ECS 601 - Introduction to MEMS

Project Report : Heat Sink and Thermal Insulation Design for MEMS Resonator

Submitted by

Roll No	Names of Students
20213	Pratik Pal
20214	Priya Shukla

Department of Electrical Engineering and Computer Science

Indian Institute of Science Education and Research Bhopal

Bhauri, Bhopal, Madhya Pradesh, India - 462 066

2023-24 Semester I

Contents

Chapter 1

Introduction

In space applications where complex temperature and vacuum conditions dominate, the efficient use of flexible electronic components is a particular challenge This work focuses on the special aspect of temperature control in spacecraft resonators on the snow. Resonators play an important role in aerospace systems, serving a variety of applications from communications to navigation. However, their optimum performance depends on maintaining a stable temperature.

The hostile environment of space with high temperature fluctuations and the use of strong winds requires a complex temperature control system This project aims to develop, implement and test specialized system a applications designed to meet and ensure the unique challenges posed by the space environment.

This report provides detailed insights into the design concepts, processes, and results during the development of the thermal management system While exploring the thermal challenges based on space and particle requirements for resonant performance of the complexities, this project seeks to contribute to the development of advanced space technologies which requires reliable operation of the resonators in the situation.

The project's main objective is to design a temperature management system for space-based sensors, as we know that temperature goes too low and too high in space. This temperature variation affects the performance of any electronic system (which in this case is a MEMS Resonator). In such a case, we can make a temperature management system to keep the resonator's temperature steady. The project aims to design a sensor that will be put inside a box. The idea is to maintain the inner temperature constant irrespective of drastic temperature variations in space. We plan to test various ideas for keeping the resonator's temperature constant. We have planned to put a Peltier below the sensor, which will switch its performance according to the space temperature and sink the heat from the sensor. For this project we have designed a Peltier chip from scratch and designed a thermal management box inside which the MEMS resonator will be placed when it is operated in space. The details of all the executed designs of the Peltier Chip and the thermal management system are summarized in chapter 2 and chapter 3 respectively. The project uses the COMSOL Multiphysics software for carrying out all the simulations and analysing the data obtained after performing of the simulations.

Chapter 2

Design of the Peltier Chip for Thermal Management

2.1 Introduction and Description of a Peltier Chip

A Peltier chip, also known as a thermoelectric cooler or TEC (thermoelectric cooler module), is a semiconductor device that uses the Peltier effect to achieve active heat transfer between two materials -There is a case where electricity flows through a circuit in which two types of conductors are involved, causing heat absorption at one junction and radiation at another. A Peltier chip is a series of thermocouples made of semiconductor materials, usually bismuth telluride or similar materials. These thermocouples are electrically connected in series and thermally coupled in parallel. When a direct current (DC) is applied to a Peltier chip, electrons move from the higher temperature side (heat source) to the lower temperature side (heat sink), absorbing heat on the hot side and releasing it on the positive side the cold side of the temperature . The key characteristics of a Peltier effect based thermal cooler includes compact design, reversible operation, solid-state operations and efficiency considerations. There has been a lot of development on the materials for fabrication of a Peltier chip in order to increase performance so that it can be applied to more areas which requires thermal management systems [1]. The dual powered automatic Peltier Effect cooler [2] has also helped in designing the Peltier chip for the MEMS resonator for space applications for this project.

2.2 Design of the Peltier Chip Model Using One Thermocouple

In this design we solve the heat transfer and electric field in a thermoelectric leg type of a structure. The Peltier effect is used for cooling purposes in this device. This device according to the application which is to thermally insulate the MEMS resonator which will be of few microns dimensions. The dimension of the Peltier chip model is 1 mm X 1 mm X 6 mm which means that the Peltier chip has a base area of 1 mm^2 and has a height of 6 mm . This design perfectly aligns with our requirements since we want to design a thermal insulator box of atmost 1 cm X 1 cm X 1 cm dimension. The designed model of the Peltier chip is shown in figure 2.1.

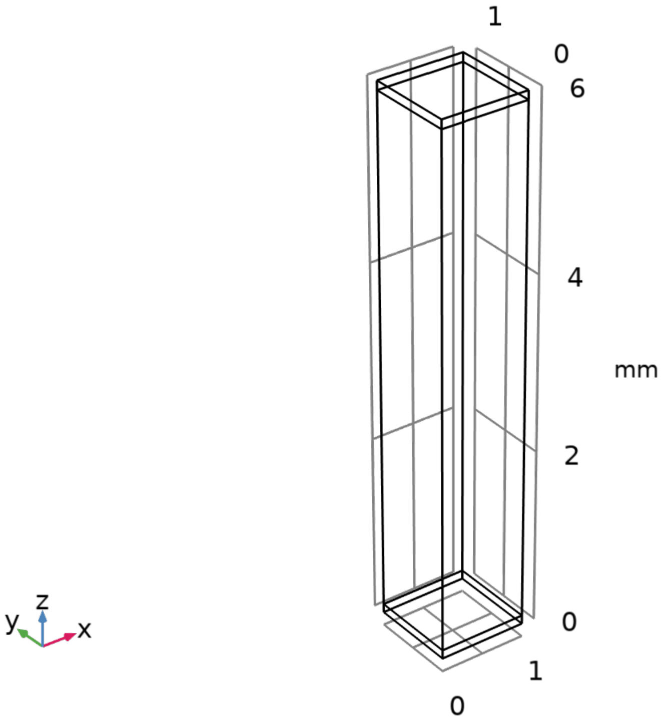

Figure 2.1: Model of the Designed Peltier Chip

The top and the bottom base of the chip is made using copper and the thermocouple is made using bismuth telluride (Bi_2Te_3). We have made the system using one thermocouple since this has to be used for space applications and we have constraint on the area to be used and the payload which can mbe used in the maximum condition in order to launch the sensor without any failure. To simulate out design in the software we have used the Heat Transfer and Solid module of COMSOL. We have provided the potential difference between the two plates to be 0.2 Volts. After applying the potential difference the current starts to flow and the external heat is transferred from the cold plate to the hot plate which generally is connected to a heat sink in order to maintain the temperature difference between the plates. The main equations which govern the heat conduction and the current flow that is the thermoelectric effect are given in equation 2.1.

$$\begin{aligned} P &= S \cdot T \\ q &= P \cdot J \\ J_e &= -\sigma S \nabla T \end{aligned} \tag{2.1}$$

where P is the Peltier Coefficient, S is the Seeback Coefficient, T is the temperature, J is the current density, σ is the conductivity and J_e is the electron current density. After the simulation is performed, the temperature plot across the two plates and the isosurface temperatures is shown in figure 2.2.

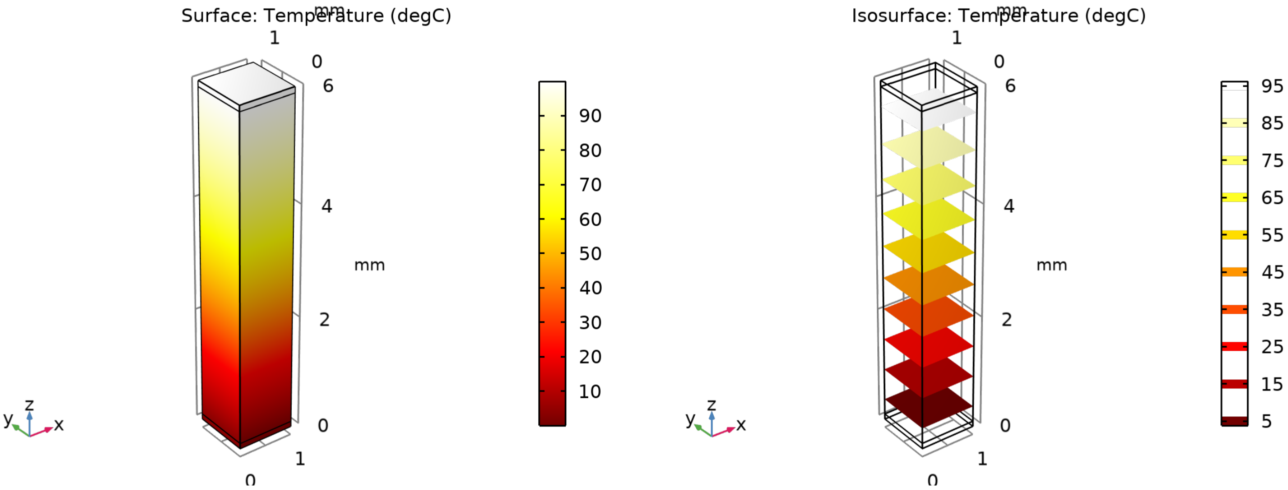

Figure 2.2: Temperature Profile and the Isosurface temperatures of the Peltier Chip.

The plot of the electric potential acrross the Peltier Chip is shown in figure 2.3.

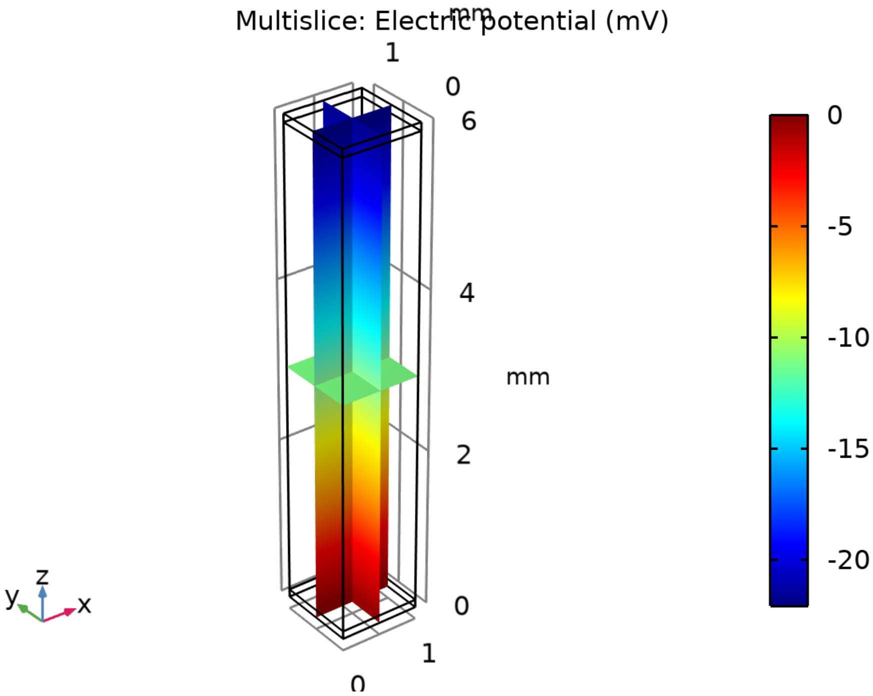

Figure 2.3: Electric Potential of the Designed Peltier Chip.

In this simulation we have also used the Electromagnetic Heat Source sub module in order to provide with an external heat source which can almost replicate the external temperature fluctuations which can occur in the environment.

2.3 Design of the Peltier Chip Model Using Two Thermocouples

In this model we have used two thermocouples in place of one as in the previous design. We have used copper as the material for the hot and the cold plates, bismuth telluride as the material for the thermocouple and bottom and the top plates as alumina. The area of the base plate is 3 X 0.5 μm^2. The height of the thermocouple is taken to be of 1.5 μm. The design of the model is shown in figure 2.4.

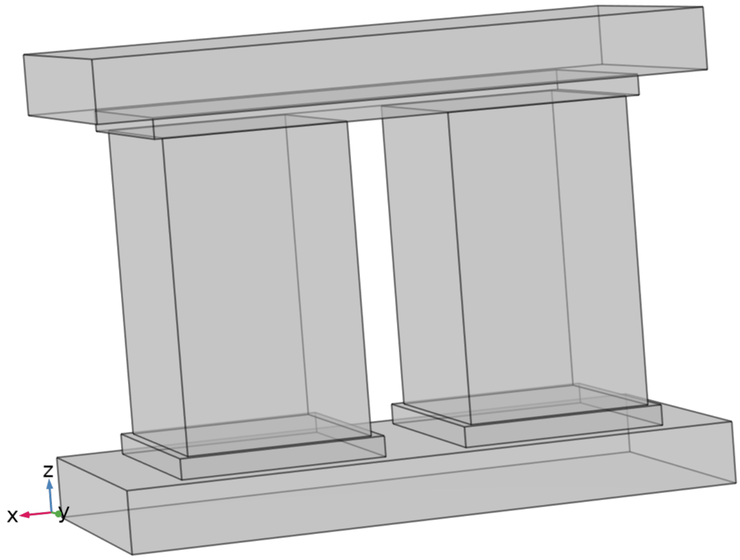

Figure 2.4: Design of the Peltier Chip using two Thermocouples.

The model optimizes the dimensions of the Peltier chip which more suites to the requirements since the dimensions are taken in the micron range. This will ensure that the thermal insulation has enough space inside it so that more such Peltier chips or some other thermal insulation mechanism can be implemented in order to withstand the high temperature difference in the space atmospheric conditions. The equations 2.1 govern the thermoelectric phenomena in the Peltier chip. Also, the heat transfer in the solid in the governed by the following equation 2.2

$$\rho C_p \frac{\partial T}{\partial t} = \nabla \cdot (k \nabla T) + Q \tag{2.2}$$

where ρ is the density of the material , C_p is the specific heat capacity, k is the thermal conductivity of the material and the Q is the heat energy from the heat source. In this simulation we have also used the Electromagnetic Heat Source sub module in order to provide with an external heat source which can almost replicate the external temperature fluctuations which can occur in the environment.

The DC voltage applied across the the hot and the cold plates is 0.1 Volts. After performing the simulation, the temperature profile and the isothermal contours in Kelvin (K) are shown in figure 2.5.

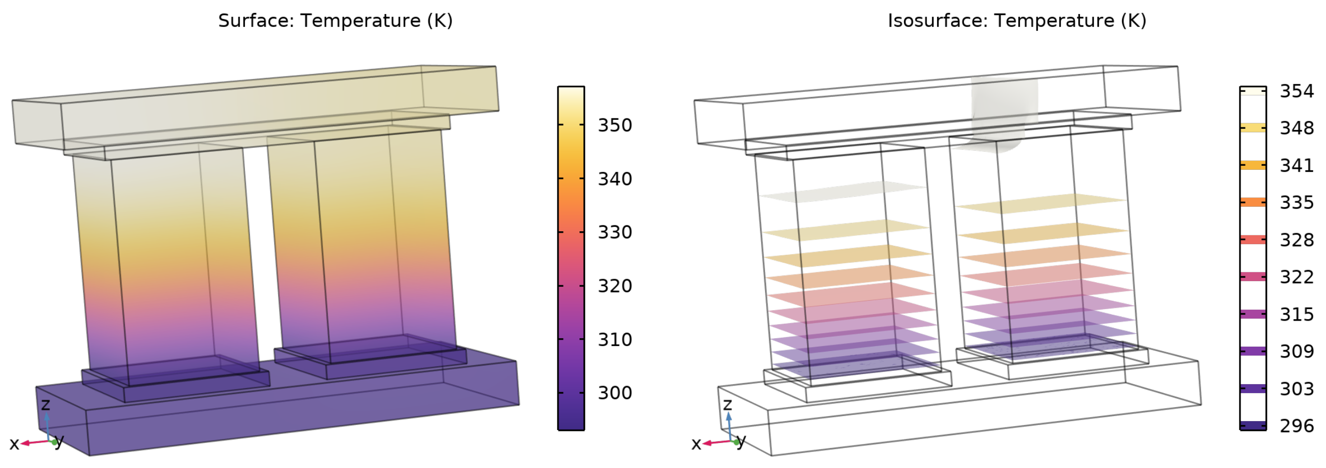

Figure 2.5: Temperature Profile and the Isosurface temperatures of the Peltier Chip using two Thermocouples.

The electric potential in Volts across the Peltier Chip and the electric field in V/m is shown in figure 2.6.

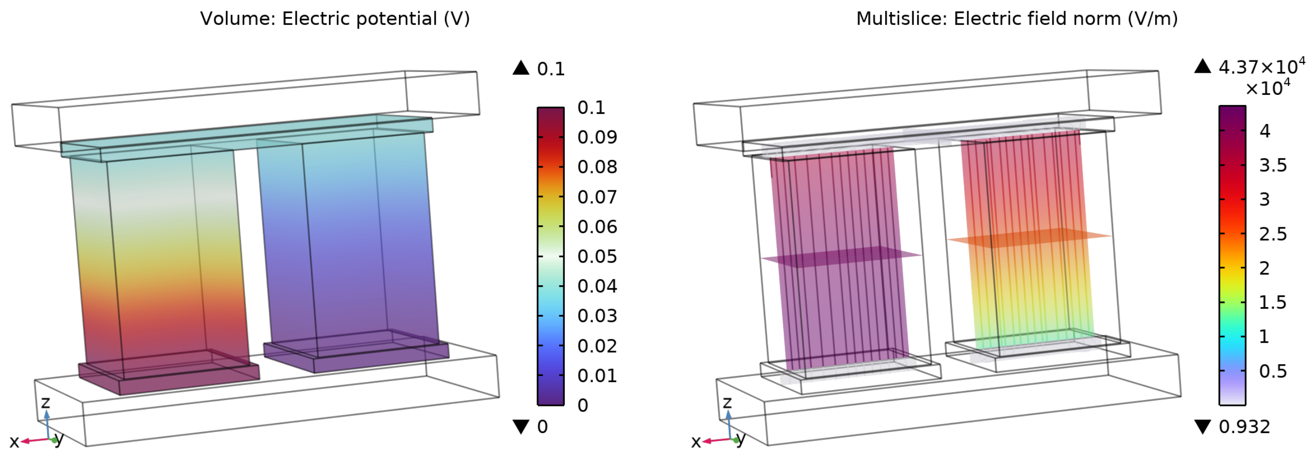

Figure 2.6: Electric Potential Profile and the Electric field distribution of the Peltier Chip using two Thermocouples.

2.4 Observations from the Simulation Results

From the results of the simulation of the Peltier chips it has been observed the optimum temperature profile is obtained when the bias voltage 0.2 Volts and 0.1 Volts respectively. The dimensions of the design are optimised as much as possible in order to use it for the thermal management system for the MEMS resonator. Therefore our designed model can be used in space applications as we have considered almost all the Physics required for the analysis and the temperature of the cold plate is optimum to keep the system at a constant temperature without much variations.

Chapter 3

Design of Thermal Insulating System for MEMS Resonator

3.1 Introduction and Description

At MEMS scale, due to the relatively large surface to volume, the heat losses become significant. Therefore an efficient heat transfer system is required in order to ensure that the heat is not trapped in the chip. The design if the thermal insulating box involves careful consideration of the material selection and insulation techniques and to also ensure that the box provides adequate structural support to protect the MEMS resonator and maintain its intergrity over varying temperature conditions. he box should be compact, lightweight, and capable of effectively isolating the MEMS resonator from ambient temperature changes. Extensive research work has been carried out to ensure thermal insulation of different types of sensors. As mentioned earlier space conditions are quite harsh in terms of the temperature difference. A novel thermal insulation design is proposed for radioisotope generators [3] which produce very high temperature during its operation. In space, similar conditions prevail since there are large temperature differences and the resonator has to kept in constant temperature in order to make it work efficiently.

3.2 Design of the Thermal Insulating Box

In this problem we have designed a thermal insulating box of length 20 cm, width of 6 cm and height of 8 cm. We have used aluminium as the material to design the insulating box layered with polypropylene and polyurethane as two layers. The box is filled with air. To model our resonator we have placed a box which is filled with water which basically can be thought as some heat sink which is associated with the sensor. The dimensions of the box which is present inside is 8 X 3 X 2 cm. The materials used are the same as that of the thermal insulator that is aluminium layered with two layers each of polypropylene and polyurethane. Since we have used water as a fluid therefore the heat transfer equation which governs the process which is given in equation 3.1

$$\rho C_p \frac{\partial T}{\partial t} + \rho C_p u \cdot \nabla T + \nabla \cdot (k \nabla T) = Q + Q_p + Q_{vd} \tag{3.1}$$

where ρ is the density of the material , C_p is the specific heat capacity, k is the thermal conductivity of the material, Q is the heat energy from the heat source and u is the heat flux. The simulation is carried at a time interval of 24 hrs and considering the weather and temperature of Rajasthan in the month of May so that we can analyse the model in the high temperature. The model of the insulator is shown in figure 3.1.

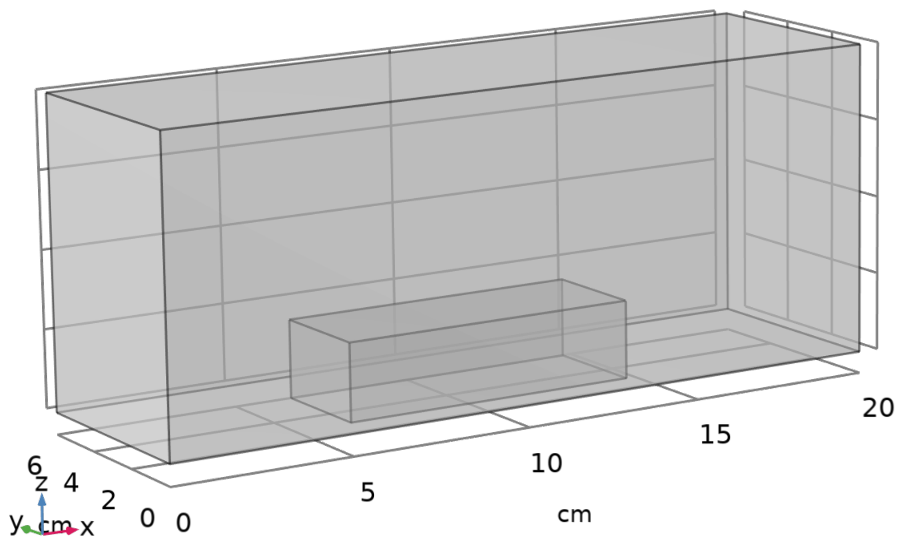

Figure 3.1: The model of the thermal insulator.

After simulating the surface temperature profile of both the outer and the inner box and the isothermal contours is shown in figure 3.2.

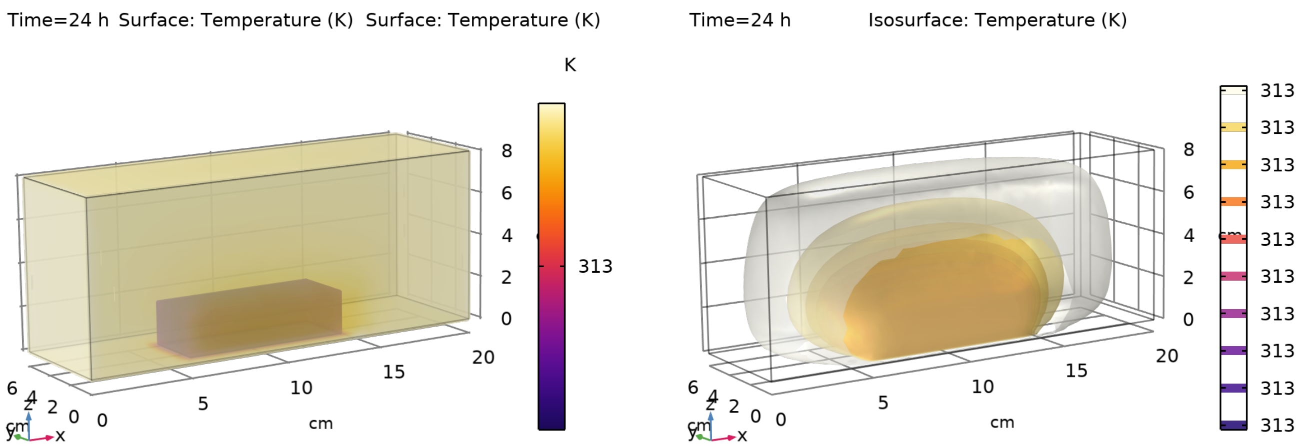

Figure 3.2: Temperature profile and the isothermal contour of the insulator.

From the simulation results we can see that the outer box can maintain the temperature by atleast an amount of 10 Kelvins with respect to the outside temperature. Since we used water as fluid the temperature of the inner box is quite less than that of the outer thermal insulator which has resulted in insulating the inside box which is replicated as the sensor. The constraint with this design is that the dimensions have to be a little more optimised so that it can be used for the space applications as mentioned earlier since we have an area and payload constraints. Otherwise, our model is perfectly functioning as thermal insulator at a limited temperature difference of the external conditions.

3.3 Design of a Model of Second Thermal Insulator for MEMS Resonator

In this design of the thermal insulator we try to study the surface-to-surface radiation. The model treats thermal radiation as an energy transfer between boundaries and external heat sources where the medium does not participate in the radiation (transparent medium). We have used aluminium as the material to design the insulating box layered with polypropylene. The box is filled with air. To model our resonator we have placed a box which is filled with water which basically can be thought as some heat sink which is associated with the sensor. The material that of the box inside is same as that of the outer thermal insulator box The model is shown in figure 3.3.

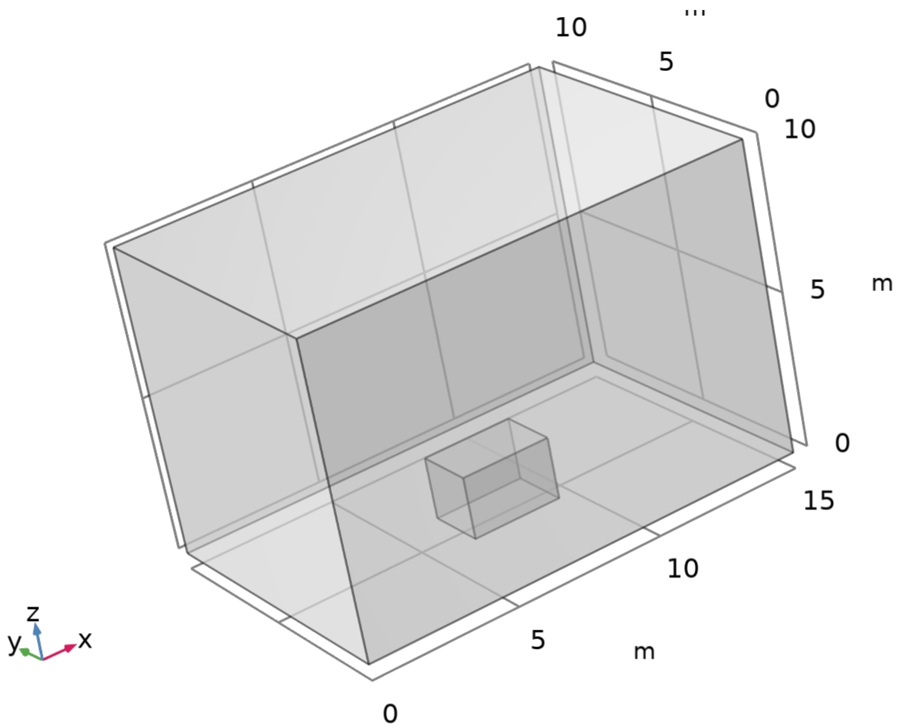

Figure 3.3: The model of the thermal insulator for studying surface-to-surface radiation.

After simulating the model, the surface radiosity of the outher thermal insulator in W/m^2 is shown in figure 3.4 and the surface radiosity of the inner box is shown in figure 3.5. The radiometric term radiosity means the rate at which energy leaves a surface, which is the sum of the rates at which the surface emits energy and reflects (or transmits) energy received from all other surfaces.

Radiosity simulations are usually based on a thermal engineering model of emission and reflection of radiation using finite element approximations.

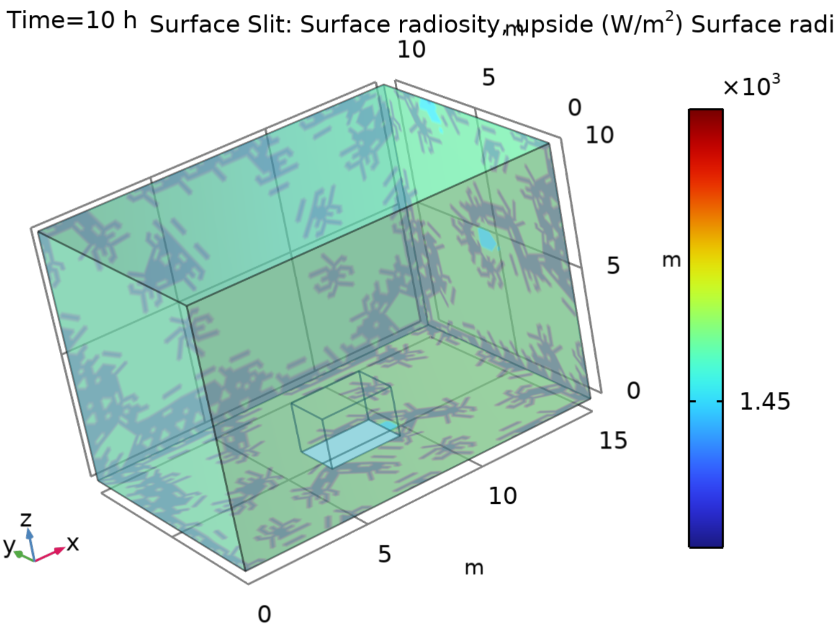

Figure 3.4: The surface radiosity profile of the outer box.

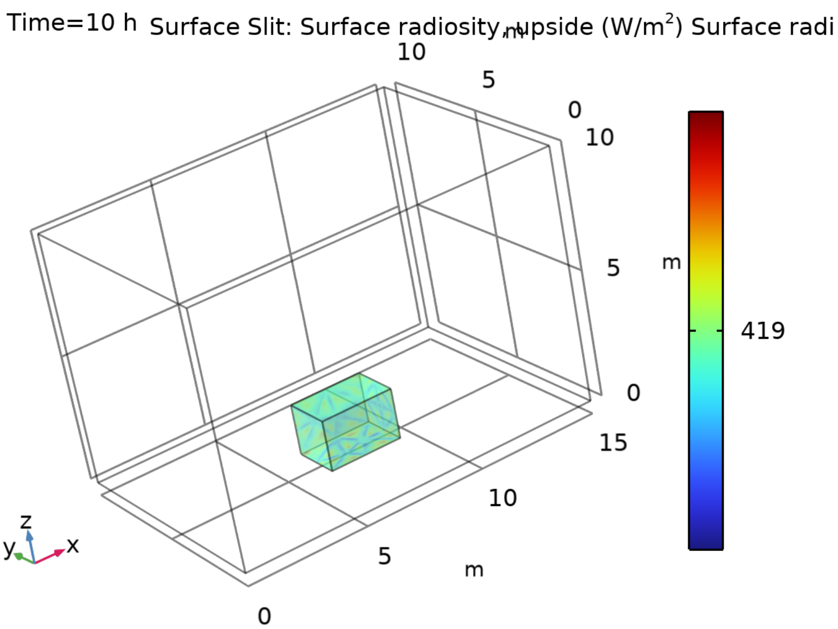

Figure 3.5: The surface radiosity profile of the inner box.

From the simulation result it is very evident that the surface radiosity of the outer box is almost ten times more than that of the inner box. The resason for this observation is that the since the outer box works absorbs more heat energy being directly exposed to the external environmental conditions and thereby does not allow the heat energy to get transfered into the inner box which is modeled as the MEMS sensor. Therefore, we can conclude that the outer thermal insulator shields the inner box from the external heat energy which results its surface radiosity becoming higher than that of the inner box. The only constraint with this model is that of the dimensions since this model was designed to study the surface-t0-surface radiation of the outer and the inner boxes. The dimensions need to be more optimised in order to use it for space applications.

3.4 Observations and Future Work

Space is the medium where heat is transferred by radiation or conduction. Space instruments are mostly enclosed by some shield and box hence conduction way of heat transfer is dominated. The outer components get heated by the solar radiation. The most fundamental solution to space based thermal issue is to minimize the solar absorptivity and maximize IR emissivity. Our future plan is to apply a coating with the specific optical properties that can reflect back the most of the heat coming from the solar radiation. From our research, we found the most efficient solution the "FEP Tapes" that is used in recent space mission as the thermal reflector. Second-surface silver Fluorinated Ethylene Propylene (FEP) tapes offer excellent performance as radiator coatings, reflecting incident solar energy (low solar absorptivity) while simultaneously emitting spacecraft thermal energy efficiently (high IR emissivity). We will use this tape to cover the outer box of the sensor which ensures the reflecting back the maximum radiation coming from the sun and acts as a good emitter.

For cooling the internal sensors we plan to put the Pyrovo Pyrolytic Graphite Film (PGF) thermal straps developed by Thermotive have already flown in optical cooling applications for high altitude cameras and avionics on larger spacecraft. The specific thermal conductivity of this material has been shown to be 10x better than aluminum and 20x better than copper. In the oposite weather condition when temperature will be considerably low to operate the sensors, we plan to put a kapton heater another side of the thermal straps and will take the advantage of it's higher conductivity to transfer the heat from heater to sensors.

Chapter 4

Conclusion and Contribution

In conclusion, the design and implementation of a thermal insulation system for MEMS sensors represents a major advance in microelectromechanical systems The main goal of this work is to solve the thermal management challenges of MEMS sensors, insulation system developed has shown remarkable success in achieving this objective. In this work we have tried to optimize the design dimensions which was one of the most crucial and challenging part of the project since the behavious of the materials and a system as a whole behaves quite differently when implemented at a macro level and micro level since the Physics changes with the dimensions.In this project we have designed two categories of thermal insulating systems - one which uses the Peltier effect and the other a thermal insulating box design using suitable maerials which shield the inner sensor from the external heat temperature. The insulation system presented in this project not only effectively shields MEMS sensors from external thermal influences but also optimizes their performance by maintaining a stable and controlled operating temperature. The implementation of this project has helped us a lot in understanding the critical technology and engineering which is present and considered during the designing and implementation of a thernal management systems for micro sensors. The project not only enhances the understanding of thermal considerations in MEMS sensor design but also opens avenues for future research and innovation in the broader realm of microelectromechanical systems.

4.1 Individual Contributions

The designing and simulation of the Peltier Chip using one thermocouple was done from the side of Pratik Pal and the designing and simulation of the Peltier Chip using two thermocouples was done from the side of Priya Shukla. The designing, simulation and study of the temperature difference of inside and outside of the sensor is done by Priya Shukla and the study of the surface radiosity and designing of the second thermal insulator was done by Pratik Pal. The preparation of the report and the presenstation was done equally from both the sides.

References

[1] L. A. Nimmagadda, R. Mahmud, and S. Sinha, "Materials and devices for on-chip and off-chip peltier cooling: A review," *IEEE Transactions on Components, Packaging and Manufacturing Technology*, vol. 11, no. 8, pp. 1267–1281, 2021.

[2] N. Islam, R. Islam, J. Rana, and H. U. Zaman, "A novel design of a dual-powered automatic peltier effect cooler," in *2020 IEEE Region 10 Symposium (TENSYMP)*, pp. 287–290, 2020.

[3] X. Wang, W. Chan, P. Fisher, R. Liang, and J. Xu, "Thermal insulation design of portable radioisotope electrical generators," in *2019 19th International Conference on Micro and Nanotechnology for Power Generation and Energy Conversion Applications (PowerMEMS)*, pp. 1–5, 2019.