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Thermal and Cost Analysis of Insulating Materials for Steam Pipe

A PROJECT REPORT

SUBMITTED IN PARTIAL FULFILLMENT OF THE

REQUIREMENTS FOR THE AWARD OF THE DEGREE

OF

MASTER OF TECHNOLOGY

IN

Department of Mechanical Engineering

Submitted by:

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2K21/THE/14

Under the supervision of

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DEPT. OF MECHANICAL ENGINEERING

DELHI TECHNOLOGICAL UNIVERSITY

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CANDIDATE'S DECLARATION

I, Prashant Kumar Shanker (2K21/THE/14), student of MTech (Thermal Engineering), hereby declare that the Project Dissertation titled — "Thermal and Cost Analysis of Insulating Materials for Steam Pipe", which is submitted by me to the Department of Mechanical Engineering, DTU, Delhi in fulfilment of the requirement for awarding of the Master of Technology degree, is not copied from any source without proper citation. This work has not previously formed the basis for the award of any Degree, Diploma, Fellowship or other similar title or recognition.

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CERTIFICATE

I hereby certify that the Project titled "Thermal and Cost Analysis of Insulating Materials for Steam Pipe", which is submitted by Prashant Kumar Shanker (2K21/THE/14), for the fulfilment of the requirements for awarding of the degree of Master of Technology (MTech) is a record of the project work carried out by the student under my guidance & supervision. To the best of my knowledge, this work has not been submitted in any part or fulfilment for any Degree or Diploma to this University or Elsewhere.

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ABSTRACT

Keywords - Economic thickness, Cost Optimization, Thermal Analysis, Steam Pipe.

This Project aims to determine the economic insulation thickness for various materials and perform a thermal analysis to find the insulation material thickness's heat flux and temperature distribution. We also conduct a cost analysis to find the minimum cost according to a MATLAB program's economic insulation thickness. Finally, we calculate the payback period using the heat flux with and without insulation. To achieve these objectives, we develop a MATLAB program that finds the economic insulation thickness for a given set of parameters such as temperature difference, insulation conductivity, outside convective heat transfer coefficient, etc. The program outputs the consistency required to minimise insulation cost and heat loss. We then use this thickness value in ANSYS to create the 2D geometry of the steam pipe with insulation. After completing the geometry, we perform a thermal analysis on ANSYS Fluent to find the insulation material's heat flux and temperature distribution. Finally, we conduct thermal research for different insulation materials and compare the results to determine the most effective insulation material in reducing heat loss. Once we obtain the heat flux values, we perform a cost analysis to determine the savings from insulation. Cost saving includes considering the initial cost of insulation and the yearly savings in energy costs. We also calculate the payback period to determine the time it would take for the insulation to pay for itself. From the results we obtain, we observe that the directional heat flux plays a crucial role in determining the performance of the insulation material. A higher directional heat flux in the insulation material indicates better insulation performance. In conclusion, this project provides a comprehensive approach to finding the economic thickness of insulation, determining the thermal performance of insulation materials and analysing the cost and payback period of insulation. These findings can be used to select insulation materials for steam pipes and design energy-efficient systems.

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PRASHANT KUMAR SHANKER

2K21/THE/14

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List of Symbols, Abbreviations

ri – Radius of pipe

L - Pipe length

Ta - Ambient temperature

Ts - Steam temperature

ho - Outer heat transfer coefficient

kins - Thermal conductivity of insulating material

Cins - Insulation cost

Q - Heat transfer rate

n - Interest Rate factor

Td - Temperature difference between the steam and ambient air

U - Overall Heat Transfer Coefficient

ro - Radius of pipe after Insulation

tins - Thickness of Insulation

P1 – Insulation cost

P2 - Heat loss cost

Chapter 1
Introductions

The increasing demand for energy in various sectors has driven a higher utilisation of pipelines for fluid transportation. Water, oil, natural gas, steam, and chemicals are among the fluids transported through these pipelines. To keep precise temperatures and pressures, it is crucial to ensure the transportation of these fluids. Heat loss in pipelines poses a significant challenge, leading to reduced efficiency, higher energy consumption, and increased operational costs, particularly in high-pressure fluids like steam.

Insulation is often used in pipelines to reduce heat loss. However, the amount of heat lost through insulation depends on the type and thickness of the insulation used. Thus, determining a pipeline's economically viable insulation thickness is essential to ensure thermal efficiency and cost-effectiveness. In addition, choosing a suitable material is critical for reducing heat loss.

This project focuses on determining the economic insulation thickness for a steam pipeline and evaluating the thermal performance of various insulation materials. Moreover, the project involves assessing the cost-effectiveness of insulation implementation on the channel. We use ANSYS Fluent software for analytical calculations and numerical simulations for this project.

The project entails determining the insulation material's heat flux and temperature distribution for different thicknesses and materials. The thermal performance of the insulation materials is assessed based on their heat loss reduction capabilities. The cost-effectiveness analysis encompasses the initial insulation cost, energy savings achieved, and payback period.

In conclusion, this project aims to provide valuable insights into the thermal performance and cost-effectiveness of different insulation materials for steam pipelines. The results of this project can assist pipeline designers, engineers, and operators in making informed decisions regarding the selection and utilisation of insulation materials.

1.1 Overview

This project aims to identify the most cost-effective insulation thickness for steam pipes and assess the thermal efficiency of the insulation material in different operating conditions. Heat transfer through pipes can result in considerable energy waste, and insulation is commonly employed to decrease this loss. However, the insulation thickness used is often higher than the ideal thickness, causing an increase in material and installation expenses. This project aims to establish the most economical insulation thickness, minimising material and installation costs while providing adequate insulation to prevent excessive heat loss.

To accomplish this goal, we first used MATLAB to perform a cost analysis of insulation thicknesses for several different insulation materials, including fibreglass, rock wool, and calcium silicate. We then determined the most economical insulation thickness for each material, considering the cost of the insulation material, the installation cost, and the energy savings resulting from reduced heat loss.

Next, we used ANSYS Fluent to perform a thermal analysis of the insulation material for the chosen thickness under various operating conditions. We analysed the heat flux and temperature distribution across the insulation material for different steam pipe diameters and thicknesses. We also investigated the effect of changing the insulation material on the thermal performance of the insulation.

Finally, we used the results of our cost and thermal analyses to determine the payback period for each insulation material and thickness. This payback period represents the time it takes for the energy savings resulting from reduced heat loss to offset the initial material and installation costs. By comparing the payback periods for different insulation materials and thicknesses, we can identify the most cost-effective insulation solution for steam pipes.

Overall, this project aims to provide practical guidance for selecting insulation materials and thicknesses for steam pipes to minimise energy loss and reduce costs.

1.2 Background

In many industries, it is essential to have thermal insulation to lower heat transfer, save energy, and improve efficiency. Insulation is a flexible material that can cover a range of items, including pipes, tanks, vessels, and boilers. The amount of heat that passes through the insulation depends on various factors, like the thickness of the insulation, the material's conductivity, and the temperature difference. The thickness of the insulation is a crucial factor in determining how much heat passes through it. Therefore, it is essential to accurately determine the appropriate insulation thickness to conserve energy and decrease heat transfer.

Various insulation materials are available in the market, such as fibreglass, mineral wool, polystyrene, polyurethane foam, and cellular glass. Each insulation material has a different thermal conductivity; its performance depends on the specific application and operating conditions. Therefore, the appropriate insulation material is necessary based on its thermal conductivity and other properties.

Selecting the appropriate insulation material and thickness influences expenses and energy conservation. In addition, identifying the optimal insulation thickness can significantly decrease energy usage and achieve cost savings. Therefore, it is imperative to conduct a comprehensive analysis to ascertain the most suitable insulation thickness and its impact on expenses and energy savings.

In this project, we aim to determine the economic thickness of insulation for a steam pipe using various insulation materials such as fibreglass, mineral wool, polystyrene, polyurethane foam, and cellular glass. We will conduct a detailed analysis to determine the optimal thickness of insulation based on its impact on energy savings and cost. We will also analyse the temperature distribution and heat flux across the insulation material to understand its thermal performance. The findings of this research can assist in enhancing insulation design, leading to lower energy consumption and costs in a range of industrial settings.

1.3 Insulating material

Steam pipes are commonly insulated using different types of materials. Here are the most frequently used materials, along with their respective properties.

- Fibreglass: Fiberglass is a commonly used insulation material because it is affordable and easy to install. It has a thermal conductivity range of 0.035-0.045 W/m-K and can tolerate temperatures up to 450°C.
- Mineral Wool: Mineral wool is insulation material derived from natural rock or slag. Its thermal conductivity ranges from 0.035 to 0.045 W/m-K, making it a highly efficient insulator. Additionally, it can withstand high temperatures of up to 700°C.
- Calcium Silicate: Calcium Silicate is a reliable insulation choice for high-temperature steam pipes. This material can handle temperatures up to 1000°C and has a thermal conductivity of 0.045-0.055 W/m-K.
- Cellular Glass: Cellular glass is a type of insulation material made from recycled glass that is not organic. It can handle temperatures up to 480°C and has a thermal conductivity range of 0.035-0.050 W/m-K.
- Aerogel: Aerogel is an insulation material that performs exceptionally well, with a thermal conductivity ranging from 0.013 to 0.020 W/m-K. It is highly effective in insulating and can endure temperatures as high as 650°C.
- Polyurethane Foam: Many people use polyurethane foam as an insulating material for steam pipes because it is highly efficient and easy to install. It has a thermal conductivity of 0.018-0.023 W/m-K and can withstand temperatures up to 120°C.

These properties of insulating materials will be used for the cost analysis of the economic thickness of insulation for various materials using the MATLAB program and showing thermal analysis on ANSYS.

1.4 Objectives

This project aims to determine the economic insulation thickness for steam pipelines using various insulation materials. The project aims to achieve the following objectives:

- We aim to determine the insulation thickness that provides the best value for a steam pipe by analysing multiple insulation materials using the MATLAB program. The primary objective is to minimise heat transfer and associated costs while meeting the required thermal performance criteria. The outcome will determine the ideal insulation thickness.
- We aim to assess how well the insulation thickness chosen performs in terms of thermal efficiency. We will use ANSYS software to conduct a thermal analysis and examine the insulation material's temperature distribution and heat flux to achieve this. We aim to determine the insulation's effectiveness in reducing heat transfer and keeping the temperature levels in the steam pipe at a desirable level.

- Our main objective is to perform a comprehensive cost analysis on the insulation system to ascertain its cost-effectiveness. This involves considering the cost of the materials used for insulation, installation fees, and any potential savings in energy consumption. In addition, the aim is to assess the overall cost of the insulation system and its effectiveness by calculating the payback period, which shows the time needed for the energy savings to cover the initial investment.
- Our project aims to provide engineers and industry professionals valuable insights and recommendations for industrial steam pipe applications. By analysing economic thickness and thermal performance, we can help them make informed decisions about selecting insulation materials, determining thickness, and designing for energy efficiency. Our ultimate objective is to improve energy efficiency, reduce heat transfer, and cut costs in industrial processes.
- The project aims to verify the integration between MATLAB and ANSYS software. Specifically, the project intends to prove the effectiveness of combining the MATLAB program for determining the economic thickness with ANSYS software for thermal insulation design and analysis. Successful implementation of this approach would demonstrate its feasibility.

This project aims to help engineers, researchers, and industry professionals design steam pipe insulation and maximise energy efficiency. It provides valuable tips for determining the most economical insulation thickness, analysing thermal performance, and evaluating cost-effectiveness. In addition, we aim to deliver our intended audience with valuable insights and practical guidance.

1.5 Motivation

This endeavour highlights the importance of insulation in industrial processes, particularly steam pipe systems, as it dramatically affects energy efficiency and cost savings. Steam pipes are frequently utilised in power plants, chemical plants, and refineries to transfer heat. However, they are susceptible to heat losses which result in higher energy consumption and operational costs. Therefore, implementing effective insulation can lead to significant energy savings by reducing heat losses.

We can outline the motivation for this project in the following way:

- As the demand for energy increases and its cost continues to rise, enhancing energy efficiency in industrial applications has become increasingly crucial. One effective strategy is to optimise insulation thickness and minimise heat transfer, which can significantly reduce energy losses. By consuming less energy, the operation becomes more sustainable.
- Reducing Costs: If steam pipes lose heat, it increases energy usage and operating expenses for the system. By finding the optimal thickness for insulation and installing an effective insulation system, one can save a significant amount of money throughout the system's lifespan. This project aims to offer valuable information on the cost-effectiveness of insulation and help make informed decisions about investing in insulation materials and technologies.
- The environmental impact is closely related to energy consumption and greenhouse gas emissions. The project aims to enhance insulation and decrease energy consumption to support ecological sustainability. In addition, industrial

processes can support global efforts to combat climate change and promote sustainable development by reducing their carbon footprint by minimising heat losses in steam pipes.

- Industries constantly seek ways to enhance their processes and reduce costs to remain competitive. This project proposes an effective and affordable insulation solution to grant enterprises that adopt energy-efficient designs a competitive edge and the opportunity to decrease operational expenses.
- We can improve the insulation design and analysis by combining MATLAB and ANSYS software. This project aims to demonstrate how integrating specific tools can help determine the most cost-effective insulation thickness, conduct thermal research, and enhance the accuracy and efficiency of the design process. In addition, by leveraging the strengths of these software tools, we can significantly improve the reliability of insulation design.

This project aims to enhance energy efficiency, insulation design, and cost optimisation in industrial settings by addressing these concerns. In addition, the insights and suggestions gathered from this research can assist engineers, researchers, and industry experts in making informed decisions to enhance steam pipe systems' thermal performance and energy efficiency.

Chapter 2

Literature Review

Insulation is essential in many industries as it helps maintain the temperature of fluids or gases transported through pipes. Insulation serves the purpose of minimising heat loss and conserving energy. Various insulating materials are available in the market, and each material has properties that determine its effectiveness in reducing heat loss. Therefore, it is imperative to conduct a cost analysis when selecting the ideal insulation thickness for a particular material.

Several researchers have focused on the cost analysis of insulation for different materials in the literature. For example, research by Zhang et al. (2017) presented a cost analysis of insulation for steam pipelines in China. They used rock wool, glass wool, and aerogel for insulation and found that aerogel was the most cost-effective material. In addition, Pujari et al. (2018) investigated the economic thickness of insulation for hot water pipelines using polyurethane foam insulation. They determined that the optimum insulation thickness was 45 mm.

In recent years, researchers have also utilised software programs such as MATLAB and ANSYS for thermal analysis and cost analysis of insulation. For instance, research by Zulkifli et al. (2019) used MATLAB to analyse a district cooling system's thermal and cost insulation. They studied different insulation materials such as polyurethane foam, extruded polystyrene, and fibreglass and concluded that polyurethane foam was the most cost-effective material. Additionally, research by Wang et al. (2020) used ANSYS for thermal analysis of insulation materials for liquefied natural gas pipelines. Again, they analysed different materials, such as polyurethane foam, phenolic foam, and perlite, and concluded that polyurethane foam was the most effective material in reducing heat loss.

- Chen et al. (2017) studied the thermal efficiency of various insulation materials for a district heating network in China. The study evaluated the thermal conductivity, cost, and environmental impact of rock wool, glass wool, polyurethane foam, and calcium silicate. The findings revealed that polyurethane foam was the most cost-effective option with the best thermal efficiency.
- Silveira et al. (2018) wrote a review article about the significance of insulation in industrial processes. The report compared various insulation materials, such as mineral wool, fibreglass, cellular glass, and aerogel, and evaluated their properties, such as thermal conductivity, compressive strength, durability, and cost.
- In a study conducted by Kim et al. (2016) in Korea, the thermal performance of aerogel and mineral wool insulation for a district heating pipeline was compared. According to the study, aerogel demonstrated significantly lower thermal conductivity and was more efficient in reducing heat loss than mineral wool. However, the study also revealed that aerogel was considerably more costly than mineral wool.
- In a review article by Boudier and Le-Bail (2019), numerical simulation tools, particularly Ansys, were discussed in designing and improving insulation

systems. The report emphasised the significance of considering the material characteristics, insulation thickness, and boundary conditions in creating simulation models.

- Research conducted by Song et al. (2019) examined the economic and environmental efficiency of various insulation materials for a district heating pipeline in China. The materials under comparison were polyurethane foam, rock wool, and extruded polystyrene foam. According to the findings, polyurethane foam was the most cost-effective and environmentally friendly, while rock wool had the most negligible environmental impact but was less economical.

Conducting a cost analysis for different materials is crucial to find the best insulation thickness that saves costs. Using software programs such as MATLAB and ANSYS can help perform accurate thermal and cost analyses, saving time and resources.

Chapter 3
Methodology

3.1 Methodology Overview

This project uses a step-by-step approach to find steam pipes' most cost-effective insulation thickness. Combining MATLAB and ANSYS software makes designing and analysing the insulation efficient. The following sections explain the methodology used in this project.

3.1.1 Data Collection and Parameter Selection:

- We collect data and parameters such as ri, L, Ta, Ts, ho, kins, Cins, and other relevant material properties to gather information about the steam pipe system.
- We identify the project's specific requirements and constraints, which include cost limitations, desired energy savings, and other performance criteria.

3.1.2 MATLAB Program for Economical Thickness Determination:

- MATLAB program calculates the optimal insulation thickness for steam pipes based on cost factors. This tool is beneficial for anyone who needs to make this calculation.
- The program uses mathematical equations and iterative methods to determine the optimal insulation thickness, considering heat transfer rates, material properties, and cost factors.
- The MATLAB program calculates costs for various insulation thicknesses, helping to determine the most cost-effective option.

3.1.3 ANSYS Simulation for Thermal Analysis:

- The ANSYS simulation model now includes the insulation thickness that was optimised using the MATLAB program.
- A 3D model of the steam pipe system is created in ANSYS, accurately representing the pipe geometry, insulation layers, and surrounding environment.
- Boundary conditions, including temperature and heat flux, are applied to simulate real-world operating conditions.
- The ANSYS Fluent module performs thermal analysis and obtains temperature distributions, heat flux profiles, and other relevant thermal parameters.

3.1.4 Analysis and Evaluation:

- The thermal analysis results from ANSYS are analysed to assess the insulation system's performance.
- We analyse heat flux profiles to assess insulation's effectiveness in minimising heat transfer.
- The temperature distributions are analysed to pinpoint areas with thermal gradients or hotspots in the insulation system.
- To determine the savings from the insulation system, we calculate the reduction in heat loss and energy costs.

3.1.5 Comparison and Optimisation:

- To confirm the accuracy and consistency of the findings, we compared the results from the MATLAB program and ANSYS simulation.
- Performing sensitivity analysis helps evaluate how to input parameter changes affect the economic thickness and cost savings.
- To achieve optimal results that are both cost-effective and meet performance standards.

3.1.6 Documentation and Reporting:

- We have documented the analysis results in a detailed report, including findings, observations, and conclusions.
- We thoroughly explain our methodology, assumptions, and limitations to ensure transparency and the ability to reproduce our work.
- Visual aids such as graphs, tables, and visualisations can improve the understanding and interpretation of data, resulting in a more effective presentation of results.

This project uses a methodology to gather helpful information on determining the appropriate insulation thickness for economic purposes, analysing the thermal properties of steam pipe systems, and evaluating potential cost savings. We use MATLAB and ANSYS software tools in industrial settings to improve energy efficiency and lower operating costs. Our structured, thorough approach aims to make informed decisions and optimise insulation designs.

3.2 Thermal Formulas and Parameters:

This project uses various thermal formulas and parameters to examine how heat moves in steam pipe systems and how well insulation works. These formulas and parameters are essential for comprehending heat transfer processes and measuring the impact of insulation on energy efficiency. The following section thoroughly explains the thermal procedures employed and their corresponding parameters.

3.2.1 Heat Transfer Rate Formula:

To determine the heat transfer rate (Q), you can use this formula:

$$Q = n * Td * 24 * 300 * 2 * \pi * ri * L * U$$

3.2.2 Overall Heat Transfer Coefficient (U):

In the heat transfer process, the overall heat transfer coefficient (U) results from the combined impact of conduction, convection, and radiation. Can be calculated U by using the following formula:

$$U = 1 / ((ri / kins) * \log (ro / ri) + (ri / (ro * ho)))$$

3.2.3 Insulation Thickness (tins):

To calculate the insulation thickness (tins), subtract the inner radius from the outer radius of the insulation.

$$tins = ro - ri$$

3.2.4 Cost Analysis Formulas:

The thickness of an insulation system is determined based on the optimal cost structure. The three main cost components in this cost structure are:

- The cost of the insulation system proper, i.e., capital cost
- The cost of the maintenance of the installed insulation system
- The cost of the energy lost through the insulation system

We need to add the overhead costs under similar conditions to calculate the total costs of a particular insulation thickness. To determine the annual costs of the insulation system, we must calculate the investment cost multiplied by an escalation factor and then add in the maintenance costs. It is essential to compare the yearly expenses to those incurred due to energy loss. The thickness of insulation required for a specific application will depend on the insulating material's characteristics and the equipment's intended use. To determine the economic thickness needed to achieve the minimum total cost, we must perform a calculation.

Remember that methods are used to determine the correct insulation thickness. The primary purpose of this is to use on even surfaces. However, they may need to account for the cost of insulating valves fully and bends or the expenses of accommodating staggered joints or multiple layers. Therefore, exploring alternative systems and comparing them is necessary to determine the most advantageous economic insulation thickness. One effective way to accomplish this is by utilizing the 'minimum total cost method' equation.

Total annual costs = (investment x escalation factor + maintenance) + operating costs (energy loss).

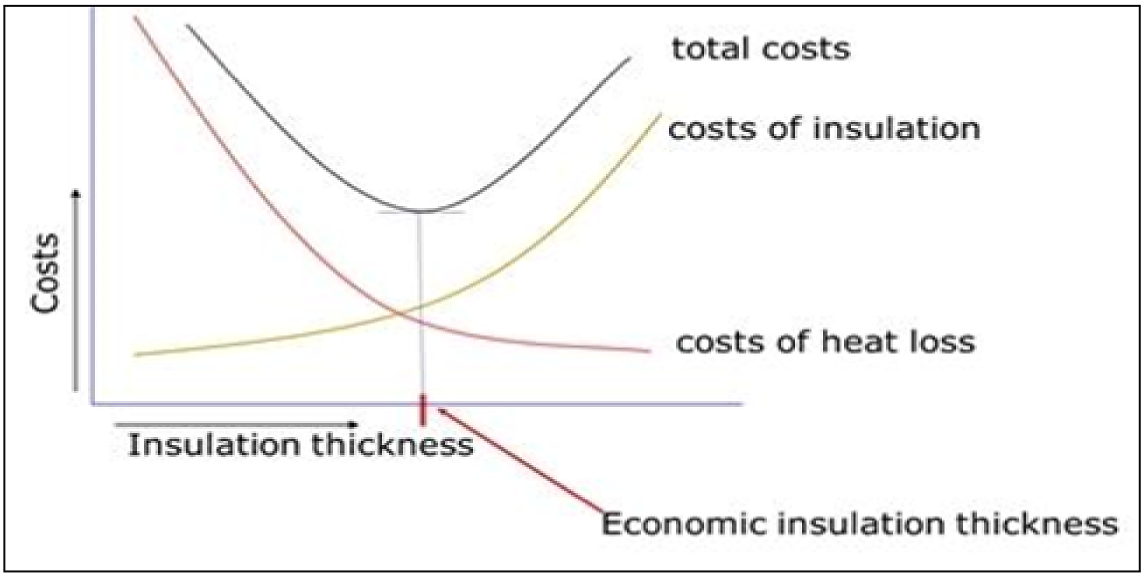

Fig 3.2.4.1: Costs vs insulation thickness

The method is based on minimization of total present cost taking into consideration an interest rate. We shall take up the case of an insulated pipe carrying a hot fluid (e.g., steam).

The various terms and quantities involved are as follows

1. Length of the pipe section = L, m
2. Outer radius of the insulation = ro, m
3. Inner radius of the insulation (this is the same as the outer radius of the pipe) = ri, m
4. Thermal conductivity of insulation = kc, kcal/h m °C
5. Film coefficient at the outer surface of insulation = ho, kcal/h m² °C
6. Pipe wall temperature (temperature of the inner surface of the insulation) = Ti, °C
7. Ambient temperature - To, °C
8. Cost of insulation = C', Rs/m²
9. Insulation life = n, yr.

Cost of heat energy = CH, Rs/kcal.

If (ro – ri) is the insulation thickness and h, the outer surface heat transfer coefficient, the overall heat transfer based on the inner radius of insulation if given by

$$U_i = \frac{1}{\frac{r_i}{k_c}\ln(r_o/r_i) + \frac{r_i}{r_o h_o}} \text{ kcal / h m}^2 \text{ °C}$$

Rate of heat loss (per year), Q = (2 πri L) Ui (Ti – To) (24) (300) kcal

= (2 π ri L) Ui (Ti – To) (7.2 X 10^3)kcal

(300 working days a year, on the average, is assumed).

Cost of heat loss = Q X C_h Rs/yr

If i is the fractional amount compound interest rate (compounded annually), the total present value of heat loss P, over the service life of the insulation (n years) given by:

$$P_1 = \sum_{j=1}^{n} \frac{QC_H}{(1+i)^j} \text{ Rs}$$

Volume of insulation applied = π(ro^2 – ri^2) L m^3

Present value of the insulation, P_2 = π(ro^2 – ri^2) L C' Rs

The total present value or cost

$$P_T = \sum_{j=1}^{n} \frac{QC_H}{(1+i)^j} + \pi(r_o^2 - r_i^2)LC'$$

$$= C_H\left[\sum_{j=1}^{n} \frac{1}{(1+i)^j}\right](2\pi r_i L)\left[\frac{1}{\frac{r_i}{k_c}\ln(r_o/r_i) + \frac{r_i}{r_o h_o}}\right](T_i - T_o)(7.2 \times 10^3) + \pi(r_o^2 - r_i^2)LC'$$

The optimum insulation thickness is obtained by putting.

$$\frac{dP_T}{dr_o} = 0$$

Economic Thickness of insulation = **(ro – ri) m**

Total Cost (Ptotal):

Ptotal = P1 + P2 Yearly

After determining the total insulation cost yearly, do a thermal analysis on Ansys to calculate heat flux with and without insulation. To determine the payback period, we must first calculate the cost savings:

Yearly Savings (savings_yearly): To determine yearly savings, multiply the heat loss cost without insulation by the number of working days a year.

savings_yearly = (Heatfluxwithout - HeatfluxwithINS) * cost of energy per kWh

Yearly Total Cost (Ptotal_yearly): To calculate the annual expense, multiply the total cost by the number of working days per year.

Ptotal_yearly = Ptotal * 365

The payback period is the duration needed to recoup the initial investment through yearly savings

payback_period = totalcost_yearly/ savings_yearly

The thermal analysis utilises formulas and parameters to evaluate heat transfer rates, determine the ideal insulation thickness, calculate insulation and heat loss costs, and assess the payback period. These formulas can quantify the energy savings and cost benefits of various insulation materials and thicknesses, leading to informed decision-making for enhancing energy efficiency in steam pipe systems.

3.3 Flowchart & Program

Analysing the thermal properties of insulation in steam pipe systems requires various steps and calculations. First, it is essential to evaluate heat transfer characteristics to determine the appropriate insulation thickness and potential cost savings. The flowchart below outlines the process and includes parameters and formulas from earlier sections.

1. Start

- Begin the thermal analysis of the insulation in steam pipe systems.

2. Define Parameters

Set the necessary parameters for the analysis:

n, Td, ri, L, kins, ho, Cins, initial_cost

3. Generate Insulation Thickness Range

- To evaluate, create a range of insulation thickness values (tins_vals).
- Specify the minimum and maximum thickness based on practical considerations.

4. Iterate over Insulation thickness

- For each insulation thickness value (tins), perform the following steps:
- Calculate the outer radius of the insulation (ro) using the formula: ro = ri + tins
- Calculate the overall heat transfer coefficient (U) using the formula: U = 1 / ((ri / kins) * log (ro / ri) + (ri / (ro * ho)))
- Calculate the cost of insulation (P1) using the formula: P1 = n * Cht * Td * 24 * 300 * 2 * π * ri * L * U
- Calculate the cost of heat loss (P2) using the formula: P2 = 3.14 * (ro * ro - ri * ri) * L * Cins
- Calculate the total cost (Ptotal) by summing P1 and P2: Ptotal = P1 + P2
- Store the Ptotal value for each insulation thickness.

5. Find Optimal Insulation Thickness

- Determine the insulation thickness (min_tins) corresponding to the minimum total cost (min_Ptotal) from the calculated values.

6. Calculate Yearly Total Costs and Savings

- Calculate the yearly total cost (Ptotal_yearly) by multiplying Ptotal by 365.
- Calculate the yearly savings (savings_yearly) based on the cost of heat loss without insulation (heatfluxwithout - heatfluxwithINS) * 24 * electricity_cost) Multiplied by 365.

7. Calculate the Payback Period

- Compute the payback period by dividing the initial cost (initial_cost) by the yearly savings (savings_yearly).

8. Plot Results

- Generate plots to visualise the relationship between insulation thickness (tins) and total cost (Ptotal), cost of insulation (P1), and cost of heat loss (P2).

9. Output Results

- Display the minimum total cost (min_Ptotal) and the corresponding insulation thickness (min_tins).
- Display the insulation cost at the minimum total cost (P1_vals(min_idx)).
- Display the heat loss cost at the minimum total cost (P2_vals(min_idx)).
- Display the payback period for the insulation material.

10. End

- Conclude the thermal analysis of insulation in steam pipe systems.

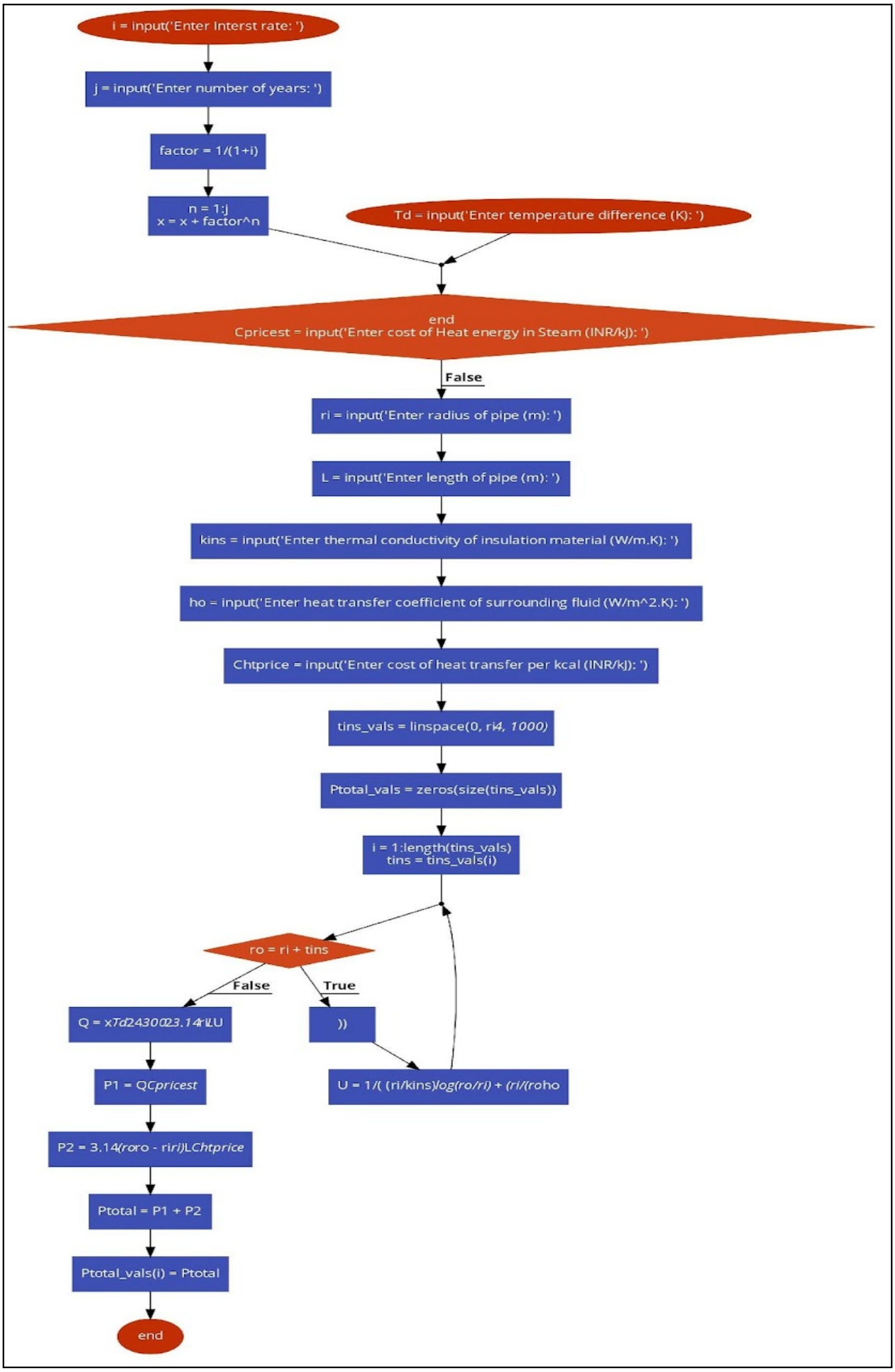

Fig 3.3.1: Flow Chart of MATLAB Program

MATLAB Program

```
% Get user inputs
i = input ('Enter the Interest rate: ');
j = input ('Enter the number of years: ');
factor = 1/(1+i);
x = 0;
for n = 1: j
x = x + factor^n;
end
electricity_cost = 7;
Cht = input ('Enter the cost of Heat energy in Steam (INR/kJ): ');
Td = input ('Enter temperature difference (K): ');
ri = input ('Enter ri of pipe (m): ');
L = input ('Enter L of pipe (m): ');
kins = input ('Enter the value of  K for insulation  (W/m.K): ');
ho = input ('Enter ho of surrounding fluid (W/m^2.K): ');
Cins = input ('Enter the cost of heat transfer per kcal (INR/kJ): ');
% Optimize insulation thickness
tins_vals = linspace(0, ri*4, 1000);
Ptotal_vals = zeros(size(tins_vals));
for i = 1: length(tins_vals)
tins = tins_vals(i);
ro = ri + tins;
U = 1/((ri/kins) *log(ro/ri) + (ri/(ro*ho)));
Q = x*Td*24*300*2*3.14*ri*L*U;
P1 = Q*Cht;
P2 = 3.14*(ro*ro - ri*ri)*L*Cins;
Ptotal = P1 + P2;
Ptotal_vals(i) = Ptotal;
End
```

% Find minimum value and index

[min_Ptotal, min_idx] = min (Ptotal_vals);

% insulation thickness at the minimum value

min_tins = tins_vals(min_idx);

% heat flux is taken from ansys by doing thermal analysis

heatfluxwithout = input ('Enter Heat flux without Insulation(kW): ');

heatfluxwithINS = input ('Enter Heat flux with Insulation(kW): ');

% Calculate the payback period

ro = ri + min_tins;

U = 1/((ri/kins) *log(ro/ri) + (ri/(ro*ho)));

Q = n*Td*24*300*2*3.14*ri*L*U;

P1 = Q*Cht;

P2 = 3.14*(ro*ro - ri*ri)*L*Cins;

Ptotal = P1 + P2;

% Convert total cost to yearly cost

Ptotal_yearly = Ptotal * 365;

% savings per year from reduced heat loss

savings_yearly = (heatfluxwithout - heatfluxwithINS) * 365 * 24 * electricity_cost;

payback_period = Ptotal_yearly / savings_yearly;

% plot total cost vs insulation thickness

figure;

plot (tins_vals, Ptotal_vals,'b-');

ylabel('Total Cost (INR)');

xlabel('Insulation Thickness (m)');

title ('Insulation Thickness Optimization', 'FontSize', 14, 'FontWeight', 'bold', 'Color', 'black');

% plot payback period vs insulation thickness

figure;

plot (min_tins, payback_period,'bo');

hold on;

plot(tins_vals,Ptotal_vals./savings_yearly,'r-');

```
ylabel('Payback Period (years)');
xlabel('Insulation Thickness (m)');
title ('Payback Period Optimization', 'FontSize', 14, 'FontWeight', 'bold', 'Color', 'black');
legend ('Minimum Payback Period', 'Payback Period vs Insulation Thickness');
% print results
fprintf('Min Total Cost: %f INR\n', min_Ptotal);
fprintf('Insulation Thickness at Min Total Cost: %f m\n', min_tins);
fprintf(' Insulation Material Cost at Min Total Cost: %f INR\n', P1);
fprintf('Heat Loss Cost at Min Total Cost: %f INR\n', P2);
```

3.4 Material Cost and Thermal Conductivity:

The choice of materials and their properties are essential in achieving the project's goal of determining the best insulation thickness for steam pipes. After several conversations and discussions, the project team identified the following materials and properties relevant to the project.

Table 3.4.1: Insulating Materials with Cost (per m3) & Thermal Conductivity (W/m.K).

S.No.	Insulating Material	Cost per cubic meter	Thermal Conductivity
1	Mineral Wool Insulation	INR 800-1000	0.037
2	Fibre Glass Insulation	INR 1000-1200	0.030
3	Polyurethane Foam Insulation	INR 3000-3500	0.022
4	Cellular Glass Insulation	INR 4000-5000	0.035
5	Aerogel	INR 5000-6000	0.015

Chapter 4

2D - Geometry

The ANSYS software is used in a project to analyse heat transfer behaviour, temperature distribution, and heat flux distribution in a cylindrical pipe with insulation. Employing ANSYS 2D modelling and geometry, it provides a solid platform for simulating and visualising these phenomena, giving a thorough understanding of the thermal characteristics of the system.

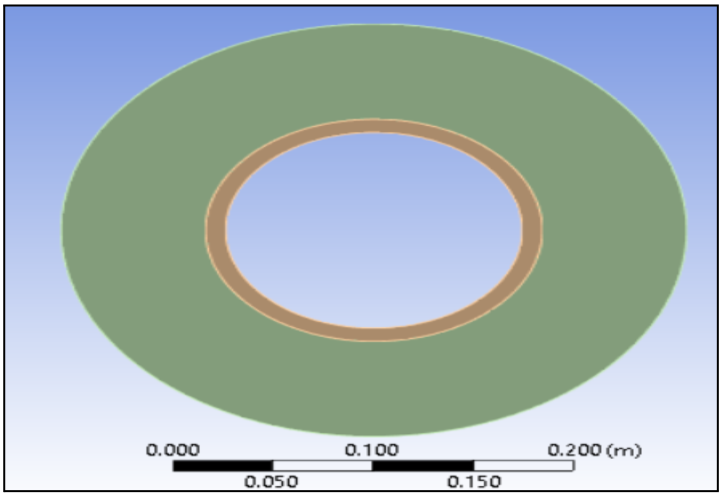

Fig 4.1: Geometry of Steampipe with Insulation.

Mesh of the Geometry:

To accurately simulate a physical system and get reliable results, it is crucial to mesh the geometry correctly. Meshing involves discretising the geometry into minor elements to capture localised temperature and heat flux variations. Employing a well-crafted and optimised mesh is vital for precise and dependable simulation outcomes. This will aid in the convergence of numerical analysis. In addition, choosing the right option is essential proper mesh dimension and arrangement help in accurately evaluating insulation thickness and other vital factors.

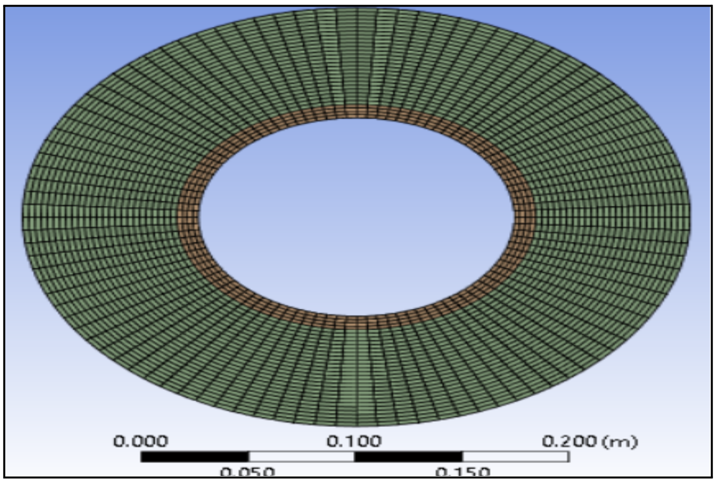

Fig 4.2: Mesh of the Geometry.

Temperature Distribution:

This image displays the temperature distribution across the thickness of a pipe, as determined by the Ansys 2D model. The temperature is represented by a colour gradient, with red indicating the highest temperature and blue telling the lowest. We plotted the temperature profile along the radial direction of the pipe. As we move from the inner surface to the outer surface, the temperature decreases due to heat transfer from the inner surface to the surrounding fluid.

Studying the temperature distribution along a steam pipe and its insulation provides valuable information about spreading heat. This enables us to pinpoint areas where temperatures are too high or too low and understand how these variations impact the system's performance, material durability, and safety. Additionally, analysing the temperature distribution helps us assess how well the insulation works to maintain the desired temperatures inside the pipe and minimise heat loss.

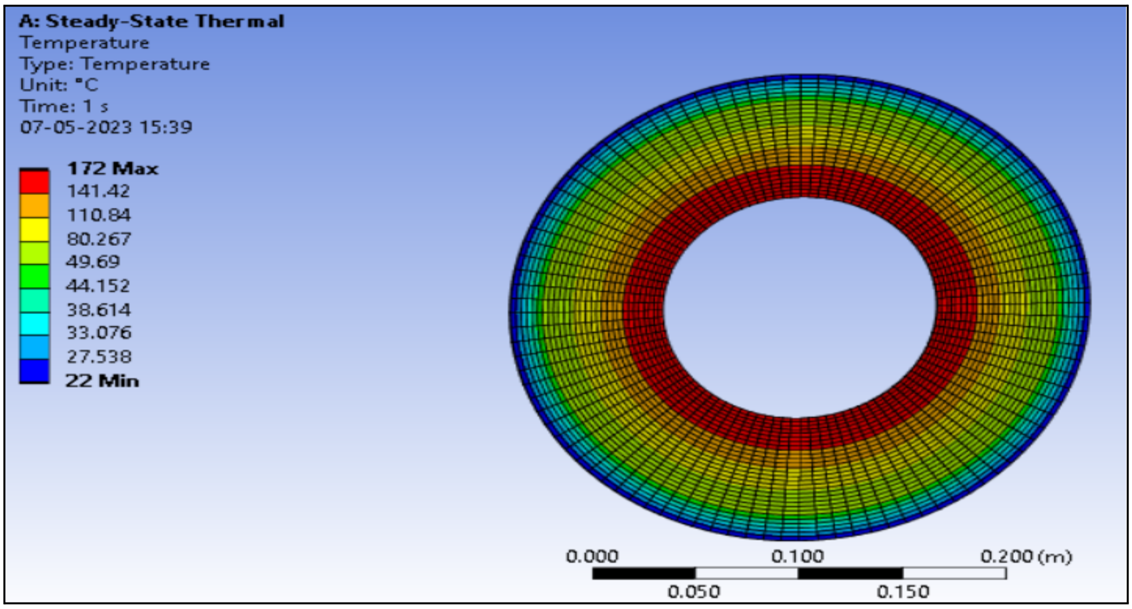

Fig 4.3: Temperature Distribution of the Geometry.

Heat Flux Distribution:

This image displays the heat flux distribution on a pipe's outer surface as obtained from a 2D Ansys model. The colour gradient scale represents the heat flux intensity, with red indicating the highest and blue telling the lowest. We can see the heat flux profile around the pipe. The heat flux is highest at the top and bottom of the pipe and lowest on the sides. This is because the fluid flow in the axial direction causes heat transfer at the top and bottom.

Analyzing the dispersion of heat flux is crucial in understanding the movement of heat within a system. In addition, this analysis lets us pinpoint areas with high or low heat transfer rates. This information is precious when aiming to enhance insulation, as it facilitates the identification of the most effective locations to minimise heat loss. Furthermore, it helps us identify critical regions where additional insulation may be necessary to reduce heat transfer.

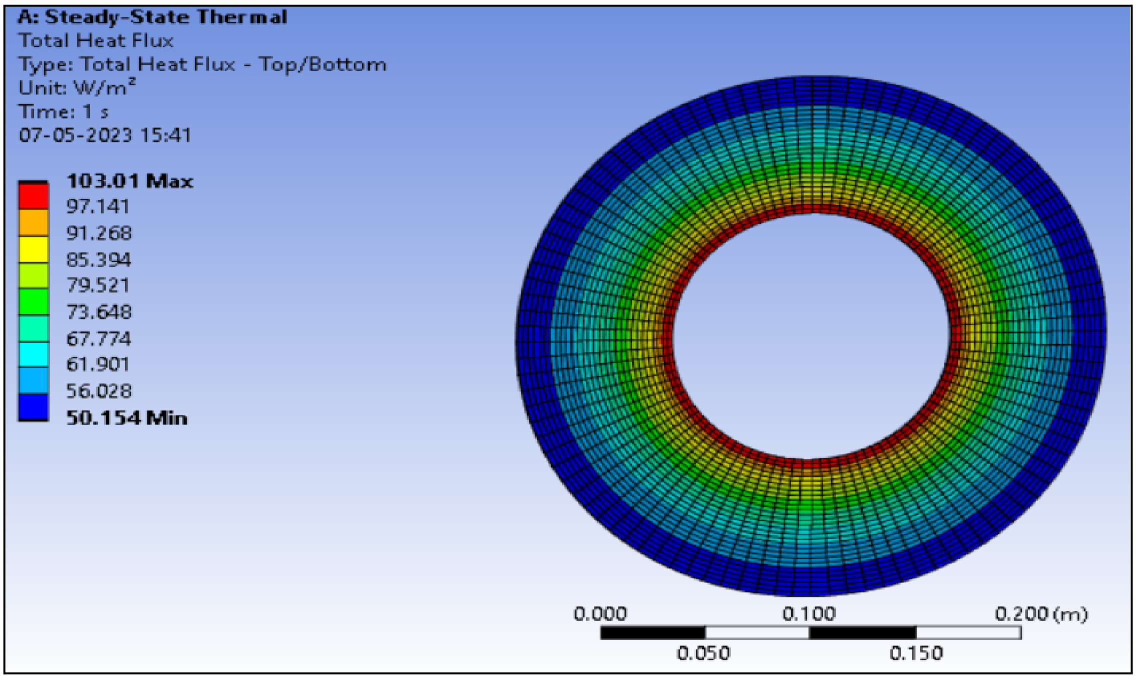

Fig 4.3: Heat Flux Distribution of the Geometry.

Directional Heat Flux Distribution:

Analysing directional heat flux distribution can acquire valuable insights about heat transfer within a system can develop by analysing directional heat flux distribution. With this information, we can pinpoint the specific regions that need attention. Heat transfer is the most significant and preferential path of heat flow. By optimising the insulation design based on this analysis, we can enhance heat transfer in desired directions and minimise it in undesired directions. This analysis is essential in systems like steam pipes, where controlling the movement of heat flow is crucial. In addition, it helps minimise heat loss in specific directions.

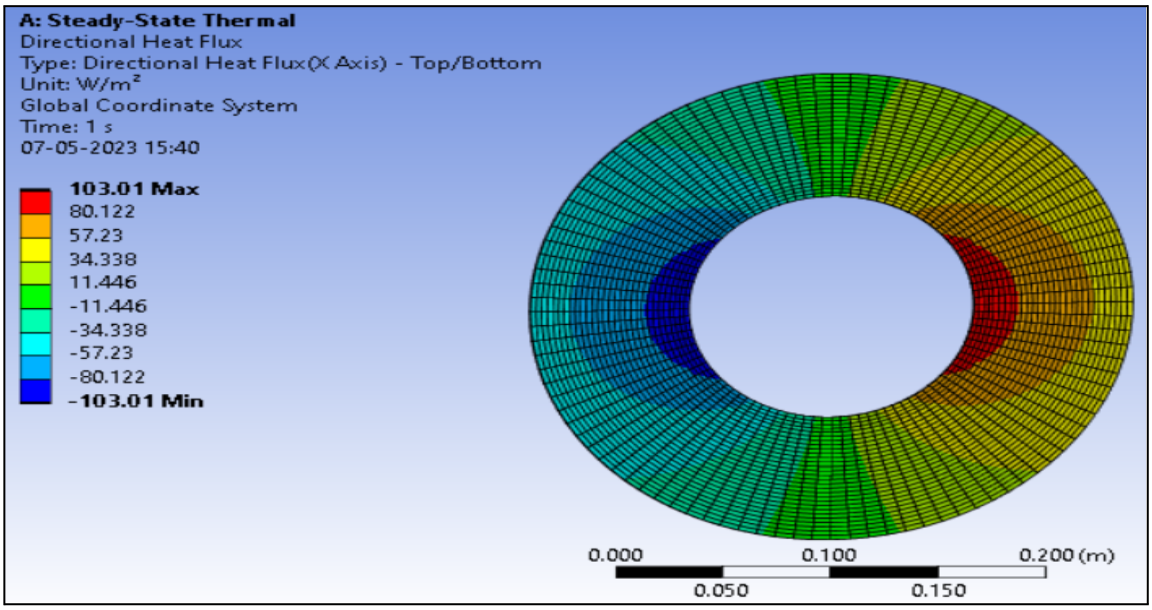

Fig 4.4: Directional Heat Flux of the Geometry.

Chapter 5

Results and Discussion

We conducted a study to assess different insulation materials for steam pipes, focusing on their performance and cost-effectiveness. We started by considering the thermal conductivity values of various insulation materials, including Fibreglass, mineral wool, cellular glass, aerogel, and polyurethane foam. Then, we compared these materials based on their thermal conductivity properties, which fell within the 0.013-0.050 W/m-K range.

Then, we analysed the economic insulation thickness for the steam pipes. Finally, we formulated a cost function considering insulation and heat transfer costs to find the minimum total cost. We found that the economic thickness varied for each insulation material, with aerogel having a thickness of 0.073m resulting in a total cost of 1550 INR and cellular glass, with a thickness of 0.107m resulting in a total cost of 2593 INR.

Table 5.1: Total Cost (Rs) and Economic Thickness (m) for Insulating Materials

S.No.	**Insulating Materials**	**Total Cost**	**Economic Thickness**
1	**Mineral Wool Insulation**	2244	0.139
2	**Fiber Glass Insulation**	1966	0.126
3	**Polyurethane Foam Insulation**	1796	0.096
4	**Cellular Glass Insulation**	2593	0.107
5	**Aerogel**	1550	0.073

Studies have demonstrated that increasing the interest rate can decrease the overall expenses of insulation. However, when the heat transfer coefficient increases for all insulating materials, the cost also increases. Conversely, reducing temperature differences leads to a substantial decrease in the total insulation cost for insulating materials. To lower the overall cost, increase the insulation thickness. The ideal thickness required can be determined. Based on thermal conductivity and temperature resistance, aerogel has the lowest thermal conductivity of 0.015 W/m-K, followed by Polyurethane Foam, Fiberglass / Mineral Wool, and Cellular Glass. Figures 5.1 to 5.5 demonstrate that when the heat transfer coefficient increases, the insulation cost rises quickly and stabilises at a higher value.

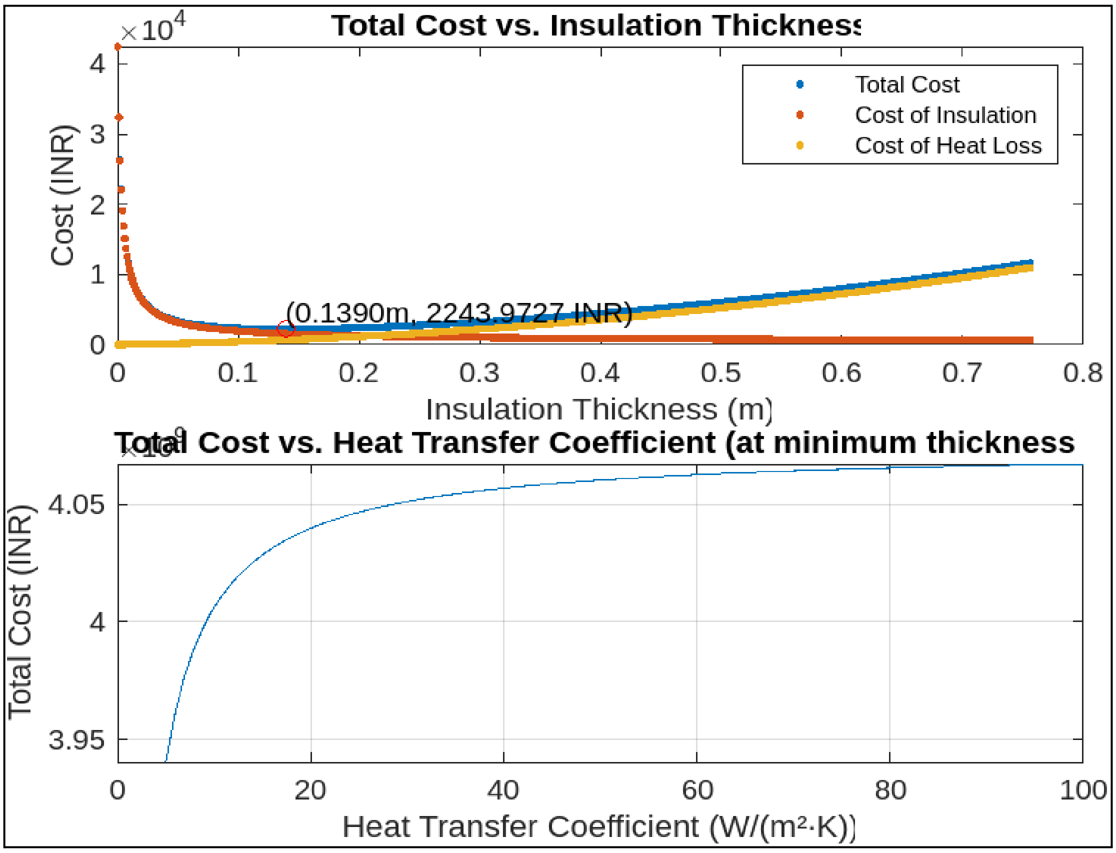

Fig 5.1: Cost vs tins and ho for Mineral Wool

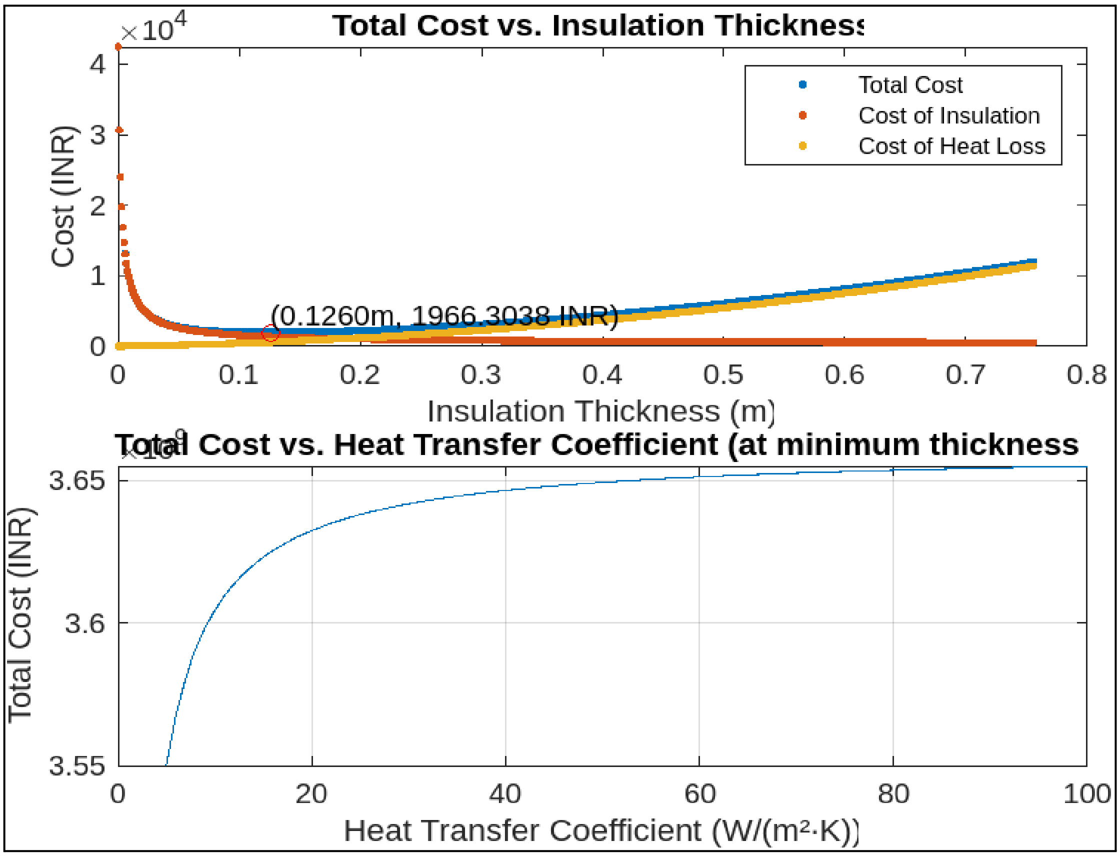

Fig 5.2: Cost vs tins and ho for Fibre Glass

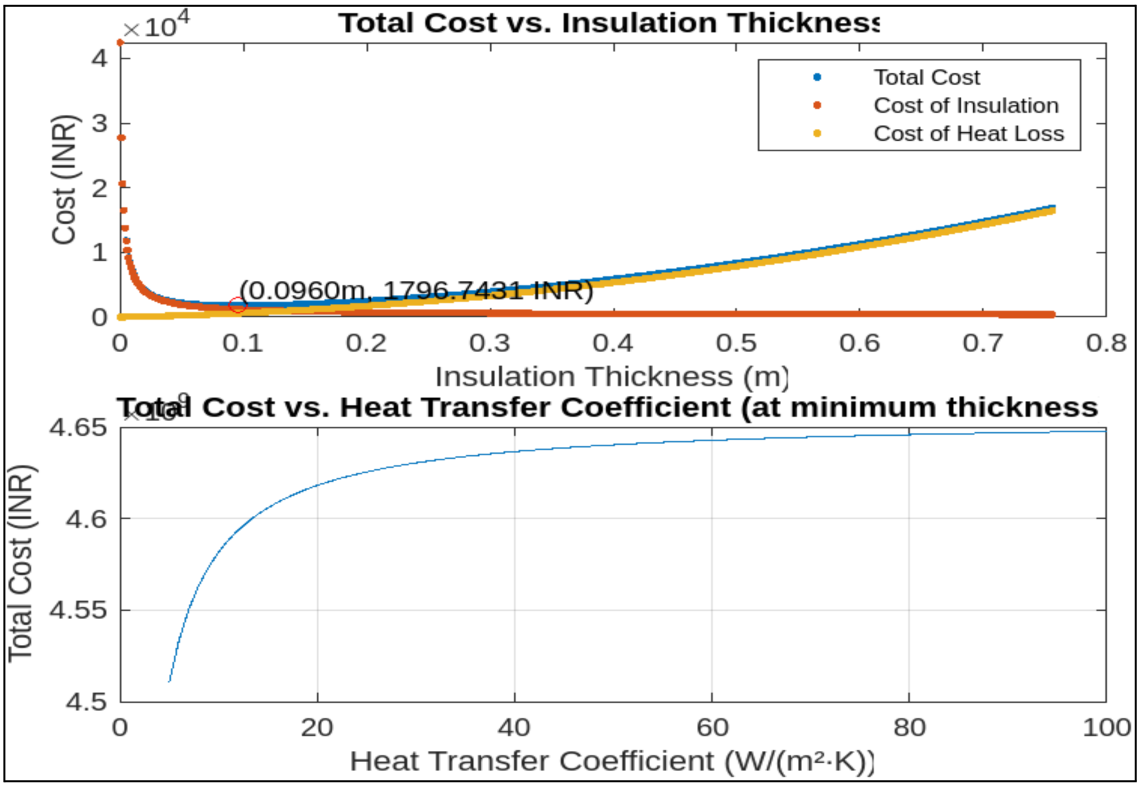

Fig 5.3: Cost vs tins and ho for Polyurethane Foam

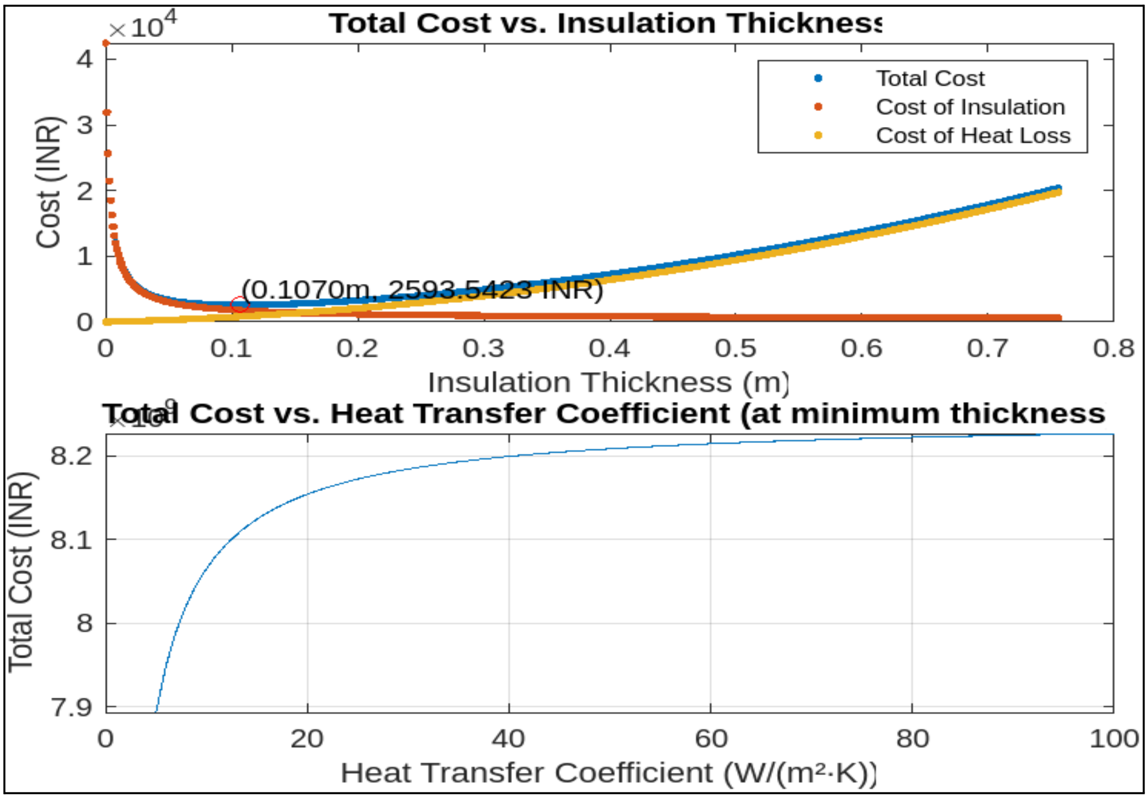

Fig 5.4: Cost vs tins and ho for Cellular Glass

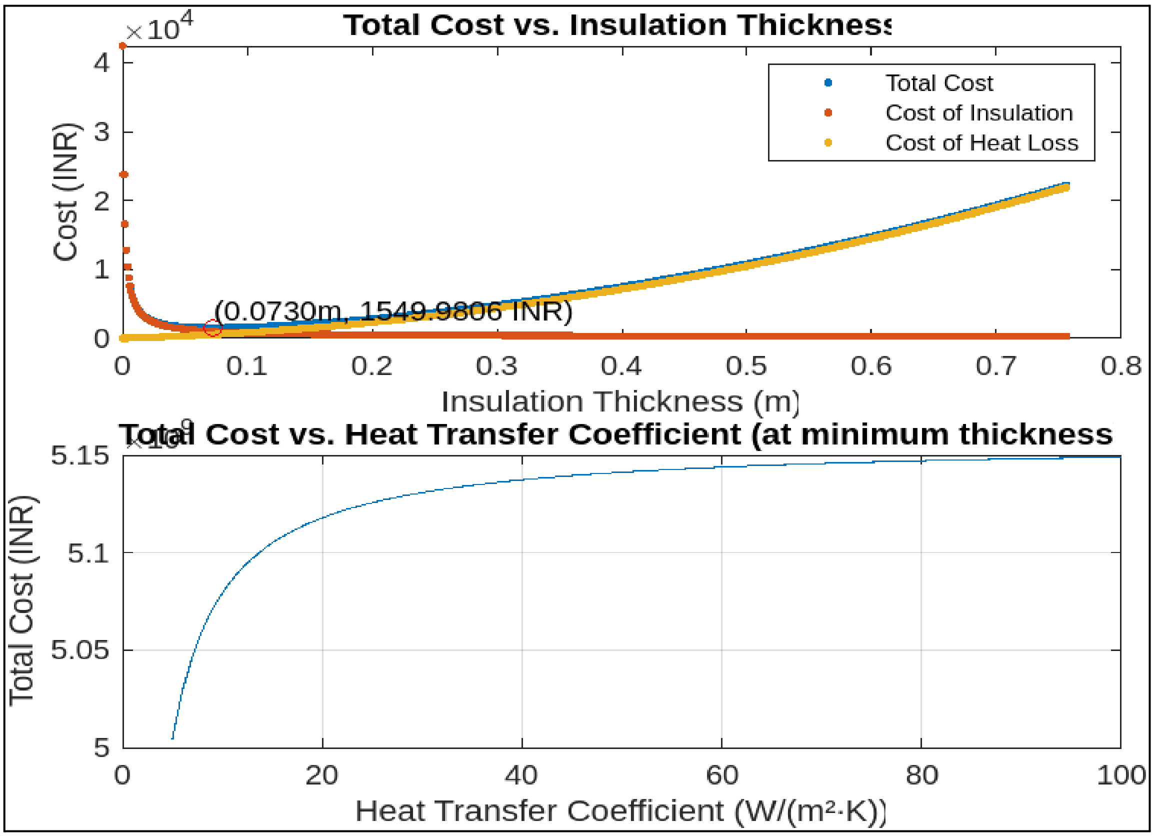

Fig 5.5: Cost vs tins and ho for Aerogel

Using Ansys for thermal analysis, we gained valuable insights about the temperature distribution along the steam pipe while using various insulating materials. The temperature profile varied throughout the pipe, with higher temperatures near the inner surface and cooler temperatures towards the outer surface. The type of insulating material used was crucial in reducing heat transfer and maintaining lower temperatures on the outer surface of the pipe. For optimal heat transfer and minimal temperature differences, choosing insulating materials with lower thermal conductivity, such as aerogel or cellular glass, is imperative. Conversely, selecting materials with higher thermal conductivity, like fibreglass and polyurethane foam, will inevitably lead to higher outer surface temperatures on the pipe.

The temperature distribution along the insulation thickness shows that the temperature decreases gradually from the pipe's inner surface towards the outer surface. Eventually, it reaches the ambient temperature. However, different insulation materials have varying rates of temperature decrease.

Insulation materials have different temperature slopes. Aerogel cools down quickly and requires less thickness to reach the ambient temperature. Polyurethane Foam Insulation efficiently reduces heat transfer and has good insulation properties. Cellular Glass insulation effectively reduces heat transfer and provides a dependable insulation barrier. Fibreglass gradually reduces temperature through its thickness. Mineral Wool has the lowest slope but still effectively reduces heat transfer. The graph below displays the temperature distribution across the thickness of insulation.

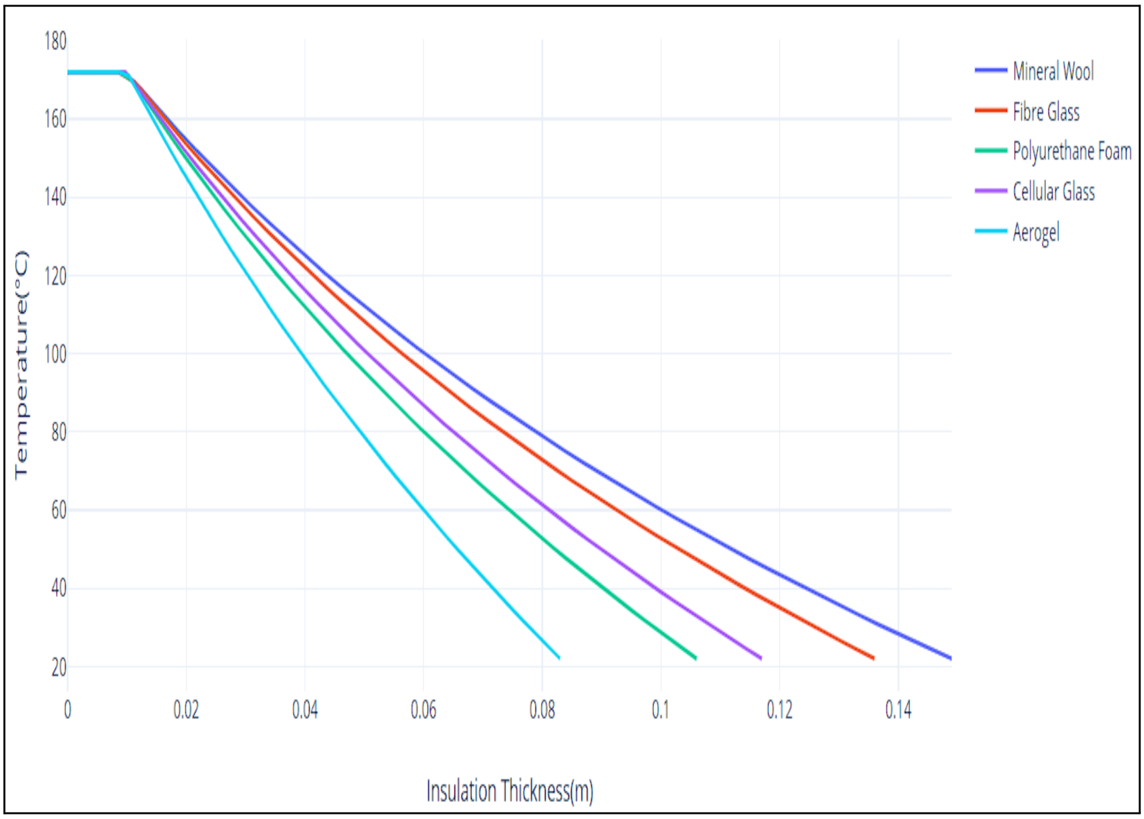

Fig5.6: Variation of Temperature along thickness

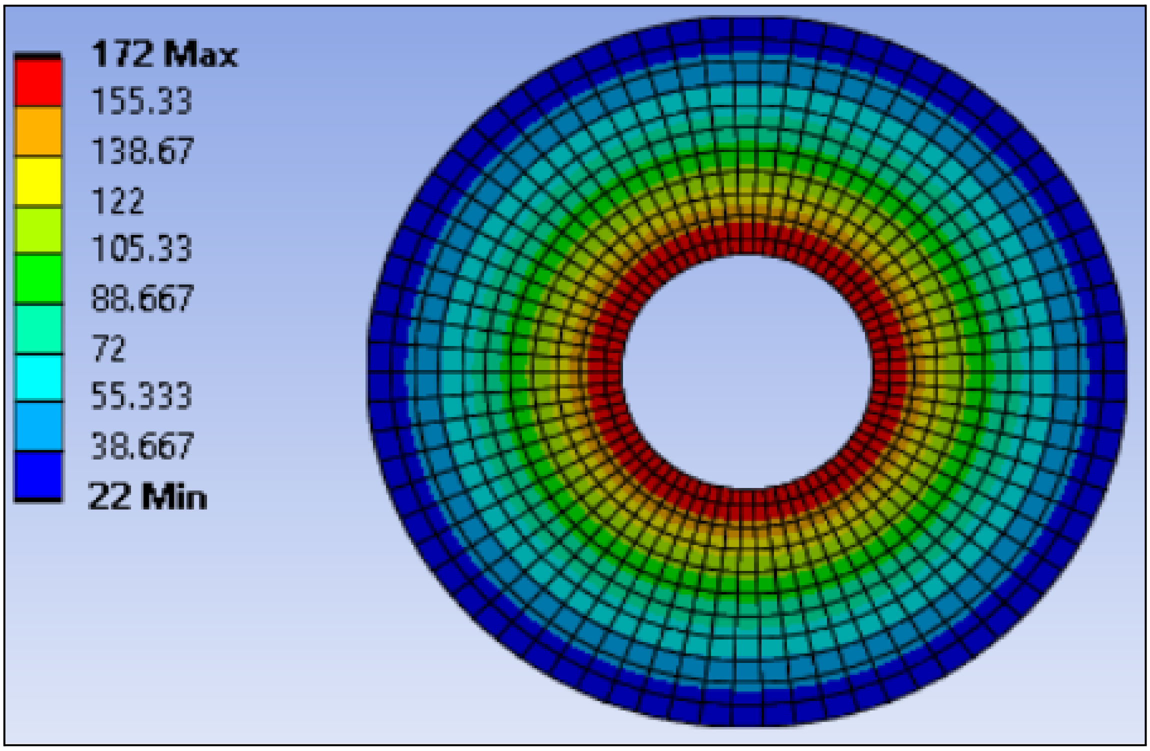

Fig5.7: Temperature distribution for Mineral Wool

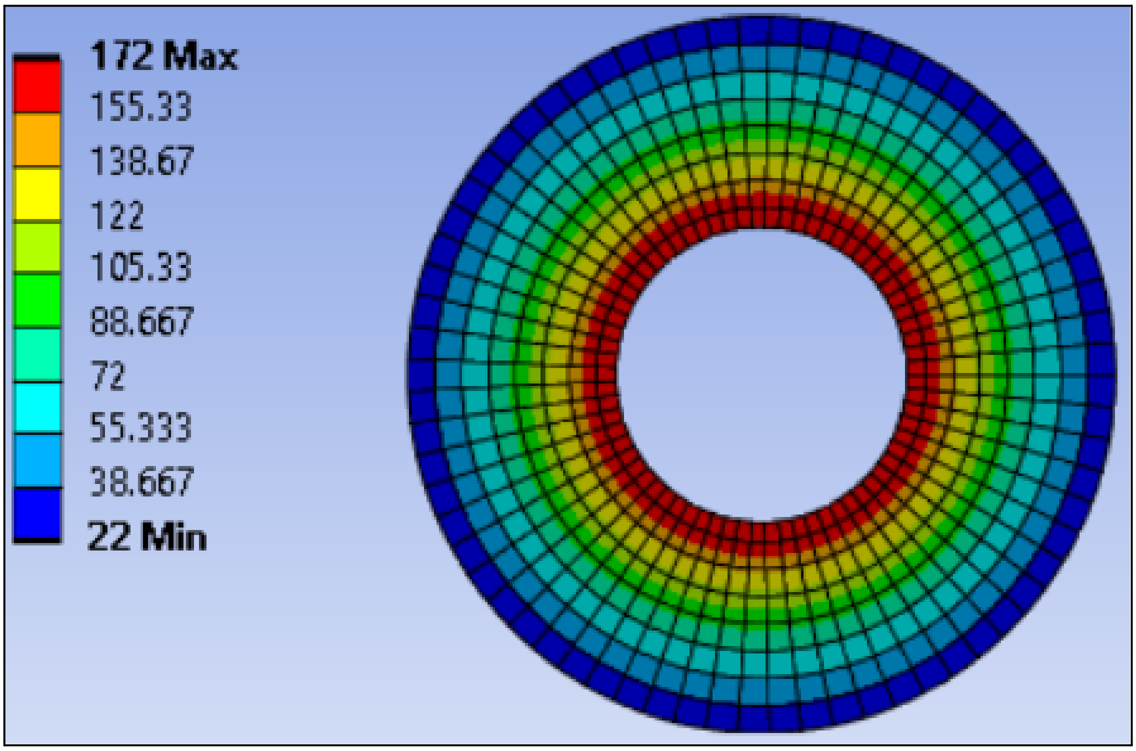

Fig5.8: Temperature distribution for Polyurethane Foam

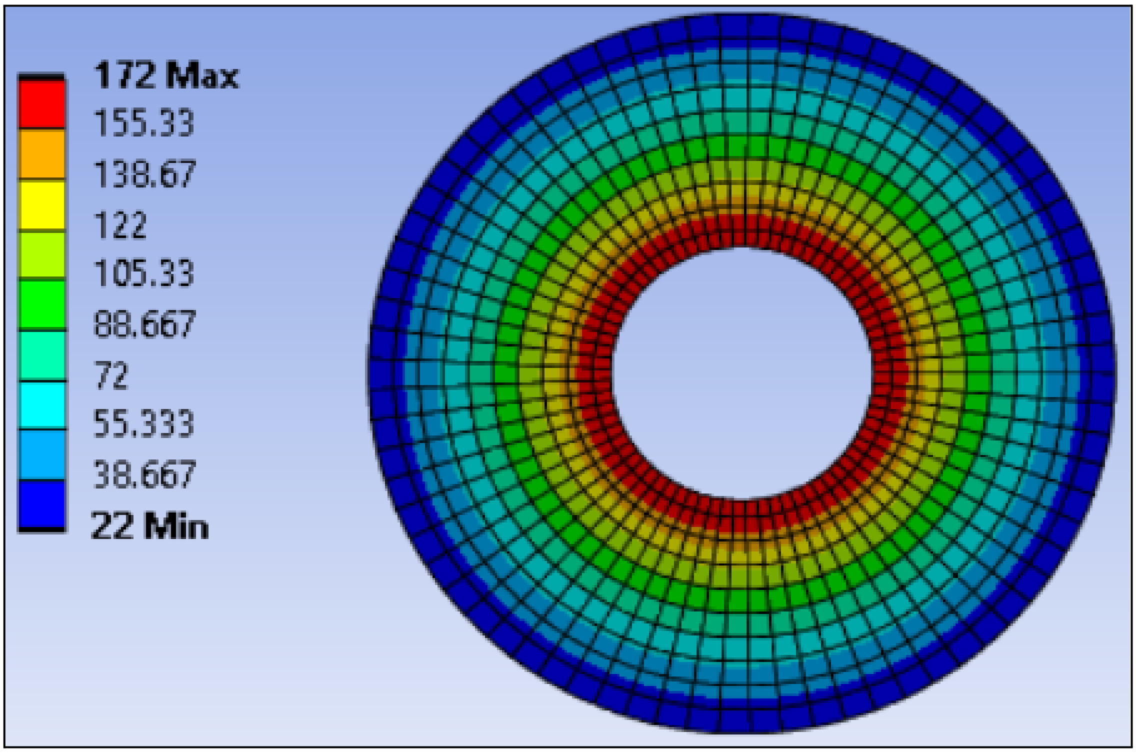

Fig5.9: Temperature distribution for Fibre Glass

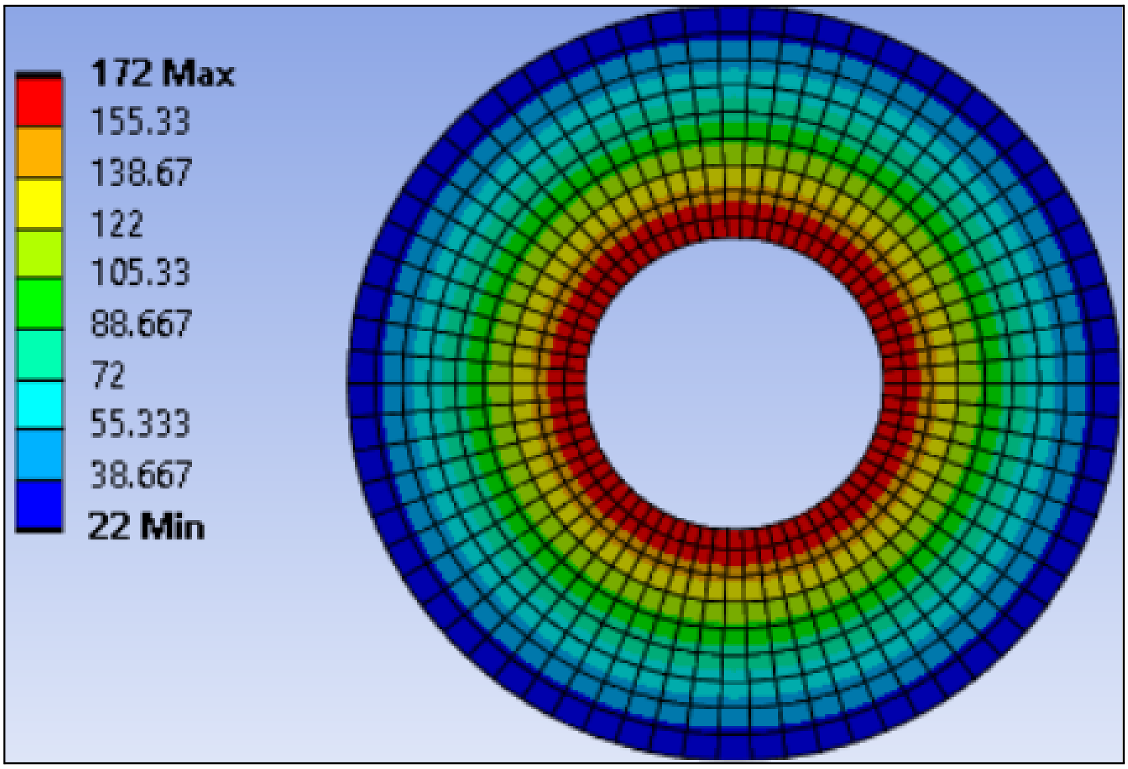

Fig5.10: Temperature distribution for Cellular Glass

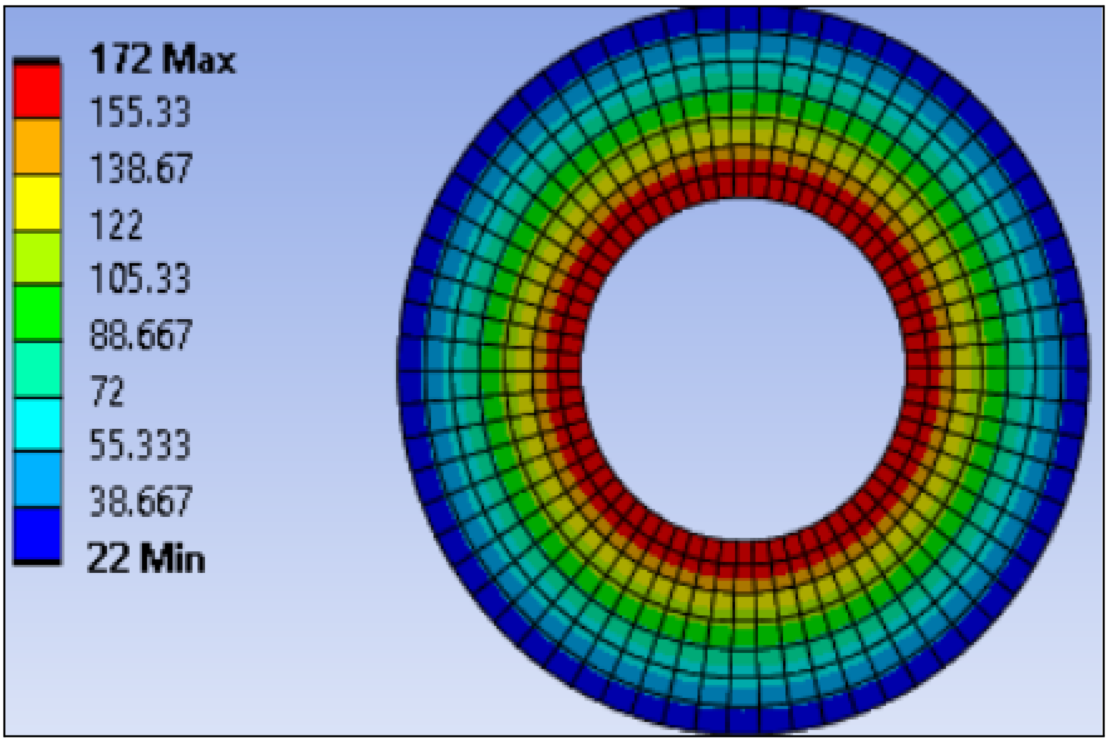

Fig5.11: Temperature distribution for Aerogel

We conducted a thermal analysis to assess the effectiveness of various insulating materials for steam pipe insulation. They examined how heat moves through the pipe from the centre to one side. The graph illustrates each material's performance at various points along the pipe's radius.

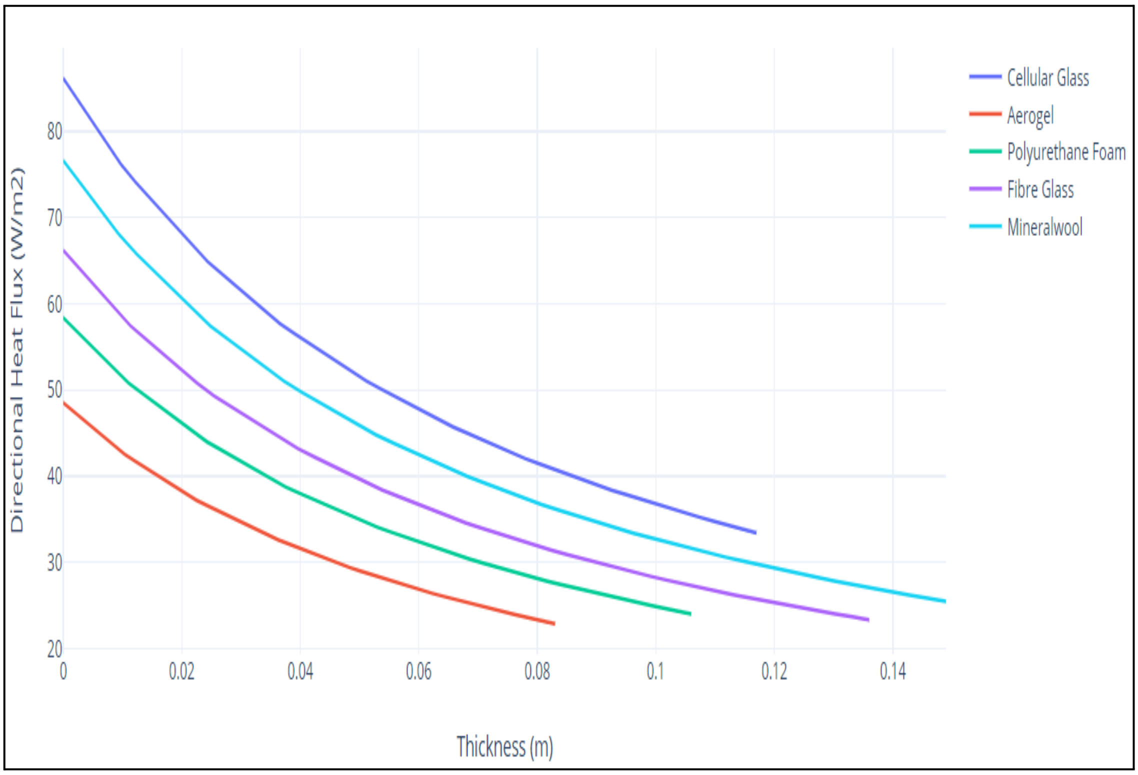

Fig5.12: Variation of Heat flux along thickness

After examining the graph, the heat flux decreases as we approach the outer radius of the steam pipe, regardless of the insulating material used. This indicates that the insulation effectively reduces heat transfer from the pipe's inner surface. Moreover, the directional heat flux analysis offers valuable insights into the heat flux values for each type of insulating material. The figures below display each insulating material's maximum and minimum heat flux.

Different insulation materials have varying properties that affect temperature distribution and heat flux. Temperature distribution can help determine the insulation thickness needed. For example, Aerogel cools down quickly and needs less insulation, while Polyurethane Foam, Cellular Glass, Fiberglass, and Mineral Wool have decreasing slopes.

When analyzing the distribution of heat flux, which indicates the heat transfer rate, the location of Cellular Glass plays a role and is affected by factors like thermal conductivity and insulation thickness. Compared to Aerogel and Polyurethane Foam, Cellular Glass has a lower ability to conduct heat due to its relatively low thermal conductivity. Therefore, even with a moderate temperature gradient, Cellular Glass shows a lower heat flux than the other materials.

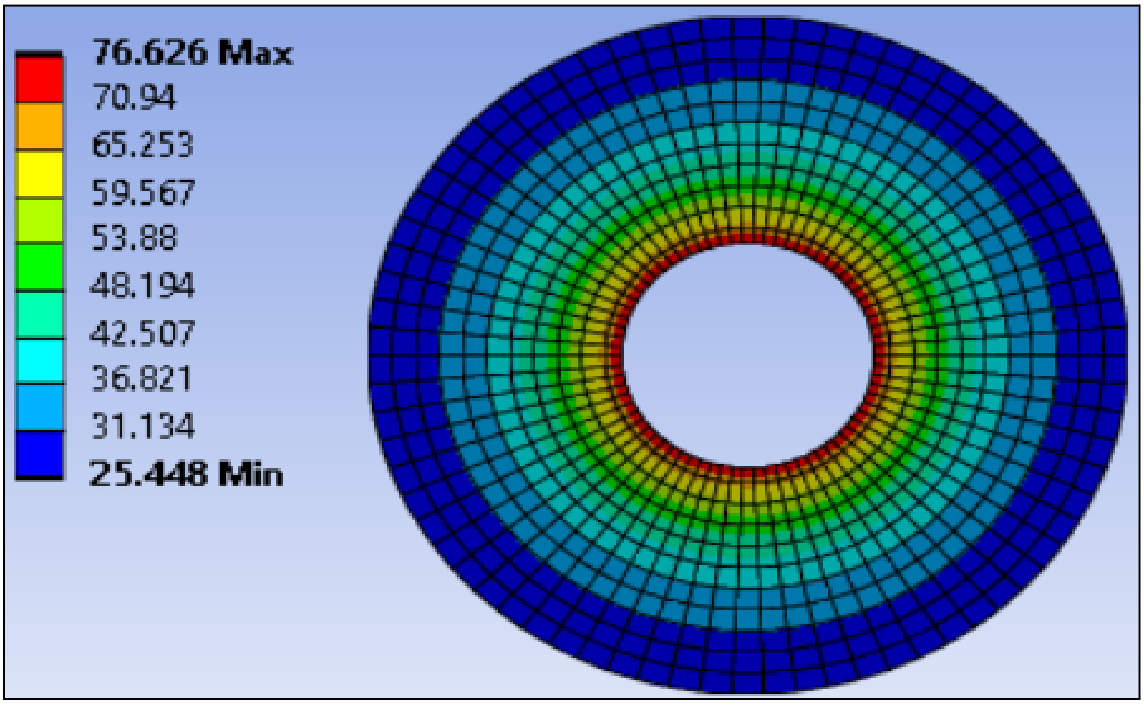

Fig5.13: Distribution of Heat Flux in Mineral Wool

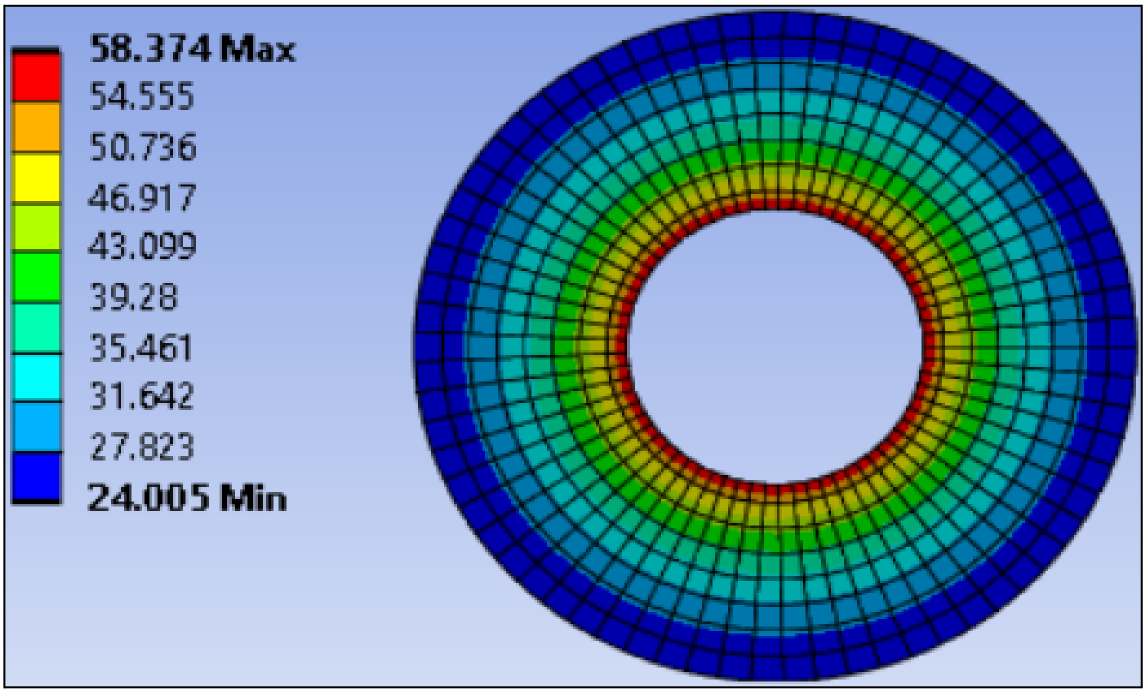

Fig5.14: Distribution of Heat Flux for Polyurethane Foam

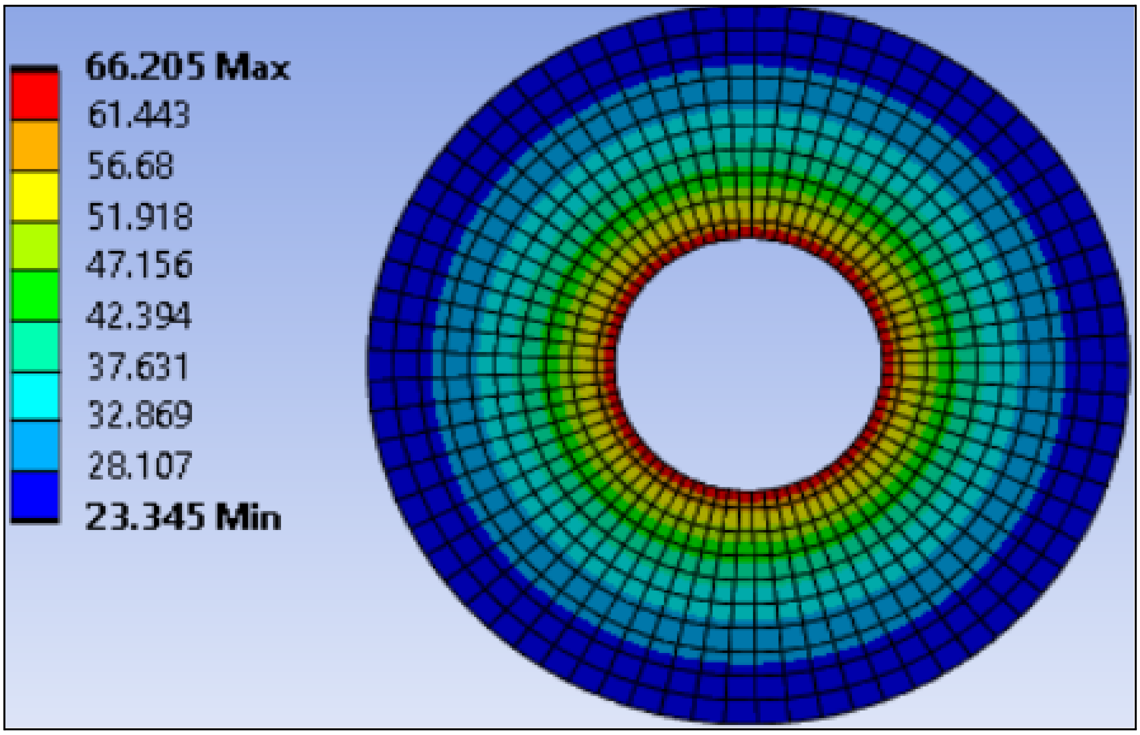

Fig5.15: Distribution of Heat Flux for Fibre Glass

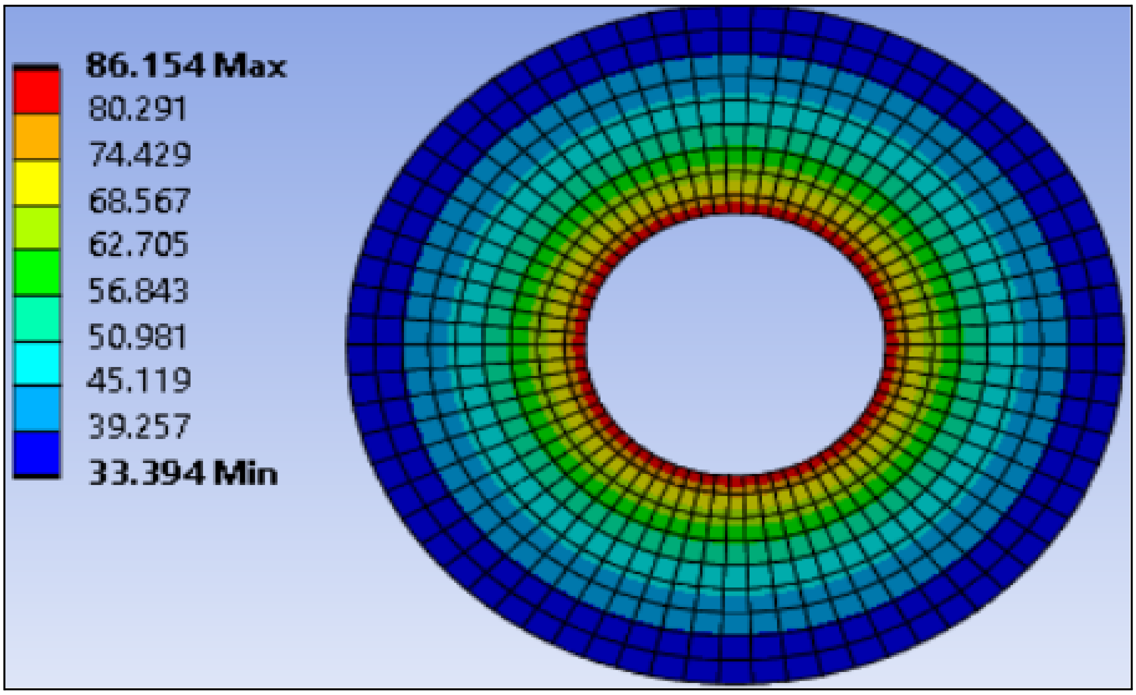

Fig5.16: Distribution of Heat Flux for Cellular Glass

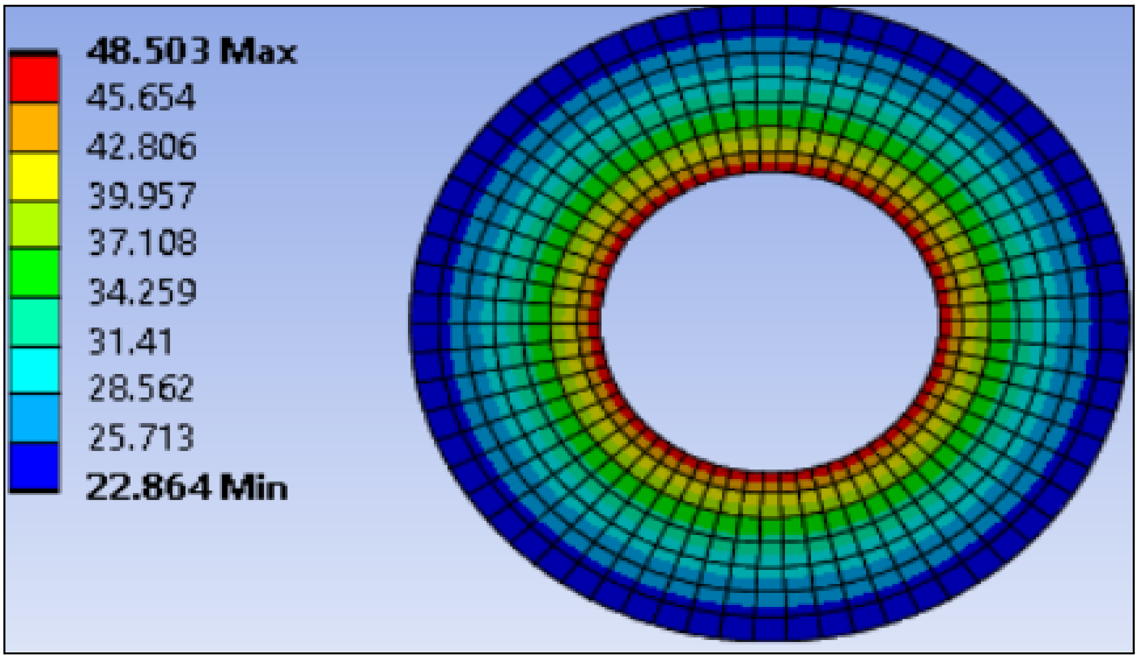

Fig5.17: Distribution of Heat Flux for Aerogel

The values provided show the level of heat flow that occurs on the surface of steam pipes for different types of insulation. It is worth noting that Cellular Glass has the highest maximum heat flux, followed by Mineral Wool, Fiberglass, Polyurethane Foam, and Aerogel. Additionally, we calculated the payback period for each insulating material based on its total costs. This period represents the time required for the cost savings from insulation to cover the initial investment cost.

Table 5.2: Payback Period of different Material

S.No.	Insulating Materials	Saving Cost Yearly (Rs)	Payback Period (Month)
1	Mineral Wool Insulation	194	8.5
2	Fiber Glass Insulation	190	8
3	Polyurethane Foam Insulation	229	7
4	Cellular Glass Insulation	114	12
5	Aerogel	262	6.2

Out of all the insulation materials analyzed, aerogel provides the highest annual cost savings, totalling Rs 262. Additionally, it has a short payback period of only 6.2 months, indicating its high efficiency in reducing heat transfer and cost savings over a relatively short period.

On the contrary, Cellular Glass Insulation has the lowest annual saving cost of Rs114 and the most prolonged payback period of 12 months. However, despite its insulation advantages, it may take longer to recoup the initial investment due to its higher costs.

Regarding insulating materials like Fibre Glass Insulation, Polyurethane Foam Insulation, and Mineral Wool Insulation, they all have similar costs for heat transfer and payback periods, though there are slight differences. As a result, these materials provide moderate insulation performance at reasonable prices, and their payback periods are relatively shorter than Cellular Glass. However, based on research, Aerogel is the most cost-effective insulation material with the shortest payback period. Nevertheless, when choosing a suitable insulating material, one should consider other factors like installation requirements, durability, maintenance, and specific project needs. Ultimately, selecting the best insulating material for steam pipe insulation requires a thorough evaluation of cost-effectiveness, thermal performance, and project requirements to ensure optimal insulation efficiency and long-term benefits.

Chapter 6

Conclusions

Our project involved a detailed thermal analysis in assessing and enhancing insulation materials used for steam pipes in power plants. We examined several factors, including thermal conductivity, temperature resistance, cost-effectiveness, and heat transfer coefficients, to provide helpful information on the selection and effectiveness of different insulation materials. Our study has yielded some essential points to remember:

- It is important to note that Aerogel is the thinnest insulation material, measuring only 0.073m. In contrast, Mineral Wool is the thickest insulation material, measuring 0.139m.
- The cost of each material is different. Cellular Glass Insulation is the most expensive, priced at 2593 INR, while Aerogel is the cheapest at 1550 INR.
- Different materials have varying insulation and heat transfer costs, with trade-offs between the costs specific to each material.
- When thermal conductivity increases, insulation costs decrease while heat loss costs increase. As a result, the total cost increases.
- When the heat transfer coefficient increases, the total cost will increase quickly and then level off for higher heat transfer coefficient values.
- Aerogel has the lowest thermal conductivity of 0.015 W/m-K, making it highly temperature-resistant.
- As one progresses beyond the central point of a steam conduit, the magnitude of thermal energy will progressively decrease. Aerogel has the lowest heat flux, while Cellular Glass has the highest heat flux at the outer surface.
- As the payback period increases, so does the total insulation cost linearly.
- Aerogel has a pay period of six months, followed by Polyurethane Foam Insulation, Fiber Glass Insulation, Mineral Wool Insulation, and Cellular Glass Insulation.

- Aerogel has the highest cost saving annually, followed by Polyurethane Foam Insulation, Mineral Wool Insulation, Fiber Glass Insulation, and Cellular Glass Insulation.

To sum up, assessing and choosing the suitable insulation material for steam pipe insulation projects is crucial. Project managers can make better decisions by relying on informed insights. In addition, to meet their project requirements while staying within their energy efficiency goals and financial restrictions, they can compare the effectiveness, cost, and payback periods of various insulation materials.

This project's results are valuable for steam pipe insulation. They offer a detailed understanding of the trade-offs between thermal performance, cost, and payback periods. With the suggested insulation materials and optimisation strategies, industrial processes can minimise heat loss, enhance energy efficiency, and save much money over time.

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[19] Author links open overlay panelTianhu Zhang a b, a, b, c, and AbstractThe direct buried steam pipeline with effective insulation has great potential application in the district heating systems. In this study, “Economic thickness and life cycle cost analysis of insulating layer for the Urban District Steam Heating Pipe,” Case Studies in Thermal Engineering, https://www.sciencedirect.com/science/article/pii/S2214157X22003045 (accessed May 26, 2023).

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