Characterization of a Peltier module working as a thermoelectric generator

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Abstract: We studied the suitability of current thermoelectric devices as electrical power generators, measuring the I-V curves of a Peltier cooler under field-like conditions. We designed an experimental system that allowed the Peltier module to work under a constant thermal input flux or a constant temperature difference. From these I-V curves we have calculated the thermoelectric figure of merit and the conversion efficiency of the device, comparing it with maximum theoretical values.

I. INTRODUCTION

Liquified natural gas (LNG) is brought form Algeria to Barcelona by huge carrier ships at -162°C. Once delivered in the harbor it is stored in tanks about 100.000 m^3 of capacity, and has to be vaporised to be able to use it as a combustible. The vaporisation is done using sea water at room temperature. We know that LNG is predominantly methane, so assuming that the density of liquid methane is $\rho = 422.36$ kg/m^3 and his latent heat of vaporisation is $L = 510.83$ kJ/kg, we can estimate the amount of heat Q_{LNG} needed to evaporate the LNG stored in one of this tanks since

$$Q_L = mL \quad m = \rho V \tag{1}$$

This gives us $Q_{LNG} \approx 2 \cdot 10^{13} J$, which corresponds to the electrical energy consumed by a population of 4000 inhabitants during a year.

Currently this huge amount of *cold* energy is thrown to the envirornment as cooled water each time a vaporisatoin process is performed. In addition, nowadays 30% of the energy in industrial processes is lost by waste heat. More examples could be shown of how are we loosing and wasting energy that could be reused or partially recovered to preserve our future.

The aim of this study is to get a deeper insight of current thermoelectric (TE) devices as electrical power generators under real field conditions, and suggest possible applications that could recover wasted heat and improve energy harvesting, reducing greenhouse gas emissions and improving energetic efficiency.

For that, two paths have been followed.

A) **Theoretical**: We have get a clear understanding of thermodynamics behind thermoelectricity, studying which are the TE effects and which relations we find between them. This is developed in section II.

B) **Experimental**: We have characterized a Peltier module working as a electrical power generator. In order to obtain the I-V curves under different conditions we have designed and mounted a experimental system to apply a temperature difference accross the TE module while measuring the voltage output and the electrical current output of the device. This is developed in section III.

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II. THEORETICAL BASIS

A. TE Effects and Kelvin's Relations

When describing a thermoelectric device, e.g. a thermocouple, 5 effects must be taken into account, wich are [1–3]: Fourier, Joule, Seebeck, Peltier and Thomson effects. Each one is governed by a physical parameter, characteristic of every particular material, that is the *coefficient of thermal conductivity*, λ, the *resistivity*, ρ, the *Seebeck coefficient*, α, the *Peltier coefficient*, π and the *Thomson coefficient*, τ, respectively.

Seebeck, Peltier and Thomson effects are known as the reversible TE effects, which are strongly related by the two *Kelvin's relations*. In fact, one can deduce from those relations that

$$\pi_{AB} = T(\alpha_A - \alpha_B) \tag{2}$$

$$\tau_A - \tau_B = -T\frac{d}{dT}(\alpha_A - \alpha_B); \tag{3}$$

a simple substraction and a derivative of the respective Seebeck coefficients for materials A and B forming the TE device determine the remainding TE coefficients. Therefore, to describe TE reversible effects we only need to have well characterized the Seebeck coefficient for a certain material.

B. TE generator

A TE generator is a device that provides electrical power from a temperature difference, see Fig. (1). The analogy with a heat engine is evident, and it has the advantage that excludes any moving mechanical parts or working fluids to obtain power from a heat source. The

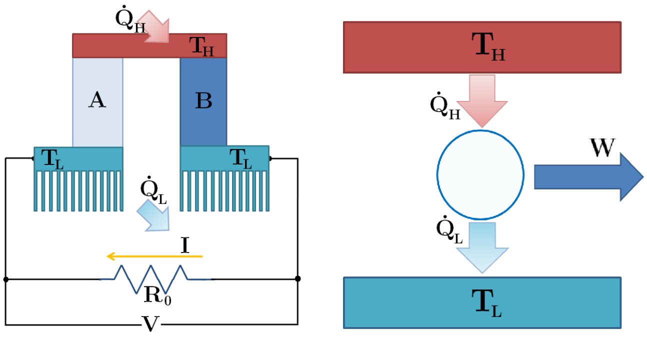

FIG. 1: The behavior of a TE generator corresponds to a heat engine working between a hot source at temperature T_H and a cold sink at temperature T_L.

main parameter that evaluates the suitability of a thermoelectric material for energy conversion is the TE figure of merit, Z, defined as [3]

$$Z = \frac{\alpha^2}{\rho\lambda}, \tag{4}$$

the higher Z, the best the material for TE applications. In addition, the maximum conversion efficiency, η_{max}, is proportional to Z, meaning that with the measure of Z one characterizes completely any TE device. There are many methods to measure the figure of merit, either measuring separetly α, ρ and λ or directly, using the Harman method [4] or the Min-Rowe method [5, 6]. In ths work we used the method based on I-V curves, firstly proposed by G. Min [6], because of its simplicity and the possibility to make measurements under field-like conditions.

To characterize a TE device or module we work under two different conditions, a *constant temperature difference*, ΔT or a *constant thermal input flux*, $\dot{Q}$. When operating under contant ΔT, the current I and voltatge V delivered to the load resistance are given by [3, 6]

$$I = \frac{\alpha\Delta T_0}{R_i + R_0} \tag{5}$$
$$V = \frac{R_0}{R_0 + R_i}\alpha\Delta T_0, \tag{6}$$

where R_i is the internal resistance of the generator, R_0 is the load resistance and $\alpha\Delta T_0$ is the voltage generated because of the Seebeck effect, being $\Delta T_0 = (T_H - T_L)/2$. From Eqs. (5) and (6) G. Min obtained the following relation between I and V:

$$V = \alpha\Delta T_0 - R_i I. \tag{7}$$

When operating under constant input power $\dot{Q}$, the temperature gradient across the device will change with the value of the load resistance, so the expressions for I and V are slightly different. The relation found between I and V is

$$V = \frac{\alpha\Delta T_0}{1 + ZT_M} - R_i I, \tag{8}$$

where T_M is a parameter that depends on T_H, T_L and the ratio of the load resistance to the internal resistance, $s \equiv R_0/R_i$,

$$T_M \equiv \frac{(1+2s)T_H + T_L}{2(1+s)^2} \tag{9}$$

Apparently both linear curves given by Eqs. (7) and (8) should have the same slope. However, due to the fact that T_M also depends on R_0, representing the two I-V curves results into two different straight lines that coincide for $R_0 \to \infty$, that is, for open circuit conditions, but are not parallel [6].

From a pair of curves I-V, one measured for the TE device operated for a constant ΔT, and the other for a constant $\dot{Q}$, we can calculate the figure of merit according to the following equation

$$Z = \frac{1}{\overline{T}}\left(\frac{I_\Delta}{I_Q} - 1\right), \tag{10}$$

where I_Q and I_Δ are the short circuit current, when operating under constant $\dot{Q}$ and constant ΔT, respectively, and $\overline{T}$ is the average temperature across the TE device

$$\overline{T} = \frac{T_H + T_L}{2}, \tag{11}$$

being T_H and T_L the temperatures for open circuit conditions. Knowing the value of Z we can calculate the maximum theoretical conversion efficiency ([3, 6])

$$\eta_{max} = \frac{1}{4}\Delta T_o Z, \tag{12}$$

It is to be noted that $\dot{Q}$ and ΔT curves have to be obtained **ensuring that the initial temperature difference ΔT_0 is the same for both curves**. In this conditions, it should be possible to calculate the before mentioned parameters. A part from the expression for the conversion efficiency presented on Eq. (12), one can also calculate η as its own definition: the ratio between the power generated to the input heat flux $\dot{Q}$

$$\eta_Q = \frac{P_{max}}{\dot{Q}}, \tag{13}$$

where P_{max} can be calculated as the maximum point of a P-V curve. As $P = V \cdot I$ and I has a linear dependence with V, plotting the output power P in front of the output voltage V should result in a parabolic curve.

III. EXPERIMENTAL SYSTEM

A schematic diagram of the different components of the experimental system is shown in Fig.(2). The system is composed by the following elements:

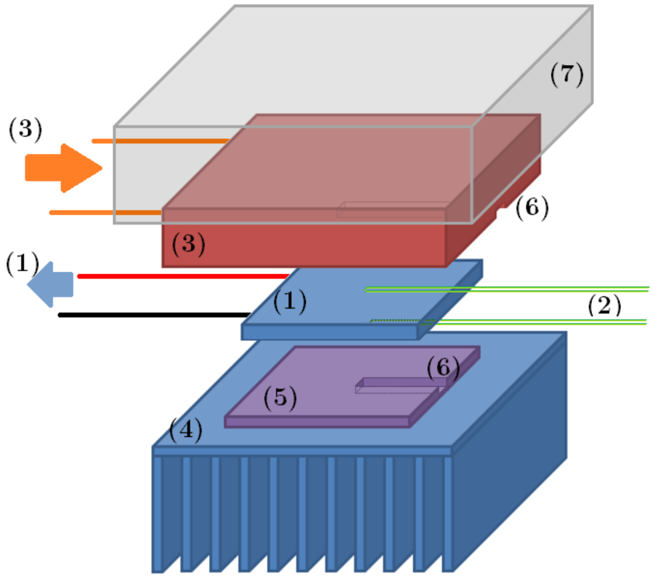

FIG. 2: Simple drawing of the experimental system used to characterize the Peltier module.

(1) **Peltier module**. The TE module characterized is a commercial Peltier cooler. This modules are formed by an array of PN junctions, as shown in Fig.(3), and is typically used as a regrigerator or a heat pump: when a current flows trough the module one of the junction warms up (hot side) and the other cools down (cold side). Red and black wires of the Peltier are connected to the measurement system, see Fig.(4).

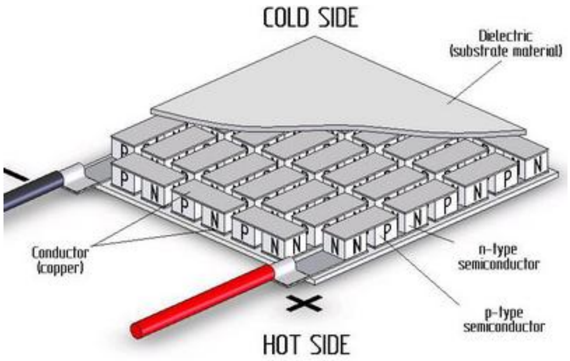

FIG. 3: Schematic diagram of a Peltier cooler. *According to The Renewable Energy Website: http://www.reuk.co.uk/*

(2) **Thermocouples**. We used K type thermocouples to measure the temperature of both hot and cold sides of the TE module.

(3) **Heater**. Made of an aluminum block with embedded resistances. Once connected to a power source (orange wires) it dissipates electrical energy due to Joulean power loss. In this way we can control precisely the amount of $\dot{Q}$ delivered to the heater.

(4) **Heat sink**. We used a computer fan-cooled heat sink to ensure that the cold side remains always at room temperature. Because of the thermal conductivity of the device, heat passes through the module warming up the whole device, decreasing the temperature difference.

(5) **Thermal contacts**. We prepared two elements to ensure good thermal contact between the Peltier module and both the heater and the heat sink. Firstly, we used a silicone based thermal grease, and secondly, we took profit of the cooper contact layer of the heat sink to fit the Peltier module.

(6) **Straight grooves**. We milled a groove in both aluminum and cooper sides touching the Peltier module to avoid thermal contact with the thermocouples, that could alter the temperature measurements of both sides of the TE device. We also ensured not to spread thermal grease around the thermocouples.

(7) **Insulator cover**. To avoid as far as possible heat flow from the heater to the enviorment, and from the lateral sides of the TE module, we used an expanded polystyrene cover, so the heater and the module remained isolated.

To measure the I-V curves we used a variable load resistance connected in series to an ammeter and a voltmeter connected in parallel to the whole circuit, as shown in Fig.(4). To reach as far as possible the short circuit conditions, the ammeter was programmed to work always at its higher range (3 A), so the shunt resistance was the lowest (0.1 Ω). All the multimeters used to measure voltage, current and temperature (thermocouples) where connected using GPIB connections so all data acquiered could be monitorized and automatically saved on a computer.

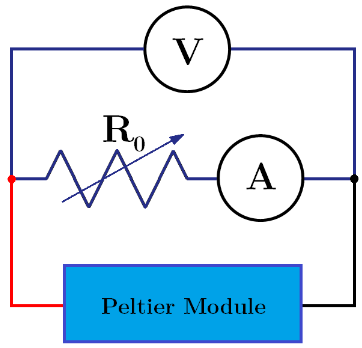

FIG. 4: Circuit used to measure the I-V curves.

With this simple system we can easly inforce constant $\dot{Q}$ conditions, by applying a known electrical power. However, it is not so simple to ensure a constant temperature difference, because when decreasing the load resistance value, the electrical current flowing through the device increases, which implies changes of the temperature at both hot and cold sides. For this reason, to mantain ΔT consant we need to increase the input power as we decrease R_0. In order to quantify this phenomena we made different transient measures from the stationary state at a constant power input, to the stationary state at $\dot{Q} = 0$, for different values of the load resistance.

IV. RESULTS AND DISCUSSION

Let us first disccuss the results of the transient curves, presented in Fig.(5). From the experimental data we

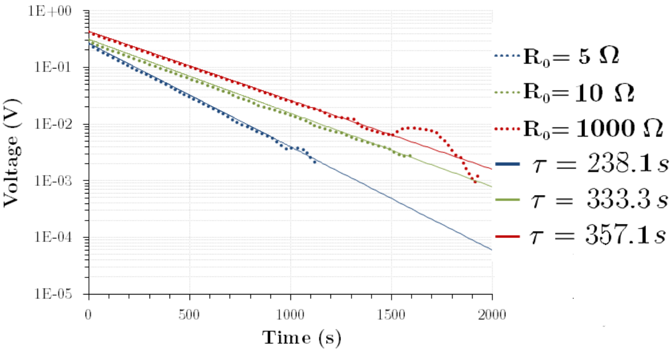

FIG. 5: The y-axis is in logarithmic scale. Three different transient curves were obtained for R_0 = 5, 10 and 1000 Ω. Dot lines represent the experimental transient curve. Solid lines represent the linear adjustment.

could fit a decreasing exponential curve, obtaining diferent time constants, τ. As we could expect, the lower the load resistance, the lower the τ. In fact, for lower R_0, the temperature in both sides changes fastly and reaches the stationary state sooner than for higher R_0.

The I-V curves obtained under constant $\dot{Q}$ and constant ΔT conditions are those presented in Fig.(6). Different constant input power and initial temperature

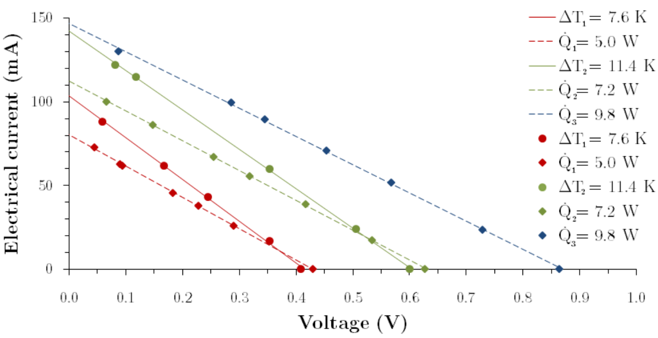

FIG. 6: The ♦ marker represents experimental points obtained under constant ΔT conditions. The • marker represents experimental points obtained under constant Q conditions. Continuous and dashed lines correspond to the linear adjustment of the experimental data (constant Q and constant ΔT conditions respectively).

difference have been established. We made measurements for constant $\dot{Q}_1 = 5.0$ W, $\dot{Q}_2 = 7.2$ W and $\dot{Q}_3$ =9.8 W and for constant $\Delta T_1 = 7.6$ K and $\Delta T_2 = 11.4$ K, at room temperature $T_L = 24.0 \pm 0.5$ °C. This linear I-V curves, experimentally obtained, are consistent with those theoretically found by G. Min [6].

By performing curve fitting, we have calculated the values of I_Q, I_Δ (Table I), considering the error associated to the linear adjustment. From values presented on

I-V used	ΔT_o (K)	$\overline{T}$ (K)	I_Q (mA)	I_Δ (mA)
$\dot{Q}_1$,ΔT_1	7.6 ± 0.1	300.8 ± 0.6	80.2 ± 0.5	103.3 ± 1.5
$\dot{Q}_2$,ΔT_2	11.4 ± 0.1	302.7 ± 0.6	112.3 ± 0.5	142 ± 1

TABLE I: Values of $\overline{T}$ have been calculated using Eq. (11). Values I_Q and I_Δ have been calculated trough linear regressions of the experimental data for $\dot{Q}_1$, ΔT_1, $\dot{Q}_2$ and ΔT_2 curves.

Table I we can calculate Z and η_{max}, according to Eqs. (10) and (12). First of all, as we can see in Table II, both pair of curves give us barely the same value for Z, which has to be a constant for a given TE module or material. Considering the errors on the linear adjustment and errors in temperature measurements we verify that Z values coincide.

I-V used	Z (10^{-4} 1/K)	η_{max} (%)
$\dot{Q}_1$,ΔT_1	9.6 ± 0.9	0.18 ± 0.02
$\dot{Q}_2$,ΔT_2	8.7 ± 0.5	0.25 ± 0.02

TABLE II: Values of η_{max} calculated from our experimental results. Conversion efficency increases with ΔT_o.

Secondly, we observe that η_{max} calculated in Table II increases with ΔT_o, wich is consistent with efficiency dependence on ΔT_o, see Eq. (12). Finally, we must outline that maximum theoretical conversion efficiency values are very small, under 1 %.

To reach a better understandig of the experimental system, we compared the obtained η_{max} with the efficiency conversion measured from the constant $\dot{Q}$ curves, using Eq. (13). We calculated the different P_{max} by plotting the output power P vs. the output voltage V, which fits a parabolic curve, as it is observerd in Fig.(7). We saw that the maximum power generated by the Peltier module was greater for constant ΔT curves than for constant Q curves, when starting from the same temperature difference across the TE device. As we could expect, this is due to the fact that for ensuring a constant ΔT during the measurement process it is necessary to increase the input power of the heater block, to balance out the effect of a electrical current flowing through the TE device.

As we know the constant $\dot{Q}$ delivered to the heater, we can obtain the conversion efficiency of our TE device, see Table III.

Comparing results of Tables II and III we observe that the conversion efficency of our Peltier module working

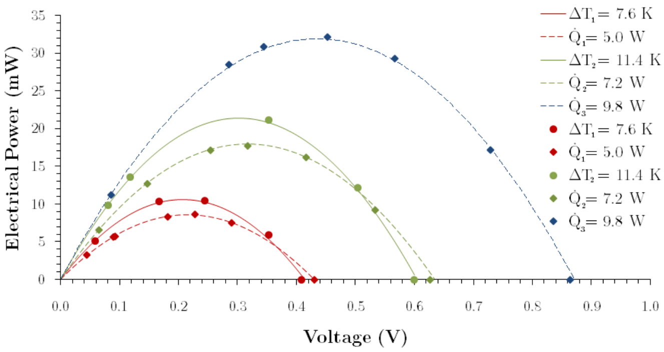

FIG. 7: Power output in front of voltage output. The legend for the markers is the same as in Fig.(6).

Curve	$\dot{Q}$ ±0.1 (W)	P_{max} (mW)	η (%)
$\dot{Q}_1$	5.0	8.6 ± 0.3	0.17 ± 0.01
$\dot{Q}_2$	7.2	17.6 ± 0.9	0.24 ± 0.03
$\dot{Q}_3$	9.8	126 ± 1	1.28 ± 0.02

TABLE III: Conversion efficiency calculated trough the maximum output power of the Peltier module and the delivered power to the heating block.

under real conditions is very similar to the maximum efficiency calculated using I-V curves experimentally acquired. This lead us to rely on the aproximation that barely all the power transferred to the heater passes trough the Peltier module. We should take into account that to ensure the room temperature at the cold side of the TE device we used a computer fan-cooled heat sink, which consumed 12.2 W, so if we sum to the heating power the cooling needed power we would obtain a smallest conversion efficiency.

V. CONCLUSIONS

On one hand, we forced a Peltier module to work as a TE generator, under real field conditions, and we could obtain measurable electrical power, starting from small temperature differences.

On the other hand, we have calculated the conversion efficiency, obtaining a maximum value of $\eta = 1.28$ % when operating in constant $\dot{Q} = 9.8$ W conditions. This value is big enough to consider applications in fields as energy harvesting and waste heat recovering, two examples of such are:

- **Supply wearable electronic devices**. We obtained valuable electrical power from very small temperature difference. De difference between human body and room temperature is about 11 K. In this conditions we measured a maximum power about 100 mW, which is enough to supply small wearable electronic devices on smart textiles.
- **Industrial waste heat recovery**. Waste heat from high temperature industrial processes as thermal power plants or oil refining plants has a average temperature about 373 K. That provides us a temperature difference of about 75 K, from which a thermoelectric module could extract energy.

Further experiments should characterize the TE device working under high temperature differences, to analize its behaviour under more agressive conditions. Moreover, additional research is needed to study the scalability of TE modules, to adapt them for wearable applications.

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