Thermoelectric Power Generation: Peltier Element versus Thermoelectric Generator

(TEC vs. TEG)

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***Abstract*—This paper presents a detailed comparison between Peltier elements (also called thermoelectric coolers (TEC)) and thermoelectric generators (TEG) for the usage as thermoelectric power generators. Whereas the former is normally known for cooling applications or heat pump uses, it can also be used as generator. Today, thermoelectric energy harvesting systems find more and more utilization, e.g. in wireless sensors or exhaust pipes. The efficiency of thermoelectric materials for the low temperature sector (between 0 °C and 200 °C) is actually not very high, but the costs for TEGs are. As TECs and TEGs consist of the same thermoelectric material for this temperature sector (Bi_2Te_3), the upcoming question is in which temperature range and under which conditions expensive TEGs can be replaced by cheap TECs. Therefore, in this contribution, TECs and TEGs are tested and compared under the same conditions.**

***Index Terms*—Energy conversion, Energy harvesting, Power generation, Thermoelectric devices, Thermoelectricity.**

I. Introduction

Nowadays, the consciousness for pollution, climate warming and exhaustible energy sources is increasing and hence, there are more and more attempts to counteract against these factors. One point, among many others, is to use the primary energy carrier more efficient. Only 20 % of the originally inserted primary energy in Germany is used wisely, whereas the other 80 % goes as waste heat into the environment, [1]. The further utilization of this heat is reasonable and a contribution on the way to the energy transition.

If there are high exhaust gas temperatures, a stirling engine [2] or an organic Rankine cycle [3] can be used to convert the heat energy in electrical energy. If the temperatures are too low or a more reliable and maintenance-free energy production is requested, thermoelectric energy harvesting systems can be used. They normally consist of thermoelectric generators (TEG), which deliver a voltage, as soon as a temperature difference is applied over the device. This effect is called Seebeck effect and will be explained in Sect. II. In the last ten years, the research in the field of thermoelectric energy harvesting systems (EHS) increased. Improvements mainly owe the progress in the material science, especially the nanotechnology, [4]. With more knowledge in new thermoelectric materials, TEGs become more and more efficient and so a reasonable economic usage is imaginable. However, at the moment only TEGs based on bismuth telluride (Bi_2Te_3) are commercially available, well-known sellers are European Thermodynamics Limited [5], Hi-Z Technology Inc. [6] and Marlow Industries Inc. [7].

There are a lot of fields of application for thermoelectric power generation respectively thermoelectric EHSs, which are analyzed and tested from different research groups. For example in [8], the authors propose a combined thermoelectric and photovoltaic EHS for an organic fertilizer plant with a power output of 290 mW, or in [9], where the authors analyze different application possibilities in an aerospace environment. Here, promising heat sources are the engine and engine bay, electrical and hydraulic actuators, electronic systems, cabin lining and the crown of an aircraft. The developed demonstrator delivered a power output of 42 mW. Even with the small temperature difference between human body and environment, thermoelectric EHSs are possible. [10] shows a thermoelectric EHS of human body heat in a shirt for wearable sensors, which generates between 0.5 and 5 mW. Beside these low power applications, there are also research projects with significantly higher power outputs. [11] presents a new method to recover industrial waste heat using a TEG based EHS and heat pipes. The developed system recovers 7 W of electrical power. In [12], a thermoelectric power generation system for industrial furnaces is developed with cascaded TEGs. The EHS delivers 4 kW. At our Chair, we have also done research projects on thermoelectric EHSs. For example, a self-supplying electrical thermostat and a fireplace, where the heat of the fire during barbecue is converted [13], were developed and build-up. With the gained energy during barbecue, an amplifier is supplied and there is the possibility to load a mobile phone and hear music. At the moment, we are going to build up a thermoelectric EHS at the exhaust gas pipe of a heating.

Although, all these systems normally do not deliver that much energy, they are autarcic, fulfil their purpose to supply a certain application and in the best case deliver a small amount of extra energy. The biggest disadvantage is the high cost of the thermoelectric generators. Average prices for TEGs are between 30 and 60 € depending on their dimensions and their power output specifications. As Peltier elements (about 2,50 € per element) are significantly cheaper than TEGs, the question is why not use them instead. This will be analyzed in the following.

Section II delivers some basic knowledge about thermoelectricity and Sect. III illustrates the similarities and differences between TEGs and TECs. In Sect. IV, a TEG and a TEC are used under the same conditions for power generation. The experimental setup is described and the results are evaluated and compared with simulation results. Section V gives the conclusions.

II. THERMOELECTRICITY

Thermoelectricity is the field which deals with the relations between temperature and electricity. It is based on three effects, the Seebeck Effect, the Peltier Effect and the Thomson Effect, [14]. The Seebeck Effect predicates that an electrical potential occurs in a conductive material, when a temperature gradient is applied, thus it is an electromotive force. Thereby, a thermoelement consist of two different thermoelectric materials, which are electrically connected at their ends. If both junctions have different temperature levels, a voltage as a function of the applied temperature difference occurs:

$$\alpha_{AB} = U / \Delta T \,, \tag{1}$$

where α_{AB} is the difference of the Seebeck coefficient of material A and B, U is the Seebeck voltage and ΔT the temperature difference. A TEG consists of a multiplicity of thermocouples, which are connected electrically in series and thermally in parallel. The outer endings are ceramic wafers to electrically insulate the thermocouple junctions. The structure of a TEG and also a TEC is shown in Fig. 1.

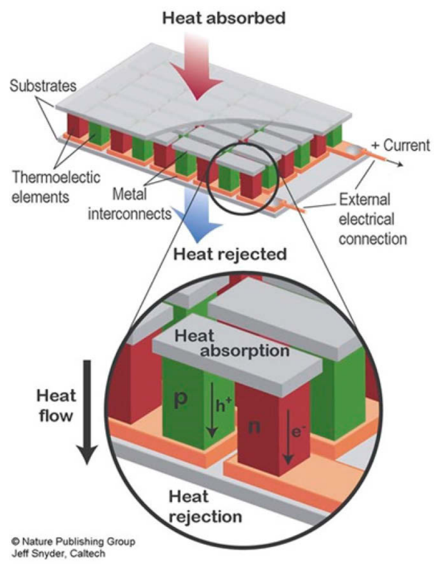

Fig. 1: Structure of a TEG/TEC, visible are the thermocouples, the metal bridges as well as the ceramic plates, [15].

The maximum efficiency of TEGs is calculated after (3):

$$\eta_{TEG} = \frac{\sqrt{1+ZT}-1}{\sqrt{1+ZT}+T_{low}/T_{high}} \cdot \eta_C \,, \tag{3}$$

with ZT is the figure of merit and η_C the Carnot efficiency, whereas ZT is defined as

$$ZT = (\sigma\alpha^2 T)/\lambda \,, \tag{4}$$

where σ is the electrical resistivity and λ the thermal conductivity. From (3), it is visible, that the efficiency of a TEG depends on the both temperature levels and the figure of merit. It will have its maximum, when ZT goes toward infinity. The figure of merit in turn depends on the material properties, namely α, σ and λ. Consequently, the properties of the thermoelectric material are of crucial importance for the efficiency of a TEG.

Besides the Seebeck Effect, the Peltier Effect occurs, when an electrical current flows through a junction of two different thermoelectric conductors. The connection of a voltage source drives a current through the conductor and thus changes the heat transport. So, it is possible to cool down one side, whereas the other will be heated. Colloquially, the Peltier effect is often called a reverse Seebeck effect, but in effect, they are two different phenomena. The Thomson Effect can normally be neglected. It is defined as the degree of warming per unit length and results from the current density through the conductor, in which a uniform temperature gradient is present. The Peltier coefficient of material A/B (π_{AB}) is given by (2):

$$\pi_{AB} = \Phi_{th} / I \,, \tag{2}$$

where Φ_{th} is the rate of heat flow and I the applied current.

In the case of TECs, which are normally used as heat pumps or cooling devices, the crucial factor is the coefficient of performance (COP). The maximum COP (ϕ) for TECs is defined in the following equation:

$$\phi_{\max} = \frac{T_{high}(\sqrt{1+ZT}-T_{low}/T_{high})}{(T_{low}-T_{high})(\sqrt{1+ZT}+1)} \,. \tag{6}$$

Here, both temperature levels and again the figure of merit and thus, the properties of the thermoelectric material are of crucial importance for the efficiency of a TEC, too.

Finally, it can be said that in the case of TEGs and TECs different physical effects are used, but that the figure of merit is for both the determining parameter and consequently the thermoelectric material. In both cases, the same conditions of the thermoelectric material are provided and so it is identically for the two devices in the same temperature range.

III. Similarities and Differences Between TECs and TEGs

The previous chapter has shown the physical effects which are used in thermoelectric devices (TECs and TEGs) and has depicted the figure of merit and its importance for both applications. Now, the similarities and differences between TECs and TEGs will be represented.

A. Similarities Between TECs and TEGs

Figure 2 shows a TEG and a TEC side by side. At first glance, they look very similar. Both have the same dimensions, encircling ceramic plates and a red and black wire. Also identical is the used thermoelectric material. In both cases it is Bi_2Te_3, which is the standard material for TECs and the most common material for TEGs, especially if they are constructed for the usage in a temperature range between 0 and 250 °C (compare the same requirements on the material, see Sect. II). At the moment, Bi_2Te_3 is for this range the optimal thermoelectric material with a ZT value of about 0.7 for room temperature. Not visible in Fig. 2, but given in the datasheets of the TEC [16] and the TEG [17] is the number of thermocouples. For these examples, they consist in both cases of 127 thermocouples, which are connected electrically in series.

B. Differences Between TECs and TEGs

Figure 3 and Fig. 4 show the visible differences. In Fig. 3, the side view of both devices is shown in comparison, below the TEG and above the TEC. It is obviously, that the thermocouples of the TEC are surrounded by a filling material and the couples of the TEG not. However, there are also TEGs which are surrounded by a filling material. Furthermore, the thickness of both devices is different. The TEC is a little bit thicker than the TEG, whereas the dimensions of the ceramic plates are in both cases identical. Figure 4 illustrates the inner life of the devices and it is apparent, that the thermoelectric legs have different dimensions. Moreover, there are also some more invisible differences. In total, there are five points, where the two devices can in general differ from each other, [18].

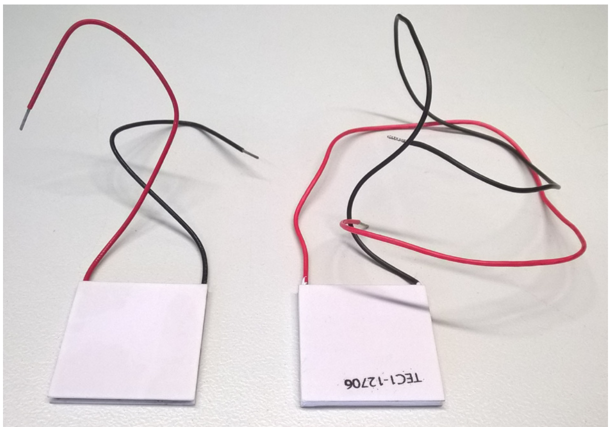

Fig. 2: A picture of a TEG (left) and a TEC (right) side by side.

Fig. 3: Side view in comparison, below the TEG and above the TEC

1) Ceramic Plates: The ceramic plates of TEGs are exposed to higher temperatures and consequently, this means a higher stress. Especially, the thermal cycling provides a high stress for the ceramic material. That is the reason, why some TEGs have slitting on the face to destress the module.

2) Soldering: As TECs are constructed for applications around room temperature, a standard solder is used, whose melting point is 138 °C. In the case of Bi_2Te_3-TEGs, the soldering has to withstand temperatures above 200 °C.

3) Wires: The lead wires of TEGs are attached on the cold side of the device to protect them from the heat. Moreover, the wires are stiffer, as the insulating material is very often Teflon, which endures higher temperatures and so they are harder to bend. Additionally, the wires are thinner, because TEGs carry less current than TECs; TEGs between 1 and 2 A and TECs between 4 and 6 A, see Fig. 2. Therefore, the wires of TECs are thicker and as a result of the lower temperature, PVC is used as insulating material.

4) Dimensions of Thermoelectric Legs: In Fig. 4, the inner life of both thermoelectric devices is presented and it is visible, that the thermoelectric legs have different dimensions. The TEG has larger elements, whereas the TEC has smaller, but higher elements. The larger elements size in TEGs means a larger heat flow through the device and thus a higher power output.

5) Lapping: A further difference between TEGs and

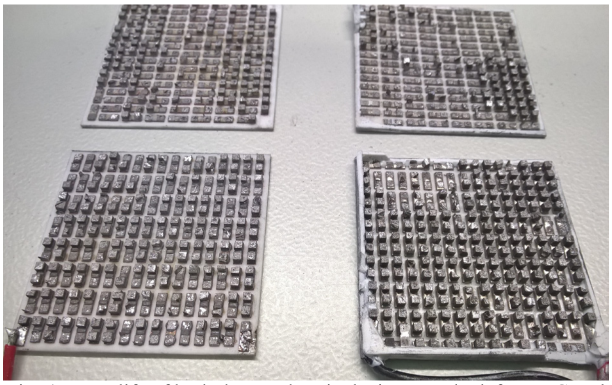

Fig. 4: Inner life of both thermoelectric devices, on the left a TEG and on the right a TEC.

TECs is the accuracy of the thickness. In TECs, the thickness is not very exact, whereas in TEGs the thickness of different devices has to be very uniform. Normally, in EHSs many TEGs are connected in series to generate a higher power output and so it is very important, that a uniform contact of all TEGs is ensured. Otherwise, there would be an under-heated TEG, which reduces drastically the power output of the complete system, [19].

IV. Thermoelectric Power Generation

As the similarities and the differences between TEGs and TECs are now familiar, the upcoming question is whether it is reasonable to replace a TEG by a TEC in an EHS or not. Therefore, two thermoelectric devices, a TEG at the price of 35.85 € [17] and a TEC at the price of 2.37 € [16], are selected. Table II shows a comparison between both devices with the given data from the datasheets. The gray columns highlight the similarities. The general differences for these specific examples, as described in Sect. III B, are compared in Table I.

An experimental set-up is planned to measure firstly the open voltage and in a next test procedure the generated electrical power. Figure 6 shows the set-up. A heating plate serves as heat source and a CPU-cooling element as heat sink. Figure 5 presents a close-up view. Visible is the TEG (later replaced by the TEC), which is enclosed by two copper plates to guarantee a uniform heat distribution on the device surfaces. Moreover, one channel is cut into each copper plate to position a PT1000 temperature sensor inside. With it, it is possible to measure the hot and the cold temperature on both sides of a thermoelectric device. The data acquisition is done with LabJack U6®, which is directly connected with a PC, running LabView 2015®. To measure the produced electrical power, a load resistance with a value of 2.9 Ω is connected to the thermoelectric device as can be seen in Fig. 6.

The test procedure is identical in both scenarios. The heating plate is switched on, the temperature increases and after a certain time, the heating plate is switched off. In the case of the TEC, the heating plate is switched off, when a hot side temperature of 135 °C is reached.

In addition, a simulation is done with Modelica®/ Dymola®. The measured temperatures are given to the models of a TEC and a TEG and the open circuit voltages as well as the produced electrical power, with a connected load of 2.9 Ω, are simulated. For the modeling of thermoelectric devices, the 'Thermoelectric Generator' library in Modelica® is used, which has first been outlined in [20], refined in [21], and extended in [22].

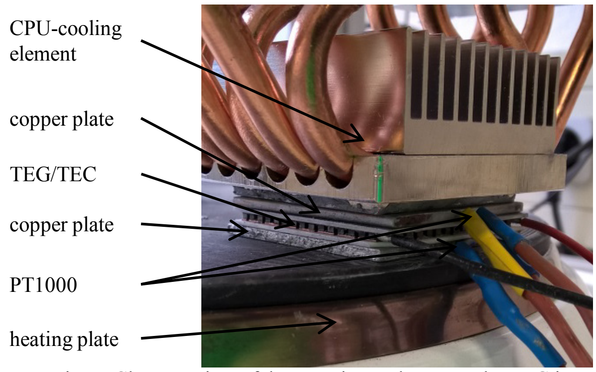

Fig. 5: Close-up view of the experimental set-up. The TEG is visible as well as the copper plates, which enclose the TEG, and the cables of the PT1000 temperature sensors for measuring the hot and cold TEG/TEC side temperature.

The results of the measurements and the simulation are shown in Fig. 7 and Fig. 8. Figure 7 shows the measured open circuit voltage (U_{OC}), the simulated open circuit voltage ($U_{OC,sim}$) and the hot side temperature (T_{hot}) of each device plotted against the temperature difference. It is visible that the open circuit voltage of the TEC is higher than of the TEG for the same temperature difference applied and at almost the same temperature levels (compare hot side temperature curves). A possible reason is the fact that the thermoelectric legs in the TEC are longer and so, the contact effects can be neglected. The long thermoelectric legs are optimized to achieve the maximum COP. The shorter legs in the TEG are optimized for power generation, but with this length, they are more susceptible to the contact effects and they in turn reduce the open circuit voltage, [23]. Moreover, the simulation shows the same effect, higher open-circuit voltage of the TEC, and is almost identical with the real data, except the end of the lines.

TABLE I. Differences for these specific examples of a TEC and a TEG in relation to the five points from Section III.

Section III …	TEC1-12706	GM250-127-14-10
B 1) (Ceramic Plates)	Al_2O_3	very probably also Al_2O_3
B 2) (Soldering)	BiSn (melting point at 138 °C)	A different solder as it withstands higher temperatures than 138 °C
B 3) (Wires)	Diameter of the wires is identical, but the TEG wires are attached at the cold side and they are stiffer.	
B 4) (Thermoelectric Legs)	smaller, higher legs (1.4 x 1.4 x 1.7 mm)	larger and lower legs (1.5 x 1.5 x 1.1 mm)
B 5) (Lapping)	No information as only one device per type is examined.	

TABLE II. Comparison of the selected TEC (TEC1-12706, [16]) and TEG (GM250-127-14-10, [17]). The data are from the datasheets with the exception of the ceramic material for the TEG (it is a plausible assumption). The gray areas are matches of the Two Devices (except the thickness). The index L stands for the load values and R_i for the inner resistances.

Device	Dimensions	T_{hot}	$\Delta T_{max}/T_{cold}$	I_{max}/I_L	U_{max}/U_L	R_i	Q_{max}/Q	Number couples	Thermoelectric material	Ceramic material	Solder material
TEC1-12706	40x40x3.9 mm	50 °C	75 °C (ΔT_{max})	6.4 A (I_{max})	16.4 V (U_{max})	2.3 Ω	57 W (Q_{max})	127	Bi_2Te_3	Al_2O_3	BiSn (138 °C)
GM250-127-14-10	40x40x3.4 mm	250 °C	30 °C (T_{cold})	2 A (I_L)	4.96 V (U_L)	2.49 Ω	~ 198 W (Q)	127	Bi_2Te_3	*Al_2O_3*	N.N.

Fig. 6: Experimental set-up to measure in a first round the open circuit voltage of a thermoelectric device and in the next step the generated electrical power. A heating plate serves as heat source and a CPU-cooling element as heat sink.

In the case of the TEG, the switch-off temperature is 235 °C. It depends on the maximum operation temperature for each device. The TEC/TEG is destroyed for temperatures over 140 °C/250 °C.

In Fig. 8, the produced electrical power of the TEG and TEC as well as the simulated electrical power of both is compared. To measure the produced power, a constant load resistance (2.9 Ω) is connected to the thermoelectric device and the load voltage is tapped. Obviously is that the produced electrical energy for both devices are approximately identical. For smaller temperature differences, the TEC is even more powerful, compare inset in Fig. 8.

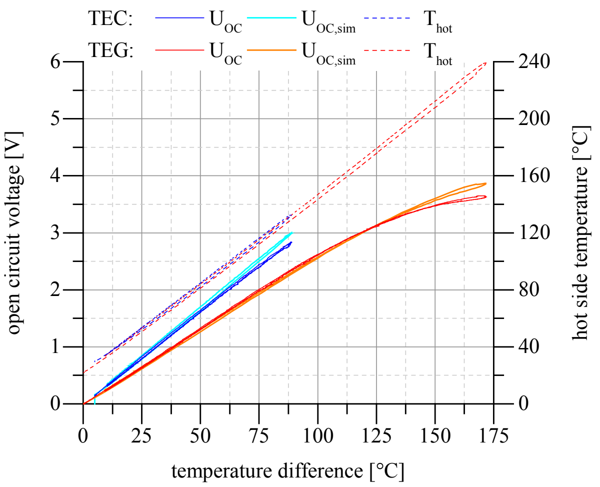

Fig. 7: Comparison of the measured and simulated open circuit voltage between TEG and TEC, plot against the temperature difference.

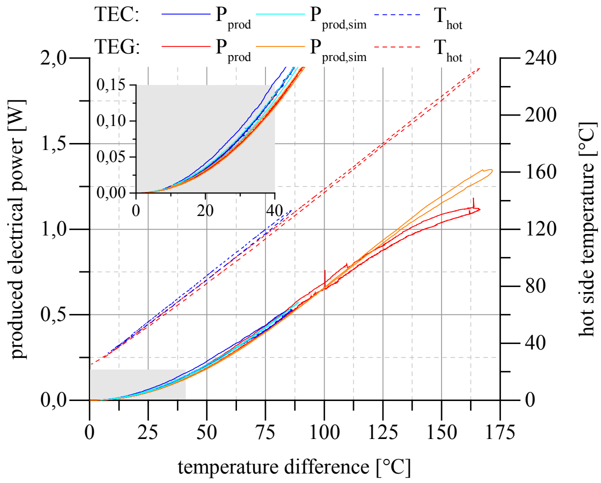

Fig. 8: Comparison of the measured and simulated produced electrical power between TEG and TEC, plot against the temperature difference. The inset shows an enlargement for the low temperature differences.

Here, only a constant load resistance is connected to guarantee similar conditions for both devices. In an optimal EHS, the usage of a maximum power point tracker (MPPT) to increase the electrical power output is recommended. In addition, it is apparent in Fig. 7 and Fig. 8 that no hysteresis phenomena occur.

An application example is the self-supplying electrical thermostat, which is installed at our Chair, using TECs instead of TEGs, see Fig. 9. The thermoelectric device is located between an aluminum half-shell, which is directly attached on a heating tube, and a passive cooling element. The temperature difference over the device is about 3 °C and the EHS produces about 3.5 mW. This electrical energy is stored in an accumulator and is enough to supply the electrical thermostat. The costs of the hardware and the electronics stay equal, but with the usage of the TEC instead of the TEG, a cost savings of 33.48 € are achieved.

V. Conclusions

In this contribution, the general similarities and differences between thermoelectric cooler (Peltier elements, TEC) and thermoelectric generators (TEG) are explained.

Switching box electrical thermostat TEC with cooling element

Fig. 9: Self-supplying electrical thermostat using a TEC instead of a TEG. In the middle is the electrical thermostat, on the right the attached TEC with the cooling element and on the left the switching box with MPPT and accumulator.

After that, two real devices (one TEG and one TEC) are selected, tested and simulated under the same conditions and finally compared. It has been found, that for the power generation in the temperature range between 0 and 100 °C a TEC can be used just as well as a TEG. For low temperatures, between 20 and 40 °C, the TEC is even a little bit better. This result is very decisive for the development of economically worthwhile thermoelectric energy harvesting systems (EHS). By the fact, that a TEC is 15 or more times cheaper than a TEG, small thermoelectric EHS can find a wider field of applications. Either, the costs can be reduced or for the same investment more TECs can be installed and thus more electrical energy can be produced.

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