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Research Article

Development of Ultra-Low Temperature Cooling System Based on Peltier Module

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Abstract:
In recent years, with the development of medical methods utilizing genes and cells, the requirement for low-temperature transportation (cold chain) has increased. Also, to transport the corona vaccine, a low temperature environment up to -80℃ is demanded. Nowadays, the commonly used cooling method is the compressor type applied to refrigerators and air conditioners, but they are not suitable for portable transportation. In thermoelectric cooling, Peltier modules, as components applicable to cooling, are very suitable for building cooling systems due to their simple structure, light weight, low noise and most importantly, no refrigerant is required. In this study, a cooling system has been developed based on Peltier modules instead of using the traditional compressor to obtain an environmentally friendly ultra-low temperature environment. The purpose of this research is to fabricate the cooling device that can reach -30℃. In this study, firstly, the calculation has been performed to select the suitable Peltier module. Secondly, a cooling device experimental system was established. Finally, the cooling experiments of was carried out. As a result of the experimentations, in the case of water cooling, it can be confirmed that the minimum temperature of the cooling device could reach -38° C.

Keywords: *Ultra-low temperature, Thermoelectric cooling, Peltier module, Water cooling*

1. Introduction

Many materials, such as biological samples, vaccines, and laboratory reagents, require extremely low temperatures to maintain their stability and prevent degradation. These materials can be stored for long periods of time in freezers that operate below -80℃. In recent years, with the development of medical methods utilizing genes and cells, the requirement for low-temperature transportation (cold chain) has increased. Also, to transport the corona vaccine, a low temperature environment up to -80℃ is also demanded. However, the commonly used cooling method is the compressor type applied to refrigerators and air conditioners, but they are not suitable for portable transportation. Therefore, it is important to suggest a new cooling method for cold chain without using compressor.

Thermoelectric cooling has been attracting the increasing interest in recent years due to the development of technologies of producing highly efficient thermoelectric materials and the number of advantages brought by the thermoelectric energy conversion [1]. The important device for thermoelectric cooling is called Peltier Module (PM) which is only driven by direct electric current. When direct electric current flows into PM, one side (cooling side) of the PM absorbs heat from the environment while releasing heat from other side (heating side). If the heat is released

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quickly and efficiently, the cooling side can absorb external heat as much as possible. At this case, when PM's cooling side is surrounded by a closed space, the closed space including the object inside the closed space will be cooled. The advantages of using PM as an alternative method of refrigeration are listed as follows; (1) having no mechanical moving parts; (2) being highly reliable;(3) compact in size; (4) light in the weight; (5) requiring no working fluid, (6) most importantly, requiring no use of refrigerants [2].

So far, products made using PMs are gradually increasing on the market. For example, REON POCKET, a neck-cooler to prevent heatstroke, was designed by SONY. But the cooling temperature is above 0℃. As for small type of refrigerators using PMs, the lower temperature is only -10℃. In regard to the studies related to the utilization of cooling method based on Peltier modules, N.Zhu has designed a PM cooling system to cool the positioning device where ball screw is used and it was reported that the thermal expansion was controlled within 5μm. However, the lower temperature was only -8℃ [3]. Besides, Mohamed Ali Kassab designed and constructed a thermoelectric cooling system based on a Peltier module and tested its performance under different conditions. Nevertheless, the cooling system was able to achieve a temperature difference of up to only 20℃ [4]. For all these researches, the common point is that only heat sink contacted with the heating side is used for heat releasing, which has limit to some extent. According to the authors' investigation, in order to realize a low temperature below -30℃ for cold chain, method of efficiently releasing heat from the PM was very important [5]. The transfer of heat from the hot side of the PM is of key importance from the point of view of achieving the best efficiency of the investigated cooling system [6].

Therefore, the aim of this study is to firstly suggest a two-stage cooling method to realize a ultra-low temperature cooling system of -30℃. Two-stage cooling method means that two PMs (upper PM and lower PM) are used at the same time and contacted with each other closely. Upper PM is contacted with the container to be cooled while lower PM is used for cooling the heating side of the upper PM and will release heat by external cooling method such us air cooling or water cooling.

During the research, firstly, a design calculation for ultra-low temperature based on heat transfer and thermal cooling principle has been performed to select the suitable PM. Secondly, by introducing the abovementioned two-stage cooling method, a cooling device experimental system was established and the cooling experiments was carried out under the conditions of air cooling or water cooling to find the most suitable cooling method. Finally, a PID control method was added to accurately control the internal temperature of the cooling device.

2. Cooling Principle

There are three phenomena between electricity and heat in metals and semiconductors, Seebeck effect, Peltier effect, and Thomson effect, and these are called the thermoelectric effect. In this research, the authors used the calculation formula of Seebeck effect and the Peltier effect to choose the most suitable Peltier module the authors are going to use in our cooling system.

Seebeck effect is a phenomenon discovered by T.J. Seebeck in 1821. As shown in Fig. 1, when two different metals A and B are connected at both ends and there is a temperature difference between the two connection points, an electromotive force V is generated in the circuit. This electromotive force V is called thermos electromotive force [7].

As shown in Fig. 2, the Peltier effect is the phenomenon in which heat is absorbed or dissipated at the connection when two metals A and B are connected when a DC current is passed through the circuit composed of the two metals [8]. This thermoelectric conversion effect was discovered by J.C.A. Peltier in 1834. The thermoelectric conversion device based on this effect is called a Peltier module (PM).

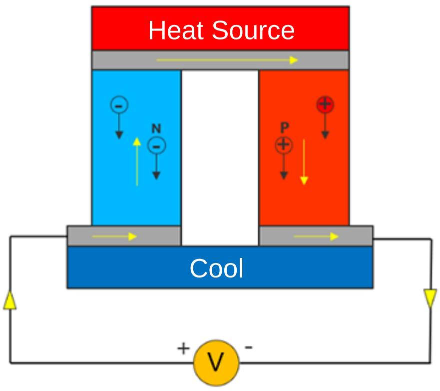

Fig. 1. Seebeck effect

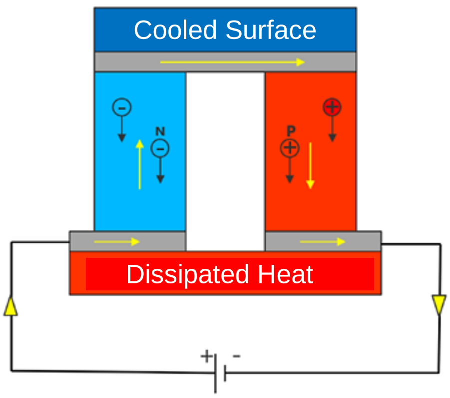

Fig. 2. Peltier effect

When DC current is applied to the Peltier module, the temperature of the surface (cooling side) of the PM decreases, and the temperature of the back surface(heating side) will increase [9]. Therefore, low-temperature cooling can be realized by releasing the heat of the cooling surface. When an electric current I is passed through the Peltier element, the amount of heat Q_p absorbed or dissipated per unit time has the following relationship where π_{AB} is the Peltier coefficient.

$$Q_p = \pi_{AB} I \tag{1}$$

3. Thermal Design of Low-Temperature Cooling Device and Selection of Peltier Module [5]

To select an appropriate PM, it is necessary to calculate the amount of heat transferred to the target temperature by using the cryogenic cooling device. For this purpose, the authors calculated the amount of heat absorbed per unit time required for the PM. Equation 2 shows the amount of heat transfer Q_{si} that flows from the ambient temperature T_e through the insulation material.

$$Q_{si} = S(T_e - T_c)/\{(1/\alpha) + (t/\lambda)\} \tag{2}$$

In Equation1, S, T_c, α, t, λ are the total surface area of the aluminum block, setting temperature, heat transfer coefficient, thickness of the aluminum block, and the heat conductivity.

Moreover, if the temperature of the cooling tank (volume V, specific heat C_1, specific gravity ρ_1) before cooling is T_0, the amount of heat $Q_{\tau 1}$ per unit time to reach the setting temperature T_c after time τ is shown in Equation 3.

$$Q_{\tau 1} = C_1 \rho_1 V(T_0 - T_c)/\tau \tag{3}$$

If the air temperature of the cooling vessel before cooling is T_0, the amount of heat $Q_{\tau 2}$ per unit time to reach the set temperature T_c after time τ is shown in Equation 4.

$$Q_{\tau 2} = C_2 \rho_2 V(T_0 - T_c)/\tau \tag{4}$$

The amount of heat absorbed per unit time Q_c required for the Peltier module is shown in Equation 5.

$$Q_c = Q_{si} + Q_{\tau 1} + Q_{\tau 2} \tag{5}$$

By calculating Q_c, it is possible to choose a suitable Peltier module for our study. Since an aluminum container (C = 883 J/kg·K, ρ = 2700 kg/m^3) with dimensions of 280 mm (W) x 190 mm (D) x 150 mm (H) and heat insulating material of Styrofoam (t = 0.02 m, λ = 0.025 W/m·K) are used, assuming ambient temperature $T_e \fallingdotseq T_0$ = 25°C ("≒" means approximately equal to), setting temperature T_c = -20°C, and arrival time τ = 5 min, then $Q_{si} \fallingdotseq$ 7.11 W,

$Q_{\tau 1}$≒41.21 W, $Q_{\tau 2}$≒0.47 W, Q_c≒48.79 W, by comparing Peltier modules from various companies, TEC1-12706 is chosen for this study [10].

4. Experiment

4.1 Experiment System for Cooling Device

As shown in Fig. 3, experiment system for cooling device consists of container covered with heat insulating material of Styrofoam, two PMs serving as two-stage cooling, external cooling apparatus(heat sink, fan, water pump), power sources for both PMs, thermocouples, DC galvanometer, voltage regulator, and Arduino and PID controller. For the external cooling apparatus (Fig. 4), water-cooling and air-cooling were used respectively. Arduino and PID control were introduced to effectively control the temperature inside the cooling device.

4.2 PID Control Design for Device

In the experiment, the authors constructed a PID control system [11] and controlled the internal temperature of the cooling device by adjusting a rotary encoder. A schematic block diagram of the PID control system is shown in Fig. 5. The authors used the internal temperature of the cooling device as the control variable for the target value. The PID control equation for the Peltier module voltage is shown in Equation 6.

$$dMv = Kp * (e - e_1) + Ki * e + Kd * ((e - e_1) - (e_1 - e_2)) \quad (6)$$

dMv , e, e_1, e_2, Kp, Ki, and Kd are the voltage of the Peltier module, current temperature, next temperature, third temperature, proportional gain, integral gain, and the differential gain, respectively.

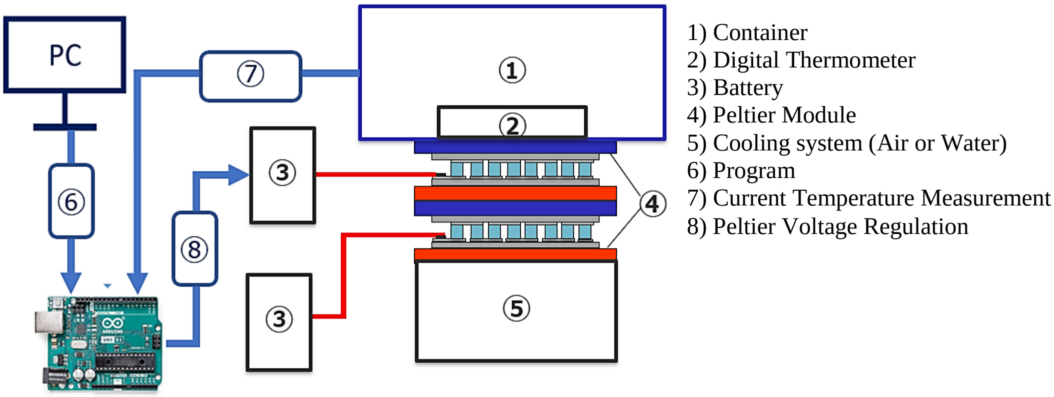

Fig. 3. Basic structure of electronic cooling container with aluminium block.

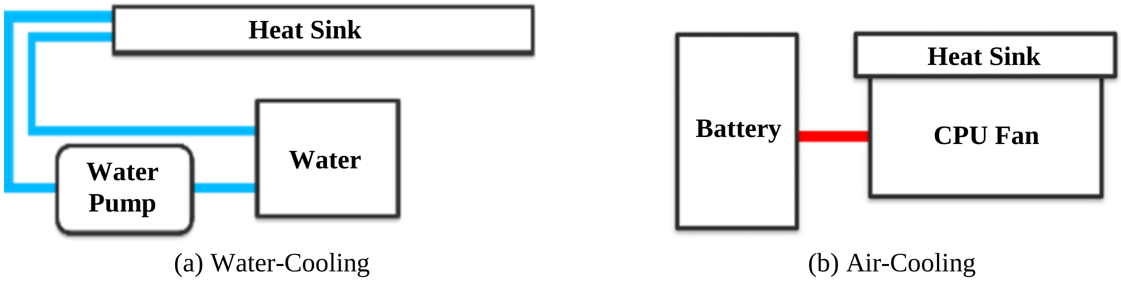

Fig. 4. Structure of water cooling and Air cooling.

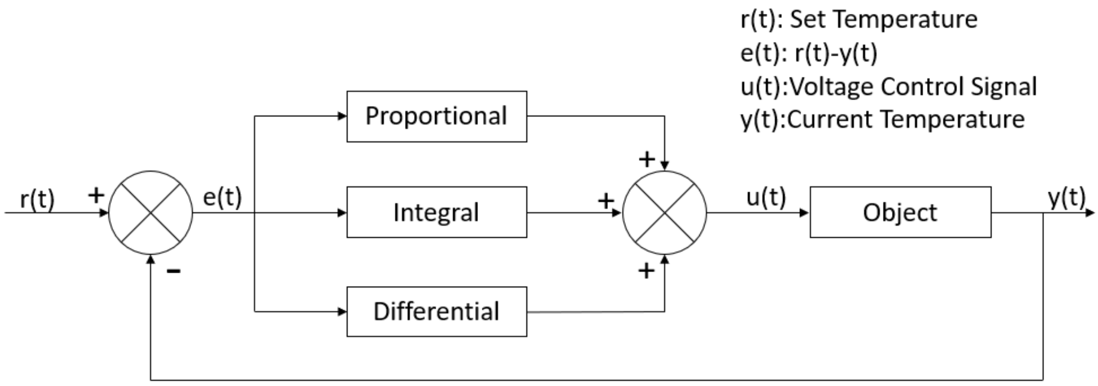

Fig. 5. PID control system.

4.3 Experiment Conditions and Method

The air-cooling and water-cooling experimental equipment using the Peltier module and the PID controller are shown in Figs. 6-8, respectively. The wind speed of the air-cooling fan is 5.5m/s and the circulating water volume of the water cooling is 17L/h. In the experiment, the room temperature was 24.5℃ and the humidity was 36%. For two stage cooling, the voltage for the upper Peltier module is set to 5V and the lower Peltier module to 12V and the temperature of the cooling device are measured. In addition, by setting PID controller parameters of Kp=4.0, Ki=0.06 and Kd=30.0, the temperature inside the water-cooling system was controlled.

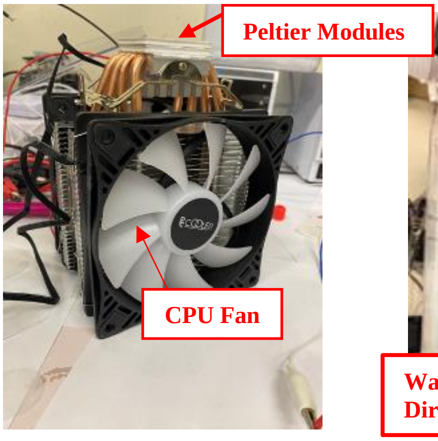

Fig. 6. Air cooling system.

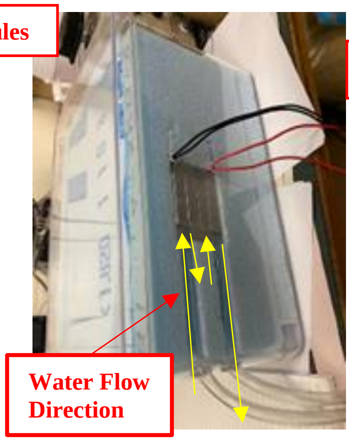

Fig. 7. Water cooling system.

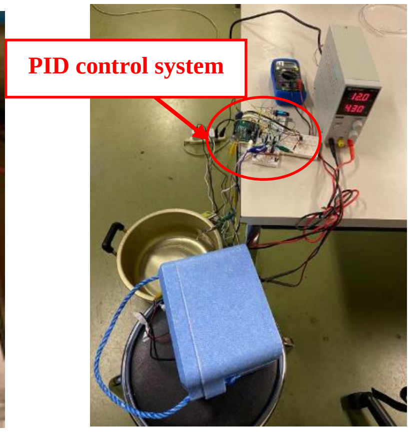

Fig. 8. Cooling system with PID control.

5. Results and Discussions

5.1 Temperature Changes of Cooling Device

Temperature changes of cooling device for air-cooling and water-cooling is shown in Fig. 9, it is found that at time of 0.5 minutes after the cooling system is activated, temperature decreasing speed for both of air-cooling and water-cooling are almost the same. It was found that the surface temperature of the Peltier dropped to -10℃, but after that, in case of the water-cooling type, the temperature dropped faster, and after 5 minutes, the temperature reached -38℃. This is because that the heat from the heat-dissipating surface was able to escape more quickly than in the air-cooling method. Compared with previous studies, it is possible to obtain a much lower temperature of the cooling system by using two-stage cooing method, which verified the potential capacity of the two-stage cooing method and paved the way for realizing ultralow temperature cooling portable devices.

5.2 PID Control

Cooling experiment was conducted using the above-mentioned PID control system for the target temperature inside the container equipped with the cooling device. The target temperature was set to 0°C. Figure 10 shows the voltage change in the control process. Under PID control, the voltage across the Peltier module gradually decreased over time, and when the target temperature was reached, it became 0V. Figure 11 shows the cooling temperature change using both PID control and a water-cooling system. It was found that the internal temperature of the cooling device reached the target temperature after about 20 minutes. Almost similar results were obtained when this experiment was repeatedly forth times. This experiment proves that it is feasible to use the PID control method to control the temperature of the cooling device.

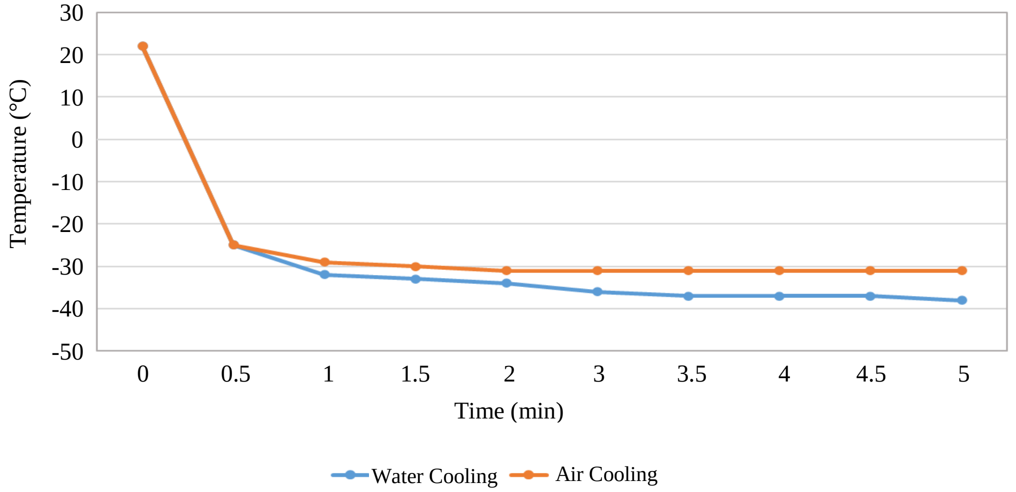

Fig. 9. Cooling results of air-cooling and water-cooling systems

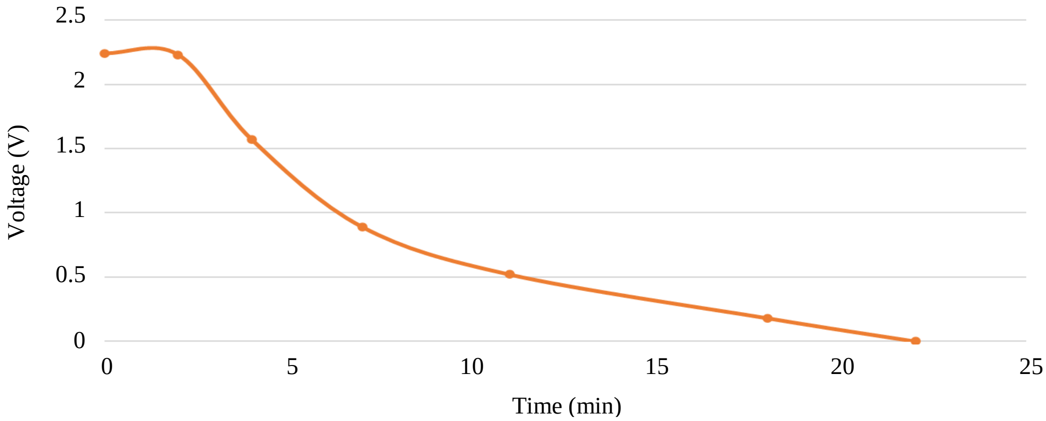

Fig. 10. Relationship between Voltage and Time

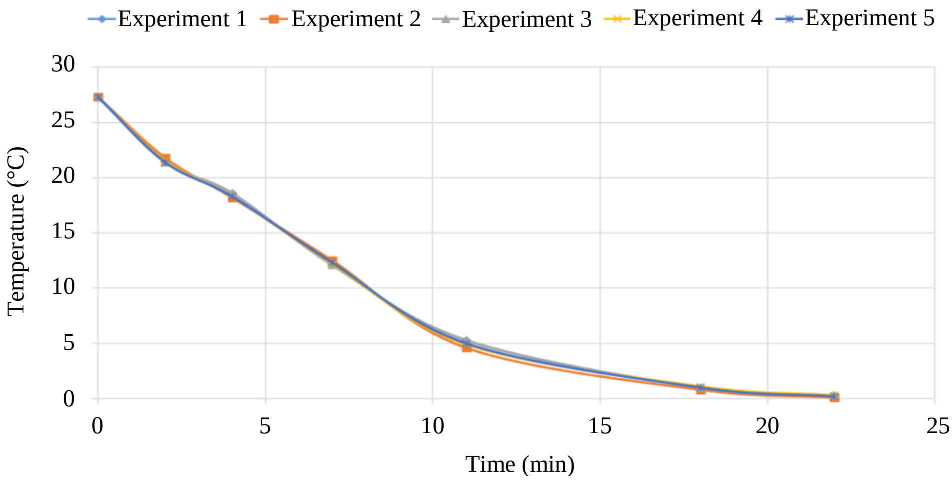

Fig. 11. Relationship between the internal temperature of the cooling container and time

6. Conclusion

Through testing different cooling systems, some conclusions were obtained as follows:

1) In the case of water cooling, it was confirmed that the minimum temperature of the two-stage cooling Peltier module reached -38℃.
2) Under the same conditions, the cooling temperature was lower with water cooling than with air cooling.
3) When a DC current was passed through the cooling device, the surface temperature of the Peltier module reached the minimum temperature in about 5 minutes, and the temperature was maintained.
4) When using PID control system, the internal temperature of the cooling device reached the setting temperature of 0℃ after about 20 minutes.

In the future, based on the two-stage cooling method and PID control system, by using some insulation materials with lower heat conductivity, decreasing the contact thermal resistance between the PM with heat sink and improving the heat releasing capacity of the cooling system, a cooling system whose internal temperature of the cooling device at -80℃ could be possibly realized.

Nomenclature

Q_p	Peltier heat (W)
π_{AB}	Peltier coefficients
I	Electric current (from A to B)
Q_{si}	Heat transfer through the insulation material (W)
S	Total surface area of the aluminium block (m^2)
T_e	Environment temperature (°C)
T_c	Current temperature (°C)
α	Heat transfer coefficient (m^2/s)
t	Thickness of the aluminium block (m)
λ	Heat conductivity (W/m·K)
$C_{\rho 1}$	Specific heat capacity (J/kg·K)
V	Volume of the cooling tank (m^3)
T_0	The temperature of the cooling tank before cooling (°C)
τ	Time (s)
Q_c	Heat absorbed per unit time required for the Peltier module (W)

List of Equipment Used to Build the Prototype:

1. Digital thermometer (DS18B20)
2. P-Channel MOSFET (2SJ334)
3. N-Channer MOSFET (2SK2232)
4. Peltier Module (TEC1-12706)

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