

Natural Convection in a Square Enclosure Cooled by Peltier Effect

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Abstract -In this paper, natural convection in a square enclosure cooled by Peltier effect is investigated numerically. The thermoelectric cooler is assumed to be mounted on the left sidewall of the enclosure. The right sidewall of the enclosure is at constant temperature and horizontal walls are adiabatic. Flow is assumed to be two dimensional, Newtonian, and incompressible. Governing equations are derived using Boussinesq approximation. Computational results are obtained for values of electric current ranging from 2 to 8A. The results show that a thermal plume develops at the bottom left part of the enclosure in the early stage of the flow. Flow field consists of a counter clockwise cell. As the electric current and hence the heat flux on the left wall of the enclosure increases, a secondary circulation cell develops at the bottom part of the enclosure as a result of the thermal plume. With the thermoelectric cooler, very low temperatures can be reached within a relatively short time.

Keywords: Natural convection, enclosure, Peltier effect, thermoelectric cooling.

1. Introduction

When a current flows through a junction between two conductors, heat flux is generated at the junction. This is known as Peltier effect and was discovered by Peltier in 1834. Accordingly, a Peltier or thermoelectric device transfers heat from one side of the device to the other side by consuming the electric energy. The Peltier devices are mainly used in cooling applications and the efficiency of these systems are significantly lower than that of conventional compressor-based cooling systems. They operate at about 10% efficiency, whereas the efficiency of a compressor-based refrigerator is about 30% (Gurevich and Lugvinov, 2007). On the other hand, they have small size and weight and they are highly reliable; their lifetimes are quite long. The Peltier coolers have also no moving parts; therefore, they are vibration and noise free and need less maintenance. Furthermore, as opposed to the conventional compressor-based cooling systems, there is no need for the usage of flammable or environmentally harmful refrigerants. Therefore, TECs have found lots of application areas such as vehicle refrigerator, automobile seat cooler, portable picnic cooler, residential water cooler, computer microprocessor cooler (Gurevich and Lugvinov, 2007; DiSalvo, 1999; Venkatasubramanian et al., 2001).

Bismuth telluride (Bi_2Te_3) is used in mostly used commercial thermoelectric coolers because it is the best thermoelectric material around the room temperature. Alternating legs of p-doped and n-doped Bi_2Te_3 are connected electrically in series and thermally in parallel. In the p-doped legs, positively charged holes transfers heat in the same direction as the current flow, and in the n-doped legs, negatively charged electrons transfers heat in the opposite direction (Mann, 2006). As a result, heat is transferred from the cold side to the hot side in both legs. Coolers used in commercial applications are generally composed of dozens of pairs of legs in order to maximize cooling per unit area (Mann, 2006).

There are limited number of studies on thermoelectric cooling and they are mostly focused on the performance of the cooling system. Dabhi et al. (2012) studied the performance of thermoelectric refrigeration system and found that the COP first increases with an increase in the current and then decreases with the further increase in the current. The COP decreases with an increase in input power. Furthermore, the COP decreases with an increase in the temperature difference. Similar results were obtained in the study conducted by Francis et al. (2013) on performance evaluation of thermoelectric coolers. Nogueira and Camargo (2003/2004) studied the performance of an air conditioning system based on Peltier effect and concluded that the maximum temperature difference between the hot and cold side of the thermoelectric module is one of the most important parameters in performance evaluation of the air conditioning system. Bian and Shakouri (2006) investigated the effect of inhomogeneous thermoelectric materials on cooling performance of thermoelectric cooler. They found that the maximum cooling temperature can be greatly increased by using inhomogeneous thermoelectric material. They found that a cooling enhancement of 35% can be achieved for graded Silicon crystals. Chang et al. (2007) experimentally investigated the thermal performance of a thermoelectric air-cooling module with a heat sink. Their results show that TEC resistance decreases and heat sink resistance increases with an increase in input current. Furthermore, results also show that TEC resistance increases and heat sink resistance decreases with an increase in heating power of the heat source. The effect of thermoelectric cooling on performance of a CPU. Their results show that optimized thermoelectric modules combined with two-phase (liquid/vapour) passive devices can further improve the cooling capability of a CPU compared to conventional air cooling technologies at reasonable thermoelectric cooler (TEC) power consumption. A novel air conditioning system based on thermo-electric cooling was proposed by Kemiklioğlu and Solmaz (2014) for automotive vehicles. Their results show that although the performance is less than a typical AC system based on a cooling cycle, it is cheaper to build and manufacturing process is simpler.

In this study, natural convection in a square enclosure cooled by a thermoelectric cooler is investigated numerically and the effect of magnitude of the electric current on the flow and heat transfer in the enclosure is discussed by primarily streamlines and isotherms.

2. Analysis

The geometry and the coordinate system for the problem considered in this study are shown in Fig. 1. Thermoelectric cooler is mounted on left sidewall of the enclosure with a width of W and height of H . The right wall of the enclosure is maintained at T_h . The horizontal walls of the enclosure are assumed to be adiabatic. The cooling rate of thermoelectric device depends on the temperature difference of hot and cold surface. The cooling rates of the thermoelectric cooler used in this study are shown in Fig. 2 for various values of the pertinent parameters. It is assumed that the hot side of the thermoelectric cooler is attached to a perfect heat sink so that it remains at ambient temperature.

In this study, flow is assumed to be Newtonian, steady and incompressible. The buoyancy effects are formulized by the Boussinesq approximation. The governing equations then take the following form.

$$\rho \nabla \cdot \mathbf{u} = 0 \quad (1)$$

$$\rho \frac{\partial \mathbf{u}}{\partial t} + \rho (\mathbf{u} \cdot \nabla) \mathbf{u} = \nabla \cdot \left[-p + \mu \left(\nabla \mathbf{u} + (\nabla \mathbf{u})^T \right) \right] + \rho g \beta (T - T_h) \mathbf{j} \quad (2)$$

$$\rho C_p \frac{\partial T}{\partial t} + \rho C_p \mathbf{u} \cdot \nabla T = \nabla \cdot (k \nabla T) \quad (3)$$

where \mathbf{u} is the velocity, p is the pressure, T is the temperature, ρ is the density, μ is the dynamic viscosity, β is the coefficient of thermal expansion, C_p is the specific heat, g is the gravitational acceleration and k is the thermal conductivity.

The governing equations are subjected to the following initial and boundary conditions:

$$\mathbf{u} = \mathbf{0} \text{ at the walls and at } t=0 \tag{4}$$

$$q = q_w \text{ at the left sidewall} \tag{5}$$

$$T = T_h \text{ at the right sidewall and at } t=0 \tag{6}$$

$$\partial T / \partial y = 0 \text{ at } y=0 \text{ and } y=H \tag{7}$$

where q is the heat flux.

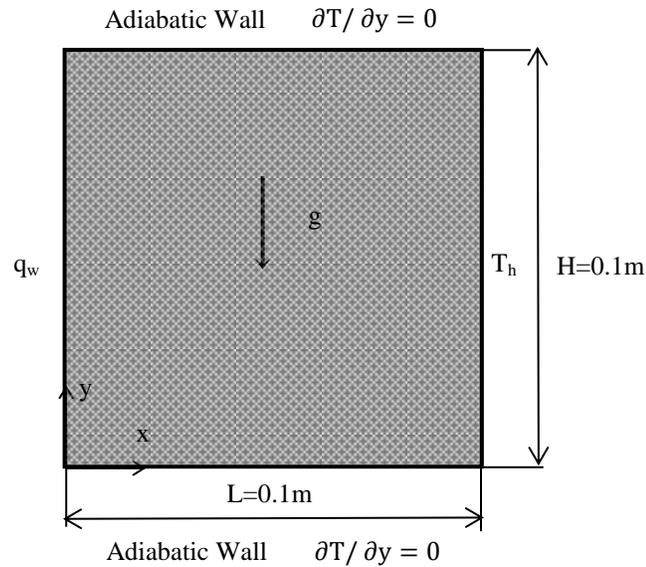


Fig. 1. Geometry and coordinate system.

The performance curves of the thermoelectric device considered in this study are shown in Figure 2. The heat flux produced by the thermoelectric cooler is given in Table 1 for various values of the electric current.

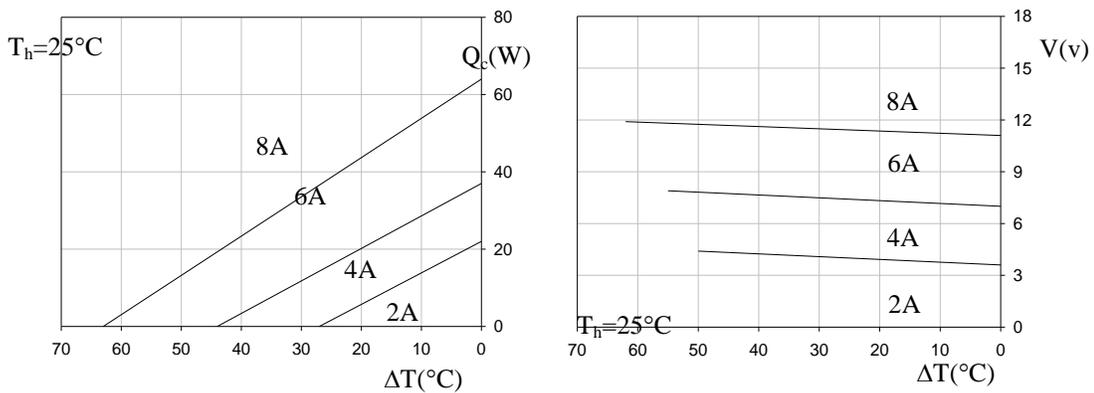


Fig. 2. Performance curves of the thermoelectric cooler used in this study (TEC1-12708, 2012).

3. Results and Discussion

The solutions are obtained by a finite element analysis and simulation software. Absolute convergence criterion is taken as 10^{-4} for each variable in the equations. The solution domain was meshed with triangular mesh elements. Small size mesh elements are used near the walls of the enclosure

where the velocity and temperature gradients are high. The results were obtained by a parallel sparse direct linear solver, which is based on a Level-3 BLAS update. The numerical results have been validated by obtaining the results for an air filled enclosure heated differentially and comparing the results with the benchmark results of De Vahl Davis and Jones (1983) (see Kahveci (2007)).

Table. 1. Heat flux for $T_h=25^\circ\text{C}$ and various values of electric current of thermoelectric cooler.

I=2A	$q_w = -[22 - 0.815 * (25 - T)] / (1600 * 10^{-6})$
I=4A	$q_w = -[37 - 0.841 * (25 - T)] / (1600 * 10^{-6})$
I=6A	$q_w = -[64 - 1.016 * (25 - T)] / (1600 * 10^{-6})$
I=8A	$q_w = -[72 - 1.075 * (25 - T)] / (1600 * 10^{-6})$

The streamlines and isotherms in the flow field are shown in Figs. 3-6 for various values of the electric current. Cooling flow particles descend along the left cold of the enclosure until they reach the bottom wall. Then they are shifted rightward along the bottom wall of the enclosure. After they reach the right wall of the enclosure they begin to ascend while they are heated along the hot right wall of the enclosure. After they reach to the top wall, they are shifted toward the left cold wall and flow paths are completed. As it can be seen from the figures that there is a quiescent region at the right part of the enclosure in the early stage of the flow. Furthermore, a thermal plume develops at the bottom left part of the enclosure. Flow regime evolves to a boundary flow regime as the flow becomes developed. This is clear from the steep thermal gradients along the left and right walls of the enclosure and formation of a plateau at the core region of the enclosure. As electric current and hence the heat flux increases, a secondary circulation develops at the bottom part of the enclosure as a result of the thermal plume. The secondary circulation disappears as the flow becomes developed as a result of the horizontal thermal diffusion. Heat flux on the left wall of the enclosure is higher in the early stage of the flow and a decrease towards a constant value is seen in the later stage. Therefore, strong natural convection currents in the early stage of the flow lose momentum and flow evolves to a developed stage. It can also be inferred from the results that the low temperatures are reached by thermoelectric cooling within relatively short times.

The evolution of average temperature in the enclosure is seen in Fig. 7 for various values of the electric current. Increase in the electric current decreases the temperature significantly. On the other hand decrease in the temperature slows down when the electric current is decreased beyond a certain value. It can be observed from Fig.7 that flow becomes developed in 40 seconds. Average temperature in the enclosure decreases approximately to 12°C for I=2A, to 4°C for I=4A, to -5°C for I=6A and to -7°C for I=8A.

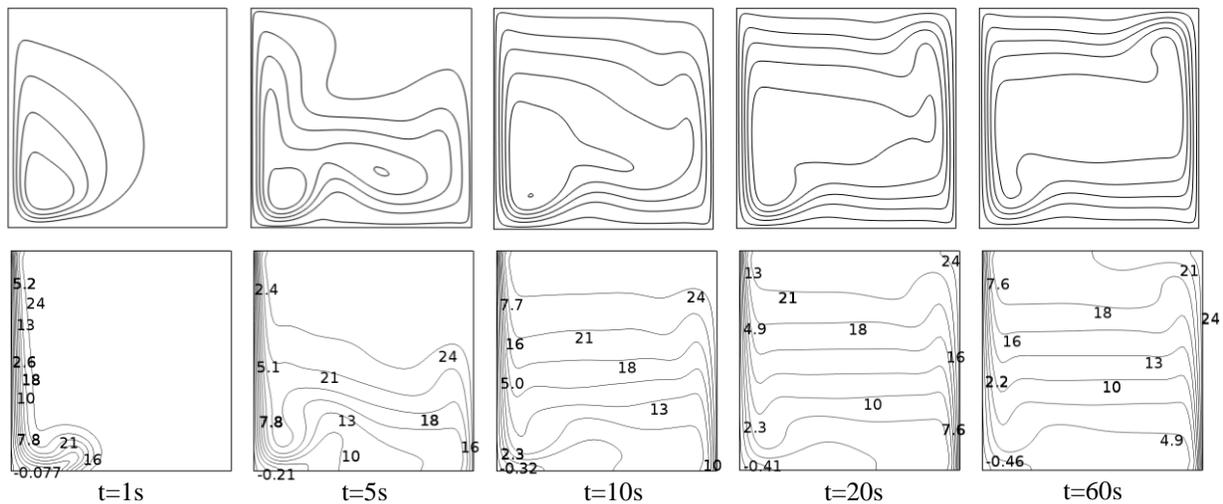


Fig. 3. Streamlines (top) and isotherms (bottom) for I=2A.

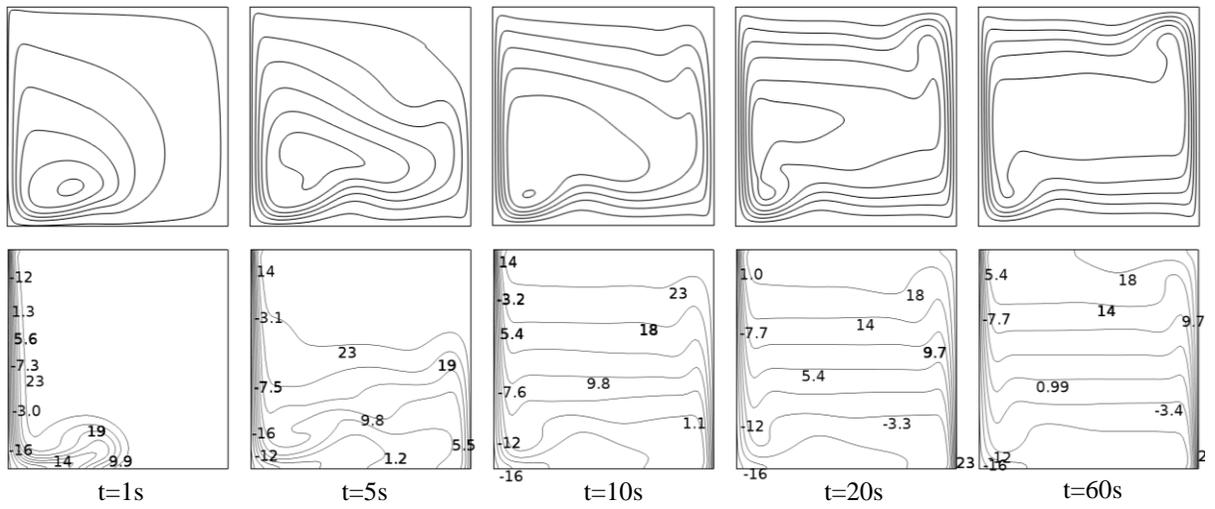


Fig. 4. Streamlines (top) and isotherms (bottom) for $I=4A$.

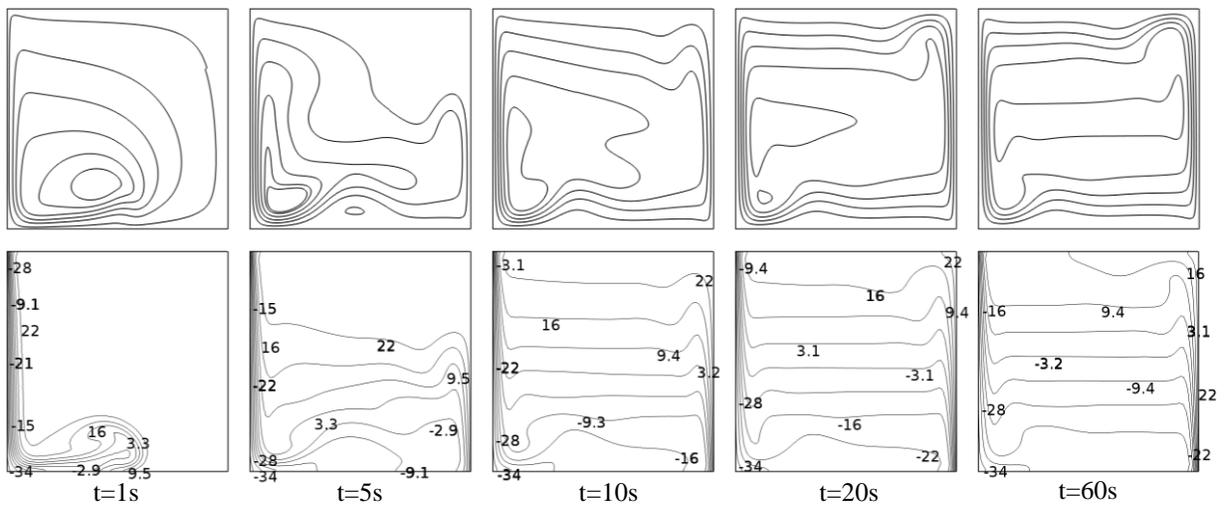


Fig. 5. Streamlines (top) and isotherms (bottom) for $I=6A$.

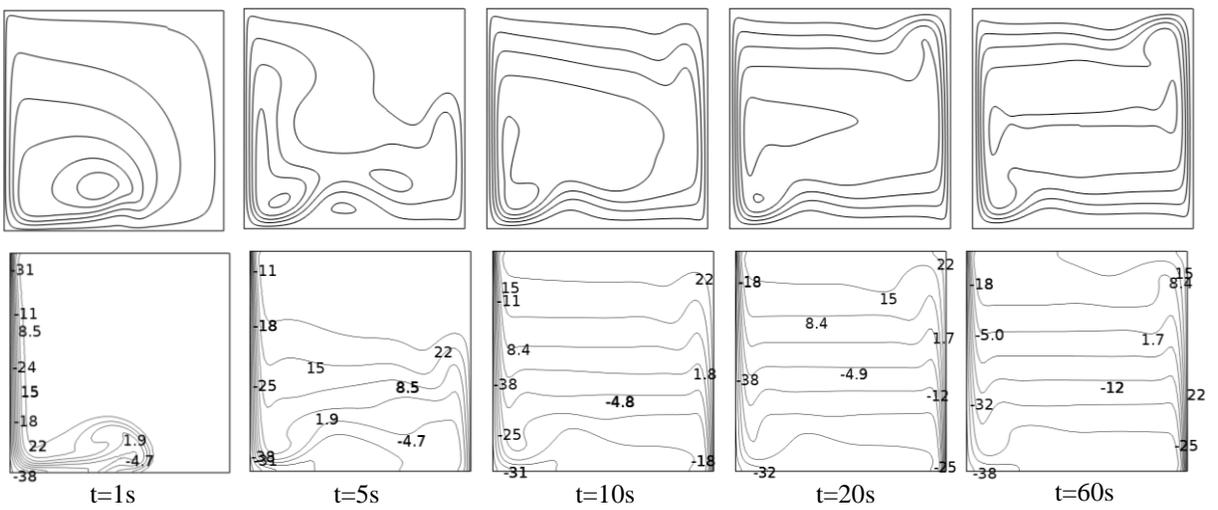


Fig. 6. Streamlines (top) and isotherms (bottom) for $I=8A$.

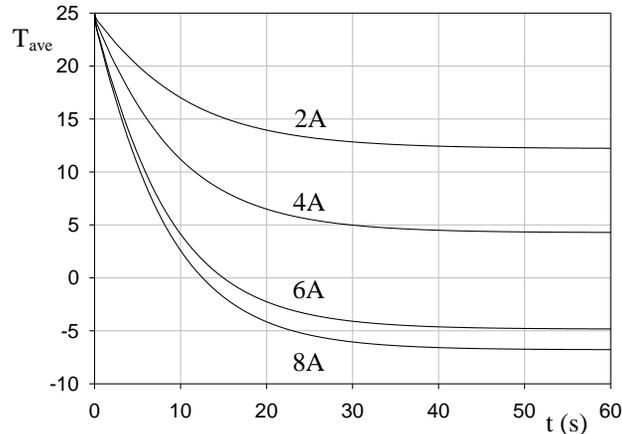


Fig. 7. Average temperature in the enclosure during thermoelectric cooling.

4. Conclusion

Natural convection in a square enclosure cooled by Peltier effect is investigated numerically for various values of electric current. A thermal plume develops at the bottom left part of the enclosure in the early stage of the flow. A counter clockwise cell is present in the flow field of the enclosure. As the electric current and hence the heat flux increases, a secondary circulation cell develops at the bottom part of the enclosure as a result of the thermal plume present in the flow field. With the thermoelectric cooler, very low temperatures can be reached within a relatively short time.

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