Thermodynamic Model of Semiconductor Refrigeration System Based on Peltier Effect

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Abstract. With the development of society, people's requirements on the comfort of environment have been further improved. The semiconductor refrigeration technology, with the increase of material merit, has been greatly developed and widely used in civil and military fields. This paper, starting from the Peltier effect, first of all analyzes the influence of optimal coefficient and temperature difference on semiconductor refrigeration system in two kinds of extreme conditions. In addition, the curves of various factors on the semiconductor refrigeration are determined, which intuitively reflect the effects of various factors on the semiconductor refrigeration and their relationship. Secondly, based on the simulation results of the thermodynamic model, the impact of various factors on the semiconductor refrigeration system is simulated and the temperature change in a small range of space is determined. What’s more, the impacts of various factors on the semiconductor refrigeration is summed up, and optimized suggestions are put forward. The study results showed that the performance of semiconductor refrigeration system is influenced by many factors. Through the study of effects of various factors on the semiconductor refrigeration, the temperature changes of semiconductor refrigeration in space are simulated, which can provide technical support for the development of semiconductor system.

1. Introduction

Semiconductor refrigerator is portable device developed according to the research on the Peltier effect. Its principle is that, when the DC current flows into the semiconductor materials, it will produce the heat transfer and form hot and cold end. Since that the structure of the semiconductor refrigerator is simple, wear resistant, long using time, and quickly cooling, and it does not use CFC refrigerant such as air pollution and produces no noise, when it is accessed to the reverse current, it can make the hot and cold end conversion [1]. Because of these advantages, the semiconductor refrigerator developed rapidly in many fields, such as civilian car refrigerator, freezer used in medical field, nuclear submarine air conditioning and aerospace spacesuit in military aspect and so on [2]. With the gradual improvement of the semiconductor material optimal value coefficient, the semiconductor refrigerator has already got rid of the limitation of small power, and gradually developed to high power. This study analyzes the relationship between the various factors on the refrigerating capacity and refrigeration efficiency, generating the relationship curves. By determining the factors, the relationship between the thermal resistance, cooling capacity and cooling efficiency of the hot and cold end is determined, and the three-dimensional relationship curve is established.

2. Basic principle of semiconductor refrigeration

2.1 Peltier effect

Semiconductor refrigeration is a kind of refrigeration technology, which is composed of five kinds of effects, as shown in Figure 1.

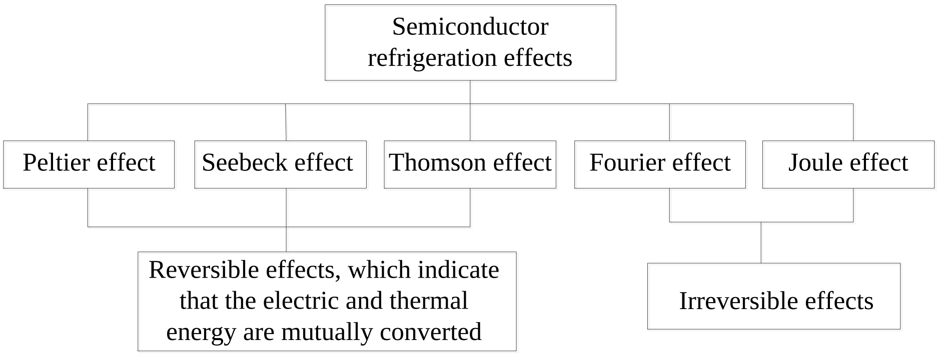

Figure 1. Semiconductor refrigeration effects composition diagram

When an electric current passes through a closed loop composed of different conductors, it produces an endothermic or exothermic effect at the interface of the conductor. This absorbed or released heat is called Peltier heat [3]. After the current is applied, the heat of the cold end of the semiconductor cooler flows to the hot end, so the temperature of the cold end is reduced, and the temperature of the hot end is increased, which is called the Peltier effect. The sketch of the Peltier effect is shown in Figure 2. It is clear that the direction of the current will directly affect the absorption or release of heat of the metal end, and the relationship between heat and current is as follows:

$$Q = \pi I \tag{1}$$

In (1), π refers to the Peltier coefficient, $\pi = (\alpha_1 - \alpha_2)^T$, and α_1 and α_2 are thermoelectric electromotive forces.

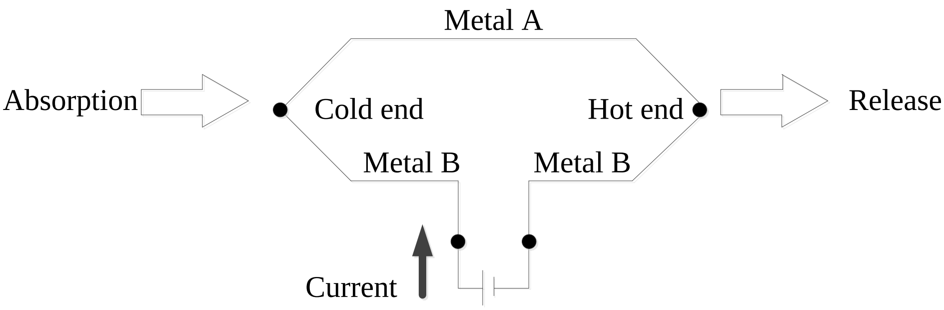

Figure 2. Peltier effect

2.2 Thermodynamic analysis of ideal state semiconductor refrigeration

In the application of semiconductor refrigeration, when the thermal resistance of the hot and cold end is ignored, the hot and cold ends can carry out the most ideal heat transfer with the surrounding medium [4]. At the same time, in the ideal state, the semiconductor refrigeration system will produce Joule heating and Thomson heat when the Peltier heat is generated. When calculating the amount of cooling or cooling efficiency, Joule heat and Thompson heat are the two non-negligible heats [5]. And the thermodynamic model of ideal semiconductor refrigeration cycle is shown in Figure 3.

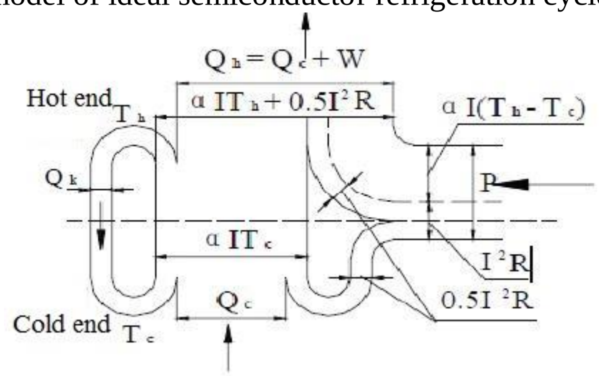

Figure 3. Thermodynamic model of ideal semiconductor refrigeration cycle

In order to derive the semiconductor refrigeration system, we have made some simplifications, as shown in Figure 4 below.

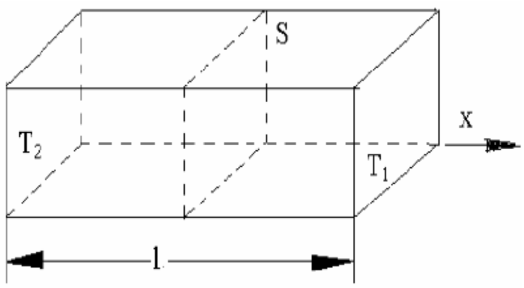

Figure 4. Semiconductor arms model

Sectional area S of the model is equal to the length L, and the resistivity ρ, thermoelectric power α and thermal conductivity λ are also equal [6]. These parameters kept constant in the effect of temperature. For a small range of temperature difference, the production of this material is still relatively easy to achieve.

(2) We can take any one arm to carry out the thermal analysis. The thermal effect of Peltier is taken as a uniform heat flux, and the heat generated by the Joule effect is regarded as the internal heat source of galvanic arm [7].

(3) The model is simplified as a one-dimensional steady state model, and the heat transfer in the system only exists in the current direction.

2.3 Two extreme conditions of semiconductor refrigeration in ideal state

2.3.1 Maximum refrigeration efficiency

Refrigerating capacity Q_c and power P are the curve equations about the current I. When the current reaches a certain value, Q_c and P reach the maximum [8]. The state parameter under the condition of the maximum refrigeration coefficient is obtained：

(1) The optimal working current $I_{\varepsilon\max}$ (unit: A):

$$I_{\varepsilon\max} = \frac{\alpha(T_h - T_c)}{R\left(\sqrt{1+ZT_m} - 1\right)} \tag{2}$$

In (2), T_m refers to the average temperature, $T_m = \frac{1}{2}(T_h + T_c)$, $Z = \frac{\alpha^2}{KR}$.

Refrigeration coefficient $Q_{\varepsilon\max}$:

$$Q_{\varepsilon\max} = \varepsilon_{\max} P_{\varepsilon\max} = \frac{2K\Delta TM(M - T_h/T_c)}{(M-1)(1+T_h/T_c)} \tag{3}$$

It is known that, to increase the value of ε, it is necessary to make $Z(T_h+T_c)$ larger as much as possible. In addition, the refrigeration efficiency is closely related to the optimal value coefficient Z [9]. At the same time, it is related to average temperature and the temperature difference (T_h-T_c) in the hot and cold end of semiconductor. In the same temperature difference conditions, the efficiency of semiconductor refrigerator running in the higher temperature, is higher than that in the lower temperature.

2.3.2 Maximum refrigeration capacity

Some major parameters on the condition of maximum refrigeration state are obtained.

(1) The maximum working current $I_{Q\max}$ (unit: A) [10]:

$$I_{Q\max} = \frac{(\alpha_p - \alpha_n)Tc}{R} = \frac{\alpha T_c}{R} \tag{4}$$

(2) The maximum refrigeration capacity $Q_{C\max}$:

$$QC\max = \alpha I_{Q\max} T_c - \frac{1}{2} I^2{}_{Q\max} R - K(T_h - T_c) \tag{5}$$

3. Thermodynamic analysis of semiconductor refrigeration system

In fact, in the refrigeration operation of semiconductor, the heat between the cold and hot end of the semiconductor refrigeration system exchanges with the surrounding medium [11]. In the following, on the basis of the basic theory, steady state semiconductor refrigeration system model is simplified and established. What's more, through the model, the impact of various factors on the semiconductor refrigeration and the relationship between various factors are analyzed. The purpose is to provide guidance for the practical design and operation of the semiconductor refrigeration system.

3.1 Semiconductor refrigeration model under steady state

There are four parts in semiconductor refrigeration system: semiconductor cooler, cold end heat exchanger, hot end heat exchanger, and cold and heat source, as shown in Figure 5.

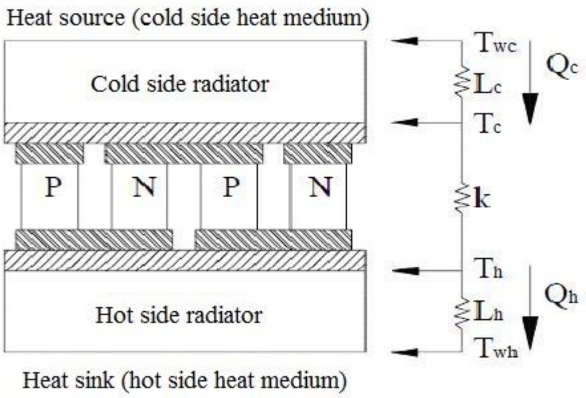

Figure 5. Components of a semiconductor refrigeration model

According to the laws of thermodynamics, the heat coefficient is: $\eta = \varepsilon + 1$.

The local temperature reaching the desired temperature is our purpose of making use of semiconductor refrigeration. But the hot and cold end temperature is generally difficult to be measured, while the medium temperature in hot and cold end of semiconductor is very easy to be measured [12]. We replace the cold end temperature by the medium temperature, then we can easily calculate various parameters results. Such replacement is meaningful for the design or operation of semiconductor refrigeration. More importantly, we can study the performance characteristics of semiconductor refrigeration system by measuring the medium temperature in the cold and hot end of semiconductor.

The semiconductor refrigeration system in the operation process, its performances are subject to many factors. The main factors include the current I, the temperature of the medium (T_c, T_h) and other conditions. The internal resistance (R), the internal heat conduction (K), hot and cold end heat transfer resistance (rc, rh) also have an important role in the performance of semiconductor refrigeration.

3.2 Influence of optimal value coefficient on semiconductor refrigeration performance

The optimal value coefficient plays a very important role in semiconductor refrigeration system. It can be reflected in the influence of internal performance in the thermodynamic cycle on the system. In the actual operation of system, the optimal value coefficient is restricted by the operation temperature, the hot and cold end heat resistance and other factors. As a result, the influence of the optimal value coefficient on the semiconductor refrigeration system should be considered from many aspects [12]. The relationship between the optimal value coefficient and total resistance, thermal conductivity, and Seebeck coefficient is shown in the following formula and figures:

$$R_a = \frac{A_a^2}{ZK_a} \tag{6}$$

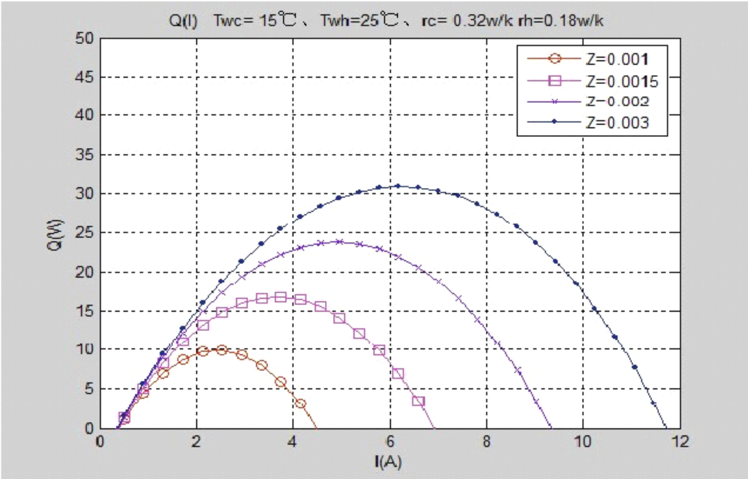

Figure 6. The relationship between cooling capacity and current under different optimal value coefficients

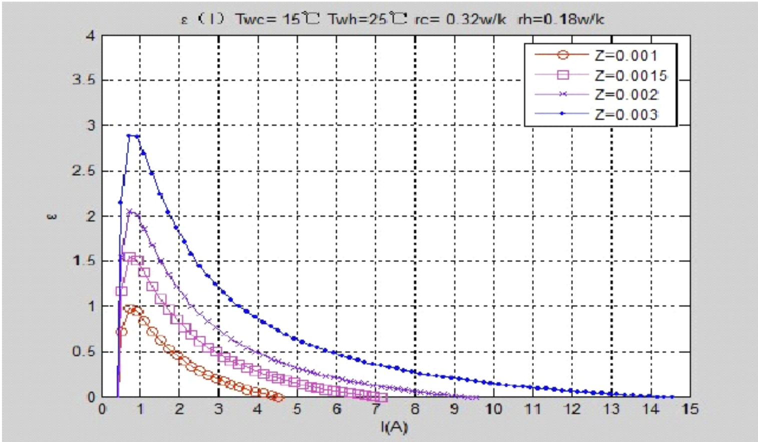

Figure 7. The relationship between refrigeration coefficient and current under different optimal value coefficients

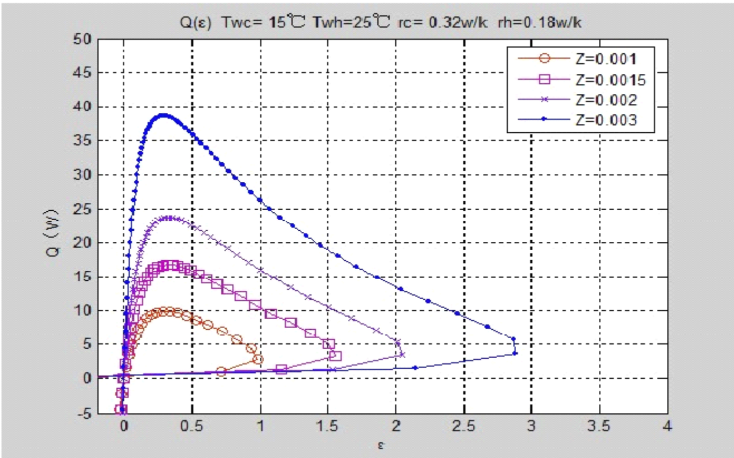

Figure 8. The relationship between the amount of cooling and the refrigeration coefficient under different optimal value coefficients

The optimal value coefficient has a decisive influence on the performance of semiconductor refrigeration system [13]. The relationship between the refrigeration capacity, the coefficient of refrigeration and the relationship between the current and the quality factor Z are as follows：

Figure 6-8 showed that, with the increase of the refrigeration coefficient, the refrigeration capacity and refrigeration coefficient of the system will increase. Under the same optimal value coefficient, the refrigeration capacity and the refrigeration coefficient of the semiconductor refrigeration system will show a parabolic relationship with the current. For the refrigeration capacity, the corresponding current significantly increases with the increase of optimal value coefficient when the refrigeration capacity reaches the maximum value. From Figure 6, It can be seen: when the optimal value coefficient is lager in the normal work of the semiconductor, the normal working range of the current value will be larger. From Figure 6, it can be seen: when the refrigeration coefficient reaches the maximum value, improving the optimal value coefficient is not obvious for improving the maximum value, and the current change is also not great.

4. Conclusion

The steady state thermodynamic model was established to simulate the relationship between the maximum refrigeration capacity and the maximum refrigeration coefficient of various parameters for the semiconductor refrigerator. The relationship between the semiconductor refrigeration capacity and the refrigeration coefficient is analyzed under different parameters. It provides the numerical guidance for the design of semiconductor refrigerator. In the actual operation of the system, the running state in the two extreme conditions cannot meet the actual requirements, and the scope of engineering operation is between the two parts [14]. It is pointed out that the optimal value coefficient Z is the main factor limiting the semiconductor refrigeration. The higher the value coefficient is, the higher the performance of the system is, and the larger the working area of the current is. When the refrigerating capacity reaches the maximum, the current increases with the increase of the refrigeration coefficient. Based on the analysis of the numerical relationship between different temperature differences between hot and cold, the relationship between the refrigerating capacity of semiconductor refrigeration and refrigeration coefficient is discussed.

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