Int. J. Therm. Sci. (2001) 40, 911–916

S1290-0729(01)01277-7/FLA

Analysis of a thermoelectrical device for active heat transfer control

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(Received 3 July 2000, accepted 4 January 2001)

Abstract — The purpose of this study is to assess a novel and rapid cooling system, which employs a heat transfer control device, realized by the application of a thermoelectric principle (Peltier effect). This system is able to actively control the heat transfer by keeping a subject medium at constant temperature, and a sudden and efficient cooling can be achieved by changing the direction of electric flow in the system.

The adopted scheme is very reliable as no moving parts are considered, and can achieve cooling of large heat flux under large temperature differences, which is impossible during steady cooling by standard Peltier elements.

The proposed model is solved numerically and the results are compared with those obtained by a small-scale experiment, reported herein. Heat flux comparable to that of boiling R113 was attained from the subject medium: water at 20 °C was cooled down to 0 °C within 4 s. © 2001 Éditions scientifiques et médicales Elsevier SAS

heat transfer control / cooling / thermoelectrical effect / modeling

Nomenclature

A	section area	m^{-1}
c	specific heat	$J \cdot kg^{-1} \cdot K^{-1}$
E	electric potential	V
i	electric current	A
k	heat transfer thermal conductivity	$W \cdot m^{-1} \cdot K^{-1}$
l	length	m
T	temperature	K
q	thermal flux	$W \cdot m^{-2}$
x	coordinate	m
Z	figure of merit	K^{-1}

Greek symbols

α	Seebeck coefficient	$V \cdot K^{-1}$
Δ	variation	
ρ	density	$kg \cdot m^{-3}$
σ	electrical conductivity	$m \cdot \Omega^{-1}$
τ	time	s

Subscripts

0	initial
1	location, *figures 1, 4* and *5*
2	location, *figures 1, 4* and *5*
b	location, *figures 4* and *5*
opt	optimal

1. INTRODUCTION

It is widely recognized that the irreversible thermodynamics contributes to elucidate on the connection between thermodynamic and transport phenomena. The body of the related theory now spans almost one century and a half, as thermodynamic considerations were first applied to the treatment of thermoelectricity, perhaps the most intriguing irreversible process, by W. Thompson in 1854. The first observation of a thermoelectric phenomenon, a compass needle deflection in the vicinity of a heated bi-metallic closed loop, was reported even

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earlier by T.J. Seebeck (1823). Several theoretical approaches have been proposed to the macroscopic description of thermoelectricity, but a consistent phenomenological theory was only permitted following L. Onsager (1931) coherent scheme [1]. Since then, a number of applications have been realized for practical purposes with varying success, but specially in space navigation these elements have proven irreplaceable, as shown by the radioisotopes heat/electricity conversion for old-timer Voyager 1 and 2 spacecrafts and today Galileo and Cassini probes. Earthbound, the interest in electric cooling studies is still sustained by their potential application in a variety of fields where their reliability (no moving parts are involved) and modularity (a number of Peltier modules may be assembled at will as a stack) proves essential, e.g., in transportation systems, where they are selected to perform thermal conditioning [2], and in basic experiences of phase change dynamics during micro-gravity flights [3, 4].

Basically, a thermoelectric converter consists of a number of alternate ingot-shaped n- and p-type semiconductor elements, which are electrically connected in series with metal strips, sandwiched between two electrically insulating but thermally conducting ceramic plates to form a module. As a temperature difference is maintained across this module, electrical power will be delivered to an external load and the device operates as a generator. Conversely, when an electric current is passed through the module, heat is absorbed at one face of the module, rejected at the other face, and the device works as a refrigerator.

Peltier effect and its applications have been traditionally analyzed in so far by assessing their steady-state performance [1, 5]. Recently, a typical application in the applied mechanics field has been studied by combining a thermoelectric device with a shape memory alloy (SMA), to realize a compact actuator whose basic characteristics have been assessed [6–8]. Moreover, a SMA-based thermoelectric actuator which simultaneously acts as a mean to actively control heat transfer to the SMA has been proposed [9]. The actuator has then been applied into the bioengineering field [10–12].

In this paper, a novel and rapid cooling system is proposed, which employs the transient behavior of a combination of Peltier elements. Although large-scale thermoelectric cooling can hardly match the performance of refrigerant systems, due to its inherent inability to achieve a steady cooling regime and yield a high heat flux under a large temperature difference, a Peltier-effect based, computer-controlled device can offer a rapid and efficient cooling if its active control features are opportunely exploited.

Such a device acts as a heat pump by its ability to work both as a cooler and as a heater. If a Peltier-based device is used as a heater, its COP (Coefficient of Performance = heat release / power consumption) can be more than unity. When the temperature difference between heating and cooling spots is small, the COP for cooling and heating may become much larger than unity by properly adjusting the range of working temperature. Therefore, it would be feasible to apply or extract more thermal energy, to or from the subject medium, than the supplied electrical energy.

The purpose of this paper is first to carry forth a theoretical analysis, in which a non-equilibrium condition is described, to exploit the active heat transfer features. Then a small-scale experiment is set up to verify the correctness of the analysis. The adopted scheme, which has the additional advantage of being very reliable as no moving components are considered, can achieve cooling of large heat flux under large temperature difference, which is impossible during steady cooling by standard Peltier elements.

2. WORKING MODE TO THE ACTIVE HEAT TRANSFER CONTROL

The device must basically consist of a copper heat sink, to minimize conduction resistance, and two Peltier elements, as shown in *figure 1*. The properties of the employed semiconductor are the following: thermal conductivity $k = 1.5$ W·m^{-1}·K^{-1}, Seebeck coefficient

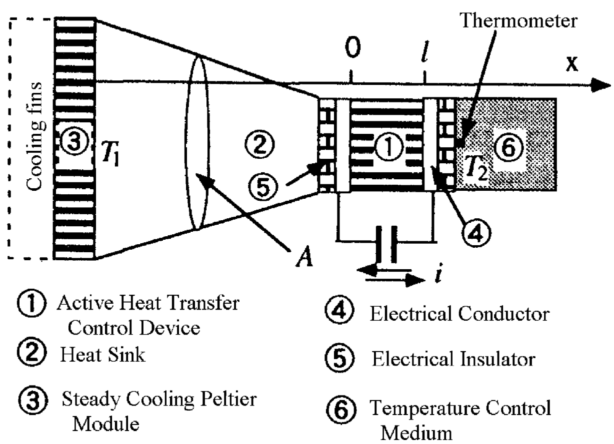

Figure 1. The adopted one-dimensional conduction model.

$\alpha = 2.0 \times 10^{-4}$ V·K^{-1}, heat capacity $c \cdot \rho = 1.229 \times 10^6$ J·m^{-3}·K^{-1}, electrical resistivity $\sigma = 1.0 \times 10^5$ Ω^{-1}·m^{-1}. The figure of merit of the subject Peltier element is calculated as $Z = \alpha^2 \sigma \cdot k$. When $T < 373.14$ K, these properties are given as a function of the temperature with the following:

$$
\begin{aligned}
k &= 1.39848 \times 10^{-5} \cdot T^2 - 2.279536 \times 10^{-3} \cdot T \\
&\quad + 1.646574 \\
\alpha &= \left(-0.088626 \cdot T^2 + 46.927945 \cdot T \right. \\
&\quad \left. + 18740.079\right) \times 10^{-8} \\
\sigma &= 1.0 \times 10^{10} / \left(3.3203856 \cdot T^2 - 722.301045 \cdot T \right. \\
&\quad \left. + 113914.176\right)
\end{aligned}
$$

Finally, the value of Z is 2.7×10^{-3} K^{-1} at $T = 323.14$ K.

The two Peltier elements are placed in different sections of the apparatus and have different functions. The element labeled as 1 acts as the control element proper, being in contact with the working medium, as the electric current supplied to it may be reversed at will. Peltier element 3 works steadily as a dissipator to the environment by means of an adequate fin bank.

Let us assume that, as initial condition, the control medium is a T_2 temperature, when the heat sink is at T_1, being $T_1 < T_2$. The electric current supplied by the computer control to the Peltier element 1 is such that it works in the heating mode, so that a heat flux is applied to the control medium. The provided heat flux is exactly the same that would be otherwise transferred across a $(T_2 - T_1)$ temperature difference, from the control medium to the Peltier element 3. Thus, $T(x = l) = T_2$ and the surface at $x = l$ (the separation between the control medium and the heat sink) results as it were adiabatic.

When the rapid cooling function needs to be implemented, the direction of the electric current in the Peltier element 1 is reversed. Heat is absorbed from the control medium in a very short time, and transferred to the Peltier element 3 through the heat sink. In this fashion, a very high heat transfer rate is applied to the control medium, and a rapid response can be achieved, as the electric transfer velocity is high compared to the velocity of diffusion of heat. Naturally, the same arrangement can be used in a reversed function, by reversing the working modes of the Peltier elements and the sink.

3. MODEL DEVELOPMENT AND ANALYSIS

As mentioned in the Introduction, the behavior of present Peltier elements arrangement is transient, as it is its interaction with the heat control medium and sink. A Peltier element consists of positive p and negative n semiconductor branches, and since the direction of the electric potential flowing through the p elements and related Seebeck coefficient are opposite to those pertaining to the n element, then the equations that govern the thermoelectric balance on both branches are identical. By assuming that the heat flux and temperature be uniform in all sections normal to x, three different segments can be outlined (heat sink, Peltier element 1 and control medium for $x < 0$, $0 \leqslant x \leqslant l$ and $x > l$, respectively) and a governing one-dimensional differential equation can be written by formulating the change of internal energy in time as the sum of thermal and electric power by unit length:

$$A\rho c \frac{\partial T}{\partial \tau} = \frac{\partial Aq}{\partial x} + Ai \frac{\partial E}{\partial x} \tag{1}$$

where the variation of electric potential E with x is given by

$$\frac{\partial E}{\partial x} = -\alpha \frac{\partial T}{\partial x} - \frac{i}{\sigma} \tag{2}$$

and the total heat flux q is customary written as the sum of the heat conduction and Peltier heat flux:

$$q = -k \frac{\partial T}{\partial x} + \alpha T i \tag{3}$$

By letting $\alpha \to 0$ in every section of the apparatus except in the heat transfer elements, and $\sigma \to \infty$ in sections which are not affected by the electrical flux, equation (1) describes the spatial and time distribution of temperature in the entire domain.

4. MODEL APPLICATION

Let us start by assuming a steady-state regime as the initial condition for the heat transfer elements and control medium. If the thermophysical properties are constant with τ and the area A is constant with x, such an initial condition is written from rearranging equation (1):

$$\frac{\partial^2 T}{\partial x^2} + \frac{i^2}{\sigma k} = 0 \tag{4}$$

Upon integration, by adopting the boundary conditions $T(0) = T_1$, $T(l) = T_2$, with $T_1 < T_2$, the following expression for the gradient of temperature is written:

$$kA\frac{\partial T}{\partial x} = -\frac{i^2}{\sigma}\left(x - \frac{l}{2}\right) + kA\frac{(T_2 - T_1)}{l} \tag{5}$$

By applying this expression for $x = l$, the heat flux becomes:

$$q(l) = \frac{li^2}{2\sigma} + \alpha T_2 i - \frac{k(T_2 - T_1)}{l} \tag{6}$$

Since for $\tau < 0$ we have $q(l) = 0$, the electric current and related potential to sustain such adiabatic condition are the following:

$$i_0 = -\frac{\sigma\alpha T_2}{l} + \sqrt{\left(\frac{\sigma\alpha T_2}{l}\right)^2 + \frac{2\sigma k(T_2 - T_1)}{l^2}} \tag{7}$$

$$\Delta E = -\alpha(T_2 - T_1) - \frac{il}{\sigma} \tag{8}$$

Starting at the initial condition ($\tau = 0$), the cooling effect is activated by inverting the supplied electrical current. The heat flux becomes immediately negative, reaching its maximum, as determined by applying equation (6), for a correspondent optimal current given by the following value:

$$i_{\mathrm{opt}} = -\frac{\sigma\alpha T_2}{l} \tag{9}$$

In *figure 2* the analytical dependence of thermoelectric characteristics i_0 and ΔE on the temperature difference $T_2 - T_1$ is reported. The results were obtained for a bismuth telluride thermoelectric element having $l =$ 1.4 mm, while the physical properties are evaluated at $T_2 = 300$ K. In *figure 2* the heat flux for $x = 0$ is also plotted. As expected, the electric current and potential needed to keep the adiabatic condition at $x = l$ increase with the temperature difference. The heat transfer rate at $x = l$ may readily be determined, across the given temperature difference and the realized heat flux. For the initial condition $q(l) = 0$, such heat transfer rate is null.

In *figure 3* the dependence of the negative (cooling) heat flux on the temperature difference $T_2 - T_1$, upon inversion of the electric current, is shown. The four curves reported pertain to four different feeding current cases:

(1) the absence of supplied current ($i = 0$),
(2) the current that satisfies $\Delta E = 0$ in equation (8) which corresponds to the short circuit case,
(3) the initial current i_0 and
(4) the optimal current i_{opt}.

The maximum cooling flux obtained in the last calculation exercise varied in the 1.2–2.3 × 10^5 W·m^{-2} range, which is of the same order of magnitude to that of nucleate boiling heat transfer of R113.

Now, as the heat transfer is however finite at $x(l)$ for $(T_2 - T_1) \to 0$, correspondingly $k(l) \to \infty$. This indicates that the heat transfer may be apparently varied from 0 to ∞ before and after the inversion of the current. Since the electrical control is relatively simple to obtain, in comparison to alternate means of controlling the extracted heat from the subject medium, the proposed system shows an excellent ability to realize an active heat transfer control with no mechanical devices involved.

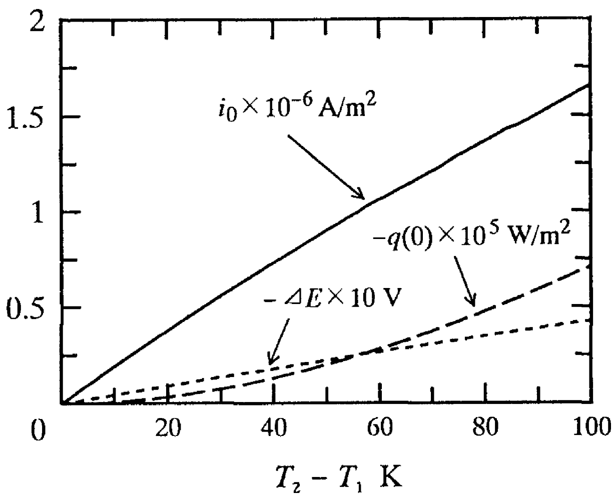

Figure 2. Analytical solutions of initial condition for $q(l) = 0$.

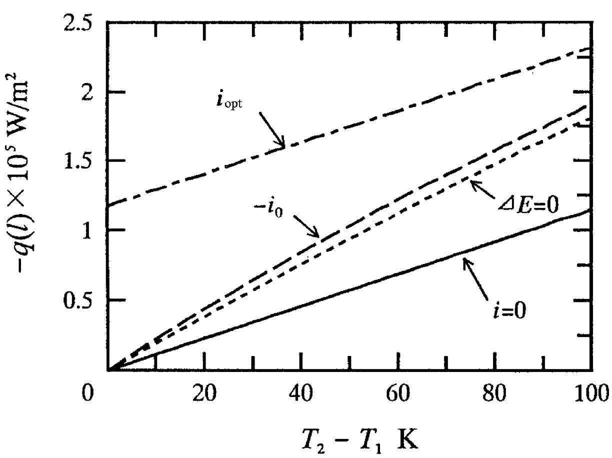

Figure 3. Transient heat flux at $x = l$ just after inversion of electric current.

5. COMPARISON WITH THE EXPERIMENT AND CONCLUSIONS

In order to verify the presented analysis with reference to a real cooling performance, an apparatus based on design depicted in *figure 1* has been realized and inserted in an experimental configuration, which is reported in *figure 4*.

The scope of the apparatus is to rapidly cool down a small quantity of liquid water by using a 8 by 8 mm Peltier element on the active control side (1), and a 30 by 30 mm Peltier element on the copper heat sink side (3). On the control side an alumina plate is provided to uniform the heat flux from the control medium (6). This system has been adopted in an experiment to investigate pure diffusion fields without double diffusive convection during a micro-gravity flight [4]. In order to compare experimental measurements with theoretical results, equation (1) is integrated, together with its boundary and initial conditions, by discretisation and solved. For sake of simplicity the temperature dependence of physical properties, as the additional thermal resistance due to the presence of ceramic plates for the connection of Peltier electrodes and the heat generated within them, have been neglected, and temperature has been considered as uniform in the section that separates the control element from the control medium.

Model performance has been reported in *figure 5*, together with related experiment. One can observe the cooling time, which is extremely rapid: water in reservoir (6) has been cooled down from 20 °C to 0 °C in 4 s, due to

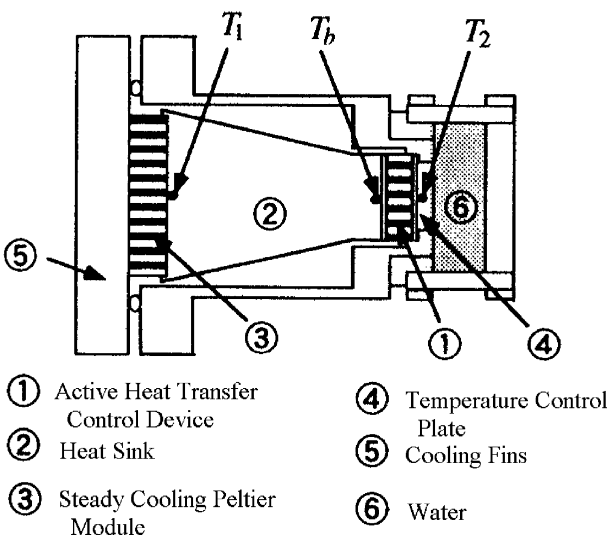

Figure 4. The experimental apparatus.

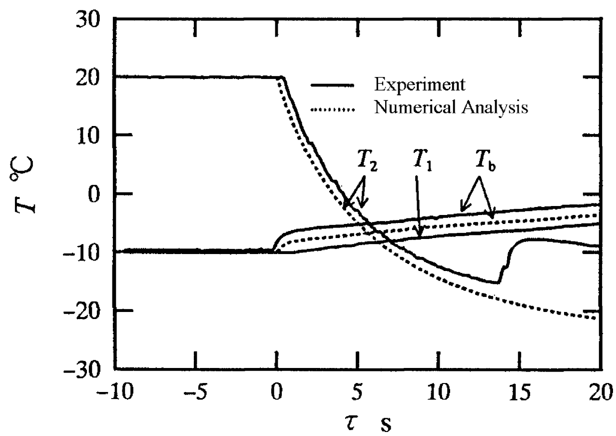

Figure 5. Rapid cooling performance of water by a practical temperature control system.

the high heat flux applied. In the successive time period of 10 s water has been subcooled to −15 °C. Then ice start to form, thus an increase of temperature is observed due to the release of the solidification enthalpy. As for the calculated T_2, it keeps on decreasing with time, as the model is not able to account for this behavior. Cooling flux which is obtained in first 4 s of the experiment is assessed to as approximately 4×10^4 W·m^{-2}, which is different to the one obtained from the use of *figure 3* when the optimal current i_{opt} is employed, i.e., $q = -1.4 \times 10^5$ W·m^{-2}. This difference is due to the fact that the optimum value in *figure 3* does not include the thermal resistance of ceramic plates of a Peltier module and that of thermal conducting grease between the module and metals. The agreement between experiment and analysis is favorable, and therefore the potential of the presented principle has been proved, in order to achieve a high heat flux which can be actively adapted to various working modes.

Acknowledgements

E. Nino and G. Ruocco wish to thank Dr. Kuniko Nishiyama for the kind assistance with the draft paper. S. Maruyama would like to express his gratitude to Dr. S. Sakai, Research Associate of Institute of Fluid Science, Tohoku University for his assistance for revising the text.

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