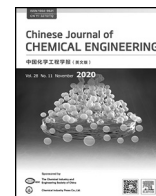




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Article

Design of structure and control system of semiconductor refrigeration box

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ABSTRACT

In order to create low temperature environment for the valve testing, a new type of semiconductor refrigeration box based on semiconductor refrigeration chip and programmable logic controller (PLC) control system is designed. The power of the semiconductor refrigeration chip is determined by calculating the heat dissipation characteristics of the semiconductor refrigeration box. Combining natural convection heat dissipation with forced air cooling, the heat sink of semiconductor refrigeration chip is designed. In the control strategy, switch control is combined with an intelligent control strategy. Adaptive single neuron optimization algorithm based on quadratic optimization is adopted to adjust and optimize the parameters of the proportional-integral-derivative (PID) controllers in real time. Taking into account the limited hardware capabilities of the PLC, the Jacobian information in parameter adjustment is redesigned into a simplified form of identification. The actual test results of refrigeration box show good control performance.

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1. Introduction

Semiconductor refrigeration technology which is known as thermoelectric refrigeration technology is a refrigeration method based on thermoelectric phenomena [1]. The so-called thermoelectric phenomenon refers to that when direct current pass through the closed loop which is composed of two different materials, there will be a phenomenon that one contact surface is cold and the other is hot [2]. Thermoelectric refrigeration generally selects semiconductor material. This material contains a large amount of electrons and holes, which can be called carriers. The flow of carriers from one material to another forms current. Since the potential energy of carriers of different material is different, according to the law of energy conservation, when carriers pass through the junction of two materials, they will absorb or release energy [3,4]. The absorption and release of this energy is manifested by the cooling or heating of the material. Fig. 1 is a thermocouple composed of an N-type semiconductor element and a P-type semiconductor element. When direct current passes through the connection point of different material, heat is transferred. At the connection point above (cold end), the current flows from the N-type to the P-type, and the endothermic temperature drops [5]. At the connection point below (hot end), the current flows from the P-type to the N-type, and the exothermic temperature rises. Single thermocouple has very limited heat absorption. Fig. 2 is the structure of a semiconductor refrigeration chip which is composed of a plurality of semiconductor thermocouples connected in series. On the endothermic

and exothermic surface, the cold surface and the hot surface are composed of insulating ceramic sheets [6,7]. The refrigeration device of temperature control box designed in this paper is mainly composed of semiconductor refrigeration chips.

The heat dissipation effect of the hot surface of the semiconductor refrigeration chip has a great influence on the refrigeration performance [8]. An important research direction in the field of semiconductor refrigeration is to improve the heat dissipation method of the hot surface of the semiconductor refrigeration chip [9–12]. At present, the heat dissipation of the semiconductor hot end mainly includes natural convection heat dissipation, forced air cooling, liquid cooling and heat pipe cooling [13]. Natural convection heat dissipation is applied commonly in the heat dissipation of semiconductor refrigeration equipment. Aluminum heat sink is used as a bridge for heat exchange between environment and the refrigeration chip [14]. The heat sink first derives heat from the hot end and then dissipates it into the air. Forced air cooling mainly relies on the fan to accelerate heat exchange. Compared to natural convection heat dissipation, the device size can be much smaller [15]. Considering the ease of use and cooling effect of the device, we rule out the liquid cooling method and the heat pipe cooling method. In this paper, we combined the advantages of natural convection heat dissipation and forced air cooling to redesign the heat sink. The aluminum finned heat sink is stuck to the hot surface of the semiconductor refrigeration chip, and a fan is installed at the fin.

At present, switch control is commonly used in the field of semiconductor refrigeration control, this paper improves on this. A new type of semiconductor refrigeration control system based on programmable logic controller (PLC) and semiconductor refrigeration chips is established.

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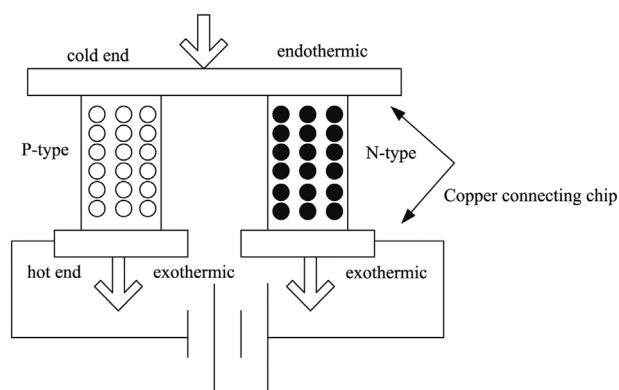


Fig. 1. Semiconductor thermocouple.

The physical structure three-dimensional design of the semiconductor refrigeration box is accomplished by using SolidWorks. Manufacture semiconductor refrigeration box by selecting suitable materials. Determine the power of the semiconductor refrigerating chip by calculating the heat dissipation characteristics of the semiconductor refrigeration box. The working state of the semiconductor refrigeration chips is controlled by the PLC control signal through the driving circuit. Through theoretical research and practical testing, two control methods are adopted. In the presence of large range of temperature difference, the method of switching control is used to determine the number of semiconductor refrigeration chips that need to be operated. When the temperature difference is reduced to a certain range, semiconductor refrigeration chips are controlled by PLC signal with direct current (DC) pulse width modulation (PWM). In order to implement precise control, the intelligent control algorithm is introduced. Adaptive single neuron optimization algorithm based on quadratic optimization is adopted to adjust and optimize the parameters of the proportion integration differentiation (PID) controllers in real time. The author of this paper designed an algorithm in a previous paper to identify Jacobian information generated by quadratic optimization through radial basis function (RBF) neural network [16]. In the semiconductor refrigeration control system, this paper simplifies the Jacobian information identification because it is directly controlled by the PLC with limited hardware performance. Experiments show that this design achieves stable and precise control.

2. Structure Design of Semiconductor Refrigeration Box

2.1. Box hardware structure

The designed semiconductor refrigeration box should not only maintain the temperature inside the box under the condition of temperature difference inside and outside, but also ensure that the temperature inside the box is uniform. Under this premise, it is necessary to maintain a certain air flow and reduce the existence of temperature dead angle in the refrigeration box. At the same time, it is necessary to provide enough working and heat dissipation space for the control

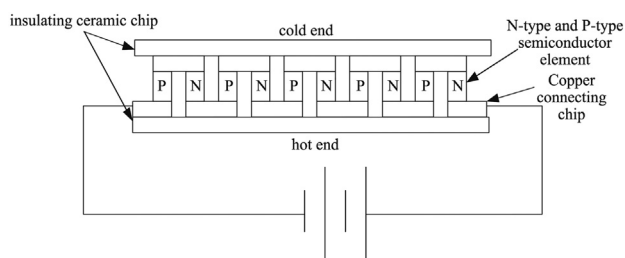


Fig. 2. The structure of semiconductor refrigeration chip.

system of the whole system and the hot end of the semiconductor refrigeration chip, so it is necessary to independently design and optimize the refrigeration box structure.

The entire device is designed to cuboid composed of aluminum box, heat insulating layer and refrigeration equipment. Internal dimension is designed to 380 mm × 200 mm × 200 mm. The refrigeration equipment is composed of semiconductor refrigeration chip, aluminum finned heat sink and electric fan. In order to ensure good refrigeration effect, the refrigeration equipment is designed on the front and rear wall of the box. The control device shell needs detailed three-dimensional structure design. Three-dimensional design software SolidWorks is mainly used. Based on the selection of semiconductor refrigeration chips and hot-end heat sink and the analysis of their working states, the determination of the fixed installation position of the device is completed, and then the standard structural design of the entire control system is realized. The cross-sectional structure of the semiconductor refrigeration box is shown in Fig. 3. The inner space is shown in Fig. 4. The outer shape is shown in Fig. 5.

The box includes an inner, outer and filling layer. The outer layer mainly serves as fixed support and protection, so it needs good strength. It is suitable to select low-density and high-strength material. The inner layer also needs to maintain good strength and sealing. In addition, the inner box should hold a certain amount of heat conducting liquid, so the inner layer must have the characteristic of no chemical reaction to common liquid such as water and oil. In the end, 2 mm thick aluminum plate is selected as material of the outer and inner layer. Another benefit of aluminum material is good thermal conductivity which makes the cold surface of the semiconductor refrigeration chip transfer heat well. Aluminum has thermal conductivity of up to $230 \text{ W} \cdot \text{m}^{-1} \cdot \text{K}^{-1}$. The filling layer mainly acts as heat insulator to prevent the loss of cold, so it is necessary to fill with low thermal conductivity material. Polyurethane is selected as material of the filling layer. Thermal conductivity of polyurethane is $0.035 \text{ W} \cdot \text{m}^{-1} \cdot \text{K}^{-1}$.

The refrigeration devices on the front and rear wall of box have the same composition which includes semiconductor refrigeration chip, aluminum finned heat sink and electric fan. The cold surface of the semiconductor refrigeration chip is directly stuck to the aluminum box wall, and the hot surface of the semiconductor refrigeration chip is closely attached to the aluminum finned heat sink. Both contact surfaces are coated with thermal silica gel to ensure good fixing and heat conduction effect.

2.2. Box thermal load analysis and refrigeration unit design

The thermal load analysis of the semiconductor refrigeration box can be performed to determine the refrigeration capacity of the semiconductor refrigeration chip, then obtain the required refrigeration chip power and the number of chips. Thermal load of the box consists of three parts: heat leakage of the box Q_1 , storage heat Q_2 and other heat Q_3 .

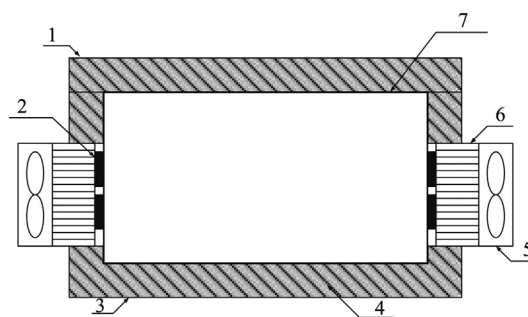


Fig. 3. Longitudinal section structure of semiconductor refrigeration box. 1—Box cover; 2—Refrigeration chip; 3—Aluminum outer layer; 4—Insulation material; 5—Electric fan; 6—Aluminum finned heat sink; 7—Aluminum inner layer.

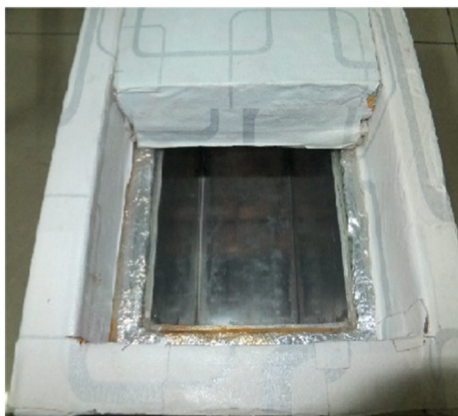


Fig. 4. Aluminum inner box of semiconductor refrigeration box.

- (1) Heat leakage of the box includes three parts: leakage heat of the polyurethane insulation layer, leakage heat of the box cover and the box seal, and heat bridge leakage formed by the internal structure of the refrigeration box.

Heat transfer of the polyurethane insulation layer can be seen as a single layer heat transfer process. The amount of heat transfer Q_a :

$$Q_a = KA(t_1 - t_2) \quad (1)$$

$$K = \frac{1}{\frac{1}{\alpha_1} + \frac{\delta}{\lambda} + \frac{1}{\alpha_2}} \quad (2)$$

A - the area of the outer surface of the box, unit: m^2 ;

K - the heat conduction coefficient;

δ - the total thickness of polyurethane insulation layer, unit: m ;

λ - the thermal conductivity of polyurethane materials, unit: $W \cdot m^{-1} \cdot K^{-1}$;

α_1, α_2 - the surface heat transfer coefficient of the outer surface and inner surface of the insulation layer relative to air, unit: $W \cdot m^{-2} \cdot K^{-1}$.

The thermal conductivity of the polyurethane insulation layer is $0.047 W \cdot m^{-1} \cdot K^{-1}$. For this refrigeration system, α_1 is $9.5 W \cdot m^{-2} \cdot K^{-1}$ and α_2 is $0.8 W \cdot m^{-2} \cdot K^{-1}$. The laboratory test



Fig. 5. External shape of semiconductor refrigeration box.

environment temperature is $26^\circ C$, and the internal temperature of the refrigeration box is $6^\circ C$. The temperature difference between inside and outside of the refrigeration box is $20^\circ C$. Considering the size of the refrigeration box, leakage heat of the polyurethane insulation layer is $20.76 W$.

Leakage heat at the lid and the box seal is calculated as 20% of Q_a , which is about $4.15 W$. Heat bridge leakage generated by the internal structure of the refrigeration box is calculated as 10% of Q_a , which is about $2.08 W$.

In summary, the heat leakage of semiconductor refrigeration box is:

$$Q_1 = 20.76 + 4.15 + 2.08 = 26.99 W \quad (3)$$

- (2) The semiconductor refrigeration box is equipped with heat conducting liquid, whose heat is calculated by condensing $3.5 L$ of water in the tank into ice for two hours.

$$Q_2 = \frac{(mct_1 + mr - mc_b t_2)}{2 \times 3.6} \quad (4)$$

In the formula, m indicates the mass of water ($3.5 kg$); c indicates the specific heat capacity of water ($4.19 kJ \cdot kg^{-1} \cdot K^{-1}$); r indicates the heat of solidification of water ($377 kJ \cdot kg^{-1}$), c_b indicates the specific heat capacity of ice ($2 kJ \cdot kg^{-1} \cdot K^{-1}$), t_1 is the initial temperature of water ($25^\circ C$), t_2 is the freezing temperature of water ($0^\circ C$). After calculating the above data, Q_2 is $40.74 W$.

- (3) The valve to be tested need to be placed in the aluminum inner box of the refrigeration box. The body part of the valve is in the heat conducting liquid. The mechanical movement of the valve itself generates heat. The valve stem of the electric valve is connected to the motor. Some of the heat is transferred through the valve stem. For the convenience of calculation, the heat in this part is calculated as 10% of the sum, which is $6.77 W$.

The total thermal load of the system:

$$Q = Q_1 + Q_2 + Q_3 = 74.5 W \quad (5)$$

The total refrigeration capacity of the semiconductor refrigeration chips should be greater than $74.5 W$. The refrigeration power of one TEC1-12706 refrigeration chip is $56.5 W$, and the efficiency of the refrigeration chip is generally about 50%. It is calculated that more than three refrigeration chips are required. In order to ensure the efficiency of the experiment, the refrigeration control system selects four semiconductor refrigeration chips for refrigeration. Two semiconductor refrigeration chips are connected in series, forming one refrigeration unit. Two refrigeration units are installed on the front and rear surface of the refrigeration box and are powered by two $24V$ DC regulated power supply.

3. Control System Design of Semiconductor Refrigeration Box

3.1. Control system structure

The structure of refrigeration control system of the temperature control box is shown in Fig. 6. The controller is S7-200 PLC, the human-machine interaction device is SMART1000 touch screen, and the execution components are the semiconductor refrigeration chip units and heat sinks. One refrigeration unit contains two semiconductor refrigeration chips. The real-time control signal of the S7-200 controls the starting and stopping of the semiconductor refrigeration unit. The temperature information of the heat transfer oil in the refrigeration box is obtained by

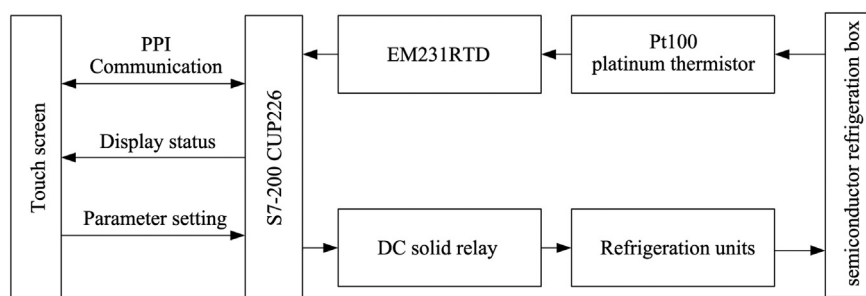


Fig. 6. Structure of the refrigeration control system.

Pt100 platinum thermistor and EM231RTD module. DC solid state relay (DDR) connects the control circuit with the drive circuit.

The working process of the control system: PT100 platinum thermistor temperature sensor collects the temperature in the refrigeration box, converts it into analog electric signal and sends it to EM231RTD module. After digital-to-analog conversion, the temperature data in the CPU of S7-200 is compared with the set temperature on touch screen. The program determines whether to start the semiconductor refrigeration chip units and the number of units. When temperature difference is greater than 10 °C, two units of refrigeration chips are simultaneously turned on. When temperature difference is between 3 °C and 10 °C, only one unit of refrigeration chips is turned on. When temperature difference is less than 3 °C, adaptive single neuron proportion integration differentiation-pulse width modulation(PID-PWM) control strategy based on quadratic optimization is implemented on one unit of refrigeration chips.

The S7-200 uses low current circuit to control high current circuit containing semiconductor refrigeration chips through DC solid state relay. The touch screen monitors the entire refrigeration control process. The temperature information and the operating status of the semiconductor refrigeration chips can be displayed through the touch screen.

3.2. Drive circuit design

In the refrigeration control system, the control circuit of the semiconductor refrigeration chip needs to pass high current. Taking one semiconductor refrigeration chip as example, the current reaches 6.5A, but the maximum current of the relay output of the S7-200 is 2A, the refrigeration chip power exceeds the PLC output power. The design which the S7-200 control circuit is isolated from the peripheral drive circuit by the DC solid state relay realize the control of the high current drive circuit with low current control circuit.

As shown in Fig. 7, in the control system, the input of the DC solid state relay is connected to the output relay circuit of the S7-200, and the output

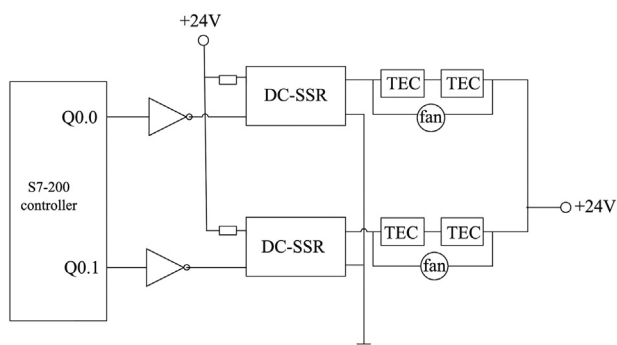


Fig. 7. Drive circuit diagram of semiconductor refrigeration chip.

is connected to the drive circuit of the refrigeration chip unit. The control circuit of the S7-200 is powered by the S7-200's own 24V DC power supply. The refrigeration circuit is powered by two self-made 24V DC regulated power supplies. There are 4 semiconductor refrigeration chips, each with rated voltage of 12 V. Two chips are connected in series and connected in parallel with an electric fan rated voltage of 24 V.

3.3. S7-200 temperature control program design

The S7-200 program flow chart of refrigeration control is shown in Fig. 8.

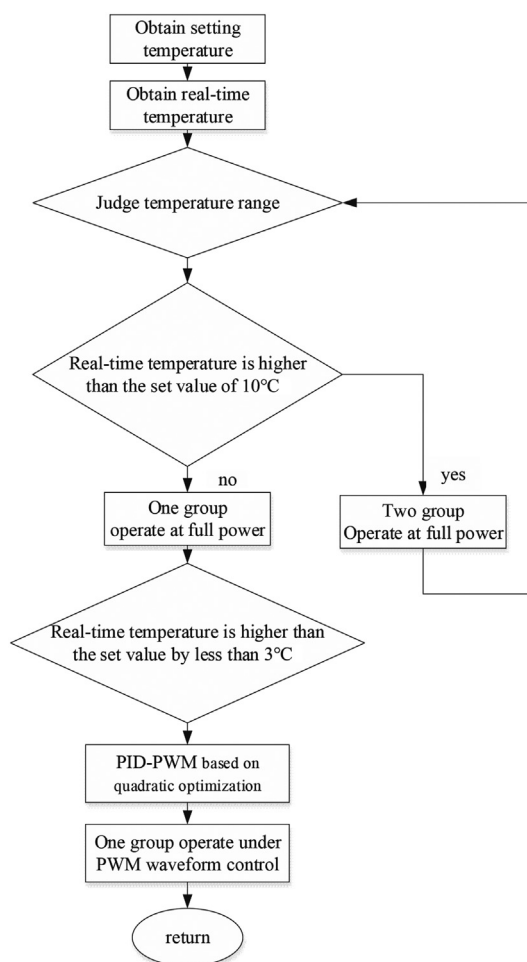


Fig. 8. S7-200 program flow of refrigeration control.

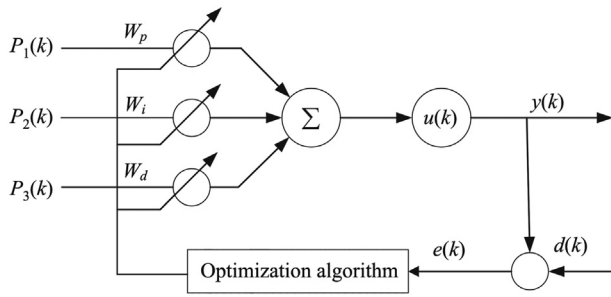


Fig. 9. The adaptive single neuron PID algorithm based on quadratic optimization.

The main part of the program adopts combination of switch control and adaptive single neuron PID-PWM control. Switch control is mainly based on the temperature difference to determine the number of semiconductor refrigeration chip units in operation. PID-PWM is implemented on one semiconductor refrigeration chip unit. Adaptive PID based on quadratic optimization realizes precise adjustment of temperature. The PID output determines that the PWM waveform generator of the PLC emits a suitable PWM wave. Due to the limitation of PLC hardware, the algorithm adopts the strategy which approximates the Jacobian information in PID parameter adjustment. Although this approximation strategy is weaker in accuracy than the strategy in which Jacobian information is identified by RBF or other neural network, the final control effect is still good.

The first function of the S7-200 program is to obtain the actual temperature data in the semiconductor refrigeration box from the EM231RTD module and the target temperature data from the touch screen. The program obtains the difference between actual temperature and target temperature. If the temperature difference is over 10 °C, two units of refrigeration chips are activated. If the difference is between 3 °C and 10 °C, only one unit of refrigeration chips is activated. If the difference is less than 3 °C, adaptive single neuron PID based on quadratic optimization control PWM waveform which is applied to one unit of semiconductor refrigeration chips through DC solid state relay.

The adaptive single neuron PID algorithm based on quadratic optimization is shown in Fig. 9. The usual single neuron PID control uses hebb learning rule or Delta learning rule [17–20]. We proposed single neuron learning rule using quadratic optimization in the previously published paper. In that paper, learning rule needed to use the RBF neural network to identify Jacobian information [16]. Considering the hardware performance of the PLC, this paper simplifies this process.

The system adjusts the control weight W_p , W_i , W_d of the controller by minimizing the performance index and identifying the Jacobian information [21–23]. $d(k)$ is reference input signal, $y(k)$ is the actual output of the system. PID controller output control is

$$u(k) = W_p P_1(k) + W_i P_2(k) + W_d P_3(k) \quad (6)$$

$$\text{In which, } P_1(k) = e(k), P_2(k) = \sum_{j=1}^k e(j) \times T, P_3(k) = \frac{e(k) - e(k-1)}{T}.$$

In the formula, $e(k) = d(k) - y(k)$, T is the sampling time. Define performance indicator $E(k) = \frac{1}{2}(d(k) - y(k))^2$, then

$$\begin{aligned} W_t(k) &= W_t(k-1) + \eta_t(d(k) - y(k)) \frac{\partial y}{\partial u} \frac{\partial u}{\partial W_t} \\ &= W_t(k-1) + \eta_t(d(k) - y(k)) \frac{\partial y}{\partial u} P_o(k) \\ t &= p, i, d, \quad o = 1, 2, 3 \end{aligned} \quad (7)$$

In the formula, η_p , η_i and η_d is the learning rate of proportion, integral and differential respectively. is the Jacobian information which can be identified by the RBF or diagonal recurrent(DR) neural network recognizer [24,25]. The actual output $y(k)$ and input $u(k)$ of the system are used as the input of the recognizer. The error of the actual output and the identification network output of the system is used as the adjustment signal of the recognizer. In order to facilitate implementation on the PLC, the Jacobian information is calculated by the following formula. Although this reduces the accuracy of the calculation, it is easy to implement.

$$\frac{\partial y}{\partial u} = \frac{y(k+1) - y(k)}{u(k) - u(k-1)} \quad (8)$$

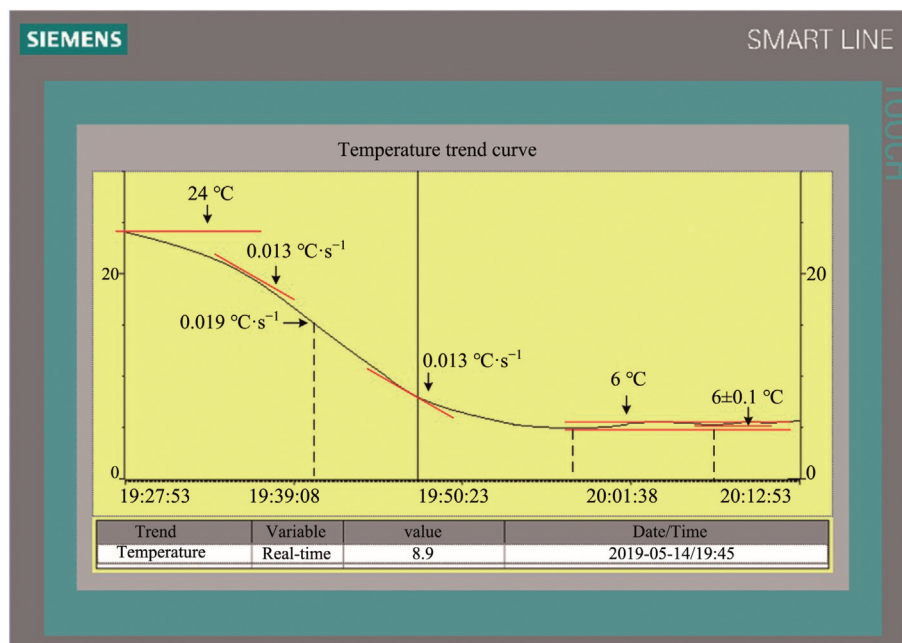


Fig. 10. Temperature trend curve.

Table 1
Temperature control real-time data

t/s	T/°C	t/s	T/°C	t/s	T/°C
0	24.2	1300	9.1	2200	6.0
200	22.7	1400	8.5	2300	6.1
400	20.5	1500	7.4	2400	6.0
700	18.9	1600	6.8	2500	5.9
800	17.1	1700	6.2	2600	6.0
900	15.2	1800	5.7	2700	6.0
1000	13.6	1900	5.8	2800	6.0
1100	11.2	2000	5.9	2900	6.0
1200	10.1	2100	6.0	3000	6.0

4. Refrigeration Effect

The historical temperature curve in Fig. 10 recorded refrigeration process of the semiconductor refrigeration box with 3 L heat transfer oil. The control target was to reduce the temperature of heat transfer oil from actual temperature 25.2 °C (room temperature 26.5 °C) to 6 °C (the platinum thermal resistance probe was partially inserted into the heat transfer oil). The device was turned on at 19:20, and the temperature finally dropped to 6 °C. The whole process took more than 40 min. The temperature trend curve recorded the temperature stabilization process from the time when the device was turned on 7 min later to the time when the temperature stabilized at 6 °C. Real-time temperature control data was shown in Table 1.

It can be seen that the temperature change was slow in the initial stage (19:20 to 19:27) due to the hysteresis of box structure and heat transfer oil. Starting from 19:27, the refrigeration rate was accelerated under the driving of two units of semiconductor refrigeration chips. Temperature dropped faster and faster. The refrigeration rate increased from $0.013\text{ }^{\circ}\text{C}\cdot\text{s}^{-1}$ to $0.019\text{ }^{\circ}\text{C}\cdot\text{s}^{-1}$. When the temperature difference was lower than 10 °C, one unit of semiconductor refrigeration chips stopped working. Due to the refrigeration inertia, the fastest temperature decreasing occurred 30 s later after closing one unit of semiconductor refrigeration chips. As the temperature difference dropped to 3 °C, the adaptive single neuron PID-PWM control was activated. PLC adjusted PID weight parameters in real time by the quadratic optimization index of real-time temperature and target temperature and simplified Jacobian information. The PID control signals in the PLC adjusted the PWM waveform to implement control of one unit of semiconductor refrigeration chips. We can see the refrigeration rate slowed down significantly from 8.5 °C. The maximum overshoot 0.8 °C occurred at 1750 s. This overshoot was acceptable considering refrigeration inertia. After stabilization, the real-time temperature in the semiconductor refrigeration box was within the temperature range of the target temperature of $(6 \pm 0.1)^{\circ}\text{C}$, which could meet the requirements.

5. Conclusions

The refrigeration box designed in this paper uses semiconductor refrigeration technology. The main results include the design of the refrigeration hardware and the control system. In the design of refrigeration hardware, the key point is improving the heat dissipation effect of the hot surface of the semiconductor refrigeration chip. Our design is to adhere the hot surface of the semiconductor refrigeration chip to the aluminum finned heat sink. The thermal silica gel is used to ensure high

thermal conductivity. The fan is mounted on the fin to further improve heat dissipation efficiency. This design ensures good refrigeration effect on the cold surface of the semiconductor refrigeration chip. The hardware of the control system includes touch screen and PLC. Touch screen plays the role of control parameter input and control effect display. Intelligent algorithm is implemented in PLC. In the design of control algorithms, switch control is combined with an intelligent control strategy. Adaptive single neuron optimization algorithm based on quadratic optimization is adopted to adjust and optimize the parameters of the PID controllers in real time. The Jacobian information in parameter adjustment is redesigned into a simplified form of identification in order to facilitate implementation in the PLC. The actual test results of refrigeration box show good control performance.

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