

The theoretical analysis and experimental research on the optimal condition of semiconductor refrigeration

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Abstract. The traditional limiting conditions have the biggest refrigeration quantity condition and the biggest refrigeration coefficient condition, there is a special operating mode during these conditions, enabling to both have the big refrigeration quantity and the small power loss, this operating mode is "Optimum condition". This article first carried on the theoretical analysis to the semiconductor's optimum condition, inferred optimum electric current's theoretical formula; Carried on the experiment again to a semiconductor refrigeration box by regulating current changing operating mode, which had analyzed performance parameter's change situation under 8 kinds of condition experiments, carried on the regression analysis to the experimental data, obtained the regression equation thus discovered optimum electric current corresponding optimum condition. Carried on working under this condition, and then obtained the big refrigeration quantity and small power, which enhanced the refrigeration performance of semiconductor refrigerator. The experimental result and the theoretical analysis result tallied basically.

1. Introduction

Semiconductor refrigeration has two conditions: the biggest refrigeration quantity condition and the biggest refrigeration coefficient condition [1~3]. In the biggest refrigeration quantity condition, although the refrigerating capacity is the largest, but consumed large power, get smaller refrigeration coefficient; In the biggest refrigeration coefficient condition, although the economy is good, consumed less power less, but the refrigerating capacity is small. Between the two conditions, it must have a special condition, which not only have larger refrigerating capacity, but also have small power consumption; this condition is the "optimal condition". Working in the optimal condition of semiconductor refrigeration, we can reduce the power and cost, so that the comprehensive benefit of semiconductor refrigeration achieve the optimal condition, improve the cooling performance of semiconductor refrigeration. So we need to find out the optimal condition of thermo-electric refrigeration, which has a realistic significance to save energy, reduce costs, and improve the economic benefit.

1. The theoretical analysis of semiconductor refrigeration's the optimal condition

The refrigerating capacity formula of the semiconductor refrigeration is known:

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$$Q = \alpha T_c - \frac{1}{2} I^2 R - K \Delta T \quad (1)$$

Power is:

$$W = \alpha I \Delta T + I^2 R \quad (2)$$

To the type (1), let be $d(Q)/dI = 0$, abstained:

$$I = \alpha T_c / R \quad (3)$$

Put type (3) into type (1), the maximum refrigerating capacity can be obtained:

$$Q_m = \frac{\alpha^2}{R} \left[\frac{T_c^2}{2} - \frac{\Delta T}{Z} \right] \quad (4)$$

Maximum power consumption:

$$W_m = \frac{\alpha^2}{R} T_c T_h \quad (5)$$

Let be $\theta_Q = \frac{Q}{Q_m}$, θ_Q expressed the proximity of refrigerating capacity Q relative to maximum refrigerating capacity Q_m . $\theta_W = \frac{W}{W_m}$, θ_W expressed the proximity of The power consumption W Relative to the maximum power consumption W_m ; $\theta = \theta_Q - \theta_W$, θ expressed comprehensive parameters of the capacity and power consumption. Obviously, the greater θ , shown that the greater the difference between θ_Q and θ_W , mean is that the value of θ_Q is big, the value of θ_W is small. Let be $\frac{d\theta}{dI} = 0$, we Can get the current value when θ is maximum, this is the optimal current, the corresponding condition is the optimal conditions [4~6]. There are:

$$\theta_Q = \frac{Q}{Q_m} = \frac{\alpha T_c - \frac{1}{2} I^2 R - K \Delta T}{\frac{\alpha^2}{R} \left[\frac{T_c^2}{2} - \frac{\Delta T}{Z} \right]} \quad (6)$$

and:

$$\theta_W = \frac{W}{W_m} = \frac{\alpha I \Delta T + I^2 R}{\frac{\alpha^2}{R} T_c T_h} \quad (7)$$

so:

$$\theta = \theta_Q - \theta_W = \frac{T_c T_h \left(\alpha T_c - \frac{1}{2} I^2 R - K \Delta T \right) - \left[\frac{T_c^2}{2} - \frac{\Delta T}{Z} \right] (\alpha I \Delta T + I^2 R)}{\frac{\alpha^2}{R} \left[\frac{T_c^2}{2} - \frac{\Delta T}{Z} \right] T_c T_h} \quad (8)$$

Let be $d(\theta)/dI = 0$, abstained:

$$IR[T_c T_h + 2\left[\frac{T_c^2}{2} - \frac{\Delta T}{Z}\right]] = T_c^2 T_h \alpha - \alpha \Delta T \left[\frac{T_c^2}{2} - \frac{\Delta T}{Z}\right] \quad (9)$$

$$I_s = I = \frac{\alpha}{R} \frac{[T_c^2 [T_h - \frac{\Delta T}{2}] + \frac{\Delta T^2}{Z}]}{[T_c (T_c + T_h) - 2 \frac{\Delta T}{Z}]} \quad (10)$$

Among them: T_c is the cold-side temperature of the semiconductor chip; T_h is the hot-side temperature; ΔT is the temperature difference of hot-side and cold-side; α is the thermo-electromotive force; R is the resistance.

This study selected thermopile model which is TEC1-12705 type, its performance parameters are: electric double logarithmic $n=127$; the thermo-electromotive force ratio $\alpha = 127 \times 2 \times 2.06 \times 10^{-4} \text{ V/K} = 0.0518 \text{ V/K}$; Thermopile resistance $R = 2.25 \Omega$; thermal conductivity of Material K = $16.1 \times 10^{-2} (\text{W} / \text{cm} \cdot \text{K})$; The optimal value coefficient of material $Z = 2.8 \times 10^{-3} \text{ K}^{-1}$.

Take that the temperature difference of hot-side and cold-side $\Delta T = 20 \text{ k}$, the cold-side temperature $T_c = 287 \text{ k}$, put above performance parameters into the formula can be concluded that the current I of optimal conditions $I = 3.980753 \text{ A}$.

2. The construction of experimental device

The experiment object is a small refrigerating box of space 12 L, power supply is 0-12 V adjustable dc power supply which is produced of Shanghai Fudan, temperature measurement use thermocouple. Unearthed a rectangular openings on the edge of the box body arm side, the cold-side of refrigeration arm clingy with an aluminum block, and daub thermal conductive silicone, left-side close to the cooling box, and right-side close to the semiconductor refrigeration piece. The hot-side of refrigeration piece connected to the radiator, filling heat insulation material around the perimeter of the semiconductor.

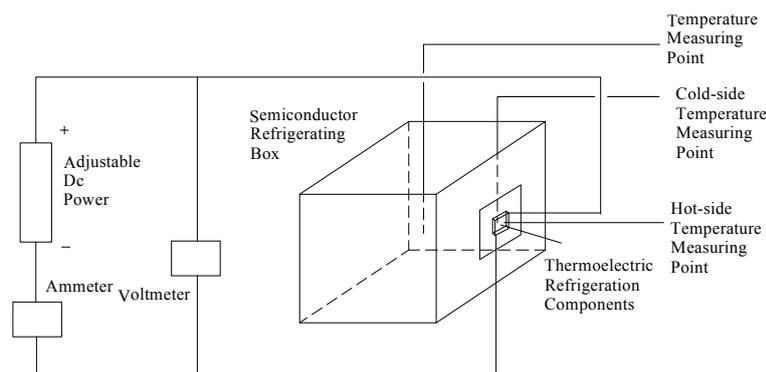


Figure 1. Experimental system structure.

In order to reduce the contact thermal resistance between radiator with semiconductor refrigeration piece, enhanced thermal conductivity, daub evenly a layer of thermal conductive silicone between them, and daub between the cold-side of refrigeration piece and heat dissipation aluminum as well. Bolt between heat conduction fin and heat insulation plate, daub thermal conductive silicone between the contact surfaces in order to reduce the contact thermal resistance. Figure 1 is experimental system structure.

3. The scheme determination of experiments

After experimental device is determined, do experimental research under different working conditions, change working condition of this system by adjusting the current. Conduct experiment in different electrical flow of 8 groups, measured cold-side and hot-side temperature of semiconductor refrigeration piece under different working conditions, under the corresponding conditions calculate performance parameters such as refrigerating capacity, refrigeration coefficient, power, etc. through comparison the parameters such as θ_Q 、 θ_W and θ , choose the optimal condition of semiconductor refrigeration.

The experiment use natural cooling heat at the cold-side and use air cooling at the hot-side, which fin add fan for heat dissipation.

4. The result of the experiment and analysis

Because the semiconductor refrigeration piece's working current of 2.2 A under biggest refrigeration efficiency condition, the condition of the working current of 5 A under maximum refrigerating capacity condition which this experiment selected. So conduct the experimental conditions working in 2.2, 2.6, 3, 3.4, 3.8, 4.2, 4.6 and 5 A. In eight experiments, the experimental data record every minute, after one hour temperature constant basically, get the results of the experiment is as follows:

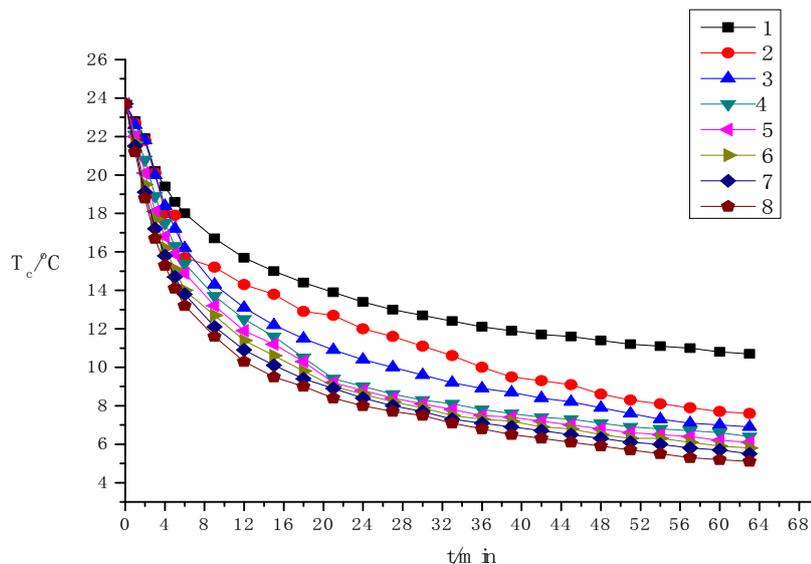


Figure 2. The cold-side temperature curve changing with time under 8 kinds of working condition.

As shown in Figure 2 is the cold-side temperature curve changing with time under 8 kinds of working condition, the Figure shows that the working current is 2.2 A, cold-side temperature of semiconductor refrigeration piece stability in around 11 °C after 1 hour, with the increase of working current I, when the current is 5 A, the cold-side temperature of semiconductor refrigeration piece stability in 5 °C after 1 hour, eventually the cold-side temperature is lower than which is in 2.2 A.

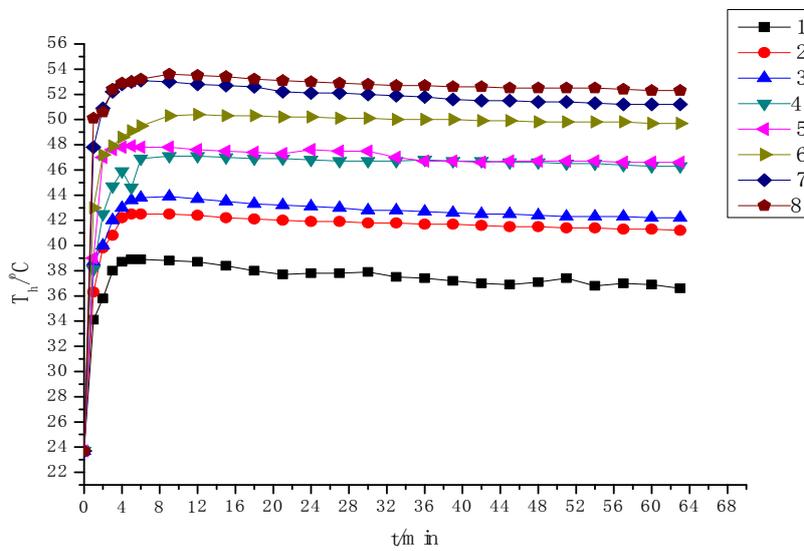


Figure 3. The hot-side temperature curve changing with time under eight kinds of working condition.

Figure 3 is the hot-side temperature curve changing with time under eight kinds of working condition, the Figure can be seen, when the working current is 2.2 A, hot-side temperature stability in 37.2 °C after 1 h, with the increase of working current, when the current is 5 A, the hot-side temperature stability in around 52.3 °C after 1 hour, is much higher than which is in the 2.2 A.

It is known from above analysis, with the increasing of working current I , The drop rate of semiconductor refrigeration piece's cold-side temperature increase, and the ultimately stability cold-side temperature gradually reduce. With the increasing of working current I , the rise rate of semiconductor refrigeration chip's the hot-side temperature also increase, finally stable hot-side temperature rise. Therefore, in order to obtain lower cold-side temperature, we can increase working current appropriately, therefore gain better refrigeration effect.

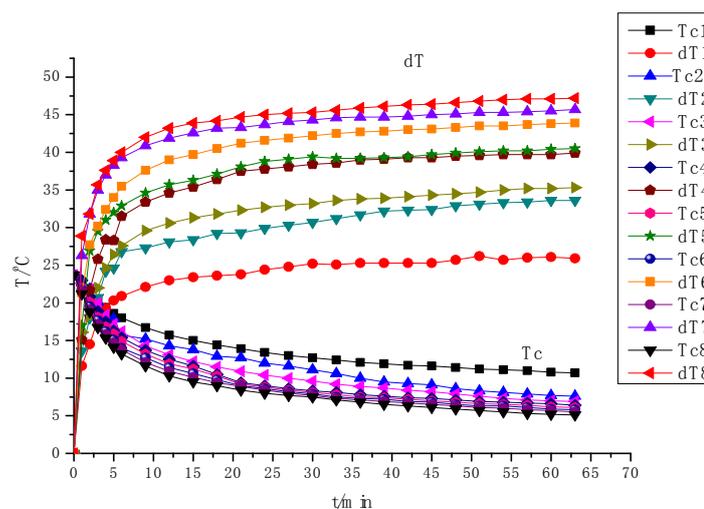


Figure 4. The curve of cold-side temperature and the temperature difference between hot-side and cold-side.

Figure 4 is the curve of cold-side temperature and the temperature difference between hot-side and cold-side, the Figure can be seen, when the working current is 2.2 A, the temperature difference between hot-side and cold-side finally stability in 26 °C, along with the increasing of the working current, the temperature difference between hot-side and cold-side of semiconductor refrigeration piece increase, the cold-side temperature drop, when the current is increased to 5 A, the temperature difference between hot-side and cold-side of semiconductor refrigeration piece is 47.2 °C. Thus, increase working current of the semiconductor refrigeration piece can increase the temperature difference between hot-side and cold-side, and decrease the cold-side temperature.

So it can be concluded, in order to improve the performance of semiconductor refrigeration, get lower cold-side temperature, we can improve the current, increase the temperature difference between hot-side and cold-side. But due to the increase of the working current, the hot-side temperature will gradually rise, the consumed power will also increase, so looking for the optimal current must be between 2.2 A and 5 A.

Take the temperature difference between hot-side and cold-side $\Delta T = 20\text{k}$, we can find cold-side temperature when the temperature difference between hot-side and cold-side is 20k under every working condition electric from diagram, calculate refrigerating capacity Q_m , power W_m and refrigeration coefficient ε , under the biggest refrigerating capacity condition (5A), then calculate the corresponding refrigerating capacity Q , power W and refrigeration coefficient ε under every working conditions, and according to $\theta_Q = \frac{Q}{Q_m}$ and $\theta_W = \frac{W}{W_m}$ calculate θ_Q and θ_W , work out $\theta = \theta_Q - \theta_W$ eventually. Refrigerating capacity θ_Q , power θ_W , refrigeration coefficient θ under each working conditions are listed in the following table:

Table 1. The comparison table of experiment performance parameter under the eight kinds of working condition.

Working condition	current	Refrigerating capacity	Consumed power	ε	$\theta_Q = \frac{Q}{Q_m}$	$\theta_W = \frac{W}{W_m}$	θ
1	2.2	11.67693	13.76782	0.848132	0.343237	0.219582	0.123655
2	2.6	16.58728	20.37692	0.814023	0.487574	0.324991	0.162584
3	3	22.16013	28.64537	0.773603	0.651385	0.456864	0.194521
4	3.4	23.78448	30.45754	0.780906	0.699132	0.485766	0.213366
5	3.8	27.24993	35.96753	0.757626	0.800997	0.573645	0.22735
6	4.2	30.99592	43.57283	0.711359	0.911109	0.694941	0.214516
7	4.6	32.69867	53.62726	0.60974	0.96116	0.855299	0.105861
8	5	34.29128	62.7905	0.546122	1.007974	1.001443	0.006531

Because θ is greater, which represent that the difference between θ_Q and θ_W is greater, the larger θ_Q is, the smaller θ_W is, mean that the refrigerating capacity is larger, power is smaller, the condition which corresponding to the current is the optimal conditions. From table 1 it can be seen that with the increase of current, the refrigerating capacity has increased as well, but the consumed power also will increase, and the optimal condition require that refrigerating capacity is larger, and consumed power is smaller, that is θ maximum operating condition. So it can be seen from the table θ corresponding to 3.8 A is the maximum, we can deduce that the optimal current is about 3.8 A.

From the data of current I and θ , we can see that with the increase of current I , θ first increase then decrease, namely I and θ are parabola relationship, and there is a current value I which make θ is maximum θ_m . Let be the relationship equation between I and θ as follows: $\theta = a + b_1I + b_2I^2$.

It is a nonlinear equation, I and I^2 as two variables respectively, and then there is binary linear relationship between θ and I, I^2 , so build forms as follows:

Use Excel software [return] function to do a regression analysis, the regression equation is established.

Table 2. Data statistical Figure.

θ	I	I^2
0.123655	2.2	4.84
0.162584	2.6	6.76
0.194521	3	9
0.213366	3.4	11.56
0.22735	3.8	14.44
0.214516	4.2	17.64
0.105861	4.6	21.16
0.006531	5	25

The regression equation is:

$$\theta = -0.74858 + 0.572291I - 0.08374 I^2$$

Optimal curve as follows:

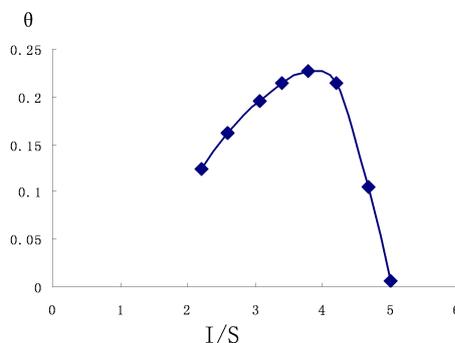


Figure 5. The optimal diagram.

Calculate the optimal current corresponding to θ reaches the maximum value by the statistics function of Excel software:

Table 3

$\theta = -0.74858 + 0.572291I - 0.08374 I^2$	
The objective function	
0.229199 $I =$	3.952173

When $I = 3.952173$, θ is maximum 0.229199, the experiment result $I = 3.952173$ basically tallies with the results of numerical calculation in front of $I = 3.980753$. So the condition corresponding electrical current is the optimal condition, the electric current is the optimal current value.

5. Conclusions

Due to the maximum refrigerating capacity condition and maximum refrigeration coefficient condition all belong to the theoretical limit conditions. In the maximum refrigerating capacity condition, although the refrigerating capacity is the largest, but it consume large power, get smaller refrigeration coefficient; in the maximum refrigeration coefficient condition, although the economy is good, consumption is less, but refrigerating capacity is small. Therefore, the optimal operating condition can make the semiconductor refrigeration have larger refrigerating capacity and low power consumption.

- In this paper, theoretically analysis on the optimal condition of semiconductor refrigeration, deduce the formula of optimal current, find out theoretical optimal condition.
- Experimental study was carried out on a small refrigeration space, by changing the current draw eight kinds of conditions, and conduct eight experiments, it is concluded that rule which the hot-side and cold-side temperature of semiconductor refrigeration piece changing with the time.
- According to the experimental data, using the regression analysis, it is concluded that the regression equation, find out the optimal current, and draw the optimal curve.
- It can be seen by the above data, the optimal current numerical experiment and the optimal current value of theoretical analysis are basically the same.

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