THERMAL DESIGN AND PERFORMANCE ANALYSIS OF A PELTIER-BASED PORTABLE BEVERAGE COOLING DEVICE

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Examiner(s): Professor Liyao Xie

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ABSTRACT

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This thesis focuses on the design and analysis of a thermoelectric beverage cooler intended for localized cooling at room temperature.

The thesis first introduces the basic principles of thermoelectric cooling and analyzes the heat transfer mechanisms related to beverage cooling. Based on the above theoretical foundation, a cylindrical desktop thermoelectric beverage cooler structure scheme is proposed.

For the preliminary performance estimation, the beverage was approximated as a liquid with thermal properties similar to those of water. The effective inner diameter of the inner container was set to 95 mm, and the effective liquid height was set to 150 mm. Based on the theoretical estimation, when the initial beverage temperature was 25 °C and the cooling duration was 1200 s, the average beverage temperature was estimated to decrease to approximately 22 °C. Under this condition, the average cooling capacity of the system was approximately 11.1 W. When the thermoelectric module was assumed to operate at 6 V and 3.0 A and the fan power was taken as 1.2 W, the average coefficient of performance was preliminarily estimated to be approximately 0.58.

The preliminary analysis indicates that the proposed thermoelectric beverage cooler has the potential to provide a limited cooling effect for a single beverage container under room-temperature conditions.

SYMBOLS AND ABBREVIATIONS

Roman characters

A	heat transfer area	m^2
C_p	specific heat capacity	J/(kg·K)
d	diameter	m, mm
h	convective heat transfer coefficient; height	$W/(m^2 \cdot K)$ m, mm
I	electric current	A
k	thermal conductivity	W/(m·K)
m	mass	kg
P	electrical input power	W
Q	heat quantity	J
Q_c	cooling capacity	W
q	heat transfer rate	W
R	electrical resistance	Ω
r	radius	m, mm
T	temperature	°C, K
t	time	s
U	voltage	V
V	volume	m^3
x	distance in heat transfer direction	m

Greek characters

α	incidence angle	°
ΔT	temperature difference	K, °C
η	efficiency	%

λ	thermal conductivity	W/(m·K)
ρ	density	kg/m³

Dimensionless quantities

COP	coefficient of performance

Subscripts

avg	average
c	cold side
f	fluid
h	hot side
i	initial
in	input
f	final
s	surface
TEC	thermoelectric module

Abbreviations

COP	Coefficient of Performance

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DECLARATIONS

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The originality of this thesis has been reviewed with the Turnitin similarity checking service.

AI usage

The author of the thesis, Kangbo Sun, used the following AI-tools during the preparation of the thesis:

1. ChatGPT
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Responsibility

The author, Kangbo Sun, takes full responsibility for the content of this thesis and has reviewed and edited the content generated by the possible use of AI tools.

1 Introduction

This chapter introduces the background, motivation, and research scope of the thesis. It first explains the relevance of compact thermoelectric cooling devices, then presents the basic concept of thermoelectric cooling, reviews related research, and outlines the structure of the thesis.

1.1 Research Background and Significance

With the continuous development of society, people's attention to energy utilization efficiency and living comfort has been increasing. This has also driven the continuous progress of related cooling technologies. Nowadays, people have a faster pace of life. During their daily study, work and travel, they have a more obvious demand for convenient and practical small cooling devices. Especially in spaces with limited areas such as offices, dormitories and cars, being able to obtain beverages at the appropriate temperature at any time has become a practical concern for many users.

Although traditional compression refrigeration technology is widely used and well-developed, its equipment is usually large, generates certain noise during operation, and has many internal mechanical components with a relatively complex system structure. Therefore, it is not suitable for miniaturization and portable applications. In contrast, developing a cooling device with a smaller size, simpler structure, and capable of meeting personalized usage needs is more in line with the modern development direction of energy conservation and portability. Therefore, this thesis selects semiconductor cooling technology as the research object and explores its application in small beverage cooling devices. This research not only has certain engineering application prospects but also has reference significance for the design and optimization of related small refrigeration devices.

1.2 Overview of Thermoelectric Cooling

The core of semiconductor cooling technology is the Peltier effect. This is a solid-state cooling technology that achieves cooling by passing a direct current through a circuit

composed of two different semiconductor materials, allowing heat to be transferred from one end to the other. TERs are small, light in weight, reliable, insensitive to the position of orientation, low noise, handy, and cheap (He et al., 2015).

Compared with the traditional refrigeration systems based on compressors, semiconductor cooling has the following significant advantages:

- Compact structure: No need for a compressor, condenser or complex piping system, significantly reducing the size of the equipment.
- No moving parts: The system operates extremely quietly and has high mechanical reliability with low maintenance requirements.
- Environmentally friendly: No use of any chemical refrigerants, avoiding damage to the ozone layer in the atmosphere.
- Precise temperature control: By adjusting the magnitude and direction of the input current, it is possible to achieve precise temperature regulation and rapid switching between heating and cooling modes.

These characteristics make it particularly suitable for portable or space-constrained application scenarios such as beverage cooling.

1.3 Current Research Status

At present, there are various types of small refrigeration devices available on the market, while research on semiconductor beverage coolers is still in a stage of continuous optimization. The main direction of this research has gradually shifted from simple feasibility verification to performance optimization. Current studies mainly concentrate on three aspects (material improvement, structural optimization, and system integration).

Studies have shown that by optimizing the thermal contact method at the cold end (such as 'wet contact') and the heat dissipation structure, the cooling rate of semiconductor beverage coolers can be significantly enhanced (Filin, 2020).

1.4 Research Content and Thesis Structure

The main task of this thesis is to conduct a complete design and performance analysis of a semiconductor beverage cooler. The main research contents include:

1. Semiconductor cooling theory study: a brief overview of the Peltier effect and its application in beverage cooling.

2. Structural scheme design: Design the basic physical structure of the semiconductor beverage cooler, including the heat exchange system at the cold and hot ends.

3. Engineering drawing output: Complete the 3D modeling of the design scheme and output standard 2D engineering drawings. Design improvement suggestions: Based on the Theoretical estimation, discuss design considerations.

2 Theoretical Foundation

This section explains and elaborates on the theoretical calculation principle of the thermoelectric cooler.

2.1 Thermoelectric cooling principle

Thermoelectric cooling is a solid-state technology that uses the Peltier effect to create a heat flux at the junction of two different types of materials. Unlike conventional vapor-compression systems, it eliminates the need for moving parts, such as compressors, and the use of chemical refrigerants (Zhao and Tan, 2014).

Thermoelectric cooling does not achieve cooling through a compressor. Instead, it utilizes semiconductor materials to transfer heat from one side to the other under the drive of direct current. Due to its small size, simple structure, and greater environmental friendliness during use, this technology is increasingly valued in small refrigeration devices. Currently, it has been extensively studied and applied in portable cooling devices, heat dissipation of electronic components, and beverage cooling, among other areas.

In a practical thermoelectric cooler, the Peltier effect at the junctions is the primary mechanism for heat transport, although the Thomson effect and Joule heating also influence the overall temperature distribution and performance of the semiconductor elements (Goldsmid, 2016).

2.1.1 Peltier effect

The three main thermoelectric effects are the Seebeck, Peltier, and Thomson effects. While they are related by the Kelvin relations, the Peltier effect is the one specifically responsible for the cooling or heating process in a thermoelectric device when an electric current is applied (Goldsmid, 2016).

The main heat transfer mode of the semiconductor cooling cup is based on heat transfer and convective heat transfer. Additionally, the Peltier effect plays a very important role in this process, as it is the core mechanism behind the cooling process.

In a closed loop composed of two different metals, if the temperatures at the two contact points are different, an electric potential difference will be generated at the contact points, resulting in the formation of an electric current. This is the Seebeck effect. The opposite of this is the Peltier effect, where in a closed loop composed of two different metals, if a direct current is passed through, the two nodes will become a cold point and a hot point. When electrons move from a material with lower conductivity to a material with higher conductivity, energy is absorbed, thereby causing a cooling effect. Conversely, at the opposite junction, due to the increased electron movement, energy is released in the form of heat. This semiconductor cooling cup achieves the cooling of the liquid by applying a certain current to the semiconductor material, transferring the heat from the water in the cup to the external environment.

The Peltier effect enables thermoelectric cooling systems to operate without the use of refrigerants and without the need to incorporate mechanical moving parts within the cooling module. As a result, these systems possess advantages such as compact size, low noise, and relatively easy control (Zhao and Tan, 2014). However, at the same time, the performance of thermoelectric cooling is highly dependent on the heat dissipation conditions at the hot end. If the hot end fails to promptly and effectively discharge heat, the temperature difference between the two sides of the module will be affected, and the overall cooling effect of the system will significantly decline (Chein and Huang, 2004).

2.1.2 Seebeck effect

The Seebeck effect is a fundamental phenomenon of the thermoelectric effect. When two different conductive (or semiconductor) materials form a closed circuit, if there is a temperature difference between the two nodes, an electric potential (voltage) will be generated in the circuit, causing the charge to move directionally and forming an electric current (if the circuit is closed). This effect is the physical basis of thermocouple thermometers, thermoelectric power generation, and other technologies. Its essence lies in the different energy distributions and mobilities of free electrons/carrying charges in

different materials. At the high-temperature end, the carrying charges acquire higher energy due to thermal excitation and diffuse towards the low-temperature end, resulting in the accumulation of charges at the two ends of the material and the formation of an electric potential difference. The essence of this process is that thermal energy is directly converted into electrical energy, which is the reverse process of the Peltier effect.

2.1.3 Thomson effect

The Thomson effect refers to the evolution or absorption of heat when an electric current passes through a single material with a temperature gradient along its length. The Thomson heat source density is commonly expressed as:

$$Q_{Th} = \tau j \nabla T \tag{1}$$

where $\tau$is the Thomson coefficient. Moreover, under conditions where the Peltier effect occurs, a temperature gradient is established, and consequently the Thomson effect may arise naturally (Lashkevych et al., 2018).

Compared with the Seebeck effect and the Peltier effect, the Thomson effect plays a relatively minor role in the engineering design of small thermoelectric cooling devices. In many simplified analyses, it is usually not a primary consideration. However, from the perspective of the completeness of thermoelectric theory, the Thomson effect remains an important component of the thermoelectric phenomenon.

2.1.4 Thermoelectric refrigeration working mechanism

The operation of the thermoelectric cooling system can essentially be understood as a "heat pump" process. When the thermoelectric module is connected to a direct current power supply, the charge carriers in the semiconductor undergo directional movement, transporting heat from the cold end to the hot end. The cold end absorbs heat from the beverage container, while the hot end discharges heat to the surrounding environment through the radiator and forced air cooling.

For the thermoelectric beverage cooler designed in this thesis, its working process can be summarized as follows: The system inputs electrical energy to drive the thermoelectric

module to operate; The cold end of the module absorbs heat from the inner metal of the container; Then, the heat is transferred through the thermoelectric module to the hot end; Finally, the hot end discharges the heat into the environment through the action of a small fan. As this process continues, the temperature of the beverage gradually decreases.

2.2 The structure and working mechanism of the thermoelectric module

The performance of the thermoelectric cooling system is largely dependent on the thermoelectric module itself. The thermoelectric module is the core component of the cooling system. The material composition, internal structure and installation method of the thermoelectric module will directly affect the final cooling effect.

2.2.1 The basic structure of the thermoelectric module

The basic unit of the thermoelectric cooler is the n-type and p-type thermoelements. These semiconductor components are usually connected in series in the circuit and arranged in parallel in the direction of heat transfer (Zhao and Tan, 2014). Each semiconductor pair is connected through copper conductors and solder joints, forming a complete thermoelectric loop. Ceramic plates are set on both sides of the module, which are used to provide electrical insulation, mechanical support, and a stable heat transfer surface.

When current passes through these p-n type semiconductor pairs, the thermoelectric module will exhibit the phenomenon of absorbing heat on one side and releasing heat on the other side. Since a module usually contains many groups of semiconductor pairs inside, it can transfer a considerable amount of heat, which can basically meet the usage requirements of small refrigeration devices.

In the thermoelectric beverage cooler studied in this thesis, the thermoelectric module is installed between the bottom of the beverage container and the external heat dissipation structure. The inside of the module is connected to the cooling surface, and the outside of the module is connected to the heat sink, which helps to transfer the heat from the beverage efficiently

2.2.2 Heat Pumping Process in the Module

The thermoelectric module process is essentially driven by the migration of electrons and holes within the semiconductor material. When direct current passes through the module, the junction in which the generation of charge carriers takes place is cooled, and the junction in which their recombination takes place is heated (Górecki and Posobkiewicz, 2022) It can be regarded as a heat pump. Moreover, the thermoelectric module itself does not store "cold energy", and its function is to continuously transfer heat from the cold end to the hot end. The performance of a thermoelectric cooler depends on various parameters like applied electric current, hot and cold side temperatures, the electrical contact resistance and the thermal resistance of heat sink on the hot side (Kaiprath and Kumar, 2023).

This indicates that in the design process, the design of the heat sink and cooling fan is just as important as the selection of the thermoelectric module itself.

2.3 The heat transfer theory related to beverage coolers

Factors such as heat conduction, convection, thermal resistance and insulation all affect the system's ability to extract heat from the beverage and maintain a low temperature state (excluding the thermoelectric effect).

2.3.1 Heat conduction

Heat conduction is the process by which heat is transferred within a material due to the existence of temperature gradients. In beverage coolers, heat conduction mainly occurs in the inner container and the thermoelectric modules.

Heat conduction can be expressed by Fourier's law:

$$q = -kA\frac{dT}{dx} \tag{2}$$

In the formula, materials with higher thermal conductivity are more conducive to heat transfer. Therefore, we need a metal with high thermal conductivity efficiency, which can transfer the heat in the beverage to the thermoelectric module more quickly.

If the material of the shell has excessive heat conductivity and lacks sufficient insulation, external heat may also more easily enter the cooling area. Therefore, we need to use metals with higher thermal conductivity inside, and metals with lower thermal conductivity on the outside.

2.3.2 Convective heat transfer

Convection heat transfer refers to the heat exchange that occurs between the surface of a solid and the flowing fluid. In a thermoelectric beverage cooler, the most critical convective process takes place at the hot end, specifically the heat exchange between the surface of the heat exchanger and the surrounding air. Additionally, there is also natural convection or forced convection between the outer surface of the shell and the ambient air.

Convective heat transfer can usually be expressed by Newton's law of cooling:

$$q = hA(T_s - T_f) \tag{3}$$

This formula indicates that the convective heat transfer capacity depends on the heat transfer coefficient, temperature difference, and available heat transfer area. When designing a cooling cup, fans or heat dissipation fins can be added to enhance the efficiency of heat dissipation.

2.3.3 Thermal resistance and heat leakage

Heat leakage refers to the phenomenon where environmental heat enters the cooling area in an abnormal manner. In the thermoelectric cooling beverage designed in this thesis, the uneven openings on each surface and the rough workmanship resulting in surface gaps can all lead to heat leakage.

Reducing heat leakage is very necessary. This is particularly important for small cooling devices because unwanted heat gain increases the passive heat load on the thermoelectric module and reduces the net cooling capacity available for the beverage (Ferrotec n.d.; Coherent, 2022).

For the cylindrical beverage cooler proposed in this thesis, except for the necessary heat transfer area at the cold end, the rest of the structure should be covered with insulation layers as much as possible to reduce the external heat load. Therefore, the insulation design is not only a structural design issue, but also a key factor affecting energy efficiency and cooling stability.

2.4 Theoretical basis of semiconductor refrigerators

In order to evaluate the performance of this thermoelectric beverage cooler, we need to take into account multiple indicators: cooling capacity, performance coefficient, temperature difference, cooling time and energy consumption.

2.4.1 Refrigeration capacity

The cooling capacity refers to the amount of heat removed from the cold end within a unit of time. The cooling capacity can directly indicate the strength of the cooling capability. The cooling capacity determines how quickly the system can remove heat from the liquid.

However, increasing the cooling capacity usually requires a greater electrical input and stronger heat-end heat dissipation capability. Therefore, in actual design, we need to balance the cooling capacity with energy consumption, structural complexity and heat management capabilities comprehensively (Coherent, 2022).

3 Thermal Performance Analysis of a Thermoelectric Cooling Cup

The design concept of this research is not merely to achieve a large cooling power, but to strike a balance between miniaturization, feasibility and structural simplicity. Specifically, this thesis first starts from the cooling requirements of the beverage itself, and makes an initial estimation of the required cooling capacity of the system; then, by considering heat leakage, contact thermal resistance and heat dissipation capacity at the heat end, it analyzes the working conditions of the thermoelectric module; finally, based on the results of the thermal analysis, it designs the structural scheme of the cooling cup, including the inner liner, the contact method at the cold end, the heat end radiator, the cooling fan, the insulation layer and the top opening control, etc.

3.1 Physical model and assumptions

In order to conduct a preliminary engineering analysis of the thermoelectric cooling cup, a simplified physical model was established in this study. The device is mainly composed of a metal inner liner, a thermoelectric module, a hot-end heat sink, a cooling fan, an insulation layer, and an outer shell. The thermoelectric module is arranged near the bottom of the cup body, with its cold end in contact with the bottom of the inner liner, used to absorb the heat from the beverage; the hot end is connected to the heat sink, and through the fan, the air-side heat exchange is enhanced, thereby discharging the heat to the environment.

Based on the existing structural parameters of this study, the effective inner diameter of the inner liner is set at 95 mm, and the effective liquid column height is set at 150 mm. For ease of calculation, the beverage is approximated as a liquid with similar thermal properties to water, and the environmental temperature is set at 25 ℃. This geometric setting is consistent with the refrigeration cup structure established in the previous part of this study.

Since this study is mainly aimed at the preliminary design research at the undergraduate level, the following basic assumptions are made:

(1) Beverages are regarded as homogeneous liquids, and their density and specific heat capacity are taken as the typical values of water at room temperature;

(2) The initial temperature of the beverages is uniform, and the environmental temperature remains constant during the cooling process;

(3) The internal temperature of the liquid is handled using an average temperature model, and the transient temperature field is not precisely solved;

(4) The thermoelectric module operates under constant voltage and current conditions during the analysis period;

(5) The heat transfer process at the hot end is represented by an equivalent forced convection boundary, and a complete air flow field model is not established;

(6) There are heat leaks from the cup wall, bottom structure, and top opening in the system, but this is discussed in this chapter using an engineering approximation method;

(7) Based on the calculation, the thermal resistance is 0.52 K/W;

(8) The analysis results of this chapter are mainly used for scheme design and parameter selection.

3.2 Refrigeration capacity and Refrigeration efficiency

3.2.1 Definition

The general measure of the energy performance of a refrigeration system is the Coefficient of Performance, COP. This is defined as the useful cooling divided by the power used by the compressor (Energy Institute, 2018). The coefficient of performance is an index used to evaluate how effectively input energy is converted into cooling capacity. It reflects the ability of the refrigeration system to extract heat from a low-temperature environment while consuming a certain amount of energy.

Thermodynamic expression:

$$COP = \frac{Q_c}{W} \tag{4}$$

Q_c represents the cooling capacity absorbed by the refrigeration system from the low-temperature heat source, and W represents the input work consumed.

The energy source of the entire refrigeration system is the input electrical energy that drives electrons to flow through semiconductor materials. Heat transfer is achieved through the change in potential energy of the electrons. The specific conversion of the input power mainly takes the following forms: First, Peltier heat (effective heat transfer). Peltier heat can be further divided into heat absorption at the cold end (refrigeration capacity) and heat release at the hot end. Heat absorption at the cold end occurs when electrons interact with the lattice near the cold end and absorb the heat from the liquid in the cup [Q_C] (i.e., the refrigeration capacity), which is the effective output of the system. Heat release at the hot end occurs when electrons release energy at the hot end and release heat to the external environment Q_H. According to the law of conservation of energy, we have:

$$Q_H = Q_c + W \tag{5}$$

This formula indicates that the input electrical energy W will directly become a part of the heat released by the hot end.

3.3 Analysis of Beverage Cooling Load

In thermoelectric cooling cups, the most fundamental cooling requirement stems from the heat that must be removed to lower the temperature of the beverage itself. It is therefore necessary to first estimate the volume and mass of the beverage, as well as the amount of heat it releases within the specified cooling time. This study approximates the beverage area as a cylinder. Let the inner diameter of the inner container be 95 mm and the total height be 190 mm. Considering the thickness of the cup lid and the surplus at the top, the effective liquid height is taken as 150 mm. Then the radius of the liquid area is 0.0475 m and the height is 0.150 m. The volume of the beverage can be expressed as:

$$V = \pi r^2 h \tag{6}$$

Substituting in gives:

$$V = \pi \times (0.0475)^2 m \times 0.150 m \approx 1.063 \times 10^{-3}\ m^3 \tag{7}$$

It is approximately 1.063 L. If the beverage is roughly regarded as water, with a density of 1000kg/m^3, the mass of the liquid would be:

$$m = \rho V = 1000 kg/m^3 \times 1.347 \times 10^{-3} m^3 = 1.063\ kg \quad (8)$$

At room temperature, assuming the ambient temperature and the initial temperature of the beverage are both 25 °C, after 1200 seconds of cooling, the average temperature of the beverage drops to 22 °C. In the present study, the cooling time was set at 1200 s and the target average temperature drop of the liquid was taken as 3 °C. In this thesis, the assumed temperature decrease of 3°C should be understood as the temperature reduction within the selected short evaluation period of 1200 s, rather than the final achievable temperature of the beverage. The final temperature was not intended to be 3°C. The reason is the studied product is a small thermoelectric refrigeration cup, which is characterized by a compact structure and limited input power, this type of product has a compact structure and limited input power, so it is more suitable for gradual local cooling rather than a rapid large temperature drop. Accordingly, in the product descriptions of similar small refrigeration cups and car cooling cups on the market, the cooling effect usually takes place within a range of about 10–20 minutes. This value was used only as indicative market information rather than as experimentally verified performance data (Walmart, n.d.; Fruugo, n.d.). Therefore, setting 20 minutes as the evaluation time window for the refrigeration effect in this thesis is relevant to the actual usage scenarios. Then, the heat released by the beverage is:

$$Q = mc_p(T_i - T_f) \quad (9)$$

In this thesis, the beverage is treated as an approximation of water; therefore, we take:

$$c_p = 4180 \frac{J}{kg * K} \quad (10)$$

Assuming the initial temperature of the drink is 25 °C and the target average temperature is 22 °C, the change in temperature is:

$$\Delta T = 25K - 22K = 3\ K \quad (11)$$

Therefore, the total heat released as the drink cools from 25 °C to 22 °C is approximately:

$$Q = 1.063L \times 4180 \frac{J}{kg * K} \times 3\ ℃ = 13330.02\ J \quad (12)$$

In order to evaluate the average cooling capacity of the system within the specified time, the average cooling power needs to be calculated based on the total cooling heat and the cooling time. The expression is as follows:

$$Q_{avg} = \frac{Q}{t} \tag{13}$$

Therefore, the average cooling power can be expressed as:

$$Q_C = \frac{Q}{t} = \frac{13330.02J}{1200s} \approx 11.11W \tag{14}$$

From this, it can be seen that if only the cooling requirements of the beverage itself are considered, in order to achieve the initial cooling target set in this study, the average effective cooling capacity required by the system is approximately 11.1 W. This is a simplified estimation as it does not take into account the heat leakage from the surrounding environment.

Table 1. Effect of target temperature reduction on the required average cooling capacity

Case	Cooling duration (s)	Target temperature drop (° C)	Average cooling capacity required (W)
A	1200	2	7.4
B	1200	3	11.1
C	1200	5	18.5

Table 2. Effect of cooling duration on the required average cooling capacity

Case	Cooling duration (s)	Target temperature drop (° C)	Average cooling capacity required (W)
D	600	3	22.2
E	1200	3	11.1
F	1800	3	7.4

Table 1 shows the effect of target temperature reduction on the required average cooling capacity, while Table 2 shows the effect of cooling duration. Since the assumptions of 1200 s cooling duration and a 3 °C average temperature reduction may appear somewhat arbitrary if presented alone, this sensitivity comparison was included to show how the required average cooling capacity changes with different assumed design targets. This helps clarify

that the 1200 s / 3 °C case was adopted as a representative intermediate design case rather than as a uniquely determined or experimentally validated operating condition.

3.4 Analysis of Heat Loss and Additional Heat Loads

For small thermoelectric cooling devices, due to the limited overall cooling capacity, the environmental heat leakage has a significant impact on the actual cooling effect of the system. In this study, the heat load at the cold end not only includes the cooling capacity required by the beverage itself, but also the heat input from the side walls, bottom structure and top opening, as well as the heat loss caused by the incomplete contact between the cold end and the cup body.

From an engineering perspective, the total load at the cold end can be approximately expressed as:

$$Q_c = Q_{bev} + Q_{leak} + Q_{contact} \tag{15}$$

Firstly, due to the temperature difference between the environment and the cooling area, there will be a heat conduction leakage phenomenon in the cup wall and cup bottom areas. If the thermal conductivity of the insulation layer is too high or its thickness is insufficient, external heat will continuously enter the container area, resulting in a decline in the overall cooling effect. Secondly, the top opening is an important heat leakage path in the thermoelectric cooling cup that cannot be ignored. If there is surface unevenness, insufficient assembly pressure, or an air gap between the cold end and the cup bottom, a large contact thermal resistance will be formed, thereby hindering the effective transfer of coldness to the beverage.

Based on the relationship between thermal resistance, heat loss to the environment can be approximated as follows:

$$Q_{leak} = \frac{\Delta T}{R_{th}} \tag{16}$$

This is the total thermal resistance value. As can be seen from the formula, the thicker the insulation layer and the lower the thermal conductivity, the greater the thermal resistance

value of the system, and the less the heat leakage from the environment. Therefore, it is necessary to strengthen the design of the insulation layer and the control of the top opening.

3.5 Estimation of the system's average coefficient of performance

The setting of 6 V / 3.0 A should not be interpreted as an arbitrary value, but rather as a compromise condition achieved among the refrigeration capacity, the heat dissipation capacity at the heat end, and the system efficiency. For the thermoelectric module, although an increase in the input current may enhance the instantaneous heat extraction capacity, it will also significantly increase the Joule heat within the module. If the performance of the heat end radiator and fan is limited, an excessively high current will instead cause the temperature at the heat end to rise, thereby weakening the effective cooling capacity at the cold end and reducing the performance coefficient (COP) of the entire system. Therefore, in this study, 6 V / 3.0 A was chosen as the initial working parameters as a reasonable compromise based on engineering feasibility and thermal balance constraints. If the working voltage of the thermoelectric module is 6 V and the working current is 3.0 A, then the input power of this thermoelectric module is:

$$PTEC = UI = 6V \times 3.0A = 18\,W \tag{17}$$

If the power of the cooling fan is set at 1.2 W, then the total input power of the entire machine is:

$$P_{in} = 18W + 1.2W = 19.2\,W \tag{18}$$

Therefore, the average performance coefficient of the entire machine can be estimated as:

$$COP = \frac{Q_c}{P_{in}} = \frac{11.11}{19.2} \approx 0.58 \tag{19}$$

The preliminary estimation suggests that at room temperature, when the effective liquid filling height is 150 mm and the volume of the cooling object is approximately 1.063 L, the system can achieve a certain degree of overall cooling. The average cooling power is approximately 11.1 W and the average COP is about 0.58.

It should be noted that the COP (coefficient of performance) of thermoelectric cooling devices is generally limited under practical operating conditions, with many reported values

around 0.3–0.5 (Chen et al., 2023). The calculated COP of 0.58 in this study is therefore considered reasonable for the present design assumptions.

4 Engineering drawings and design process

At room temperature, for the users in the office or during some social gatherings, the design and modeling of the refrigeration cup were completed.

4.1 Design Requirements Analysis

The overall design of this thermoelectric beverage cooler is based on the current situation: nowadays, most young people prefer to drink cold beverages, especially in the southern regions of China. And both in Europe and in China, there is a habit of drinking iced coffee. More than 90 percent of 4,000 Chinese coffee shop consumers surveyed drink hot coffee weekly, while 64 percent consume iced coffee at least once a week, the World Coffee Portal said in a report last year (People's Daily Online, 2024).

4.2 Selection of thermoelectric module and determination of working parameters

4.2.1 The selection basis for TEC1-12706

In this thesis, TEC1-12706 was selected as the thermoelectric module for the preliminary design. This module belongs to a common single-stage thermoelectric module, featuring a mature structure, convenient acquisition, low cost, and wide application in engineering. Its typical size is approximately 40 mm × 40 mm, making it suitable for matching and installation with the bottom area of the cup designed in this thesis.

According to the analysis in Chapter 3, the average required useful cooling energy for the beverage itself is approximately 11.1 W. However, the actual system also needs to compensate for environmental heat leakage and interface losses. Therefore, the selected module should provide a cooling capacity higher than the estimated beverage cooling demand, with an appropriate design margin to compensate for environmental heat leakage,

contact thermal resistance, and other structural losses. TEC1-12706 was considered suitable for the preliminary requirements of the proposed small beverage cooling device.

If a higher current rating or a larger-sized module is adopted, although it may theoretically enhance the cooling capacity, it will also significantly increase the input power and the heat dissipation burden at the heat end, making it more difficult for the small device to maintain stable operation. On the contrary, if a smaller-sized module is selected, it may not be able to provide sufficient effective cooling under the condition of heat leakage.

From the perspective of structural size matching, the 40 mm × 40 mm module is more suitable for being arranged in the bottom area of the cup body, which facilitates the contact between the cold end and the bottom plane, and is also conducive to the installation of the heat end radiator and fan.

Based on the size range of the currently available smart temperature control cups, quick cooling cups, and vehicle-mounted cold and hot cups in the market, the diameters of the cup bodies or the corresponding containers of these products are typically around 75–90 mm. In contrast, the 40 mm × 40 mm TEC module is of a relatively compact specification, which can be arranged in the bottom area of common cups and reserve necessary installation space for the cold end contact surface, fixed structure, hot end heat sink and fan. Therefore, TEC1-12706 has a good size compatibility in the small beverage cooling device proposed in this study.

Apart from its wide availability, low cost, and geometric compatibility with the proposed 40 mm × 40 mm installation area, the selection can also be justified by its electrical and thermal performance margin. The maximum operating current is typically reported to be around 6.0 - 6.4 amperes, while the maximum operating voltage is usually within the range of approximately 14.4 - 16.0 volts. The maximum cooling capacity Q_{max} is typically reported to be around 50 - 61.4 watts, and the maximum temperature difference ΔT_{max} under standard specification conditions is typically around 65 - 70 degrees Celsius. The resistance of this module at room temperature is typically around 1.98 - 2.07 ohms. These values indicate that the cooling capacity provided by TEC1-12706 is significantly higher than the cooling requirement of approximately 11.1 watts in this study, while still remaining within the practical low-voltage direct current operating range. Therefore, TEC1-12706 can be regarded as a reasonable preliminary choice for the proposed beverage cooling device.

Figure 1. Physical picture of a thermoelectric module. Source: Mikroe (n.d.)

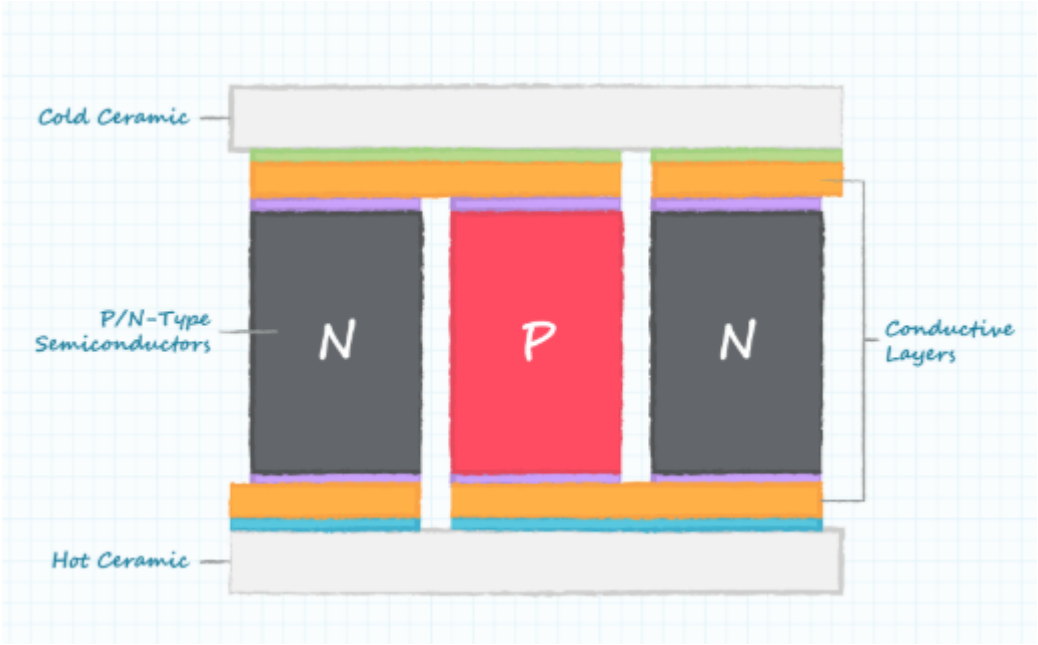

Figure 2. Structural diagram. Source: Same Sky Devices (n.d.).

Figure 1 shows the physical picture of TEC-1207, and Figure 2 is the structural schematic diagram of the thermoelectric module. The thermoelectric module is composed of alternately arranged p-type and n-type semiconductor elements inside, which are sandwiched between two ceramic plates. When powered on, one side of the module absorbs heat while the other side releases heat.

4.2.2 Determination of operating conditions

This thesis sets the operating parameters of the semiconductor module at 6 V / 3.0 A. This parameter is not merely determined for ease of access based on common power supply specifications, but is instead a compromise condition determined after simplified consideration of system thermal balance, heat dissipation capacity at the heat end, and overall efficiency.

Based on the thermal end heat balance analysis in Chapter 3, this thesis adopts 6 V / 3.0 A as the initial working condition of the module. The corresponding input power is approximately 18 W, and it was therefore used as the design basis parameter for this study.

Since no experimental test, manufacturer performance curve, or detailed thermoelectric module simulation was used in this thesis, the operating conditions were not compared as optimized performance results. Instead, the comparison was limited to the electrical input power and the corresponding heat rejection implication at the hot side. The purpose of this comparison was only to support the selection of a preliminary operating condition for the conceptual design.

Table 3. Preliminary comparison of candidate operating conditions for the thermoelectric module

Operating condition	TEC input power (W)	Fan power (W)	Total input power (W)	Comment
5 V / 2.5 A	12.5	1.2	13.7	Lower electrical input, but the available cooling margin may be limited.
6 V / 3.0 A	18	1.2	19.2	Selected as the preliminary operating condition in this thesis.
7.2 V / 4.0 A	28.8	1.2	30	Higher electrical input, leading to a higher heat rejection requirement at the hot side.

Based on the comparison in Table 3, 6 V / 3.0 A was selected as the most balanced preliminary operating condition.

4.3 Inner liner structure design

The inner liner is the core component that directly comes into contact with the beverage and participates in heat exchange. The thermal conductivity of its material has a significant impact on the cooling speed. To transfer the heat in the beverage to the cold end of the semiconductor module as quickly as possible, the inner liner should be made of a metal material with good thermal conductivity.

The inner liner should use a metal material with good thermal conductivity to enhance the efficiency of heat transfer between the beverage and the cold end. Aluminum alloy is a suitable choice. After comparing the thermal conductivity and price data of common metals, aluminum was considered the most suitable option. This is also consistent with the material selection of most cups available on the market.

Table 4. Comparison of candidate metals in terms of price and thermal conductivity.

Metal	Price (USD/kg)	Thermal conductivity near room temperature (W/m·K)	Comment
Gold	151,406.55	318.0	Very high thermal conductivity, but impractical due to extremely high cost.
Silver	2,431.56	428.0	Highest thermal conductivity among the listed metals, but too expensive for this design.
Copper	13.28	401.0	Excellent thermal conductivity and widely used in heat-transfer applications, but heavier and generally more costly than aluminum.
Aluminum	3.60	236.0	Good thermal conductivity, low density, easy processing, and suitable for lightweight structures.
Zinc	3.32	122.0	Moderate thermal conductivity, but lower than aluminum and copper.
Nickel	19.25	94.0	Lower thermal conductivity than copper and aluminum; often valued more for corrosion resistance.
Tin	48.95	68.2	Relatively low thermal conductivity compared with aluminum and copper.
Lead	1.95	35.5	Low thermal conductivity and unsuitable for beverage-contact applications due to toxicity concerns.

Source: Metal price data for gold, silver, copper, steel and aluminum adapted from Trading Economics (2026). And Adapted from Ho, Powell and Liley (1972).

As shown in Tables 4, although copper, silver and gold have higher thermal conductivity than aluminum, they are less suitable when cost and practical use are considered. Aluminum has good thermal conductivity, lower cost, low density, and good corrosion resistance due to its natural oxide layer. Therefore, aluminum was selected as the preliminary material for the inner container.

4.4 The design of the heat dissipation end

4.4.1 Estimation of total heat dissipation and thermal resistance at the hot end

For the thermoelectric cooling system, the heat dissipation capacity at the hot end directly determines whether the semiconductor module can maintain an adequate temperature difference between the hot and cold ends, thereby affecting the overall cooling effect of the system. According to the analysis in Chapter 3, under the 6 V / 3.0 A operating condition adopted in this thesis, the input power of the semiconductor module is 18 W; taking the target average effective cooling capacity of 11.1 W corresponding to the beverage cooling requirement as the design level estimate value, the total heat dissipation at the hot end can be expressed as:

$$Q_h = Q_c + P_{TEC} = 11.1 + 18 = 29.1\ W \tag{20}$$

Therefore, the heat that needs to be continuously dissipated at the hot end is approximately:

$$Q_h \approx 29.1W \tag{21}$$

In order to ensure that the semiconductor module can maintain an effective temperature difference between the hot and cold ends, the temperature at the hot end should not be too high. If the ambient temperature is set at 25 ℃ and it is desired to keep the working temperature at the hot end as close to 40 ℃ as possible. This value was selected as a preliminary design target because thermoelectric cooler design guides commonly recommend limiting the heat sink temperature rise above ambient to a moderate range, typically about 10–20 °C, since the heat sink temperature directly affects the hot-side temperature and therefore the achievable cold-side temperature (Coherent, 2022). Then the allowable temperature rise at the hot end can be taken as:

$$\Delta T_h = 40 - 25 = 15\,^{\circ}C \tag{22}$$

The equivalent total thermal resistance of the hot-end heat dissipation system can be defined as:

$$R_{th} = \frac{\Delta T_h}{Q_h} \tag{23}$$

Substituting the above values gives:

$$R_{th} = \frac{15}{29.1} \approx \frac{0.515K}{W} \tag{24}$$

That is:

$$R_{th} = \frac{0.52K}{W} \tag{25}$$

Therefore, under the 6 V operating condition defined in this thesis, the total equivalent thermal resistance composed of the heat-end radiator, interface contact layer, and air-side convection should be controlled to be around 0.52 K/W or lower. If the thermal resistance is too large, the hot-side temperature will increase significantly. This increases the temperature difference across the thermoelectric module and reduces the effective cooling capacity at the cold side.

4.4.2 Design of Heat Sink Surface Area and Fin Parameters

After knowing the heat dissipation at the hot end and the target thermal resistance, the effective heat exchange area required for the heat sink can be further estimated. The heat exchange on the air side can be expressed by the convective heat transfer relationship as:

$$Q = hA\Delta T \tag{26}$$

For the forced convection cooling method using small fans in this thesis, the average convective heat transfer coefficient on the air side can be estimated using engineering empirical values. Existing data indicate that in natural convection conditions, 10W/(m^{2} ·K) is often taken (The product is mainly used in indoor environments where natural convection is weak, so natural convection is ignored.), while in fan-driven forced convection conditions, it can be taken as (Lasance, 2011):

$$h = \frac{50\ W}{m^2 \cdot K} \tag{27}$$

If the heat dissipation at the hot end is taken into account:

$$Q_h = 29.1\ W \tag{28}$$

And take the average allowable temperature difference:

$$\Delta T = 15\ K \tag{29}$$

Then, the effective heat exchange area required for the radiator can be expressed as:

$$A = \frac{Q_h}{h\Delta T} \approx 0.0388 \tag{30}$$

Therefore, under the 6 V operating condition in this thesis, the effective heat exchange area required by the heat exchanger at the hot end is approximately:

$$A = 0.039m^2 \tag{31}$$

Based on the above estimations, the hot end of this thesis adopts an aluminum finned radiator. Aluminum has the advantages of good heat conductivity, light weight, low price, and easy processing, making it suitable for small thermal management structures. The radiator should adopt the form of "rectangular base + multiple straight fins" to balance the heat dissipation capacity and the ease of processing.

With regard to the geometric parameters of the fins, the selected values should be regarded as preliminary design values based on existing compact heat sink designs, rather than optimized results. In this thesis, no detailed pressure-drop calculation, fin-efficiency analysis, structural strength calculation, or CFD airflow simulation was carried out. Therefore, the heat sink geometry was selected by referring to commercially available small aluminium heat sinks used for TEC1-12706 thermoelectric modules and compact electronic cooling applications (Amazon, n.d).

The TEC1-12706 module itself has a standard size of approximately 40 mm × 40 mm, so heat sinks used with this module commonly have a similar footprint. For example, commercially available aluminium heat sinks for TEC1-12706 modules are often specified with dimensions of 40 mm × 40 mm × 20 mm, and they are also used for small electronic cooling applications such as PC chipsets, power ICs, LED devices, and 3D-printer stepper

motors (Amazon, n.d.; Thermonamic, 2022). In addition, general heat sink fabrication guidance shows that thin aluminium fins with thicknesses in the range of approximately 0.1–1.5 mm and fin gaps above about 1.2 mm are manufacturable in compact heat sink structures (Boyd, 2020).

Based on these reference designs and fabrication ranges, the heat sink in this thesis was preliminarily designed with a base size of approximately 43 mm × 43 mm, slightly larger than the 40 mm × 40 mm TEC module to allow installation margin. The fin height was selected as approximately 13 mm to keep the heat sink compact within the bottom space of the cooling cup. The fin thickness of approximately 0.9 mm and fin spacing of approximately 2 mm were selected as manufacturable preliminary values within the range of compact heat sink designs. The number of fins was set to 15 mainly according to the available base width and the selected fin spacing. These dimensions were not obtained from a detailed thermal or airflow optimization, and the actual thermal resistance and airflow resistance should be verified by manufacturer data, experimental testing, or CFD analysis in future work.

4.4.3 The design of the cooling fan

In the design of this thesis, small fans need to be installed on the outer side of the radiator to enhance air circulation and thereby increase the convective heat transfer coefficient.

From the perspective of structural characteristics, the hot end of this thesis is located in the bottom area of the cup body, and the air flow path on the outside of the radiator is relatively short, with overall resistance being relatively limited. Therefore, it is more suitable to use axial flow fans. Axial flow fans have the advantages of simple structure, small size, large air volume, and low cost, and are suitable for open or low-resistance cooling structures; in contrast, centrifugal fans are more suitable for high-resistance, long flow path, or complex enclosed air duct systems. Based on the compact bottom structure of this study, axial flow fans are more suitable as heat-end enhanced cooling components.

The fan parameters were selected by referring to commercially available compact axial fans with a frame size of approximately 40 mm. For example, a 40 mm × 40 mm × 20 mm Sanyo Denki axial fan is specified with an airflow of about 8 CFM and a power consumption of about 1.2 W. Therefore, in this thesis, an airflow of 8.0 CFM and a fan

power of 1.2 W were adopted as representative preliminary design values for a compact forced-air cooling arrangement (Sanyo Denki n.d.). The static pressure value of 25 Pa was used as an approximate design assumption to represent a small fan with some ability to drive air through the fin channels. However, the actual pressure drop across the heat sink was not calculated in this thesis. This parameter level is within the common performance range of existing 40–50 mm axial fans, which can meet the air penetration requirements of the small finned heat sinks and will not significantly deviate the fan parameters from the engineering reality of compact desktop devices.

Among them, the air volume is set at 8.0 CFM. This is mainly because if the air volume is too small, the air cannot be adequately circulated between the fins, and the temperature at the heat end is likely to rise. If the air volume is too large, it will cause higher noise and a larger volume, which is not conducive to the design of small desktop devices. The static pressure is set at 25 Pa, which is to ensure that the air can effectively pass through the fin channels, rather than just flowing around the outside of the heat sink. Since the heat sink used in this thesis is a fin-type rather than an open flat surface, the fan must have a certain static pressure capacity in order to fully exert the enhanced cooling effect.

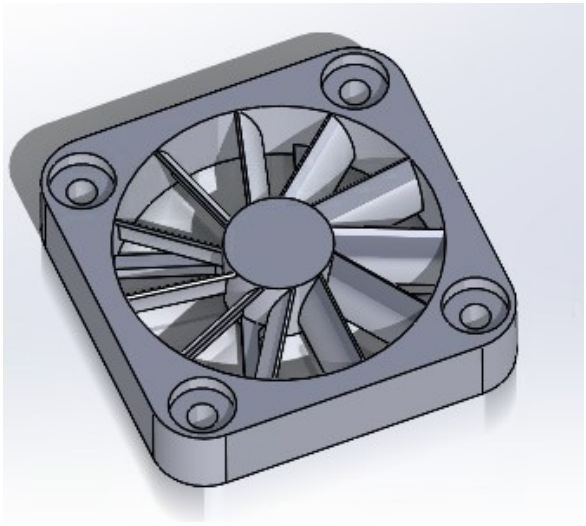

Figure 3. Heat dissipation fan model diagram

The figure 3 shows the 3D model of the axial fan, which is used to provide forced-air cooling in the system.

4.4.4 The design of the bottle cap

Since the liquid surface at the top opening of the refrigeration cup is directly exposed to the ambient air, external heat can enter the cup through natural convection and air disturbance, resulting in a significant heat leakage. To reduce the heat reflux in this part, this thesis designs a cup cover in the structure. The cup cover can reduce the direct contact area between the liquid surface and the ambient air, weaken the convective heat transfer and evaporation heat leakage in the top area, and reduce the influence of external air flow disturbance on the temperature field inside the cup. For small thermoelectric refrigeration devices, setting a cup cover helps to reduce ineffective heat input, improve the net cooling effect and cooling stability, and therefore is regarded as an important measure for controlling the top heat leakage in this thesis.

4.5 Overall structural scheme design

Based on the theoretical analysis in Chapter 2, this thesis proposes a general scheme for a cylindrical tabletop thermoelectric beverage cooler. The scheme mainly consists of an inner beverage container, a thermoelectric module, a heat-end heat sink, a cooling fan, an insulation layer and an outer shell. The system transfers heat from the beverage side to the environment side through the thermoelectric module, thereby achieving the purpose of cooling the beverage.

In terms of the overall layout, the beverage container is positioned at the center of the device. As a component in direct contact with the liquid, it is used to hold the cooled beverages. The thermoelectric module is arranged on the outer side of the inner tank, close to the bottom, so that the cold end can form good thermal contact with the inner tank, enabling the rapid transfer of heat from the beverage to the cold end of the module. The hot end of the module is connected to the heat sink, and the outer side of the heat sink is equipped with a small fan to enhance the heat dissipation capacity through forced air flow. To prevent the return of external heat, an insulation layer is set between the inner tank and the outer shell. The outermost shell is used to fix all the functional components and provide the overall appearance and mechanical protection.

There are several obvious advantages to choosing a cylindrical structure. Firstly, the cylindrical shape is similar to the common beverage cup shape, which is conducive to arranging circular or ring-shaped inner container structures and also makes it easier for users to understand its purpose. Secondly, the cylindrical structure is mechanically stable, has a regular shape, and is convenient for placement on the tabletop. Thirdly, the cylindrical outer shell is convenient for three-dimensional modeling and the output of two-dimensional engineering drawings, which is suitable for the modeling and drawing requirements of undergraduate graduation projects. In addition, the internal space of the cylinder is relatively clear, which is conducive to arranging concentric structures between the inner container, insulation layer and outer shell.

From the perspective of heat transfer paths, the working process of this scheme is as follows: The heat in the beverage first transfers to the metal inner container, then from the inner container to the cold end of the thermoelectric module, followed by the heat being transferred through the thermoelectric module to the hot end, and finally being released into the environment through the radiator and fan. At the same time, the insulation layer is used to reduce the re-entry of external heat into the system. This scheme takes into account the cooling requirements, heat dissipation requirements, and structural simplicity, and therefore is suitable as the overall design scheme of this thesis. The thermoelectric cooling chips in the model have been simplified.

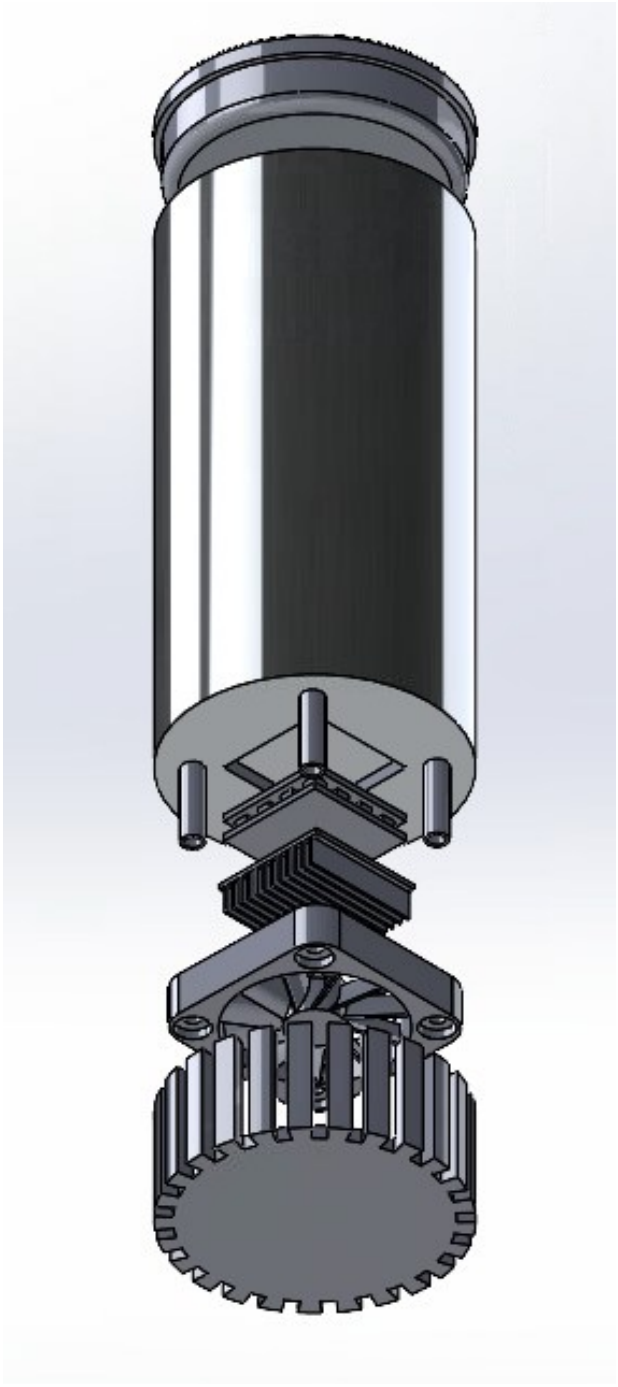

Figure 4. Exploded view of the refrigeration cup

The figure 4 shows the exploded view of the cooling cup assembly, illustrating the arrangement of the container, thermoelectric module, fan, and heat sink.

5 Conclusions

This thesis conducted a preliminary design and performance analysis of a portable beverage cooling device based on thermoelectric cooling. The basic principles of thermoelectric cooling were first introduced, and the required cooling capacity was then estimated based on the heat that must be removed from the beverage. Based on these calculations, a cylindrical cooling cup structure was proposed, consisting of a metal inner liner, a thermoelectric module, a heat sink, a fan, an insulation layer, and an outer shell.

In the calculations, the beverage was approximated as water. According to the selected dimensions, the volume of the cooled liquid was approximately 1.063 L. Under the initial assumption that the average beverage temperature decreases by 3°C within 1200 s, the heat that must be removed is approximately 13.3 kJ, corresponding to an average effective cooling power of approximately 11.1 W. When the thermoelectric module is assumed to operate at 6 V / 3.0 A and the fan power is taken as 1.2 W, the average COP of the system is approximately 0.58. This result indicates that the proposed design could theoretically provide a certain cooling effect for a beverage, although its cooling capacity is limited.

Although these factors were not specifically analysed in this thesis, the performance of the thermoelectric beverage cooling device is expected to be affected not only by the thermoelectric module itself, but also by hot-side heat dissipation, thermal contact conditions, and insulation performance. If the hot-side heat dissipation is insufficient, the temperature difference between the two sides of the module will be affected, and the actual cooling effect will decrease. At the same time, external heat entering the system through the cup wall, bottom structure, or top opening will offset part of the cooling effect. Therefore, in future design improvement, optimizing the heat sink and fan arrangement, reducing contact thermal resistance, and improving the insulation structure are more important than simply increasing the input power.

The proposed thermoelectric cooling cup has a simple structure, a small size, and no complex mechanical moving parts, which makes it suitable for small-scale and low-intensity beverage cooling. It cannot replace conventional vapor-compression refrigeration equipment and is not suitable for rapid or large temperature reduction. However, for applications such as

desktop beverage temperature maintenance or mild cooling, the proposed scheme still has practical reference value.

Due to the limited time and available conditions, prototype manufacturing and experimental testing were not carried out in this thesis. Therefore, the temperature reduction, cooling power, and COP results should be understood as theoretical estimates rather than measured performance data. In future work, a prototype could be built for temperature testing, heat leakage measurement, and comparison of different heat sink and fan configurations. These tests would help evaluate the actual cooling performance of the proposed design.

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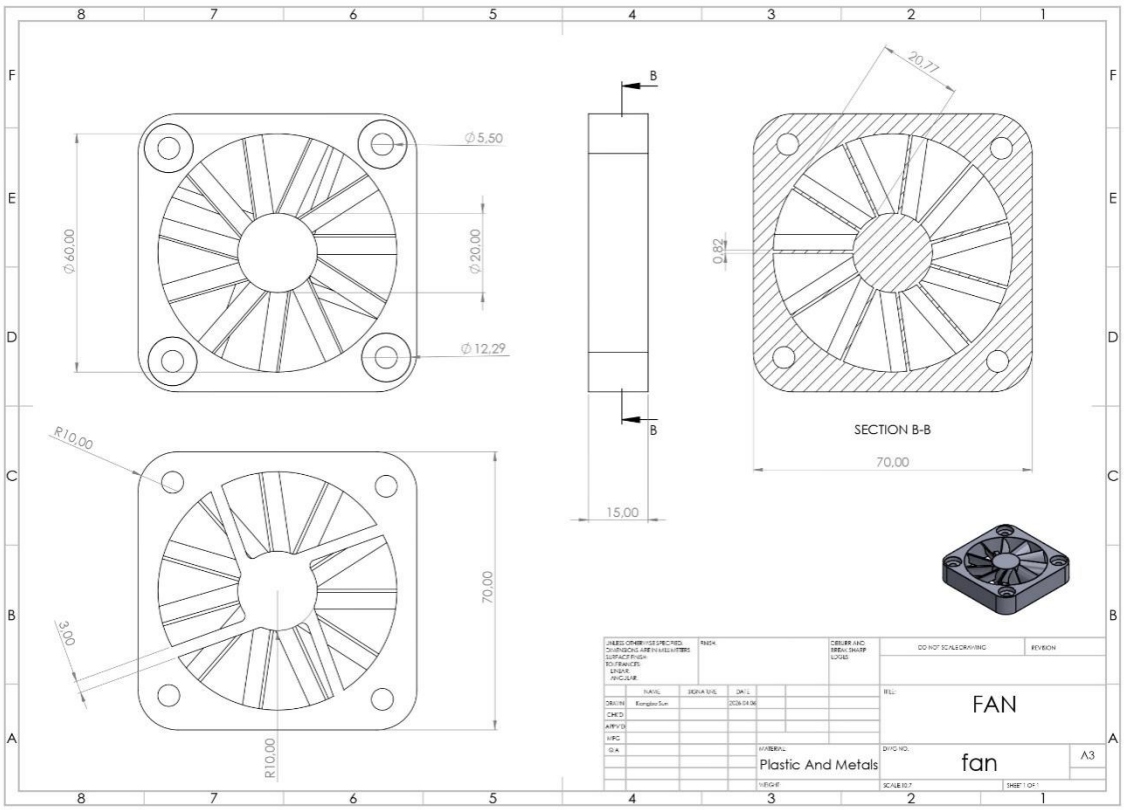
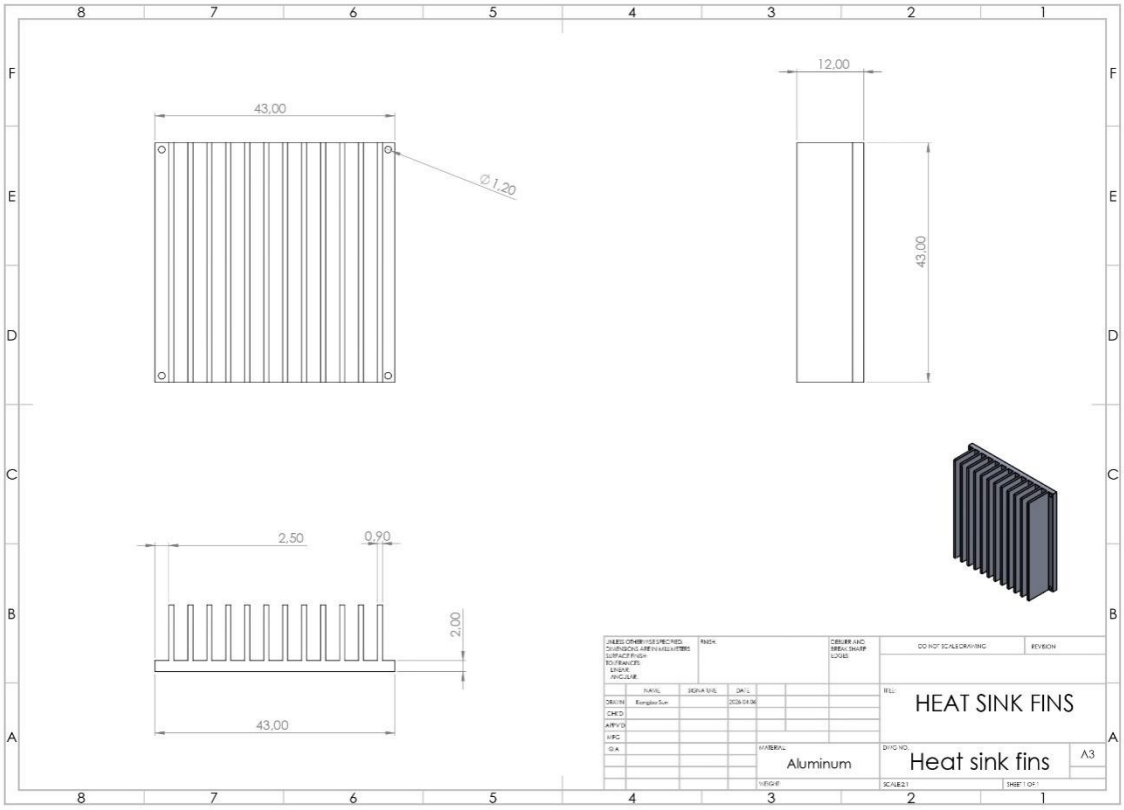
Appendix 1. Engineering drawings of thermoelectric cooling water cup and its components

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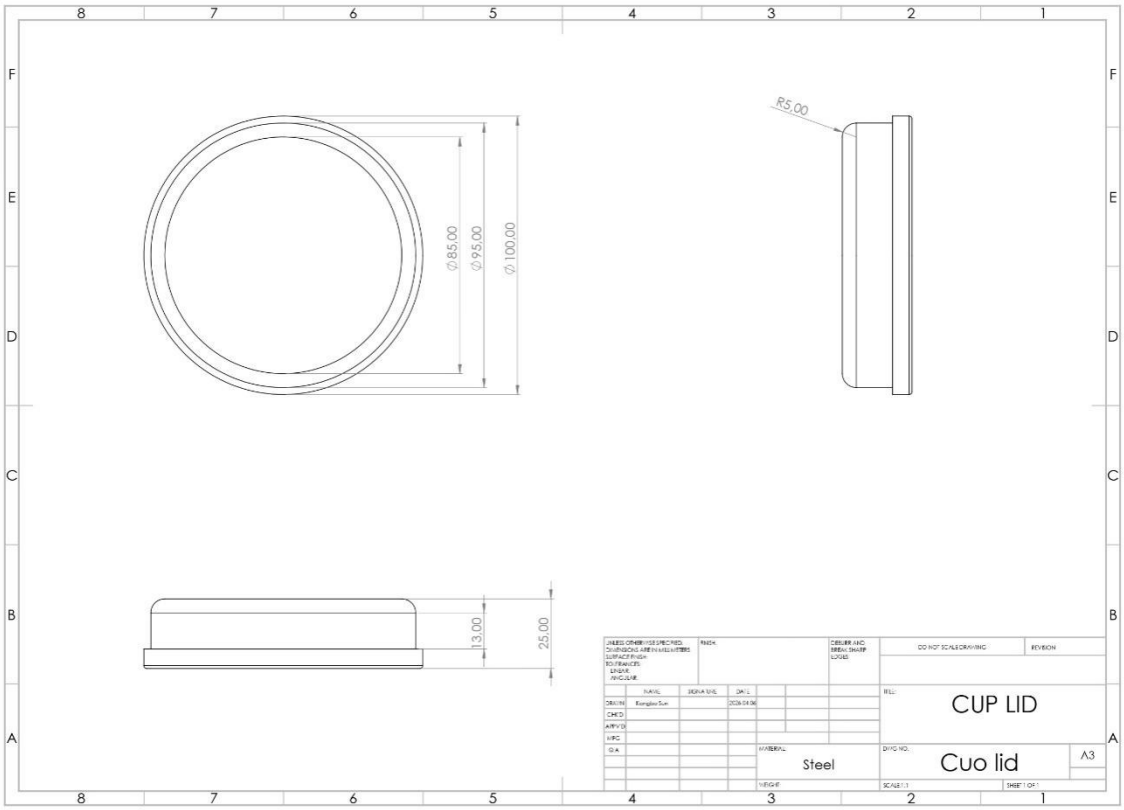
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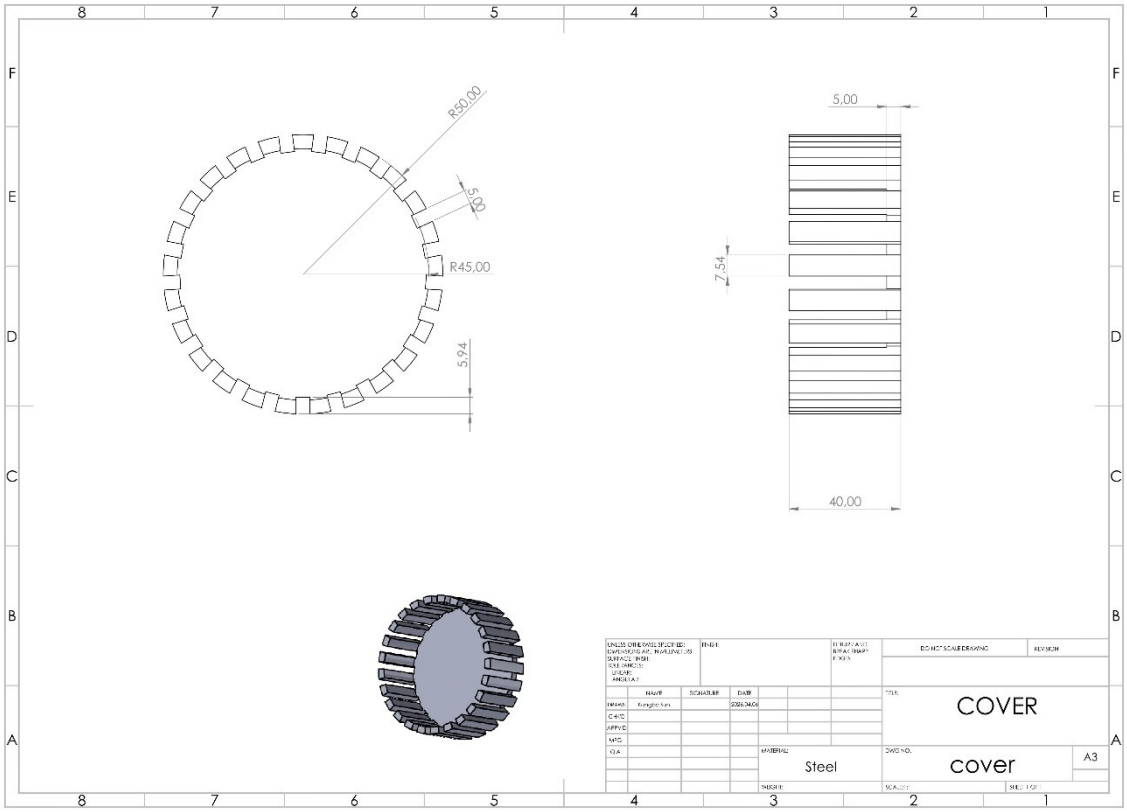
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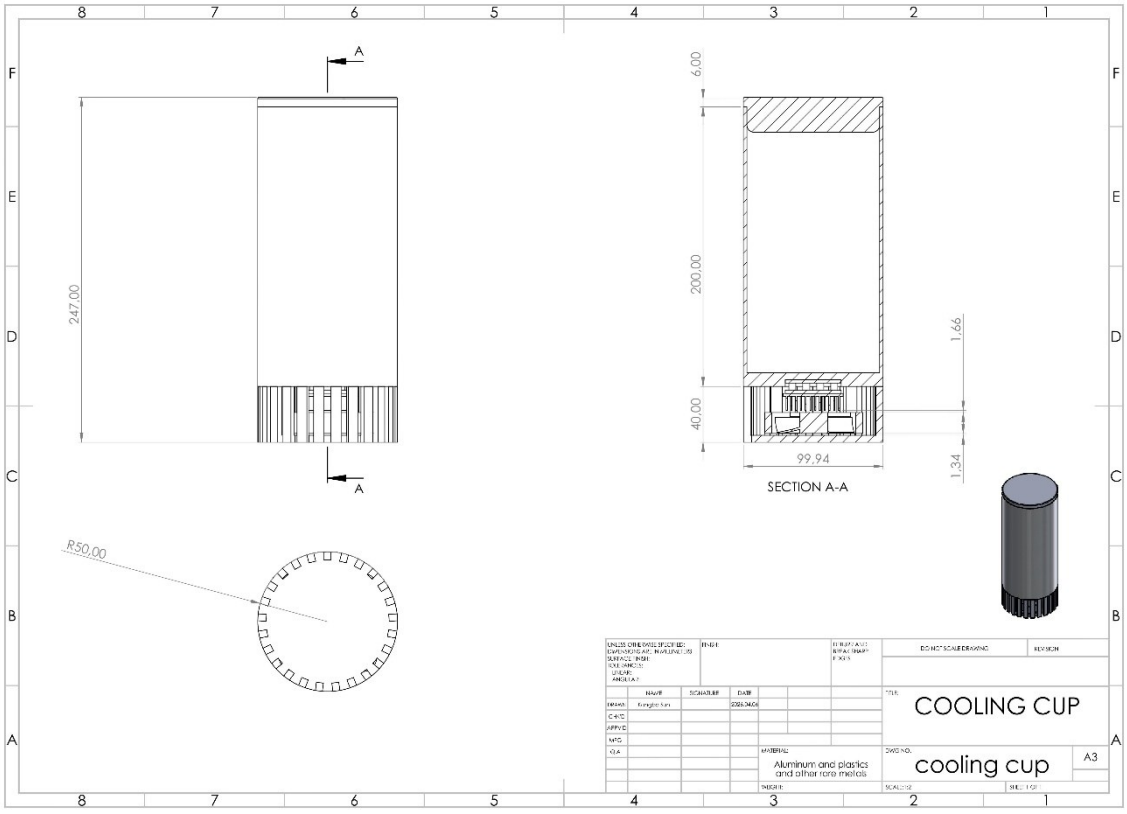
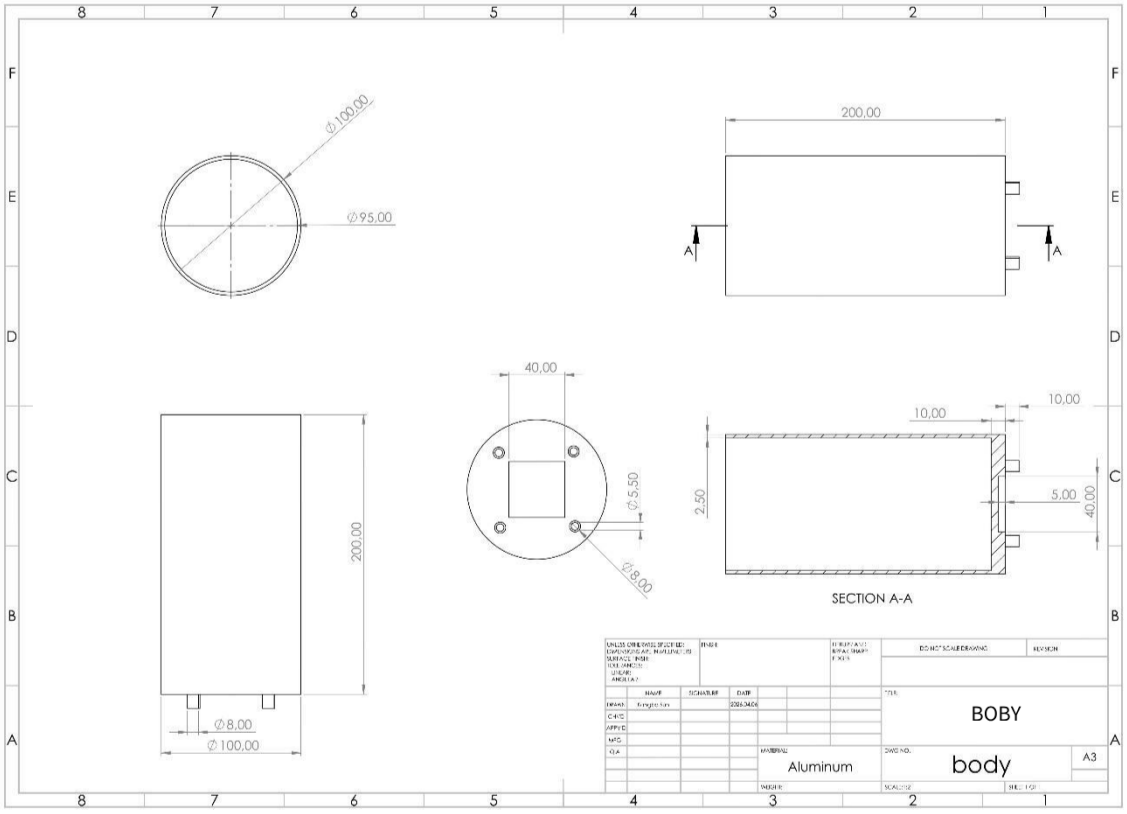
cover
A3


A
247,00
A
6,00
200,00
40,00
99,94
1,66
1,34
SECTION A-A
R50,00
COOLING CUP
Aluminum and plastics and other rare metals
cooling cup
A3


∅100,00
∅95,00
200,00
A
A
40,00
∅5,50
∅8,00
10,00
10,00
2,50
5,00
40,00
200,00
SECTION A-A
∅8,00
∅100,00
BOBY
Aluminum
body
A3