Journal of ELECTRONIC MATERIALS, Vol. 42, No. 7, 2013
DOI: 10.1007/s11664-013-2644-6

Numerical Modeling and Design of Thermoelectric Cooling Systems and Its Application to Manufacturing Machines

A. GALLO,[1] A. ARANA,[1] A. OYANGUREN,[1] G. GARCÍA,[2] A. BARBERO,[1] J. LARRAÑAGA,[1] and I. ULACIA[1,3]

1.—Mondragon Goi Eskola Politeknikoa, Mondragon Unibertsitatea, 20500 Mondragon, Spain.
2.—Enerkit Thermoelectric Solutions, CS Centro Stirling S. Coop, 20550 Aretxabaleta, Spain.
3.—e-mail: iulacia@mondragon.edu

In this work the properties of thermoelectric modules (TEMs) and their behavior have been numerically modeled. Moreover, their applications very often require modeling not only of the TEM but also of the working environment and the product in which they will be working. A clear example is the fact that TEMs are very often installed with heat-dissipating elements such as fans, heat sinks, and heat exchangers; thus, the module will only work according to the heat dissipation conditions that these external sources can provide in a certain environment. In this context, analytic approaches, even though they have been proved to be useful, do not provide enough, accurate information in this regard. Therefore, numerical modeling has been identified as a powerful tool to improve detailed designs of thermoelectric solutions. This paper presents numerical simulations of a TEM in different working conditions, as well as with different commercial dissipation devices. The objective is to obtain the characteristic curve of a TEM using a valid numerical model that can be introduced into larger models of different applications. Also, the numerical model of the module and different cooling devices is provided. Both of them are compared against real tested modules, so that the deviation between them can be measured and discussed. Finally, the TEM is introduced into a manufacturing application and results are discussed to validate the model for further use.

Key words: Numerical modeling, cooling, industrial application

INTRODUCTION

Understanding the behavior and functioning of a thermoelectric module (TEM) is a process that requires deep analysis based on very different disciplines and on very different properties of the module and its parts, such as electrical, magnetic, mechanical, and physical properties.[1] On the other hand, use of TEMs in different products produces effects that can be considered to be mainly thermal and mechanical. Due to this fact, modeling the behavior of a TEM to analyze its effect on the component in which it is designed to be assembled, complicated as it may be to introduce every discipline involved in its behavior, in most cases requires only modeling of the two above-mentioned properties. The objective of this paper is to present and discuss a finite-element (FE) model developed to be flexible and quick to allow the user to introduce it into larger models, whole-machine models in some cases, but still be able to accurately predict the thermal and mechanical behavior of the module and its effect on the surrounding components. Therefore, the main goal of this study is to introduce a model that can simulate accurately what happens when a TEM is introduced into any system, rather than describe precisely the different phenomena going on inside the module.

Over the years, many attempts have been made to model the behavior of TEMs via analytic expressions;[2]

(Received July 22, 2012; accepted May 18, 2013; published online June 7, 2013)

still, these expressions do not allow the user to directly incorporate their results into whole-machine FE models. This is the main reason why this paper is focused on an FE model rather than analytic solutions. Also, due to the increasing number and capabilities of simulation packages, many efforts have been made to create complete simulation models that include every property of TEMs, as mentioned above.[3] These models are not very flexible for attachment to whole-machine models, and they are slow in terms of computing time as they require many interactions between different simulation packages; therefore, the efforts presented here focus on a simple but accurate FE model that includes as many of those properties as necessary to provide reliable results, but as few as possible to minimize computing time.

To that end, the model created is compared against experimental results, and the same is done again when the TEM is introduced into a larger system. This model includes cooling devices used in real systems to provide efficiency curves for TEMs when required. When approaching larger models, mechanical systems with cooling needs are used for this comparison.

NUMERICAL MODELING OF THERMOELECTRIC SYSTEMS

Analytical Model

The general expressions for the heat transfer at the cold and hot surfaces (Q_c and Q_h) of a TEM are, respectively,[4]

$$Q_c = \alpha I_p T_c - \frac{1}{2} I_p^2 R - k\Delta T, \tag{1}$$

$$Q_h = \alpha I_p T_h + \frac{1}{2} I_p^2 R - k\Delta T, \tag{2}$$

where α is the Seebeck coefficient, I_p is the electric current intensity, R is the electric resistance, k is the thermal conductivity, and $\Delta T = T_h - T_c$, where T_c and T_h are the temperature at the cold and hot surface, respectively. This expression takes into account the heat generated due to the Joule effect (having the same distribution at both surfaces) and also heat losses due to heat conduction through the semiconductor due to ΔT. To avoid losses, i.e., $\Delta T = 0$, the heat transferred by the TEM must be the same as the heat generated in the application; however, this is not always feasible. This temperature gradient between the hot and cold surfaces causes two drawbacks: (i) heat is transferred from the hot surface to the cold surface of the TEM, which decreases the heat extracted from the source, and (ii) the temperature gradient causes an electromotive force (Seebeck effect) which decreases the voltage and therefore the electric current. There is always a ΔT limit for TEMs where the heat is no longer transferred from the hot to cold surface because Q_c is zero (for the TEM used in this study, $\Delta T_{max} = 70°C$).

Numerical Model of the Thermoelectric Module

The TEM analyzed in this study is an Enerkit 4040-70 reference with aluminum base, maximum intensity of 8 A, and 70 W of maximum heat. This TEM is composed of four different materials as shown in Fig. 1: aluminum base, steel bolt, copper sheet connecting the semiconductors, and Bi_2Te_3 semiconductor. The material properties used in the simulations are considered constant in the temperature range covered in this study (summarized in Table I), and properties for the semiconductor are taken from Ref. 5.

A transient heat transfer model of a single TEM has been developed using Abaqus FE commercial software. The analytical expressions for the TEMs (Eqs. 1 and 2) are integrated in a user-defined subroutine ("DFLUX"). This subroutine allows the application of time- and temperature-dependent heat fluxes at the cold and hot surfaces of the TEM. In this way, the transient term is accounted for in the solution. The last term in both equations ($k\Delta T$), corresponding to the heat transferred by conduction, is computed in the FE model considering all the contacts between the semiconductor material and the copper sheet. Perfect thermal contacts are considered in the model. Free (or natural) convective boundary conditions are considered, with a constant value of convective coefficient of h = 5 W/m^2 K. Typical values of natural convective heat transfer coefficients are: h = 2 W/m^2 K to 25 W/m^2 K.[6]

Figure 2 shows numerical results for the temperature evolution at the hot and cold surfaces for a TEM working at 8 A intensity condition. It is observed that the temperature in the aluminum bases is very homogeneous. Although the cold surface is initially cooled down, the temperature is then increased due to the heat transferred by conduction since heat cannot be dissipated. This lack of dissipative capacity of the hot base causes a conductive heat flux between the hot and cold parts. The TEM working at 8 A generates approximately 120 W. For this reason, to maximize the TEM cooling efficiency, a heat sink is necessary.

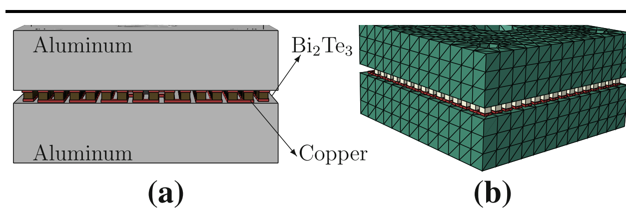


Fig. 1. Model of the thermoelectric module used in the study: (a) materials and (b) mesh.

Table I. Material properties

Material	Thermal Conductivity (W/m K)	Specific Heat (J/kg K)	Density (kg/m^3)
Aluminum	200	900	2700
Steel	50	500	7800
Copper	400	380	8700
Bi_2Te_3	2.2	200	7300

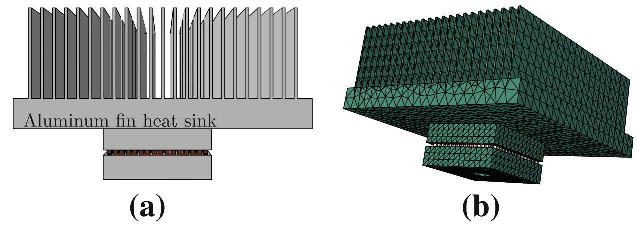


Fig. 3. Model of the TEM and heat sink: (a) materials and (b) mesh.

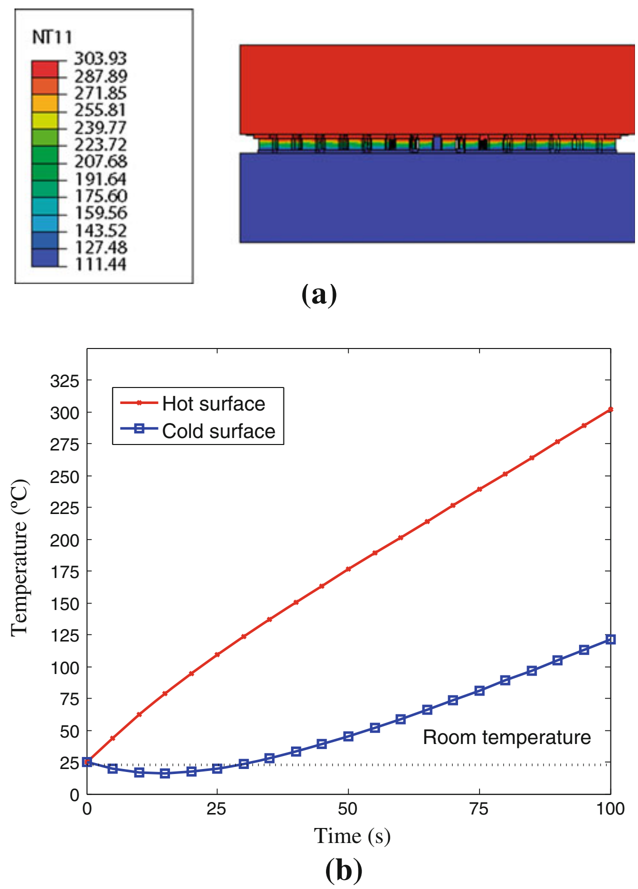


Fig. 2. (a) Temperature distribution and (b) temperature evolution at cold and hot surfaces at 8 A intensity.

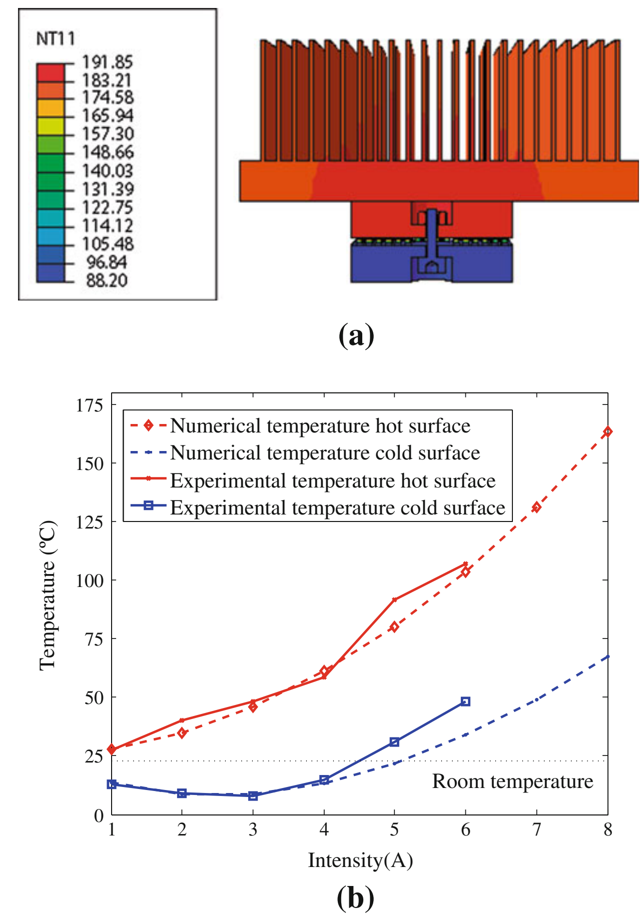


Fig. 4. (a) Steady-state temperature distribution and heat flux for the simulation at 5 A and (b) experimental versus numerical steady-state temperatures at the cold and hot surfaces for different currents.

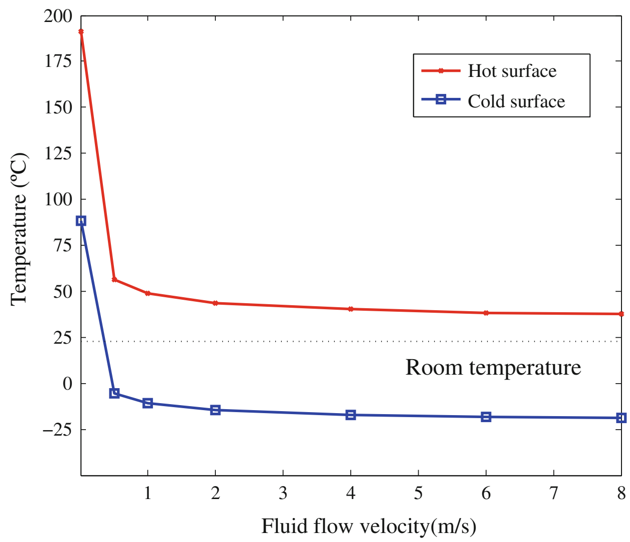
Figure 3 shows the numerical model including a finned heat sink tied to the hot aluminum base. Different working conditions (i.e., different intensities) have been analyzed to evaluate the steady-state temperatures of the aluminum bases. Figure 4 shows experimental and numerical results for a TEM with a heat sink for free convection. It can be observed that the numerical and experimental results have similar values at different current conditions, hence the developed numerical model is validated. The maximum efficiency of this TEM system without forced convection is obtained at 2 A. On increasing the current, the temperature is increased at both surfaces, and therefore a fan should be used to increase the cooling efficiency.

A conventional fan with 92 mm diameter is considered for the 100 mm × 100 mm finned heat sink used in this study. The effect of different fan air flows on the steady-state temperature has been numerically analyzed. Convection coefficients for different air flows were calculated according to the theory of forced convection for flat surfaces.[6] A constant air flow over the fins was assumed for this calculation. Results are summarized in Table II.

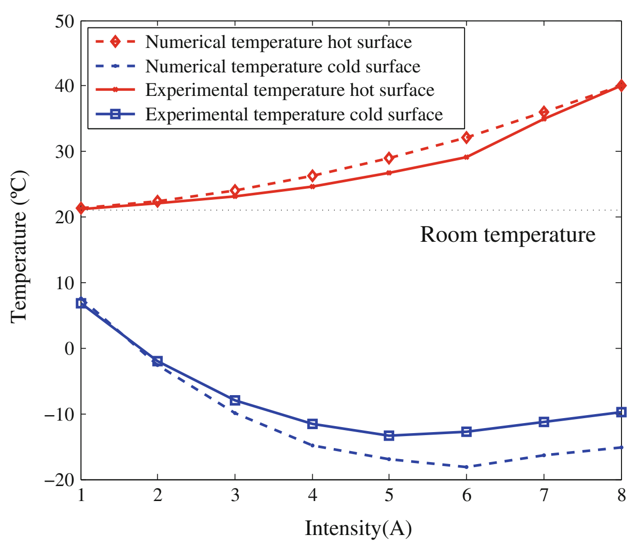
Simulations with different air flows were performed for the TEM working at maximum current

Table II. Fan characteristics and convection coefficient calculated for use in the model

cfm (ft^3/min)	Velocity (m/s)	h (W/m^2 K)
0	0	5
6.95	0.5	30.94
13.91	1	43.75
27.82	2	61.87
55.64	4	87.5
83.46	6	107.16
111.28	8	123.74



(a)



(b)

Fig. 5. (a) Temperatures at the hot and cold surfaces for different fan velocities (8 A). (b) Experimental versus numerical temperatures obtained at different working conditions with a commercial fan.

(8 A) in order to dimension the fan to be used with the TEM. In Fig. 5a the temperatures obtained for the cold and hot surfaces are plotted. It can be seen

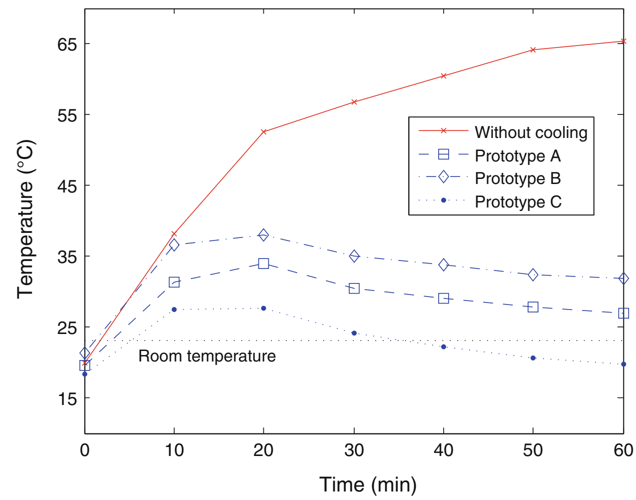


Fig. 6. Temperature evolution for the different cooling systems.

that the maximum efficiency of the fan and sink occurs at approximately 4 m/s. Increasing the velocity does not significantly increase the cooling. Therefore, the fan considered for this application is an ORIX MD925A-12 from Oriental Motor Co. The air flow is 59.7 cfm, which is approximately 4.1 m/s. In Fig. 5b, experimental validation of the model is shown for different working conditions in steady state. It is observed that there is a very good correlation between the numerical and experimental results.

INDUSTRIAL APPLICATION

The productivity and accuracy of machine tools are important aspects for manufacturers. The thermal accuracy of machine tools is becoming increasingly important considering the strongly varying operating conditions; for instance, in high-precision machines, thermal errors can represent up to 40% to 70% of the total error in a workpiece.[7] The increasingly high accelerations and feed rates cause heating of the recirculating ball screw in linear feed drives. Position measurement in feed drives therefore plays a central role in stabilizing the thermal behavior of machine tools, and usually corrector systems are used to avoid errors due to temperature increases.

Therefore, following the validation of the developed numerical model, in this study it was used to design cooling systems based on TEMs to cool a ball screw nut. To dimension the cooling system, the heat generated in the ball screw for a specific work cycle was estimated using Tenjitus's equation.[8] Different working conditions and nuts were analyzed, and the maximum generated heat was estimated to be 240 W. Taking the generated heat into consideration, three different cooling systems were designed and studied: (a) centrally located aluminum flange with two TEMs (coefficient of performance, COP = 2.4), (b) double aluminum flange with two TEMs (COP = 2.6), and (c) double aluminum flange with four TEMs (COP = 2.8).

Results for the temperature evolution of the three cooling systems are shown in Fig. 6 and compared with the temperature evolution of the ball screw nut without any cooling. It is observed that, in all cases, the maximum temperature is less than 35°C. However, in prototype A and B the temperature distribution in the nut is less homogeneous than in prototype C. Moreover, as expected, prototype C reaches the lowest temperatures (T_{max} = 27°C), and it can even cool down the nut to temperatures lower than room temperature.

CONCLUSIONS

In this study a numerical model to predict the performance of a TEM has been developed and introduced into a larger model in order to design cooling systems for machine tool components. The following conclusions can be reached based on this work:

– A numerical model for the studied TEM has been experimentally validated for different working conditions.
– The need for heat sinks in TEM systems has been numerically proven.
– Heat sink performance for different fan conditions and TEM currents has also been numerically simulated.
– Three different cooling systems based on TEMs have been used to cool a machine tool component (ball screw).

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