Simulation of Cascaded Thermoelectric Devices for Cryogenic Medical Treatment

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Abstract: This study is focused on using a thermoelectric device (TED) as an alternative to the cryogenic liquid for cooling cryosurgical probe used for cancerous tissue ablation. Thermoelectric device, namely Peltier, is a solid state device which converts electric current to thermal gradient. In past years thermoelectric devices have been successfully utilized in refrigeration and air conditioning industry for generating low temperature. Using TEDs offers advantages over conventional method for cooling the cryogenic medical device, including compact in size, light in weight and its capability to control temperature precisely. This paper presents a comprehensive analysis of the single stage and multi-stage thermoelectric device using COMSOL Multiphysics. The simulation results show the thermal performance of the single stage and cascaded Peltier modules. Simulation results proved the possibility of generating very low temperature of -70 °C for cancerous tissue ablation, by implementing multi-stage Peltier.

Keywords: Thermoelectric device, Cryogenic, Multi-stage, Cancer tissue ablation, Medical treatment

1. Introduction

Thermoelectric modules consist of a number of N and P-type semiconductors that are connected electrically in series and thermally in parallel. These N and P-type semiconductors are connected together with copper electrodes and are sandwiched between metalized ceramic plates. The thermoelectric devices are widely used as a refrigerating device for electronic cooling, air conditioning and aerospace industry. These Peltier modules are very attractive for medical device application because, unlike current complicated vapor compression refrigerator, they are compact, lightweight device with no moving mechanical parts. This device utilizes the Peltier effect to pump heat from one side to another. Figure 1 shows that when direct current flows through the TED, positive and negative charge carriers will absorb heat energy from one side and dissipate that heat energy to the heat sink at the opposite side. Therefore the heat absorption side will be cooled while the heat dissipation side will be heated. The cooling power of TEDs contributed by three factors, namely: Peltier effect, Joule heating and heat conduction from the hot side. Peltier effect (Equation 1) is depending on the current flow which causes heat pumping from one side to another:

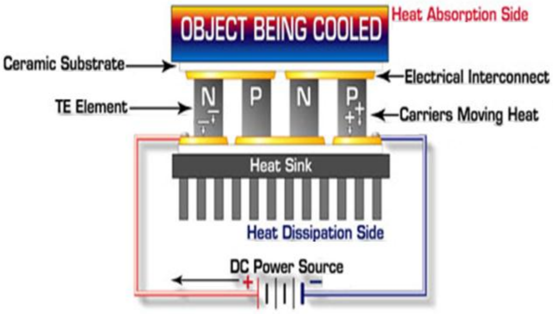

Figure 1- Peltier schematic

$$= N(\alpha \times I \times T_C) \qquad \textbf{Equation 1}$$

N:	Number of semiconductors
α:	Seebeck coefficient $[V/K]$
I:	Electrical current $[A]$
T_C:	TED cold side temperature $[K]$

On the other hand joule heating (Equation 2) refers to the heat produced due to current flow in the semiconductors in which half of the heat flows to the TED cold side whereas the other half dissipates from the hot side:

$$J = N(\frac{1}{2} \times \overline{R} \times I^2) \qquad \textbf{Equation 2}$$

$\overline{\boldsymbol{R}}$: Electrical resistance $[\Omega]$

As the heat is generated at the hot side by the Peltier effect, therefore thermal conduction may take place to affect the temperature of the cold side. This phenomenon is known as Fourier heat conduction law (Equation 3):

$$\mathrm{F}=N(\overline{K}\times\Delta T)$$ **Equation 3**

$\overline{K}$: Thermal conductance $[W/K]$

ΔT: Temperature difference $[K]$

Therefore the heat absorbed at the cold side (Q_C) is described as follows:

$$Q_C = \quad -J-F$$ **Equation 3**

P: Peltier effect $[W]$
J: Joule heating $[W]$
F: Fourier heat conduction law $[W]$

While the heat dissipated from the hot side is equal to the sum of absorption heat and input power (Equation 5):

$$Q_h = Q_C + \bar{R}.I^2 = \quad +J-F$$ **Equation 5**

2. Modeling Methods

The thermoelectric effect module in COMSOL Multiphysics has been used to efficiently model a Peltier module. The thermoelectric effects module coupled heat transfer in solids equations and electric currents equations and solved them simultaneously, to predict the temperature distribution along the Peltier device.

2.1 Governing Equations

The absorbed heat from the cold side of the Peltier module, namely cooling capacity (Equation 4), and the emitted heat from the hot side of the Peltier module (Equation 5) and coefficient of performance (COP) of the Peltier (Equation 6) may be calculated, using conventional method based on the one dimensional heat balance equation, in which the thermal conductance (Equation 7) and electrical and resistance (Equation 8) are included.

$$COP = \frac{Q_C}{P}$$ **Equation 6**

$$\overline{K} = \frac{\bar{k}.A}{L}$$ **Equation 7**

$$\overline{R} = \frac{L}{\bar{\sigma}.A}$$ **Equation 8**

The thermoelectric effect module in COMSOL software also took into account the conventional method equations. This module provides a better accuracy for modelling a thermoelectric module and it is useful in analysis and optimal design of multi-stage Peltier for cooling systems. In COMSOL software the governing equations which indicate the electric current balance (Equation 9) and energy balance (Equation 10) in the Peltier device are as follows:

$$-\vec{V}.\left(\sigma.\vec{\nabla}V\right)=0$$ **Equation 9**

σ: Electrical conductivity $[S/m]$
V: Electric potential $[V]$

$$\rho C_p\frac{\partial T}{\partial t}+\nabla.q=Q$$ **Equation 10**
$$q=-k\nabla T+PJ$$

ρ: Density $[kg/\,m^3]$
C_p: Heat capacity $[kg/\,(J.K)]$
T: Temperature $[K]$
q: Heat flux $[W/m^2]$
k: Thermal conductivity $[W/\,(m.K)]$
: Peltier coefficient $[V]$
J: Current density $[A/m^2]$

2.2 Boundary Conditions

The boundary condition was set to 0V at the base of P-type semiconductor element. The current and the voltage were applied at the base of the N-type semiconductor element. Temperature at the base of the lower alumina substrate was fixed at the room temperature, 290K. Adiabatic boundary conditions were taken on other surfaces.

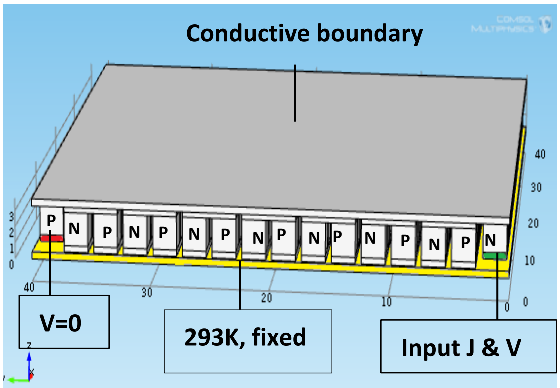

Figure 2- The Peltier example with 40×40×3.6 mm^3 dimension generated in COMSOL Multiphysics. The current density J and voltage are applied at the base of the N-type semiconductor in right hand side (green); the lower electrode at the P-type semiconductors is grounded (red). The temperature of lower ceramic substrate is kept at room temperature (yellow).

2.3 Material Properties

The Peltier device consists of numbers of Bismuth Telluride semiconductors that are connected together with copper layer and are sandwiched between Alumina plates. (Figure 3) The material properties for simulation are shown in Table 1. It is notable that the temperature independent material properties are used for the simulation.

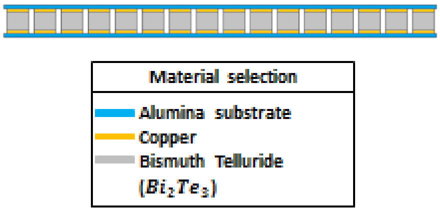

Figure 3- material selection for Peltier device

Material properties	Unit	Bismuth telluride	Copper	Alum-ina
Thermal conductivity	$\frac{W}{m*K}$	1.6	350	27
Density	$\frac{Kg}{m^3}$	7740	8920	3900
Heat capacity	$\frac{J}{kg*K}$	154.5	385	900
Seebeck coefficient	$\frac{V}{K}$	P: 200e-6 N: -200e-6	6.5e-6	-
Electrical conductivity	$\frac{S}{m}$	1.1e5	5.9e8	-

Table 1- Peltier device material properties

3. Results

3.1 Single Stage

Here a single Peltier device consists of 127 N-P junctions with $40\,(W) \times 40(L) \times 3.6(H)$ mm3 dimension is modelled in COMSOL Multiphysics. The calculated temperature difference between hot and cold side, cooling capacity (Q_C) and coefficient of performance (COP) versus various applied current (A) for single stage Peltier are shown extensively in Figure 4. An example of analysis of Peltier device subject to its maximum applied current and voltage is shown in figure 5. The results shown in this figure indicate that the maximum achievable temperature difference with Peltier device is not more than 70 K. The results shown in Figure 4 and Figure 5 proved that a single stage Peltier unable to generate the required low temperature of -70 °C (203K) for cancerous tissue ablation therefore multi-stage Peltier is needed for achieving this temperature

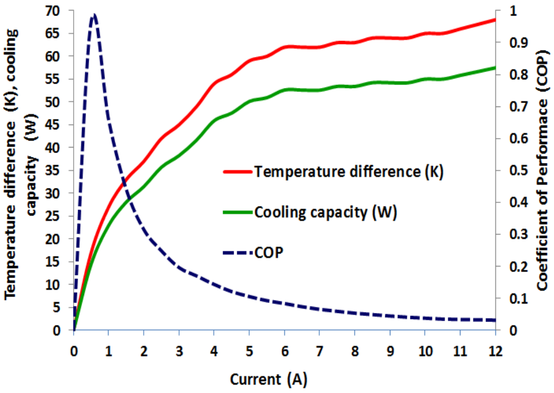

Figure 4- Simulation results of single stage Peltier. Calculated temperature difference between hot and cold side versus applied current (solid), Peltier cooling capacity (Q_C) versus applied current (cross) and Peltier coefficient of performance (COP) versus applied current (dotted).

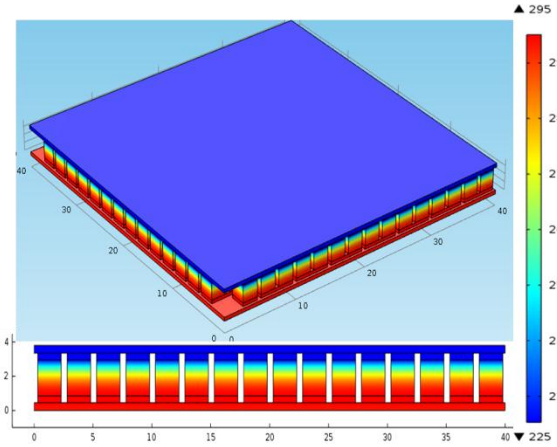

Figure 5- The resulting temperature distribution of a single stage Peltier. The applied voltage and current are 15.2 V and 12A respectively. A temperature difference of nearly 68K is achieved.

3.2 Multi-stage

Increasing number of Peltier stage for cooling system will result in achieving lower temperature at the cold side. Therefore the extensive analyses for 2-stage and 3-stage Peltier have been carried out. The results in figure 6 shows that the cold side temperature generated by 2-stage Peltier is not sufficient for cancerous tissue ablation while very low temperature, roughly 210K, can be achieved with 3-stage Peltiers. Results shown in figure 6 and figure 7 also proved that increasing number of stages will results in decreasing cooling capacity (Q_C) and coefficient of performance (COP).

Therefore removing more heat energy from TED will reduce the efficiency of the device.

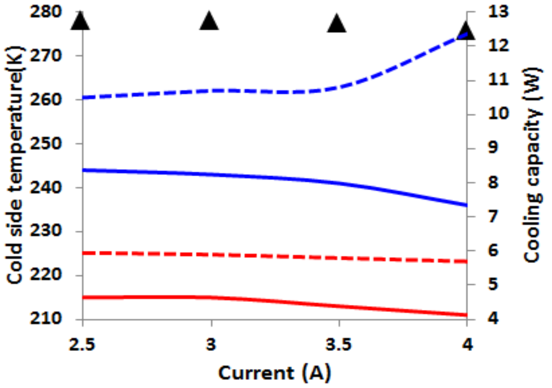

Figure 6- Interface temperature between stage one and two (triangle), Cold side temperature (solid) and cooling capacity (dotted) versus current generated by 2-stage (blue) and 3-stage (red) Peltier.

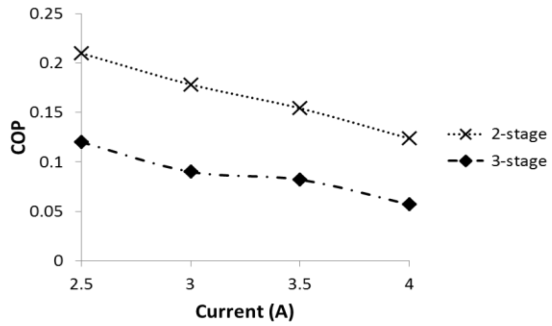

Figure 7- comparison of COP for 2-stage and 3-stage Peltier

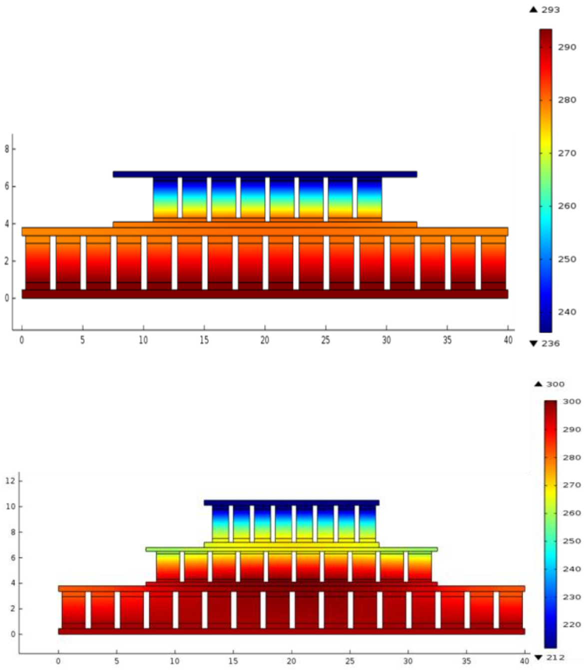

Figure 8- Comparison of temperature distribution in 2-stage (above figure) and 3-stage (below figure) Peltier both electrically connected in parallel. The result temperature generated by applying 2.5 V and 4 A to all stages.

4. Conclusions

COMSOL Multiphysics package has been adopted to simulate the thermal behaviour of single stage and multi-stage Peltier. The simulation results verify the Peltier capability for generating freezing temperature for cancer tissue ablation. Peltier thermal simulation with COMSOL Multiphysics proves to be powerful technique to predict temperature distribution in thermoelectric device. The results obtained from COMSOL enable us to develop an experimental test based on this model.

5. References

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