A Numerical Study of the Heat Transfer Management Provided by a Thermoelectric Sink-and-Fan System

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Abstract. This paper presents a mathematical model and its finite element (FEM) implementation for the thermoelectric processes that occur in a Peltier sink-and-fan device aimed at enhancing the heat exhausted by power electronics. The heat transfer management for several key parameters (the heat released by the electronic module, the ambient temperature, the convection heat transfer coefficient) is analyzed to find optimal working conditions.

1. Introduction

An important issue in the design of modern electronic systems is the heat transfer management. The heat produce by “hot” electronic devices can lead to their thermal failure, lifespan reduction of the final electronic system, or it can significantly reduce the overall performance of the device. To keep the temperature within safe working limits heat transfer methods are required. One such solution is the “Peltier” thermoelectric cooler (TEC) that can “pump” the heat exhausted by the power electronic unit.

A contemporary TEC is a solid-state device that uses the electrical current instead of the refrigerant used by the refrigerators to carry the heat released by thermal sensitive devices to the environment [1-4]. To ensure best yet economic cooling, optimal control techniques are required. Heat transfer can be controlled either by adjusting the electrical current through the TEC or by controlling the heat transfer removal rate at the hot end of the Peltier cell [5].

This paper is concerned with the numerical study of the heat transfer management provided by a TEC unit with respect to several key parameters: the heat released by the electronic module, the ambient temperature, the convection heat transfer coefficient, with the aim of finding optimal working conditions for the electronic modules.

2. The TEC used for Thermal Control

A TEC is essentially a Carnot device, and it provides for several important advantages: solid state construction, chip integrating possibility, silent operation, compact dimensions, lightweight, higher reliability, accurate temperature stability (better than +/- 0.1 °C), localized cooling, short response times to temperature change, reduced power consumption, cooling under the ambient temperature, etc. [1-4].

A single-stage TEC module is composed of thermoelectric cells made of \( n \) and \( p \)-type semiconductor columns, which are sandwiched and fixed by soldering between two ceramic plates (the hot and cold ends). The couples are connected electrically in series and thermally in parallel. Multistage TEC units are also available. They “split” the hot end – cold end temperature interval in several stages, providing for higher heat pumping efficiencies.

When a voltage is applied at the electric ports of the TEC a DC current flows through the unit, which (by Peltier effect) conveys the heat released by the device connected (thermally) to its cold end to the other (hot) end that is usually provided with a heat sink–and–fan device (figure 1) [5]. In this situation, in addition to the Joule-Lenz (electro-thermal) effect that is related to the electrical current flow through the device, Seebeck effect is a menace also
because it acts into reducing the efficiency of the heat removal by a counter electromotive force, opposite to the voltage applied to the unit.

Therefore an optimal control of heat transfer should consider the complex interactions that occur in a TEC and mathematical modeling and numerical simulation may be needed in the design phase of the unit.

3. The Mathematical and Numerical Model

The mathematical models that describes the heat and current flow thorough the TEC under steady state working conditions is [5], [8]

\[ \nabla \cdot J = 0, \quad \nabla \cdot q = 0, \]

where \( J \) [A/m\(^2\)] is the electrical current density and \( q \) [W/m\(^2\)] is heat flux density, defined by

\[ J = -\sigma \nabla V - \sigma \varepsilon \nabla T, \]

\[ q = V J - k \nabla T + \varepsilon T J. \]

Here \( V \) [V] is the electrical potential, \( T \) [K] is temperature, \( \varepsilon \) [V·K\(^{-1}\)] is Seebeck coefficient, \( \sigma \) [S/m] is the electrical conductivity, and \( k \) [W·K\(^{-1}\)m\(^{-1}\)] is the thermal conductivity. All physical properties of the thermoelectric elements are temperature dependent [5], [10].

The mathematical model (1)-(3) was solved numerically by implementing a general form coefficient form PDE mathematical model [5], [8], [11]

\[ -\nabla \cdot (\varepsilon \nabla u + \alpha u - \gamma) = 0, \quad \text{in } \partial \Omega \]

\[ \begin{align*}
    n \cdot (\varepsilon \nabla u + \alpha u - \gamma) + qu &= g - h^T \mu, & \text{on } \partial \Omega \\
    hu &= r, & \text{on } \partial \Omega
\end{align*} \]

where \( \Omega \) denotes the computational domain, \( \partial \Omega \) is the boundary, \( u \) is the dependent variable (\( T \) for the heat transfer problem and \( V \) for the electrical problem), \( n \) is the outward normal, \( \mu \) is a
Lagrange multiplier, $c$, $a$, $\gamma$, $q$, $h$, $r$, and $g$ are defined to model the two PDEs (1).

The boundary conditions (BCs) that close the problem are set as following: for the heat transfer problem, either heat flux or temperature at the cold end (the heat source), convection heat transfer on the heat sink surface, and thermal insulation for all other boundaries; for the electric field problem, either normal current density or ground (zero voltage) at the terminals and electrical insulation for other all sides.

4. Numerical Results and Discussions

A series of parametric studies were conducted on an elemental cell fitted with a heat sink – fan unit to study the sensitivity of the heat pumping efficiency.

Figure 2 presents the computational domain for the elemental TEC and the temperature distribution for 1 A pumping current, and $h = 100$ W/m$^2$K convection heat transfer coefficient.

![Figure 2](image)

It is assumed that the heat flow between adjacent elemental cells is negligible small therefore the heat transfer problem can be studied at the cell level. Symmetry BCs (with respect to the coolant flow) are used to further reduce by half the computational domain.

Figure 3 presents the average temperature at the cold end versus electrical current for $h = 20$...$180$ W/m$^2$K. The total power per elemental cell is 0.078 W and the ambient temperature is set at 293 K.

Apparently, a heat transfer coefficient less than 20 W/m$^2$K, which means in fact natural convection, does not provide enough cooling to keep the heat source (the electronic unit) at a safe temperature.

On the other hand, increasing $h$ beyond 100 W/m$^2$K may not be an option since it provides for an insignificant reduction in the average temperature, for a certain electrical current. We found that an optimal control interval for the convective heat transfer coefficient is then 20...100 W/m$^2$K.
Figure 3: Average temperature at the cold end, $T_{av,cold}$ versus the electrical current for different convection cooling conditions.

Figure 4 shows the average temperature at the cold end of the TEC as function of the convection heat transfer coefficient, for different values of the electrical current. The total heat power per elemental TEC is 0.078 W and ambient temperature is set to 293 K. Apparently, a linear control may be conveniently implemented to manage the heat exhaust.

A third parametric study, summarized in Figure 5, was conducted to outline the influence of the heat source power, $Q$ [W], upon the temperature at the cold end of the TEC for different values of the electrical current. The convection heat transfer coefficient is 100 W/m²K, and the ambient temperature is assumed 293 K.
Finally, the coefficient of performance (COP) of the TEC for different hot end – cold end temperature differences was studied. Figure 6 shows the COP as a function of the electrical current. It may be noticed that the TEC reaches a unique COP(I) asymptotic behavior for electrical currents exceeding 1 A.

These numerical simulation results are consistent with the available datasheet for the TEC device, prompting that such an analysis may evidence optimal working conditions for the TEC and can stand as base point for development an optimal control technique.
5. Conclusions

Modern power electronics require efficient means to exhaust the heat produced by operating at ever increasing heat transfer rates, to provide for safe thermal operating conditions. To this end, solid-state semiconductor devices may be added to the sink-and-fan systems providing for precise, controllable thermal management. This paper presents a mathematical model and numerical simulations for the thermoelectric processes that occur in a TEC under steady state working conditions, with the aim to analyze the heat transfer management provided by a TEC provided with a sink-and-fan system.

The sensitivity of the heat pumping efficiency was evaluated for different control parameters: the electrical current and the convective heat transfer of the sink-and-fan system (e.g., by adjusting the mass flow rate of the coolant – air – through the fan speed).

The COP shows off an extremum (maximum) that is sensitive to the cold to hot end temperature drop, and a unique asymptotic behavior for electrical currents exceeding 1 A. These results are consistent with the available datasheet for the TEC device.

The hot end temperature vs. the electrical current characteristic is linear while the hot end temperature vs. $h$ characteristic is nonlinear.

For a certain electrical current, the increase of the convective heat transfer coefficient $h$ above 100 W/m²K results in an insignificant reduction of the average hot and temperature.

It may be conjectured that the study may evidence the optimal working conditions for the TEC and can stand as base point for development an optimal control technique.

Acknowledgments – The work was conducted in the Laboratory for Multiphysics Modeling at UPB. The first author acknowledges the support offered by the Sectorial Operational Program Human Resources Development 2007-2013 of the Romanian Ministry of Labour, Family and Social Protection through the Financial Agreement POSDRU/107/1.5/S/76903.

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