System design and simulation of constant temperature box using semiconductor refrigeration device

Hui Zhang*

The School of Instrument Science and
Opto-electronic Engineering,
P.O. Box 1#, Hefei University of Technology,
Anhui 230009, China
Fax: +86-551-2903783 E-mail: zhanghui-nano@126.com
*Corresponding author

Kuang-Chao Fan

The School of Instrument Science and
Opto-electronic Engineering,
P.O. Box 1#, Hefei University of Technology,
Anhui 230009, China

The Department of Mechanical Engineering,
National Taiwan University, Taipei, China
Fax: (02) 2364-1186 E-mail: fan@ntu.edu.tw

Jun Wang

The School of Instrument Science and
Opto-electronic Engineering,
P.O. Box 1#, Hefei University of Technology,
Anhui 230009, China
Fax: +86-551-2903783 E-mail: wangjun@hslcn.com

Abstract: This paper presents the variation law of temperature in three-dimensional space, which is cooled by the refrigeration provided by the cold side of a semiconductor. The mathematical model of the temperature field of the semiconductor refrigeration device is described, and a numerical study on the temperature profile in a semiconductor refrigeration device was carried out using this model. The problems in the present thermostated containers are discussed, the factor influencing current air organisation and temperature field are analysed. The experimental results show that forced convection is of benefit to the cold transfer and to the rise of refrigeration rate.

Keywords: semiconductor refrigeration; constant temperature box; mathematical model; numerical simulation.

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Biographical notes: Hui Zhang received his Bachelor Degree in Automation of Industry, Master Degree in Applications of Computer and PhD Degree in Precision Instrument and Machinery from Hefei University of Technology, Hefei, China. He is a professor in the School of Instrument Science and Opto-electronic Engineering at Hefei University of Technology. He is author of more than 50 papers published on journals and conference proceedings. His main research interests include modern measurement and control technology in instrumentation. He is currently studying on control theory and system of environment for Micro/Nano-meter measurement.

Kuang-Chao Fan received the PhD Degree from University of Manchester Institute of Science and Technology in UK in 1984. He is the Chair Professor of Mechanical Engineering at National Taiwan University, and also at Hefei University of Technology. He is the SME Fellow. His research interests include manufacturing metrology, precision machining, and machine tool technology. He has published more than 100 journal papers and 200 conference papers.

Jun Wang is a Master candidate in School of Instrument Science and Opto-electronic Engineering, Hefei University of Technology. Her main research fields include online measurement techniques and measurement automation.

1 The principle of numerical simulation of TEC

Thermoelectric Cooler (TEC) modules are high heat-flow devices. The efficiency of semiconductor refrigeration depends on the temperature difference between the cold and hot sides of a thermopile. This temperature difference can be remarkably reduced both by the heat loss of the enhanced hot side and by the cold dissipation of the enhanced cold side, thus leading to the rise of semiconductor refrigeration efficiency.

Semiconductor cooling is the application of Peltier effect. When a loop of two different conductors passed through DC, the temperature on one side will be very low and on the other side the temperature will be high (Deshen, 1993).

In this paper, the semiconductor refrigeration MAA050-12 (http://www.melcor.com/) which is produced by Melcor corp. is used. It can produce 15 W refrigerating capacity with 12 V power supply. It is fixed as the figure shows.

The heat transfer and air distribution of the refrigeration are simulated when it works, assuming:

- the cabinet is well blockaded, there is no air release, and the heat conductivity of the wall is low
- the air in the cabinet is incompressible; its consistency obeys the Boussingesq Hypothesis
- the airflow in the cabinet is turbulent flow
- the air in the cabinet is a transparent medium, does not participate with radioactive heat transfer and ignores the radioactive heat transfer between the walls.

Figure 1 Instruction of TEC

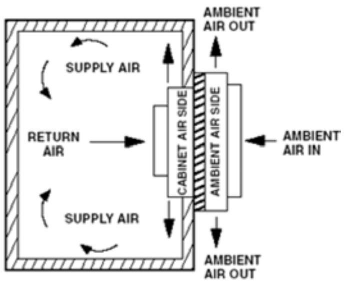
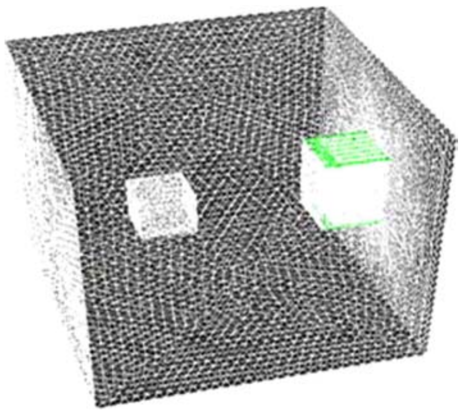


Figure 2 MAA050T-12 (see online version for colours)

Figure 3 Mesh models (see online version for colours)



When there is no heat source in the cabinet, pressure distribution and velocity vector of middle section in 3D space.

Figure 4 Pressure distribution (see online version for colours)

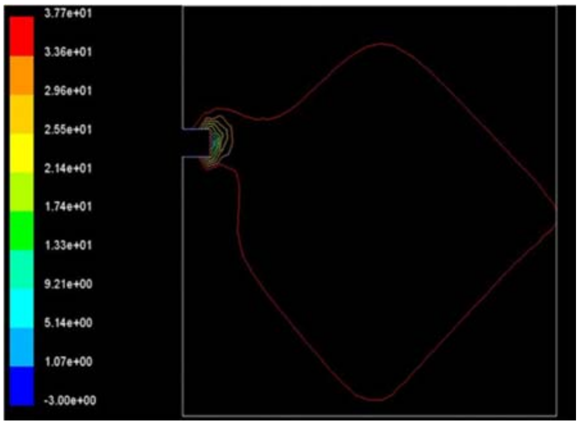
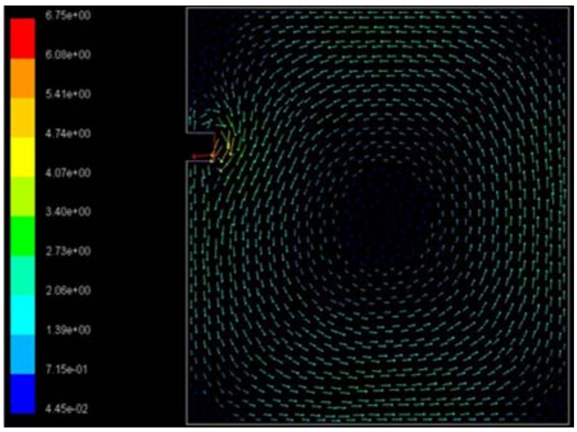
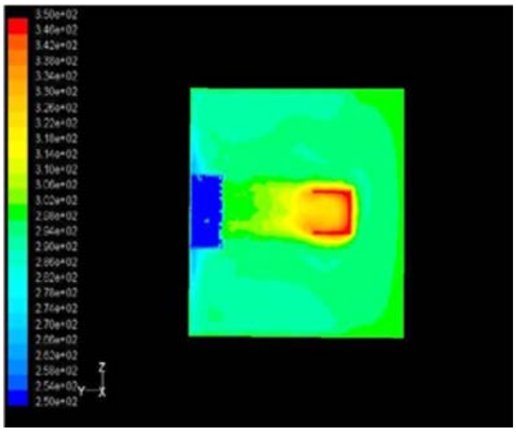


Figure 5 Velocity vector (see online version for colours)

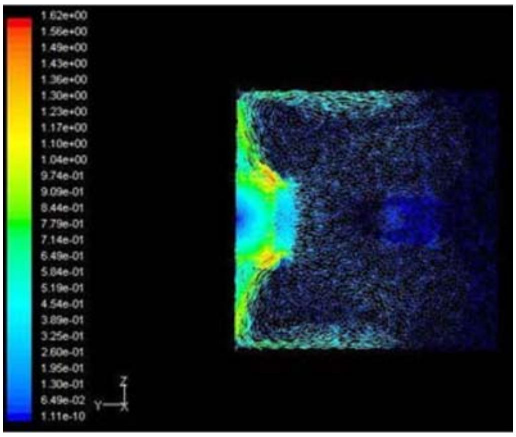


When there is one heat source in the cabinet, set 3D turbulent heat transfer model in the Computational Fluid Dynamics (CFD) software, define a FAN boundary condition in the cool side and set segregated solver, first-order implicit. We can get node's information like: temperature, velocity vector, and pressure, etc.

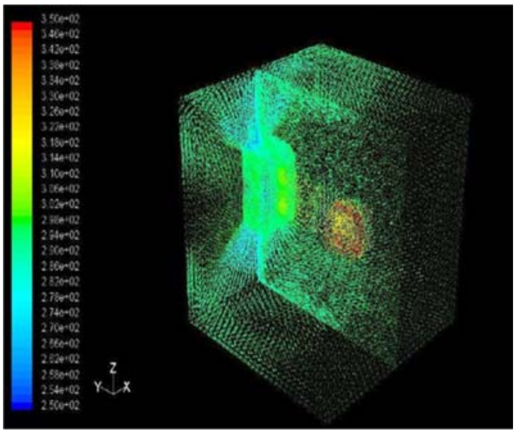
Figure 6 Simulation result of TEC: (a) temperature distribute of mid-surfaces; (b) velocity vector of mid-surfaces and (c) temperature distribute of 3D space (see online version for colours)



(a)



(b)



(c)

During steady-state operations, the heat transfer in cabinet in which semiconductor refrigeration is working is influenced by both forced convection and natural convection.

This temperature difference can be remarkably reduced both by the heat loss of the enhanced hot side and by the cold dissipation of the enhanced cold side, thus leading to the rise of semiconductor refrigeration efficiency.

The main ways to abstract heat include: natural convection heat transfer, forced convection heat transfer, water cooling, phase-change heat transfer, boiling heat transfer, etc.

DC fans can be mounted directly to MAA050T-12 on both hot and cold sides and provide forced air convection.

2 Designing of constant temperature box using TEC

Design specification of the accuracy of controlled temperature is 20 ± 0.05°C; the entire space requires high temperature uniformity, and cannot appear in any blind area of temperature or intensive air movement.

The temperature stability is attained by controlling the work current of semiconductor refrigeration, and the temperature uniformity of the working place is depending on the mechanical structure design.

In this paper, we use cube structure with three different cavities, which are: constant temperature cavity, steadying pressure cavity and refrigerating cavity. The air gets across the air return grille from the bottom of constant temperature cavity to refrigerating cavity, being cooled and mixed by semiconductor refrigeration device, then insufflated to constant temperature cavity by AC fan. In the steadying pressure cavity, the air mixed again, then through the orifice plate flowed to the working place (constant temperature cavity). By air convection heat transfer, let the cool energy, which is produced by the semiconductor refrigeration device, transfer to the constant temperature cavity, ensuring the temperature stability of working place.

To make the air distribution more uniform, we add in a wide-guide board and an orifice plate in the steadying pressure cavity. Wide-guide is a funnel-shaped board; it makes the air evenly distributed in certain area.

When the pressure of steadying pressure cavity is higher than the pressure of constant temperature cavity, the difference in pressure between the two sides of orifice plate makes piston type air flow below the orifice plate, it makes the air gained to mix sufficiently, with uniform temperature and velocity field. We use 80 mm beta glass fibre as thermal insulation material filled surrounding the box. The structure and picture of the insulated cabinet is shown here.

Figure 7 Experiment model (see online version for colours)

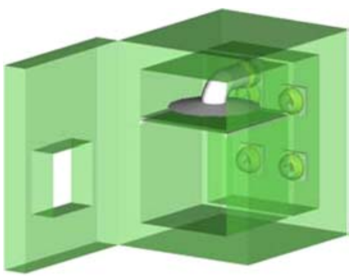
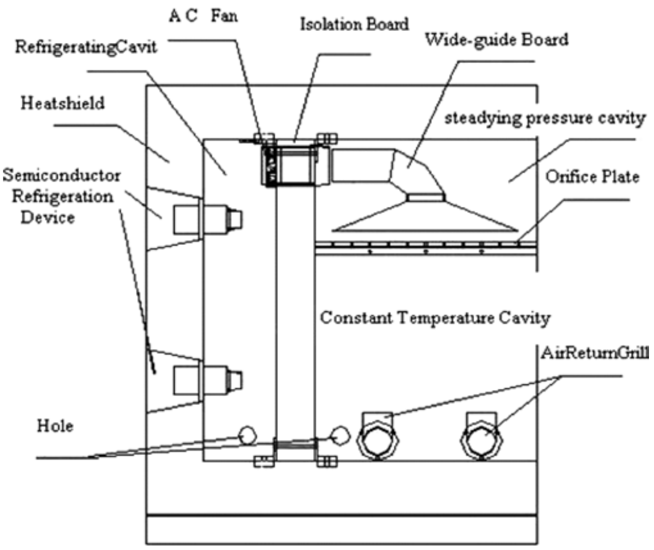


Figure 8 Structure of cabinet



3 Analysis to constant temperature box using TEC

Working condition: the insulated cabinet is placed in air conditioning room; the temperature is invariable at 25°C. The semiconductor refrigeration device is working in single direction.

The heat transfer in cabinet in which semiconductor refrigeration working is mixed convection, influenced by both forced convection and natural convection, and the airflow in the cabinet is turbulent flow. During steady-state operations, the air distribution is steady flow, but during the incipient stage of start-up it was unsteady flow. Consistency obeys to Boussingesq Hypothesis.

Study on mathematical model for flowing and heat transferring process, import tensor labelling method, it can be formulated as:

Continuous equation:

$$\mathrm{div}(u) = 0$$

Momentum equation (Navier-Stokes equation):

$$\frac{\partial}{\partial x_i}(\rho u_i u_j) = -\frac{\partial}{\partial x_i}\left(p + \frac{2}{3}\rho k\right) + \frac{\partial}{\partial x_i}\left((\mu + \mu_t)\frac{\partial u_j}{\partial x_i}\right) + \frac{\partial}{\partial x_i}\left((\mu + \mu_t)\frac{\partial u_i}{\partial x_j}\right)$$

k equation (Turbulent *k*inetic energy equation):

$$\frac{\partial}{\partial x_i}(\rho u_i k) = \frac{\partial}{\partial x_i}\left(\frac{\mu_t}{\sigma_k} \cdot \frac{\partial k}{\partial x_i}\right) + G - \rho\varepsilon$$

ε equation (Turbulent dissipation energy equation):

$$\frac{\partial}{\partial x_i}(\rho u_i \varepsilon) = \frac{\partial}{\partial x_i}\left(\frac{\mu_t}{\sigma_\varepsilon} \cdot \frac{\partial \varepsilon}{\partial x_i}\right) + (c_1 G - c_2 \rho\varepsilon)\frac{\varepsilon}{k}$$

G the kinetic energy generation item caused by mean velocity gradient:

$$G = \mu_t\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)\frac{\partial u_i}{\partial x_j}, \quad \mu_t = \rho c_\mu \frac{k^2}{\varepsilon}$$

where:

ρ	Fluid density
p	Pressure
k	Heat transfer coefficient
t	Time
u	Velocity vector
ε	Turbulent dissipation rate
k	Turbulent *k*inetic energy
μ_t	Turbulent viscosity.

The empirical parameters: $c_\mu = 0.09$, $c_1 = 1.44$, $c_2 = 1.92$, $\sigma_k = 1.0$, $\sigma_\varepsilon = 1.3$.

Symbol definition is according to Wenquan (1986).

The principle of heat transfer enhancement and field-coordinated is according to Guo et al. (1998).

Convection heat transfer is essentially a heat transfer that contains an internal heat source, the flowing of fluid is equivalent to the weight to heat source; intensity of convection heat depends on the intensity of equivalent heat source, it rests with the difference in temperature, velocity of flowing, and thermo-physical property, transport property of the fluid, and also depends on the angle between velocity vector and heat stream vector. Diminishing the angle will enhance the convection heat transfer.

The ways of enhancing heat transfer include: increase the Reynolds number, for example, increase the velocity of flow, decrease the passage diameter, increase the Pr number, and diminish the angle between velocity vector and heat stream vector, etc.

We place a wide-guide board and an orifice plate in the insulated cabinet, let the air flows through the heat source; meet the demands of diminishing the angle between velocity vector and heat stream vector, so as to enhance the convection heat transfer to a certain extent.

4 Simulating analysis on constant temperature box

- *No heat source*. The cabinet is well blockaded, there is no air release, the heat conductivity of the wall exists, and the ambient temperature is higher than the cabinet. Assuming the air in the cabinet is incompressible, its consistency obeys the Boussingesq Hypothesis. The air in the cabinet is a transparent medium; it does not participate with radioactive heat transfer; it ignores the radioactive heat transfer between the wall. The cool energy is provided by semiconductor refrigeration device; the temperature and velocity of inlet can be controlled.

With the same temperature of inlet air, increase in inlet velocity efficiency enhances the convection heat transfer, but nano-scale measurement requires the environment not to be intensive for air movement; thus during steady-state operations, the velocity of air fluid should below 1 m/s. We can choose a suitable large velocity during the incipient stage of star-up.

- *Contain heat source*. When nano-scale measurement insulated cabinet working, the main heat source in the constant temperature cavity is a piezoelectric motor; the maximum flash temperature is up to 320 K. Suppose there is a constant heat source, temperature is 323 K.

Increased inlet velocity could efficiently abate the influence of heat source; when increased to a certain degree, it will nearly have no influence on the temperature field. But reduction of the temperature of inlet airflow does not work obviously. In addition, we can isolate the heat source and cooling it separately.

Figure 9 Mesh models of cabinet (see online version for colours)

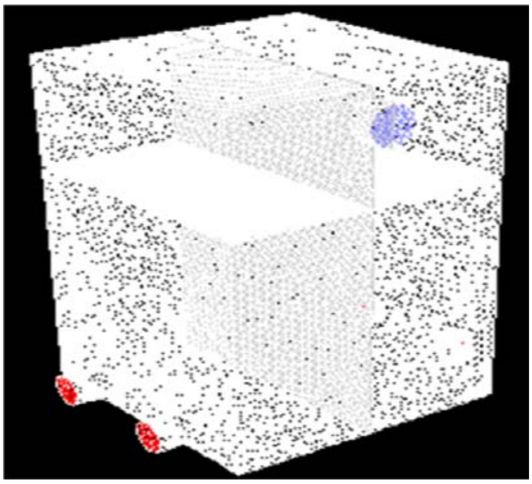
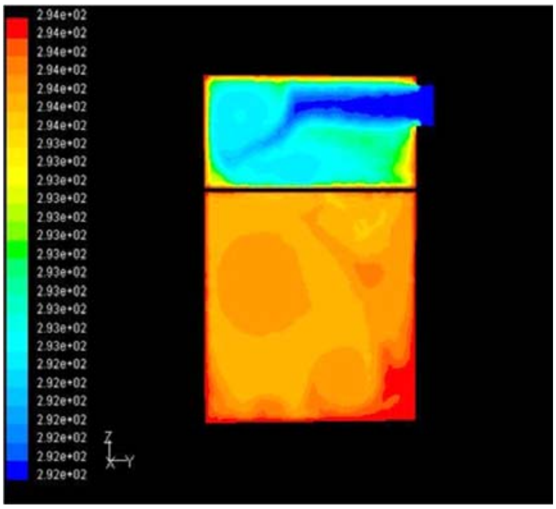
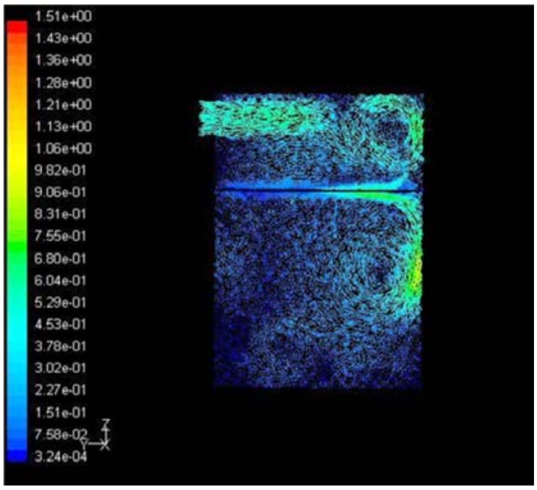


Figure 10 Simulation result of cabinet (inlet $V = 0.5$ m/s, $T = 292$ K) (a) temperature distribute of mid-surfaces; (b) velocity vector of mid-surfaces and (c) temperature distribute of 3D space (see online version for colours)



(a)

Figure 10 Simulation result of cabinet (inlet $V = 0.5$ m/s, $T = 292$ K) (a) temperature distribute of mid-surfaces; (b) velocity vector of mid-surfaces and (c) temperature distribute of 3D space (see online version for colours) (continued)



(b)

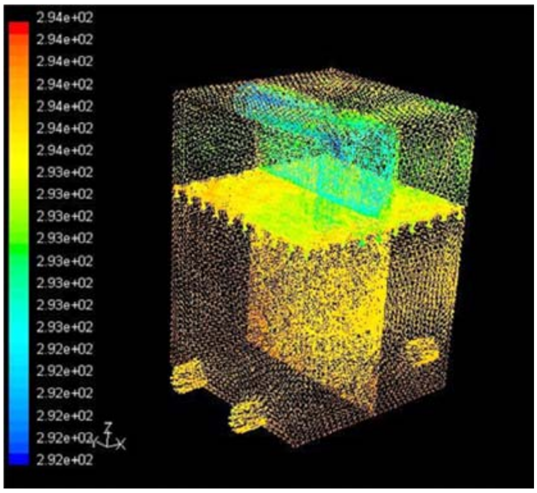
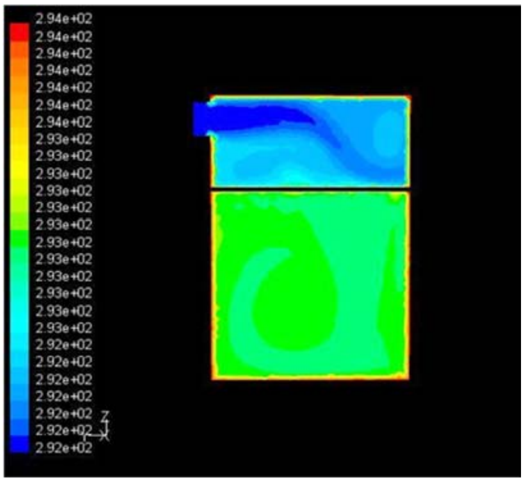
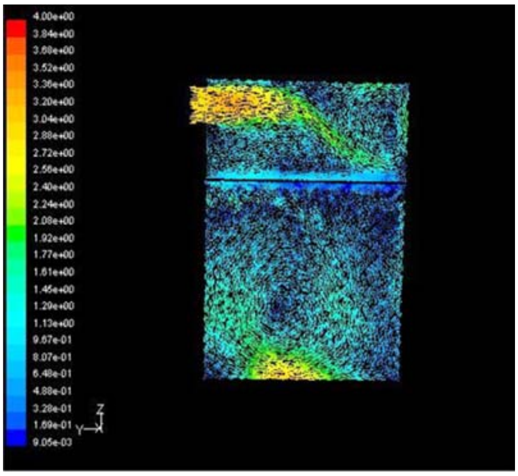


Figure 11 Simulation result of cabinet (inlet $V = 3$ m/s, $T = 292$ K): (a) temperature distribute of mid-surfaces; (b) velocity vector of mid-surfaces and (c) temperature distribute of 3D space (see online version for colours)



(a)

Figure 11 Simulation result of cabinet (inlet $V = 3$ m/s, $T = 292$ K): (a) temperature distribute of mid-surfaces; (b) velocity vector of mid-surfaces and (c) temperature distribute of 3D space (see online version for colours) (continued)



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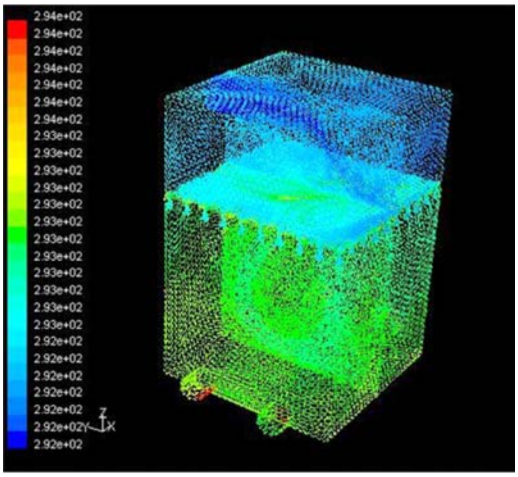
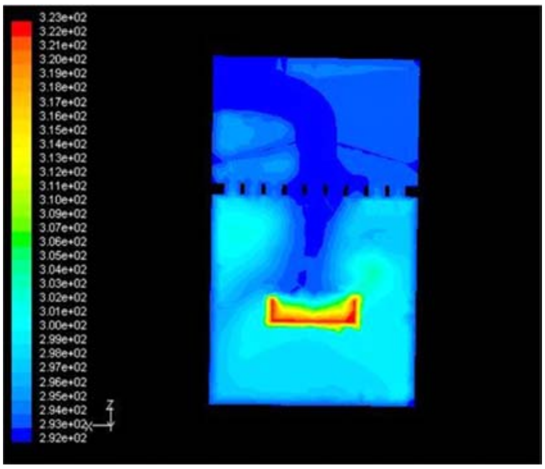


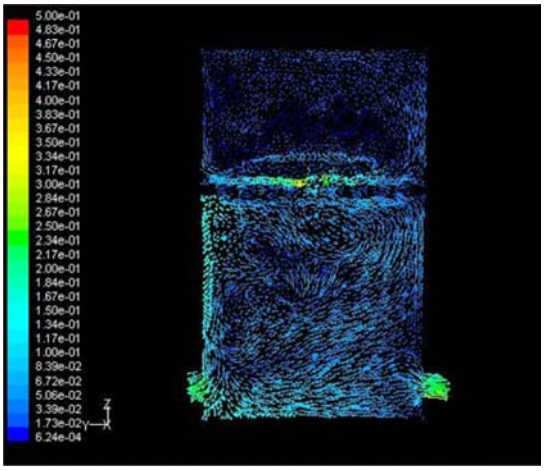
(c)

Figure 12 Simulation result of cabinet (inlet $V = 0.5$ m/s, $T = 292$ K): (a) temperature distribute of mid-surfaces; (b) velocity vector of mid-surfaces and (c) temperature distribute of 3D space (see online version for colours)



(a)

Figure 12 Simulation result of cabinet (inlet $V = 0.5$ m/s, $T = 292$ K): (a) temperature distribute of mid-surfaces; (b) velocity vector of mid-surfaces and (c) temperature distribute of 3D space (see online version for colours) (continued)



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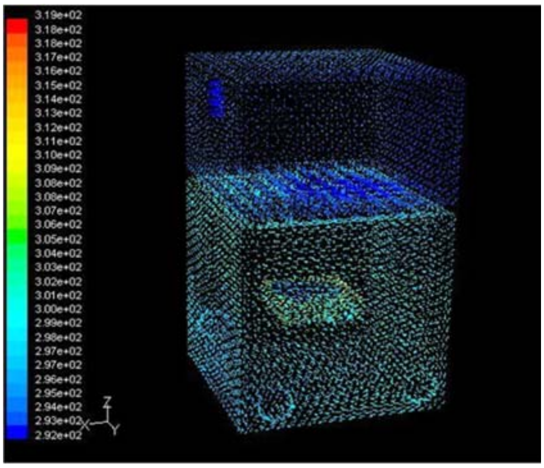
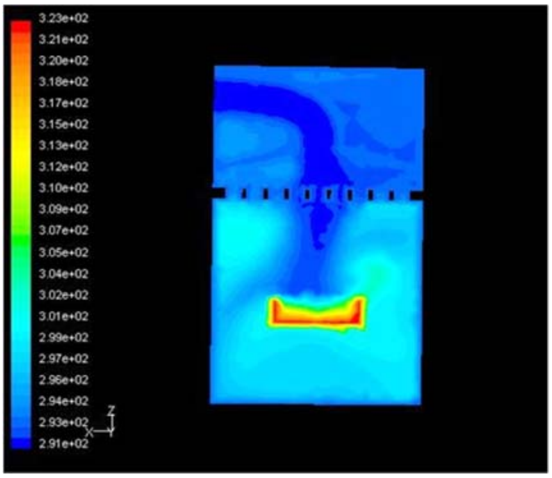


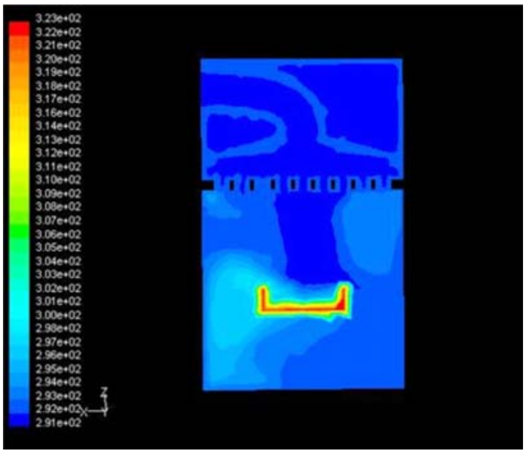
(c)

Figure 13 Simulation result of cabinet of temperature distribute of mid-surfaces: (a) inlet $V = 0.5$ m/s, $T = 291$ K; (b) inlet $V = 3$ m/s, $T = 291$ K and (c) inlet $V = 5$ m/s, $T = 291$ K (see online version for colours)



(a)

Figure 13 Simulation result of cabinet of temperature distribute of mid-surfaces: (a) inlet $V = 0.5$ m/s, $T = 291$ K; (b) inlet $V = 3$ m/s, $T = 291$ K and (c) inlet $V = 5$ m/s, $T = 291$ K (see online version for colours) (continued)



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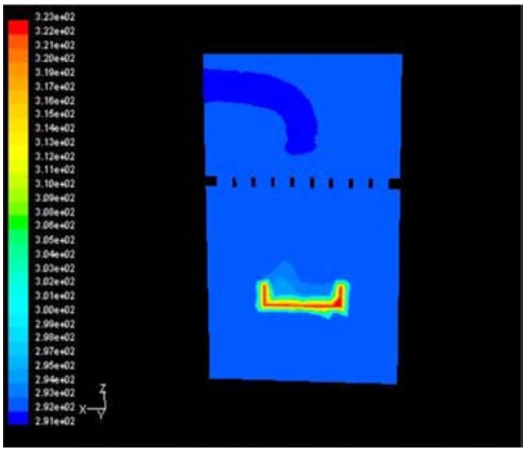

(c)

5 Conclusion

This paper presents the law of change in temperature with the passing of time of a space, which is cooled by the refrigeration provided by the cold side of a semiconductor, and is tested under the conditions of the natural and forced convection in a semiconductor refrigeration device under steady working conditions. The mathematical model of the temperature field of the semiconductor refrigeration device is described, and a numerical study on the temperature profile in a semiconductor refrigeration device was carried out using this model. The experimental results show that forced convection is of benefit to the cold transfer and to the rise of refrigeration rate.

- The DC fans on the semiconductor refrigeration device and the AC fan in the cabinet makes heat sources, it influences the temperature control and drags on the transition process.
- The coefficient of heat insulation of the cabinet is not enough.
- The radioactive heat transfer cannot be ignored.

Acknowledgement

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