TRIBHUVAN UNIVERSITY

INSTITUTE OF ENGINEERING

PULCHOWK CAMPUS

Techno-Economic Analysis of Energy Saving Opportunity by Insulating the Medical Autoclave

By:

Aman Dhakal (075BME007)

Anup Paudel (075BME010)

Binaya Subedi (075BME015)

A REPORT SUBMITTED TO THE DEPARTMENT OF MECHANICAL AND AEROSPACE ENGINEERING IN PARTIAL FULFILLMENT OF THE REQUIREMENT FOR THE DEGREE OF BACHELOR'S IN MECHANICAL ENGINEERING

DEPARTMENT OF MECHANICAL AND AEROSPACE ENGINEERING
LALITPUR, NEPAL

March, 2023

COPYRIGHT

The author has agreed that the library, Department of Mechanical and Aerospace Engineering, Pulchowk Campus, Institute of Engineering may make this report freely available for inspection. Moreover, the author has agreed that permission for extensive copying of this project report for scholarly purpose may be granted by the professor(s) who supervised the project work recorded herein or, in their absence, by the Head of the Department wherein the project report was done. It is understood that the recognition will be given to the author of this report and to the Department of Mechanical and Aerospace Engineering, Pulchowk Campus, Institute of Engineering in any use of the material of this project report. Copying or publication or the other use of this report for financial gain without approval of the Department of Mechanical and Aerospace Engineering, Pulchowk Campus and author's written permission is prohibited.

Request for permission to copy or to make any other use of the material in this report in whole or in part should be addressed to:

Head of Department

Department of Mechanical and Aerospace Engineering

Pulchowk Campus, Institute of Engineering

Lalitpur

Nepal

TRIBHUVAN UNIVERSITY

INSTITUTE OF ENGINEERING, PULCHOWK CAMPUS

DEPARTMENT OF MECHANICAL AND AEROSPACE ENGINEERING

The undersigned certify that they have read, and recommended to the Institute of Engineering for acceptance, a project report entitled **"TECHNO-ECONOMIC ANALYSIS OF ENERGY SAVING OPPORTUNITY BY INSULATING THE MEDICAL AUTOCLAVE"** submitted by Aman Dhakal, Anup Paudel and Binaya Subedi in partial fulfillment of the requirements for the Degree of Bachelor in Mechanical Engineering.

Supervisor Assoc. Prof. Dr. Ajay Kumar Jha

Department of Mechanical and Aerospace Engineering

Supervisor Asst. Prof. Sanjaya Neupane

Department of Mechanical and Aerospace Engineering

External Examiner, Er. Abian Marasini

Mechanical Engineer, WECS

Committee Chairperson, Head of Department, Dr. Surya Prasad Adhikari

Department of Mechanical and Aerospace Engineering

Date: March 12, 2023

ABSTRACT

Autoclaves are used in the most of the hospitals of Nepal for the sterilization process where most of them are uninsulated. Hence, it is possible to reduce the energy consumption in hospitals and other places where autoclaves is in operation by insulating it. This project provides an insight about optimum thickness and material for the insulation in an autoclaves. Parameters that are of our major concern are temperature, thermal conductivity, moisture and fire resistance different costs such as insulation cost, heating cost and interest and inflation rate for life cycle analysis. The dimension of autoclave was taken from the autoclave at PAHs and optimization was carried using this dimension. From our calculation taking interest rate of 9%, inflation rate 7.87%, cost of electricity NRs 12.25 per unit and the respective cost of the insulation materials glass wool and mineral wool will be best suited for insulation where they have comparable value. However, the moisture resistance property of mineral wool is excellent than that of glass wool hence it is to be chosen for insulation. The optimum thickness was found to be 62mm for insulation at PAHs with payback period nearly 8 months only and energy saved amounts of NRs 501402.8 altogether for steam generator and pressure chamber from single autoclaves. Also a single hospital comprises of minimum of 3 to 4 autoclaves which means we could save a huge amount. Based on calculated values we can conclude that the project is economically viable.

ACKNOWLEDGEMENT

First of all, we would like to express our deepest gratitude to the Department of Mechanical and Aerospace Engineering, IOE, Pulchowk Campus, Lalitpur, for providing us with the opportunity to work on a project to enhance our knowledge we have learnt throughout our Bachelors of Mechanical Engineering.

We are indebted to our supervisors, Assoc. Prof. Dr. Ajay Kumar Jha and Asst. Prof. Sanjaya Neupane, for their valuable suggestions in each and every step of our project and always pushing us to do better. It certainly wouldn't have been possible without them. We are grateful to AEPC for providing permission to get necessary data.

Finally, we would also like to extend thanks to all our colleagues and seniors who helped us with their valuable suggestions.

Aman Dhakal (075BME007)

Anup Paudel (075BME010)

Binaya Subedi (075BME015)

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

WECS	Water & Energy Commission Secretariat
DOE	Design of experiment
HAIs	Healthcare Associated Infections
PAHS	Patan Academy of health science
PSI	Per Square Inch
SSTA	Steady state thermal analysis
AEPC	Alternative Energy Promotion Center
NPV	Net Present Value
LCCA	Life Cycle Cost Analysis
EPS	Expanded Polystyrene
XPS	Extruded Polystyrene
HBCD	Hexabromocyclododecane
VOC	Volatile Organic Compound
CAD	Computer Aided Design
MATLAB	Matrix Laboratory

LIST OF SYMBOLS

k	Thermal conductivity	(W/mK)
h	Heat transfer coefficient	(WK/m^2)
α	Thermal diffusivity	(m^2/s)
Q	Total heat transfer	(J)
C_h	Total annual cost	
$\dot{Q}$	Rate of heat loss	$(watt)$
J	Cost of unit of heat	
N	Period of operation	(hr)
C_i	Total insulation cost	
G	Rate of interest on capital	(%)
Z	Cost of insulant per unit volume	
V	Volume of insulant	(m^3)
C_{total}	Total cost of operation	
C_1	Fixed capital cost	
x	Insulant thickness	
U	Overall heat transfer coefficient	(W/m^2K)
A_{surr}	Surface area of autoclave	(m^2)
T_{amb}	Temperature of environment	(K)
L	Insulating material length	(m)
i	Discount Factor	
d	Inflation Rate	
Ms	Maintenance Cost	NPR
C_v	Cost Per unit Volume	NPR/m^3
N	Lifetime in years	
Ra	Rayleigh Number	
Gr	Grasshoff Number	
Pr	Prandtl Number	
g	Acceleration due to grvity	(m/s)
β	Thermal Expansion Coefficient	$(\mu m\ /mK)$

δ	Base Height	(m)

CHAPTER ONE: INTRODUCTION

1.1 Background

An autoclave is used in medical and laboratory settings to sterilize lab equipment and waste. Sterilization with an autoclave involves the use of heat to kill bacteria and spores. Steam is used to deliver heat because it is nontoxic and inexpensive. By pressurizing the steam, high temperatures can be reached, which is necessary for sterilization. Also, autoclaving is more reliable and less likely to damage materials undergoing sterilization. The autoclaves used in dental and medical clinics are usually about the size of a microwave oven, whereas hospitals use larger units capable of sterilizing a large number of instruments simultaneously.

Figure 1: Patan Academy of Health Sciences Medical Autoclave

Sterilization in autoclaves is usually performed at 121°C, but some autoclaves can sterilize at temperatures higher than 121°C, such as 132°C and 134°C.(Sallah, Peddieson Jr, & Foroudastan, 1991) When it comes to sterilizing an object, the amount of time required depends on the material of the object, whether it is wrapped or not, and what kind of autoclave is used. To fully sterilize a large volume of media or materials, a longer sterilization cycle may be required. This will allow the steam heat to penetrate the media fully. It results in a significant loss of heat energy to the outside environment. In Order to minimize the heat loss, the autoclave should be insulated with the suitable material and suitable thickness.

Insulation of autoclaves in many hospitals has proved to be energy efficient. In the context of PAHS, after the implication of insulation in four of the autoclaves, total electricity saved in one month was found to be 1620 KWh. This saves NRs 2,47,360.5 in a year with the investment of NRs 50,000. Similarly from the analysis of insulation in the autoclave of Tilganga Institute of Ophthalmology, it shows about 11.85 minutes was saved per cycle. This can save nearly NRs 178671.15 per year. Besides this, the implication of insulation helps to minimize the surrounding temperature. The surrounding temperature of the autoclave room in PAHS reduces to (35-40) °C from (75-80) °C.

1.2 Problem statement

Every hospital is required to have Autoclave installed within their reach, and most of the hospitals have multiple Autoclave for different infected materials. Autoclaves in many hospitals in Nepal are of power within the range of 15KW to 20 KW each and for big hospitals due to the number of autoclaves installed the overall capacity is over 100KW. Most of the Autoclaves installed in the government hospital inside the valley have uninsulated Autoclave. This causes the unwanted heat loss causing more electricity consumption and also makes the working environment hotter. Autoclave consumes a huge amount of time and resources like water, electricity, and steam which contributes to a major portion of the cost. Identifying the factors contributing to media consumption and optimizing the process to lower the cost and time utilized to test the products is our prime objective.

1.3 Objectives

1.3.1 Main Objectives

To study heat transfer performance of insulated autoclaves installed in PAHS, optimize insulation methods and materials and apply modification to other autoclaves.

1.3.2 Specific Objectives

1. To study the insulation of Autoclave in PAHS.
2. To develop a mathematical model of Insulation for Autoclave.
3. To calculate the expected cost and energy saving caused by the Autoclave insulation.
4. To compare and analyze the Autoclave performance of PAHS with uninsulated Autoclave of another hospital.

1.4 Limitations

1. No actual insulation is done by us.
2. Minor losses are not considered during heat load calculations.
3. The transient heat analysis is not considered.
4. Actual number of Autoclaves couldn’t be identified in Nepal.

CHAPTER TWO: LITERATURE REVIEW

2.1 An Overview of an Autoclave

Using steam and pressure, autoclaves can do sterilization, reaching temperatures of up to 121°C and pressures of up to 2.1 Mpa (Panta et al., 2019). To make sure that all microbes are eliminated, these conditions are kept in place for a predetermined amount of time. Depending on the particular use, autoclaves come in a range of shapes and sizes. While some are large enough to sterilize industrial waste and equipment, others are small enough to be employed in a laboratory setting. Depending on the required level of control, they can either be operated manually or automatically (Hugo, 1991).

2.2 Working Condition in Autoclave

2.2.1 Temperature

A standard autoclave temperature is 121 degrees Celsius. This is hotter than boiling water. This is because simply heating something to boiling water temperature, 100 degrees Celsius (212 degrees Fahrenheit), does not sterilize it because bacterial spores can survive such temperatures. The temperature of 121 degrees Celsius, on the other hand, usually suffices.

2.2.2 Pressure

Sterilizing liquids is sometimes necessary. Laboratory reagents and biological liquids are primarily made up of water. Under standard pressure conditions, water can be heated to no higher temperature than 100 degrees Celsius since it boils at 100 degrees. Consequently, in order to increase the boiling point of water to 121 degrees Celsius (the boiling point varies directly with pressure), it is necessary to raise the surrounding pressure to 1 atmosphere (15 pounds per square inch).

2.2.3 Time

To achieve sterilization, the autoclave must be filled with enough equipment to be sterilized for the time required to achieve it. The standard time for small batches of equipment and reagents, i.e. where no container contains more than 1 liter of liquid, is 15 minutes. The time should be increased to 30 minutes for medium batches, which consist of containers with between 1 liter and 1 gallon of liquid. One hour should be used for large batches (Oyawale & Olaoye, 2007).

2.3 Thermal Insulation

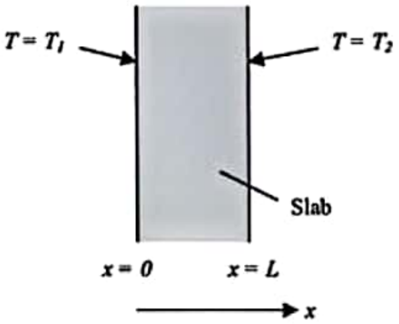
Using the right insulating materials and making design changes, thermal insulation is a strategy for reducing heat movement between spaces. The temperature difference between the inner and outside environments causes heat transfer, which can take place through conduction, convection, or radiation. The type of media that heat passes through greatly affects the pace of transfer. Insulation is an efficient way to stop the flow of unwanted heat, which can result in less energy being used by heating and cooling systems. A variety of materials, including cellulose, glass wool, rock wool, polystyrene, urethane foam, vermiculite, perlite, wood fiber, recycled cotton denim, plant straw, animal fiber (such as sheep's wool), cement, and dirt or earth, can be used as insulation. Radiant barrier, another name for reflective insulation, is another type of insulation material. (Kamal et al., 2021; Singh et al., n.d.)

R-value, U-value, and K-value are three parameters that are frequently used to assess the efficacy of bulk insulation. An insulating material's thermal resistance is gauged by its R-value. The resistance of the insulation to heat flow increases with increasing R-value. The thickness of insulation needed to attain a particular degree of thermal performance is calculated using this value.(Lau, n.d.; Singh et al., n.d.)

2.4 Thermal conductivity

In the design of heat transfer systems, such as insulation, heat exchangers, and cooling systems, thermal conductivity is particularly crucial. For instance, materials with high thermal conductivity, such metals or concrete, are poor insulators and can cause significant heat loss in the building industry. On the other hand, poor thermal conductivity materials, like fiberglass or foam insulation, are utilized to stop heat loss and boost energy efficiency. Usually, thermal conductivity is expressed in units of W/mK. Higher values of k indicate better heat conductivity in materials with higher thermal conductivity, which have larger values of k. Lower values of k, on the other hand, signify poorer heat conductivity in materials with lower thermal conductivity. In conclusion, the ability of a material to conduct heat is known as its thermal conductivity.

It is crucial to the planning and improvement of heat transfer systems in a variety of applications.



It is given by,

$$k = \frac{Q * L}{T * A * \Delta t} \quad 2.1$$

where,

k is the thermal conductivity in W/m·K

Q is the heat flow rate in W

T is the time in second

A is the surface area in m^2

L is the thickness in m

2.5 Insulation materials

The two most common types of inorganic fiber insulating materials used in south Asian market are glass wool and stone wool.(Shanmuga Sundaram & Bhaskaran, 2014) Glass wool is made of quartz sand, dolomite, resovite, and limestone, and is strengthened mechanically by being coated with adhesives and water-repellent oils. To ensure good fire resistance, these additives must only be used in small amounts. The same fundamental components as glass wool are also used to make stone wool, but the manufacturing of stone wool is characterized by higher melting temperatures and larger filaments. Rock wool is therefore better suitable for use in high-temperature applications since it is heavier and has a greater melting point. (Law et al., 2005). The insulation materials under our study is as in the table below:

Table 1: Insulation Materials with thermal conductivity (Hung Anh & Pásztory, 2021)

Materials	Thermal Conductivity (W/mK)	Cost (NRs/m^3)
Glass Wool	0.035	60,000
Rock Wool	0.038	70,000
Polyurethane	0.026	90,000
Polyisocyanurate	0.023	55,000
Cellulose Glass	0.025	2,40,000

2.6 Optimization procedure

In order to minimize heat loss to the environment and reduce energy costs, it is often necessary to maximize the thickness of insulating materials. However, the optimal thickness of insulation will depend on a number of factors, including the cost of the materials, installation, and upkeep, as well as the expected energy savings.(Sahin & Kalyon, 2004)

To determine the optimal thickness of insulation, a cost-benefit analysis must be performed, taking into account the overall cost of insulation and installation, as well as the expected energy savings over the lifetime of the insulation. The cost function to be minimized is defined based on cost data and heat transfer concepts, considering factors such as the thermal conductivity of the insulation material and the temperature gradient across the insulation.(Li & Chow, 2005; Zaki & Al-Turki, 2000)

It is important to note that simply increasing the thickness of insulation may not always be the most cost-effective solution. Therefore, a careful analysis of the costs and benefits of various insulation options must be conducted to identify the most efficient and cost-effective solution for a given application.(Başoĝul & Keçebaş, 2011)

The economic insulation thickness for a pipe depends on several factors. These include the conductivities of the materials, such as steel, epoxy, and insulation, as well as the operating and ambient temperatures. The heat transfer coefficients at the inside and outside of the steam generator, economic parameters like the cost of materials and labor, and expected annual operation hours also play a role in determining the optimal insulation thickness.(Kalyon & Sahin, 2002; Öztürk et al., 2006)

To identify the most efficient and cost-effective insulation solution, a thorough cost-benefit analysis is required. This analysis should take into account the various factors that influence the optimal insulation thickness, such as the rates of heat transfer and the energy lost, as well as the costs associated with materials and labor. The expected annual operation hours should also be considered, as they can significantly impact the total energy savings achieved through insulation. By considering all of these factors and conducting a careful analysis, it is possible to determine the most effective and economical insulation thickness for a given pipe application.(Bahadori & Vuthaluru, 2010)

Most researchers concur that the value that delivers the smallest overall life cycle is the optimum economic thickness cost. The heating transmission loads and their costs (i.e., energy expenses) drop as the thickness of the thermal insulation rises. In order to calculate the variation in the cost of the insulation as well as the present value of the energy consumption, which is regarded as wasted energy, during the lifespan of the system, the transmission loads are utilized as the input data for an economic model. On the other hand, as more material is used, the cost of insulation rises.(Keebaş et al., 2011a)

The convective heat transfer coefficient for inside and outside of the pipes are given by

$$h_i = 0.023 * Re^{0.8} * \overset{0.4}{\mathrm{Pr}}(kf / D1) \qquad 2.2$$

$$h_o = 11.28 * \left(\frac{1}{D_{ins}}\right)^{0.2} * \left(\left(\frac{2}{(Ts,o + To)}\right)^{0.181} (Ts,o - To)^{0.266} (1 + 2.86V)^{0.5} \qquad 2.3$$

where Ts,o is the average outer surface temperature of the insulation, D1 and Dins are the internal pipe and insulation diameters, kf is the fluid's thermal conductivity, V is the outside air velocity, and To is the temperature of the outside air.(Keebaş et al., 2011a)

The total internal resistance of any piping system, Rp, is equal to the summation of the surface resistances of convective heat transfer over the inside and outside surfaces of the pipe and the total internal resistance of all layers of the piping system.(Kumar et al., 2015)

$$R_{pun,ins} = 1/(h_i A_i) + ln(\frac{r_1}{r_0}) / (2\pi LK1) + 1/(h_o A_o) \qquad 2.4$$

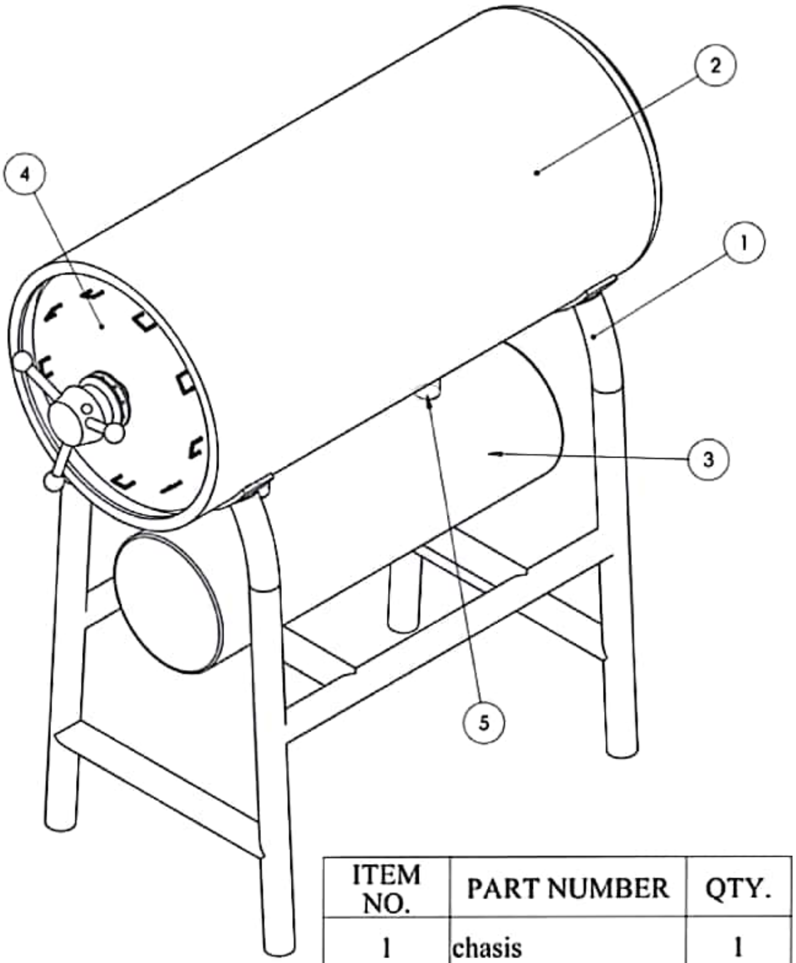
This thermal resistance depends on the layers of materials.

$$R_{pins} = 1/(h_i A_i) + ln\left(\frac{r_1}{r_0}\right) / (2\pi LK_1) + ln(\frac{r_2}{r_1}) / (2\pi Lk_2) + 1/(h_o A_o) \qquad 2.5$$

The optimum thermal insulation is the thickness and material that gives the maximum energy savings. This could be known through insulation economy or economic analysis.(Keebaş et al., 2011a)

Energy and insulation expenses are taken into account when determining the ideal insulation thickness for a pipe. The electricity needed to pump the fluid along the pipeline is a factor in the operation cost. The thickness of the insulation that is put to the pipe determines how much it will cost to insulate. The cost of energy is a concept that depends on the kind of energy source used and the amount of heat lost along each length of pipe.(Chou & Wong, n.d.; Kalyon & Sahin, 2002; Keebaş et al., 2011a; Öztürk et al., 2006; Sahin & Kalyon, 2004; Zaki & Al-Turki, 2000).

2.7 Autoclave at PAHS



ITEM NO.	PART NUMBER	QTY.
1	chasis	1
2	chamber	1
3	steam generator	1
4	Cover	1
5	steam pipe	2

Figure 2: CAD Model of PAHS Autoclave

The Patan Academy of Health Sciences (PAHS) sterilizing room consists of six pressure steam sterilizers. Among them four are horizontal cylindrical pressure steam sterilizer whereas remaining two are of horizontal rectangular type. Here, we have considered the cylindrical type in the study.

The steam sterilizer is composed of pressure chamber and the steam generator which are supported by the steel frame. It also consists of other ancillary equipments like steam pipes, valves and gauzes.

Table 2: Steam Generator Dimensions

Length	0.94 m
Outer Radius	0.15 m
Steel Thickness	0.005 m
Epoxy Thickness	0.0025 m

Table 3: Pressure Chamber Dimensions

Length	1.21 m
Outer Radius	0.29 m

Steam pipes are small in length just connecting the steam chamber and the steam generator. So, initially it is not considered to have much of impact in heat loss and ignored as a minor loss.

The valves are main valve, jacket valve, chamber valve, water valve, manual maintenance switch valve, and safety valve. Main valve is manually controlled by the operator to adjust the steam flow rate. Jacket valve is placed to control the steam flow between the steam generator and the pressure chamber. When the door of the sterilizer is opened mistakenly then the jacket valve gets turned off and chamber valve is turned on. Water valve is for the control of water flow in the steam generator. Manual maintenance valve allows to manually flow out the dirty sedimented water from the steam generator. Safety valve prevents pressure chamber to go above the designated pressure which is 0.22Mpa in this case.(*Model HA-BD200 HORIZONTAL CYLINDRICAL PRESSURE STEAM STERILIZER USER'S MANUAL*, n.d.)

The gauges included are temperature, pressure and water level gauges. Both temperature and pressure of dial gauge type are connected to steam generator and the pressure chamber each. The water level gauge is connected to the steam generator to find the level of water inside the generator.

2.7.1 Sterilization Cycle

The thermal sterilization cycle of medical industry by moist-heat or steam is governed by the international standards. The heating cycle of the sterilization process of autoclave is described in this section.

Variations in sterilization cycle types exist primarily to accommodate differences in products being sterilized. Essentially, steam sterilization is the process of applying thermal energy to achieve the desired sterilization of a product so that it can be safely consumed. Generally, for achieving the sterilization it is necessary to heat the system to the target temperature and hold the product to be sterilized to equivalent system target temperature for a minimum of 15 minutes. The target temperature is usually in between 121 degree Celsius to 135 degree Celsius (Kamal, Hmidat, & Abdallah, 2021).

The steam sterilization is done through three phases:

1. Pre-processing (or heating stage)
2. Sterilizing (or holding stage)
3. Post-processing (or cooling stage)

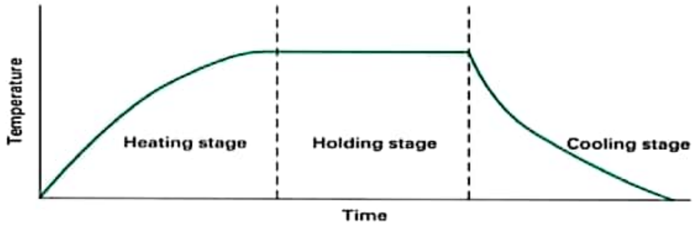


Figure 3: Stages of Sterilization

2.7.1.1 Phase I: Pre-Processing

First task in pre-processing is the removal of air from the pressure chamber as it is the biggest restraint to the steam sterilization. There are mainly two basic types of steam sterilization: gravity (class N) and dynamic air removal (class B).

The gravity air removal refers to the method of removing air from the autoclave chamber before sterilization. In a gravity air removal autoclave, the chamber is initially filled with steam, which displaces the air present. The steam then condenses and creates a vacuum, which draws any remaining air out of the chamber. This process ensures that the steam can penetrate all areas of the load being sterilized, resulting in effective sterilization.

Unlike gravity air removal autoclaves, dynamic air removal autoclaves use a vacuum pump to remove air from the chamber before sterilization. In a dynamic air removal autoclave, the chamber is first filled with steam, which heats up the load and any air present in the chamber. Once the temperature and pressure inside the chamber reach a certain level, the vacuum pump is activated, which draws out the air from the chamber.

All the autoclaves in the PAHS are gravity air removal type. In this method, the steam is introduced from the backside of the autoclave. During that process the air is pushed along the chamber to the pipe at the other end from where air get escaped until the entire chamber is filled with steam. This process is repeated two to three times to ensure a uniform distribution of saturated steam throughout the chamber and remove out the organisms accumulated in the air.

2.7.1.2 Phase II: Sterilizing

It is the period of sterilization. There is a relationship between the pressure and temperature while sterilizing. Two main techniques are proposed in medical sterilization process.

134 °C and 2.2 bar, holding period 30 min
121°C and 2.1 bar, holding period 45 min

Practically, 30 min holding time for 134 degree Celsius is not always enough. So, extended cycles are applied according to the loads type. The manufacturer's instruction for autoclave in PAHS is to hold for 45 minutes.

2.7.1.3 Phase III: Post-Processing

In this phase, the chamber temperature is allowed to cool down but the pressure inside is kept high enough to prevent condensation. Then, air in introduced to the pressure chamber. The door can be open safely after it reaches the atmospheric pressure.

CHAPTER THREE: METHODOLOGY AND EXPERIMENTAL SETUP

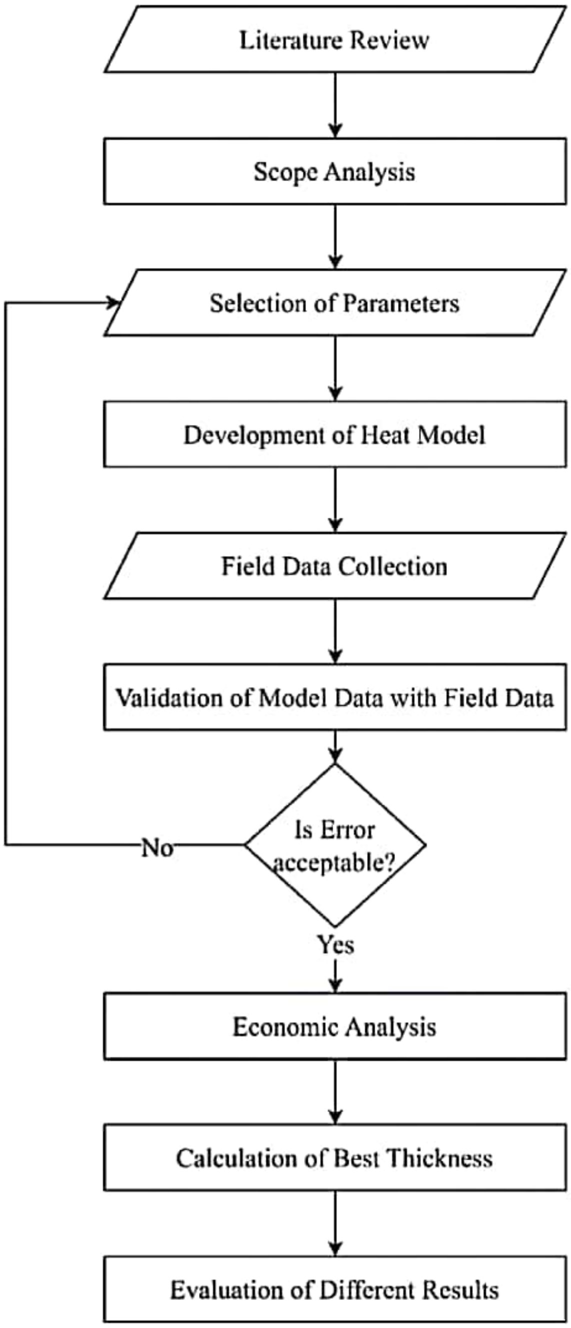


Figure 4: Methodology

3.1 Literature Review

We conducted a literature review to gather information on the current state of research, key findings, and research gaps related to economic insulation of autoclaves. We searched relevant academic databases, journals, and conference proceedings for studies investigating similar topics or methods proposed in this study..

3.2 Scope Analysis

The scope analysis was conducted to define the boundaries and limitations of this study, which focuses on the thermal insulation of the steam generator of autoclaves. The analysis involved identifying the specific research objectives related to insulation analysis.

3.3 Selection of Parameters

The selection of parameters for this study involved identifying the key variables that would be measured and analyzed to achieve the research objectives. The selection of parameters was based on the research questions, literature review, and scope analysis.

The selected parameters include the operating temperature of the autoclave, the thermal conductivity and thermal resistance of different insulation materials, and the thickness of the insulation layer.

Other parameters that may be considered include the cost-effectiveness of different insulation materials, the impact of insulation performance on energy consumption, and the effect of insulation on the sterilization proces.(Abdallah & Ismail, 2001; Soni et al., n.d.)

3.4 Development of Heat Loss Model

We have developed a heat loss model as a key component of our study, which was used to evaluate the thermal insulation performance of different materials and determine the optimal insulation thickness. The heat loss model involved simulating the thermal behavior of the autoclave system, including the steam generator and insulation layer, under different operating conditions. The model considered factors such as operating temperature and pressure, thermal conductivity and resistance of insulation materials, and insulation thickness.

3.5 Field Data Collection

Field data collection has been conducted from actual hospital autoclaves as a crucial part of this study's methodology to provide real-world data on the thermal insulation performance of autoclaves. The data collection involved visiting hospitals and collecting data on the operating temperature and the insulation thickness and materials used.

3.6 Validation of Model and Field Data

The study has included a crucial step of validating the developed heat loss model with field data collected from actual hospital autoclaves. The validation process involved comparing the simulation results obtained from the heat loss model with the field data to ensure the accuracy and reliability of the model. The collected field data was used to validate the heat loss model by comparing the predicted values with the actual values.

3.7 Economic Analysis

The economic analysis is based on the life cycle cost analysis (LCCA) method, which considers the total cost of ownership of the autoclave system over its expected service life. The LCCA method involves estimating the initial capital cost of insulation materials and installation, as well as the ongoing maintenance costs, and then calculating the net present value (NPV) of these costs over the life of the autoclave system.

3.8 Evaluation of Different Results

The evaluation of different results is an important component of this study's methodology, as it involves assessing the impact of different insulation materials and thicknesses on the thermal insulation performance and energy efficiency of autoclaves. The evaluation will involve comparing and analyzing the results obtained from the heat loss model and the economic analysis.

3.9 Selection of the Equipment

A thermal gun and clamp on ammeter were used for primary data collection. Thermal gun was used over other thermal measuring instruments because of its quick and accurate output which is important where multiple measurements need to be taken in a short period of time.

Beside this, thermal guns are portable, safe and versatile.

The range of thermal gun typically depends on the specific model and manufacturer, but most thermal gun has a range between -500C to 10000C. The temperature range also depends on the distance between gun and object being measured, as well as emissivity of the object.

The error range of thermal gun expressed as a percentage of temperature being measured, and can vary depending on the temperature range being measured. In our case where the temperature range was from 16°C to 121°C, the error range may vary from ±2%. In addition to this, the accuracy of thermal gun is affected by the angle to which the gun is held and other environmental factors.

Thermal guns can be a useful piece of data collection equipment in some circumstances, despite the fact that they have some limitations. They are frequently less accurate than contact thermometers since they are susceptible to factors like distance and the emissivity of the object, for example. Moreover, they might not be suitable for particular applications that call for contact measurements. As a result, it's vital to carefully analyze each application's needs before deciding to employ a thermal pistol to collect data. Thermal guns can be a useful piece of data collection equipment in some circumstances, despite the fact that they have some limitations.

3.10 Experimental Setup

The temperature in the steam generator and sterilizing chamber were measured to validate the result of steady state thermal analysis. So, both the generator and chamber were divided into four sections in order to measure the temperature of different sections. The figure below shows the CAD model of the steam generator and sterilizing chamber with the position where the temperature was measured.

The steam sterilizer has a diameter of 0.3256m and a length of 0,96m. The front face of the steam generator consists of an electric control panel which makes it difficult to insulate the face. The position of temperature measurement can be seen in the figure above. Maximum error of the thermal gun was about ±2%.

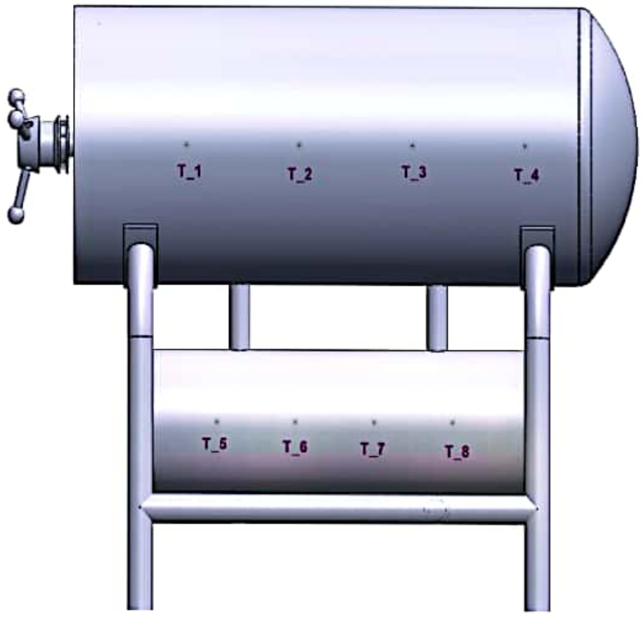


Figure 5: Temperature Measured Location Record of Experimental Data

We collected data from glass wool insulated autoclaves at PAHS, three uninsulated autoclaves at Thapathali Prasuti Griha (Thapathali), Civil Hospital (Baneshwor) and Teaching Hospital (Maharajgunj). During the measurement process, various experimental conditions were considered.

3.11 Consistency of measurement location

Consistency in the condition of data collection location is important while collecting the data because it minimizes the irrelevant variable that could affect the results. There is a greater probability that other factors may be influencing the results of the experiment when measurements are done in several places or under various circumstances.

In context of our data collection, the experiment was carried in four different hospitals within the Kathmandu valley. So, we considered the location factor has very less influence in our experimental data.

3.12 Time of measurement

An important element that might impact the precision and dependability of the data obtained in an experiment is the measuring period. Control in the timing of data collection helps to control the irrelevant variables.

3.13 Temperature Data

In order to gather data on the thermal insulation performance of autoclaves in healthcare facilities, the study team selected multiple hospitals in the region to collect temperature data from both insulated and uninsulated autoclaves. The data collection process involved visiting the hospitals and using a thermal gun to measure the temperatures of the autoclaves during normal operating conditions.

Insulated temperature data was collected from Patan hospital, which uses autoclaves with thermal insulation materials. The team used the thermal gun to measure the temperature of the autoclaves, which were covered with insulation materials to prevent heat loss. This data provided insight into the effectiveness of the insulation materials used in the autoclaves at Patan hospital and helped to validate the developed heat loss model.

Uninsulated temperature data was collected from Prasuti Griha, TU teaching hospital, and Civil hospital, which use autoclaves without insulation materials. The team measured the temperatures of the uninsulated autoclaves using the thermal gun to determine the extent of heat loss occurring during operation. This data provided valuable insights into the thermal performance of uninsulated autoclaves, highlighting the need for improved insulation to reduce energy waste and improve the safety of the autoclaves.

CHAPTER FOUR: MODELLING AND CALCULATION

4.1 Analytical Method

The analytical method in heat transfer modeling involves the use of mathematical equations to describe the transfer of heat energy through different components of a system. This approach allows for the evaluation of the energy flow and temperature changes within the system. The equations used for heat transfer modeling typically include the laws of thermodynamics, Fourier's Law of Heat Conduction, and the Heat Equation. These equations are used to calculate the rate of heat transfer between two materials and the amount of heat energy that is lost due to conduction, convection, and radiation. The accuracy of the model depends on the accuracy of the assumptions made and the accuracy of the equations used. (Madejski et al., 2022; Sutheesh & Chollackal, 2018)

The autoclave is made up of two body:

1. Steam Generator
2. Pressure Chamber

Both of these bodies are cylindrical in shape. We can apply steady state heat transfer model to the cylindrical body to calculate the amount of heat loss to the outer environment from the surface of steam generator and pressure chamber. The heat transfer model is in the normal direction to the wall surface (radially outward). Therefore, the heat transfer can be modelled as the one-dimensional model. The temperature would be only the function of radius, i.e,

$$T = T(radius) \qquad 5.1$$

Since in the autoclave, the steam inside the steam generator is maintained at constant temperature. So we can assume that the internal surface of the generator is of constant temperature and is equal to the temperature of steam.

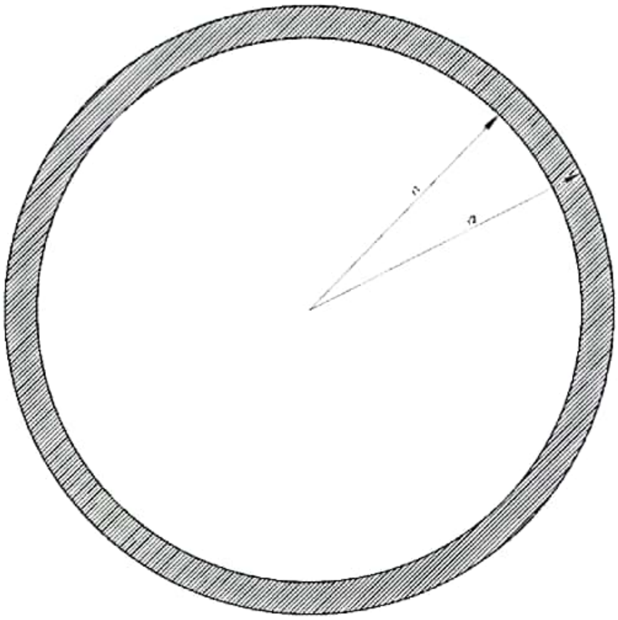


Figure 6: Uninsulated Cylinder Dimensions

If the thermal conductivity is constant, the Fourier law is given by,

$$\dot{Q}_{conduction} = -KA\frac{dT}{dr} \qquad 5.2$$

$$where, A = 2\pi rL$$

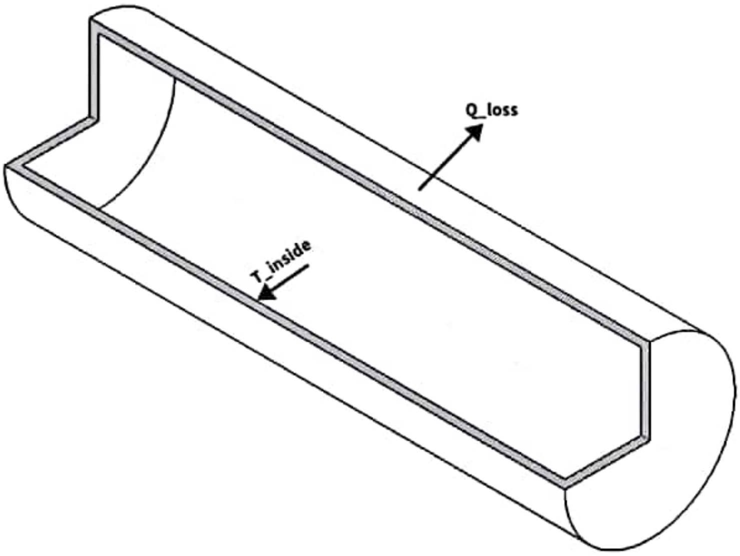


Figure 7: Uninsulated Cylinder Cut-out

Integrating above equation from inner radius to outer radius,

$$\int_{r_1}^{r_2} \frac{\dot{Q}_{conduction}}{A} dr = -\int_{T_1}^{T_2} K dT \tag{5.3}$$

$$\dot{Q}_{conduction} = 2\pi K L \frac{T_1 - T_2}{ln\left(\frac{r_2}{r_1}\right)} \tag{5.4}$$

$$\dot{Q}_{conduction} = \frac{T_1 - T_2}{R_{cylinder}} \tag{5.5}$$

$$where,\ R_{cylinder} = \frac{ln\left(\frac{r_2}{r_1}\right)}{2\pi KL} \qquad 5.6$$

$R_{cylinder}$ is the conduction resistance of the cylinder layer.

This is the heat loss model for the uninsulated generator per second per unit area.

For the insulated generator, the heat transfer model should be developed incorporating all the layers of the material.

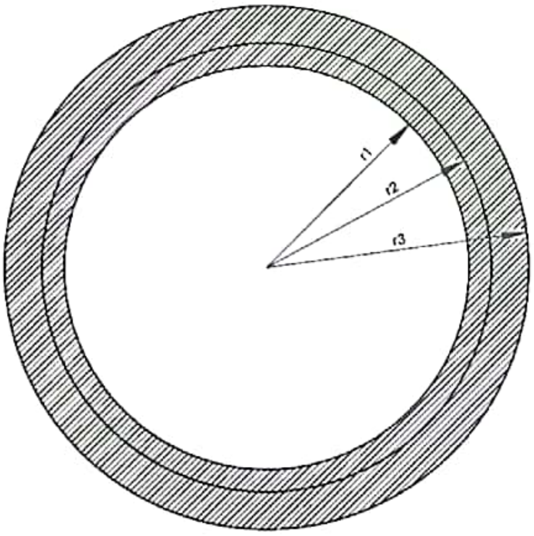


Figure 8: Insulated Cylinder Dimensions

This is the case of composite cylinder heat transfer. Since it is composed of different materials the heat transfer resistance will also change based on how thick each material is.

The internal temperature is assumed to be constant and is equal to steam temperature.

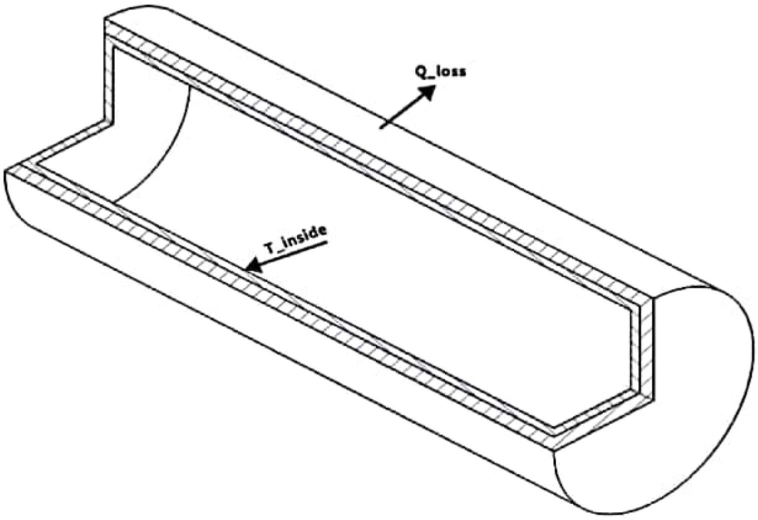


Figure 9: Insulated Cylinder Cut-out

So, the resistance of heat transfer is calculated as,

$$R_{steel} = \frac{ln\left(\frac{r_2}{r_1}\right)}{2\pi K_{steel} L} \tag{5.7}$$

$$R_{insulation} = \frac{ln\left(\frac{r_3}{r_2}\right)}{2\pi K_{insulation} L} \tag{5.8}$$

$$R_{convection} = \frac{1}{h_o A_o} \tag{5.9}$$

Where,

R_{steel} is the heat resistance provided by the internal steel material (K/W)

$R_{insulation}$ is the heat resistance provided by the insulation material (K/W)

$R_{convection}$ is the convective heat resistance (K/W)

r_1 is the radius of internal surface (m)

r_2 is the radius of steel outer surface (m)

r_3 is the radius of insulation outer surface (m)

K_{steel} is the thermal conductivity of steel (W/m.k)

$K_{insulation}$ is the thermal conductivity of insulation material (W/m.k)

L is the length of the steam generator (m)

h_o is the convective heat transfer coefficient (WK/m^2)

A_o Area of convective heat transfer surface (m^2)

The total heat resistance is obtained by simply adding all those resistance. So total heat transfer resistance becomes,

$$R_{total} = R_{steel} + R_{insulation} + R_{convection} \qquad 5.10$$

The steam generator of the autoclave comes with mirror finish and epoxy finish surface. In mirror finish generator, only steel is present. But in case of epoxy finish extra layer of epoxy is added. This epoxy layers acts like insulation and protective layer to the steam generator. The overall heat resistance of the steam generator changes with addition of epoxy layer.

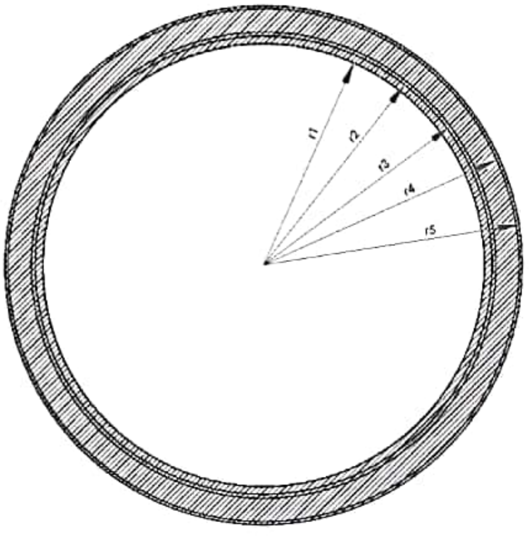


Figure 10: Insulated with Cladding Dimensions

The resistance equation becomes,

$$R_{total} = R_{steel} + R_{epoxy} + R_{insulation} + R_{convection} \qquad 5.11$$

Where,

R_{epoxy} is the heat transfer resistance given by epoxy layer which is given by

$$R_{epoxy} = \frac{ln\left(\frac{r_3}{r_2}\right)}{2\pi K_{epoxy} L} \qquad 5.12$$

Here, K_{epoxy} is the thermal conductivity of epoxy layer.

Generally the insulation is cladded with external materials. Cladding provides protection to the insulation material from environmental factors which can cause damage or degrade the insulation's performance. Cladding materials can also enhance the thermal performance of the insulation. Aluminum is generally used.(Jemmad et al., 2021)

If the aluminum cladding is also considered the heat transfer equation becomes,

$$R_{total} = R_{steel} + R_{epoxy} + R_{insulation} + R_{cladding} + R_{convection} \tag{5.13}$$

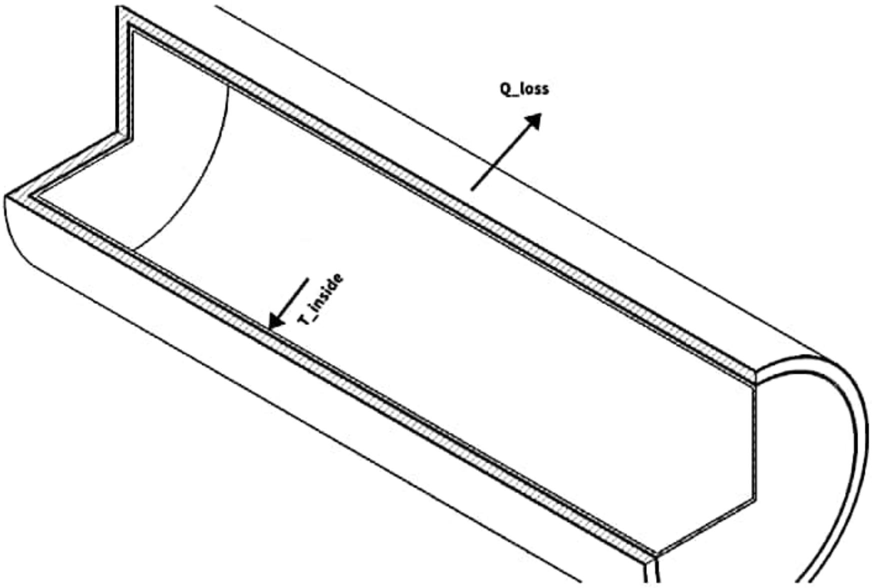


Figure 11: Insulated with Cladding Cut-Out

Where,

$R_{cladding}$ is the heat transfer resistance given by cladding material which is given by

$$R_{cladding} = \frac{ln\left(\frac{r_5}{r_4}\right)}{2\pi K_{cladding} L} \tag{5.14}$$

Here, $K_{cladding}$ is the thermal conductivity of cladding material.

The overall heat transfer coefficient is the reciprocal of heat transfer resistance,

$$U_{total} = \frac{1}{R_{total}} \tag{5.15}$$

Then, the heat transfer from the surface to the environment per m^2 per seconds is given by,

$$\dot{q}_{loss} = U_{total}(T_1 - T_{ambient}) \tag{5.16}$$

Where,

$\dot{q}_{loss}$ is the heat flux losses from the outer surface

$T_{ambient}$ is the ambient average temperature

The overall heat losses from all the surface can be calculated as,

$$\dot{Q}_{loss} = U_{total}A_o(T_1 - T_{ambient}) \tag{5.17}$$

Where,

$\dot{Q}_{loss}$ is the heat loss from the outer surface.

Here 'r' and 'A' is the dimensional parameters. These can be measured from the actual steam generator. The temperature value can also be measured from the thermometer and thermocouple. The thermal conductivity can be taken from the documented data for that material.

Convective heat transfer coefficient needs to be calculated separately. Several factors affect the convective heat transfer coefficient, including the velocity of the fluid, temperature difference between the surface and fluid, properties of the fluid, surface roughness, geometry of the solid surface, and presence of boundary layers. These factors interact in complex ways, and they must be carefully considered in any heat transfer analysis or design.

4.2 Natural convection

Typically, the heat transfer relationships associated with natural convection are established through experimental observations.

However, relations are given for the calculation of natural convective heat transfer coefficient for certain ranges of conditions. The dimensionless numbers are utilized for this.

The first step is to calculate the Rayleigh number which is given by,

$$\mathrm{Ra} = \mathrm{Gr}.\mathrm{Pr} \qquad 5.18$$

$$\mathrm{Ra} = \frac{g\beta(T_{\mathrm{surface}} - T_{\mathrm{ambient}})\delta^3}{\nu K_{\mathrm{air}}} \qquad 5.19$$

Here,

Ra is Rayleigh number

Gr is Grasshoff number

Pr is Prandtl number

g is acceleration due to gravity (m/s^2)

β is thermal expansion coefficient $(\mu m/mK)$

$T_{surface}$ is average surface temperature (K)

$T_{ambient}$ is average ambient temperature (K)

δ is the base height (diameter in case of horizontal cylinder) (m)

K_{air} is the thermal conductivity of air (W/m.k)

ν is kinematic viscosity (m^2/s)

For calculation of kinematic viscosity, thermal conductivity and thermal expansion coefficient the properties should be taken at average air film temperature. The average air film temperature can be calculated as,

$$T_f = \frac{T_{surface} - T_{ambient}}{2} \qquad 5.20$$

The thermal expansion coefficient is given by,

$$\beta = \frac{1}{T_f} \qquad 5.21$$

After the calculation of Rayleigh number, Nusselts number needs to be calculated which is given by,

$$Nu = 0.6 + \left(\frac{0.387\, Ra^{\frac{1}{6}}}{\left(1 + \left(\frac{0.559}{Pr}\right)^{\frac{9}{16}}\right)^{\frac{8}{27}}} \right)^{2} \qquad 5.22$$

The prandtl number (Pr) is taken as 0.716 for horizontal cylinder for natural convection.

The natural convection coefficient is then calculated as,

$$h = \frac{K_{air}}{\delta} Nu \qquad 5.23$$

4.3 Forced Convection

Forced convection is an important mode of heat transfer in many engineering and industrial applications, such as cooling of electronic devices, heat exchangers, and HVAC systems. The heat transfer rate in forced convection is dependent on various parameters that affect the motion and behavior of the fluid over the surface.(Madejski et al., 2022; Singh et al., n.d.)

In practice, it can be difficult to calculate all the parameters involved in forced convection heat transfer, especially in complex systems with varying fluid properties and geometries. Researchers have developed empirical correlations based on experimental data to predict the convective heat transfer coefficient. It is important to note that the accuracy of these correlations depends on the quality and applicability of the experimental data used to develop them.

For this work, the proposed correlation by (Kecebas et al.) is used for calculation of forced convective heat transfer coefficient. It is given as,

$$h_{covection} = 11.58\left(\frac{1}{D_{insulation}}\right)^{0.2}\left(\frac{2}{T_{surface} - T_{ambient}}\right)^{0.181}(T_{surface} - T_{ambient})^{0.266}(1 + 2.86V_{air})^{0.5} \quad 5.24$$

Where,

$D_{insulation}$ is the outer diameter of insulated surface (m)

V_{air} is the average velocity of air (m/s)

(Ozdemir and Parmaksizoglu) used following correlation instead of above.

For laminar flow,

$$h_{convection} = 1.25\left(\frac{T_{surface} - T_{ambient}}{2r_{insulation}}\right)^{0.25} \quad 5.25$$

For turbulent flow,

$$h_{convection} = 8.9\,\frac{V_{air}^{0.9}}{(2r_{insulated})^{0.1}} \quad 5.26$$

Where,

$r_{insulated}$ is the outer radius of insulation surface

4.4 Base Values for the Study

Table 4: Base Values for The Study

Variables	Values
Internal radius (r_1)	0.1425 m
Outer radius of steel (r_2)	0.1475 m
Outer radius of Epoxy (r_3)	0.15 m
Outer radius of Insulation (r_4)	0.175 m
Outer radius of Cladding (r_5)	0.176 m
Thickness of steel (t_{steel})	0.005 m
Thickness of Epoxy (t_{epoxy})	0.0025 m
Thickness of Insulation ($t_{insulation}$)	0.025 m
Thickness of Cladding ($t_{cladding}$)	0.001 m
Surface Temperature ($T_{surface}$)	374 K
Velocity of air (V_{air})	0.2 m/s
Length (L)	0.94
Thermal conductivity of steel (K_{steel})	45 W/mK
Thermal conductivity of epoxy (K_{epoxy})	0.2 W/mK
Thermal conductivity of insulation ($K_{insulation}$)	0.035 W/mK
Thermal conductivity of cladding ($K_{cladding}$)	247 W/mK
Inside Temperature	394 K
Discount Factor	9 %
Inflation Rate	7.87 %
Life Cycle	10 years
Operating Hours (per day)	4
Efficiency	0.95
Energy Rate	NPR 12.25/KWh
Cost of Insulation	NPR 60,000/m^3 (Glass Wool)

4.5 Validation of Heat Model

Comparing the output of the MATLAB code to actual data gathered from a comparable autoclave is necessary to validate the output of a MATLAB code. In our case, the outside temperature from an autoclave was evaluated using MATLAB code, and the findings were compared to the temperature experienced in the autoclave at PAHS. We make sure that the input parameters and boundary conditions used in the MATLAB code match those of the autoclave at PAHS hospital for the results to be validated. This includes making sure the dimension, measurements, and usage details of the autoclave does not vary.

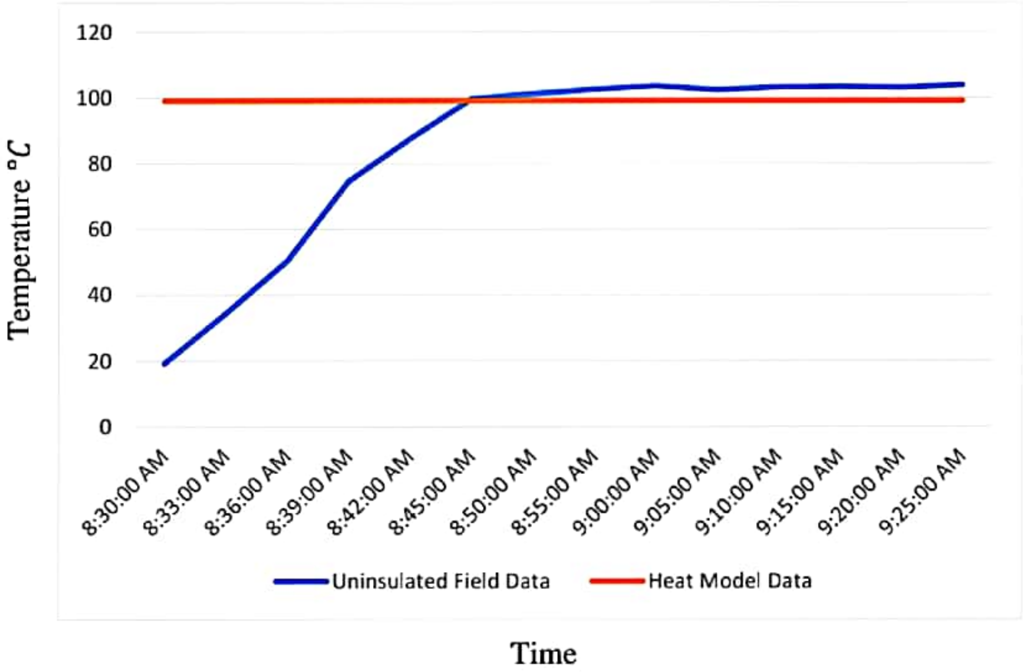


Figure 12: Uninsulated Vs Heat Model Data

In the case of uninsulated autoclaves, initially the temperature was 20°c and heating it up the steady state transfer occurred at 101°c where the heat loss to the surrounding was significant.

The heat model data cannot calculate the transient behavior of the autoclave. It can only calculate the steady state value. As we can see, the autoclave doesn't take too much time to reach steady state value, so we can use the heat model for further analysis by ignoring small time difference that requires autoclave to reach steady state value.

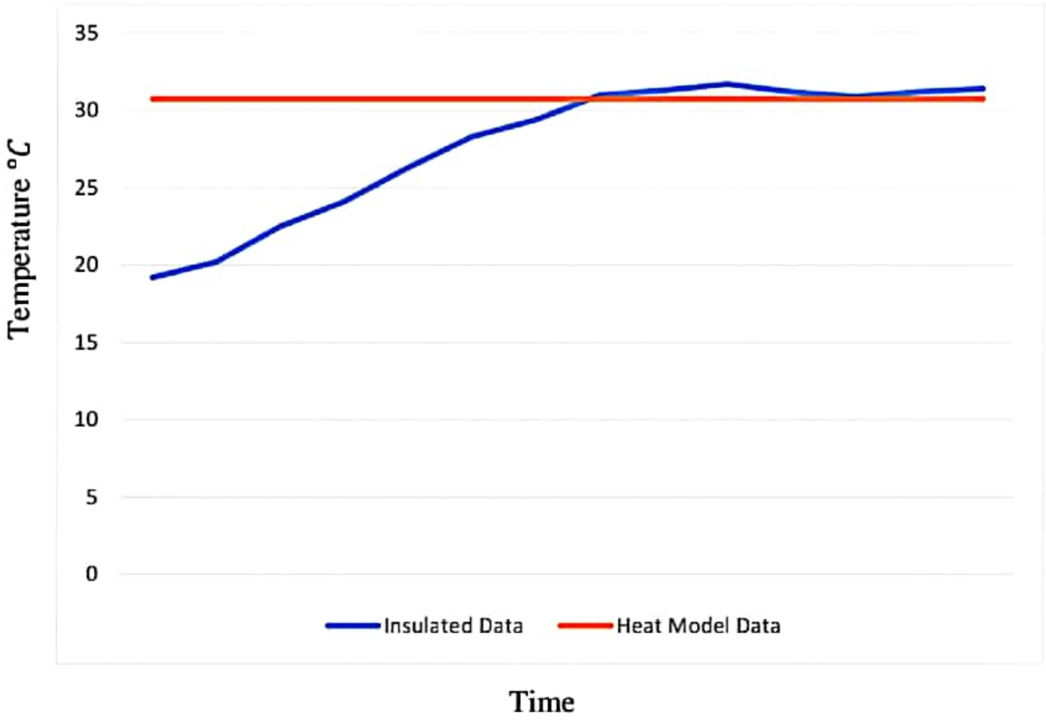


Figure 13: Insulated Vs Heat Model Data

The graph plotted for the data obtained from our experiment at PAHS and data obtained from the MATLAB shows small variation. This shows the heat model of MATLAB was valid.

4.6 Economic Analysis

To conduct an economic study, statistical tools and quantitative research techniques are frequently used. These methods can be used to assess the project's anticipated value and produce information that might aid an individual in making wise choices.

One of the most often used methods in economic analysis is the payback time calculation, which aids in determining the project's cost recovery period. One can understand how long it will take for the project to make back its initial investment and turn a profit by estimating the payback period.

4.7 Life cycle energy and expenditure analysis

This method is used to calculate the costs that could be saved on modifying the projects, creating new models etc. All the income and expenses due to installing insulation on the autoclave have been characterized by two economic parameters, P_1 and P_2. Here, initially the cost required for the production of energy for certain lifetime expressed in years is calculated then the cost required as an expenditure incorporating operation and maintenance cost resale value etc. for the same lifetime is calculated. Then it is compared one among other and if the cost required for the production of energy is found greater, then the project will be economically feasible. This means let's say a steam chamber is initially uninsulated and having huge amount of heat loss where Q is the heat that could be saved after insulation, then after insulation this Q would be saved and the cost required for the production of that particular Q and the expenses like capital, operation and maintenance etc. is compared and if energy cost is greater, then the project will be selected.

The life cycle energy/expenditure method is used here to calculate the economy. To calculate insulation economy, first it is necessary to determine the life-cycle energy ratio (P_1) and the life-cycle expenditures to initial investment ratio (P_2) due to the additional capital investment.(Daşdemir et al., 2017; Kamal et al., 2021; Keebaş et al., 2011b)

The p1 has relation with the interest rate and inflation rate and lifetime N and it has the relation as below;

$$P_1 = \frac{1}{d-i}\left[1 - \left(\frac{1+i}{1+d}\right)^N\right] \; if \; i \neq d \tag{5.27}$$

$$P_1 = \frac{N}{1+i} \; if \; i = d \tag{5.28}$$

Here i is the interest rate or discount rate while d is the inflation rate. About them a brief overview is provided below. In the context of Nepal the inflation and discount rate are not the same so the equation 5.27 will be used for the calculation.

$P_2$is the ratio of the life-cycle expenditures incurred because of the additional capital investment to the initial investment. $P_2$is defined by

$$P_2 = 1 + P_1 Ms - \frac{Rv}{(1+d)^N} \tag{5.29}$$

Where, Ms is the ratio of the annual maintenance and operation cost to the original first cost, Rv is the ratio of the resale value to the first cost. P_2can be taken as 1 if the maintenance and operation cost is zero. In this project the maintenance is not required and hence $P_2$is taken as 1.

Hence,

$$P_2 = 1 + P_1 . Ms - \frac{Rv}{(1+d)^N} \tag{5.30}$$

$$cost\ saved(Ct) = P_1 . C_1 - P_2 . C_2 \tag{5.31}$$

Here, C1 is the cost equivalent to saved energy while the C2 is the cost of insulation.

4.8 Cost equivalent to energy saved (C_1)

In hospitals, autoclaves are frequently used for sterilization. They employ a steam generator to generate steam, which is then applied to various materials and medical equipment to sterilize them. The absence of insulation on the steam generator in autoclaves, which causes heat loss to the surrounding environment, is one of the main issues.

By reducing the quantity of heat lost to the surrounding environment, an autoclave's operating costs can be brought down. The steam generator can be insulated to help retain heat and lower the amount of electricity needed to maintain the target temperature. The initial expense of insulating the steam generator is evaluated against potential long-term cost benefits, though.

It is crucial to evaluate the corresponding rate of electricity for the quantity of energy saved by insulation when assessing the cost of power usage. By doing this, it is feasible to assess the insulation project's cost-effectiveness and establish whether it is a financially sound choice.

The rate of electricity is used from the NEA annual book according to the hospital's usage and it was found to be NRs 12.25 per unit of electricity.

Mathematically,

$$Cost\ Saved = \frac{Heat\ Saved}{3.6 * 10^6 * \eta} * rate\ of\ electricity\ per\ unit \qquad 5.32$$

Where, η is the efficiency of heating

Cost Saved in NRs

Heat Saved in in J

Rate of electricity in NRs/unit

4.9 Cost of insulation (C_2)

The cost of insulation is one of the major project expenses in the case insulating the steam generating system. The amount of insulation material needed per unit volume to wrap around the steam generator is often used to assess the cost of insulation.

The annual maintenance cost is a crucial consideration in addition to the price of the insulation. This project, on the other hand, requires no annual maintenance, hence the cost of maintenance has been set at Nrs.0.

The fixed cost of labor, which is incurred initially when setting up the project, is another cost component to take into account. The overall benefit of the project will be lower the higher the cost of labor. For the project to be as economically viable as feasible, it is crucial to maintain labor costs as low as possible.

In conclusion, it is critical to take into account labor, maintenance, and insulating costs when assessing a project's economic viability, including the steam generating system. Hospitals may maximize the project's benefits and guarantee long-term sustainability by carefully examining these cost considerations and optimizing energy use.

$$C_2 = C_{ins} * V + 8000$$

Where,

C_{ins} is the cost of insulation per unit volume

V is the volume of insulation

4.10 Interest rate

There are two types of interest rates: fixed, which remains constant during the course of the loan, and variable, which is subject to vary. Common market factors that affect interest rates include inflation, the state of the economy, and the supply and demand for credit.

The cost of borrowing money will increase if the interest rate is higher, but the return on the lender's investment will increase. Meanwhile, a reduced interest rate will make borrowing less expensive, but the lender will get less return on investment.

The Nepal Rastra Bank (NRB), which serves as the nation's central bank, is very important in determining and controlling interest rates there. The cost of borrowing or the compensation given to lenders for the use of their funds is represented by interest rates. Currently, in monetary policy 2022/23 fiscal year NRB sets by increasing 1.5% with previous interest rate as 8.5%. And this is the base rate from which the rate may differs according to the clients. (Rastra Bank, 2022).

Moreover, the discount rate is more than the inflation rate as the rate of return needs to be more considering the time value as well. In our case, the inflation rate is 7.87% hence we have assumed the discount rate or interest rate to be 9%.

4.11 Inflation rate

The inflation rate, which is typically assessed annually or monthly, is a measurement of how prices of goods and services in an economy fluctuate over a specific period of time. It measures the percentage change in the average cost of a selection of goods and services that are frequently used by households.

The Nepal Rastra Bank (NRB is in charge of preserving the economy's price stability. It accomplishes this via enacting monetary policy, which has an impact on interest rates and the money supply. The interest rate that the NRB charges commercial banks to borrow money is known as the policy rate. The NRB can affect the interest rates that commercial banks charge clients for loans and other financial products by altering this rate. The NRB may raise the policy rate in order to limit the money supply and slow down economic activity when inflation becomes out of control. As a result, prices may drop as demand for goods and services declines. In contrast, if inflation is too low, the NRB may cut the policy rate to promote spending and borrowing, which may raise prices. The NRB maintains an eye on inflation in addition to monetary policy by tracking a number of economic indicators, such as the consumer price index (CPI). The CPI is used to determine the inflation rate since it tracks the average change in prices of goods and services over time. (Rastra Bank, 2022)As set by monetary policy 2022/23 the inflation would occur as 7.87% but in the first six month inflation occurred 8.02%.

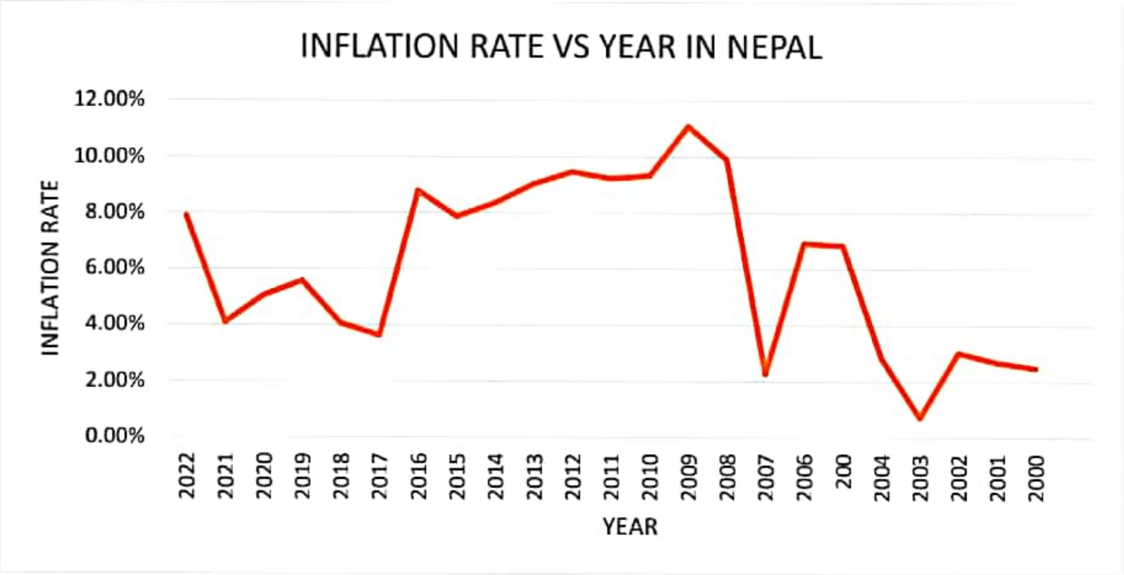


Figure 14: Inflation Rate of Nepal per Year

The graph shows that the inflation rate is not uniform throughout all fiscal years. Moreover, it mainly depends on the monetary policy of central bank which mainly focus on the money supply in the country as per requirements. In this way the predicted inflation rate for the fiscal year 2022/23 is 7.87%. Hence in our analysis we have used most recent inflation rate.

4.11.1 Payback period

The payback period is a key indicator that aids decision-makers and investors in assessing the viability and profitability of a project. Businesses can predict how long it will take to return their original investment and start making money by estimating the payback period. This data can be used to pick between various investment opportunities or to make educated decisions about whether to accept or reject a project.

In conclusion, the payback period is an important indicator for assessing the viability and profitability of a project. Businesses may manage their risk, decide whether to engage in a project, and make sure they are using their resources as efficiently as possible by determining the payback period.(Kaynakli, 2014; Keebaş et al., 2011b; Soni et al., n.d.)

4.11.1.1 Simple payback period

A popular statistic in financial analysis to assess a project's economic sustainability is the simple payback period. Calculating the basic payback period might assist establish whether the project is financially feasible in the case of insulating the steam generator in autoclaves.

The basic payback period shows how long it will take for the project's initial investment to be recouped by the cost savings it produces. The initial cost of the project would include the price of the supplies, installation, and any labor necessary in the event of insulating the steam generator. The cost savings would be brought about by the insulation's reduced impact on power use, which would lower the autoclaves' ongoing operating expenses.

When insulating the steam generator in autoclaves, the project's original cost must be divided by the yearly cost savings produced by the project in order to determine the simple payback period.

To sum up, figuring out the simple payback period can be a helpful tool for assessing the financial sustainability of initiatives like insulating the steam generator in autoclaves. It is possible to establish whether the project is financially feasible and how long it will take to return the initial investment by comparing the project's initial cost to the annual cost savings produced.

$$Simple\ Payback\ Period = \frac{Investment\ Cost}{Cost\ Saved}$$

Where,

Simple Payback Period is in Year

Investment Cost in NRs

Cost Saved in NRs/year

4.12 MATLAB for Solving Equations

We used MATLAB to optimize the insulation thickness of a system to minimize the heat transfer. In order to do this, a mathematical model simulating heat transmission across the system was created. The model was then analyzed using MATLAB in order to determine the optimum insulation thickness. Finding the insulating thickness that minimizes heat transmission while satisfying the cost is the goal of optimization.

4.12.1 Function Development

Function development is a critical step in conducting an insulation analysis of an autoclave using MATLAB. In this step, the analytical equations that govern the thermal behavior of the autoclave system are developed and coded into functions that can be called and used for analysis.

The first step in function development is to identify the relevant equations that describe the thermal behavior of the autoclave system. These equations are typically based on the principles of heat transfer, including conduction, and convection. The equations are selected based on the specific features of the autoclave system being analyzed, including its dimensions, insulation properties, and operating conditions.

4.12.2 Variable Declaration

Variable declaration is a key step in conducting an insulation analysis of an autoclave using MATLAB. It involves defining the variables that are required for the analytical equations to be solved and for the functions to be called. These variables are typically based on the specific features of the autoclave system being analyzed, including its dimensions, insulation properties, and operating conditions.

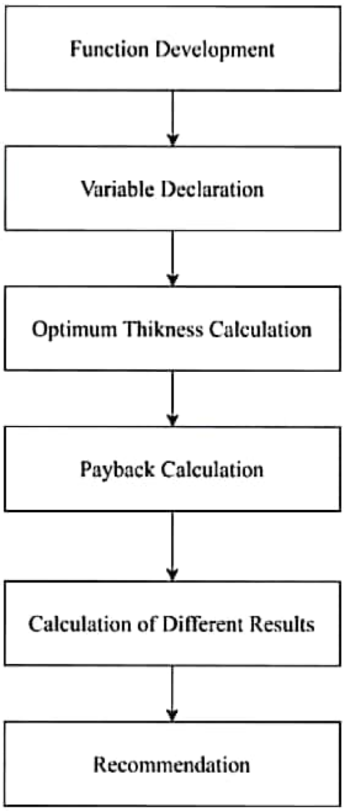


Figure 15: MATLAB Process Methodology

4.12.3 Optimum Thickness Calculation

The calculation of optimum insulation thickness is a crucial aspect of analyzing the insulation of an autoclave using MATLAB. The optimum thickness is the insulation thickness that results in the lowest total cost, taking into account the cost of the insulation material and the cost savings from reduced energy consumption. To calculate the optimum insulation thickness, various steps need to be taken. Firstly, the heat loss needs to be calculated for a range of insulation thicknesses, typically ranging from 0 to 10 cm. This is done by using analytical equations and functions. Secondly, the energy savings for each insulation thickness are calculated by comparing the energy consumption of the autoclave system with and without insulation. Thirdly, the cost savings for each insulation thickness are determined, taking into account the cost of the insulation material and the energy savings achieved. Finally, the optimum insulation thickness is determined by identifying the insulation thickness that results in the lowest total cost, taking into account both the cost of the insulation material and the energy savings achieved. MATLAB provides suitable syntax and functions to minimize the total cost function, allowing for the determination of the optimum insulation thickness. By calculating the optimum insulation thickness, it is possible to optimize the insulation design of the autoclave system, ensuring that it is both effective in reducing heat loss and cost-efficient in terms of insulation material and energy consumption.

4.12.4 Energy Savings and Payback Calculation

To calculate the payback period, the total cost of the insulation material and installation is determined, along with the annual energy savings achieved through insulation. The payback period is then calculated by dividing the total cost of the insulation material and installation by the annual energy savings achieved through insulation.

The energy savings achieved through insulation are calculated by comparing the energy consumption of the autoclave system with and without insulation. By reducing heat loss, insulation helps to improve the efficiency of the autoclave system, resulting in reduced energy consumption. The energy savings achieved through insulation can be calculated for a range of insulation thicknesses using analytical equations and MATLAB functions. The energy savings achieved for each insulation thickness can then be compared, and the optimum insulation thickness can be determined based on the minimum energy consumption.

4.13 Optimum thickness

The optimum insulation thickness is the value that gives the minimum total cost over the lifetime of operation. The total cost is the sum of the cost of insulation installation and cost of energy consumption. The installation cost include cost for insulating material, cladding and labor cost.

If insulation is not applied to the specimen, there would be high rate of heat exchange with surrounding environment, this causes high operating cost. With increasing the thickness of insulation above critical radius reduces the heat exchange to the surrounding. This decreases the operating cost but increase the installation cost. The economic thickness of insulant is that for which the sum of these two costs exhibits a minimum (Lau, 2015).

$$\frac{\partial}{\partial r_4}(P_1C_1 + P_2C_2) = 0 \qquad 4.1$$

The optimum thickness of insulation depends on a number of factors including insulation material, climate condition, and the desired level of energy efficiency.

4.13.1 Matlab Functions

Following are the functions that are made on the MATLAB:

Table 5: MATLAB Function List

Matlab Function	Input Parameters	Use
h_outside	D_o,T_surface,T_o,V_air	To calculate the overall outer heat transfer coefficient.
R_insulated_cladded_cylindrical	h,r_i,r_se,r_j1,r_j2,r_o,L, K_steel,K_epoxy,K_insulation,K_cladding	To calculated the thermal resistance provided by the insulated and cladded material on the cylindrical surface.
R_insulated_cladded_plane	h,r_j2,r_o,t_steel,t_epoxy, t_insulation,t_cladding,K_steel,K_epoxy,K_insulation, K_cladding	To calculated the thermal resistance provided by the insulated and cladded material on the plane surface.
R_uninsulated_cyl	h_o,r_i,r_se,r_j1,L,K_steel, K_epoxy	To calculate the thermal resistance of the uninsulated cylindrical surface.
R_uninsulated_plane	h_o,r_j1,K_steel,K_epoxy, t_steel,t_epoxy	To calculate the thermal resistance of the uninsulated plane surface.
heat_loss_with_insulation_ cylindrical	R_ins_c,T_inside,T_o,r_o, L	To calculate the amount of heat flux loss from the cylindrical surface.
heat_loss_with_insulation_ plane	R_ins_p,T_inside,T_o,r_o	To calculate the amount of heat flux loss from the plane surface.

insulation_volume	r_j1,r_j2,L	To calculate the applied insulation volume.
cladding_area	r_j1,r_j2,r_o,L	To calculate the applied cladding area.
p_1	d,i,N	To calculate P1.
c_1	Q_total,hours,efficiency,energy_rate	To calculate the total heating cost per year.
c_2	c_ins,V_insulation	To calculate the insulation installation cost.
c_t	p1,c1,p2,c2	To calculate the total cost of operation over the life cycle period.

4.13.2 Base Case Values

The base case values taken for the calculation are as follows:

Table 6: Base Case Values for MATLAB

Matlab Variables	Base Case Values	Meaning
r_i	0.1425	Internal radius
r_se	0.1475	Radius of junction of steel and epoxy
r_j1	0.15	Radius of junction of epoxy and insulation
r_j2	0.16:0.001:0.2	Radius of junction of insulation and cladding
r_o	r_j2+0.001	Outer radius
D_o	2*r_o	Outer diameter
t_steel	0.005	Thickness of steel
t_epoxy	0.0025	Thickness of epoxy
t_insulation	r_j2 – r_j1	Thickness of insulation
t_cladding	0.001	Thickness of cladding
T_surface	374	Surface Temperature
T_o	298	Ambient Temperature
V_air	0.2	Velocity of air
L	0.94	Length
K_steel	45	Steel Thermal Conductivity
K_epoxy	0.2	Epoxy Thermal Conductivity
K_insulation	0.035	Insulation Thermal Conductivity
K_cladding	247	Cladding Thermal Conductivity
T_inside	394	Inside Temperature
d	0.09	Discount Factor
i	0.0787	Inflation Rate
N	10	Life cycle years
hours	4	Operating hours per day
efficiency	0.95	Efficiency of Resistive boiler
Energy_rate	12.5	Energy cost per KWh
c_ins	60000	Cost of insulation per unit volume

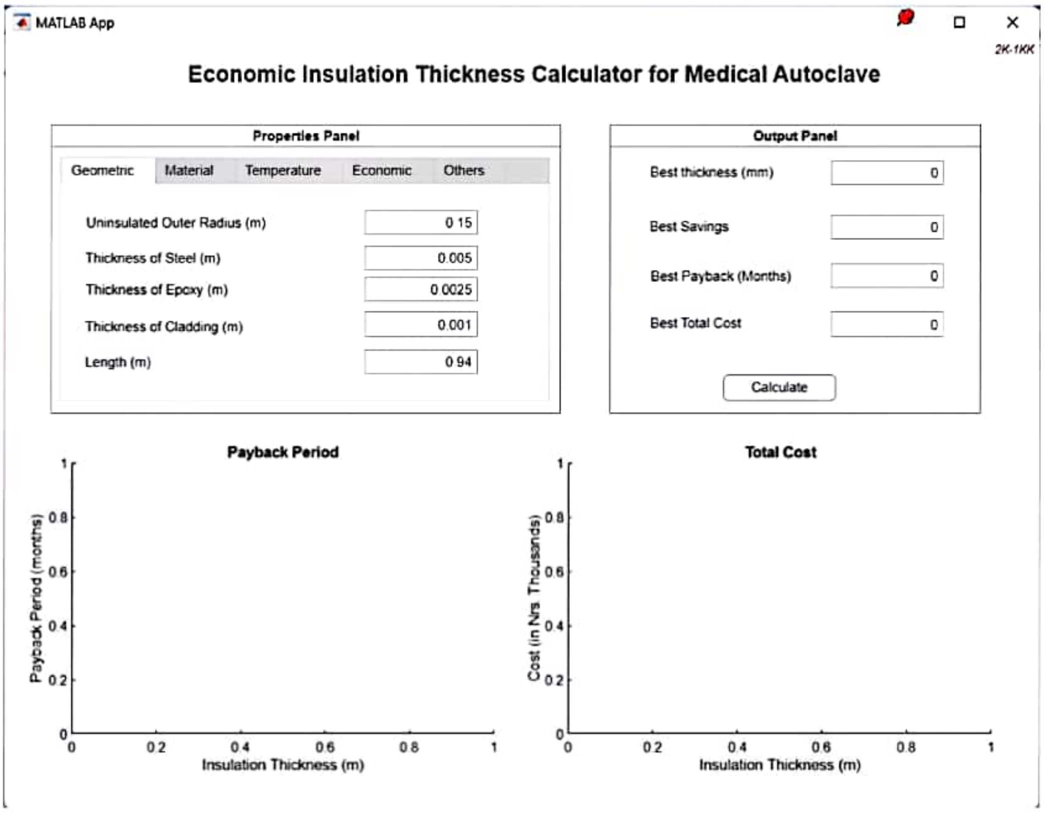
Table 7: Insulation Cost (Hung Anh & Pásztory, 2021)

Materials	Thermal Conductivity (W/m^2K)	Cost (NPR/m^3)
Glass Wool	0.035	60,000
Rock Wool	0.038	70,000
Polyurethane	0.026	90,000
Polyisocyanurate	0.023	55,000

Cellulose Glass	0.025	240,000

4.14 GUI Version of MATLAB Code

A Graphical User Interface (GUI) version of a MATLAB application has been developed for Windows operating system (separate MATLAB compiler is needed for Mac and Linux). The application is designed to package all the necessary codes and functions, making it easier to calculate economic thickness, lifecycle savings, lifecycle total cost, and payback period. The application has been packaged with the MATLAB compiler, which allows anyone to use it regardless of whether they have MATLAB installed or not.



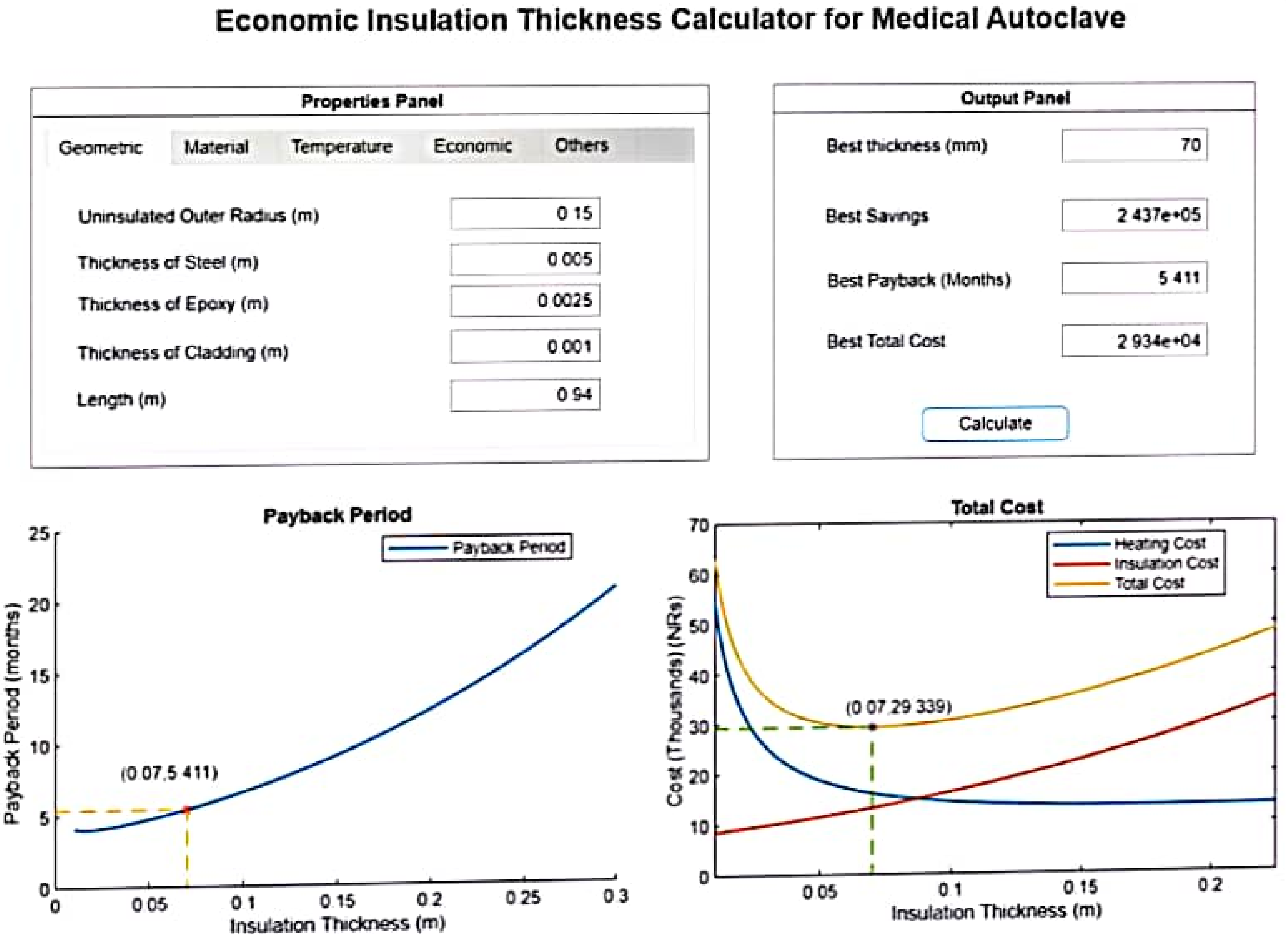
Economic Insulation Thickness Calculator for Medical Autoclave

Uninsulated Outer Radius (m): 0.15
Thickness of Steel (m): 0.005
Thickness of Epoxy (m): 0.0025
Thickness of Cladding (m): 0.001
Length (m): 0.94

Best thickness (mm): 0
Best Savings: 0
Best Payback (Months): 0
Best Total Cost: 0

Figure 16: GUI Version of MATLAB code

The GUI version of the MATLAB application consists of three main panels: the property panel, output panel, and graph panel. The property panel is divided into several tabs, 2K-1KK



Economic Insulation Thickness Calculator for Medical Autoclave

Properties Panel

Uninsulated Outer Radius (m): 0.15

Thickness of Steel (m): 0.005

Thickness of Epoxy (m): 0.0025

Thickness of Cladding (m): 0.001

Length (m): 0.94

Output Panel

Best thickness (mm): 70

Best Savings: 2.437e+05

Best Payback (Months): 5.411

Best Total Cost: 2.934e+04

4.15 Variation with insulation material

4.15.1 Glass wool

In order to determine the optimum thickness of insulation required, we plot different variables against the insulation thickness. The graph below is plotted for glass wool. The thermal conductivity of glass wool is taken as 0.035W/mK. The graph plotted to determine the optimum thickness of insulation for glass wool is shown below,

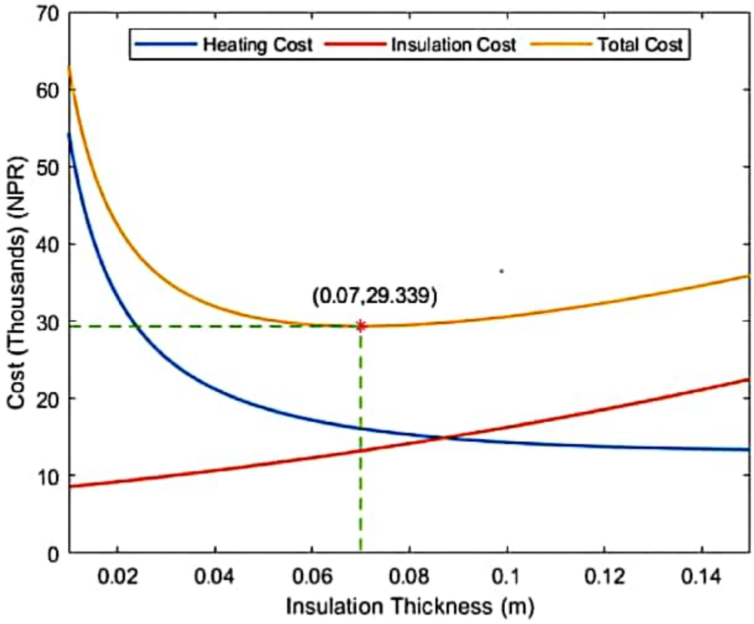


Figure 18: Total Cost vs Insulation Thickness for Glass Wool

From the graph we plotted, an insulation thickness of 70mm for glass wool looks to minimize total life cycle cost. This indicates that both decreasing the insulation thickness below 70 mm and raising the insulation thickness over 70 mm will result in higher overall expenses.

After obtaining the optimum thickness of insulation, we plot the graph to determine the payback period for the determined insulation thickness. The graph is plotted below between insulation thickness in - axis and payback period in y-axis

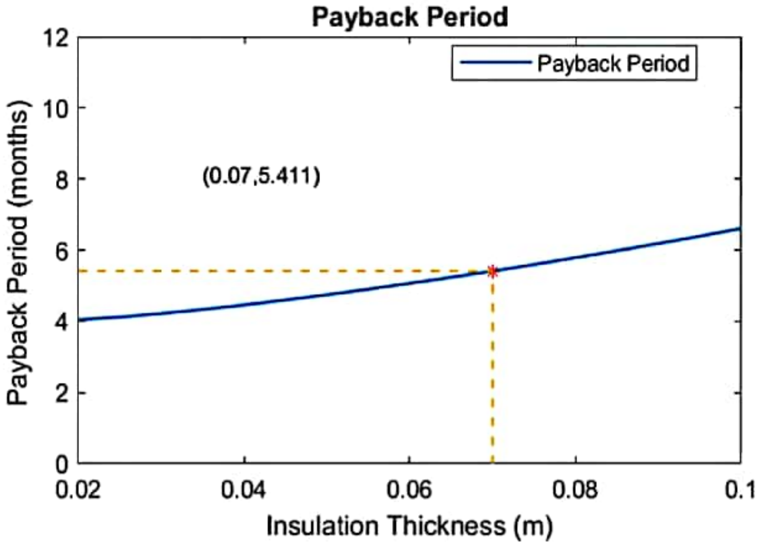


Figure 19: Payback Period for Glass wool

From the graphs plotted above, we determine the optimum thickness of insulation for glass wool to be 70mm. Based on the graph plotted for payback period against insulation thickness, the payback period appears to be 5 months and 13 days.

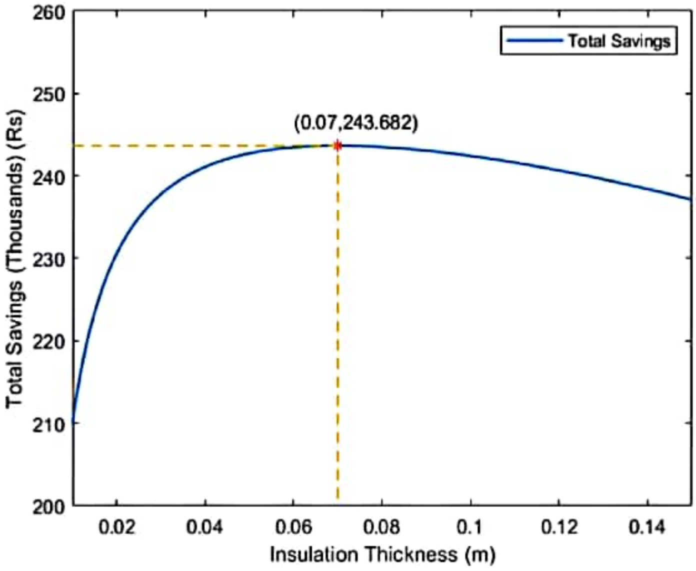


Figure 20: Energy Cost Savings for Glass Wool

This graph is plotted for total saving with changes in insulation thickness. From the graph, we observed maximum saving of NRs 243,682 is obtained for optimum insulation thickness (70mm).

4.15.2 Rock wool

The graph below is plotted for rock wool. The thermal conductivity of rock wool is taken as 0.038W/mK. The graph for life cycle cost of insulation, payback period and total saving of insulation is plotted against insulation thickness below.

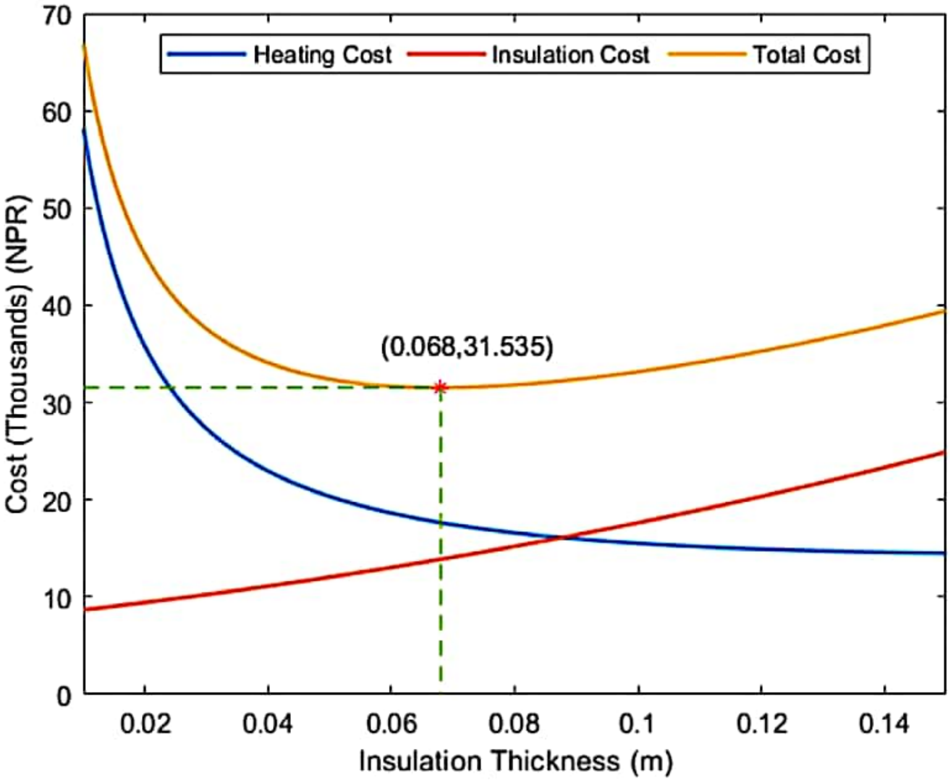


Figure 21: Total Cost vs Insulation Thickness for Rock Wool

The outcome from the graph reveals that employing rock wool insulation with a thickness of 68mm would provide the most cost-effective option for the specified application since it strikes a balance between the cost of insulation and the savings realized through lower heating costs.

From the above graph, we found the optimum thickness to be 68 mm. This ultimately helps in saving the energy cost by reducing the loss from the surface to the ambient environment. This saving will eventually balance the insulation cost. In order to find the time period to cover the insulation cost we plot the graph for payback period against the insulation thickness which is shown below.

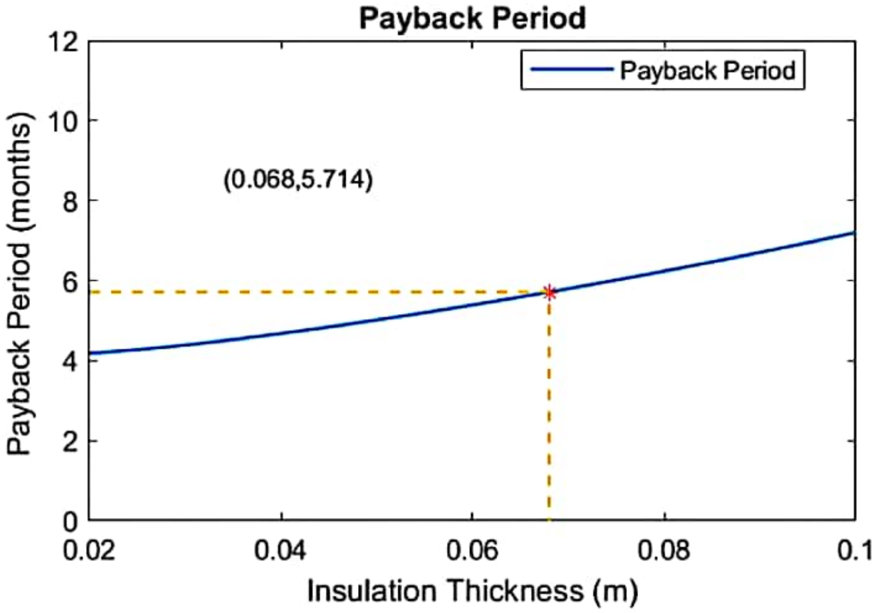


Figure 22: Payback Period for Rock Wool

The outcome indicates that adopting insulation made of rock wool with a 68 mm thickness would offer a good return on investment in terms of lower energy expenditures. From the graph, it is found that the payback period for the insulation is less than 5 months and 21 days.

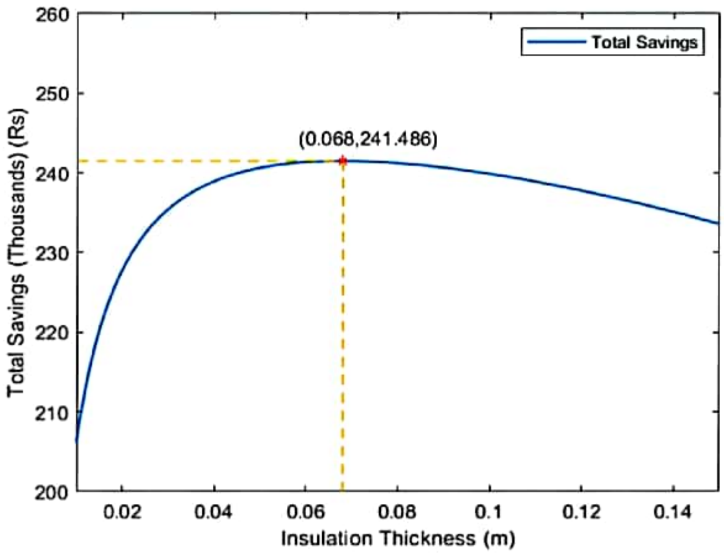


Figure 23: Energy Saving Cost for Rock Wool

The graph plotted between total saving changes with the increase in insulation thickness is shown above. From the graph, maximum saving is NRs 241,486 for the thickness of 68mm rock wool insulation.

4.15.3 Polyurethane

The graph below is plotted for polyurethane. The thermal conductivity of polyurethane is taken as 0.026W/mK. The graph for life cycle cost of insulation, payback period and total saving of insulation is plotted against insulation thickness below.

From the graph above, 54mm insulation thickness of polyurethane appears to reduce the total life cycle cost. This suggests that increasing and decreasing the insulation thickness above 54mm will both lead to increase overall costs.

From the graph above, 54mm insulation thickness of polyurethane appears to reduce the total life cycle cost. This suggests that increasing and decreasing the insulation thickness above 54mm will both lead to increase overall costs.

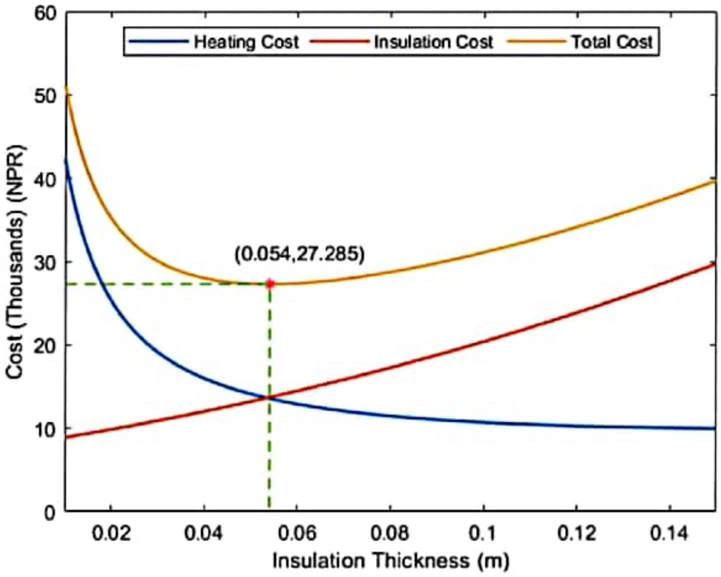


Figure 24: Total Cost vs Insulation Thickness for Polyurethane

After obtaining the optimum thickness of insulation, we plot the graph to determine the payback period for the determined insulation thickness. the graph is plotted below between insulation thickness in - axis and payback period in y-axis.

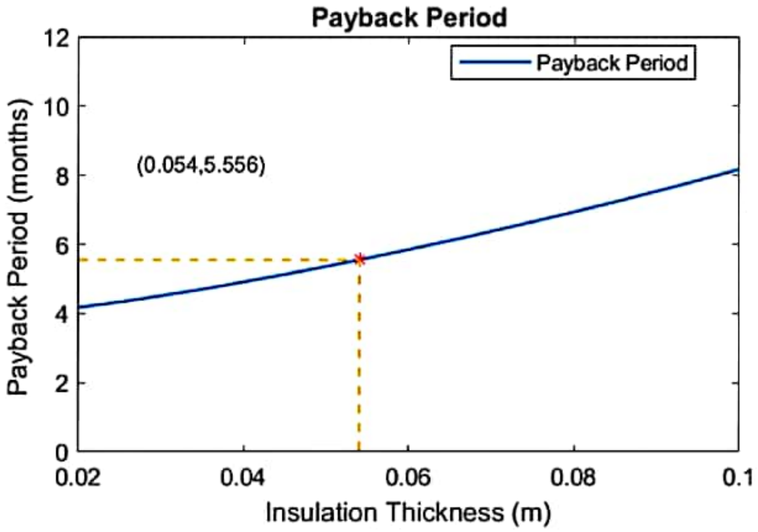


Figure 25: Payback Period for Polyurethane

The graph indicates that adopting insulation made of polyurethane with a 54 mm thickness would offer a good return on investment in terms of lower energy expenditures. From the graph, it is found that the payback period for the insulation is near about five months and 17 days.

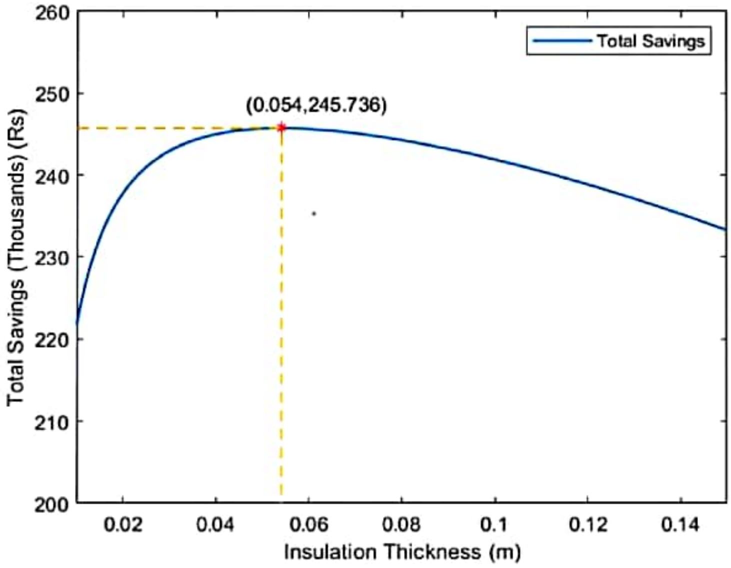


Figure 26: Energy Saving Cost for Polyurethane

Above graph shows the variation of total life cycle saving with change in insulation thickness of Polyurethane. From the graph it is observed that maximum life cycle saving is NRs 245,736 for our determined optimum thickness.

4.15.4 Polyisocyanurate

The graph below is plotted for Polyisocyanurate. The thermal conductivity of Polyisocyanurate is taken as 0.023W/mK. The graph for life cycle cost of insulation, payback period and total saving of insulation is plotted against insulation thickness below.

The outcome from the graph reveals that employing rock wool insulation with a thickness of 62 mm would provide the most cost-effective option for the specified application since it strikes a balance between the cost of insulation and the savings realized through lower heating costs. So the optimum thickness of insulation for the autoclave of our purpose is 62 mm for Polyisocyanurate.

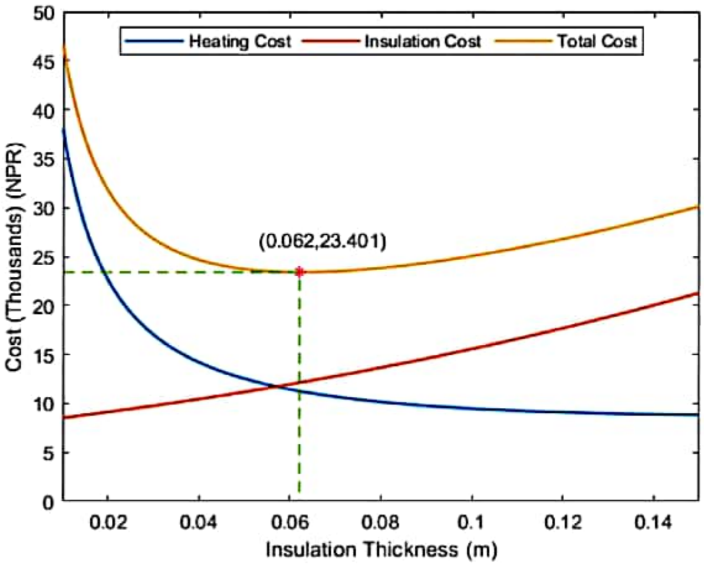


Figure 27: Total Cost vs Insulaiton Thickness for Polyisocyanurate

From the above graph, we found the optimum thickness to be 62 mm. This saves the energy cost by reducing the energy loss in the form of heat that eventually balances the insulation cost. Inorder to find the time period to cover the insulation cost we plot the graph for payback period against the insulation thickness which is shown below.

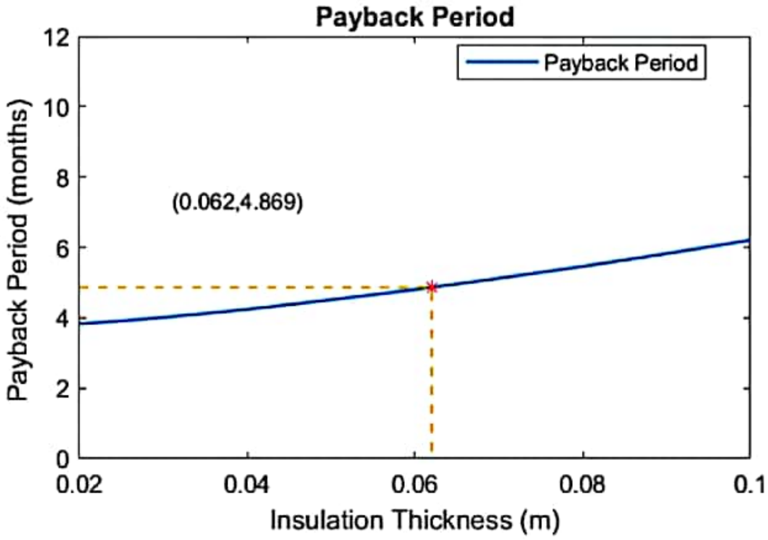


Figure 28: Payback Period for Polyisocyanurate

From the graphs plotted above, we determine the optimum thickness of insulation for Polyisocyanurate to be 62 mm. Based on the graph plotted for payback period against insulation thickness, the payback period appears to be 4 months and 26 days.

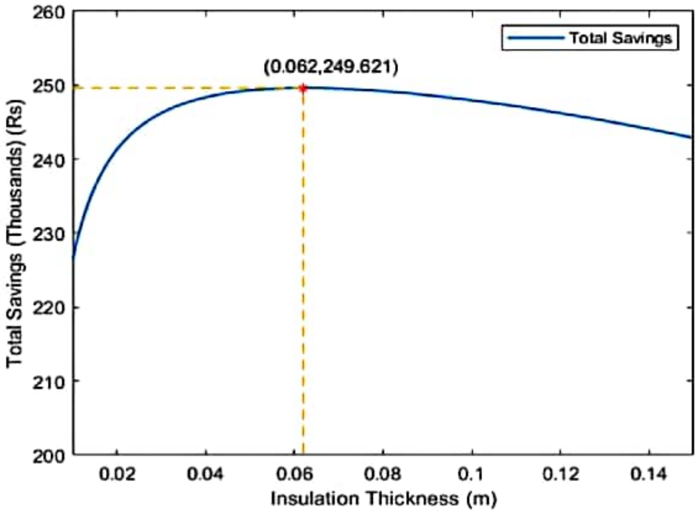


Figure 29: Energy Saving Cost for Polyisocyanurate

The graph plotted between total saving changes with the increase in insulation thickness is shown above. From the graph, maximum saving is NRs 249,621 for the thickness of 62mm rock wool insulation.

4.15.5 Cellulose glass

The graph below is plotted for Cellulose glass. The thermal conductivity of polyurethane is taken as 0.025W/mK. The graph for life cycle cost of insulation, payback period and total saving of insulation is plotted against insulation thickness below.

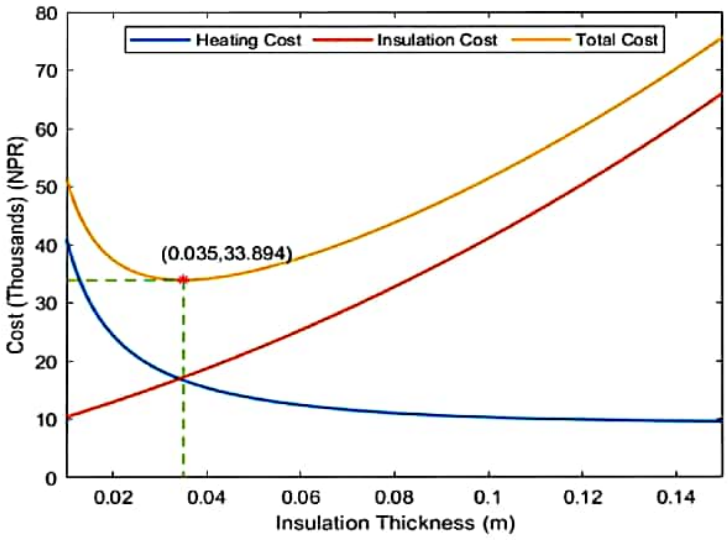


Figure 30: Total Cost vs Insulation Thickness for Cellulose Glass

According to the graph we plotted, an insulation thickness of 35 mm for Cellulose glass looks to minimize total life cycle cost. This indicates that both decreasing the insulation thickness below 35 mm and raising the insulation thickness over 35 mm will result in higher overall expenses.

The graph shows the optimum insulation thickness to be 35 mm for cellulose glass. We plot the graph to determine the payback period for the determined insulation thickness. The graph is plotted below between insulation thickness in x-axis and payback period in y-axis.

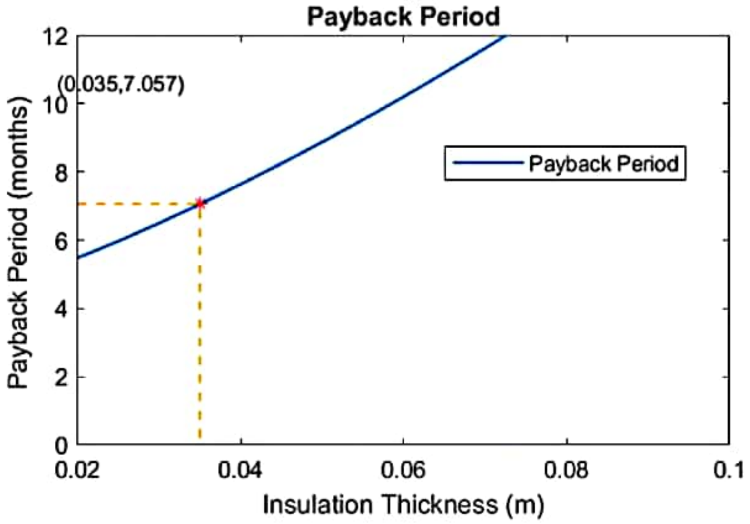


Figure 31: Payback Period for Cellulose Glass

The outcome indicates that adopting insulation made of cellulose glass with a 35 mm thickness would offer a good return on investment in terms of lower energy expenditures. From the graph, it is found that the payback period for the insulation is 7 months and 2 days.

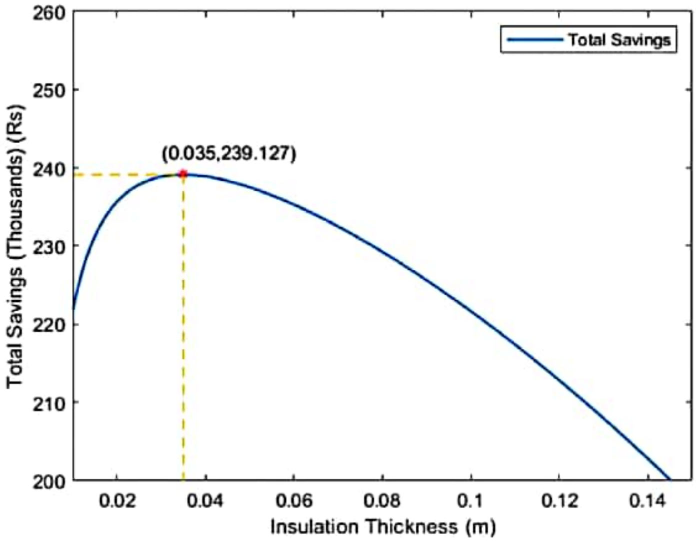


Figure 32: Energy Savings for Cellulose glass

Above graph shows the variation of total life cycle saving with change in insulation thickness of Cellulose glass. From the graph it is observed that maximum life cycle saving is NRs 239,127 for our determined optimum thickness.

Table 8: Steam Generator Results for Various Insulation

Steam Generator Insulation (Base Case Values)						
	optimum thickness (mm)	Total Cost (NRs)	Heating Cost (NRs)	Insulation Cost (NRs)	Energy Saved (NRs)	payback period (Months)
Glass Wool	70	29339	16111.3	13227.7	243.682	5.411
Mineral Wool	68	27857.3	14605	13252.3	241.486	5.714
Polyurethane	54	27285.1	13569.1	13716	245.736	5.556
Polyisocyanurate	62	23400.8	11273.9	12126.9	249.62	4.869
Cellulose Glass	35	33894	16680.9	17213.1	239.127	7.057

Table 9: Pressure Chamber Results for Various Insulation

Pressure Chamber Insulation (Base Case Values)						
	optimum thickness (m)	Total Cost (NRs)	Heating Cost (NRs)	Insulation Cost (Nrs)	Energy Saved (NRs)	Payback Period (Month)
Glass Wool	0.037	23.04	9.086	13.95	65.76	18.39
Mineral Wool	0.036	24.73	9.99	14.74	64.07	19.66

Polyurethane	0.027	23.13	8.756	14.37	65.67	18.87
Polyisocyanurate	0.033	19.52	6.699	12.82	69.28	16.42
Cellulose Glass	0.016	30.54	12.71	17.83	58.26	24.63

4.16 Variation with size of autoclave

The size of the system being insulated is one of many variables that affect the optimum insulation thickness for a given application. In general, more insulation is needed for larger systems to have the same thermal resistance as smaller systems.

This is because larger systems lose heat more quickly than smaller systems because they have a higher surface area to volume ratio. To make up for this, more insulation is required to stop heat loss and keep the temperature where it should be. However, the relationship between size and optimum thickness is not linear as the rate of heat loss decreases at the decreasing rate with increase in the size of the specimen. The dependency of optimum insulation thickness with the size can be seen from the graph plotted below

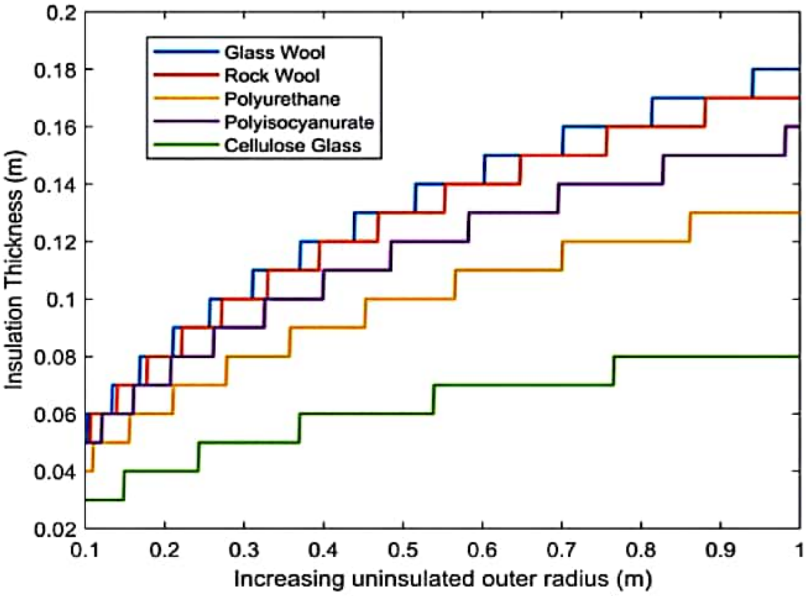


Figure 33: Variation of Optimum thickness with Autoclave Size

From the graph, it is observed that the optimum insulation thickness increases with increase in the outer diameter of the cylinder of the autoclave. The graph shows step-type behavior for varying outer diameter. This may be due to the fact that insulation performance is dependent on multiple factors, including the surface area, volume, and surface area to volume ratio. These elements in turn may affect the rate of heat transmission and the ideal thickness needed for efficient insulation.

The step-type behavior we noticed may thus be an indication that there are specific ranges of outer diameters where certain factors become prominent, causing a dramatic change in the ideal thickness of insulation needed for successful thermal insulation.

This step-type function can be changed into more linear curves with the help of a polynomial function. The general form of polynomial function is

y = A +Bx+Cx2 +Dx3 + ...

The coefficient of the polynomial equation used for each insulation is shown below in the table

Polynomial Coefficients for Size					
	A	B	C	D	E
Glass Wool	-0.0813	0.3049	-0.4431	0.3779	0.0221
Rock Wool	-0.2181	0.5796	-0.625	0.4179	0.0172
Polyurethane	-0.1642	0.4434	-0.4808	0.3177	0.0155
Polyisocyanurate	-0.1549	0.4365	-0.5041	0.3591	0.0183
Cellulose Glass	-0.2228	0.5226	-0.4691	0.2418	0.0075

Figure 34: Polynomial Curve Coefficients for Varying Autoclave Size

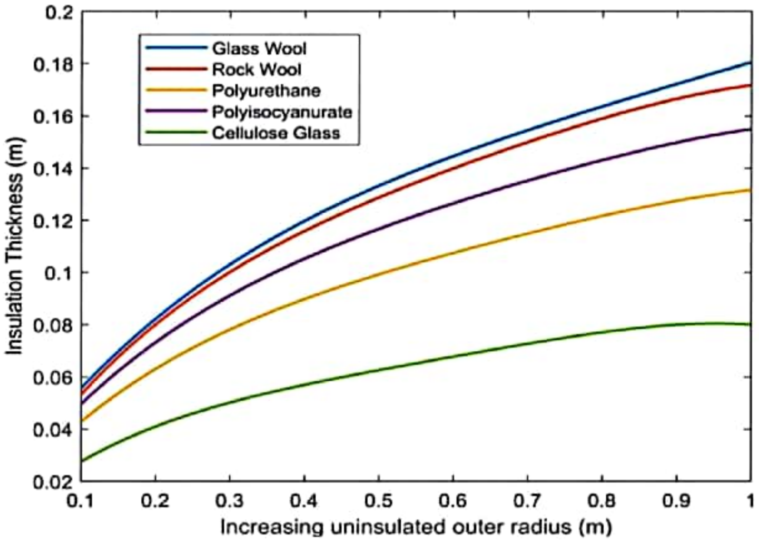


Figure 35: Curve fitted for Varying Autoclave Sizes

4.17 Variation with operating hour

As more operating hours increase, optimum thickness of insulation rises. The thickness of insulation needed to maintain the specified energy efficiency may also increase if the operating temperature rises over time. Similar to this, the amount of insulation needed may alter depending on the ambient temperature.

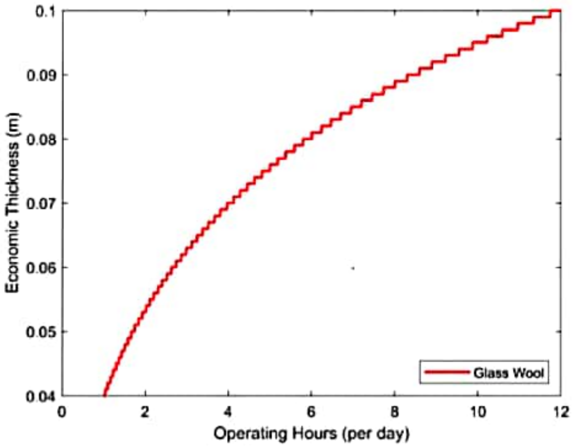


Figure 36: Economic Thickness of Insulation with varying Operating hours

From the graph, the value of optimum thickness of insulation increases with the increase in operating hour of an autoclave. This could be due to different factors such as, material degradation, fluctuation of operating condition, maintenance and repair issues. These factors are not mutually exclusive, and the actual reason for the observed step-type plot in a graph could be a combination of these factors.

This step-type function can be changed into more linear curves with the help of a polynomial function. The general form of polynomial function is

$$y = A + Bx + Cx2 + Dx3 + \ldots\ldots.$$

The coefficient of the polynomial equation used for each insulation is shown below in the table

Table 10: Polynomial coefficients for Operating Hours

Polynomial Coefficients for Operating Hours					
	A	B	C	D	E
Glass Wool	0	0.0002	-0.0024	0.0184	0.0245
Rock Wool	0	0.0002	-0.0023	0.0179	0.0235
Polyurethane	0	0.0001	-0.0018	0.0143	0.0175
Polyisocyanurate	0	0.0002	-0.0021	0.0166	0.0213

Cellulose Glass	0	0.0001	-0.0011	0.0096	0.0099

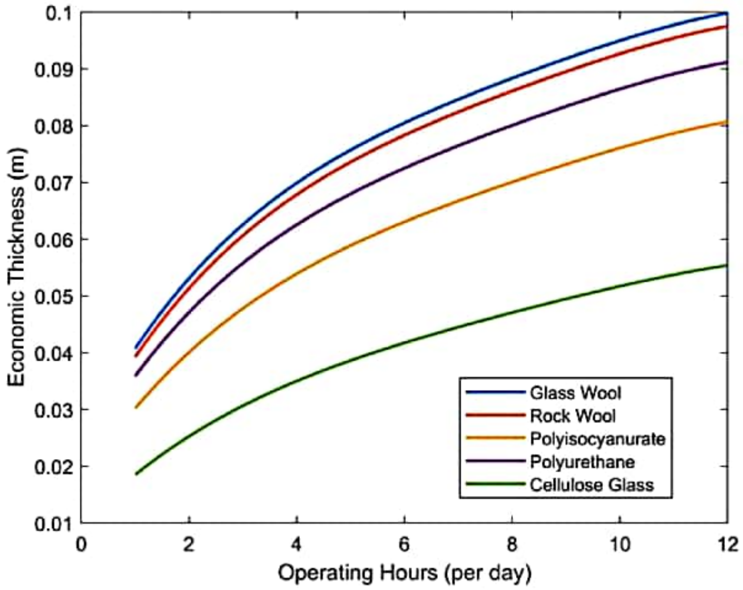


Figure 37: Curve Fitted for Varying Operating Hours for Different Materials

With the help of a polynomial equation, we obtain this linear plot from a step-type function.

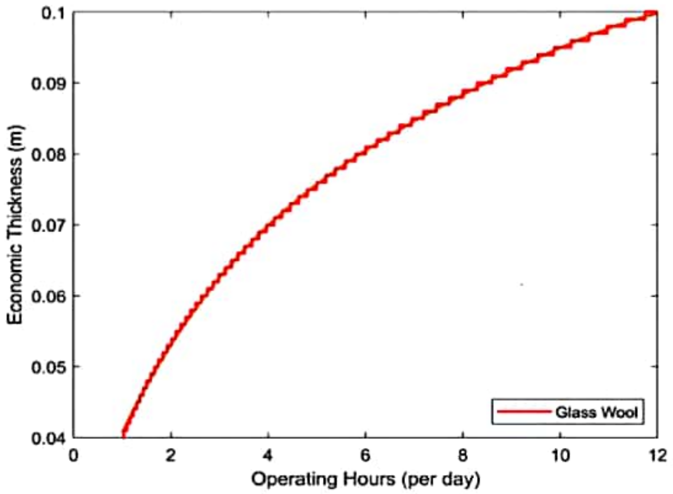


Figure 38: Curve Fitted for Glass Wool Only for Varying Operating Hours

This graph is obtained when the step-type graph and its linear form are merged together.

4.18 Variation with varying interest rate

By affecting the cost of energy and the cost of installing insulation, the interest rate can indirectly affect the ideal insulation thickness for a particular application. It can be more cost-effective to invest in thicker insulation that will yield higher long-term energy savings when interest rates are low because borrowing money to finance insulation installation is less expensive. The ideal insulation thickness in this situation may be bigger because it can save more energy and reduce installation costs. On the other hand, the cost of borrowing money rises when interest rates are high, which can make it less cost-effective to invest in thicker insulation that has a greater upfront cost. As a thinner layer of insulation may be more economical in the near term, the ideal insulation thickness in this situation may be lower. The graph plotted between the optimum thickness and interest rate shows how the optimum thickness changes with the interest rate.

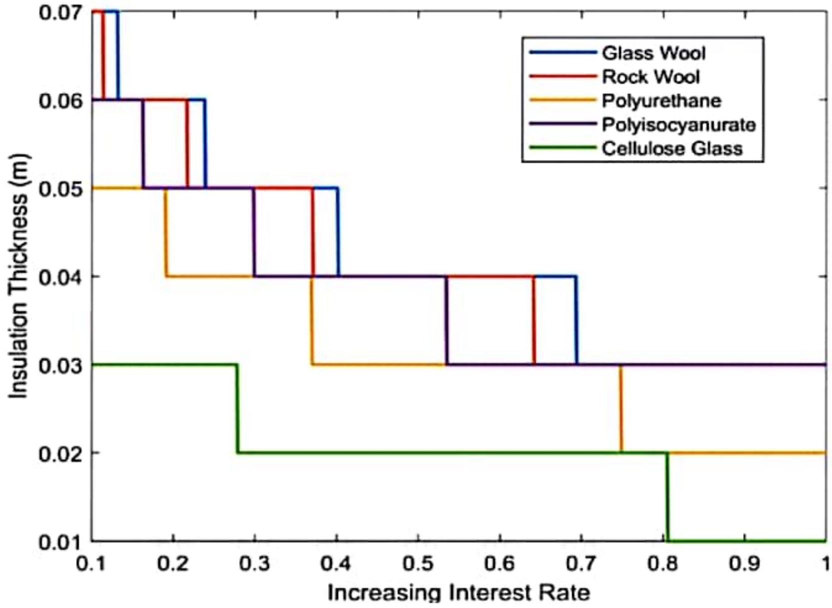


Figure 39: Economic Thickness of Insulation with Varying Interest Rate

The graph clearly depicts that the optimum insulation thickness decreases with increase in interest rate. This could be due to factors such as, increased cost of financing, increased return on investment. It is important to note that these explanations are not mutually exclusive and that there may be more than one real explanation for a step-type graph.This step-type function can be changed into more linear curves with the help of a polynomial function. The general form of polynomial function for this is

$$y = A + Bx$$

The coefficient of the polynomial equation used for each insulation is shown below in the table

Table 11: Linear Coefficients of Curve Fitting for Varying Interest Rate

Polynomial Coefficients for Interest rate		
	A	B
Glass Wool	-0.0408	0.0643
Rock Wool	-0.0385	0.0617
Polyurethane	-0.0334	0.0496
Polyisocyanurate	-0.0324	0.0556
Cellulose Glass	-0.0219	0.0319

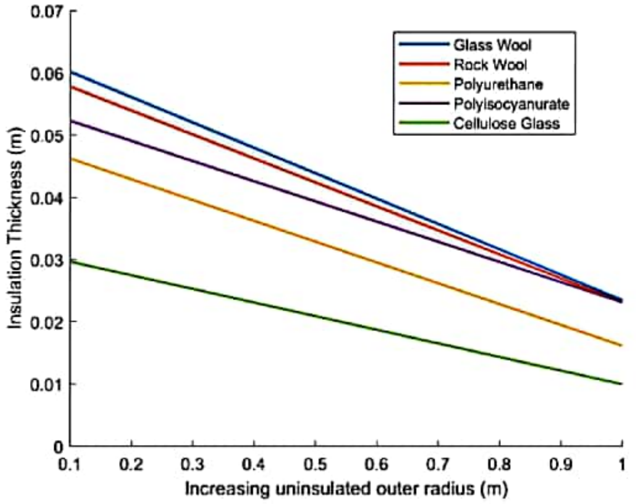


Figure 40: Linear Curve Fitted for Varying Interest Rate for Different Materials

With the help of a polynomial equation we obtain this linear plot from a step-type function.

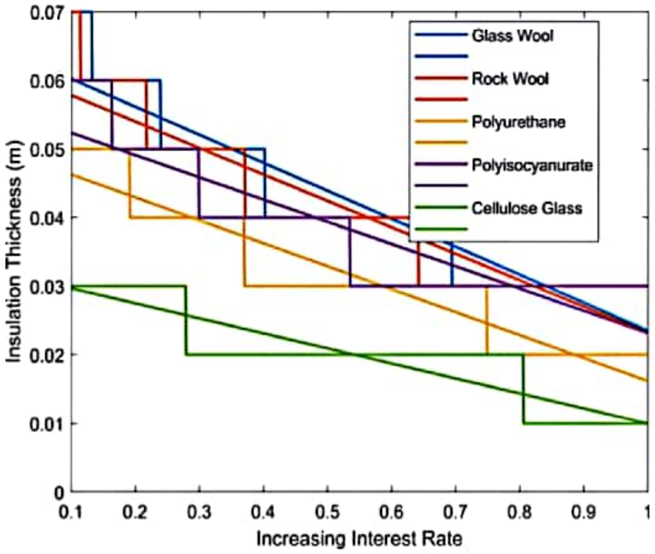


Figure 41: All data of Varying Interest Rate

This graph is obtained when the step-type graph and its linear form are merged together.

4.19 Results

4.19.1 Insulation recommendation to the hospital autoclave

Autoclaves work at high temperatures and pressures, which can provide a significant fire danger. As a result, the insulation utilized in the autoclave should be very fire resistant in order to avoid any potential fire threats. Rock wool is known to be more fire resistant than glass wool. This is due to the fact that rock wool has a greater melting point and can sustain higher temperatures without igniting. This makes rock wool a better alternative for insulation in autoclaves, where high temperatures are common.

Moisture resistance is another crucial factor to consider when choosing autoclave insulation materials. Autoclaves work at high pressures, and any leakage caused by defective gaskets, worn-out door seals, or faulty pressure relief valves can allow moisture to enter into the insulation. When compared to glass wool, rock wool is more moisture resistant because rock wool can endure high moisture levels without losing its insulating characteristics. This means that rock wool can keep its thermal performance over time, assuring autoclave efficiency.

Finally, the strong fire- and moisture-resistance qualities along with cost benefits from life cycle analysis of rock wool make it the preferable choice for autoclave insulation. These characteristics ensure that the autoclave operation is safe and efficient, with no potential for fire threats or energy loss due to moisture damage. Hence, it is recommended to use rockwool as an insulation material for hospitals in autoclaves.

4.19.2 Cost benefit analysis of insulating autoclave with rockwool

The plot was developed for total cost saved with the change in insulation thickness of rock wool. The graph was plotted considering the lifespan of insulation as 10 years, operating 6 hours a day for 300 days in a year.

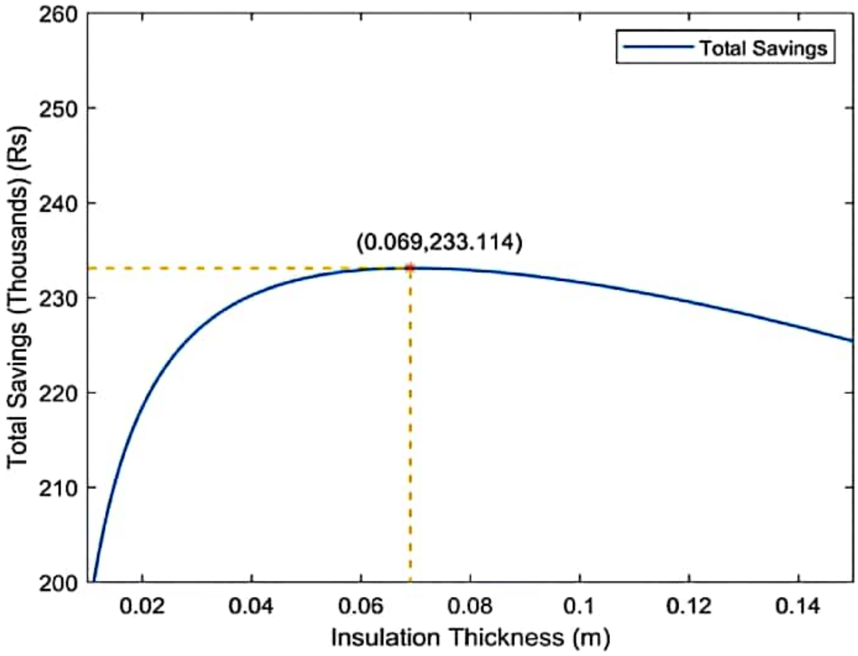


Figure 42: Total Savings Provided By the Rock Wool

Graph plotted between insulation thickness and total saving as a result of heat loss prevention shows that, at optimum thickness of insulation (69mm) we can save NRs 2,33,114 throughout its life cycle operation

4.19.3 Comparison of current insulation and optimized insulation at PAHS

Currently, the autoclave of PAHS is insulated with glass wool of thickness 25mm. The comparison between the life cycle cost, payback period and total saving for glass wool with the insulation thickness of 25mm and optimized thickness can be seen from the plot below:

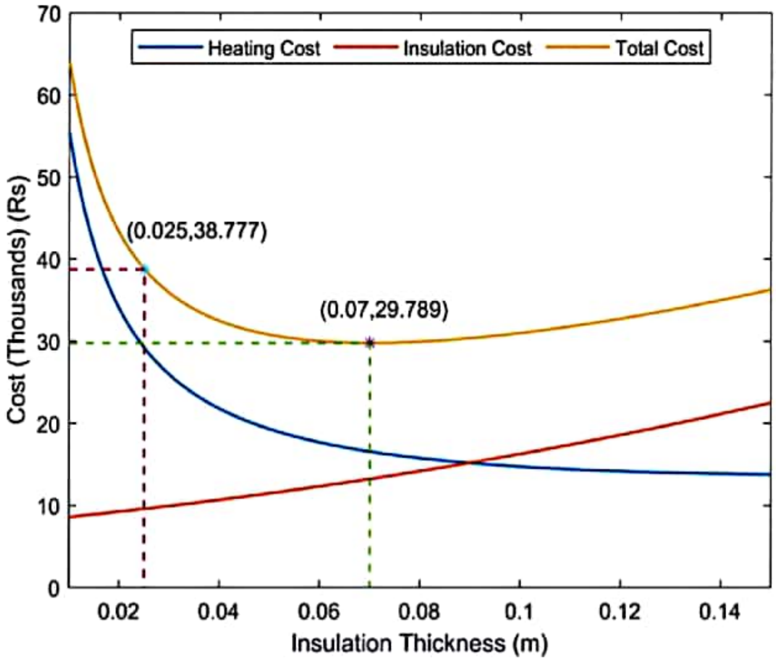


Figure 43: Current Vs Recommended Insulation of PAHS

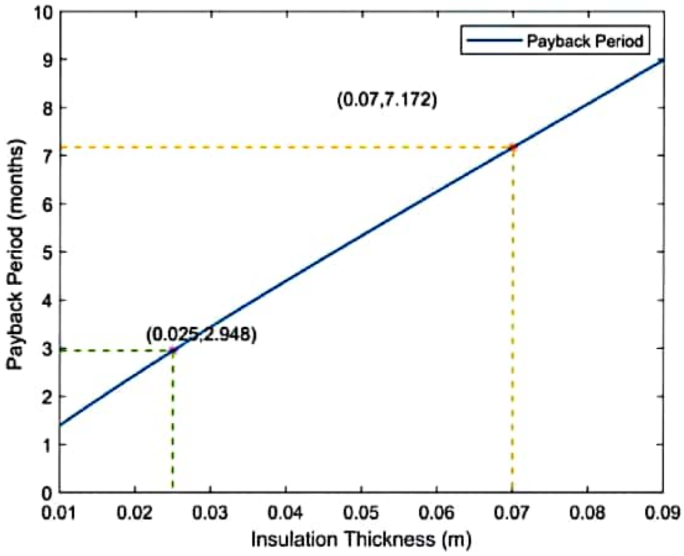


Figure 44: Payback Period of Recommended PAHS Thickness

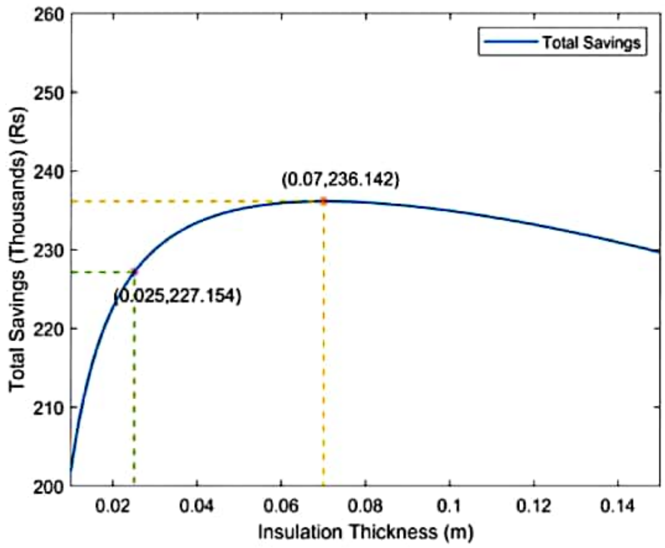


Figure 45: Energy Saving By the Recommended Insulation at PAHS

Above graphs give a clear idea on how the change in the insulation thickness changes the life cycle cost, payback period and total saving. If we change the existing thickness of 25mm to optimized thickness of 70mm, the life cycle cost would decrease from NRs 38,777 to NRs 29,789. The optimized thickness takes seven month to payback its installation cost while it would only take three month with 25mm thickness insulation but the life cycle cost of optimized thickness of insulation saves NRs 9,011 more than cost saved from original thickness.

4.20 In Context of Nepal

According to (Department of Health Services - Ministry of Health and Population - Government of Nepal, 2021), the health care statistics is as follows:

Table 12: Healthcare Service outlets in Nepal

Healthcare Service Outlets	Number
Sub Health Posts(SHPs)	2247
Health Posts	1559
Health Centres/ Primary Healthcare Centres	208
District-level Hospitals	16
District Hospital	62
Zonal Hospitals	10
Sub-regional hospitals	3
Regional Hospitals	3
Central Hospitals	8

We don't have the exact data of Autoclave sterilizer of these hospitals. We assumed a single autoclave is being used in district, two in zonal, regional and sub-regional and three in Central Hospitals. We didn't consider other healthcare outlets in this study.

Table 13: Studied Hospitals

Hospitals	No. of Hospitals	No. of Autoclaves	Total
District	62	1	62
Zonal	10	2	20
Sub Regional	3	2	6
Regional	3	2	6
Central	8	3	24
Total in Nepal			118

Based on the calculations above we can see that the total of NRs 3,09,234 amount of energy can be saved from a single autoclave after insulating both chamber and steam generator excluding the insulation cost which is only NRs 27,992.3 we could save a significant amount from single autoclave. The table above shows that there are altogether 118 hospitals using the autoclave for the sterilization. Now we can interpolate as that a single autoclave saves NRs 2,81,241.7 from which 118 autoclaves will save tentatively NRs 3,31,86,20.6 with base case scenario.

CHAPTER FIVE: CHAPTER 5: CONCLUSION AND RECOMMENDATION

5.1 Conclusion

The calculation of the optimum thickness, total cost, Heating cost, Insulating cost, Energy saved in amounts and payback period was done for both steam generator and pressure chamber. The optimum thickness of the insulation for glass wool in the case of steam generator was found to be 70 mm while 68mm, 54mm, 62mm, 35mm for mineral wool, Polyurethane, polyisocyanurate and cellulose glass wool respectively. The thickness in the case of pressure chamber was found to be 37mm, 36mm, 27mm, 33mm and 16mm for the same respective insulation materials. The variation in the thickness is due to their physical, thermal properties and cost etc.

The cost of insulation adds to the heating cost to give up total cost. The calculation on applying the materials to the steam generator shows that the heating cost is more in the case of cellulose glass which is NRs16680.9 and the lowest for polyisocyanurate i.e.NRs 11273.9. The same cost for the pressure chamber is found to be more by using cellulose glass i.e. NRs 12,710 while the lower is for polyisocyanurate i.e. NRs 6,699. Looking at the insulation cost for steam generator, the cost of insulation is more for cellulose glass which is NRs 17213.1 while the lower is for polyisocyanurate i.e. NRs 12126.9. And the case of chamber shows that the insulation cost will be more on using cellulose glass which is NRs 17,830 and lower is on using polyisocyanurate i.e.NRS 12820. Simply higher the insulation cost the less feasible will be the material, while inverse will be the relation in case of heating cost. However, optimum thickness and material is the function of all cost payback period energy saved etc. So we have to look after all other variables as well.

The energy saved is the another important criteria for the material to be chosen. The lifecycle cost analysis for its operation up to 10 years is considered. From our calculations in the case of steam generator we have found that with the use of insulation materials i.e. glass wool, mineral wool, polyurethane, polyisocyanurate and cellulose glass there won't be any huge difference however small difference ranks them where higher energy saved in amounts is in the case of polyisocyanurate which is NRs2,49,620 in 10 years while lower is for cellulose glass which is NRs 2,39,127. On applying the materials to the pressure chamber the calculation shows that the energy saved in amounts is more by using polyisocyanurate while lower is on using mineral wool i.e.NRs 69,280.

Again payback calculation is an another important criteria for selection of the material. Here, the payback period for applying on steam generator is lower in the case of Polyisocyanurate which is 4.869 months while higher is for Cellulose glass which is 7.057 months. For pressure chamber the period is lower in the case of Poluisocyanurate which is about 16.5 months and higher in the case of Cellulose glass which is 24.63 months . The lower will be the payback period the higher will be the viability of the project. However, all the variables are to be considered for the actual selection.

Here, altogether we find that the glass wool and mineral wool in both the case of steam generator and pressure chamber outperform other material looking after all costs and payback period. However if one is to be selected we have to look after its own physical properties as well. Moisture resistance is another crucial factor to consider when choosing autoclave insulation materials. Autoclaves work at high pressures, and any leakage caused by defective gaskets, worn-out door seals, or faulty pressure relief valves can allow moisture to enter into the insulation. When compared to glass wool, rock wool is more moisture resistant because rock wool can endure high moisture levels without losing its insulating characteristics. This means that rock wool or mineral wool can keep its thermal performance over time, assuring autoclave efficiency. Hence, autoclave must be insulated with mineral wool.

Based on the calculations above we can see that the total of NRs 3,09,234 amount of energy can be saved from a single autoclave after insulating both chamber and steam generator excluding the insulation cost which is only NRs 27,992.3 we could save a significant amount from single autoclave. While a single hospitals comprises of minimum of 3 to 4 autoclaves which means altogether we could save a huge amount NRs 12,08,943.7 in 10 years from a single hospital considering 4 autoclaves for a hospital. Hence it will be a great aid for every hospitals.

5.2 Recommendation

1. Every autoclave should be insulated with proper material and thickness as a lot of energy is being lost to the surroundings. For instance the material for the autoclave at Patan hospital needs to be insulated with rock wool of thickness 68mm but before it was done with glass wool of 25mm thickness which we have found not optimum.
2. The variation in the thickness and material can also occur due to the variation in operating hours for the same autoclave in different places so it should be taken into the account for the calculation.
3. The operating behavior is also important factors for minimising energy consumption. The doors of the pressure chamber shouldn't be opened time and often.
4. The leaks in pressure relief valves, door seals should be checked in a regular basis.

REFERENCES

Abdallah, A. M., & Ismail, A. L. (2001). Saving energy lost from steam boiler vessels. In *Renewable Energy* (Vol. 23). www.elsevier.nl/locate/renene

Bahadori, A., & Vuthaluru, H. B. (2010). A simple correlation for estimation of economic thickness of thermal insulation for process piping and equipment. *Applied Thermal Engineering*, *30*(2–3), 254–259. https://doi.org/10.1016/j.applthermaleng.2009.08.010

Başoĝul, Y., & Keçebaş, A. (2011). Economic and environmental impacts of insulation in district heating pipelines. *Energy*, *36*(10), 6156–6164. https://doi.org/10.1016/j.energy.2011.07.049

Chou, H.-M., & Wong, K.-L. (n.d.). *Heat transfer characteristics of an insulated regular polygonal pipe by using a wedge thermal resistance model*. www.elsevier.com/locate/enconman

Daşdemir, A., Ural, T., Ertürk, M., & Keçebaş, A. (2017). Optimal economic thickness of pipe insulation considering different pipe materials for HVAC pipe applications. *Applied Thermal Engineering*, *121*, 242–254. https://doi.org/10.1016/j.applthermaleng.2017.04.001

Hung Anh, L. D., & Pásztory, Z. (2021). An overview of factors influencing thermal conductivity of building insulation materials. In *Journal of Building Engineering* (Vol. 44). Elsevier Ltd. https://doi.org/10.1016/j.jobe.2021.102604

Jemmad, K., Hmidat, A., & Saad, A. (2021). PROMOTING INDUCTION HEATING – STEAM GENERATORS FOR MEDICAL STERILISATION: INVESTIGATION OF ENERGY-EFFICIENT DESIGN GUIDELINES. *Engineering Review*, *42*(1), 121–135. https://doi.org/10.30765/ER.1790

Kalyon, M., & Sahin, A. Z. (2002). Application of optimal control theory in pipe insulation. *Numerical Heat Transfer; Part A: Applications*, *41*(4), 391–402. https://doi.org/10.1080/104077802317261236

Kamal, J., Hmidat, A., & Abdallah, S. (2021). Energy saving analysis of medical steam sterilizer. *AIP Conference Proceedings*, *2345*. https://doi.org/10.1063/5.0049410

Kaynakli, O. (2014). Economic thermal insulation thickness for pipes and ducts: A review study. In *Renewable and Sustainable Energy Reviews* (Vol. 30, pp. 184–194). https://doi.org/10.1016/j.rser.2013.09.026

Keebaş, A., Ali Alkan, M., & Bayhan, M. (2011a). Thermo-economic analysis of pipe insulation for district heating piping systems. *Applied Thermal Engineering*, *31*(17–18), 3929–3937. https://doi.org/10.1016/j.applthermaleng.2011.07.042

Keebaş, A., Ali Alkan, M., & Bayhan, M. (2011b). Thermo-economic analysis of pipe insulation for district heating piping systems. *Applied Thermal Engineering*, *31*(17–18), 3929–3937. https://doi.org/10.1016/j.applthermaleng.2011.07.042

Kumar, D., Prakash, S., Sen, K., Sahu, G., Sharma, R., & Bohidar, S. (2015). A Review on Thermal Insulation and Its Optimum Thickness to Reduce Heat Loss. *IJIRST-International Journal for Innovative Research in Science & Technology|*, *2*. www.ijirst.org

Lau, W. (n.d.). *Numerical modelling of heat and mass transfer in a steam-air sterilisation process inside an industrial autoclave*. https://doi.org/10.26190/unsworks/2880

Li, Y. F., & Chow, W. K. (2005). Optimum insulation-thickness for thermal and freezing protection. *Applied Energy*, *80*(1), 23–33. https://doi.org/10.1016/j.apenergy.2004.02.009

Madejski, P., Taler, D., & Taler, J. (2022). Thermal and flow calculations of platen superheater in large scale CFB boiler. *Energy*, *258*. https://doi.org/10.1016/j.energy.2022.124841

Model HA-BD200 HORIZONTAL CYLINDRICAL PRESSURE STEAM STERILIZER USER'S MANUAL. (n.d.).

Öztürk, I. T., Karabay, H., & Bilgen, E. (2006). Thermo-economic optimization of hot water piping systems: A comparison study. *Energy*, *31*(12), 2094–2107. https://doi.org/10.1016/j.energy.2005.10.008

Panta, G., Richardson, A. K., Shaw, I. C., Chambers, S., & Coope, P. A. (2019). Effectiveness of steam sterilization of reusable medical devices in primary and secondary care public hospitals in Nepal and factors associated with ineffective sterilization: A nation-wide cross-sectional study. *PLoS ONE*, *14*(11). https://doi.org/10.1371/journal.pone.0225595

Rastra Bank, N. (2022). *Unofficial Translation Monetary Policy for 2022/23*. www.nrb.org.np

Sahin, A. Z., & Kalyon, M. (2004). The critical radius of insulation in thermal radiation environment. *Heat and Mass Transfer/Waerme- Und Stoffuebertragung*, *40*(5), 377–382. https://doi.org/10.1007/s00231-003-0471-7

Shanmuga Sundaram, A., & Bhaskaran, A. (2014). Optimum insulation thickness of walls for energy-saving in hot regions of India. *International Journal of Sustainable Energy*, *33*(1), 213–226. https://doi.org/10.1080/14786451.2012.759573

Singh, B., Bengt, S., Qiuwang, S., & Editors, W. (n.d.). *Lecture Notes in Mechanical Engineering*. http://www.springer.com/series/11693

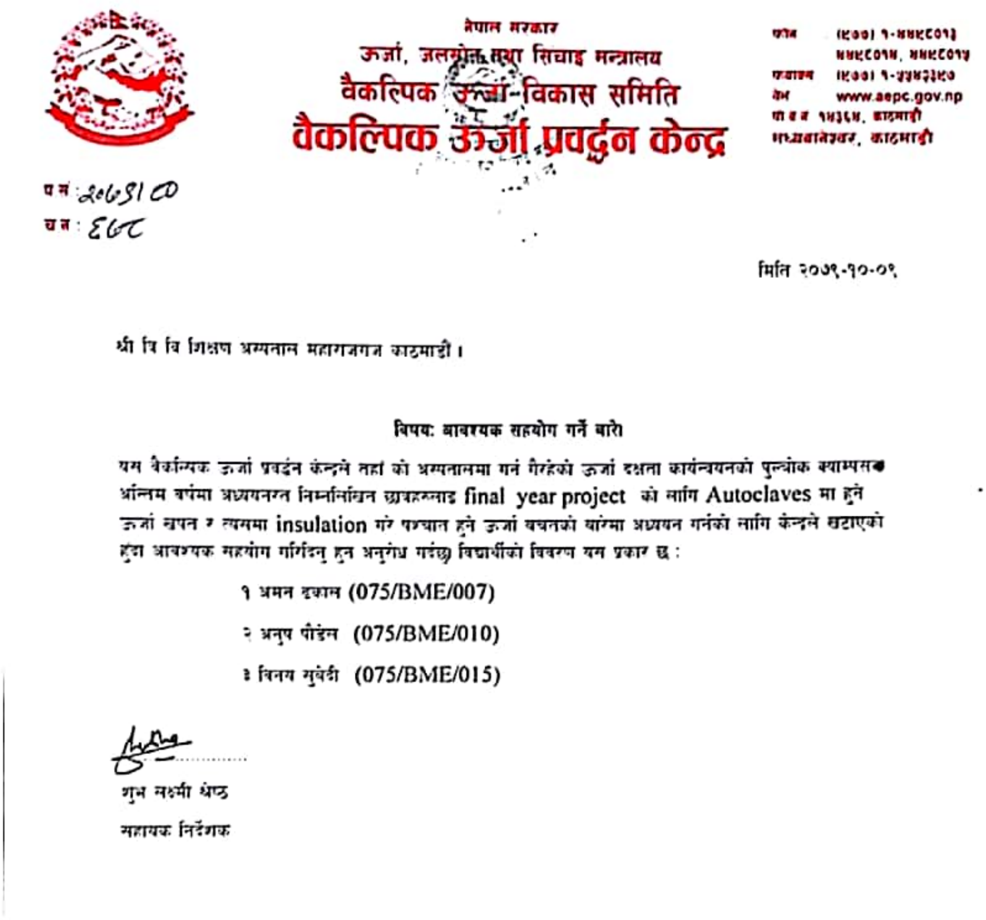
Soni, M. K., Kumar, G., Singh, M. P., Post, 1&2, & Student, G. (n.d.). Optimization of Fuel and Energy (Cost Saving) by Insulation (Calcium Silicate) in Boiler. *International Journal of Research in Mechanical Engineering*, *3*. www.iaster.com

Sutheesh, P. M., & Chollackal, A. (2018). Thermal performance of multilayer insulation: A review. *IOP Conference Series: Materials Science and Engineering*, *396*(1). https://doi.org/10.1088/1757-899X/396/1/012061

Zaki, G. M., & Al-Turki, A. M. (2000). Optimization of Multilayer Thermal Insulation for Pipelines. In *Heat Transfer Engineering* (Vol. 21).

APPENDICES

Appendix A: Letters from AEPC



नेपाल सरकार
ऊर्जा, जलस्रोत तथा सिंचाइ मन्त्रालय
वैकल्पिक ऊर्जा विकास समिति
वैकल्पिक ऊर्जा प्रवर्द्धन केन्द्र

फोन (९७७) १-४४९८०१३
४४९८०१४, ४४९८०१५
फ्याक्स (९७७) १-४५४२३९७
वेब www.aepc.gov.np
पो ब न १४३६४, काठमाडौं
मध्यबानेश्वर, काठमाडौं

प स: २०७९/८०
च न: ६८८

मिति २०७९-१०-०९

श्री त्रि वि शिक्षण अस्पताल महाराजगंज काठमाडौं।

विषय: आवश्यक सहयोग गर्ने बारे।

यस वैकल्पिक ऊर्जा प्रवर्द्धन केन्द्रले तहाँ को अस्पतालमा गर्न गरिहेको ऊर्जा दक्षता कार्यान्वयनको पुल्चोक क्याम्पस अन्तिम वर्षमा अध्ययनरत निम्नलिखित छात्रहरूलाई final year project को लागि Autoclaves मा हुने ऊर्जा खपत र त्यसमा insulation गरे पश्चात हुने ऊर्जा बचतको बारेमा अध्ययन गर्नको लागि केन्द्रले खटाएको हुँदा आवश्यक सहयोग गरिदिनु हुन अनुरोध गर्दछ। विद्यार्थीको विवरण यस प्रकार छ :

१ अमन ढकाल (075/BME/007)
२ अनुप पौडेल (075/BME/010)
३ विनय गुर्वेदी (075/BME/015)

शुभ लक्ष्मी श्रेष्ठ
सहायक निर्देशक

नेपाल सरकार
ऊर्जा, जलस्रोत तथा सिंचाइ मन्त्रालय
वैकल्पिक ऊर्जा विकास समिति
वैकल्पिक ऊर्जा प्रवर्द्धन केन्द्र

फोन (९७७) १-४४९८०१३
४४९८०१५, ४४९८०१४
फ्याक्स (९७७) १-[illegible]
वेब www.aepc.gov.np
पो.ब.नं. १४३६४, काठमाडौं
मध्यबानेश्वर, काठमाडौं

२०५३

प.सं.: २०७९/८०
च.नं.: ६७८

मिति २०७९-१०-०९.

श्री परोपकार प्रसुति तथा स्त्री रोग अस्पताल काठमाडौं ।

विषय: आवश्यक सहयोग गर्ने बारे।

यस वैकल्पिक ऊर्जा प्रवर्द्धन केन्द्रले तहाँ को अस्पतालमा गर्न गैरहेको ऊर्जा दक्षता कार्यान्वयनको पुल्चोक क्याम्पस अन्तिम वर्षमा अध्ययनरत निम्नलिखित छात्रहरुलाइ final year project को लागि Autoclaves मा हुने ऊर्जा खपत र त्यसमा insulation गरे पश्चात हुने ऊर्जा बचतको बारेमा अध्ययन गर्नको लागि केन्द्रले खटाएको हुंदा आवश्यक सहयोग गरिदिनु हुन अनुरोध गर्दछु। विद्यार्थीको विवरण यस प्रकार छ :

१ अमन ढकाल (075/BME/007)
२ अनुप पौडेल (075/BME/010)
३ विनय सुवेदी (075/BME/015)

शुभ लक्ष्मी श्रेष्ठ
सहायक निर्देशक

नेपाल सरकार
ऊर्जा, जलस्रोत तथा सिंचाइ मन्त्रालय
वैकल्पिक ऊर्जा विकास समिति
वैकल्पिक ऊर्जा प्रवर्द्धन केन्द्र

फोन : (९७७) १-४४९८०१३
४४९८०१४, ४४९८०१५
फ्याक्स : (९७७) १-५५४२३९७
वेब : www.aepc.gov.np
पो.ब.नं. १४३६४, काठमाडौं
मध्यबानेश्वर, काठमाडौं

प.सं.: २०७९/८०
च.नं.: ६७८

मिति २०७९-१०-०९

श्री सिभिल अस्पताल मिनभवन काठमाडौं ।

विषय: आवश्यक सहयोग गर्ने बारे।

यस वैकल्पिक ऊर्जा प्रवर्द्धन केन्द्रले तहाँ को अस्पतालमा गर्न गैरहेको ऊर्जा दक्षता कार्यान्वयनको पुल्चोक क्याम्पसका अन्तिम वर्षमा अध्ययनरत निम्नलिखित छात्रहरुलाइ final year project को लागि Autoclaves मा हुने ऊर्जा खपत र त्यसमा insulation गरे पश्चात हुने ऊर्जा बचतको बारेमा अध्ययन गर्नको लागि केन्द्रले खटाएको हुँदा आवश्यक सहयोग गरिदिनु हुन अनुरोध गर्दछ। विद्यार्थीको विवरण यस प्रकार छ :

१. अमन ढकाल (075/BME/007)

२. अनुप पौडेल (075/BME/010)

३. विनय सुवेदी (075/BME/015)

शुभ लक्ष्मी श्रेष्ठ
सहायक निर्देशक

Appendix B: Temperature Data

Table 14: Field Temperature Data (PAHS, November 14, 2022)

Sterilizing Chamber						Steam Generator						Time
Outlet	Side face (Distance room Inlet) (Cm)				Inlet	Outlet	Cylindrical face (Distance from Inlet) (Cm)				Inlet	
	96	72	48	24			84	60	36	12		
19.2	19.2	19.2	19.2	19.2	19.2	19.2	19.2	19.2	19.2	19.2	19.2	8:30
18.2	17.1	17.2	17.2	17.3	17.2	20.1	22.3	21.5	21	20.2	22.3	8:33
19.3	19.3	18.9	18.4	18.4	17.8	23.3	23.2	22.3	22.7	22.5	25.6	8:36
21.1	21.3	19.5	19.2	19	18.3	23.9	24.1	23.7	24.3	24.1	31.2	8:39
23.2	22.4	23	20.7	21.2	19	24.7	25.3	25.9	26.9	26.3	37.3	8:42
25.9	26.3	25.7	25.3	23.3	20.2	27.1	27.9	28.1	28.4	28.3	43.2	8:45
29.3	27	27.4	27.4	26	22.7	29	29.3	29.6	30	29.4	51.9	8:50
32.1	29.1	29.6	29.3	27.3	25.3	30.1	30.1	30.3	30.9	31	59.6	8:55
34.5	33	31.2	33.2	29.8	26.9	30.3	30.6	31.7	31.7	31.3	64.8	9:00
37.1	32.5	33.4	35.6	33.7	29.6	30.7	30.9	31.3	31.4	31.7	76.8	9:05
38.2	35.1	33.6	36.9	34.6	33.7	30.5	31.6	31.1	31.3	31.2	84.9	9:10
38.4	37.2	39.3	36.7	35.8	32.7	30.3	31.1	30.9	30.9	30.9	93.6	9:15
38.3	38.1	37.3	37.5	37.3	33.3	31.1	30.9	31.1	31.3	31.2	102.1	9:20
38.6	38.3	38.2	36.9	35.2	35.3	30.8	31.3	31.1	31.1	31.4	104.1	9:25

Appendix C: MATLAB Code

Function Definitions

Convective Heat Transfer Coefficient

```
function h_o = h_outside(D_o,T_ms,T_o,V_air)

    %% Calculation

    a = (1./D_o).^0.2;

    b = (2./((T_ms-T_o)+546.3)).^0.181;

    c = (T_ms-T_o).^0.266;

    d = (1+2.86.*V_air).^0.5;



    h_o = 11.58.*a.*b.*c.*d;

end
```

Cylindrical Surface Heat Resistance

```
function R_ins =
R_insulated_cladded_cylindrical(h_o,r_i,r_se,r_j1,r_j2,r_o,L,K_steel,K_
epoxy,K_ins,K_clad)

    %% Calculation

    R_cond_steel = log(r_se./r_i) ./ (2.*pi.*L.*K_steel);

    R_epoxy = log(r_j1./r_se) ./ (2.*pi.*L.*K_epoxy);

    R_cond_insulation = log(r_j2./r_j1) ./ (2.*pi.*L.*K_ins);

    R_cond_cladding = log(r_o./r_j2) ./ (2.*pi.*L.*K_clad);

    A_o = 2.*pi.*r_o.*L;
```

```
    R_conv_outside = 1./(h_o.*A_o);

    R_ins = R_cond_steel + R_epoxy + R_cond_insulation +
R_cond_cladding + R_conv_outside;



end
```

Plane Heat Resistance

```
function R_ins =
R_insulated_cladded_plane(h_o,r_j,r_o,t_steel,t_epoxy,t_insulated,t_



    %% Calculation

    R_cond_steel = t_steel./(K_steel.*2.*pi.*r_j);

    R_epoxy = t_epoxy./(K_epoxy.*2.*pi.*r_j);

    R_cond_insulation = t_insulated./(K_ins.*2.*pi.*r_o);

    R_cond_cladding = t_cladding./(K_clad.*2.*pi.*r_o);

    A_o = 2.*pi.*r_o;

    R_conv_outside = 1./(h_o.*A_o);

    R_ins = R_cond_steel + R_epoxy + R_cond_insulation +
R_cond_cladding + R_conv_outside;

end
```

Heat Loss Through Cylindrical Surface

```
function Q =
heat_loss_with_insulation_cylindrical(R_ins,T_inside,T_o,r_o,L)



    %% Calculation
```

```
    A_o = 2.*pi.*r_o.*L;

    U = (1./R_ins);
    del_T = T_inside - T_o;

    Q = U.*A_o.*del_T;
end
```

Heat Loss Through Plane Surface

```
function Q = heat_loss_with_insulation_plane(R_ins,T_inside,T_o,r_o)
%% Calculation
A_o = 2.*pi.*r_o;

U = (1./R_ins);
del_T = T_inside - T_o;

Q = U.*A_o.*del_T;
end
```

Insulation Volume Calculation

```
function V = insulation_volume(r_j1,r_j2,L)
    %% Calculation
    V_j1 = pi.*r_j1.^2.*L;
    V_j2 = pi.*r_j2.^2.*L;
```

```
    V_cylindrical = V_j2 - V_j1;


    V_plane = pi.*r_j2.^2.*(r_j2-r_j1);


    V = V_cylindrical + V_plane;

end
```

Cladding Area Calculation

```
function A = cladding_area(r_j1,r_j2,r_o,L)

    %% Calculation

    A = 2.*pi.*r_o.*(L+r_j2-r_j1+1);

end
```

Calculation of Economic Parameters

Calculation of P1

```
function p1 = p_1(d,i,N)

    %% Calculation

    a = 1./(d-i);

    b = ((1+i)./(1+d)).^N;


    p1 = a.*(1-b);

end
```

Calculation of C1

```
function c1 = c_1(Q,hours,efficiency, energy_rate)
```

```
    %% Calculation
    a = (Q.*hours.*3600) ./ efficiency;
    b = a./(3.6e+06);

    c1 = b.*energy_rate;
end
```

Calculation of C2

```
function c2 = c_2(c_ins,V)
    %% Calculation Details
    c2 = c_ins.*V+8000;
end
```

Calculation of C_{total}

```
function c_t = c_t(p1,c1,p2,c2)
    %% Calculation
    c_t = p1.*c1 + p2.*c2;
end
```

Main Code

Base Case Variables

```
r_j1 = 0.15;
r_j2 = (r_j1+0.01):0.001:(r_j1*3);
```

```
t_steel = 0.005;

t_epoxy = 0.0025;

t_insulation = r_j2 - r_j1;

t_cladding = 0.001;


r_i = r_j1-t_steel-t_epoxy;

r_se = r_j1-t_epoxy;


r_o = r_j2 + 0.001;

D_o = 2.*r_o;

T_surface = 273+101;

T_o = 273+25;

V_air = 0.2;

L = 0.94;

K_steel = 45;

K_epoxy = 0.2;

K_insulation = 0.035; K_cladding = 247;

T_inside = 273+121;

d = 0.09;

i = 0.0787;

N = 10;

hours = 4*0.75*300;
```

```
efficiency = 0.95;

energy_rate = 12.5;

c_ins = 60000;
```

Economic Total , Heating and Insulation Cost Plot

```
%% Calculation of convective heat transfer coefficiens

h = h_outside(D_o,T_surface,T_o,V_air);

%% Calculation of Thermal Resistance

A_o = 2.*pi.*r_o.*L;

A_p = 2.*pi.*r_o;

R_ins_c = R_insulated_cladded_cylindrical(h,r_i,r_se,r_j1,r_j2,r_o,L,
...

    K_steel,K_epoxy,K_insulation,K_cladding);

R_ins_p = R_insulated_cladded_plane(h,r_j2,r_o,t_steel,t_epoxy, ...

    t_insulation,t_cladding,K_steel,K_epoxy,K_insulation,K_cladding);

%% Calculation of Heat loss (Insulated)

Q_cylinder =
heat_loss_with_insulation_cylindrical(R_ins_c,T_inside,T_o, ...

    r_o,L);

Q_plane = heat_loss_with_insulation_plane(R_ins_p,T_inside,T_o,r_o);

Q_total = Q_cylinder + Q_plane;



%% Calculation of Insulation quantity
```

```
V_insulation = insulation_volume(r_j1,r_j2,L);

Area_cladding = cladding_area(r_j1,r_j2,r_o,L);


%% Calculation of Econcmic Parameters

% Calculation of P1

p1 = p_1(d,i,N);

% Calculation of C1

c1 = c_1(Q_total,hours,efficiency,energy_rate);

% Calculation of P2

p2 = 1;

% Calculation of C2

c2 = c_2(c_ins,V_insulation);

% Calculation of C_t

c_total = c_t(p1,c1,p2,c2);


%% Plots

% x, y variables

total_cost = c_total./1000;

heating_cost = (p1.*c1)./1000;

insulation_cost = (p2.*c2)./1000;


thickness = r_j2-r_j1;
```

```
[min_tc, min_index] = min(total_cost);

best_thickness = thickness(min_index);

total_cost_a = total_cost(min_index);

heating_cost_a = heating_cost(min_index);

insulation_cost_a = insulation_cost(min_index)

best_radius = r_j2(min_index);

Q_best = Q_total(min_index);

insulation_c = c2(min_index);

x_point = best_thickness - (best_thickness/7);

y_point = min_tc + (min_tc/7);



plot(thickness,heating_cost,LineWidth=1.5);

hold on

plot(thickness,insulation_cost,LineWidth=1.5);

plot(thickness,total_cost,LineWidth=1.5)

xlabel('Insulation Thickness (m)')

ylabel('Cost (Thousands) (NPR)')

lgd = legend("Heating Cost","Insulation Cost","Total Cost");

lgd.Location='north';

lgd.Orientation='horizontal';



plot(best_thickness,min_tc,'*r',HandleVisibility='off');
```

```
%xline(best_thickness,LineStyle="--");

%yline(min_tc,LineStyle="--")

plot([0 best_thickness best_thickness],[min_tc min_tc 0], LineStyle="--
" ...

    ,HandleVisibility='off',LineWidth=1);

text(x_point,y_point,['(' num2str(round(best_thickness,3)) ',' ...

    num2str(round(min_tc,3)) ')'])

xlim([0.01,0.15])

hold off
```

Economic Energy Saving Plot

```
%% Calculation of convective heat transfer coefficient

h = h_outside(D_o,T_surface,T_o,V_air);

h_o = h_outside(2.*r_j1,T_surface,T_o,V_air);


%% Calculation of Thermal Resistance

A_o = 2.*pi.*r_o.*L;

A_p = 2.*pi.*r_o;

R_ins_c = R_insulated_cladded_cylindrical(h,r_i,r_se,r_j1,r_j2,r_o,L,
...

    K_steel,K_epoxy,K_insulation,K_cladding);

R_ins_p = R_insulated_cladded_plane(h,r_j2,r_o,t_steel,t_epoxy, ...

    t_insulation,t_cladding,K_steel,K_epoxy,K_insulation,K_cladding);
```

```
%% Calculation of Heat loss (Insulated)

Q_cylinder =
heat_loss_with_insulation_cylindrical(R_ins_c,T_inside,T_o, ...

    r_o,L);



Q_plane = heat_loss_with_insulation_plane(R_ins_p,T_inside,T_o,r_o);

Q_total = Q_cylinder + Q_plane;



%% Calculation of Insulation quantity

V_insulation = insulation_volume(r_j1,r_j2,L);

Area_cladding = cladding_area(r_j1,r_j2,r_o,L);



%% Calculation of Economic Parameters

% Calculation of P1

p1 = p_1(d,i,N);

% Calculation of C1

c1 = c_1(Q_total,hours,efficiency,energy_rate);

% Calculation of P2

p2 = 1;

% Calculation of C2

c2 = c_2(c_ins,V_insulation);

% Calculation of C_t
```

```
c_total = c_t(p1,c1,p2,c2);



%% For Uninsulated Heat loss

R_unins_c  = R_uninsulated_cyl(h_o,r_i,r_se,r_j1,L,K_steel,K_epoxy);

R_unins_p =
R_uninsulated_plane(h_o,r_j1,K_steel,K_epoxy,t_steel,t_epoxy);

Q_c_unins =
heat_loss_with_insulation_cylindrical(R_unins_c,T_inside,T_o, ...

    r_j1,L);

Q_p_unins =
heat_loss_with_insulation_plane(R_unins_p,T_inside,T_o,r_j1);

Q_unins = Q_c_unins + Q_p_unins;

c1_unins = c_1(Q_unins,hours,efficiency,energy_rate);

p1_unins = p_1(d,i,N);

total_cost_unins = p1_unins.*c1_unins;

%% Total Savings

total_save = total_cost_unins-c_total;



%% Plots

% x, y variables

total_savings = total_save./1000;

total_cost = c_total./1000;

thickness = r_j2-r_j1;

 [max_sv, min_index] = min(total_cost);
```

```
best_thickness = thickness(min_index);

best_radius = r_j2(min_index);

best_savings = total_savings(min_index);

x_point = best_thickness - (best_thickness/7);

y_point = best_savings + (best_savings/80);



plot(thickness,total_savings,LineWidth=1.2)

hold on

xlabel('Insulation Thickness (m)')

ylabel('Total Savings (Thousands) (Rs)')

lgd = legend("Total Savings");

lgd.Location='northeast';

lgd.Orientation='horizontal';

plot(best_thickness,best_savings,'*r',HandleVisibility='off');

plot([0 best_thickness best_thickness],[best_savings best_savings 0],
...

    LineStyle="--",HandleVisibility='off',LineWidth=1);

text(x_point,y_point,['(' num2str(round(best_thickness,3)) ',' ...

    num2str(round(best_savings,3)) ')'])

xlim([0.01,0.15])

ylim([200,260])

hold off

%Plotting PAHS data
```

```
%For Economic Thickness

% plotting Patan data

p_thickness = 0.025;

p_index = find(r_j2==(p_thickness+r_j1));

p_savings =total_savings(p_index);

plot(p_thickness,p_savings,'*',HandleVisibility='off');

plot([0 p_thickness p_thickness],[p_savings p_savings 0], LineStyle="--
" ...

    ,HandleVisibility='off',LineWidth=1);

px_point = p_thickness - (p_thickness./5);

py_point = p_savings - (p_savings./80);

text(px_point,py_point,['(' num2str(round(p_thickness,3)) ',' ...

    num2str(round(p_savings,3)) ')'])

xlim([0.01,0.15])

ylim([200,260])

hold off

%For Energy Savings

% plotting Patan data

p_thickness = 0.025;

p_index = find(r_j2==(p_thickness+r_j1));

p_tc = total_cost(p_index);

plot(p_thickness,p_tc,'*',HandleVisibility='off');

plot([0 p_thickness p_thickness],[p_tc p_tc 0], LineStyle="--" ...
```

```
    ,HandleVisibility='off',LineWidth=1);
px_point = p_thickness - (p_thickness/7);
py_point = p_tc + (p_tc/8);
text(px_point,py_point,['(' num2str(round(p_thickness,3)) ',' ...
    num2str(round(p_tc,3)) ')'])
xlim([0.01,0.15])
hold off
```

For Payback Period

```
% Payback
payback = (c2./(c1_ins-c1);
total_cost = c_total./1000;
thickness = r_j2-r_j1;
[min_tc, min_index] = min(total_cost);
best_thickness = thickness(min_index);
best_payback = payback(min_index);
x_point = best_thickness - (best_thickness/3);
y_point = best_payback + (best_payback/7);
hold on
plot(thickness,payback,LineWidth=1.2)
xlabel('Insulation Thickness (m)')
ylabel('Payback Period (months) ')
```

```
lgd = legend("Payback Period");

lgd.Location='northeast';

lgd.Orientation='horizontal';

box on

plot(best_thickness,best_payback,'*r',HandleVisibility='off');

%xline(best_thickness,LineStyle="--");

%yline(min_tc,LineStyle="--")

plot([0 best_thickness best_thickness],[best_payback best_payback 0],
LineStyle="--" ...

    ,HandleVisibility='off',LineWidth=1);

text(x_point,y_point,['(' num2str(round(best_thickness,3)) ',' ...

    num2str(round(best_payback,3)) ')'])

xlim([0.01,0.1])

ylim([0,12])

hold off
```

GUI CODE

```
function CalculateButtonPushed(app, event)

            r_j1 = app.UninsulatedOuterRadiusmEditField.Value;

            r_j2 = (r_j1+0.01):0.001:(r_j1*3);

            t_steel = app.ThicknessofSteelmEditField.Value;

            t_epoxy = app.ThicknessofEpoxymEditField.Value;

            t_insulation = r_j2 - r_j1;
```

```
t_cladding = app.ThicknessofCladdingmEditField.Value;

r_i = r_j1-t_steel-t_epoxy;

r_se = r_j1-t_epoxy;

r_o = r_j2 + t_cladding;

D_o = 2*r_o;

T_surface = app.SurfaceTemperatureCEditField.Value + 273;

T_o = app.AmbientTemperatureCEditField.Value + 273;

V_air = app.VelocityofAirmsEditField.Value;

L = app.LengthmEditField.Value;

K_steel = app.SteelThermalConductivityWmKEditField.Value;

K_epoxy = app.EpoxyThermalConductivityWmKEditField.Value;

            K_insulation =
app.InsulationThermalConductivityWmKEditField.Value;
K_cladding =
app.CladdingThermalConductivityWmKEditField.Value;

T_inside = app.InsideTemperatureCEditField.Value + 273;

d = app.DiscountFactordecimalEditField.Value;

i = app.InflationRatedecimalEditField.Value;

N = app.LifeCycleYearsYearsEditField.Value;

ope_hours = app.OperatingHoursperdayHourEditField.Value;

hours = ope_hours*0.75*300;

efficiency = app.EfficiencydecimalEditField.Value;

energy_rate = app.EnergyRateEditField.Value;

c_ins = app.CostofInsulationpervolumeEditField.Value;
```

```
            ** HERE SAME AS TOTAL COST, PAYBACK PERIOD and ENERGY
            SAVING **

            app.BestPaybackMonthsEditField.Value=best_payback;

            app.BestSavingsEditField.Value=best_savings.*1000;

            app.BestthicknessmmEditField.Value=best_thickness.*1000;

            app.BestTotalCostEditField.Value = min_tc.*1000;

    end
```

Appendix C: Some Pictures