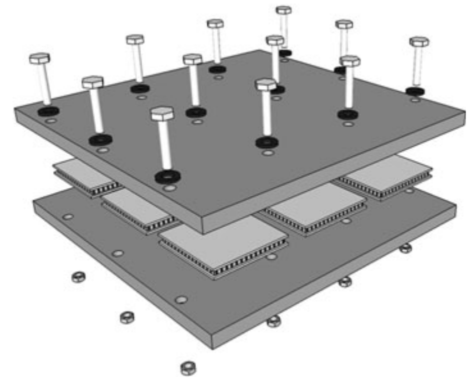

Fig. 1. Schematic view of the thermopile assembly.

Fig. 2. Lateral view of prototype.

free convection flow, R_{conv}. The heating plate (thin aluminum) actually has negligible thermal resistance, but instead here an additional thin layer of insulating material that should be added onto the stove top is considered in order to limit the TE temperature, considering the stove top (280°C) and TE (175°C) maximum temperatures. Thus, the R_{top} value must be set regarding this worst case.

According to the manufacturer, the thermal resistance of one TE module is 0.6°C/W (so for the parallel assembly R_{TE} = 0.0666°C/W) and the power generated (P) can be correlated to the TE temperature drop (ΔT_{TE}) by Eq. (1):

$$P = 5 \times 10^{-4}(\mathrm{W/^{\circ}C^2})\Delta T_{\mathrm{TE}}^2. \quad (1)$$

The free-convection resistance is estimated following the engineering correlations in Eqs. (2–5). The Rayleigh number Ra of the flow is obtained

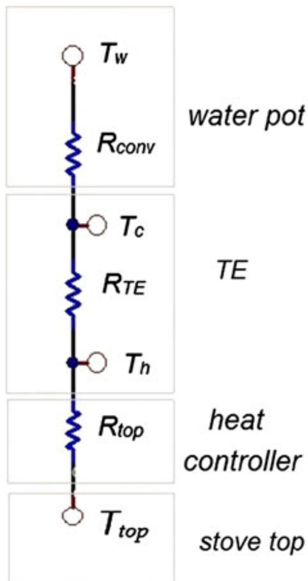

Fig. 3. Schematic of the thermal model.

from the following fluid properties: kinematic viscosity v, thermal diffusivity α, and compressibility β, and from the characteristic length L (0.2 m), gravity constant g, and temperature difference according to Eq. (2):

$$\mathrm{Ra} = \frac{g\beta(T_c - T_w)L^3}{\alpha v}. \tag{2}$$

The Nusselt number Nu of the flow is determined for laminar (Eq. 3a) or turbulent flow (Eq. 3b) as:

$$\mathrm{Nu} = 0.54\mathrm{Ra}_L^{\frac{1}{4}} \quad \text{if } 10^4 \le \mathrm{Ra} \le 10^7 \tag{3a}$$

$$\mathrm{Nu} = 0.15\mathrm{Ra}_L^{\frac{1}{3}} \quad \text{if } 10^7 \le \mathrm{Ra} \le 10^{11} \tag{3b}$$

So, the heat convective coefficient, h, is determined by Eq. 4 with the fluid thermal conductivity k:

$$h = \frac{\mathrm{Nu}k}{L}. \tag{4}$$

Finally, the convective resistance R_{conv} is calculated with the cross-section area, A, by Eq. 5:

$$R_{\mathrm{conv}} = \frac{1}{hA}. \tag{5}$$

The temperature profile along this resistance-in-series scheme is calculated from the two boundary conditions (T_{top}, T_w) using the well-known thermal–electrical analogy. Hence, the total resistance R_{tot} is related to the heating power, q, and the total temperature drop, ΔT_{tot}, by Eq. (6):

$$R_{\mathrm{tot}}q = \Delta T_{\mathrm{tot}}, \tag{6}$$

where R_{tot} is the sum of resistances:

$$R_{\mathrm{tot}} = R_{\mathrm{top}} + R_{\mathrm{TE}} + R_{\mathrm{conv}}. \tag{7}$$

Similarly, the temperature drop along each resistance is given by:

$$R_{\mathrm{top}}q = \Delta T_{\mathrm{top}}, \tag{8}$$

$$R_{\mathrm{TE}}q = \Delta T_{\mathrm{TE}}, \tag{9}$$

$$R_w q = \Delta T_w. \tag{10}$$

Hence, and for every set of temperatures (T_{top}, T_w) considered and a given R_{top} (0.108°C/W), the stationary state and power generated can be fully calculated by going through Eqs. 1 to 10 as presented in Table I for the maximum T_{top} (280°C), where R_{top} was set so that the TE never overheats.

Let us observe (Table I) that the penultimate case represents the condition in which the cold-plate temperature (T_c) reaches the boiling temperature but heat is transferred even by means of single-phase free convection, while the boiling mechanism occurs in the last case. Here the limiting condition is observed to correspond to nucleated boiling, in which the heat transfer is considerably enhanced and therefore in this condition the wall temperature (T_c) is practically set to 110°C.[13] So, this temperature determines the R_{top} value, and conversely, this value implies non-optimal generation for the lower T_{top} cases. Thus, it is interesting to study the improvement that could be obtained by adjusting the value of R_{top}. This feature is studied in Table II, in which the ideal R_{top} is calculated in each case for optimized generation. A very noticeable improvement can be obtained in this way: up to 16 W more, equivalent to an increase of 55% in TE performance. Moreover, this improvement could be greater when the stove is running at an average temperature instead of its maximum power. Table III presents comparative results between a conventional design (R_{top} = 0.108°C/W) and an improved design (tuning R_{top}) for an average (T_{top} = 200°C) stove heating power. Here an outstanding improvement is achieved, more than doubling the thermoelectric power generation.

HEAT CONTROLLER MODELING

The results of the above analysis serve as a starting point for the design of the heat controller. This device consists of a fan-assisted finned

Table I. Thermal parameters for different T_w, for T_{top} = 280°C and R_{top} = 0.108°C/W

T_w (°C)	R_{conv} (°C/W)	q (W)	T_h (°C)	T_c (°C)	P (W)
12	0.043	1230	147	65	30.3
42	0.023	1200	150	70	29.0
62	0.020	1030	159	84	25.1
82	0.018	975	169	100	21.1
100	–		175	110	19.0

Table II. Comparison between actual and ideal power generated (varying R_{top}) for T_{top} = 280°C

T_w (°C)	R_{top} (°C/W)	P_{ideal} (W)	ΔP (W)	ΔP (%)
12	0.071	45	14.7	48
42	0.071	45	16.0	55
62	0.080	34	8.9	36
82	0.095	24	2.9	14

Table III. Comparison between performance for actual power (R_{top} = 0.108) and ideal power (varying R_{top}^{ideal}) for T_{top} = 200°C

T_w (°C)	P_{real} (W)	R_{top}^{ideal} (°C/W)	P_{ideal} (W)	ΔP (W)	ΔP (%)
12	14.9	0.017	44.1	29.2	196
42	12.8	0.017	43.9	31.1	244
62	10.1	0.019	34.1	24.0	239
82	7.5	0.0225	24.2	16.7	223
100	5.9	0.025	19.0	13.1	224

dissipator. Conventionally, the fan power is used to regulate the thermal resistance of the TE heat sink,[11] and similarly here it is used to change the thermal resistance of the heating power (R_{top}) to control the temperature of the TE hot side. Thus, the finned dissipator is placed between the heat source and the TEs (instead of in its conventional position, i.e., between the TE and heat sink). However, here the fan causes the opposite behavior to the conventional case. Conventionally, the dissipator resistance decreases when the fan flow increases, but conversely, in this new application, the thermal resistance increases when the fan flow increases. Conventionally, the fan is used to improve the heat flux transferred by air convection, while here it is used to reduce the heat flux transferred by conduction through the fins. This original concept allows us to call this device a "heat controller." So, the minimum thermal resistance is obtained without a fan by conduction through the vertical fins with two interconnecting horizontal plates, as shown in Fig. 3, in which an air channel is designed to redirect the fan flow. In this condition, the heat dissipated by free convection into the closed cavities can be neglected and so

$$R_{top}^{min} = \frac{H}{SK} = 0.017^\circ\frac{\mathrm{C}}{\mathrm{W}}, \tag{11}$$

where H and S are the height and transversal cross-section of the fins, respectively; these parameters can be used to adjust the resistance to the desired value. After a preliminary design is proposed, it must be checked if a "reasonable" cooling flow (that is, created by a small fan consuming low power) could increase the R_{top} value up to six times, which is ultimately the object of this device. After some iterative trial-and-error process, a design (Table IV; Fig. 4) was selected, but it is necessary to verify that (while consuming a reasonable fan power) the R_{top} can be increased six times (to 0.108°C/W). In this case it is calculated (going again through Eqs. 1 to 10) that, for R_{top} = 0.017°C/W, the equivalent heating flux obtained is q_0 = 1922 W instead of the value (925 W) previously calculated for R_{top} = 0.108°C/W. Therefore, it can be concluded that a dissipator with an *equivalent* R_{top} can be obtained if the cooling flow can remove 947 W. This last condition must be verified by modeling the cooling flow into the flow channels. The Dittus–Boelter correlation[13] is commonly used for internal flows:

$$\mathrm{Nu} = 0.023 Re^{0.8}\mathrm{Pr}^{0.4}, \tag{12}$$

where Re and Pr are the Reynolds and Prandtl numbers of the flow, respectively, defined by:

$$Re = \frac{VD}{\nu}, \tag{12}$$

$$Pr = \frac{\nu}{\alpha}, \tag{13}$$

where V is the mean air velocity and D is the hydraulic diameter of the flow channels. Going from Eqs. (12–14) for a cooling flow of 4.7 l/s (that is V = 40 m/s), Nu = 31.9 is obtained, and thus (by Eq. 4) a heat transfer coefficient h of 152 W/°Cm^2 is estimated. Hence, using Newton's cooling law given in Eq. 14, the cooling power P can be estimated as

$$P = A_c h \Delta T, \tag{14}$$

where A_c (0.1285 m^2) is the cooling wetted area and ΔT can be estimated as the average temperature difference between the hot fins and the air flow. From Eq. 14 (using a guessed value of ΔT = 50°C) a cooling power of 976 W is obtained, which is enough to modify R_{top}. The last point is to check whether this cooling power can be transferred to the air flow by considering its energy balance in Eq. 15:

$$P = m' C_p \Delta T, \tag{15}$$

where m' is the air mass flow of heat capacity C_p = 1 kJ/kg°C and ΔT is the temperature difference

Table IV. Geometrical parameters of the heat controller design

Total width	20 cm
Fin height	3 cm
Fin/flow channel width	2.52 cm/3.9 mm
No. of fins/no. of flow channels	7/6

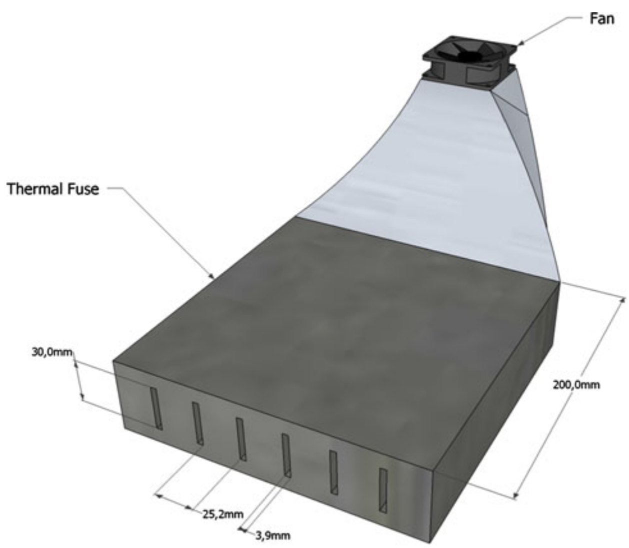

Fig. 4. Schematic view of the heat controller device.

of the flow along the dissipator (that is, between the entrance and exit conditions). From this, ΔT can be calculated at $\Delta T = 207°C$. Since the air inlet temperature can be estimated at 30°C, this ΔT value implies an exit temperature of 237°C, and so the guess value $\Delta T = 50°C$ is achieved (in this case, $T_{top} = 280°C$) very conservatively, considering that this value is related to the average temperature difference. So, it can be concluded that this dissipator could fulfill the criteria for providing a suitable adjustable thermal resistance. The fan consumption can be calculated from previous studies on the TE fan cooling dissipator,[11] as around 1.5 W, which is very reasonable for this purpose considering the improvement obtained in exchange.

CONCLUSIONS

This paper presents for the first time a conceptual design for a heat controller intended to work on TE generators mounted on uncontrolled heating sources such as firewood stoves. This is a simple thermal device that uses a fan in order to regulate the heat flow transferred by conduction through the finned system.

Thermal modeling demonstrates the feasibility of this new concept. Using a small fan with a variable cooling flow (as commonly used in electronic power units), this dissipator can increase its thermal resistance by more than six times. In this way, a stove-top generator could become a feasible solution regarding the wide range of working power of firewood stoves. As this is a preliminary design developed only up to its conceptual level, it requires further studies and experimental testing, but due to its intrinsic simplicity it seems to have a good chance of success.

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