ECE 445

Spring 2024
Senior Design Project Proposal

Multipurpose Temperature Controlled Chamber (for Consumer Applications)

TEAM 42

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1. Introduction

1.1 Problem

Oftentimes, people store food in various locations (in the kitchen, refrigerator, freezer…) with a rough idea of how the temperature of that item will change over time. In some cases, they'll come back later only to find that their food is not properly thawed or frozen. A few examples of this could include:

- Putting a drink in the freezer to make it cool down faster, only to forget about it and later find it exploded and frozen.
- Planning to cook a steak, but forgetting to move it from the freezer to the refrigerator the previous day.
- Setting food out overnight in order to prepare it for the next day only to find that it didn't thaw as expected.

After observing these problems and many others similar to them, we believe that there needs to be an intelligent device that could quickly cool or warm food without freezing or cooking it.

1.2 Solution

Our solution to this is a programmable temperature controlled chamber which allows a user to set the temperature curve of a food item they are planning on consuming in the near future. This device would be able to quickly heat or cool food to a desired temperature, then hold it at that temperature until the user is ready to use the food. Someone would use this device by placing their food item in the device's insulative chamber and closing the door. Next, the user interface would present a variety of options: standard heating or cooling presets for common food items, temperature set and hold, or the ability to set a detailed temperature curve. The user may leave and return at the desired time at which they set it to be ready. Temperature controlled chambers on the market are exorbitantly expensive and large for a household kitchen, and this design is better suited for consumer application.

1.3 Visual Aid

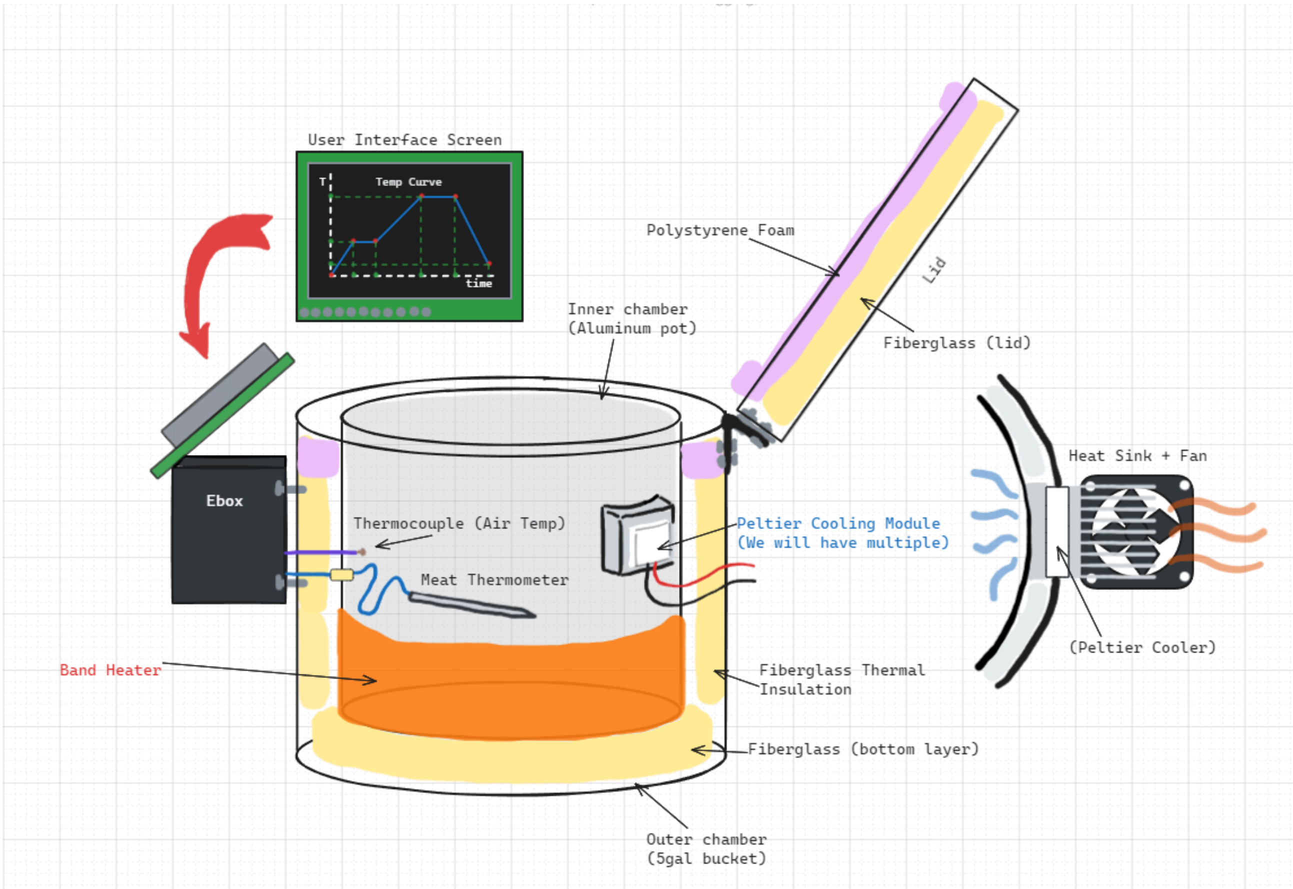


Figure 1: Temperature Controlled Chamber Design

1.4 High Level Requirements

1. The user will have the ability to set a target final temperature, heating/cooling curve and max/min temperature allowances through GUI on an LCD display.
2. The device will have a temperature floor of at most 0 degrees Celsius, and a temperature ceiling of at least 40 degrees Celsius. The temperature floor requirement includes the ability to freeze pure water.
3. The device will be able to hold temperature to within ±5 degrees Celsius of target temperature at any given time.

*This device will be powered by 120VAC while in use, so it should be able to maintain these temperatures listed above indefinitely i.e. this device should work for consecutive days, let alone multiple hours while in use.

2. Design

2.1 Block Diagram

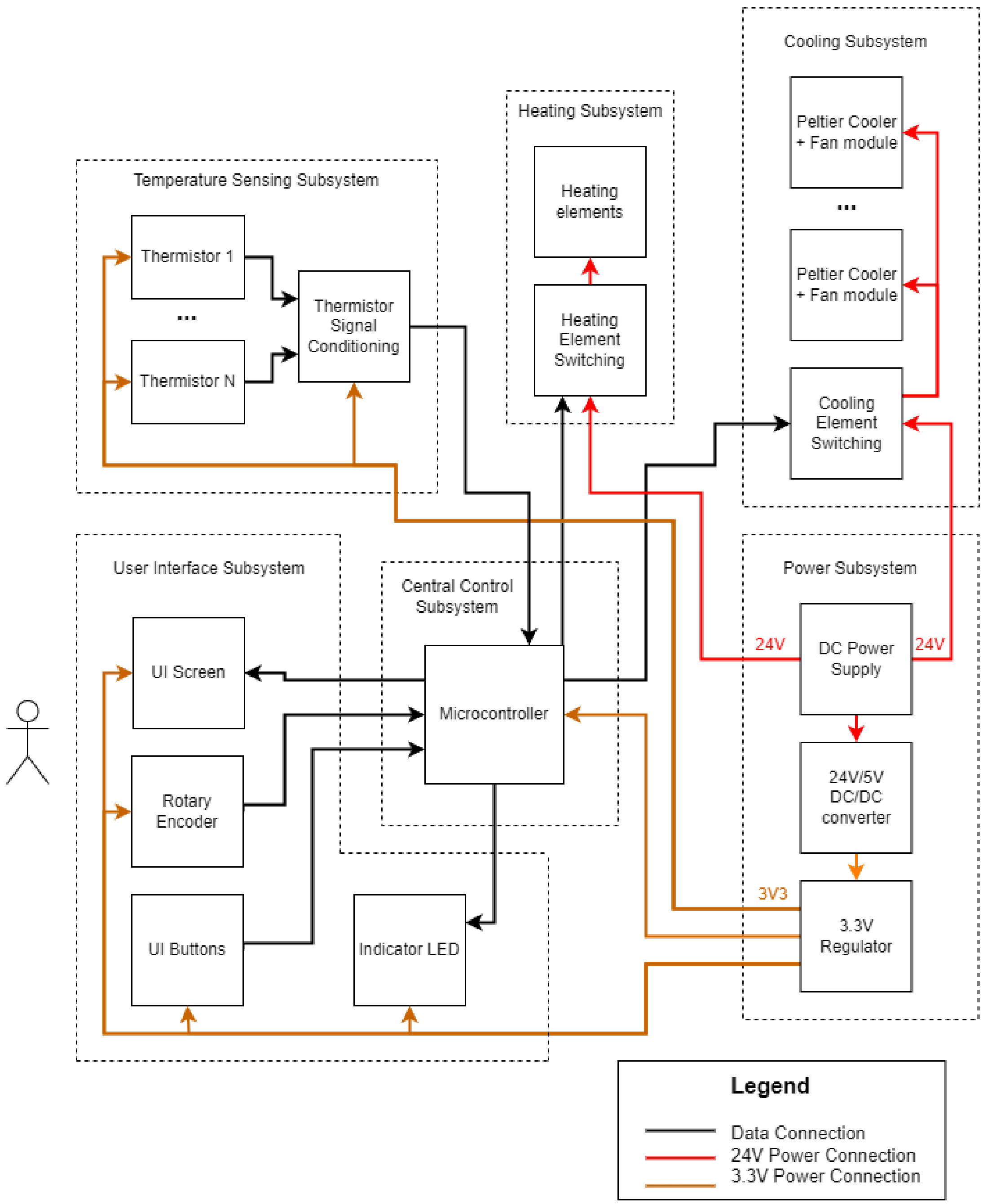


Figure 2: Block Design Diagram

2.2 Subsystem Overview and Requirements

2.2.1 Power Supply Subsystem

Description and Purpose: The power supply subsystem has the express purpose of providing the correct voltage and current to power all of the other systems in our project. It consists of various converters, starting off with an off-the-shelf 300W power supply, we will provide 24V to the rest of the systems on the device. We then feed 24V into our Peltiers and to a 24-5V Buck Converter which will then provide at least 10W to our logical level systems. Then, in order to cut down on switching noise, we use a LDO to power all of our 3.3V systems. Based on the LCD power requirements and voltage rating, we may need to increase our LDO power requirement.

Requirements: The power requirements for each module of this subsystem are listed below. These power ratings should be more than enough to power all of our systems in the project. As far as size constraints, we don't really have major limits on size and all these components should be more than enough for our requirements. Price is the biggest optimization in this list, as we use already available parts or inexpensive controllers.

Parts:

- **Off the shelf 24V Power supply**
  - **Minimum 100W requirement**
    - **EMH350PS24 Power Supply**
- **24-5V Buck**
  - **Minimum 10W**
    - **RT6285 Buck Controller**
- **5V-3.3V LDO**
  - **Minimum 1W**
    - **AP2111H LDO**

2.2.2 Central Control Subsystem

Description and Purpose: This subsystem is meant to control the whole device. At its center is a STM32 microcontroller which should have enough IO in order to read our temperature sensors, control our LCD, and run the control of our heating/cooling systems. The microcontroller will be programmed in C and the clocking is more than enough to perform all necessary functions.

Requirements: The main requirement is to have the required IO we need. So the microcontroller will need to have the correct 5 wire SPI interface required for our display, the required I2c ports for our possible temperature sensor alternatives, the 2-3 analog inputs for our thermistors, and 5-6 GPIO in order to account for the binary control of our heater relay, cooler H-Bridge, and all necessary fans. The microcontroller would also need a RTC subsystem in order to account for the long time heating/cooling curve capability.

Parts:

- **STM32F103c8 here**
- **Clocks (to run RTC) and decoupling capacitors**

2.2.3 Sensor Array

Description and Purpose: The purpose of the sensor array is to detect the correct temperatures and monitor the food/drink inside of the cooler body. We will achieve this using a number of various sensors, having a parallel layout to ensure that if one does not work during development, we can use the other. Our first sensor alternative is the TMP1075, which is an integrated temperature sensor from TI. We would probably make a daughter board with an RJ-12 connector for the I2C communication and mount this daughter board wherever we want to measure the temperature. The other alternative is using the MF52D NTC Thermistor, whose analog signal we have to process using an Opamp and then feed into an analog pin on the microcontroller.

Requirements: These sensors should fall within our planned temperature range (-5°C-45°C) and operate at the logic level voltage of our microcontroller (3.3V). Both of these parts selected fall within these requirements.

Parts:

- **I2C Temp sensor sub board with RJ-12 Connector**
    - **TMP1075**
    - **RJ-12 connector here**
- **External Thermistor with Op Amp Conditioning Circuit**
    - **NTC Thermistor here**
        - **Use this TI Circuit as an example**
        - **Into Analog input of microcontroller**
        - **TLV9002 Opamp**

2.2.4 Cooling Subsystem

Description and Purpose: Thermoelectric (Peltier) coolers will provide the cooling. These work as heat pumps, so we'll need heat sinks and cooling fans to dissipate the heat they produce. The thermoelectric coolers and fans will be run off of the same higher voltage DC that powers the heating element.
We want to have the option to run the thermoelectric coolers in reverse while the chamber is heating to prevent their heat sinks from cooling down the chamber. To do this we'll need to power the thermoelectric coolers through an H-bridge so that we can reverse their polarities. The H-bridge can be composed of two N-channel MOSFETs and two P-channel MOSFETs, and can be controlled by the microcontroller, allowing us to use PWM to vary the power supplied to the thermoelectric coolers.

Requirements: The cooling subsystem should be able to reach a temperature of 0°C. This means that all of our Peltier modules should be able to withstand this temperature. Our MOSFETs should be able to handle a drain to source voltage rating of 24V and should have a constant current rating of at least 10A to handle peak currents and the possibility of adding more coolers. The active cooling fans should be able to be powered by our 24v system and the heatsinks have to be the correct size to fit our Peltier module.

Parts:

- **Peltier Modules**
- **H-Bridge**

- **MOSFET and MOSFET Driver**

○ **Active Cooling – Fans**

○ **Passive Cooling – Heatsinks**

2.2.5 Heating Subsystem

Description and Purpose: The purpose of the heating subsystem is to provide a positive temperature velocity when we want to quickly heat up the environment in the chamber. We would use Nichrome heating wire or a Band Heater wrapped around the bottom of the chamber to provide the necessary heat. This is a fairly simple system and it will be controlled through a relay capable of handling AC power.

Requirements: The Nichrome Wire or Band Heater should have the capability to reach at least 40°C and hold that temperature. It should also be large enough to wrap around our 10 inch inner pot. The control systems should be able to be controlled through a single GPIO and handle the necessary voltage/current of our heating/cooling coil.

Parts:

○ **Nichrome Heating Wire or Band Heater**
  - **24V or 120VAC across the wire.**

○ **High Power Relay and Driver**

2.2.6 User Interface Subsystem

Description and Purpose: The purpose of the UI System is for the user to interact with our device. It should allow the user to use buttons and encoders and a full color LCD touchscreen in order to set heating curves, time of the device, and certain pre-set programs such as thawing of steak or cooling of a drink.

Requirements: The technical requirements for this section are not as important as the UI/UX considerations. We would like to give the user a fine grain adjustment option, in this case the encoder, and a select/cancel option, in the form of the buttons. We also want an alternative input method in case our button/encoder scheme is lacking, in which case the LCD module should have a touch screen. The LCD module itself should be able to be powered off of 3.3V or 5v and communicate with 3.3V logic level GPIO over SPI so that our microcontroller can properly interface with it. It would also be preferable to have a way to offset graphics processing on the LCD in order to prevent having too much MCU compute power dedicated to screen processing.

Parts:

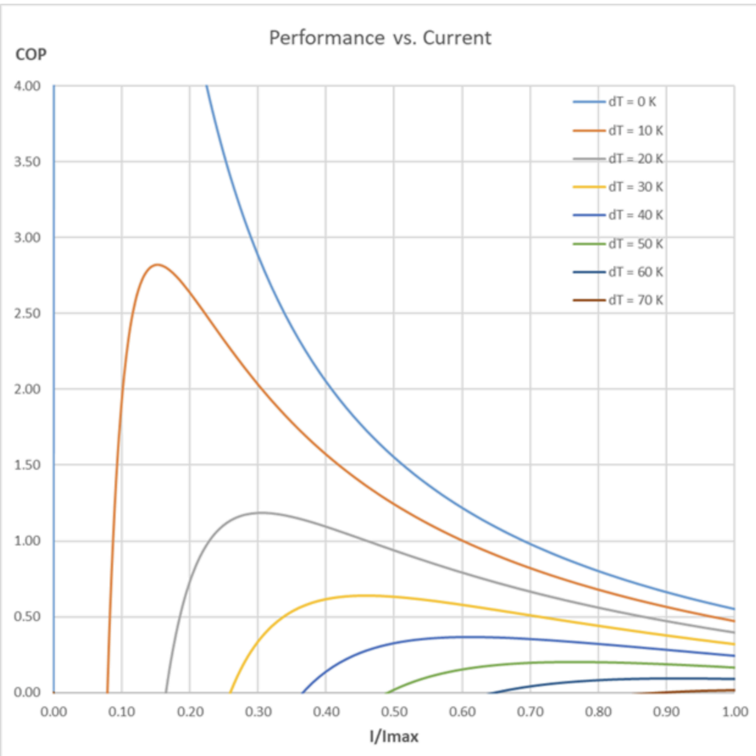
○ **Color LCD Module**
  - **SPI communication**
  - **Minimum 3” Full Color**
  - **Touchscreen capability for alternate input**
    - ○ **4” ST7796S Hosyond Display here**

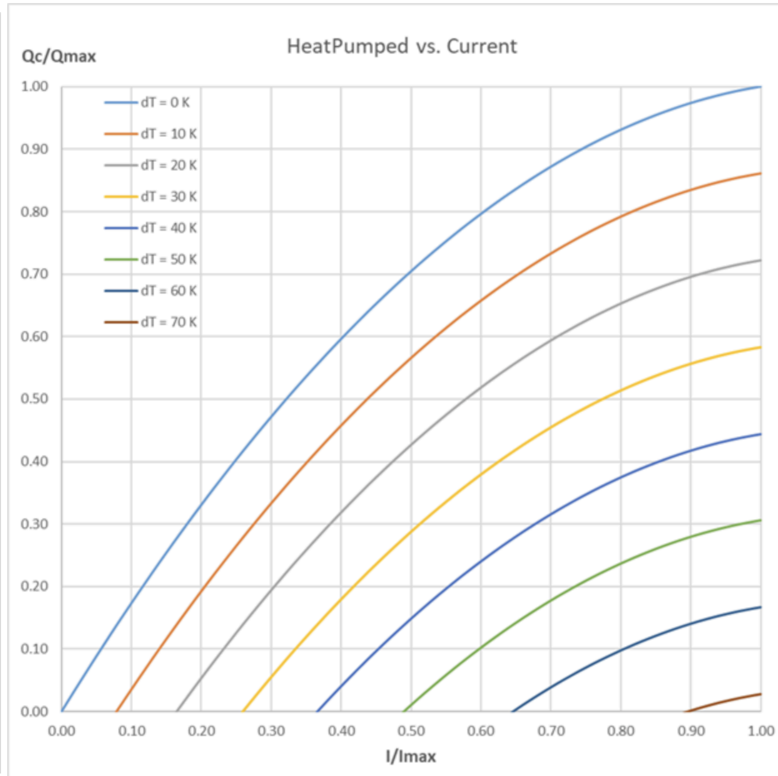
○ **Buttons**

○ **Encoder**
  - **Rotary Encoder for User input**
    - ○ **PEC12R with Switch**

2.3 Tolerance Analysis

2.3.1 Coefficient of Performance





Figures 3 and 4: COP efficiency and Heating Power vs Current trends

The Coefficient of Performance is the efficiency at which heat is removed from the inside chamber with respect to the power drawn from the Peltier cooler, and is strongly related to the current drawn by the cooler and the temperature difference dT between the hot and cold sides. The highest COP is the optimal point to run the cooler. However, the COP changes as the temperature of the chamber, and thus, temperature difference changes. Based on the characteristics, such as the maximum current and heating power, provided from the TEC1-12706 datasheet, we can estimate crucial properties of the chamber.

2.3.2 Analysis

The variable we'll be running an error analysis on will be $T_{c,min}$, the minimum temperature achievable by our chamber.

We obtained specifications for the TEC1-12706 thermoelectric (Peltier) cooler module from the Conrad Electronics datasheet [5], and data about the thermal conductivity of fiberglass insulation from The Engineering ToolBox's website [6].

Assumptions

For this error analysis, we'll be making the following assumptions:

1. Peltier cooler hot side temperature $T_h = 30°C$. This is 10°C above standard room temperature. (20°C)
2. We will use four TEC1-12706 thermoelectric cooling modules.
3. We will operate each Thermoelectric cooling module at a current of 3 [A]. From the Meerstetter Engineering articles [4], this seems to be the optimal current to balance temperature gradient with coefficient of performance.

Calculations

First, we need to calculate the thermal energy flow needed to cool our chamber to some temperature T_c. To do this, we'll need the surface area of our chamber, the thermal conductivity of our insulation, and its thickness.

$$(1) \qquad Q_c(chamber) = \frac{k_{ins} SA}{t_{ins}} \Delta T \quad [W]$$

Where:

- $Q_c(chamber)$ is the energy flow from our cold chamber to the environment
- k_{ins} is the thermal conductivity of our insulation, with units $[\frac{W}{mK}]$
- SA is the surface are of our cold chamber, with units $[m^2]$
- t_{ins} is the thickness of our insulation, with units $[m]$
- ΔT is the temperature difference between the inside of the chamber and the external air, in units $[°K]$

Since our inner chamber will be a cylinder with a 10" diameter and a height of 12", and our outer chamber will be 1 inch larger on all sides, we can approximate the surface are of our chamber as:

$$\phi \approx 11" = 0.28 \ [m]$$

$$h \approx 13" = 0.33 \ [m]$$

$$h \approx 13" = 0.33\ [m]$$

$$SA \approx 2\pi(\frac{\phi}{2})^2 + \pi\phi h = 0.413\ [m^2]$$

We also know that t_{ins} will be 1" = .0254 $[m]$.

$$t_{ins} = 0.0254\ [m]$$

From The Engineering ToolBox [6], the thermal conductivity k_{ins} for fiberglass insulation has a roughly linear relationship with temperature between 250°K and 400°K which can be approximated as:

$$k_{ins} \approx \frac{1}{7500} T_{ins}(^\circ K) \quad [\frac{W}{mK}]$$

Where $T_{ins}(^\circ K)$ is the temperature of the insulation in Kelvin. Since our equation for $Q_c(chamber)$ is in terms of ΔT, we'll rewrite k_{ins} in terms of ΔT:

$$T_{ins} \approx T_{external} - \frac{1}{2}\Delta T$$

(Assume $T_{external}$ is $300^\circ K$)

$$k_{ins} \approx \frac{300 - 0.5\Delta T}{7500} \quad [\frac{W}{mK}]$$

Inserting these values into equation (1), we can obtain an expression for $Q_c(chamber)$ in terms of ΔT:

$$(2) \qquad Q_c(chamber) = \frac{16.26(300 - 0.5\Delta T)}{7500}\Delta T \quad [W]$$

Next, using the Conrad Electronics datasheet for the TEC1-12706 module [5], we fitted a line to the $Q_c/\Delta T$ curve corresponding to 3 [A]. The tolerance given by the datasheet for thermal parameters was ±10%, so we applied this tolerance to the vertical axis intersect:

$$(3) \qquad Q_c(Peltier) \approx 40 \pm 10\% - \left(\frac{8}{11}\right)\Delta T \quad [W]$$

By setting $Q_c(chamber)$ equal to $Q_c(Peltier)$, we can find the point at which our Peltier coolers aren't able to cool the chamber any further. (ΔT_{max}) Since we have four Peltier coolers, we'll multiply equation (3) by four:

$$Q_c(chamber) = 4Q_c(Peltier)$$

$$\frac{16.26(300 - 0.5\Delta T_{max})}{7500}\Delta T_{max} = 4\left(40 \pm 10\% - \left(\frac{8}{11}\right)\Delta T_{max}\right)$$

The result is a quadratic equation that can be solved using the quadratic formula:

$$\Delta T_{max} = \frac{3.559 - \sqrt{3.559^2 - 4(.00108)(160 \pm 16)}}{2(.00108)}$$

The two resulting values for ΔT are:

$$\Delta T_{max} = \{40.966, 50.213\} \quad [^\circ K]$$

We can obtain $T_{c,min}$ by subtracting these values from the hot side temperature T_h:

$$T_{c,min} = T_h - \Delta T_{max}$$
$$T_{c,min} = 30^\circ C - \Delta T_{max}$$
$$T_{c,min} = \{-10.966, -20.213\} \quad [^\circ C]$$

Putting this result in terms of a tolerance:

$$T_{c,min} = -15.590 \pm 4.623 \quad [^\circ C]$$

3. Ethics and Safety

3.1 Safety

When the device is under construction, proper safety procedures are extremely crucial. We will make sure to use necessary PPE when working with tools and components. We will also ensure a clutter-free workspace, check our tools regularly, and clean up the workspace afterwards. Also, high voltage tests will be performed in a controlled environment. Power tools will be turned on only when testing device characteristics and will be powered off directly after use to prevent accidental injury or damage.

Fire Safety

The drastic temperature changes this device exhibits requires heating elements located toward the bottom of the container. Without proper precaution, this could pose fire hazards, or at the very least, extreme heats unsafe for human touch. Layers of fiberglass will be used around and underneath the container, as well as between the container and the lid. This will act as heat insulation.

Electrical Safety

Heating wires at high voltages pose significant safety risks, especially if short circuits or other failures occur. The original plan was to use resistive coils to act as the active heating, but after further consideration, we decided to substitute this heating method with a band heater. The band heater wraps around the food/drink to be heated, reducing the electrical safety hazard concern for this subsystem.Also, we will incorporate as many enclosures to isolate subsystems when possible. The electric box will be located outside the outer chamber, ensuring it will not be affected and cause any electric hazards by the extreme temperature changes inside.

3.2 Ethics

As stated in the IEEE Code of Ethics Section I, it is our obligation to “disclose promptly factors that might endanger the public or the environment.” The highest safety priority is that the user may operate the device with absolutely no risk, with the two most critical factors described above.

We will willingly address any ideas to improve safety. Regarding Section II and III of the Code, every team member's contribution is valued, encouraging a collaborative environment. We will “treat all persons fairly and with respect, and to not engage in discrimination based on characteristics,” and will have zero tolerance for this behavior. We will maintain these standards throughout the semester, ensuring a supportive and ethical working environment.

4. References

[1] Conrad Electronic SE. “Specification of Thermoelectric Module.” (), [Online]. Available: https://asset.re-in.de/add/160267/c1/-/en/000189115DS02/DA_TRU-Components-TEC1-12706-Peltier-Element-15V-6.4A-65W-L-x-B-x-H-40-x-40-x-3.8mm.pdf (visited on 02/08/2024).

[2] IEEE. ”IEEE Code of Ethics.” (2024), [Online]. Available: https://www.ieee.org/about/corporate/governance/p7-8.html (visited on 02/08/2024).

[3] Meerstetter Engineering. “Peltier Elements.” (2024), [Online]. Available: https://www.meerstetter.ch/customer-center/compendium/70-peltier-elements#D_Heatpumped%20vs%20Current (visited on 02/08/2024).

[4] Meerstetter Engineering. “Peltier Element Efficiency.” (2024), [Online]. Available: https://www.meerstetter.ch/customer-center/compendium/71-peltier-element-efficiency (visited on 02/08/2024).

[5] Conrad Electronics SE. “Specification of Thermoelectric Module TEC1-12706” [Online] Available: https://asset.re-in.de/add/160267/c1/-/en/000189115DS02/DA_TRU-Components-TEC1-12706-Peltier-Element-15V-6.4A-65W-L-x-B-x-H-40-x-40-x-3.8mm.pdf (visited on 02/08/2024).

[6] The Engineering ToolBox “Thermal conductivity of fiberglass insulation - temperature and k-values.” [Online] Available: https://www.engineeringtoolbox.com/fiberglas-insulation-k-values-d_1172.html (visited on 02/08/2024).