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Development of a numerical methodology for evaluating physical properties and technical specifications in thermoelectric devices

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Abstract. Typically, the performance evaluation of thermoelectric devices is done using experimental methods and analytical models, which require detailed information on the thermoelectric properties of the materials that make up the thermoelectric devices. However, this type of information is generally not available. Due to this situation, the present investigation seeks to develop a numerical methodology to determine the performance of thermoelectric devices, using technical reference specifications that are normally provided by the manufacturer, such as maximum current, maximum voltage, maximum temperature difference, and efficiency. The numerical model is made up of a series of equations based on thermoelectric phenomena, which generates a contribution in the area of physics. The results obtained are validated through experimental comparisons and the technical data of the thermoelectric devices. The comparison between the different results shows a maximum error of 5%. Therefore, the developed methodology is considered a robust tool for the realistic analysis of the performance of thermoelectric generators and thermoelectric coolers. The foregoing will allow massive use of this type of device in industrial applications and its commercial accessibility.

1. Introduction

Thermoelectric devices (DTE) can be used in cooling, heating, and electrical generation processes [1–4]. This type of device is considered especially useful due to its absence of moving parts, minimal need for maintenance, ability to operate quietly, and being environmentally friendly [5–7]. DTE are used in a wide range of fields. These include its application for the conversion of solar thermal energy to electrical energy [8], the recovery of latent heat from exhaust gases in internal combustion engines [9,10], and in applications space for the energy supply of computer equipment.

Additionally, its use in heating, air conditioning, and ventilation applications in the vehicular sector has been investigated [11,12] in order to replace air conditioning systems based on regular compressors. Due to their scalability, DTE is a promising candidate for controlling temperature-sensitive equipment, surgical tools, telecommunication applications, thermal control, and complementary systems in alternative energy sources [13–15].

In recent years the production of thermoelectric generators has expanded, which implies a wide range of thermoelectric devices available for your choice. To evaluate the performance of DTE, it is necessary to have information related to performance curves and maximum parameters. However, comparing the different alternatives is difficult due to the lack of standardized norms between manufacturers. The foregoing makes it necessary to develop experimental tests, which is impractical for the end-user of the product due to the cost, the need for an experimentation bench, and the time required.

An alternative to this problem is the use of thermoelectric equations for the theoretical evaluation of the efficiency of DTE. The drawback of this methodology is the need to know particular characteristics of the DTE, such as electrical resistance, Seebeck coefficient, among others. However, this type of information is generally not available to the end-user [16].

The manufacturers' technical data sheet usually presents thermoelectric parameters related to their maximum performance, such as maximum voltage, maximum current, maximum power and maximum efficiency, and maximum temperature differences. Several studies available in the literature describe alternative methodologies to determine DTE properties based on its maximum parameters. Lee, *et al.* [17] proposed a theory for the prediction of the performance of thermoelectric modules. The proposed method depends on the maximum performance parameters for the construction of equations that allow determining the material properties of a DTE. From this information, it is possible to describe the performance analytically.

Lineykin and Ben-Yakoov [18] studied the material properties of thermoelectric modules from different manufacturers. From the maximum performance parameters, the properties of the Seebeck coefficient, thermal conductance, and electrical resistance were determined. The results obtained describe an adequate concordance in comparison with the information provided by the manufacturer. Similarly, Zhang [19] reconstructed the performance curves of thermoelectric modules from the maximum current, voltage, and temperature. The process was validated through experimental tests.

The present study aims to develop a numerical methodology that allows evaluating different performance parameters in thermoelectric devices, such as thermoelectric generators (TEG) and thermoelectric coolers (TEC). The methodology is based on technical specifications that are normally provided by the manufacturer, such as maximum current, maximum voltage, maximum temperature difference, and efficiency. Experimental tests determine the reliability of the methodology. In this way, it seeks to provide a tool that allows a broad and rapid evaluation of the characteristics of the different DTE available on the market.

2. Methodology

Two models of thermoelectric generators were selected for the study: TEG-HZ-2 and TEG-12-4-01-L, and thermoelectric coolers: TEC-RC-12-04 and TEC-C2-30 -1503. Both devices are based on thermoelectric effects. However, TEG is focused on energy recovery applications, and TEC is focused on cooling and heating applications. The thermoelectric properties of the TEG were calculated from the technical specifications, as shown in Equation (1), Equation (2), and Equation (3) [20].

$$\rho = \frac{A \cdot V_{max}^2}{4n \cdot L \cdot \dot{W}_{max}}, \tag{1}$$

$$\alpha = \frac{V_{max}}{n \cdot (T_h - T_c)}, \tag{2}$$

$$Z = \frac{4}{T_h \cdot \left[\eta_c \cdot \left(\frac{1}{\eta_{max}} + \frac{1}{2}\right) - 2\right]}, \tag{3}$$

where ρ is the electric resistivity, α is the seebeck coefficient, and Z is the figure of merit. A is the area of the surface section, L is the length, and n is the number of couples of the semiconductors. V_{max}, $\dot{W}_{max}$ and η_c is the are the maximum voltage, maximum power, and Carnot efficiency. T_h and T_c are the temperature on the hot and cold side. Similarly, the properties of the TEC are calculated using Equation (4), Equation (5), and Equation (6) [21].

$$\rho = \frac{\alpha \cdot A \cdot (T_h - \Delta T_{max})}{L \cdot I_{max}}, \tag{4}$$

$$\alpha = \frac{V_{max}}{n \cdot T_h}, \tag{5}$$

$$Z = \frac{2\Delta T_{max}}{(T_h - \Delta T_{max})^2}, \tag{6}$$

where I_{max} is the maximum current and ΔT_{max} is the maximum difference between hot and cold side of TEC. The thermal conductivity (k) of TEG and TEC is determined from Equation (7) [20].

$$k = \frac{\alpha^2}{\rho \cdot Z}. \tag{7}$$

TEGs are devices responsible for producing electrical energy. Generally, it is connected to energy-consuming equipment that causes load resistance (R). Equation (8) and Equation (9) describing the heat flow on the hot and cold side of the TEG [18].

$$Q_h = \alpha \cdot T_h \cdot I - \frac{R \cdot I^2}{2} + k \cdot (T_h - T_c), \tag{8}$$

$$Q_c = \alpha \cdot T_c \cdot I - \frac{R \cdot I^2}{2} + k \cdot (T_h - T_c). \tag{9}$$

The variables of electrical power, voltage, and current of the TEG are calculated using Equation (10), Equation (11), and Equation (12) [22].

$$\dot{W} = \alpha \cdot I \cdot (T_h - T_c) - R \cdot I^2, \tag{10}$$

$$V = \alpha \cdot (T_h - T_c) - I \cdot R, \tag{11}$$

$$I = \frac{\alpha \cdot (T_h - T_c)}{R + R_l}. \tag{12}$$

The thermal conversion efficiency (η) is determined from the relationship between the electrical power output and the heat flux transferred to the TEG, as shown in Equation (13) [22].

$$\eta = \frac{\dot{W}}{\alpha \cdot T_h \cdot I - \frac{R \cdot I^2}{2} + k \cdot (T_h - T_c)}. \tag{13}$$

TECs are devices that consume electrical energy and are usually connected to a power source with a specific current. The way to determine the heat, power, and voltage fluxes is similar to that shown in Equations 1 to 6. However, the thermal efficiency in the TEC is determined by the coefficient of performance (COP), which implies a relationship between the cooling or heating power and the electrical input power, as shown in Equation (14) [22].

$$COP = \frac{\alpha \cdot T_h \cdot I - \frac{R \cdot I^2}{2} + k \cdot (T_h - T_c)}{\alpha \cdot I \cdot (T_h - T_c) + R \cdot I^2}. \tag{14}$$

Figure 1 shows the configuration of the experimental bench used in the study. The heat input was carried out using a cartridge heater. The cooling system consists of a heat exchanger, which uses water as the cooling flow. The elements of the equipment are coupled with bolt clamps and locking nuts.

Thermal grease is applied to minimize the contact resistance between the surfaces. The thermoelectric device is connected to an electronic load to simulate the effect of electrical resistance.

Additionally, a power supply is used for the electrical supply in the case of the TEC. To minimize heat losses, a thermal insulator was applied to the lateral surface of the aluminum blocks. Temperature measurement is carried out using type K thermocouples. The experimental bench is connected to a data acquisition system for reading and recording the measurement instruments.

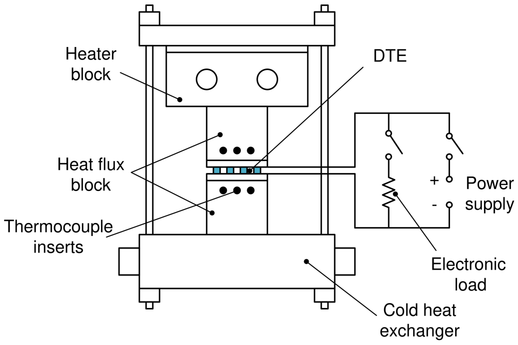


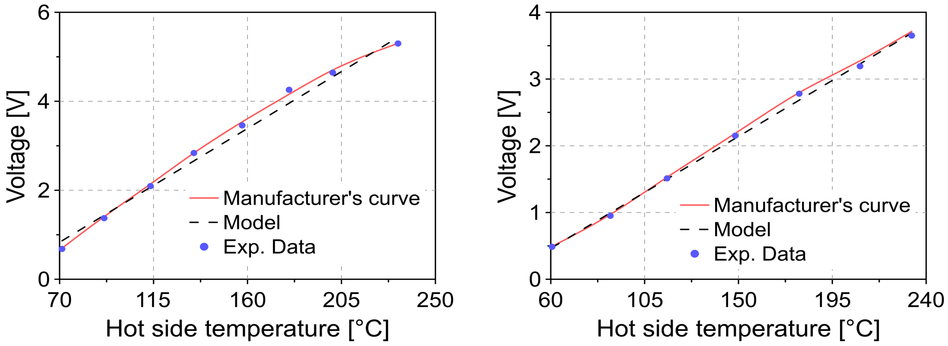
Figure 1. Thermoelectric device test bench.

3. Results

Figure 2, Figure 3, and Figure 4 show the comparison of the proposed model (dashed black line), the experimental results (blue points), and the information provided by the manufacturer (solid red line) for parameters the voltage, electrical power, and thermal efficiency conversion in the two TEG models.

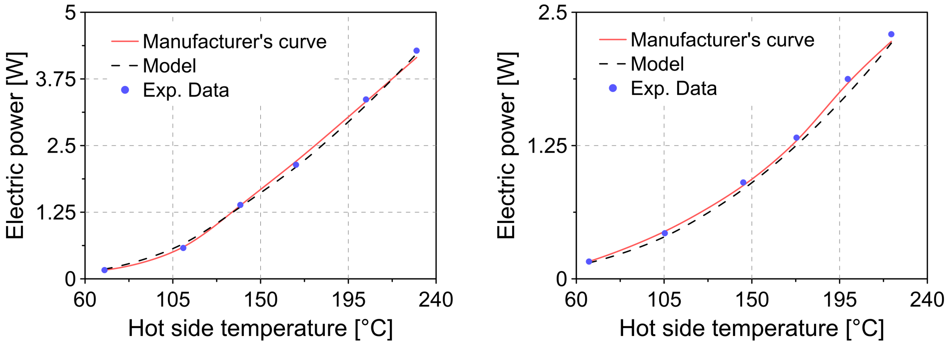
The comparison between the model results and the experimental measurements shows an adequate prediction of the model. It was observed that an average relative error of 1.60% between both results for the two TEG models. In general, the prediction of the model decreases for high-temperature conditions. However, the maximum relative error remained below 2.4%. When comparing the curve of the mathematical model and that supplied by the manufacturer, a maximum error of 5% was evidenced. This greater difference can be attributed to the greater uncertainty caused by changes in the measurement instruments and the configuration of the test bench used to characterize the TEGs.

The analysis of the deviation of the electrical power and thermal efficiency parameters in the TEG shows that the maximum error when comparing the mathematical model and the curves described by the manufacturer was 4.1% and 4.5%, respectively (see Figure 3 and Figure 4). This percentage of error is considered acceptable since the properties of the materials change slightly as a function of temperature. Therefore, its thermoelectric characteristics do not remain unchanged. Despite the above, it was possible to achieve an adequate concordance between the predictions of the model and the data reported by the manufacturer and the experimental tests carried out.



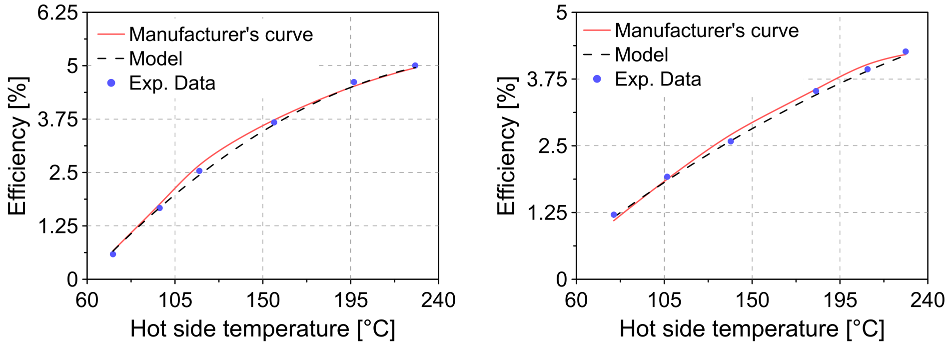
(a) (b)

Figure 2. Analysis of the output voltage for the different TEG models (a) TEG-12-4-01-L, (b) TEG-HZ-2.



(a) (b)

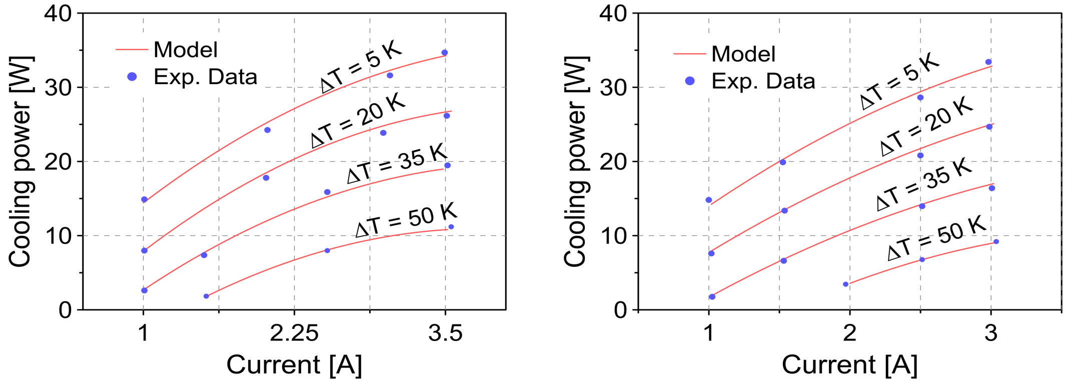
Figure 3. Analysis of the electric power for the different TEG models (a) TEG-12-4-01-L; (b) TEG-HZ-2.



(a) (b)

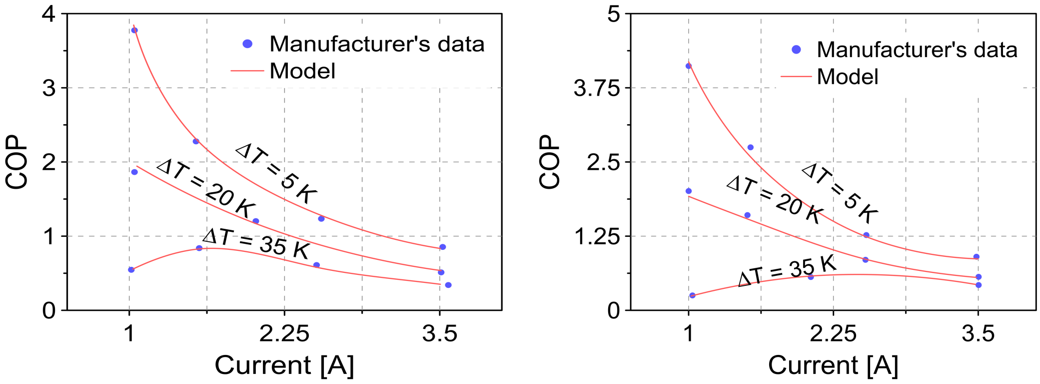
Figure 4. Efficiency analysis for the different TEG models (a) TEG-12-4-01-L; (b) TEG-HZ-2.

Figure 5 and Figure 6 depicts the comparison between the cooling power and COP in the two TEC models determined from the numerical model (solid red line) and the experimental results (blue points). From the results, a high concordance between both sources was demonstrated for a current range between 1 A to 3.5 A. To guarantee the reliability of the mathematical model in the TEC, a comparison is made with the information provided by the manufacturer. The results of this comparison are shown in Figure 6. It was observed that the relative error between the curve of the numerical model and the manufacturer's data was kept below 4.4%.



(a) (b)

Figure 5. Analysis of the cooling power for the different TEC models (a) TEC-C2-30 -1503; (b) TEC-RC-12-04.



(a) (b)

Figure 6. COP analysis for the different TEC models (a) TEC-C2-30-1503; (b) TEC-RC-12-04.

The study carried out shows that it is possible to determine the thermoelectric properties of DTEGs, such as the seebeck coefficient, the figure of merit and thermal conductivity, through the joint use of the mathematical models that govern the thermoelectric phenomena and the maximum technical parametrics of the DTE (voltage, current, and temperature). The above is a novel methodology that explains and quantifies the performance losses associated with the degradation of the material, negative thermoelectric effects (Thomson effect), and increases in thermal and electrical resistance due to the ability to observe the change in thermoelectric properties of DTEs directly.

4. Conclusions

In this paper, a numerical methodology is proposed to evaluate the performance of thermoelectric devices, such as thermoelectric generators and thermoelectric coolers, by using the maximum specification parameters provided by the manufacturers. The results predicted by the numerical model are compared to the information provided by the manufacturer and experimental tests.

The results obtained show that the proposed methodology is a reliable tool for the prior evaluation of commercial thermoelectric devices. In this way, it is possible to predict parameters of electrical power, energy conversion efficiency, and cooling capacity in the particular conditions of each end-user.

Additionally, the analysis of thermoelectric devices from thermoelectric properties such as electric resistivity, Seebeck coefficient, the figure of merit, and thermal conductivity allows establishing a base reference condition to identify conditions low performance operating conditions and decrease in device efficiency.

The comparison between the results obtained through the developed numerical model, the experimental data, and the manufacturer's information showed a maximum relative error of 5%. This deviation can be attributed mainly to the consideration of constant properties in the model since these thermoelectric properties undergo slight changes as a function of the temperature to which the material is subjected. However, the maximum error obtained does not preclude using the methodology as a tool for a comprehensive evaluation of thermoelectric devices offered in commerce.

In general, the calculation methodology presented is a practical tool that allows designers to evaluate the capacity of thermoelectric modules for the particular conditions of each implementation system. In this way, it is possible to better predict the real performance that generation and cooling systems based on thermoelectric modules will have. Future research will focus on improving the accuracy of the calculation methodology, considering the effect of temperature on thermoelectric properties in thermoelectric generators and thermoelectric coolers.

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