



Master Thesis

Temperature chamber with Peltier cell

Study programme: N0714A150003 Mechatronics
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Master Thesis Assignment Form

Temperature chamber with Peltier cell

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Rules for Elaboration:

1. Specify the prospective application fields of the temperature-controlled chamber. Design chamber dimensions and limit temperatures and composition of materials. Create an analytical heat balance calculation. Optimize the design to achieve the required parameters.
2. Build a first-principles simulation model of the chamber, including the effect of ambient temperature changes. Use this model to select a suitable Peltier cell and verify that the required minimum and maximum temperatures inside the chamber are achievable under the full range of expected ambient temperatures. Determine the chamber time constants for heating and cooling. Try to estimate the time constants of the temperature sensor and Peltier cell.
3. Build a prototype chamber. Using the built chamber prototype, check that both the steady-state and dynamic behavior of the chamber matches the behavior of the simulation model created in the previous part of this assignment. Explain any differences and analyze their effect (if any) on the chamber's expected uses and controllability.
4. Program a mobile control application as a human interface for the temperature chamber.

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- [1] RIMBALA, Jan a Jan KYNCL, 2022. Possibilities of Improving COP of Peltier Cells Operating as a Heat Pump. In: 2022 22nd International Scientific Conference on Electric Power Engineering (EPE): 2022 22nd International Scientific Conference on Electric
[2] LYSKAWINSKI, Wieslaw a Wojciech SZELAG, 2018. Analysis of cooling and heating system with Peltier cell. ITM Web of Conferences [online]. 19, 01032. ISSN 2271-2097. Available from: doi:10.1051/itmconf/20181901032

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ABSTRACT

The thesis explores the Design, analysis, and applications of portable cold storage systems utilizing Peltier devices. The objective is to develop efficient and reliable cooling solutions that provide precise temperature control for perishable goods, pharmaceuticals, and other temperature-sensitive products. The design methodology for portable cold storage systems is presented, considering factors such as cooling capacity, thermal management, insulation, power requirements, and size constraints. The selection of appropriate heat sinks, fans, and insulation materials is discussed, along with integrating Peltier devices into the overall system. Experimental testing is conducted to validate the performance of the designed portable cold storage system.

Building a Prototype will also be the goal to be achieved such that the simulation results can be compared and reviewed. The findings of this thesis aim to facilitate the development of more efficient and sustainable cooling solutions for a wide range of applications.

Keywords: Peltier, Cold Storage.

ABSTRAKT

Tato práce se zabývá návrhem, analýzou a aplikacemi přenosných chladících systémů využívajících Peltierova zařízení. Cílem je vyvinout účinná a spolehlivá řešení chlazení, která poskytují přesnou kontrolu teploty zboží náchylného k poškození, léčiv a dalších teplotně citlivých produktů. Práce představuje metodiku návrhu přenosných chladících systémů s ohledem na faktory jako je chladicí kapacita, tepelný management, izolace, požadavky na napájení a omezení velikosti. Dále se diskutuje o výběru vhodných chladičů, ventilátorů a izolačních materiálů spolu s integrací Peltierova zařízení do celkového systému. Experimentální testování je provedeno k ověření výkonu navrženého přenosného chladícího systému.

Cílem práce je také vytvoření prototypu, který umožní porovnávání a revizi výsledků simulace. Tato práce si klade za cíl usnadnit vývoj účinnějších a udržitelnějších řešení chlazení pro širokou škálu aplikací.

Klíčová slova: Peltier, přenosný chladicí systém

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LIST OF ABBREVIATIONS

Abbreviation	Parameter
<i>TEC</i>	Thermoelectric coolers
<i>EMF</i>	Electromotive Force
<i>WHO</i>	World Health Organization
<i>COP</i>	Coefficient of Performance
<i>EPS</i>	Expanded Polystyrene Insulation
<i>XPS</i>	Extruded Polystyrene insulation
<i>3D</i>	3 Dimensions
Q_c	Thermal load generated at the cold side of the Peltier (W)
ΔT	Difference Temperature (°C)
<i>PLA</i>	Polylactic Acid
<i>l</i>	Length (mm)
<i>b</i>	Breadth (mm)
<i>h</i>	Height (mm)
°C	Degree Celsius
<i>U</i>	Value of Insulation
<i>A</i>	Surface Area (m ² / cm ²)
T_A	Ambient Temperature (°C)
T_I	Internal Chamber Temperature (°C)
Q_{trans}	Transmission Loads (W)
Q_{vacc}	Product load (Vaccines) (W)
C_p	Specific Heat Capacity (KJ/kg. °C)
<i>m</i>	Mass (kg)

Q_{Equip}	Equipment Load (W)
Q_c	Total Cooling load – Required (W)
Bi^2Te^3	Bismuth Telluride
I_{max}	Maximum Input Current (A)
V_{max}	Maximum Voltage (V)
Q_{max}	Maximum Power (W)
ΔT_{max}	Maximum Temperature difference at 300K (°C)
T_h	The temperature at the Hot end (°C)
T_c	The temperature at the cold end(°C)
k	Thermal conductivity of Bi^2Te^3 (W/m.K)
N	Number of couples
ρ	electrical resistivity of Bi^2Te^3 ($\Omega.m$)
R	The electrical resistance of the Module ($\Omega.m$)
S_{AB}	Seebeck coefficient of Bi^2Te^3 (V/K)
$R_{peltier_hot}$	Thermal resistance on the Hot side of the Peltier for Operating conditions (°C/W)
$R_{peltier_cold}$	Thermal resistance on the Cold side of the Peltier for Operating conditions (°C/W)
R_{tp}	The thermal resistance of the thermal paste (°C/W)
R_{cu}	The thermal resistance of the Copper flat plate (°C/W)
R_{hot_hs}	The thermal Resistance of the Heatsink placed at the Hot side of the Peltier (°C/W)
R_{cold_hs}	Thermal Resistance of the Heatsink placed at the cold side of the Peltier (°C/W)
R_{hot}	The resistance between the Junction to Ambient (°C/W)
$Area_{hs_hot}$	Area of the heatsink placed on the hot side (cm ²)

$Area_{hs_cold}$	Area of the heatsink placed on the cold side (cm ²)
h_{-}	Heat transfer coefficient (W/ (m ² C))
Nu	Nusselt Number
Re	Reynolds Number
Pr	Prandtl Number
R_v	Volumetric Thermal Resistance
CFM	Cubic Feet per Meter
LFM	Linear Feet per Meter
TIM	Thermal Interface Material
$T_{chamber}$	Temperature inside the chamber

1. INTRODUCTION

According to the direction of the current flow, Jean Peltier observed in 1834 that when a current connects two different conductors, the junction of those materials would either absorb or release heat. Thomas Seebeck found current would flow when a temperature gradient was introduced across the junction of two different metals thirteen years ago. The foundation of thermoelectrics was these two findings (“How Peltier Cooling Works,” n.d.). Peltier-based cooling systems offer an alternative solution for vaccine storage that is both energy-efficient and cost-effective. These systems use solid-state thermoelectric cooling technology based on the Peltier effect to maintain precise temperature control.

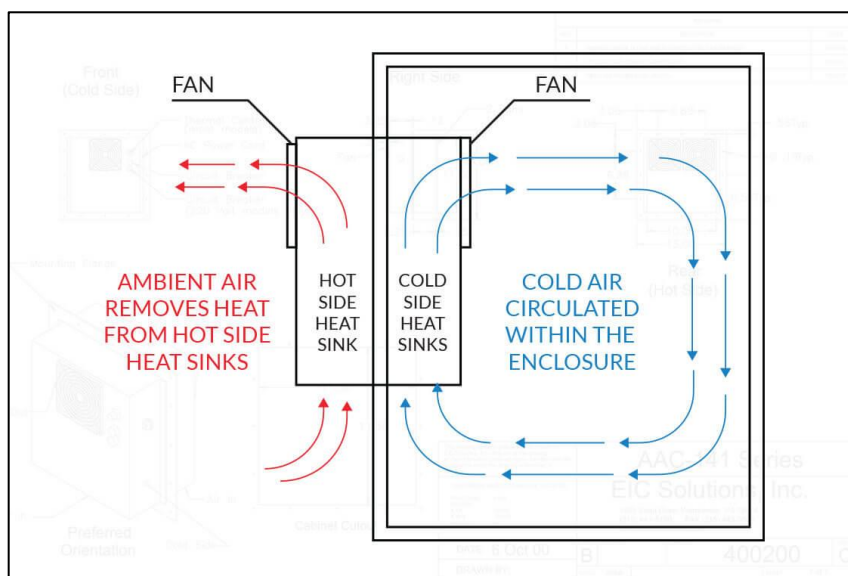


Image 1. Working Thermoelectric assembly (Courtesy: (“How Peltier Cooling Works,” n.d.))

Peltier-based systems have several advantages over traditional compressor-based systems, including lower energy consumption, reduced maintenance requirements, and the ability to maintain temperature stability during power outages. These systems have the potential to improve the Reliability and accessibility of cold Storage, which could have a significant impact on various application outcomes. This paper will explore using Peltier-based cooling systems for our thermal chamber, including their Design, performance, and potential applications. We will examine the current state of research in this area and discuss the implications for future developments in vaccine storage technology.

To construct the thermal Casing, it is necessary to concentrate on the Design of the case, which should be able to trap the thermal condition within the defined storage space; the defined temperatures are achieved by using Peltier modules as the stream cooling module, which will need to be regulated with an Arduino Uno microcontroller. The ultimate goal of our Project, which will be realized after project completion, is to make it portable. This will be the focus of our Final Thesis, but for now, a small prototype will be presented.

Peltiers, also known as TEC - Thermoelectric Coolers, have various advantages as the Cooling element provides high Reliability, no mechanical moving parts, compact size and lightweight, and no working fluid. Though the TEC effect was discovered at the start of the 19th Century, it was not rapidly developed until the mid of 19th Century. Even now, Peltiers are not a widely chosen option for cooling applications as it also has a few disadvantages like higher costs, lower energy efficiency, and hard to control, which are why peltiers have their applications restricted (Crotti, 2019).

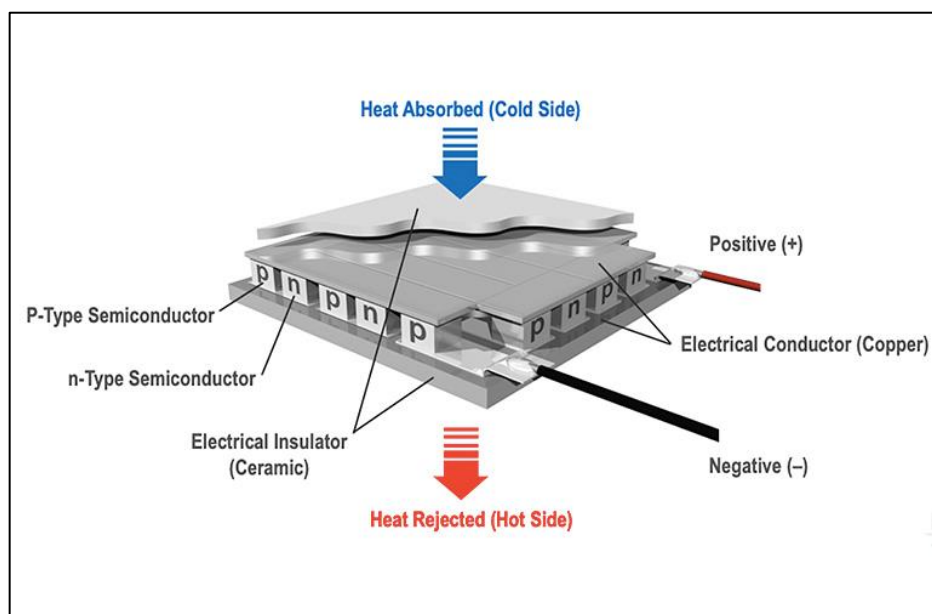


Image 2. Model of a Peltier (Courtesy: (Crotti, 2019)).

A thermoelectric phenomenon known as the Peltier effect happens when two conductors, usually semiconductors, come together. Heat is transferred from one side to the other due to the movement of electrons across the junction, which produces the effect. When an electrical current passes through a junction, heat is either absorbed or released from the junction due to the Peltier effect.

The Seebeck effect, which creates an electromotive force (EMF) at a temperature gradient between two distinct conductors, is the foundation of the Peltier effect. The diffusion of charge carriers as electrons from the hot to the cold side of the junction results in a potential difference between the two conductors, which causes the Seebeck effect. When the current flow is reversed, the Peltier effect happens, causing heat to either be absorbed or released at the junction. A P-N junction is created by sandwiching two semiconductors, commonly p- and n-type materials, to create a Peltier device (Ong et al., 2018; Zhao and Tan, 2014). An electrical current runs through the device when a voltage is placed across the junction, making one side hot and the other cold. By switching the polarity of the applied voltage, the hot and cold sides of the device will swap, reversing the direction of the current flow (“TEM construction,” n.d.).

The materials employed, the device’s size, and the temperature differential across the device are all variables that affect a Peltier device’s efficiency. A drawback of Peltier devices is that they lose efficiency at high temperatures, restricting the situations in which they may go unused. However, future advancements in thermoelectric materials and device design are anticipated to solve these constraints and broaden the uses of Peltier-based cooling systems. Current storage equipment for COVID-19 vaccines includes standard refrigerators, freezers, and ultra-cold freezers (WHO, 2021). However, these traditional storage methods have temperature control and energy efficiency limitations.



Image 3. Portable Vaccine storage systems (Courtesy: (“Portable Vaccine Cold Storage Solutions | Accucold®,” n.d.))

The proposed Peltier-based cold storage unit has the potential to be more efficient than current storage equipment for several reasons. Peltier devices are solid-state thermoelectric coolers that are energy efficient and can provide precise temperature control. They operate using a Peltier effect, which creates a temperature difference by applying an electrical current to two dissimilar conductors. Peltier-based cold storage units can also be designed to be portable and easily transportable, which could be beneficial.

1.1. MOTIVATION & SCOPE

The main goal of structuring the Model of the Thermal chamber is that it could serve a wide range of applications, including emergency relief situations of the need to transport any medical compound using our thermal Casing though this is considered one of the key points extending the Design. Our ideology for the cold Storage is to handle a set temperature within the chamber between $-5\text{ }^{\circ}\text{C}$ to $45\text{ }^{\circ}\text{C}$. Ideally, This could set intrusive parameters in storing various things, providing a wider application. A few notable applications,

- **Transport and Storage of Pharmaceuticals:** Peltier-equipped portable cold storage units can transport and store temperature-sensitive drugs, vaccines, and medical equipment. Peltier technology's precision temperature management ensures that the items stay within the necessary temperature range, preserving their effectiveness and quality.
- **Perishable foods, drinks, and other temperature-sensitive goods** can be transported using portable cold storage units based on Peltier technology. Catering services, outdoor events, food delivery services, and small-scale food enterprises that need temporary or transportable cold storage solutions may find this to be especially helpful.
- **The ability to maintain samples, specimens, and reagents** at certain temperatures makes portable cold storage devices with Peltier cooling useful for field researchers and scientific expeditions. This is crucial for research involving biological samples, environmental monitoring, and remote study locations without access to conventional refrigeration.
- **Agriculture and horticulture:** Harvested crops, seeds, and plant specimens may be preserved using Peltier-based portable cold Storage in the agricultural and horticultural industries. It can assist in preserving the quality, viability, and freshness of agricultural products when they

are transported, going from field to market or in isolated locations without access to traditional refrigeration.

- Mobile Laboratory and Testing Facilities: Mobile labs and testing facilities can use portable cold storage units, including Peltier cooling technology. These units can offer a controlled environment to maintain the stability and integrity of delicate laboratory chemicals, samples, and specimens during field testing, research, or diagnostic procedures.
- Emergency circumstances and disaster relief attempts can benefit greatly from portable cold Storage with Peltier cooling. In places afflicted by natural disasters, wars, or humanitarian crises where infrastructure and power supply may be disrupted, it can store vital medical supplies, vaccinations, and food items.

All the applications reviewed above have various approaches that might need some changes with the Design and operating parameters; thus, the basic goal is set, and the modulation for developing the case for different approaches wouldn't be an issue. The ongoing situation over Covid also stated a possible emerging factor in developing one Cold Storage that could yield a source for transportation within manageable cost. The vaccines should be stored at the proper temperature between 2°C and 8°C. Extreme temperature exposure can weaken the efficacy of vaccines and reduce their effectiveness or render them worthless (Pambudi et al., 2022).

Handling COVID-19 vaccinations can be challenging for some reasons, including cost, mobility, Storage, and transportation (Rinaldi et al., 2023). Directed by WHO, all countries should extend the opportunity to cover the farthest immunity reach, including the rural and remote populations ("Global COVID-19 Vaccination Strategy in a Changing World," n.d.). Getting our view and the idea of using a thermal enclosure with a temperature regulator can provide a practical and effective solution for Storage, as the planned temperature range should define the required thermal changes within the system.

Few perks of using Peltier as a thermal element:

- Peltier devices can maintain a specific temperature range, which is necessary for the thermal chamber. The products may be maintained at a specific temperature range.
- Peltier devices can sustain a constant temperature over time, which is crucial for maintaining a constant temperature within the chamber.

- Peltier-controlled storage devices are lightweight and portable, making them the perfect choice for thermal storage devices.
- Peltier devices are more energy-efficient than traditional refrigeration systems, which can be advantageous in areas with limited power supply. (Ezeani and Chuku, 2015).

2. LITERATURE REVIEW

Starting up with my thesis, the form of familiar cautions was raised. It was very much clear that without clearly defining relevant findings to carry out further. Various literature & References were bounded to help me ensure means of validation; a few of the common constraints mentioned below were the main obstacles moving further with the Design & Simulation.

- How should the Design of the Casing be?
- What components could be used for insulation?
- What will be the internal thermal load, and how to sort out the thermal calculations?
- Choosing the appropriate Peltier
- Design Parameters
- How to dissipate the heat/cold from the Peltier to the surrounding?
- Selecting the right Heatsink
- What should be the Approach for Simulation?

Starting with a review, the primary critics in modeling such a closed enclosure to maintain the internal temperature with Peltier are described below.

Table 1. Literature Review

Author	Year	Criticality	Description
Pambudi et al.,	2022	Parameters to store Vaccines	This paper aims to cold chain management of Covid Vaccines, and the parameters involved in vaccine storage were observed.
WHO articles	2021,2020	Types of vaccines & storage instructions	WHO articles widely discussed the storage regulations for specific vaccines & also briefed on the constraints of the cold chain supply faced by countries in vaccinating the rural population.
Crotti n.d; TEM construction n.d.	2019	The basic working of Peltier Modules	These few blogs very well explain the basic working of Peltier modules.
Al-Madhhachi and Al-Najideen,	2021	Peltier operated Vaccine storage	This article was much related to our thesis model. The paper discusses a refrigeration system operated with Peltier Module powered by solar power.
Evans,	2017	Cooling load Calculation	A brief explanation of how to calculate the Total cooling load for an enclosure was given along with the methodology to calculate the Cooling loads of various models included in the total Cooling load.
Martinez et al.,	2016	Peltier effect-based	The paper discusses the necessary calculations for deriving thermal

		refrigerators	Load conditions within an enclosure & also gives a brief overview of insulation properties for the enclosure.
Slanina et al.;	2018	Peltier Parameters	The main parameters for Cooling load calculations and Peltier's Parameters like COP , Q_c , ΔT , and other calculations for designing and selecting the appropriate Peltier were discussed up to the mark.
Shi et al.	2023		
Zhao and Tan,	2014	Thermoelectric Cooling	An in-depth explanation of thermoelectric cooling & its properties answers the Model to determine the COP of a thermoelectric material.
TEC Modules	--	Peltier Module – Datadsheet	This document gives brief outcomes and basic parameters of the Peltier we chose.
MIT App Inventor	--	Mobile Application	An open-source online VI which help designing mobile applications.
Hasanzadeh et al.	2023	Insulation using polymeric foams	This paper gives a clear understanding of insulation using foams.
Ong et al.	2018	Heatsink & heat transfer	The parameters for the heat transfer over the heat sink could be reviewed.

The references listed above are only a few that have helped me move forward in the means of guidance that has ethically helped me in achieving validation of my results.

3. METHODOLOGY

Before further discussion, the initial flow begins with the initial Design stated for the Closure because the Thermal load could only be defined such that appropriate components could be chosen. It stands for the strong concept for making the Model as all the needed parameters & calculations are defined with the interpreted data & validated. All these help in overcoming the basic constraints that could be faced in designing such a Peltier-based storage, like

- **Temperature range:** temperature-sensitive products require specific temperature ranges for Storage. The Peltier cooling system must be designed to maintain those temperature ranges accurately and consistently to prevent any degradation of the products. Depending on the type of component being stored. Therefore, the Peltier cooling system must be designed with temperature sensors, a feedback control system, and a reliable power supply to maintain the required temperature range.
- **Power consumption:** Peltier cooling systems require electrical power, which could be a significant constraint in resource-limited settings. The system's power consumption should be considered during the design process. The Peltier cooling system should have energy-efficient components and a power management system to optimize the unit's power consumption.

Focusing on power efficiency while designing the Peltier-based cold storage unit is crucial to lessen this restriction. This may be accomplished by enhancing the unit's Design, including the choice of its parts, its configuration, and the insulation it uses. The Peltier device's power consumption may be decreased by minimizing the temperature disparity when feasible by using a microprocessor to monitor and regulate the Temperature within the storage unit. This method also makes the efficient use of electricity possible. Additionally, installing a battery backup system helps guarantee that the cold storage unit keeps running even when the power goes out.

- **Thermal Insulation:** The cooling unit needs adequate insulation to prevent heat loss to the surrounding environment. The insulation should be chosen carefully to balance the thermal performance and cost. The insulation should withstand environmental conditions and protect the stored products from temperature fluctuations. The most commonly used polymeric foams for thermal insulation purposes, such as EPS and XPS, have low thermal conductivities between **30** and **40** mW.m⁻¹.K. (Hasanzadeh et al., 2023)

- **Size and weight:** The cooling unit must be compact and lightweight to facilitate transportation and deployment in areas with limited storage space. The Peltier cooling system should be designed to be portable, easy to move, and have a compact form factor. The cooling unit should also be designed to withstand rough handling during transportation.
- **Cost:** The cost of the cooling unit is an important factor to consider; it should be designed to be cost-effective without compromising on its quality and performance. The cost of the unit should include not only the manufacturing cost but also the maintenance and operational cost.
- **Maintenance:** The cooling unit must be designed for easy maintenance and repair to ensure its long-term reliability and functionality. The Peltier cooling system should be designed with components that can be easily replaced or serviced. The system should also have an easy-to-use control interface to facilitate troubleshooting and maintenance.
- **Environmental conditions:** The cooling unit must be designed to function in various conditions, such as humidity and ambient Temperature. The Peltier cooling system should be designed to withstand harsh environmental conditions, including high humidity and extreme temperatures. The system should also be designed with adequate ventilation and air filtration systems to prevent contamination of the stored products.

3.1. Design Approach

The Approach to deal with the 3D Model was carried forward with the student version of Creo Parametric, a 3D modeler used to design & model various products in general. This software paves as the solution to Design the required 3D Model for our cooling System. The initial enclosure was divided into two sections, namely.

- The outer shell
- Insulation layer

3.1.1. The outer shell

It is nothing other than the rigid structure used as the outer Casing; this layer was modeled as a 3D-printed layer made from PLA. The most widely used substance for 3D printing is polylactic acid (PLA). This biodegradable plastic is created from renewable resources like cornstarch. It is simple to use, and its main advantage is its low melting point (“What Material Does a 3D Printer

Use? ” 2021). There are various benefits to using PLA as the exterior shell material for the Peltier-based cold storage unit. First, because it is a lightweight material, the storage unit’s Design is more transportable and manageable. Second, it has strong thermal insulation qualities that may aid in keeping the storage unit’s inside Temperature where it should be. Furthermore, because PLA is also a food-grade polymer, Another consideration when using PLA in a cold storage unit is its thermal properties.

The usage of PLA is, however, subject to several restrictions. It has a relatively low glass transition temperature (between 60 and 65 °C), implying it may distort or soften at high temperatures. This might be an issue if the storage unit must function in an environment with high ambient temperatures or is exposed to direct sunlight. Furthermore, PLA is not as robust or long-lasting as some other materials. Thus the exterior shell may be vulnerable to breaking or cracking if dropped or put under mechanical stress. While PLA has good thermal insulation properties, it may not be sufficient to maintain the desired temperature within the chamber.

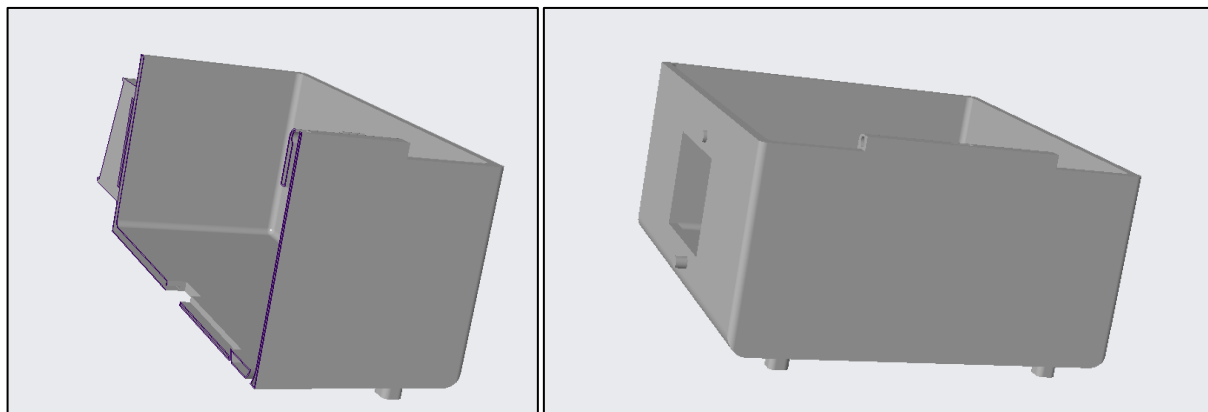


Image 4. 3D Model of the outer shell. (Courtesy: Modeled in CREO)

The above image represents the 3D Model of our Design created with Creo. The thickness of the shell was given to be **5mm**. The surface area of the layer is also remarked simultaneously, which will be used in the later part of the calculation for determining the overall Cooling load of the system. Since our Design will be a closed model with an empty extrusion inside, we calculate the Total Area of the shell by calculating the area of two prisms, which is then subtracted to define the area of our outer shell. All the calculations are carried out with Matlab, and the Mat scripts are also attached along with the calculations for reference.

Length (l) = 200mm.

Breadth (b) = 200mm.

Height (h) = 110mm.

Area of the Rectangular Prism = **Area of the Base** (top & Bottom) * **Lateral Area** (Sides);

Area of the Base = $l * b$; ... (1)

Lateral Area = $2lh + 2bh$; ... (2)

```
%%
    %Area of the side walls of the outer Shell
    L_PLA = 0.13;
    l_side_PLA = 200/1e3;
    b_side_PLA = 110/1e3;
    A_side_PLA = 4.*(l_side_PLA*b_side_PLA);

    %%
    %Area of the Ceiling & Floor of the outer Shell
    l_CF_PLA = 200/1e3;
    b_CF_PLA = 200/1e3;
    A_CF_PLA = 2.*(l_CF_PLA*b_CF_PLA);

    %%
    TOTAL_PLA_AREA = A_side_PLA+A_CF_PLA
```

Source Code 1. Area of side walls for Outer shell (Courtesy: MATLAB script).

The area is calculated and represented in **m²**.

Area of the Base = **0.080m²**

Lateral Area = **0.088m²**

From above, the total area of the outer shell was defined as **0.162m²**.

3.1.2. The Insulation layer

The secondary layer suppressed on the outer shell is our system's main source of insulation. The Peltier-based cold storage unit's insulating layer is a crucial part since it aids in maintaining a constant and stable internal temperature. The following are featured to be the main applicative observations.

Temperature control: By acting as an extra barrier between the inside of the unit's contents and the outside world, the insulating layer aids in preventing temperature variations (Chen et al.,

2022). This is crucial for medications like insulin and vaccinations since they must be kept at specific temperatures to be effective. Energy efficiency: The insulating layer can aid in lowering the energy needed to maintain the specified temperature range by minimizing heat transfer between the internal Temperature & the ambient Temperature depending upon the thickness of the layer (Martinez et al., 2016). This can save running expenses and improve the environmental friendliness of the device.

Overall, the insulating layer is crucial to the performance and dependability of the Peltier-based cold storage unit and should be carefully built and tested to guarantee that it satisfies the application's particular needs. With the requirements over choosing the right insulating layer, it was clear to use a material capable of trapping the internal Temperature with consideration over the ambient Temperature, **XPS** – Extruded Polystyrene is the Material chosen for the secondary insulative layer. To form a closed-cell structure, polystyrene is extruded using a process that also uses blowing agents (Li et al., 2020). The outcome is a foam board with a consistent, flat surface with superior insulating capabilities and a flash point of around 355°C for approximately a thickness of 2mm (Han et al., 2013), which is an added advantage of using it in our system as it overrates the reversed temperature difference produced by the Peltier considering the worst-case scenario.

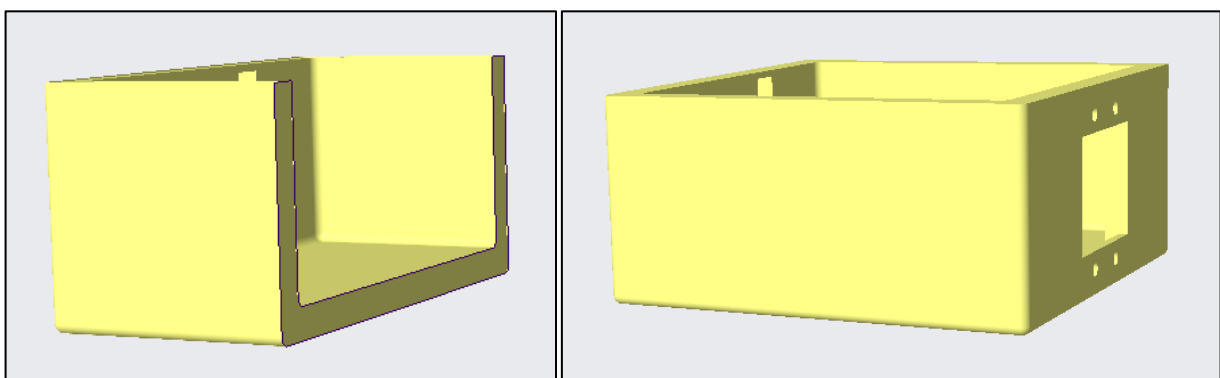


Image 5. Secondary Layer/Insulative layer (Courtesy: Modeled in CREO)

The image represented above is our cooling system's extruded 3D model Insulation layer. The dimensions & surface area calculations of the Model is as follows; similar to the Outer shell, the area is calculated in the same manner.

Length (l) = 190mm.

Breadth (b) = 190mm.

Height (h) = 95mm.

Area of the Rectangular Prism = **Area of the Base** (top & Bottom) * **Lateral Area** (Sides);

Area of the Base = $l * b$ (same as equation (1)) ;

Lateral area = $2lh + 2bh$ (same as equation (2)) ;

```
%%
    %Area of the side walls of the Insulation Layer
L_XPS = 0.3;
l_side_XPS = 190/1e3;
b_side_XPS = 95/1e3;
A_side_XPS = 4.*(l_side_XPS*b_side_XPS);

%%
    %Area of the Ceiling & Floor Insulation Layer
l_CF_XPS = 190/1e3;
b_CF_XPS = 190/1e3;
A_CF_XPS = 2.*(l_CF_XPS*b_CF_XPS);

%%
TOTAL_XPS_AREA = A_side_XPS+A_CF_XPS
```

Source Code 2. Surface area calculations for Insulation layer (Courtesy: MATLAB script).

Area of the Base = **0.076 m²**;

Area of the side Walls = **0.072 m²**;

From above, the total area of the insulation layer was defined as **0.150m²**.

After designing the layers for the outer shell, the formal Design looks like image 8. Now, with the basic 3D Model of our system, we can gather solutions to compute the Net Cooling load from the designed parameters.

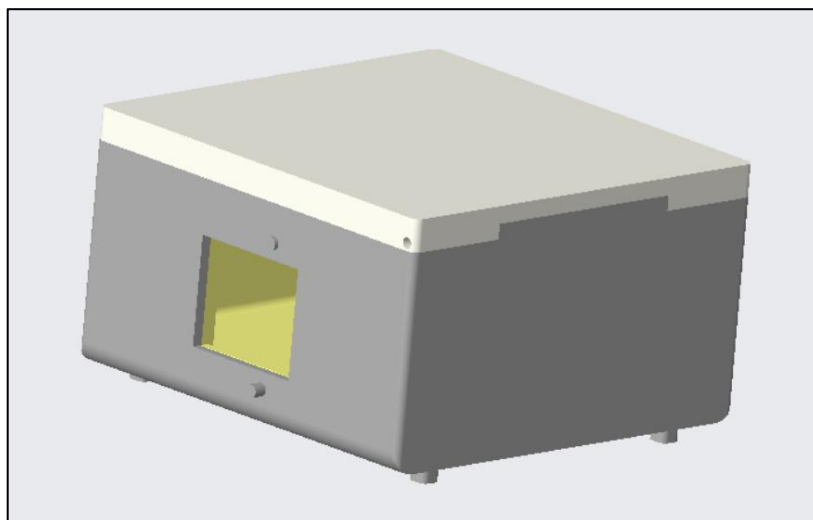


Image 6. 3D Model representing the Outershell & Insulation Layer. (Courtesy: Modeled in CREO)

3.2. Cooling load Calculations

Moving forward with the cooling load calculations, it was necessary to gain a solid knowledge of the chosen materials' thermal properties and compare it with criticality, as the results play a vital role in selecting the Peltier. The cooling load estimations of a Peltier-based cold storage unit depend highly on the design parameters and materials selected. These elements are essential for sustaining the range of temperatures needed to store these goods (Hasanzadeh et al., 2023).

The thickness of the insulation layer, the kind and placement of the Peltier modules, and other design elements of the unit, such as the size and form of the storage compartment and the insulation layer, directly impact the cooling load estimates. These variables impact how well the unit can maintain the specified temperature range and how much heat load it will bear.

The materials selected for the Peltier modules, insulating layer, and other parts of the unit are equally important to the calculations for the cooling load. The cooling load of the unit is directly impacted by the thermal conductivity and heat transfer coefficient of these materials, which influence their capacity to transmit or resist heat transfer; it is crucial to analyze the design parameters and materials used carefully. Any underestimation or omission of these elements might result in an insufficient cooling load capacity, which would lower the quality and effectiveness of the stored goods ("How is the cooling load calculated?" 2018). What is the need for determining the Cooling load? It was a common question to be raised.

Typically, thermal energy is transmitted into the cold Storage through the ceiling, walls, and floor. Heat always attempts to enter a cold place because of the temperature difference between the inside and exterior of the cold chamber, which is much colder than its surroundings constituting transmission load. A further modification must account for the increased heat transfer if the cold Storage is exposed to direct sunshine. The next category is product loads; this explains why the arrival of new things heats the previously cold space. The second factor to consider is the internal load, the heat produced by internal components, such as the cooling fans (Evans, 2017).

3.2.1. Transmission Loads

The side Walls, floor & Ceiling are considered for the cooling load calculations; the transmission losses are to be calculated as the transmission losses from the structure of our system. As we discussed, the Model of the outer shell & Insulation layer above from the determined data lets us

compute the transmission load through the structure. The calculation of transmission loads for our system can be derived by using the following formula (3) followed by the Matlab script,

$$Q_{trans} = U \times A \times (T_A - T_I) \times 24. \quad \text{(Evans, 2017)} \quad \dots (3)$$

Q = Total Heat load

U = Value of Insulation

A = Surface Area (Sides of the walls + Floor & Ceiling)

T_A = Ambient Temperature

T_I = Internal temperature

```
%%
Amb_temp = 25;
Int_temp = -5;
TOTAL_HEAT_LOAD_TRANSMITTED_PLA = L_PLA*TOTAL_PLA_AREA*(Amb_temp-Int_temp)*24;
TOTAL_HEAT_LOAD_TRANSMITTED_XPS = L_XPS*TOTAL_XPS_AREA*(Amb_temp-Int_temp)*24;
HEAT_LOAD_OF_STRUCTURE = TOTAL_HEAT_LOAD_TRANSMITTED_XPS+TOTAL_HEAT_LOAD_TRANSMITTED_PLA
```

Source Code 3. Calculation of Transmission loads (Courtesy: MATLAB script).

As we have determined the Surface area for both the models of our system, and based on the formula mentioned above for calculating the transmission loads from the outer walls of the Casing, such that the transmission load was determined as follows,

The load transmitted through Outershell made out of PLA = **30.2 Watts**;

The load transmitted through the Insulation layer made out of XPS = **13.5 Watts**;

Total Transmission load = load from PLA+load from XPS (***Q_{trans}***) = **43.7 Watts**.

3.2.2. Product Load

This is the crucial part of cooling load calculations. The products to be stored inside our cooling System have a specific heat and temperature difference which is also considered. Where the products to be stored inside will have a specific cooling load, the consideration for 30 vaccines is considered, and the product load could be calculated based on the formulation below.

$$Q_{vacc} = m \times C_p \times (\text{product inlet temp} - \text{Internal temp})/3.6 \quad \dots (4)$$

(Evans, 2017)

Parameters of the product,

C_P = Specific heat capacity (KJ/kg. °c)

m = mass of the product (kg)

3.6 = Conversion constant (J - Wh)

Product Inlet Temp = Temperature of product before placing it into the system (°C)

Internal temp = Set temperature inside our system (°C)

```
%%
vacc_HE =4.182;
m = 0.005;
Vacc_In_temp = 25;
Chamber_temp = -5;
Q_vacc = vacc_HE*m*(Vacc_In_temp - Chamber_temp)/3.600; %Converting from kJ to kWh
%Taking 30 vaccine shots as storage
Q_vacc_WH = Q_vacc*30
```

Source Code 4. Calculation of Product load (Courtesy: MATLAB script).

The product load calculated, considering placing the vaccines/insulins, the $C_P = 4.18$ is the specific heat load. I am using the specific heat of the water as referring to the vaccines, with m considered the mass of the vaccine given as approx. 0.005kg. The derived data calculate the Overall Product load (*Source Code 4*) (Q_{vacc}) as **5.3W**.

3.2.3. Equipment Load

The equipment load is the constraint that calculates the equipment kept inside the cooling system, like the cooling Fan that dissipates the heat from the cold side of the Peltier in our system.

$$Q_{Equip} = fans \times time \times wattage \text{ (Evans, 2017)} \quad \dots (5)$$

fans = the number of fans

time = fan daily run hours (h)

wattage = the rated power of the fan motors (W)

```
%% Equipment load from fans
n_fans = 2;
t = 2;
fan_watt = 3; % Approximated data
Q_fan = n_fans*t*fan_watt
```

Source Code 5. Calculation of Equipment load (Courtesy: MATLAB script).

The equipment load calculated for our system contains only two fans with an operating power of 3 watts. Thus the overall equipment load for our system is **12W**. Now, having all the required data and validating the results with most references derived from the Overall cooling load of our system is determined along with a safety factor of **30%**; it is estimated as follows,

$$\text{Total cooling load } (Q_c) = Q_{trans} + Q_{vacc} + Q_{Equip} * \text{Safety factor} \quad \dots (6)$$

(Evans, 2017)

```
%%
Total_cooling_load = Q_fan+Q_vacc_WH+TOTAL_HEAT_LOAD_TRANSMITTED_XPS+TOTAL_HEAT_LOAD_TRANSMITTED_PLA;
Safety_factor = 1.3;
```

Source Code 6. Calculation of overall Cooling load (Courtesy: MATLAB script).

Altogether, the Overall Cooling load of our system derived from equation (Source Code 6) is said to be **$Q_L = 79.2$ Watts**. With the data analyzed and Validated, we can select the Peltier Module. It quantifies how much heat must be evacuated from our system to keep it at the right Temperature. This number is helpful because it may be used to size the required components, such as the heat sinks and fans, and to choose the proper cooling system, such as a Peltier-based cooling system.

The cooling load may also assess the system's energy effectiveness. The system's energy efficiency increases with decreasing cooling load, which is crucial for long-term and cost-effective operation. Additionally, we may assess the effectiveness of our system and highlight possible advantages of employing a Peltier-based cooling system by contrasting the cooling load of the built thermal enclosure with current storage solutions.

3.3. Selecting Components

The component selection process is a crucial step in the Design and development of our System. With our required working parameters and the known values from the cooling load (Q_L), we can now select the Peltier modules based on our requirements. Our Design is structured in such a way that Storage with such operating parameters finds itself either power consuming, making the Peltier

not so efficient, and on the other hand, the pumping capacity is not upto the mark, so it is a situation to stay in between, But the Approach of our System is unique. Operating two Peltiers simultaneously at a conceptual power input will be a highly effective solution for our Design; the selection of the Peltier Model is explained below.

3.3.1. Peltier Module

Our goal from the start relies completely on this part of the Project; the main cooling element we have planned for our system is the Peltier module. As stated above, selecting the right Peltier modules is crucial. Peltiers or Thermoelectric coolers are devices operated on the principle of the Peltier effect, transferring heat from one junction to another when circuited (“How Peltier Cooling Works,” n.d.; Slanina et al., 2018). Two semiconductors of dissimilar materials join together to form a thermocouple when the voltage across the circuit current flows through the semiconductor’s junctions, making it hotter on one side and colder on the other. Thus the possibility of having Peltier modules as the main cooling element has advantageous and disadvantageous.

Advantages:

1. Compact Size: Peltier modules are compact and have a small form factor, making them ideal for limited-space applications.
2. Precise Temperature Control: Peltier modules provide precise temperature control, allowing for accurate and stable temperature regulation.
3. Reliability: When Operating Conditions, Proper Regulation & Design parameters are met, Peltier’s outperforms their Reliability
4. Energy Efficient: Peltier modules are energy efficient and require only a small amount of power to operate, which makes them ideal for portable and battery-powered applications.

Disadvantages:

1. Low Efficiency: Peltier modules are inefficient and require much power to provide a significant temperature differential, which can be problematic for applications requiring a large cooling or heating capacity.
2. Heat Generation: Peltier modules generate heat on both sides of the Module, which can be a problem in applications where heat dissipation is limited.

3. Limited Cooling Capacity: Peltier modules have a limited cooling capacity, which can be a problem where a large amount of heat has to be dissipated.

The basic working of the Peltier is explained as follows, P-type and n-type semiconductor materials are placed between two ceramic plates to form Peltier modules. A grid-like structure alternately connects the p- and n-type materials. A DC sent through the Peltier module produces a temperature differential between the ceramic plates. The direction of the current flow affects the direction of the temperature differential. The Peltier effect is reversible, which means that by simply switching the applied voltage's polarity, the temperature differential's direction may change. Peltier modules can therefore be utilized for both cooling and heating purposes.

The Peltier module's ability to conduct cooling depends on several variables, including the semiconductor components' material characteristics, the current passing through it, and the temperature differential between its hot and cold sides. However, compared to other cooling systems, the efficiency of Peltier modules is somewhat low. From the calculated cooling load Q_L we have chosen **ATS-TEC40-35-018** as our Peltier module; it is made up of the Material known as bismuth telluride (Bi^2Te^3) is frequently utilized in Peltier devices. It is a thermoelectric material, which enables it to convert a change in Temperature into an electrical voltage or current or the opposite. In Peltier devices, an electric current is sent through the Bi^2Te^3 material to produce a temperature differential across the Material. As a result, heat is dissipated from one side of the device while being absorbed on the other. Depending on which way the current flows, this method can be utilized for cooling or heating.

Bi^2Te^3 is the perfect material for Peltier devices, it is efficient in converting the temperature differences into electrical power, as indicated by its high thermoelectric figure of merit. Additionally, it has a low thermal conductivity, making it an efficient heat insulator. Bi^2Te^3 does, however, have significant drawbacks that may impair the functionality of Peltier devices.

Thermal stability is one of the key restrictions. Bi^2Te^3 is susceptible to thermal deterioration at high temperatures, resulting in a decline in its thermoelectric characteristics and, eventually, a loss of efficiency (Lyskawinski and Szelag, 2018). Since we have used 2 Peltier modules simultaneously to bring our system to the required temperature and regulate it continuously, the total heat load will be fragmented. The following table expresses the parameters of the Peltier.

Table 2. Parameters of the Peltier Module (Courtesy: TEC Modules – Datasheet).

S.No	Description	Parameters
1.	Part Number	ATS-TEC40-35-018
2.	I_{\max} (Amps)	8
3.	V_{\max} (Volts)	24.1
4.	Q_{\max} (Watts)	111.5
5.	ΔT_{\max} ($^{\circ}\text{C}$)	68
6.	Internal Resistance (Ω)	$2.35\Omega \pm 10\%$
7.	Weight (g)	25
8.	No. Of Couples (N)	199
9.	Dimensions (mm)	40 x 40 x 3.5

Crucial considerations should be made for using two Peltier modules operating cooperatively, as the power inputs play a vital role in the operation of a Peltier module. The reason to select this Peltier as the crucial cooling element is because the maximum output Q_{\max} is above our required Cooling load of our System Q_L , and we will be powering up two peltiers at the same time, in turn, which means twice the power is generated such that it spaces advantageous for our need such that the operating current could be balanced based on our differed voltage. The COP of the Module relies greatly on the factors of the basic principles of the Module itself; There are a set of equations that defines the performance of a TEC.

For example, if one wants to maintain a cold temperature (T_C) at a certain level for a specific amount of current (less than I_{MAX}) to extract a specific amount Q_C (less than Q_{MAX}) from the cold side, the hot side temperature (T_h) can be found from the Q_C equation. The following equations for Q_h , V , and COP can be used to find the values of Q_h , V , and COP (Ong et al., 2018; TEC, n.d.). The correlations are as follows:

The voltage across the Module,

$$V = 2N[S_{AB} (T_h - T_c)] + IR \quad \dots (7)$$

Heat Pumped (Cold Side),

$$Q_c = 2N \left[S_{AB} I T_c - 2N \frac{k\rho}{R} (T_h - T_c) \right] - I^2 R \quad \dots (8)$$

Heat Rejected (Hot Side),

$$Q_h = 2N \left[S_{AB} I T_h - 2N \frac{k\rho}{R} (T_h - T_c) \right] + I^2 R \quad \dots (9)$$

Coefficient of Performance (COP),

$$COP = Q_c / VI \quad \dots (10)$$

(Tsai and Lin, 2010)

I is the input current to TEC module (A)

V is the voltage across the TEC module (V)

S_{AB} is the Seebeck coefficient of Bi²Te³ material (V/K)

R is module electrical resistance (Ω)

k is the thermal conductivity of Bi²Te³ material (W/m•K)

ρ is the electrical resistivity of Bi²Te³ material (Ω•m)

T_h is hot side temperature (K)

T_c is cold side temperature (K) (TEC, n.d.)

Estimated Values,

$$S_{AB} = 200 \times 10^{-6} \text{ V/K}$$

$$k = 1.5 \text{ W/mK (at 300 K)}$$

$$\rho = 10 \times 10^{-6} \text{ } \Omega \cdot \text{m}$$

$$N = 199$$

$$I = 2A$$

$$T_h = 73 \text{ }^\circ\text{C} \text{ (Calculated from max. } \Delta T \text{ mentioned from the datasheet)}$$

$$T_c = -5 \text{ }^\circ\text{C}$$

$$R = 2.35 \text{ } \Omega$$

```

N = 199;
S_ab = 200*1e-6;
I = 2;
Th = 73;
k = 1.5;
R = 2.35;
row = 10*1e-6;
Tc = -5;
Q_h = 2*N*((S_ab*I*Th)-(2*N*((k*row)/R)*(Th-Tc)))+(1/2*I^2*R);
Q_c = 2*N*((S_ab*I*Tc)-(2*N*((k*row)/R)*(Th-Tc)))-(1/2*I^2*R);
V = 2*N*(S_ab*(Th-Tc))+I*R;
COP = Q_c/V*I;

```

Source Code 7. Peltier Module calculations (Courtesy:MATLAB code).

With all the parameters for calculation, the find outs about the correlations of our selected Peltier device are the calculated results derived from (*source code 7*) above.

$$Q_c = 84.3 \text{ W}$$

$$Q_h = 62.5 \text{ W}$$

$$V = 10.9 \text{ V}$$

$$COP = 2.3$$

The results that have been derived give us a positive move in selecting the required Peltier Module; the values validated from the calculations state that for a given input of **2 A** operated at a voltage (V) of approx. **11 V** that gives out a power output of **22 W** puts a cooling load on the cold side (Q_c) around **84 W** approx. and around **63 W** aprox. On the Hot side, if the Peltier with all put together, the COP is calculated to be around **2.3**. This value states that for every **1 W** of energy consumed, **2.3 W** of load moved from the cold side to the hot side (TEC, n.d.), which shows that selected modules state great effectiveness and efficiency in meeting our system's requirements.

Though these values turn out to be positive, the next stage will have to be finding the solution to

decipate the energy dissipated from the sides of the heat sinks. This measure is crucial because there are chances for thermal runaway where the Temperature of a system increases uncontrollably, leading to the system's rapid and potentially catastrophic failure. In thermal runaway, the heat generated by the system exceeds the ability of the cooling system to remove the heat, leading to a positive feedback loop where the Temperature continues to increase until the system fails. Though the prescribed rating of peltiers falls around 138 °C, which is much beyond our utilization, we need to integrate Heat sinks on both sides of the Peltier to move the energy to the surroundings with the help of cooling fans.

Next, we will continue over the calculations of the Heat Sinks for integrating them with the hot & cold sides of the peltiers. This component stands a critical stake in dissipating the energy efficiently from the Peltier, protecting it from over-rating. To move on with the thermal calculations for sizing the right heat sinks for our Peltier devices, we must know the Temperature difference ΔT of the Module with our input parameters. To know the temperature difference between the two sides, it is necessary to know the T_h Hot side temperature and T_c . In the above calculation, the results were derived based on ΔT_{max} mentioned as per the datasheet, but dynamically the difference temperature varies based on the operating parameters, well clearly explored in the later part of the simulation.

3.3.2. Heat Sinks

Peltier cooling systems frequently employ heat sinks to dissipate the thermal energy produced by the Peltier device. When the Peltier device is in use, energy is transferred from one end to the other, and if the heat produced by the device is not adequately dispersed, it may build up. This can result in thermal runaway when the device's Temperature keeps rising, damaging the Peltier device and other components. A heat sink gives the heat a wider surface area to evaporate, enabling more efficient cooling (Martinez et al., 2016). Typically, it is constructed of a material with high thermal conductivity, like copper or aluminum, and it incorporates fins or other elements that improve the surface area for heat dissipation.

Heatsinks are not used only for the Hot sides of the Peltier but also along the cold sides of our system, but the calculations are crucial and complicated, which needs to be solved to find out the possible heat sink that needs to be used for our system. The selection of heatsinks plays a vital role in maintaining the efficiency of the Heatsink; some of the viewed advantages & disadvantages of having a heatsink for our system are stated below,

Advantages:

- Better heat dissipation: Heat sinks effectively dissipate heat from the Peltier device to avoid overheating and possible damage to the object.
- Enhanced cooling efficiency: Peltiers may function at lower temperatures due to improved heat dissipation, which enhances cooling efficiency.
- Longer lifespan: Including heat sinks can increase the Peltier device's lifespan by minimizing overheating and consequent thermal damage.

Disadvantages

- Additional expense: The price of heat sinks may increase the Peltier device's total price.
- Weight and size gain: The peltier's weight and size may rise if a heat sink is included, which might be a drawback in some applications.
- Installation difficulty: Additional knowledge or tools may be necessary to install the heat sink onto the Peltier device properly.
- Limited efficiency: Heat sinks might not always be efficient, especially if the Peltier is utilized in high-power applications. ("Advantages and disadvantages of heat sinks made of aluminum," n.d.)

To select the appropriate Heatsink, it is necessary to incorporate various streams of calculations and define them rightly. The method we would move forward with for designing our heat sink is based on validating the required Surface Area of the Heatsink and comparing the resistances of our Heat sinks & Peltiers.

Let us start with comparing the thermal resistances followed by sizing based on the surface area and the thermal resistance; to ensure that the heatsink selection is righteous for our system, we need to calculate the Thermal resistances for both Heatsink and our systems and the overall heat sink resistance should be lower than that of the overall, if it is greater than the overall Resistance of our System then it notifies that the chosen Heatsink did not meet the requirement. ("Understanding Thermal Dissipation and Design of a Heatsink," 2011)

First, let's calculate the Thermal Resistance of the System on our hot side; all the calculations are considered against the usage of operating a single peltier as it is needed to design the heatsinks for the max parameters and correctly size them for the system.

$$R_{peltier_hot} = \Delta T / Q_h \quad \dots (11)$$

$\Delta T = 68 \text{ }^\circ\text{C}$ (Max. Temp difference is considered).

$Q_h = 62.5 \text{ W}$ (Referred to equation (9)).

The thermal Resistance of the Thermal Paste used should be considered as well; the thermal paste is a TIM (Thermal Interface materials) generally used to help heat spread evenly across the area of contact; when two surfaces are placed one over the other, the area of contact is not completely conducive as there are chances of air gaps between the two surfaces this may infer losses over heat transfer. To overcome this, such compounds are used to increase the contact area while increasing the heat transfer rate between the surface of contact (Rahmani et al., 2014). The thermal pasting used by us is just a commercially available **ARCTIC MX-4** (“ARCTIC MX-4 Thermal Compound (4g) - Teplovodivá pasta | Alza.cz,” n.d.) with a rated Thermal conductivity $C_{tp} = 8.5 \text{ W/mK}$

Now the thermal resistance of the selected thermal paste can be calculated as,

$$R_{tp} = \textit{Thickness} / (\textit{Area} * C_{tp}) \quad \dots (12)$$

$\textit{Thickness} = 1 \text{ mm}$ (considering a layer of paste applied across the contact)

$\textit{Area of contact} = 0.0016 \text{ m}^2$

The next component that inhibits thermal resistance for our system is a TIM, a 4mm *50 mm * 50 mm copper plate placed right over the thermal pasting. This is placed to increase the contact area between the Heatsink and the Peltier. The calculations for considering copper plate are as follows,

$$R_{cu} = \textit{Thickness} / (k_{cu} * \textit{Area of material}) \quad \dots (13)$$

$\textit{Thickness} = 0.004 \text{ m}$

$k_{cu} = 0.401$ (thermal conductivity of copper) (“Copper,” 2023)

$\textit{Area of material} = 0.005 \text{ m}^2$

We have mentioned all possible Thermal resistance requirements considering the hot side of the Peltier. To calculate the overall resistance of our hot side,

$$R_{hot} = R_{peltier_hot} + R_{tp} + R_{cu} \quad \dots (14)$$

After analyzing the method to calculate the thermal resistance of heatsinks for the hot side, all the results will be shown below, and a comparison of results will be made. To calculate the thermal Resistance of the Heatsink that is to be used on the hot side of the Peltier along with the TIMs

$$R_{hot_hs} = \frac{T_j - T_a}{Q_h} \quad \dots (15)$$

(“Understanding Thermal Dissipation and Design of a Heatsink,” 2011)

R_{hot_hs} (Thermal Resistance of the heat sink)

$T_j = 73$ °C (max Temperature on the Hot side)

$T_a = 25$ °C (considered room temperature)

Q_h considers the energy that needs to be dissipated through the hot side

```
%%
%TIM RESISTANCE
CU_L = 0.004;
CU_K = 401;
CU_A = 0.0025;
R_TIM = CU_L/(CU_K*CU_A);

%%
%HS RESISTANCE
Tj = 73;
Ta = 25;
Q_h = 63;
Q_c = 85;
R_HS_hot = (Tj-Ta)/Q_h;
R_HS_cold= (Tj-Ta)/Q_c;

%%
%PELTIER RESISTANCE
Del_T = 68;
R_Pel_hot = Del_T/Q_h;
R_Pel_cold = Del_T/Q_c;

%%
%THERMALPASTE RESISTANCE
TP_L = 1*1e-3;
TP_Cond = 8.5;
TP_area = 0.04*0.04;
R_TP = TP_L/(TP_area*TP_Cond);

%%
%OVERALL RESISTANCE
R_Overall_hot = R_TP + R_Pel_hot+R_TIM;
R_Overall_cold = R_TP + R_Pel_cold+R_TIM;
```

Source Code 8. Thermal resistance calculations (Courtesy: MATLAB)

Table 3. Hot Side Thermal Resistance Results

S. No	Parameter	Result
1.	R_{tp}	0.073 °C/W.
2.	R_{hot_hs}	0.761 °C/W.
3.	R_{hot}	0.995 °C/W.

In this way, we have defined all the required resistances of our system and heatsink for the hot side operations. The results of the calculations are shown above the source code for the calculations. The above-tabulated values are the results of the calculations made out to determine the Thermal Resistance of the hot side of the system against the Heatsink. In the same way, the calculations made for the cold side of the system are also given below,

Table 4. Cold side Thermal Resistance Results

S. No	Parameter	Result
1.	R_{tp}	0.073 °C/W.
2.	R_{cu}	0.004 °C/W.
3.	R_{cold_hs}	0.564 °C/W.
4.	R_{cold}	0.877 °C/W.

From the results tabulated above, the heat sink's thermal resistance falls lower than our System's Thermal Resistance. Now we will also compare the sizing based on the surface area method.

To calculate the required surface area of the hot side of the heat sink,

$$Area_{hs_hot} = Q_h / (h \times R_{hs}) \quad \dots (16)$$

(“ChatGPT,” n.d.)

$h = ?$ (heat transfer coefficient)

To calculate the heat transfer coefficient, which is the ability of the Material to conduct, that is, the amount of heat transferred through the unit area of the Material per unit in time. It can be calculated as follows

$$h = (Nu * k) / L \quad \dots (17)$$

$Nu = 3.660$ refers to the Nusselt number

$L = 77 \text{ mm}$ refers to the length of the surface

$k = 0.024 \text{ W/mK}$ refers to the thermal conductivity of air (for $25 \text{ }^\circ\text{C}$ and atmospheric pressure)

As we need to define the Nu which needs to be determined so the calculation below states for the Nusselt number concerning laminar flow is as follows,

$$Nu = 0.664 * Re^{(1/2)} * Pr^{(1/3)} \quad \dots (18)$$

(“Heat transfer coefficient,” 2023)

Re and Pr are the Reynolds number and Prandtl number for air in laminar flow for forced convection, which we further solved later. From the form above in (equation 18), the determined Nusselt’s number is approximately $Nu = 3.660$. The calculated heat transfer coefficient is $h = 15.6 \text{ W/ (m}^2\text{C)}$ from (equation 18).

Now we know that we will be considering the operation of two Peltiers, which means that the load is split between the Peltiers. Now considering max operating conditions for the modules with the load split between them, the calculated required surface area for the heat sink on the hot side is calculated as $Area_{hs_hot} = 107.02 \text{ cm}^2$ The Model of the heat sink used for the hot side and its dimensions are given below concerning images.

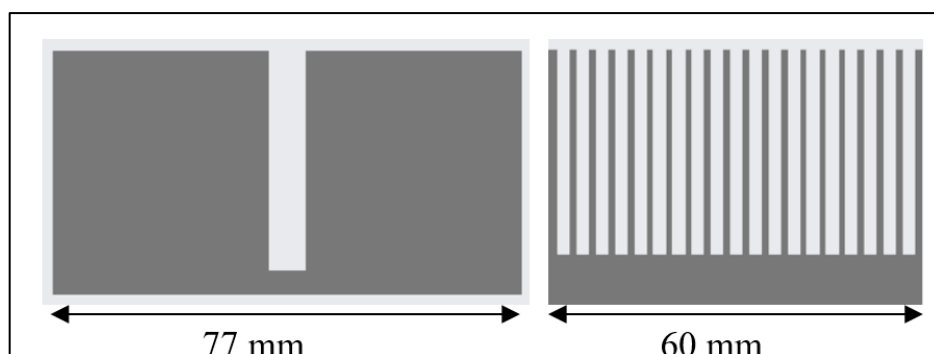


Image 7. Model of the heat sink used on the outside.

Now, knowing the required minimum surface area for the hot side, we can select a heat sink higher than that which will size the Heatsink perfectly for our purpose. Now in my system, I have planned to use a commercial heatsink with a total area of **105.2 cm²**, which is higher than our required heat sink area.

It is to know that we have inculcated the calculations considering the maximum Temperature difference ΔT_{max} , which is 68 °C for our calculations such that operating the two Peltiers to achieve the chamber temperature, the functionality is not going to utilize the maximum power of the Peltier's such that we can be sure that Heat sink chosen for the hot side of the Peltier functions efficiently. In the same way, the calculations are carried out to determine the Heatsink that needs to be placed on the cold side. The approx. $Area_{hs_cold} = 13 \text{ cm}^2$. And the Model of the selected Heat sink is shown below,



Image 8. Heat sink used on the cold side of the Peltier (Courtesy: ("Heatsink 1 ks," n.d.))

The purpose of using a heat sink for the cold side of the Peltier's is because the cold junction of the Peltier produces energy but a medium to dissipate the energy to the surrounding is not possible to overcome that a heat sink is used followed by a cooling fan mounted over it which initiates forced convection. Now to check if the heat sink is sized correctly, the surface area of the heat sink needs to be calculated which is calculated based on the following parameters,

$$\text{Base Area} = 2lb + 2lh + 2bh = 2 (50*50) + 2 (50*1) + 2 (50*1);$$

$$\text{Fin area} = 2lb + 2lh + 2bh = 2 (2*1) + 2 (2*9) + 2 (9*1);$$

$$\text{Number of fins} = 143$$

$$\text{The total area of the Heat sink} = \text{Base area} + \text{Fin Area} * \text{Number of Fins}$$

The surface area of the heat sink is calculated at approx. **14 cm²**. In comparison, it is greater than the required, making it a righteous selection of the heat sink for the cold side of the system. Now

with the right heat sinks selected for our system, we can move forward with the forced convection setup for our heat sink setup, which will be heat sinks incorporated with cooling fans for both ends, including the cold & hot sides of the Peltier.

3.3.3. Cooling system

The cooling System incorporates the medium used to dissipate the existing energy to the surrounding with cooling fans that enable forced convection over the heat sinks. The heatsinks transfer a particular amount of energy from the source, which is the Peltier Device which dissipates the energy from both sides of the Peltier from both hot and cold sides of the Peltier, the energy held in the heat sink is stored upto a particular limit which will be increasing concerning time, that is the energy gained on the heat sink should be somehow dissipated from the medium to keep the device in its operating efficiency to safeguard the modules from thermal runaway.

While moving forward with the heat sink calculations, the initiation of forced convection parameters was priorly placed within calculating the surface area for which the heat transfer coefficient h is calculated, which is none other than the amount of heat transfer through a unit area that is dependent on the laminar body correlations concerning Nusselt number Nu , which has dependency over the Re and Pr which are also correlations of Reynolds number and Prandtl number for air in laminar flow (“Heat transfer coefficient,” 2023) In the final stage of calculations for the system this part entirely holds the validation of the components that are chosen. We will recheck the heatsink sizing based on the volumetric resistance approach, which validates along with forced convection more critically.

To calculate the required Volume of the Heatsinks, we need to know the basic data, such as the values for the Airflow; the calculation for Airflow is as follows.

$$V = (Q \cdot R_v) / \Delta T \quad \dots (19)$$

(“Heat Sink Size Calculator,” n.d.)

V – Required Volume of the Heatsinks

Q – the load transmitted

R_v – Volumetric thermal Resistance

ΔT – Temperature difference

Here, we do not know the value of R_v , which is calculated based on some considerations made

from the table below,

Table 5. Volumetric Thermal Resistance - R_v (Courtesy: (“Heat Sink Size Calculator,” n.d.))

Airflow	Operating properties	R_v
Natural Convection	Less – No noise	500–800
≈ 200 LFM	Gentle – very low noise	150–250
≈ 500 LFM	Moderate air/noise	80–150
≈ 2000 LFM	Fast air / loud noise	50–80

To know the Airflow of our desired fans, we need to determine its Airflow in LFM, with consideration a cooling fan of $50 \times 50 \times 15$ mm dimensions selected for the hot side of the system. The cooling fan selected has an airflow of 8.34 CFM mentioned in the datasheet (PCMAX, n.d.), which, when calculated to LFM, gives us the value of approximately 300 LFM, which means that from the above table, our Volumetric resistance R_v for the hot end of the Peltier is determined as 80-150 considering the value of 130 LFM for our calculations.

Now substituting the values generates the required volume of the Heatsink, which is calculated at approx. **81 cm³**. Now with the known value for the required volume of the Heatsink, the heat sink selection is validated along with consideration for forced Convection (“Heat Sink Size Calculator,” n.d.).

The selected heat sink has a volume of approx. **85 cm³**, which comparatively is over the border, also states that the sizing of the heat sink is validated. This ensures that the selected Heatsink is perfectly sized for our needs since the calculations were made for peak considerations of different temperatures, ensuring the Peltier modules operate in safe zones, eliminating the thermal runaway.

Now we have derived all our required calculations our Design of the cooling System now can be designed, and the simulation model based on the selected components & calculated values will be put together, giving out the result of the simulation of our system before moving forward with the initiating the Simulation part let’s have an overview of the selected components and also the thermal setup of our prototype.

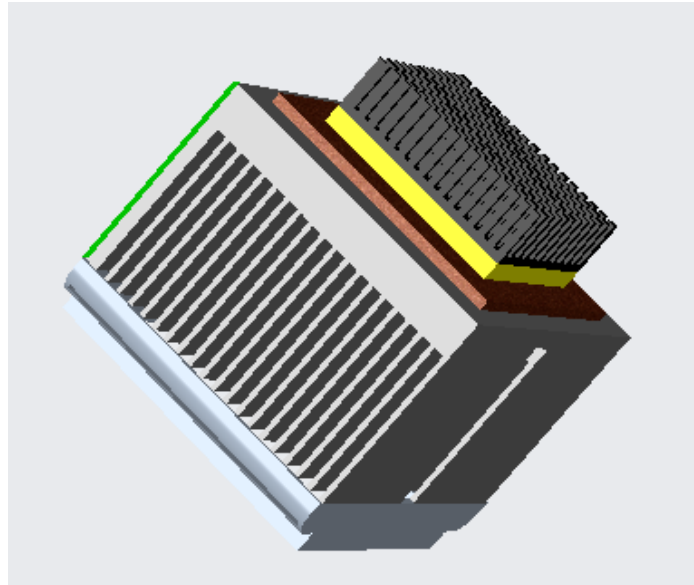


Image 9. 3D Model of the thermal structure (Courtesy: CREO Parametric)

The Components chosen and validated for their operating conditions and the thermal structure of the system are shown (image 9) from the following assumptions and validations through calculations. The final Design of the entire System is given below (image 10), followed by the component selected, and its key validations are also tabulated below,

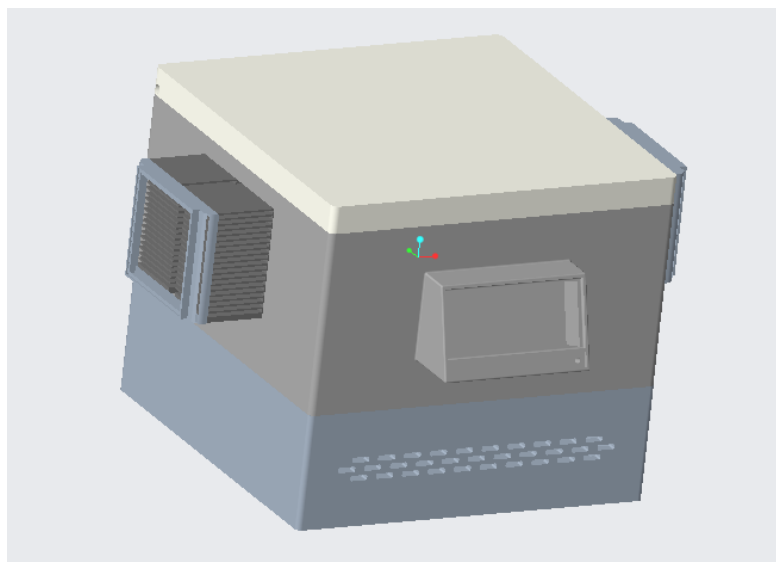


Image 10. 3D Model of the Design (Courtesy: CREO Parametric)

Table 6. Component selection

Component selected	No. Of items used	Parameter
Peltier Module	2	ATS-TEC40-35-018
TIM – Thermal Paste	2	Artic MX-4
TIM – Copper Plate (Hot Side)	1	50 × 50 × 4 mm copper plate
Heatsink Cold side	2	40 × 40 × 11 mm al Heatsink
Heatsink Hot side	2	60 × 77 × 36 mm al Heatsink
Cooling Fan - Cold side	2	40 × 40 × 10 mm commercial cooling fan
Cooling Fan – Hot side	2	50 × 50 × 15 mm commercial cooling fan

3.4. Simulation

The data analyzed and validated from the above calculations will be set as basic poles of inputs for our simulation to replicate every component as a model and proceed with simulating. The simulation will give out steady state observation of our system, giving us clarity over providing insights like the system's behaviour that could be analyzed and results could be validated. Having such a simulation model created will give us results that are analyzed, performance predicted, and design optimization considering limitations of risk mitigations.

By computing different simulation scenarios of our system, we could analyze all the possible outcomes of our system for different operating parameters, visualize the results and check if the system operates in the stable zone. Also, at the same time, computing the simulation could give us the possible fragility the system could face when the system overrates the safe operating zones; that is, in more specific terms, we will be able to observe the thermal runaway when overriding the safe limits.

First, moving over to the structuring of the simulation, the overall Model of the operatable simulation is placed below,

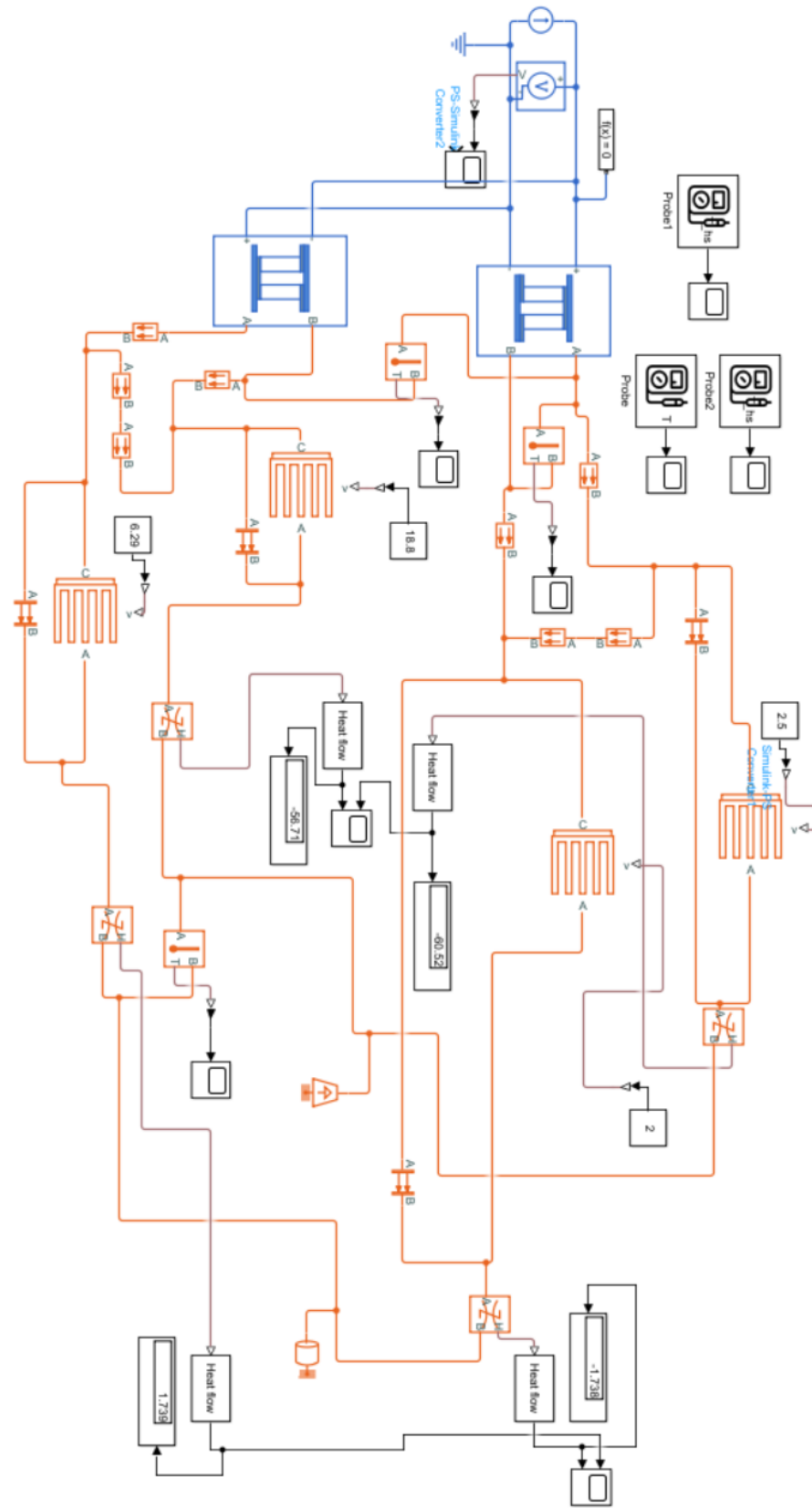

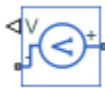

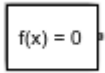


Image 11. Simulation model of our system (Courtesy:SIMULINK – MATLAB model)

The simulation model was created using SIMULINK from MATLAB; the Thermal simulation proceeded with simulink because the simulation could be carried out more efficiently as Simulink provides various thermal element blocks that perform various actions based on our required specifications. As mentioned earlier, the overall system operations will be regulated with the operation of two Peltier Modules, and the simulation model will be constructed with the same. The Model of our simulation will be presented below, followed by a brief explanation of the elements used in our simulation,

The above (*Image 12*) mentioned represents the simulation model for our system. It contains various thermal elements combined in series interconnection representing each component we have chosen. And on the successful build of the simulation model, we could measure appropriate changes concerning time, the parameters like ΔT , *Temperature regulated within the chamber*, *Heat flow rate*, and *Temperature over the heat sinks*. Before reviewing the simulation model in operation, let’s look at all the blocks and elements used in our Simulation model (*Tables 7 & 8*).

*Table 7. Thermal Components Used on the Simulation Block
(Courtesy: SIMULINK library - (“Thermal Models - MATLAB & Simulink,” n.d.))*

S.No	Component Used	Representation	Parameter of the Component
1.	Direct Current Source		Constant DC Power source (Independent of voltage).
2.	Voltage Sensor		Block represents the ideal voltage across the circuit under operating conditions.
3.	Electrical Reference		Electrical Grounding.
4.	Solver Configuration		Solver configuration.





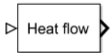
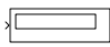







5.	Peltier Device		The Peltier module block represents our physical modules.
6.	Scope		Graphical data represented.
7.	PS-SM Converter		Converts Physical signal to Simulink signal.
8.	Constant		The constant Block represents the constant value as an input signal.
9.	Convertor		A similar type of PS – SM convertor.
10.	Display		Represents the data in the display.
11.	Probe		Represents the variables of any selected block.

Table 8. Thermal elements used on the simulation Block

(Courtesy: SIMULINK library - ("Simulink Documentation," n.d.))

S.No	Component Used	Representation	Parameter of the Component
1.	Temperature sensor		Measures the temperature difference between two ports
2.	Conductive Heat Transfer		This Block represents the conduction property for flat surfaces.

3.	Radiative Heat Transfer		This Block represents the radiation effect over a surface.
4.	Heat flow rate sensor		The Block measures the heat flow rate from Port A to Port B.
6.	Heatsink		The Heatsink block incorporates the physical heatsink parameters into the simulation model to ensure power dissipation.
7.	Temperature Mass		Represents a physical mass that reflects the combination of flow through it storing internal energy

With the above elements mentioned, the overall simulation model was developed as shown (*Image 12*), with connections made with each component making it a physical phasing of the Model initiating the basic parameters of the simulation. Starting with the source current and a voltmeter connected in source with the Peltier modules, the Peltier modules are generalized with our selected modules with initial parameters of the Block with Seebeck coefficient set to S_{AB} , Total electrical Resistance around 2.5 ohms, thermal conductance of 1.5 W/K are set parameters for the Peltier module blocks which will represent our physical Module used in our system. Followed by conductive heat transfer from TIM stuck over the Peltier; in our case, the thermal paste applied, which is considered as 1mm of thickness of the paste, is considered as input parameter with thermal conductivity for both sides of the Peltier modules and the convection insulation for two layers the outer shell and insulation layer is connected across the hot and cold sides of the Peltier.

We were followed by heat sinks at both ends of the device, which represents, as per our system, the heat sink parameters are set as per the block parameters, which will set forced convection with a constant connected as 2.5m/s for the hot side and 2.0m/s for the cold side as the cooling fan is used in our system followed by other parameters like the number of fins, base length, base height, flat plate height, etc. Over to this, the heat flow rate sensor is placed, and the indicator is connected to the display and scope with a PS-SM converter which is later connected to thermal mass at the end

of the cold side, which is that the thermal mass block represents the chamber with a mass stored within it. And the other hot end is connected to the Ambient. Also, three Probes were used to measure the steady state changes inside the chamber. The temperature change could be measured, and the other two probes track the heat sinks connected at two ends of the system.

The simulated results will be tabulated and plotted below in the Results and Discussion part. The simulations were made with different operating parameters of the system, and the main area of results that will be reviewed will be the monitored internal Temperature of the chamber, heat sink temperatures, ΔT difference temperature between the ends of the Peltier, ΔT vs Input Current.

3.5. User Interface – Mobile Application

The mobile application approach was moved forward with an easy approach for basic communication and Design which was possible to move forward with it, and it was made possible with the help of an open-source website (“MIT App Inventor,” n.d.) which is capable of designing the mobile application with our required communication with the controller could be established and able to transfer the float bits to and fro establishing a friendly working interface. (Image 12) shown below, is the Model of the interface that we will be using in our Mobile Application.

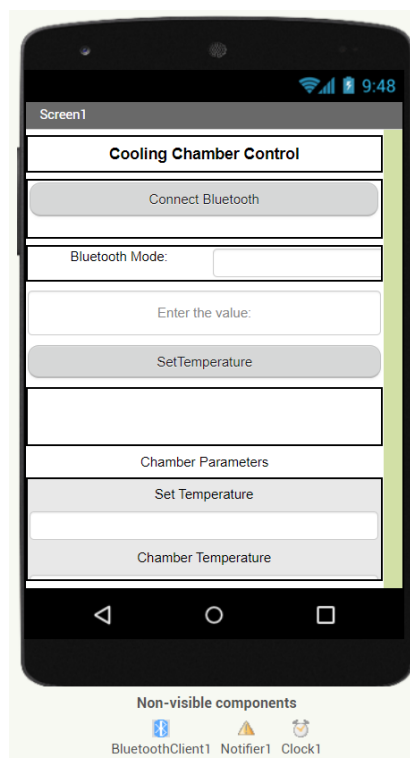


Image 12. Structure of the Mobile Interface (Courtesy: (“MIT App Inventor,” n.d.))

After creating the interface, the first part of the Application development is the establishment of basic Bluetooth connectivity. The blocks below are shown in (Image 18) where the Bluetooth connectivity is established with the Bluetooth client with the access address followed by the calling of the Bluetooth client to our Bluetooth Module connected to the Arduino module. Later the connection parameter is shown whether the connection is established or not to be shown in the application interface.

Plot 1. Block for Bluetooth connection establishment for the interface (Courtesy: (“MIT App Inventor,” n.d.))

Plot 2. Block for to and fro communication of data between the interface and the controller (Courtesy: (“MIT App Inventor,” n.d.))

Part two of the Block performs the transfer of the user-inferred data to the controller through the connected Bluetooth Module, which will infer changes to the set Temperature and, followed by the returning of data from the controller, will be captured in bytes as text, this gives the communication between the user interface from the mobile application and the micro-controller.

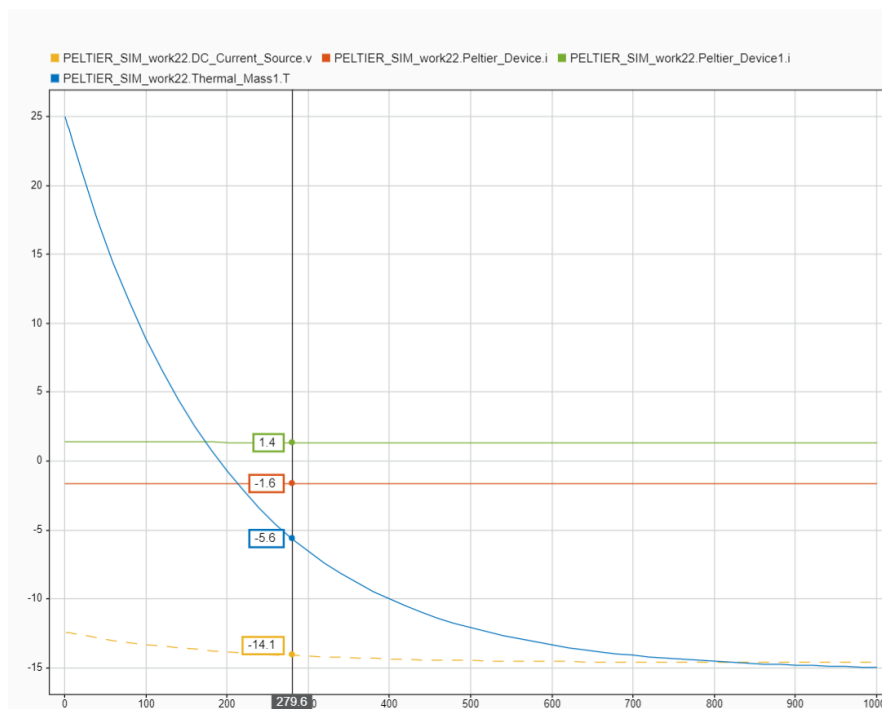
4. RESULTS & DISCUSSIONS

To successfully ensure the validated results fit tight with the components selected is sized rightly for the system could be reassured in simulating the results of the Model so that we can have a pre-look at operation changes covered. The initial simulated result below (*Plot 3*) will be the results of our goal that can be reached in a particular time with a particular current given as input,

$I = 3 \text{ A}$ (Input current)

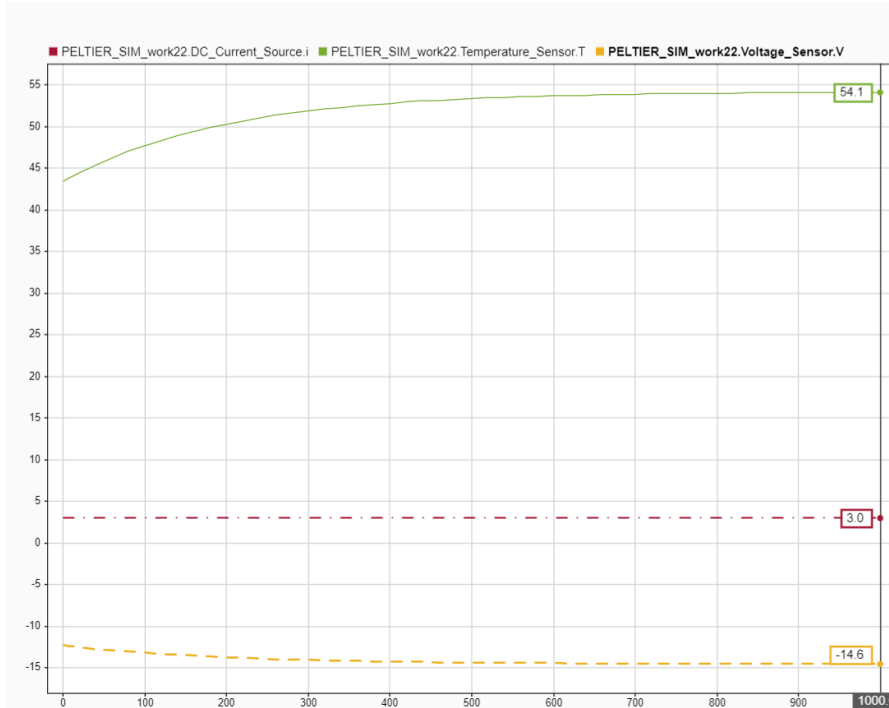
$V = 12\text{--}14 \text{ V}$ (Induced voltage across the circuit)

$T_{\text{chamber}} = -5 \text{ }^{\circ}\text{C}$ (Goal Temperature)



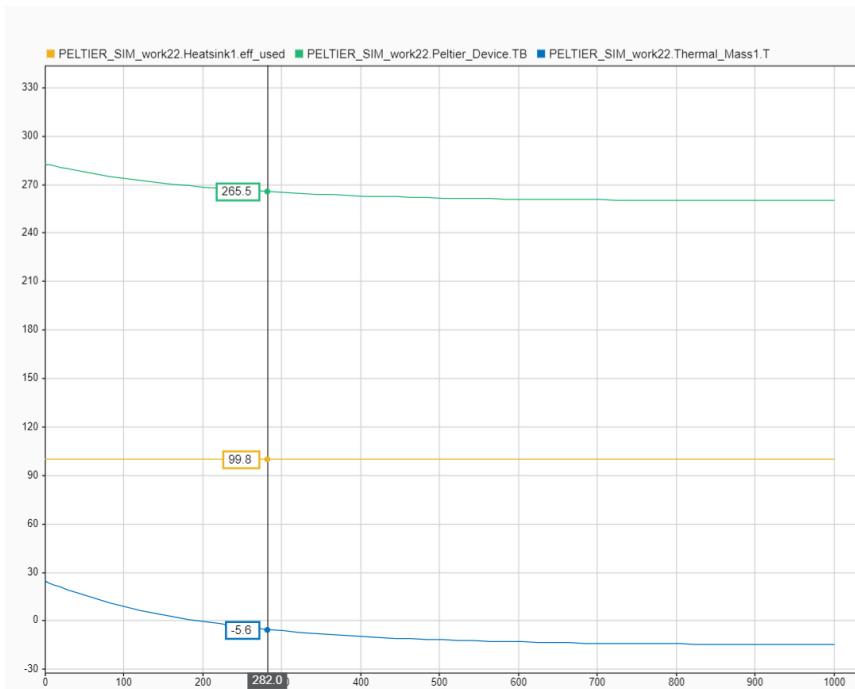
Plot 3. Internal chamber temperature vs. operating current & voltage (Courtesy: Simulation graph – data inspector)

The internal chamber to reach the specific Temperature of $-5 \text{ }^{\circ}\text{C}$ for the operation of two peltiers with 3A of current driven by a voltage of 14 V takes approx. It takes around 6 minutes to drop down from the ambient Temperature of $25 \text{ }^{\circ}\text{C}$. Also, we can see that the possible temperature reach could be approx. $-14 \text{ }^{\circ}\text{C}$. Next, let's plot the ΔT for the applied input power,



Plot 4. ΔT vs. the applied input current and voltage (Courtesy: Simulation graph – data inspector)

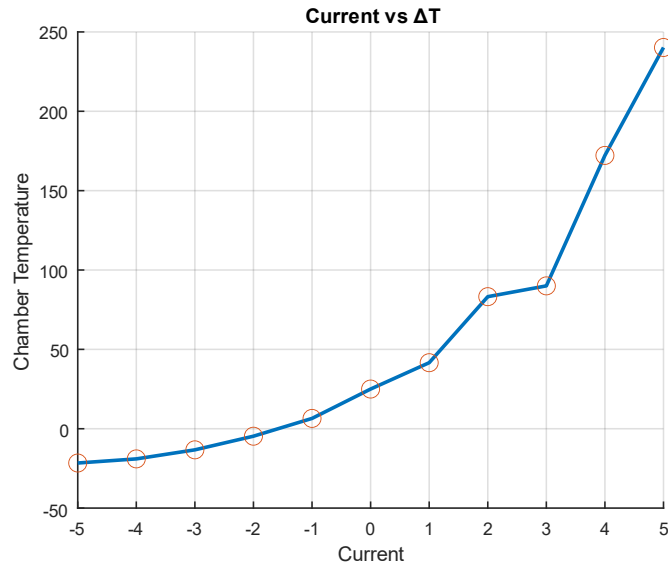
From the generated result of our system simulation, we have determined for the operating current and voltage of 3 A and 14 V, the possible difference temperature ΔT is read to be at 54 °C. Finally, let's plot the Temperature change within the chamber vs. Temperature on the cold side of the Peltier and the efficiency of the heatsink.



Plot 5. Internal chamber temperature vs. cold side heatsink efficiency and heatsink operating temperature

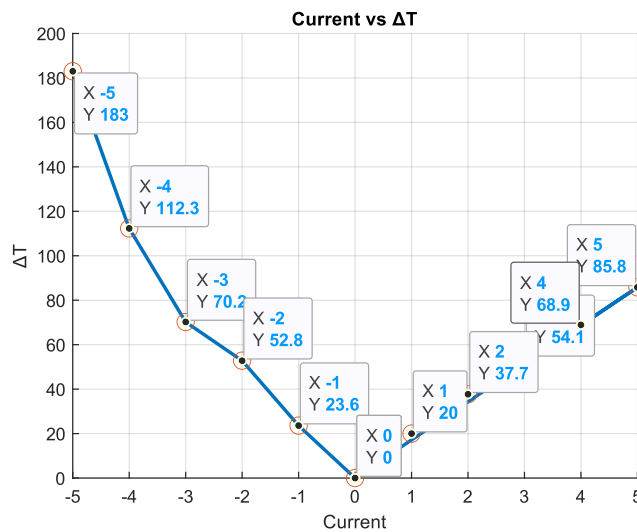
(Courtesy: Simulation graph – data inspector)

Forced convection in the cold side of the Peltier to cool down the surroundings from the above plots the Temperature recorded at the heat sink with the internal Temperature of $-5.6\text{ }^{\circ}\text{C}$ in the chamber is approximately 265.5 Kelvin is approx. $-7.6\text{ }^{\circ}\text{C}$. Now let us see the Relation between current induced vs. difference temperature ΔT



Plot 6. Graphical plot of Current vs. Chamber Temperature (Courtesy: MATLAB)

The final simulated result that will be plotted will be the internal temperature changes concerning varying input parameters. This is done to have an optimistic view of the thermal runaway exceeding the safety limits of the Peltier could be viewed.



Plot 7. Graphical plot of Current vs. ΔT (Courtesy: MATLAB)

In the above graph, the operating voltage up to 3 A keeps the Peltier under safe operating conditions, beyond which 4 A and 5 A over rates the peltier and get the difference temperature above the notified limit.

Now all the segments of the requirements for the Design and validation of the Thermal Systems are made, the regulation for the internal Temperature will be proposed using a Mobile Interface Application which could communicate with the Arduino module, which my colleague's thesis will regulate. The extent of the mobile application from my end limits is establishing a connection with the Module with Bluetooth Module placed along with the Arduino and data transfer between the interface and the control module.

5. PROTOTYPE

For the initiative to build a prototype for the thesis, the motivation moved us to create a miniature prototype, but not the same as the system we have created now. The miniature prototype is defined with different parameters and operated with a single Peltier module. The prototype will establish a dimensioning of $120 \times 120 \times 70$ mm as the internal chamber size, which gives us different operating conditions based on the above calculations and formulations stated above, giving us an easier approach to defining the parameters of the prototype, the required cooling load for the built prototype is approximate. 39 W. And for the inferred load, the calculations were performed, and a similar simulation model was also generated to compare the results and cross-check them.

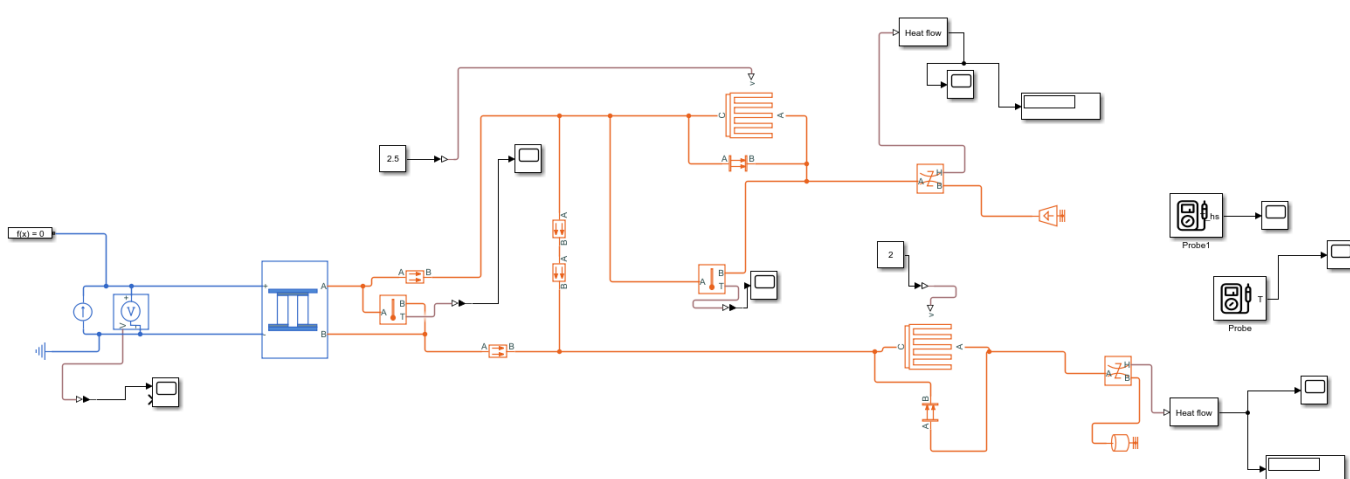


Image 13. Simulation model of the prototype (Courtesy: Simulink)

We determined the required changes for the set operating conditions from the simulation model. These results will help compare our built prototype’s dynamic changes; we might get an idealogy of how our system would work when the real-time prototype with our fully validated system could be reliable. Before moving forward with the results and comparisons, let’s view the prototype.

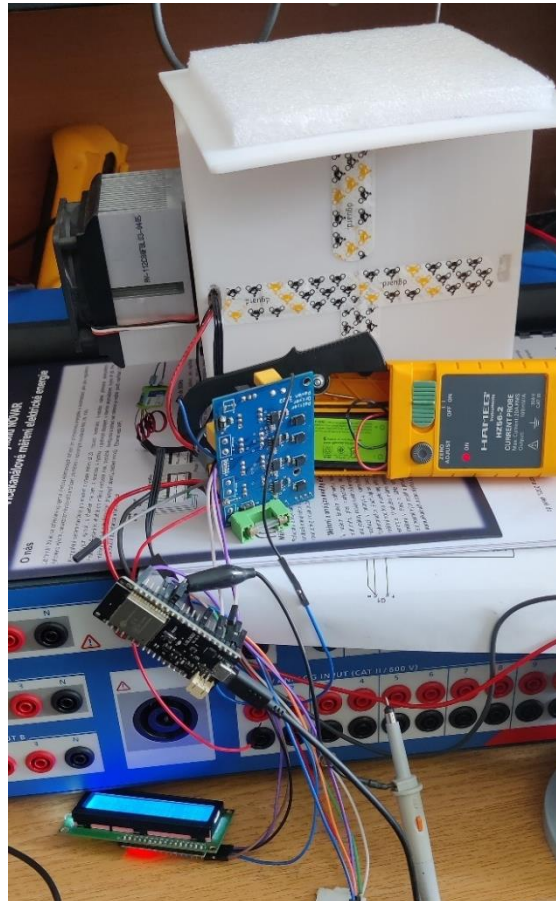
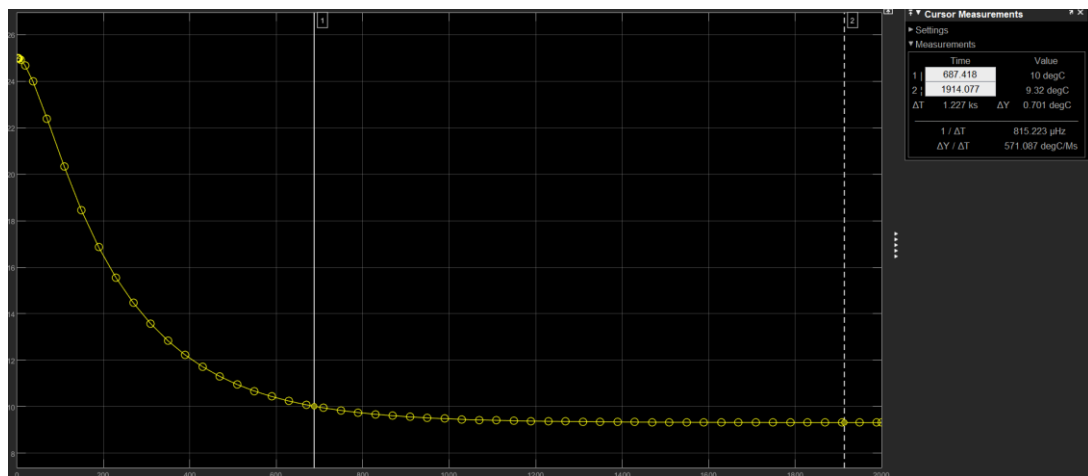
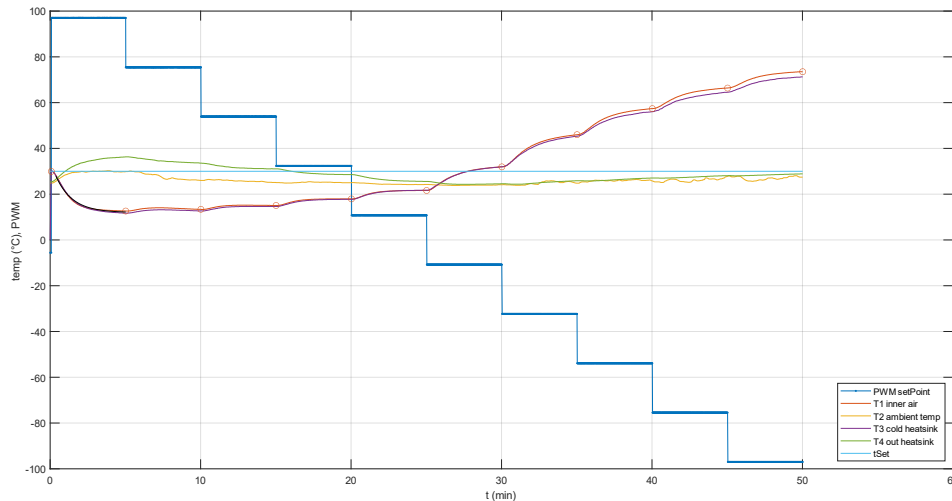


Image 14. Prototype setup for live simulation.



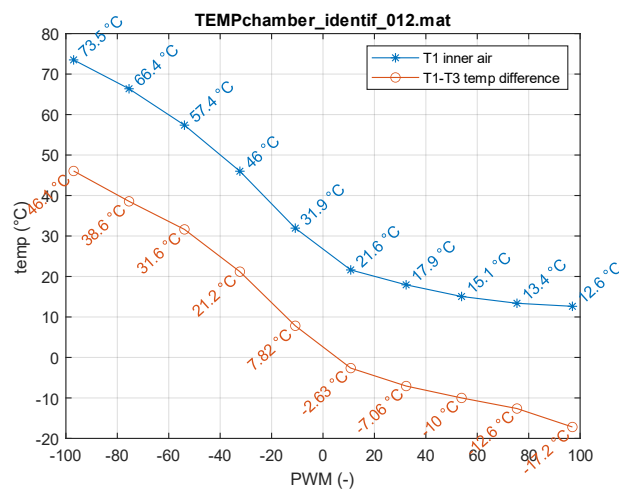
Plot 8. Simulation of Internal temperature change vs. Time (CourtesyMatlab)

From the above-simulated graph, we can see that with an operating parameter set to 5 A, we were able to measure a maximum internal temperature within the chamber approximately upto 9.6 °C which, when compared to (Image 23) the live results obtained from the prototype, states the maximum internal Temperature of the chamber was measured to be approximately 12.5 °C.



Plot 9. Possible measurements made with the prototype (Courtesy: MATLAB)

The above graph represents the dynamic changes incurred on the prototype, which compares with various properties like PWM regulating factor, Inner air temperature, Ambient Temperature, and Heat Sink temperature. These parameters are measured and plotted with the live operation of the prototype, which was operated for 50 mins in a varying pattern of the PWM. The results suggest that the system dynamics can put a temperature critical of 13 °C within 6 mins compared to the simulation, which takes approximately. Two hundred ninety seconds which is also approximately 6 mins.



Plot 10. Temperature Difference vs Internal temperature based on the PWM operating the Prototype

6. CONCLUSION

With all the possible Approaches to get the Model of our Thermal Casing working as per our requirement, starting from Persuading the calculations of the required load to having to select the right components and validating the results, and finally getting developing a simulation and a small prototype the goal of the thesis was addressed in every phase of the Relation. The outcome derived was the desired Temperature reviewed on the simulated Model of our system and the prototype to understand if it is working practically. Also, the mobile application used as the interface to control the system was built to ease the interaction for the end user.

The elaborative proceedings have been addressed, and the results were revised, which states the completeness of the thesis and beyond which the influence of this topic targets for future development of commercial units with complete functionality with seamless regulation of the system.

7. REFERENCES

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LIST OF SUPPLEMENT MATERIALS

S. No.	File Name	Usage
1.	FINAL_DESIGN_ASSEM (<i>Folder</i>)	Contains all the Sub 3D Design files that are used in the Final Assembly
2.	Final_as.asm	Final Assembly File
3.	Heat_trans.m	Matlab code for calculating the required Cooling Load
4.	HEATSINK_CALCULATIONS.m	Sizing calculations for Heatsink
5.	Q_H.m	Parameters of Peltier Calculations
6.	STEADY_STATE.m	Steady state calculations to plot the graph
7.	TEMPchamber_identif_012.m	Code to measure the live simulation results from the Prototype
8.	THERMAL_CASE_APP.apk	Mobile application establishing user interface.
9.	PELTIER_SIM_work22.slx	Simulation model created using simulink
10.	PROTO_SIM1.slx	Simulation model created using simulink for the Prototype