COLLEGE OF SCIENCE AND TECHNOLOGY

UNIVERSITY OF RWANDA

College of Science and Technology (CST)

DESIGN AND SIMULATION OF THERMAL PERFORMANCE OF SOLAR WATER HEATER BASED ON DIFFERENT INSULATION MATERIAL BY USING COMSOL MULTIPHISICS SOFTWARE

By: IRAGUHA Etienne

REG.NO: 222022392

Supervisor: Dr. BINAMA Maxime

Co_Supervisor: Dr. MUSENGIMANA Antoine

Thesis to be submitted in partial fulfillment of the requirements of the award of the degree of the Master of Science in Renewable Energy in the college of science and technology (CST).

October 2025

Declaration

I declare that this dissertation results from my work and has not been submitted for any other degree at the University of Rwanda or another institution. It has been passed through the Anti-plagiarism system and found the complaint and this is the approved final vision of the dissertation.

Printed names:

IRAGUHA Etienne

Signature:

Date:

Co-Supervisor's names: Doctor

MUSENGIMANA Antoine

Signed:

Date:

Supervisor's names:

Doctor BINAMA Maxime

Signed:

Date

Dedication

To My Family, and Friends, May God Bless you for your support to me during the studies period.

Acknowledgment

I would like to begin by thanking the Almighty God who has been my help and the source of my strength throughout the duration of my studies. I would like to express my sincere gratitude to my supervisors Dr. BINAMA Maxime; Dr. MUSENGIMANA Antoine for guidance, encouragement, and support throughout the course of this work. It was an invaluable learning experience for me to be one of their students. From them I have gained not only extensive knowledge, but also a careful research attitude. I express my gratitude to African Center of Excellence in Energy for Sustainable Development (ACE-ESD) staff for their commitment to make possible to study during my study period and we finished the course work on time. My thanks are extended to my colleagues in cohort 5 who shown their contribution to build the friendly academic area at ACE-ESD.

Abstract

This study investigates the thermal performance of solar water heaters based on different insulation material by using Comsol Multiphysics software. The main aim was to evaluate how different operational parameters specifically water flow rate and insulation materials affect the efficiency of solar collectors and storage tanks. The analysis was conducted under exterior temperatures of 17 °C, 25 °C, and 30 °C, representing cold, medium, and warm climates, respectively. Previous research highlights the critical role of system parameters and material selection in improving thermal efficiency and reducing energy loss. Building on this, the study underscores the importance of optimizing insulation and flow rates to enhance solar water heater performance, particularly in Rwanda, where climate conditions and economic considerations significantly influence energy system adoption.

The simulation of the solar collector and tank was carried out using *COMSOL Multiphysics*. Different operating conditions were tested, focusing on three main insulation materials wood, glass wool, and fiberglass and varying water flow rates. The system's thermal performance was evaluated by analyzing heat retention and losses under three climate conditions (17 °C, 25 °C, and 30 °C). The objective was to determine the optimal flow rate for domestic applications and identify the insulation material that delivers the best thermal performance across different environmental conditions.

This study found that a water flow rate of 0.02 kg/s optimally balanced temperature rise and water availability for domestic use. Fiberglass insulation demonstrated superior thermal performance, followed by glass wool, while wood insulation proved inadequate due to excessive heat loss. Fiberglass and glass wool tanks maintained stable temperatures across various climates, whereas wood tanks struggled in colder conditions. The findings highlight the critical importance of insulation material selection and system optimization for thermal efficiency. For Rwanda, recommendations include promoting high-performance insulation, subsidizing solar water heating systems, and establishing design and installation standards. Further research is needed on economic feasibility, long-term durability, and renewable energy integration.

Keywords: Thermal Performance of Solar Water Heaters.

Table of Content

LIST OF ABBREVIATIONS

IPRC:	Integrated Regional College
KWh:	kilo Watt hour
LCC:	Life Cycle Cost
MININFRA:	Ministry of Infrastructure
MW:	Mega Watt
PV:	Photovoltaic
RE:	Renewable Energy
SWH:	Solar Water Heater

CHAPTER 1: INTRODUCTION

1.1. Background

Nowadays, there is a rising global demand for clean energy to mitigate the environmental crisis resulted from use of coal, oil, etcs. . The needed energy is used but not limited to lighting systems, industrial use, heating and ventilations, but also to water heating. The efficient use of the clean generated energy will contribute to the sustainable development of the user's communities and country by providing cost saving, improving quality of life while protecting the environment [1]. Solar water heating systems capture energy from the sun by using solar collector to heat water and store in storage tank for homes and businesses, instead of using electricity, natural gas, wood or any other means which are having negative impact to the environment [2]. A solar water heater save some billion thermos of natural gas a year to be used on thermal systems for production of electricity to consumer or for heating and ventilation and this has a positive impact on prevention of global warming, reduce dependence on imported fuel, and ease the price of natural gas [3].

Solar water heaters are one of the most efficient heating systems since they can go up to 87% of energy reaching on the collector from the sun [3]. It provides several advantages like heating water at low cost, clean service, and environment friendly.

One of the most important factors in their design and manufacturing is the relation between thermal conductivity of materials used for heat exchanging process especially in collector and insulating material for avoiding heat loss. The thermal conductivity of piping constructing a collector is very important to estimate the rate at which heat is exchanged between water and hot pipes and at which heat is lost when no sunshine is available especially at night or rain period and at which heat is lost in the tank through heat exchanging process between tank and external cold air [4].

Another factor to be considered in design is that solar energy is exploitation causes challenges since the sun shine is intermittent at one time it is high enough and at another time it is no longer available . Thus, overheating of solar water heaters takes place when heat can no longer be dissipated because the maximum temperature is reached [2]. In summer, heat absorbed by collector can easily cause water to approach boiling point and this cause high pressure in the tank and this cause damage especially busting. The temperature pressure relieve valve is not sufficient, since it can be easily damaged after successive overheating incidents and its damage is of big economic and technical cost [5]. This research will compare the insulation material used on solar water heaters, their thermal efficiency, pressures and temperature at different corners as well as the speed.

1.2. Problem Statement

Solar water heaters are used as alternative source of energy as compared to conventional systems and reduce the dependence to fossil fuel which creates greenhouse gas emission to atmosphere and this result in climate changes and other associated environmental impact. The efficiency is highly influenced by heat exchanges between collector pipes, tank and surrounding air which depends on the type of insulation materials property and their thickness. Some material becomes hot in short time which increase the heat exchanging process with the fluid in short time but also loose the same heat quickly due to their thermal conductivity. Other material takes long get heat but also to loose what has been captured take some time.

To enhance thermal performance of solar water heaters, the insulation material are used on both tank and solar collector. Even-though, different insulation material such as fiber glass, wool which gives a high level of resistance, durability at low cost, and better thermal performance are the mostly used, some parameters like thermal conductivity, weather, aging, and cost play a crucial role in choosing the best insulation material for specified operating region.

As in Rwanda we are adopting climate friendly technology, solar water heaters are gaining traction at a moderate pace. Their performance in the Rwandan climate zone, which are moderate, hot and cold still not well understood. In this context, through COMSOL MULTI-PHYSICS is will be used in this research to analyse the thermal performance of solar water heaters under difference insulation material in the above mentioned Rwandan climate zone.

By conducting comparative analysis, this research will give the most suitable insulation material to the specified zones and contribute to the manufacturing of efficient and low cost solar water heater technologies that fit.

1.3. Objectives

1.3.1. Main objective

The main objectives of this research is the thermal performance analysis of solar water heater under Rwandan's climate by using COMSOL Multiphisics software.

1.3.2. Specific objectives

- ❖ Data collection across Rwanda in 3 regions (Bugesera,Nyabihu, Rutsiro and Huye).
- ❖ Simulation the solar collector under different operating conditions such as water flow, and insulation material.
- ❖ Simulation of tank with different insulation under outer temperature 17, 25 and 30 degree Celsius, which represent the average temperature in clod, moderate and hot zone, respectively.
- ❖ Comparative analysis of Results.

1.4. Scope of the study

This study's scope is organize as follows:

- ❖ Geographical scope: Data collection in 3 regions which represent climent of Rwanda (Hot, moderate and cold regions).
- ❖ Simulation and comparative analysis of solar collector and water tank under different operating conditions.

1.5. Expected Outcomes and Significance of the Study

1.5.1 Expected Outcomes

- ✓ A comparison of insulation material used in solar water heaters for evaluating thermal conductivity and efficiency.
- ✓ Guidelines for selecting the best insulation material to enhance the performance and durability of solar water heaters

1.5.2 Significance of the Study

- ✓ Identify the best insulation materials in minimizing heat loss and promoting high energy efficiency.
- ✓ Optimize the insulation of solar water heaters by utilizing solar energy which reduce dependence on fossil fuels and promoting clean energy.
- ✓ Promote Sustainable Development goal especially on affordable and Clean Energy and climate action.

1.6. Thesis Outline

Chapter 2 reviews solar water heater construction and their feature, insulation material and their different application toward environment protection, their designs and simulations and their various types and their contribution on carbon emission reduction in atmosphere.

Chapter 3 deals with methodology used in the research including data collection from different location, type of data and method that will be used in data analysis. Here COMSOL Multiphysics is the software tool to be used in the design and simulation.

Chapter 4 discusses design and construction and simulation of solar water heater components COMSOL Multiphysics. These include tank, collector, insulator selection and other accessories. Simulation is based on changing the insulation materials for analysis the thermal performance, input and out pressure, the inner tank pressure as well as the velocity and flow rate.

Chapter 5 discusses on simulations different insulation materials and their results obtained

Chapter 6 will provide conclusion and recommendation

1.7. Research Limitations

This research project has the following limitations

- ✓ Budget for implementing the prototype
- ✓ Limited time which caused the simulation of few insulation materials as compared to the existing ones
- ✓ The accuracy of data recorded in different districts can lead to small result deviations
- ✓ The research focus on small-scale solar water heaters (200 litters) and then results are not directly applied to larger scale solar water heater for commercial or industrial applications.
- ✓ Computing capacity of computers for COMSOL multiphysics

CHAPTER 2: REVIEW ON WATER HEATERS

2.1. Introduction

Solar energy is the most highly potential of the alternative energy sources, and universally available sources. It is an attractive concept because of the combination of solar energy and the heat pump, which can improve the quality of the energy available and show potential for different applications. The application of solar energy includes water heating in the domestic sector, health institution and tourism sector. One of the popular devices that harnesses solar energy which can replace the electric water heater is the solar water heater and its system is called solar water heating system. Therefore, this research provides a review of various solar collectors in solar water heating systems and its applications. Their view consists of an introduction to solar water heater systems including the active and passive systems, basic components of solar water heating and its latest researches and advances of solar water heaters.

2.2. Previous related research work

The performance of flat plate solar water heaters (FPSWHs) is a multifaceted issue governed by the complex interaction of design choices, operational parameters, and prevailing environmental conditions, as extensively documented in a wide range of studies. The critical role of design considerations has been underscored, particularly the selection of appropriate absorber plate materials, optimal absorber and glazing coatings, and the overall system configuration, to maximize the benefits derived by users of these systems. These design choices are aimed at achieving the best combination of heat absorption while simultaneously minimizing heat loss to the surrounding environment [1] . Performance factors affecting FPSWHs have been comprehensively reviewed, highlighting the importance of parameters such as the number of fins used to enhance heat transfer, the glazing type employed, the number of passes the water makes through the collector, the specific geometry of the fins, and site-specific environmental factors in optimizing heat transfer rates. The review encompasses the effects of internal modifications, like fins, but also stresses the importance of material properties like thermal conductivity and surface coatings for the absorber plate [2].

Researchers have extensively explored various methods to enhance heat transfer within FPSWH collectors. Investigations of double-pass systems incorporating internal fins have demonstrated notable improvements in collector efficiency compared to single-pass designs. A double-pass internally finned collector performs better than a single-pass collector without internal fins under specific conditions (I = 1.0 kJ $m^{-2}s^{-1}$, m = 9 kg s^{-1}, R = 1, n = 4 and Nf = 2), suggesting that both multiple passes and internal enhancements contribute synergistically[1]. The choice of glazing and absorber materials exerts a substantial impact on the overall performance of FPSWHs. The researchers in 2018 examined the effect of glazing layers, noting that double glazing generally provides better efficiency than single glazing. They cite Benslama's work, reporting efficiencies of 42% for double glazing versus 30% for single glazing. Kalidasan et al. are also referenced to examine the efficiency with the function of the number of cover plates.

To analyzed the thermal efficiency and cost-effectiveness of solar water heaters manufactured in Rwanda, emphasizing the importance of high thermal conductivity in absorber plates and suggesting aluminum as a superior alternative to galvanized iron in this context [2]. at the result found that better solar radiation always provides higher thermal efficiency with high thermal conductivity absorber plate[2].Focused on the thermodynamic analysis of a solar flat plate water heater utilizing an extended surface absorber tube, demonstrating that extended surfaces recorded higher temperatures and improved heat transfer rates compared to plain tubes. According to the heat transfer rate is high at maximum solar intensity [3].Experimentally investigated the use of glass as an absorber material, comparing different types of glass and concluding that absorber black painted clear toughened glass sandwich types provided the highest thermal efficiency then they found that absorbent black painted clear toughened glass sandwich types provide maximum temperature of outlet water as well as have highest thermal efficiency.

These combined studies collectively underscore the importance of optimizing a diverse range of design and material aspects to maximize the performance and overall efficiency of flat plate solar water heaters. Strategies such as the utilization of extended surfaces, as explored by Balaji, and the adoption of alternative absorber materials, such as glass, as investigated by and represent promising avenues for improving the overall effectiveness of these systems. The integration of internal fins and grooved tubes, as studied Ho and chilambarasan also shows significant potential to enhance the heat transfer capabilities of these collectors.

The introduction from Selvam emphasizes that the simplest way to absorb solar energy is by a flat plate solar water heater, which directly converts solar radiation into heat without any instruments. They discuss the basic components: glass cover, absorber plate, insulation, and riser tube. The glass cover acts as a heat wave protector and the selection of material is based on thermal conductivity. Higher thermal conductivity leads to better heat absorption[3], also note that many types of fins have been utilized to faster heat transfer rate than plain tubes, since fins are exposed to the inner surface of riser tube and have direct contact with water. Fluid flow through internally finned tubes is not circular and not laminar even at lower velocities.

They explain that a flat plate solar collector performs with conduction, convection, and radiation. Energy from the sun hits the absorber plate, which diffuses heat into the riser tube. Increasing Fourier's number improves heat exchange between the riser tube and absorber plate. Water entering temperature is typically lower than the riser tube temperature, so heat flows from the riser tube to the water by forced convection.

In summary, the research indicates that FPSWH performance hinges on optimizing multiple parameters, including materials, design, and internal enhancements to maximize heat transfer and minimize losses.

2.3. Solar water heater operation principle

The conventional SWH system, as shown in figure below, consists of a discrete collector, which is designed to maximize solar absorption and reduce heat losses. The solar collector could be either a black-painted flat-plate absorber bonded to copper piping and covered with a transparent glass (flat-plate collector) or copper tubing surrounded by evacuated and selectively coated glass tubes (evacuated-tube collector). When solar radiation passes through the transparent glass or evacuated tubes and impinges on the collector with its high absorptive surface, a large part of the energy is absorbed by the collector and is then transferred to the fluid to be transported in the pipes. The heat transfer fluid, usually a mixture of water and antifreeze fluid, is either pumped
(active system) or driven by natural

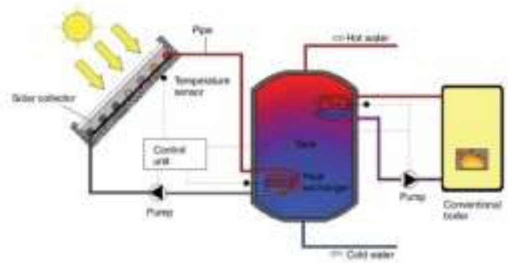

Figure 2.1 Schematic diagram of Conventional system of SWH

Convection (passive system) through the collector to a coil heat exchanger at the bottom of a cylinder tank (indirect system), where the heat is further transferred to a storage tank or is used directly. The tank is usually insulated and may contain an auxiliary heater, for example, electric immersion heater or conventional boiler for winter use.

2.4. Classification of SWH

2.4.1. Passive and Active Systems

Based on whether the SWH system requires pumps or not to function, SWHs are categorized into two basic configurations: passive or active systems. Passive systems transfer heat from the collector to the tank located above the collector by natural circulation, which could supply hot water at a temperature of the order of 60°C, and are the most commonly used solar water heaters for domestic applications.

Active systems use an electric pump to circulate water through the collector. A check valve may be required to prevent reverse water circulation. The efficiency of an active SWH system is usually between 35% and 80% while that of the passive system is in the range of 30%–50%. An advantage of the active system is that the collector does not need to be close to the tank and hence can be used in multistory buildings. However, the drawbacks of the active system include: it’s dependent on electricity and the fact that it is more complicated in nature and requires the need of experienced personnel to ensure optimal operation. This leads to the active system, having much higher running costs than the passive system.

Direct and Indirect Systems SWH systems, which do not include a heat exchanger, are called direct systems, while the SWHs, which are fitted with heat exchangers, are called indirect systems

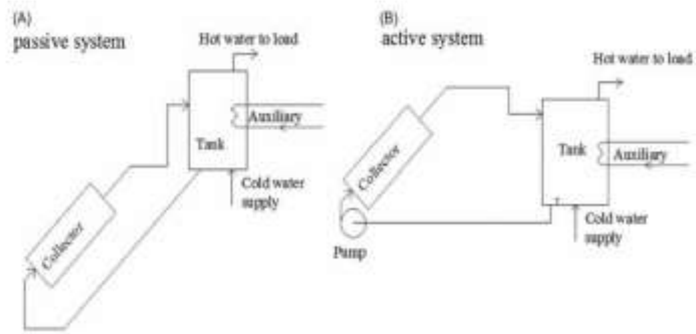

Figure 2.2 Schematic diagram of Passive and Passive system

2.4.2. Direct and Indirect Systems

SWH systems, which do not include a heat exchanger, are called direct systems while the SWHs, which are fitted with heat exchangers, are called indirect systems

In a direct system, the service water is directly circulated between the water tank and the collector, while in an indirect system, a heat transfer fluid, usually antifreeze, distilled water, or an organic fluid, is circulated through the solar collector. A heat exchanger is employed to affect the heat transfer from the collector to the service water in the tank. The heat exchanger could be inside or outside the hot water tank as shown in Fig. 6.5A and B. The indirect system, in most situations, performs better than the direct one. The in direct system is less climate-selective and more suitable for use in regions experiencing cooler temperatures.

2.5 Types solar collector

Solar collectors are differentiated based on their motion, i.e., stationary, single-axis tracking, two-axis tracking, and operating temperature.

Non-concentrating types of collectors are permanently fixed in a specific position, and they do not track the sun. The types of solar col lectors that come under this section are reviewed below. Flat plate collectors (FPC) are usually fixed permanently at one specific position. They do not require any sun tracking, and the circulating fluid acts as a heat transfer medium. FPC consists of transparent glazing glass to pass the sunrays, back absorber sheet, which absorbs the maximum amount of heat and transfers to the circulating fluid. The insulation layer beneath the plate reduces the amount of heat/ conduction loss, and the copper tubes can be attached to the absorbing plate, as shown in Fig. 8. The most common techniques, such as CFD or finite element method (FEM), can help avoid structural analysis issues and other design flaws. Moreover, these techniques (CFD, FEM, etc.) support the study of temperature distribution in collector and water/ circulating fluid.

2.6 Insulation

Solar water heating is a highly sustainable method of extracting thermal energy from the sun for domestic and industrial use. In residential buildings, thermal energy from a Solar Water Heater (SWH) can be used to heat spaces, shower, clean, or cook, either alone or in combination with conventional heating systems such as electricity- and fossil- fuel- based heaters. In the industrial sector, SWsHs can be used in various high- temperature fluid processes, including chemical processing, manufacturing, power generation, and construction. Despite the technological advancements in water heating systems, there are still some significant technical and economic challenges that limit their widespread adoption and commercialization. Despite their potential to revolutionize the industry, these systems remain in the shadows of unsustainable water heating solutions [12].

Insulation of a solar water heater is important for both performance and protection from freezing. Here are some key points:

a) Use insulation to reduce heat loss and increase performance**.**
b) Consider using a pre-made solar collector or black painted sheet metal
c) An insulated box or frame can hold the collector and maximize heat retention**.**
d) The glass or plastic cover creates a greenhouse effect to trap heat inside the collector**.**

CHAPTER 3: METHODOLOGY

In this research project, there is requirement of data related to weather condition in different area like temperature, irradiance , wind speed and direction, precipitation that are having a direct impact on heat loss on solar water heaters for developing, analyzing, simulating and choosing the best the best material with minimum heat loss but with cost effectiveness.

Part of the research is going to talk about the method and materials used in the research project, research approach, the method which is used in data collection from different sites, the selection of sampling areas, the research process, data analysis and simulation by the use of COMSOL Multiphysics software.

3.1. Data collection

Solar data have been collected from various locations across Rwanda. The selection of data collection sites was based on the environmental conditions prevalent in the country. Although the climate in Rwanda is relatively uniform, variations in solar irradiation, wind speed and direction, temperature humidity have influence in performance of solar water heaters. The Rwandan climate can be categorized into three zones which are hot areas including Eastern province like Bugesera and Nyagatare, medium areas such as part of Southern and Western Province like Nyanza, Muhanga, Nyamasheke and Rusizi and cold areas especially in Northern province and a part of Western province like Nyabihu, Rutsiro, Gicumbi and Rulindo.

The data have been recorded while considering all these regions by sampling on location in each case so that the change in temperature is considered while choosing the best insulation materials that can keep heat for longtime for the best efficient system.

3.1.2. Data collection Tools

- **Lux meter**

A lux meter in Fig 3.1 is a device used to measure the illuminance of a surface, typically expressed in lux (lx), which quantifies the amount of light per unit area. It is has been used in data solar data recording of solar irradiance in different locations.

Figure 3.1 Lux meter

- **A pyranometer**

A pyranometer in Fig 3.2 has been used as a device to measure solar irradiance available on the selected areas.

Figure 3.2 pyranometer

- **Watch**

While recording the time is also very important, and it was done every 15min from 6h00 to 18h00 to be able to have the amount of sunshine available in the chosen location.

3.2 Simulation in COMSOL

Simulation with COMSOL software involves using a powerful multiphysics platform to model and analyze complex systems across various engineering disciplines. COMSOL allows users to simulate physical processes by integrating different physics phenomena, such as structural mechanics, fluid dynamics, heat transfer, and electromagnetics, into a unified model. This capability enables engineers and researchers to predict real-world behavior, optimize designs, and solve challenging problems in a virtual environment, making COMSOL an essential tool for innovation and development in science and engineering.

Construction of solar water heater in COMSOL multiphysics will involve different type of materials, shape, and measurement, capacity of solar collector, solar tank and piping, and insulation materials which will be used to simulate the system performance for choosing the best insulation materials that can withstand the subjected conditions.

3.3 Solar water heater construction in COMSOL multiphysics

The collector is one of the most components of a solar water heater which is responsible for collecting solar radiations and converting them into heat. It consists of flat-plate a collector which is painted in black color surface according to its property of absorption, with fluid tubes inside. The collector absorbs solar radiation, heating the fluid inside, which then transfers the heat to water in a storage tank. This will occur based on high density of cold water as compared to hot water this means that also hot water tends to occupy the top of the tank while the bottom of the tank.

3.3.1. Solar Collector construction using Comsol multiphysics Software.

A solar collector is a device that absorbs sunlight and converts it into usable heat energy, primarily for heating water or indoor spaces. Its key components include an absorber plate, which captures and converts solar radiation into heat, and a transparent cover (glazing) that protects the absorber while reducing heat loss. Insulation helps minimize heat loss from the back and sides, while a heat transfer fluid carries the absorbed heat to a storage system or point of use.

Finally, the casing provides structural support and shields the system from external elements.

Table 3.1 Solar collector construction dimension

Name	Expression	Value	Description
glass_th	5[mm]	0.005 m	Glass plate thickness
L_box	100[cm]	1 m	Box side length
H_box	15[cm]	0.15 m	Box height
box_th	10[cm]	0.1 m	Thickness of plastic box

3.3.2. Solar collector parts

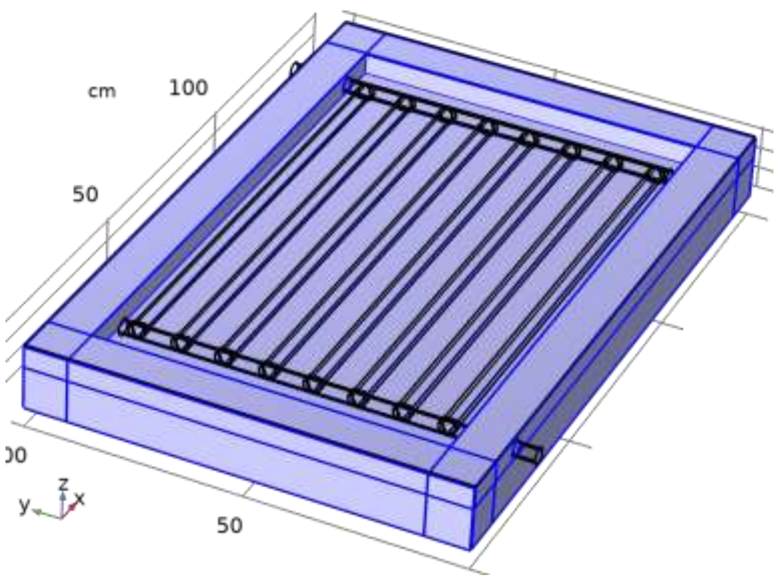

Figure 3.3 Solar collector box

Solar Collector Box acts as a structural structure of the collector, habitat all internal components. It is usually made of durable, light materials such as plastic or metal. The design of the box ensures stability and provides insulation to reduce heat loss. Its dimensions (eg, 1 meter x 1 meter x 0.15 m) are adapted for efficient heat absorption while maintaining a suitable compact form for residential use.

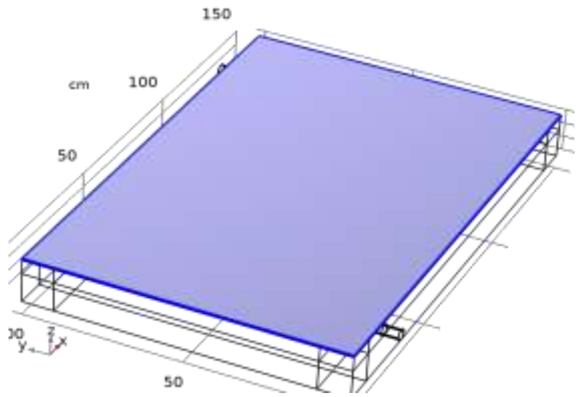

Figure 3.4 Glass Cover

Glass cover is an important component that allows solar radiation to penetrate while implicating the heat inside the collector. The thickness of 5 mm is commonly used to balance durability and light transmission. The glass creates a greenhouse effect, which increases the ability of the collector to absorb and maintain the heat, which is necessary to maximize thermal efficiency.

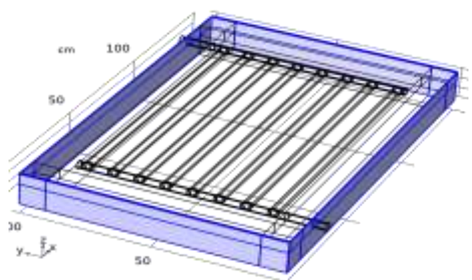

Figure3.5 External Side Walls

The outer side walls of the solar collector provide structural support and additional insulation. These walls are usually made of plastic or metal -like materials, which have insulation layers to reduce heat losses. The choice of thickness and material (eg, 10 cm plastic) ensure that the collector can withstand environmental conditions while maintaining internal temperature.

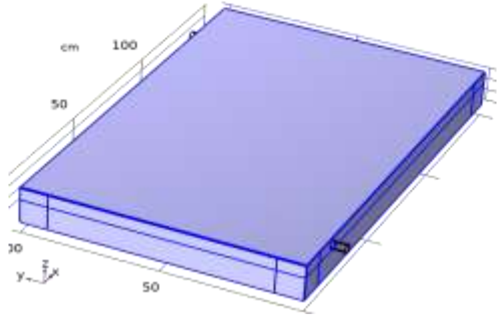

Figure3. 6 complete solar collector

The entire solar collector integrates the box, glass cover and side walls in a functional unit that is designed to efficiently absorb and move solar energy. The combination of these components ensures optimal performance, with a glass cover that maximizes solar absorption, the box providing structural integrity, and the side walls offer insulation. Together, these parts create a system capable of continuously giving thermal performance under various climatic conditions.

3.4. Tank construction

The tank is having three different layers which are the inner tank designed to store hot water. This is covered by the second layer which is having high thermal resistance to keep the captured heat again loss. While the last one is the outer sheet which protect the inner tank and the insulator against air contact.

Table 3.2 Tank construction dimension

Name	Expression	Value	Description
D_inner	40[cm]	0.4 m	Outer diameter
Th_GS	1[mm]	0.001 m	Thickness of the outer G Steel
Th_insolator	10[cm]	0.1 m	Thickkess of the insolator wool
Th_SS	2[mm]	0.002 m	Thickness of the inner steel
H_inner	80[cm]	0.8 m	Outer heigh of the tank
D_inlet	1[inch]	0.0254 m	
D_outlet1	1[inch]	0.0254 m	Outlet to loop
D_outlet2	.75[inch]	0.01905 m	Outlet to usage

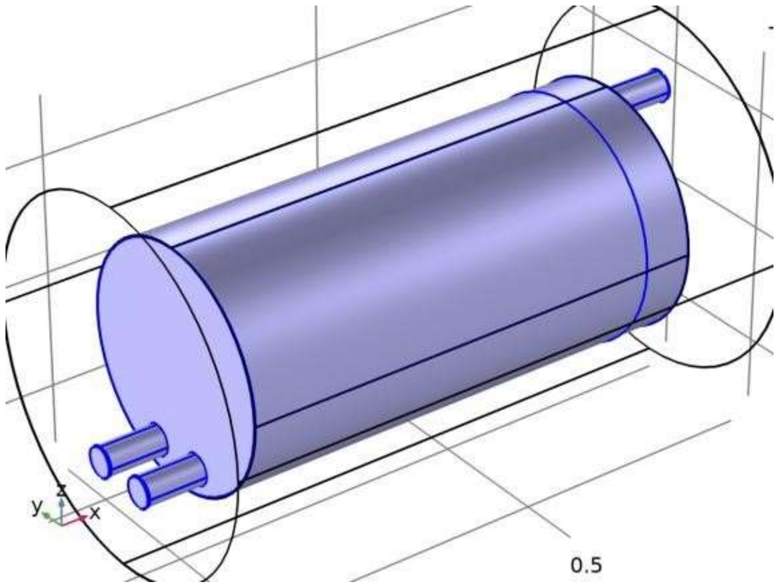

Figure 3.7 Inner tank

On this tank, there is input pipe for supplying water from the main pipeline supply and the output pipe for supplying water to the collector as they are seen on bottom left side of the tank. On the other side especially top right side, the pipe is for supplying/fetching hot water stored in the tank.

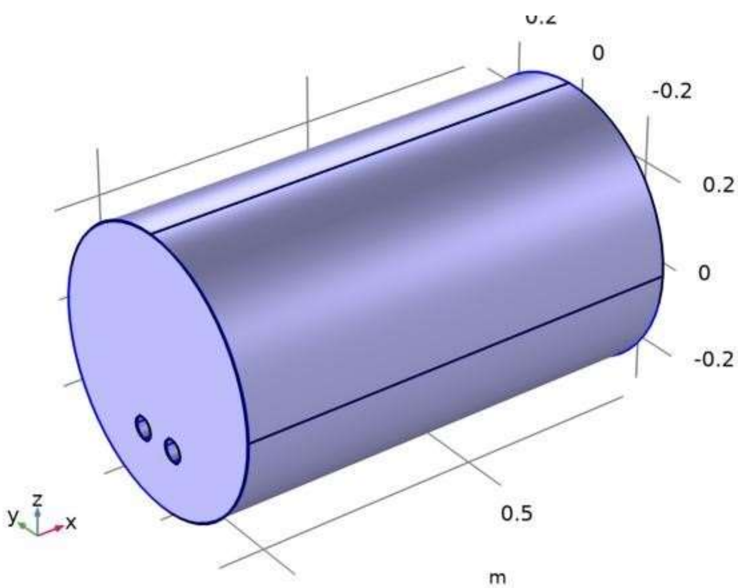

Figure 3.8 Insulation material around the inner tank

The insulation material has been developed around the inner tank with the thickness described in the previous table of dimensions. Around all of these two shapes, the outer tank also has been constructed which produced the final geometry as it is seen in the following final geometry

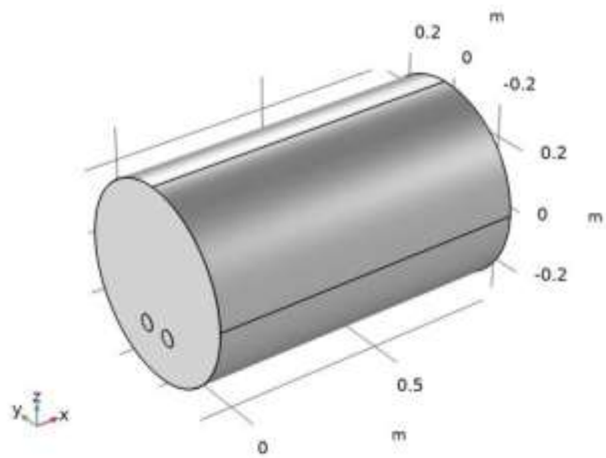

Figure3.9 Tank geometry

3.4.1 Material selection

The outer tanks sheet has been chosen to be iron in this simulation due to the cost of iron as compared to the one of other materials.

Table 3.3 Iron sheet property for outer tank

Name	Value	Unit	Property group
Heat capacity at constant pressure	440	J/(kg·K)	Basic
Density	7870	kg/m³	Basic
Thermal conductivity	76.2	W/(m·K)	Basic

The insulation material has to be also chosen which is the research point on this thesis, here the selection will be between glass fiber blanket, glass wool and wood. In this case each material has its own properties

Table3.4 Glass fiber blanket for insulator

Name	Value	Unit	Property group
Thermal conductivity	1.1	W/(m·K)	Basic
Density	140	kg/m³	Basic
Heat capacity at constant pressure	0.9	J/(kg·K)	Basic

Inner tank has to have the property that compatible with health so that it cannot cause diseases due to corrosion.

3.4.2 Tank simulations

The tank is simulated in COMSOL multiphysics where the intended outcome is to analyze the behavior of heat exchanging process between air surrounding the tank and water inside so that heat loss can be estimated and therefore the efficiency can be obtained. The heat loss is an expression of time which mean that the input in the constructed system is water which is flowing at a given speed and time at which heat loss is done.

CHAPTER 4: DATA ANALYSIS

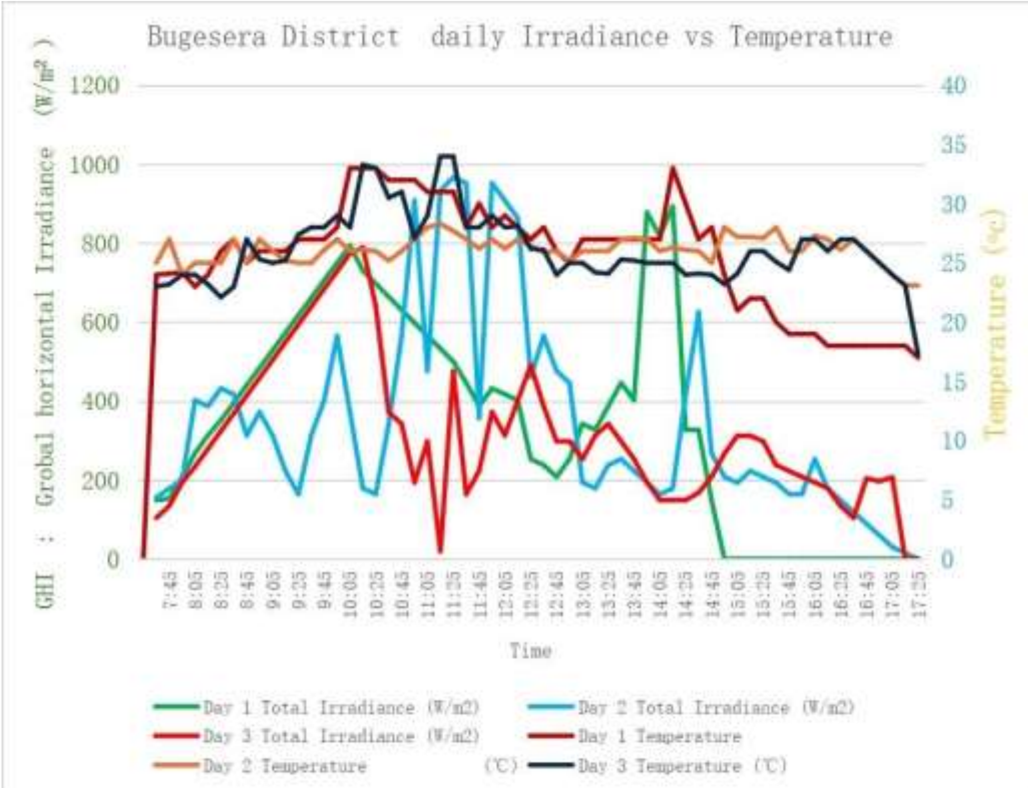

Figure 4. 1 Comparing data recorded at the BUGESERA district

Figure 4.1 shows solar radiation recorded in Bugesera and variation in temperature. It highlights trends such as the effect of temperature at the level of peak solar capacity and radiation around the afternoon.

This figure 4.2 compares daily variations in solar radiation and temperature trends in possibly recorded days. The peaks and valleys in the graph throw light on how the local weather conditions affect the solar capacity.

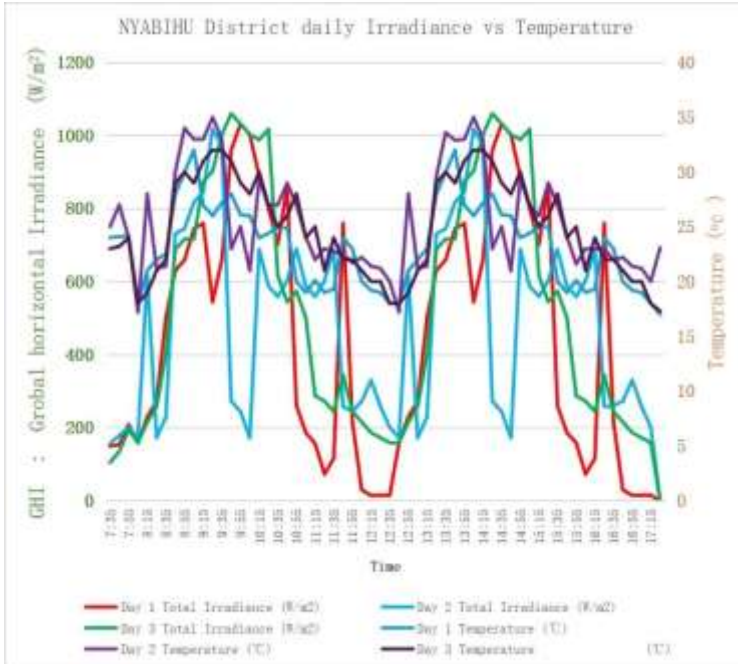

Figure4. 2 Comparing data recorded at the NYABIHU district

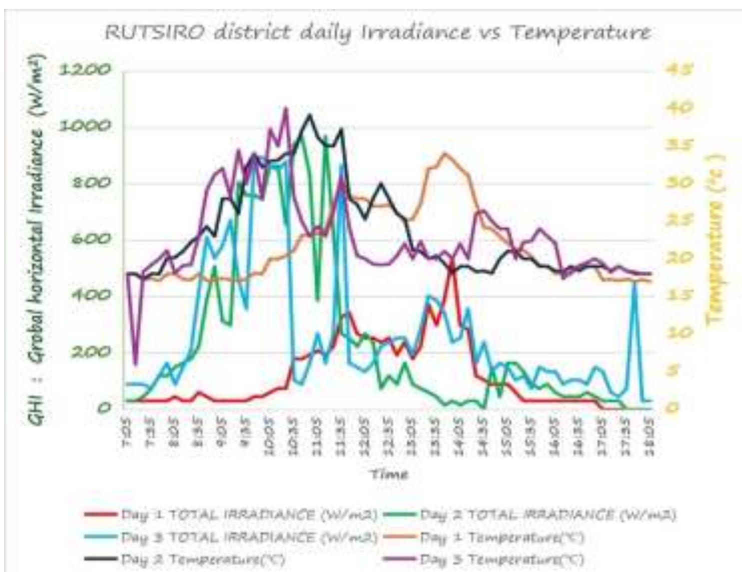

Figure 4.3 Comparing data recorded at the RUTSIRO district

Figure 4.3 shows the comparison of three days data recorded at Rutsiro, This visualization highlights relatively low solar capacity in status compared to other Districts. In the graph, the peaks and troughs show how the solar intensity occurs throughout the day.

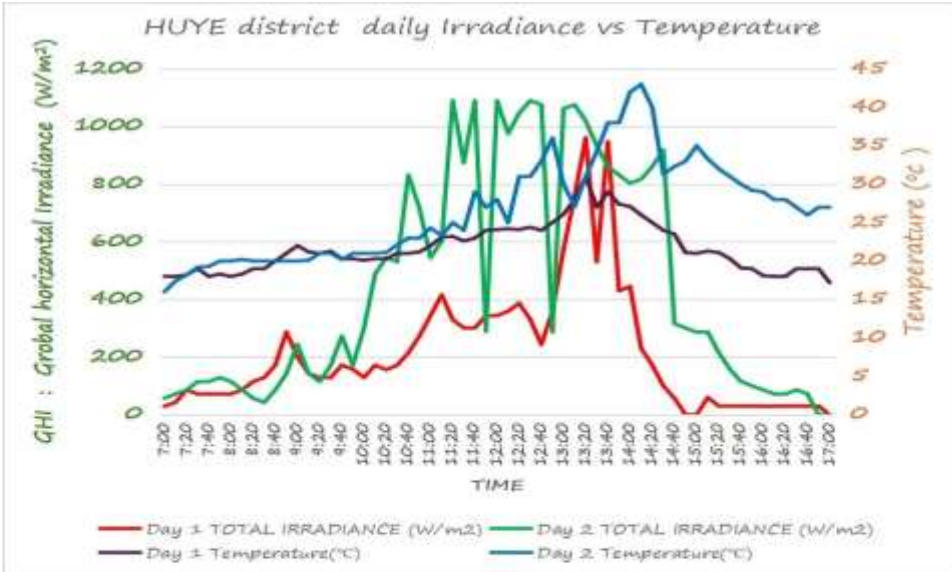

Figure 4. 4 Comparing data recorded at HUYE District

This figure 4.4 provides a visual representation of radiation and temperature trends in Huye. It may indicate cloud cover effect or weather variation on various days. It is showing peak sun is between 11:20 am to 13:10 pm sun set almost at 17 pm, This location is good for solar ,it has radiation which more than 1000 W/m^2 at peak sun hours .

Chapter 5: RESULTS AND DISCUSSION

5.1 Solar Collector

5.1.1 Performance of solar collector under different regions

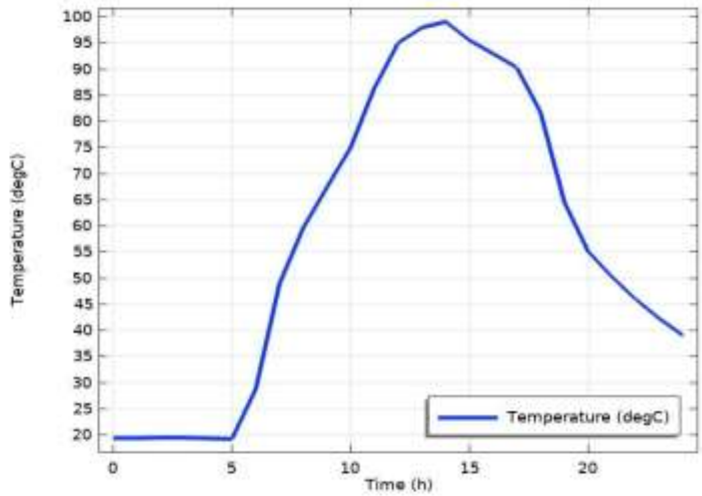

Figure 5. 1 Solar Collector Temperature graphical presentation in hot region

Figure 5.1 reflects the temperature profile of a solar collector over a 24 -hour period in a warm area. The temperature remains stable at about 20ºC during early hours (0–5 hours), indicating minimal solar radiation. As the sun rises, the temperature increases continuously, it reaches 99.041 ° C between 6 and 14 hours. After 12 hours, the temperature begins to fall with a low solar radiation. This pattern reflects the specific heating and cooling cycle of a solar collector in a warm climate, where the peak temperature is obtained during the afternoon.

5.1.2 Water temperature variation graphical presentation in solar collector

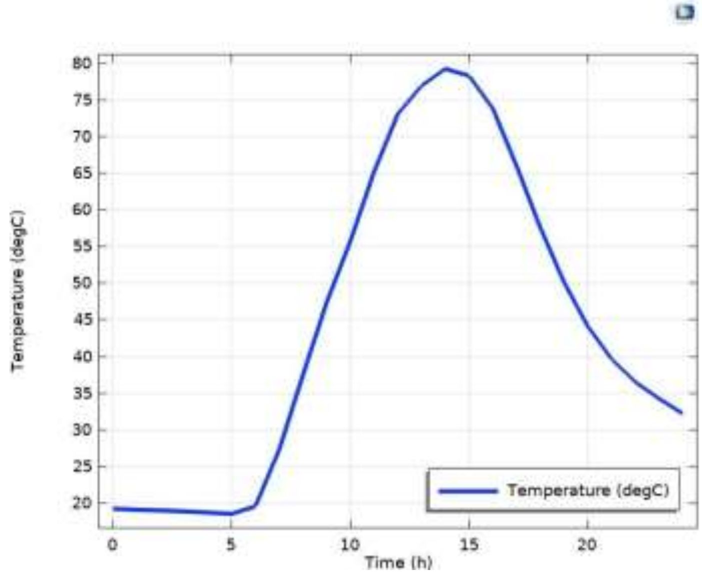

Figure 5.2 Water temperature variation graphical presentation in solar collector in moderate and cold region

Figure 5.2 compares the water temperature variation in moderate and cold regions. In moderate regions, the temperature rise is more gradual, while in cold regions, the temperature increase is slower due to lower solar radiation. The graph highlights the impact of regional climate on the efficiency of solar collectors.

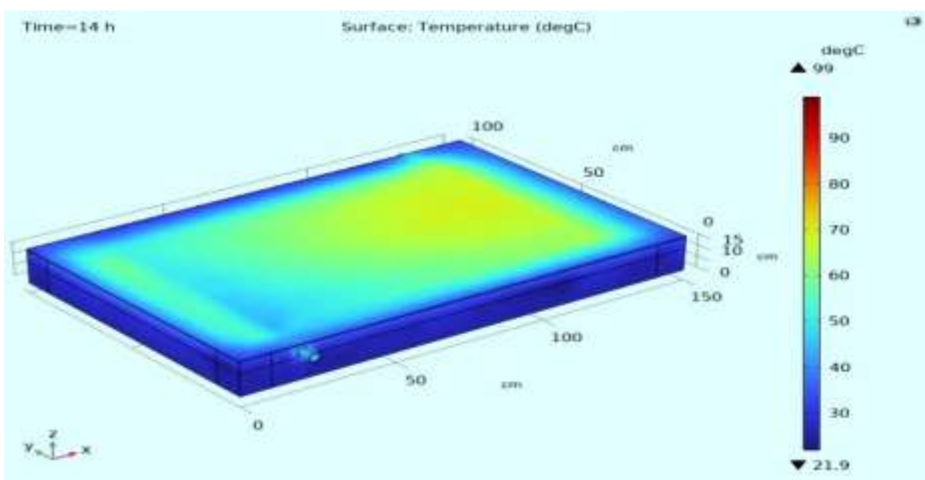

Figure 5.3 Solar Collector color map with transparent cover

Figure 5.3 shows the simulation of a solar collector with an insulator, pipes, and an absorber plate. The absorber plate collects solar radiation, the insulator prevents heat losses, and the pipes attached to the absorber plate allow water flow, transferring heat from the absorber plate.

5.1.3 Insulation

A. Wood Insulator

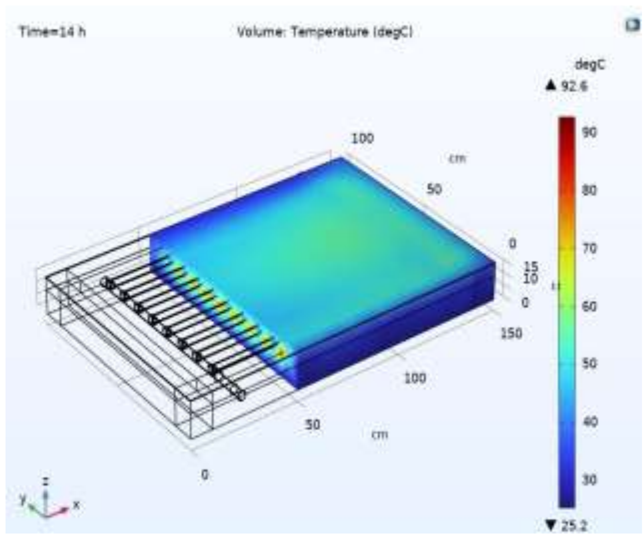

Figure 5. 4 solar collector with Wood Insulator simulation result

This figure 5.4 show how wood insulator provides moderate insulation, as seen in the temperature profile. The temperature rise is steady but is higher than Glass fiber Insulator.

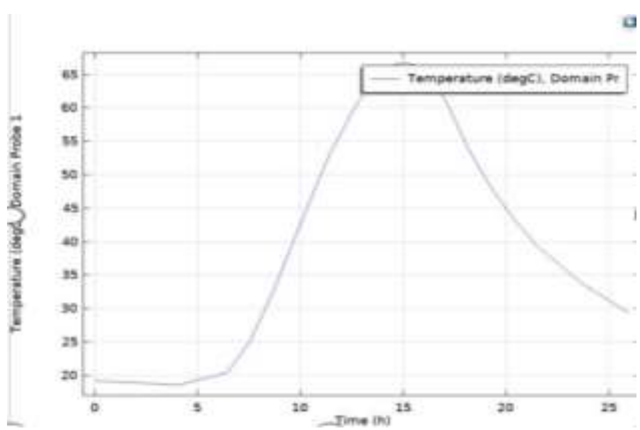

Figure 5. 4 Wood Insulator

Here figure 5.4 of wood insulator provides moderate insulation, as seen in the temperature profile. Here the first 5 hours of a day the temperature ranges between 18-19 ^{o}c but rises from the 6th hour of a day. The temperature rise is steady but is higher than Glass fiber Insulator.

B. Glass wool Insulator

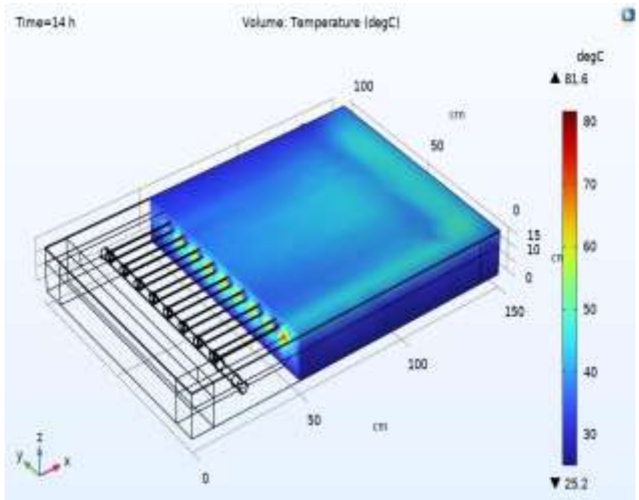

Figure 5.5 Glass wool Insulator

Figure 5.5 Glass wool insulation shows better thermal performance compared to wood. The temperature rise is more pronounced, and the heat retention is improved, as evidenced by the higher temperatures in the graph.

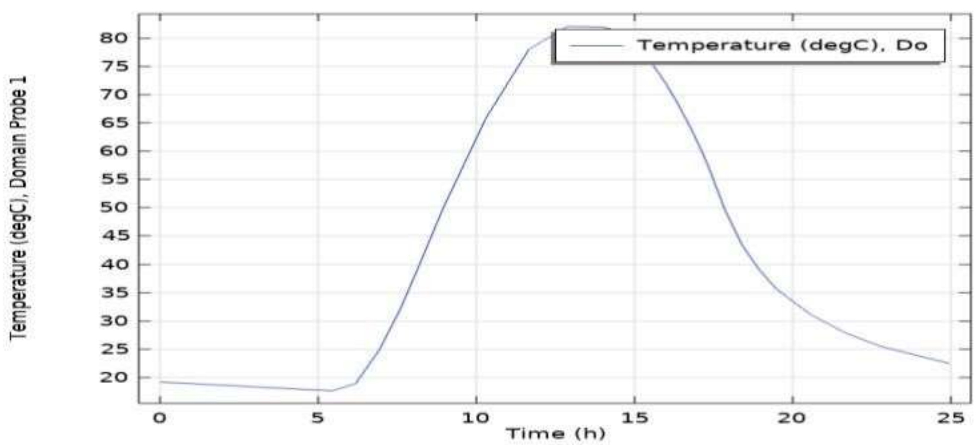

Figure 5.6 Glass wool insulation

This graph 5.6 of Glass wool insulation shows better thermal performance compared to wood. The temperature rise is more pronounced, and the heat retention is improved, as evidenced by the higher temperatures in the graph.

Glass fiber Insulator

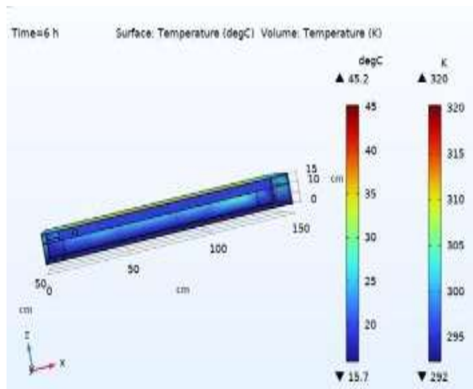

Figure 5.7 Glass fiber Insulator

Figure 5.7 shows how Glass fiber insulation demonstrates the good performance . The temperature rise is rapid, and the heat retention is good, making it the efficient insulator for solar collectors but not best as the Glass wool and wood insulator.

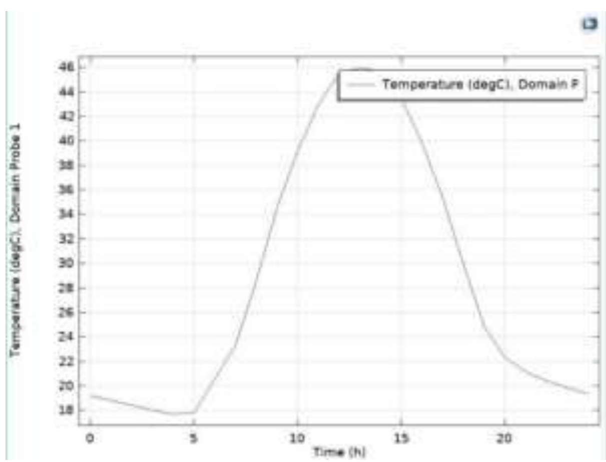

Figure 5.8 Glass fiber insulation

Figure 5.8 Glass fiber insulation demonstrates the also a good performance. The temperature rise is rapid, and the heat retention is good, making it the efficient insulator for solar collectors but not best as the Glass wool and wood insulator

5.1.4 Water flow of house hold with 3 different water flow rate (Glass wool insulator)

A normal water mass flow rate for a typical household faucet is around 0.02 - 0.03 kg/s which translates to roughly 2 - 3 gallons per minute (GPM) depending on the water pressure and pipe size.

a. Color map of temperature variation and Temperature graphical presentation for water flow of 0.01 kg/second

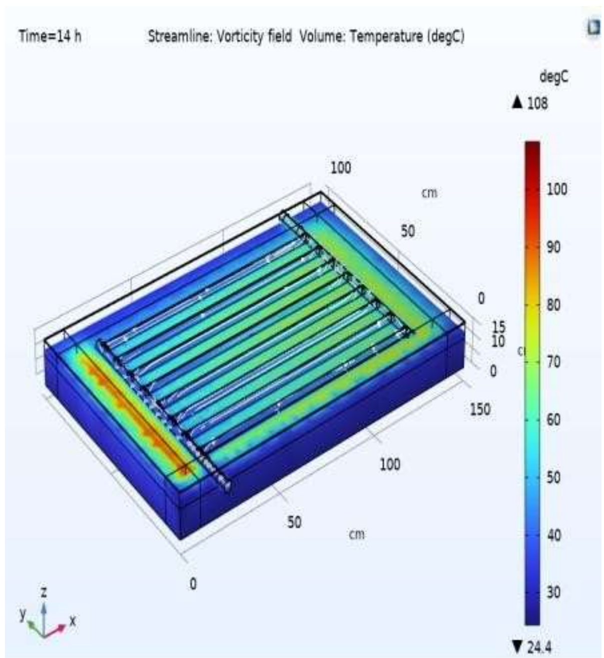

Figure 5.9 Color map of temperature variation-profile cross section

Figure 5.9 show Color map of temperature variation T-profile cross section. At a low flow rate of 0.01 kg/s, the water temperature rises significantly, indicating efficient heat transfer.

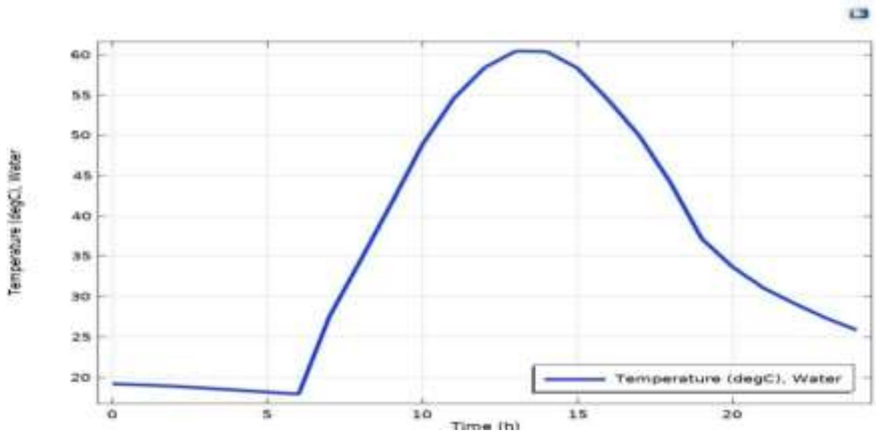

Figure 5.10 Temperature graphical presentation for water flow of 0.01 kg/second

Figure 5.6 shows temperature graphical presentation for water flow of 0.01 kg/second. At a low flow rate of 0.01 kg/s, the water temperature rises significantly, indicating efficient heat transfer

b. Color map of temperature variation and Temperature graphical presentation for water flow of 0.02 kg/second

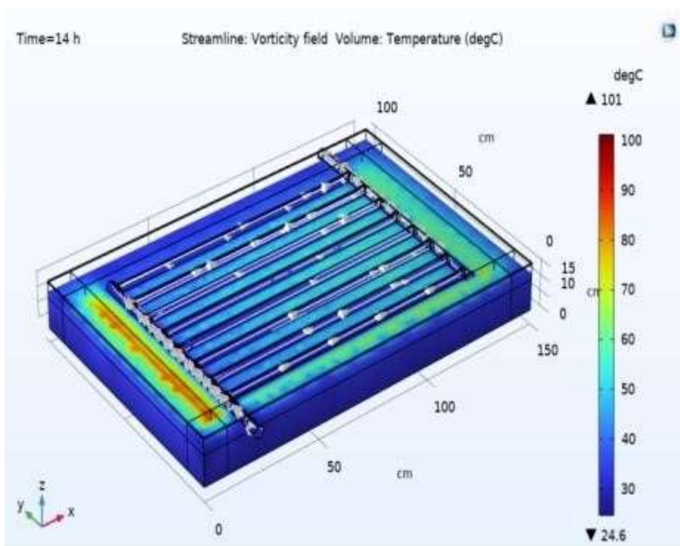

Figure 5. 11 Color map of temperature variation T-profile cross section

Figure 5.11 shows Color map of temperature variation T-profile cross section. At a flow rate of 0.02 kg/s, the temperature rise is moderate, balancing heat transfer efficiency with practical water availability. This flow rate is closer to typical household usage.

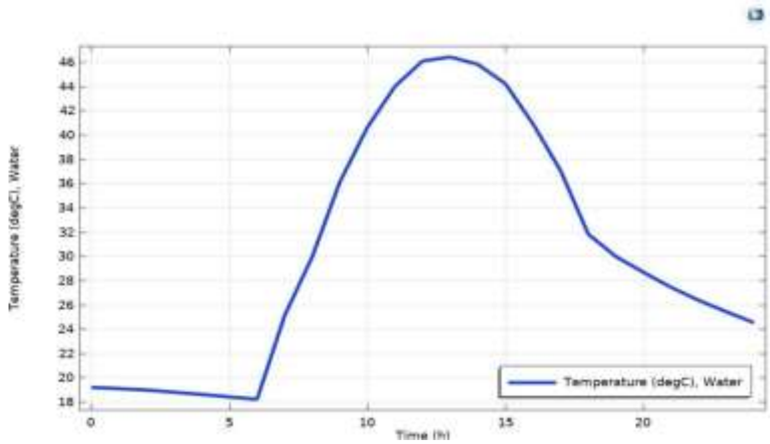

Figure 5.12 Temperature graphical presentation for water flow of 0.02 kg/second

Figure 5.12 Shows Temperature graphical presentation for water flow of 0.02 kg/second. At a flow rate of 0.02 kg/s, the temperature rise is moderate, balancing heat transfer efficiency with practical water availability. This flow rate is closer to typical household usage.

c. Color map of temperature variation and Temperature graphical presentation for water flow of 0.03 kg/second

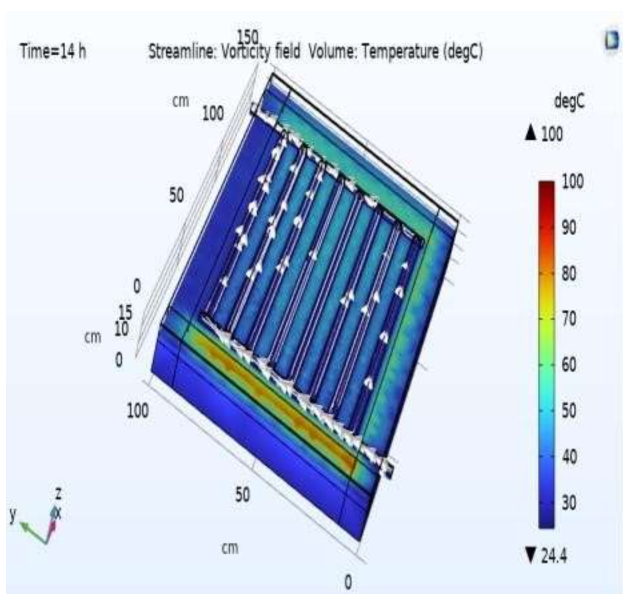

Figure 5.13 Color map of temperature variation

Figure 5.13 shows Color map of temperature variation. At a higher flow rate of 0.03 kg/s, the temperature rise is less pronounced, indicating that the system struggles to heat the water efficiently at this rate. This suggests a trade-off between flow rate and temperature

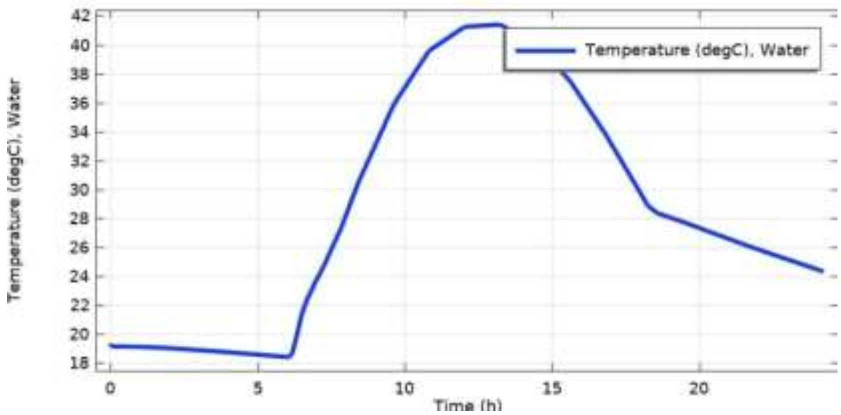

Figure 5.14 Temperature graphical presentation for water flow of 0.03 kg/second

Figure 5.14 shows Temperature graphical presentation for water flow of 0.03 kg/second. At a higher flow rate of 0.03 kg/s, the temperature rise is less pronounced, indicating that the system struggles to heat the water efficiently at this rate. This suggests a trade-off between flow rate and temperature

5.2 Solar Tank

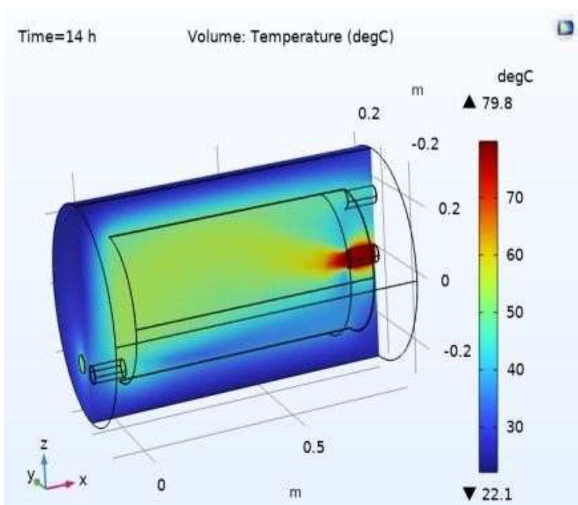

Figure 5.15 Solar Tank

Figure 5.15 illustrates hot water flow from the solar collector with 79.8^{o}C to the solar tank, mixing with cold water. The simulation shows that hot water concentrates opposite the outlet pipe for water usage. Based on the density principle, hot water with lower density rises, while cold water with higher density sinks. The simulation suggests placing the outlet pipe at the same level but on the opposite side to ensure easier access to hot water.

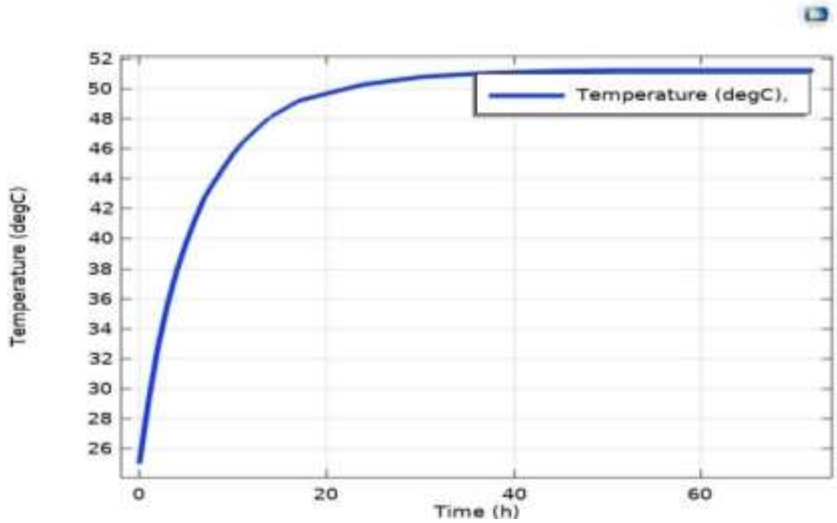

Figure 5.16 Solar Tank simulation graphical representation

Figure 5.16 the simulation shows hot water (79.8°C) flowing into the solar tank and mixing with cold water. The hot water rises due to its lower density, while cold water sinks. The outlet pipe placement is crucial for ensuring easy access to hot water. The graph shows the temperature distribution within the tank, with higher temperatures near the top.

5.4.1 glass wool Insulation

Figure 5. 17 shows Glass wool insulation effectively retains heat in the solar tank, as seen by the higher temperatures in the graph. This material is suitable for maintaining hot water temperatures over time.

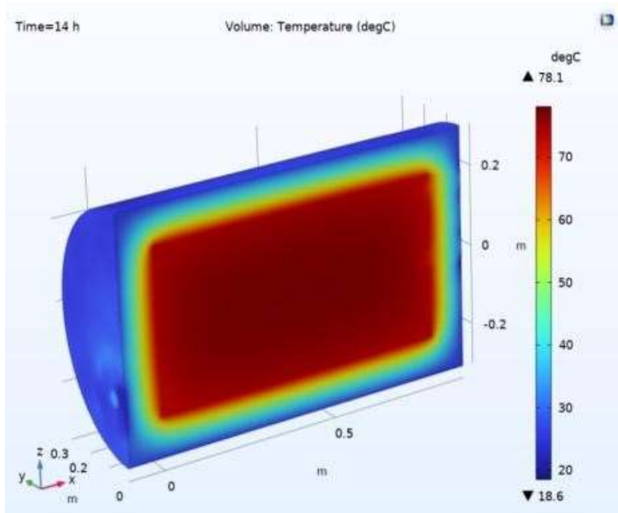

Figure 5.17 Glass wool Insulation color map

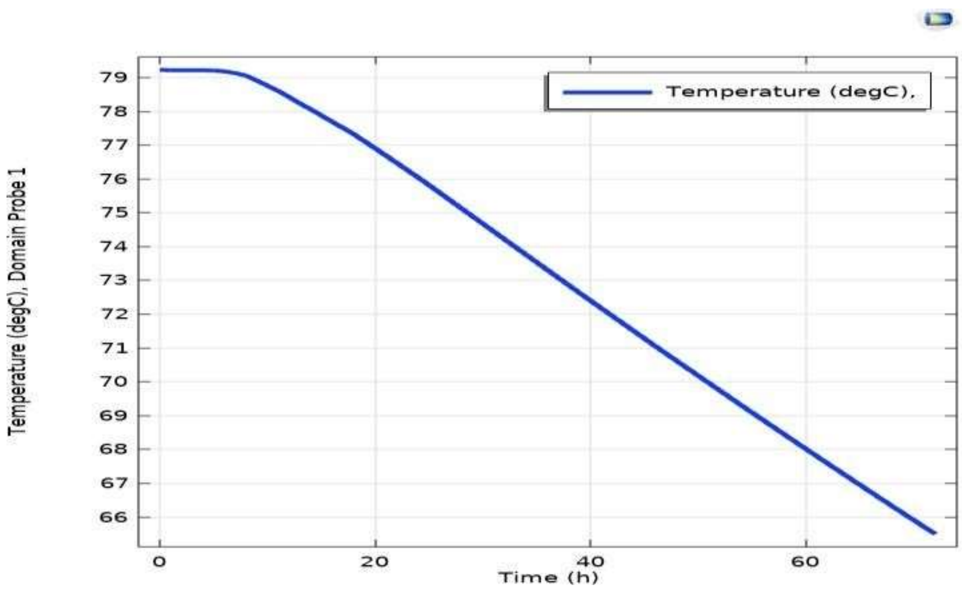

Figure 5.18 Glass wool insulation graphical presentation

Figure 5. 18 shows how Glass wool insulation effectively retains heat in the solar tank, as seen by the higher temperatures in the graph. This material is suitable for maintaining hot water temperatures over time.

5.4.2 Fiber glass Insulation

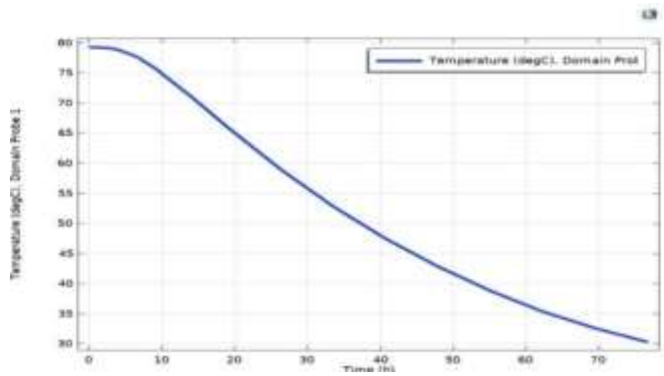

Figure 5.19 Fiber glass Insulation graphical representation

Figure 5. 19 shows how Fiber glass insulation performs similarly to glass wool, with good heat retention. The temperature distribution is uniform, indicating efficient insulation.

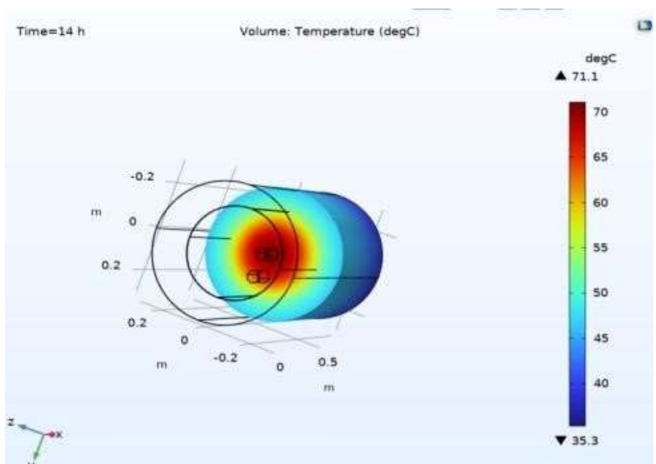

Figure 5.20 Fiber glass insulation color map

Figure 5. 20 show how Fiber glass insulation performs similarly to glass wool, with good heat retention. The temperature distribution is uniform, indicating efficient insulation.

5.4.3 Wood Insulation

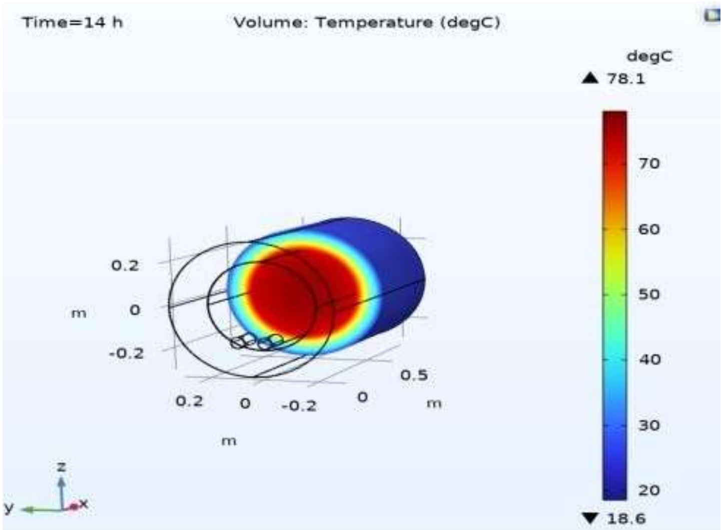

Figure 5.21 wood Insulation color map

Figure 5.21 show how Wood insulation is less effective, though it show mediate temperatures in the graph. Heat loss is more significant, making wood a less desirable insulation material for solar tanks.

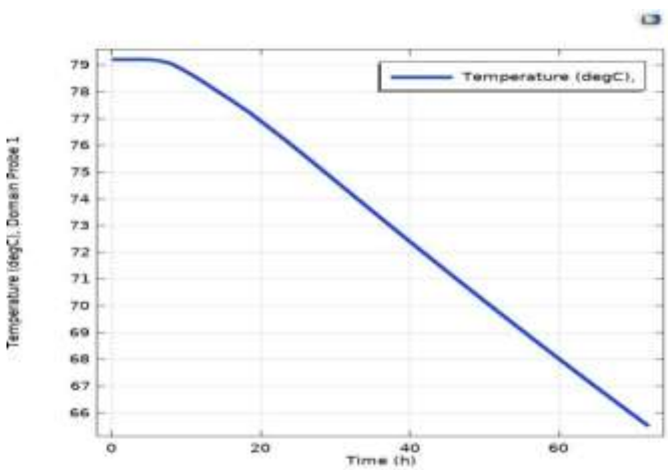

Figure 5. 22 Wood insulation graphical representation

Figure 5.22 show how wood insulation is less effective, though it show mediate temperatures in the graph. Heat loss is more significant, making wood a less desirable insulation material for solar tanks.

5.5. Thermal performance of solar water heater at 17ºC outer temperature.

5.5.1. Solar water heat Tank with Fiber Glass insulation

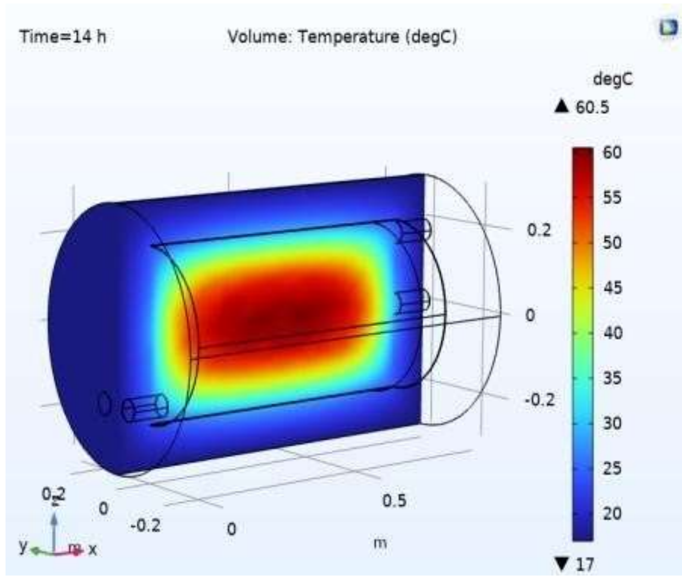

Figure 5. 23 Fiber Glass insulation color map

Figure 5.23 show that at 17°C, fiber glass insulation loss heat as it have not a stable temperature within the tank, makes it have high heat loss

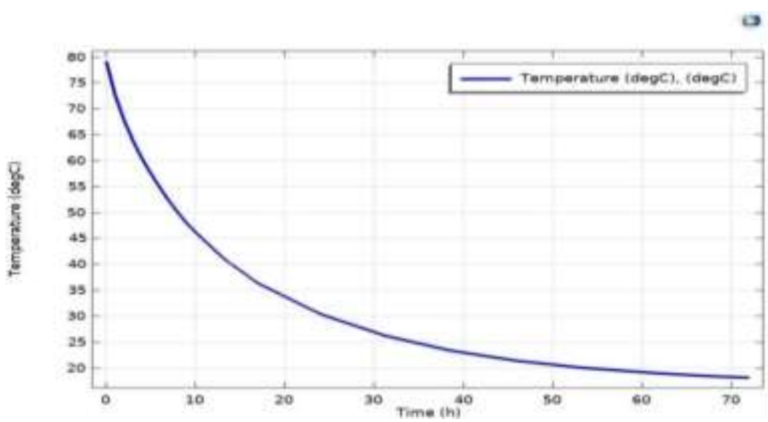

Figure 5. 24 Fiber Glass insulation graphical representation

At 17°C, fiber glass insulation loss heat as it have not a stable temperature within the tank, makes it have high heat loss. Figure 5.24 Graphical presentation of water temperature distribution in Tank using fiber glass insulation

5.5.2 Solar water heater Tank with Glass wool insulator.

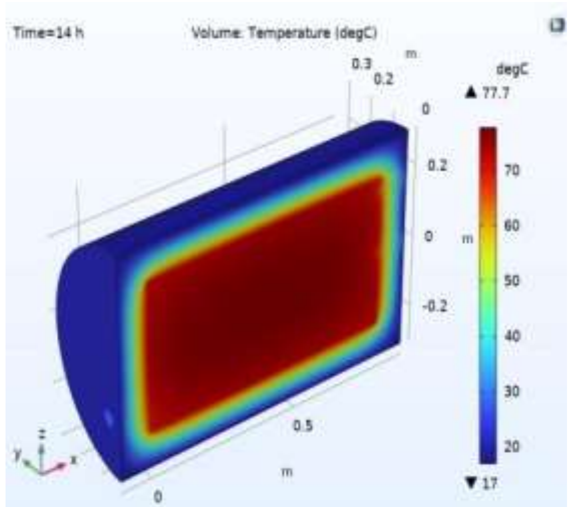

Figure 5. 25 Glass wool insulator color map.

Figure5.25 shows how Glass wool insulation also performs well at 17°C, not similar temperature retention to fiber glass.

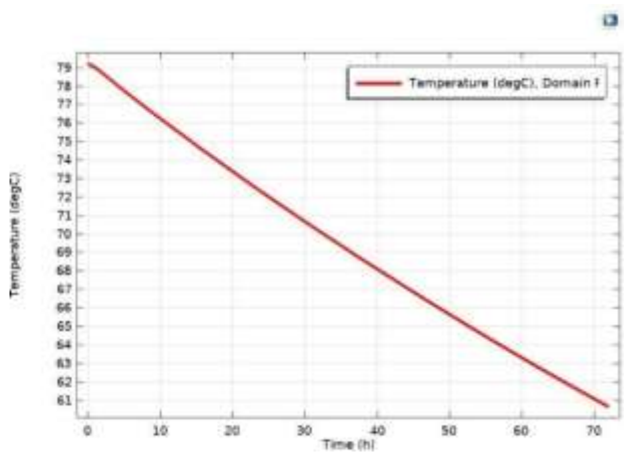

Figure 5. 26 Presentation of water temperature distribution in Tank using Glass wool insulator

Figure 5.26 shows Graphical presentation of water temperature distribution in Tank using Glass wool insulator. Glass wool insulation also performs well at 17°C, not similar temperature retention to fiber glass.

5.5.3 Solar water heater Tank with wood insulator.

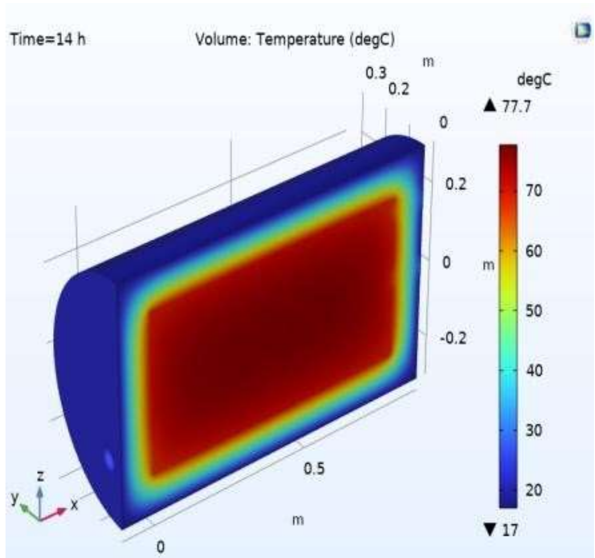

Figure 5.27 wood insulator color map

Figure 5. 27 shows how wood insulation struggles to retain heat at 17°C, as seen by the lower temperatures and greater heat loss in the graph.

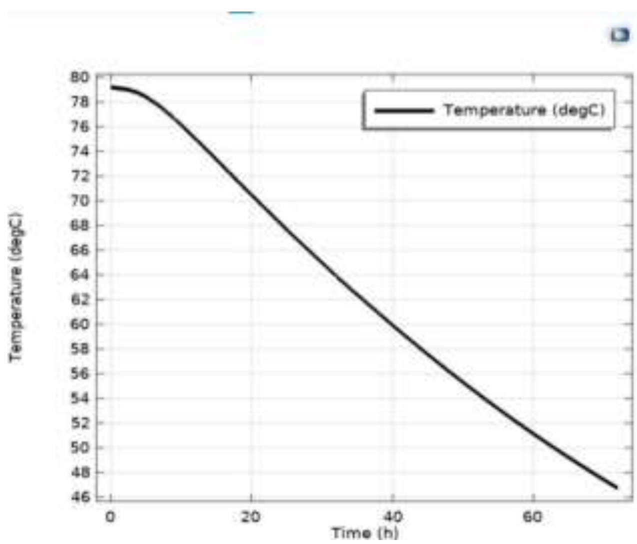

Figure 5. 28 Graphical presentation of water temperature distribution in Tank using wood insulator.

Figure 5. 28 show a Graphical presentation of water temperature distribution in Tank using wood insulator. This graph shows that wood insulations helps maintain heat more than 3 days , the

temperature at first day was 79.8 ^{o}c and at third was at 46.8 ^{o}c. it perform as second insulator to glass wool.

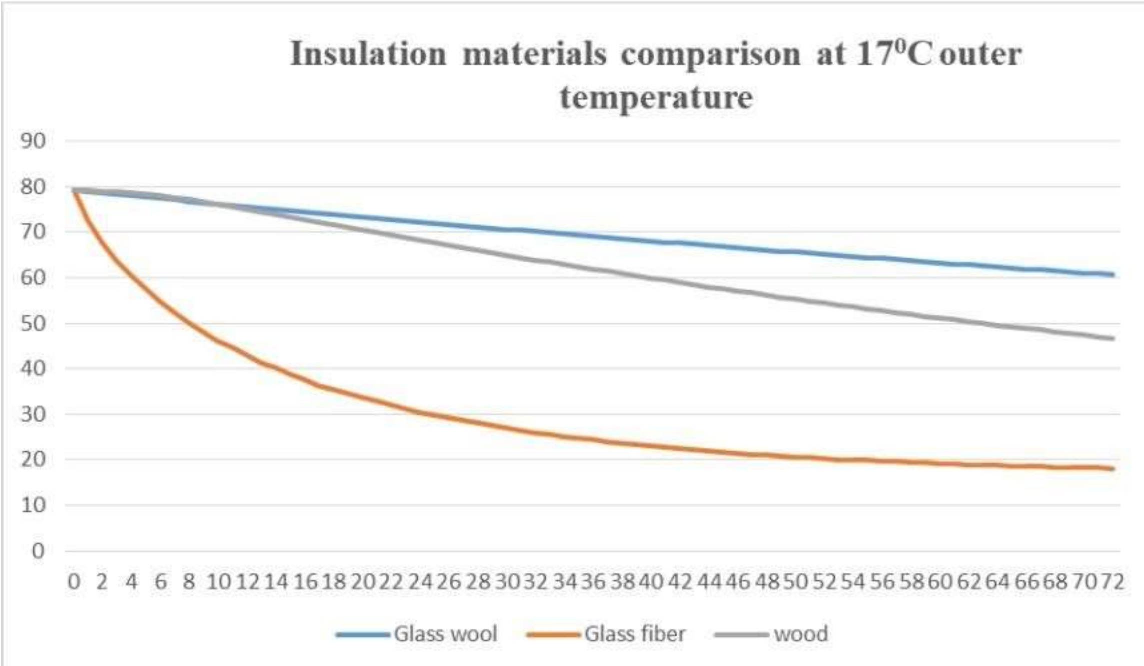

Figure 5.29 Insulation materials comparison at 17 ^{o}c outer temperature

Figure 5. 29 is showing the comparison of performance of insulation material at 17 ^{o}c were fiber glass losses temperature than wood and glass wool insulators. At the external temperature of 17 ° C, the thermal performance of the solar tank varies significantly depending on the insulation materials used, representing a cold area. Fiber Glass Insulation: Fiber Glass Insulation maintained a stable temperature within the tank with minimal heat loss. The same temperature distribution indicates efficient insulation, making it an excellent option for cold climate. Glass Wool Insulation: Glass Wool also performed well at 17 ° C, with similar temperature retention as fiber glass. Its thermal resistance effectively stopped heat loss, ensuring that the water remained warm over time. Wood Insulation: Wood insulation struggled to maintain heat at 17 ° C, which caused significant heat loss. This material is not suitable for cold climate, as it fails to provide adequate thermal protection.

5.6 Thermal performance of solar water heater at 25 o C outer temperature.

5.6.1 Simulation of water Heat Transfer in solar water heat Tank with Fiber Glass insulation

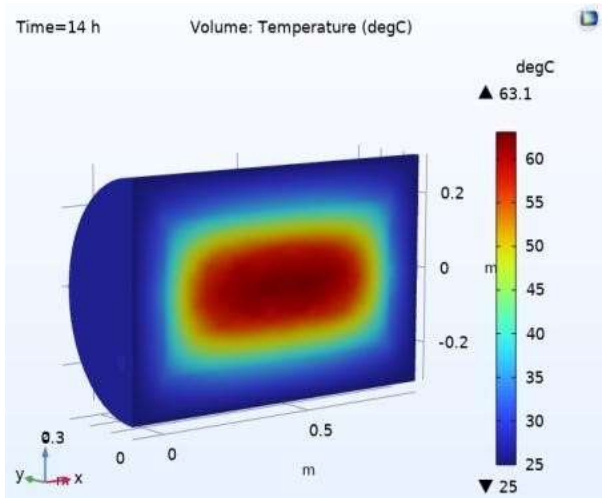

Figure 5.30 fiber glass insulation color map

Figure 5.30 shows that At 25°C, fiber glass insulation loss heat as it have not a stable temperature within the tank, makes it have high heat loss

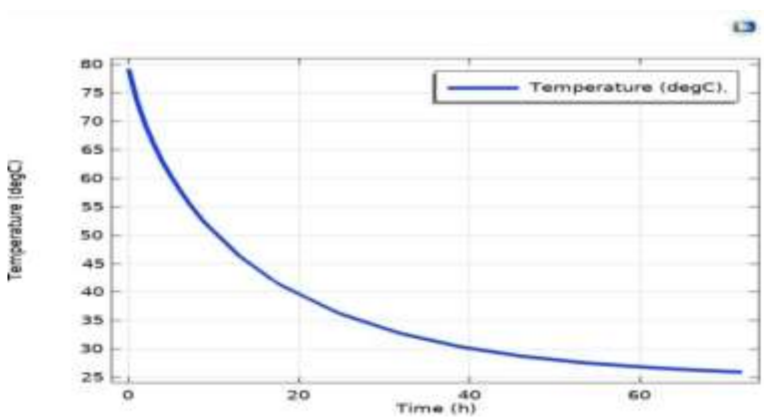

Figure 5.31 fiber glass insulation graphical representation

At 25°C, fiber glass insulation loss heat as it have not a stable temperature within the tank, makes it have high heat loss. Figure 5 31 Graphical presentation of water temperature distribution in Tank using Fiber Glass insulation

5.6.2 Simulation of water Heat Transfer in solar water heat Tank with Glass wool insulation.

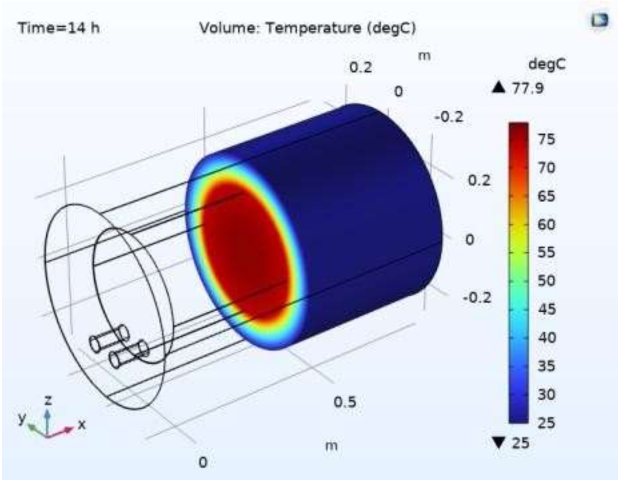

Figure 5.32 glass wool insulations color map

Figure 5. 32 illustrate that glass wool insulations perform better than other kinds of insulation under same conditions.

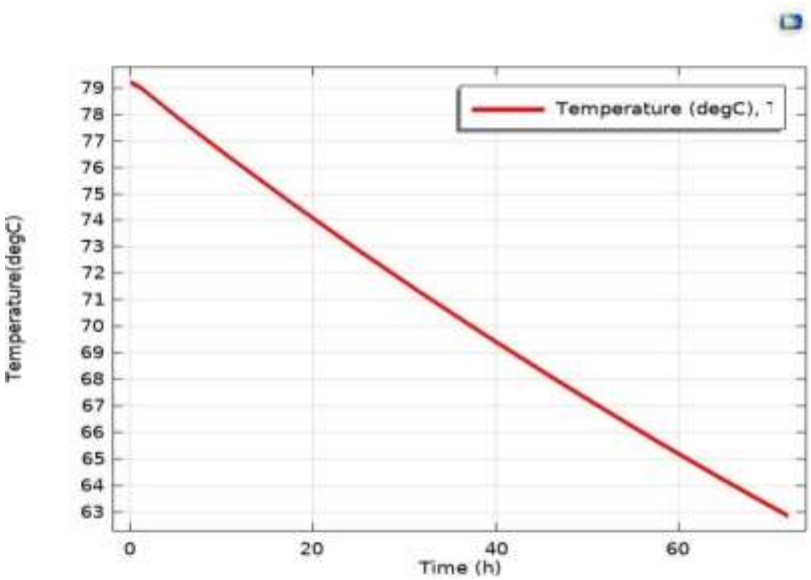

Figure 5.33 Glass wool insulations graphical representation

This Figure shows that glass wool insulations helps maintain heat more than 3 days , the temperature at first day was 79.8 ^{o}c and at third was at 62.8 ^{o}c. Figure 33 Graphical presentation of water temperature distribution in Tank using Glass wool insulation

5.6.3 Simulation of water Heat Transfer in solar water heat Tank with wood insulation

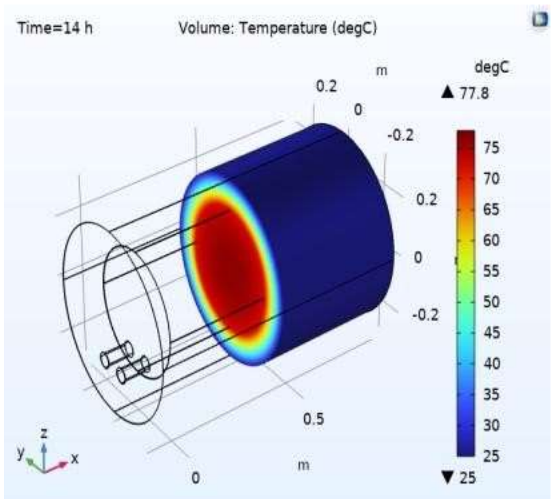

Figure 5.34 wood insulation color map

This figure 5.34 shows that wood insulations helps maintain heat more than 3 days , the temperature at first day was 79.8 ^{o}c and at third was at 51.5 ^{o}c. it perform as second insulator to glass wool.

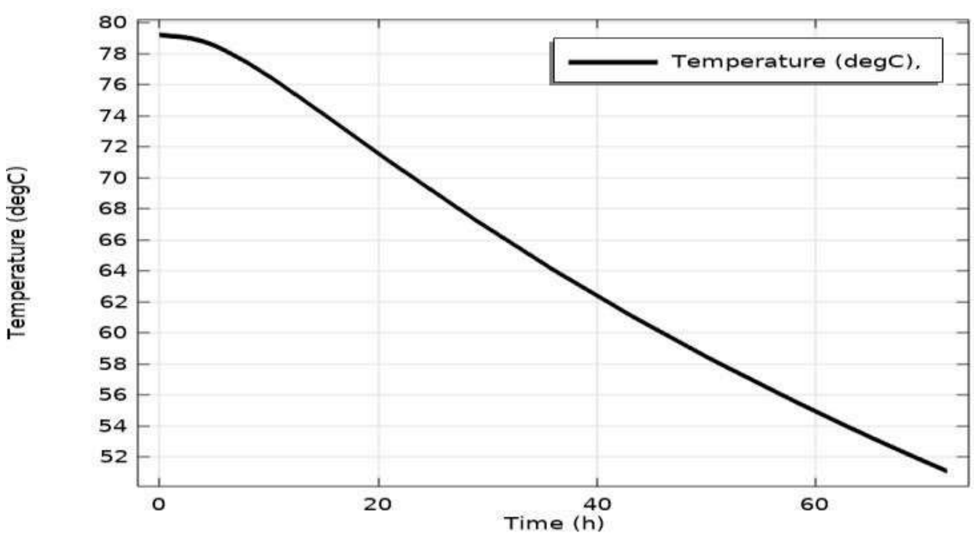

Figure 5.35 presentation of water temperature distribution in Tank using wood insulation

This figure 5.35 shows that wood insulations helps maintain heat more than 3 days , the temperature at first day was 79.8 ^{o}c and at third was at 51.5 ^{o}c. it perform as second insulator to glass wool.

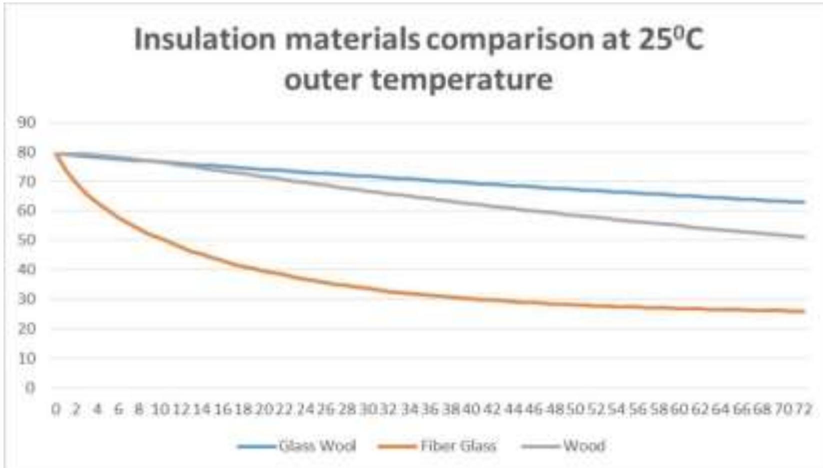

Figure 5.36 insulation materials comparison at 25^{0}c outer temperature

Figure 5.36 graph is showing the comparison of performance of insulation material at 25 ^{o}c were fiber glass losses temperature than wood and glass wool insulators. At an external temperature of 25 ° C, representing a medium region, the performance of insulation materials improved, but the differences between them remained clear. Fiber Glass Insulation: Fiber Glass continued to perform well with efficient heat retention and similar temperature distribution. Its thermal properties make it ideal for moderate climate. Glass Wool Insulation: Glass Wool showed the same performance as fiber glass, which caused a stable temperature and minimum heat loss. This is a viable option for medium climate, especially where cost is a concern. Wood Insulation: Wood insulation performed better at 25 ° C compared to 17 ° C, but it still lagged behind fiber glass and glass wool. Although this may be sufficient in some cases, it is not the most efficient option for medium climate.

5.7. Thermal performance of solar water heater at 30o C outer temperature.

5.7.1 Simulation of water Heat Transfer in solar water heat Tank with Fiber Glass insulation.

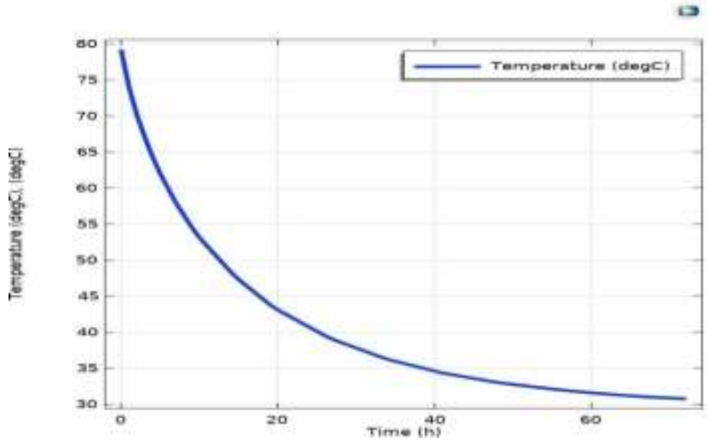

Figure 5.37 graphical representation of Fiber Glass insulation.

This figure5.37 shows that At 30°C, fiber glass insulation loss heat as it have not a stable temperature within the tank, makes it have high heat loss.

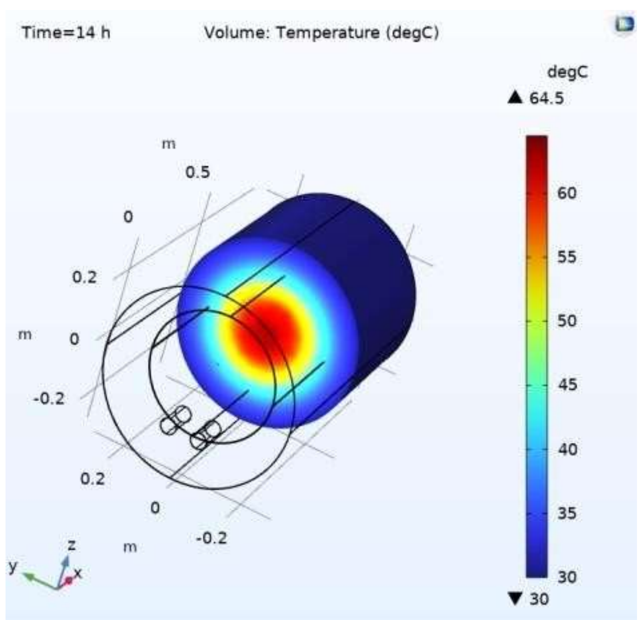

Figure 5. 38 Fiber Glass insulation color map.

The figure 5.38 is a color map showing that At 30°C, fiber glass insulation loss heat as it have not a stable temperature within the tank, makes it have high heat loss.

5.7.2. Simulation of water Heat Transfer in solar water heat Tank with Glass wool insulation.

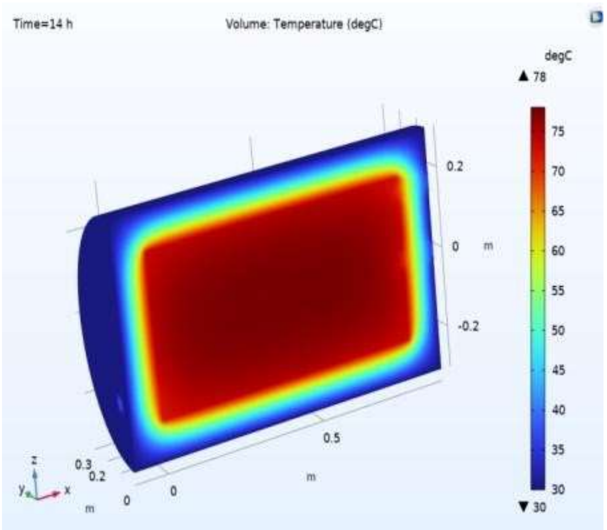

Figure 5.39 Glass wool insulation color map

Figure 5.39 shows that glass wool insulations helps maintain heat more than 3 days , the temperature at first day was 79.8 ^{o}c and at third was at 64.3 ^{o}c.

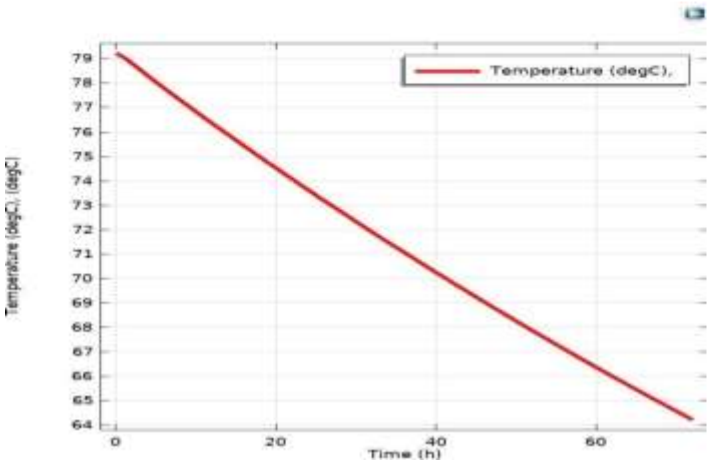

Figure 5.40 graphical representation of Glass wool insulation

This figure 5.40 shows that glass wool insulations helps maintain heat more than 3 days , the temperature at first day was 79.8 ^{o}c and at third was at 64.3 ^{o}c.

5.7.3 Simulation of water Heat Transfer in solar water heat Tank with wood insulation.

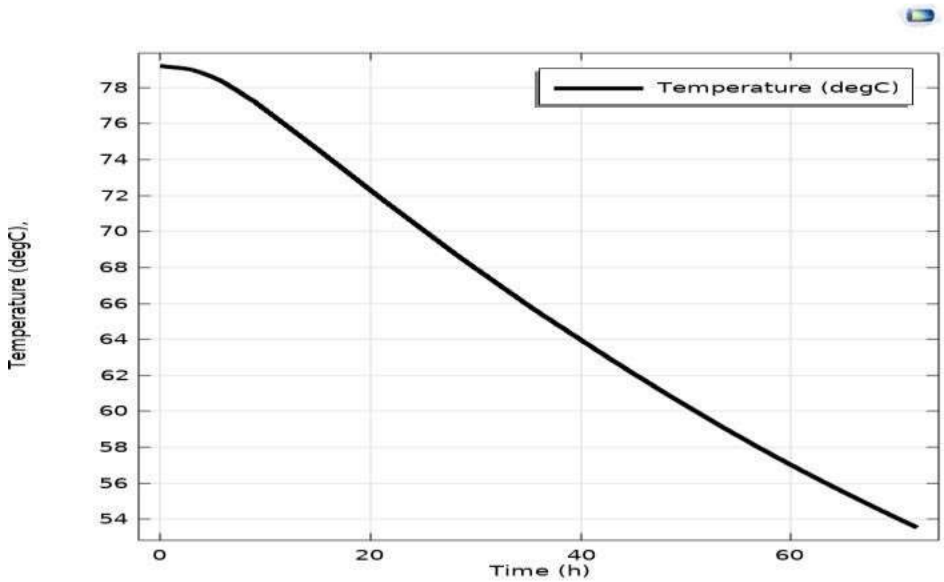

Figure 5.41 wood insulations graphical representation

Figure 5.41 shows that wood insulations helps maintain heat more than 3 days , the temperature at first day was 79.8 ^{o}c and at third was at 53.8 ^{o}c. it perform as second insulator to glass wool.

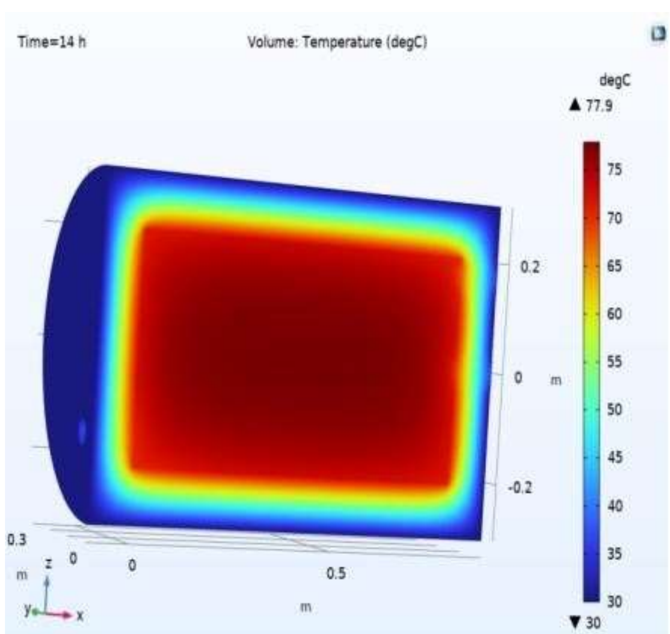

Figure 5.42 wood insulations color map

Figure 5.41 shows that wood insulations helps maintain heat more than 3 days , the temperature at first day was 79.8 ^{o}c and at third was at 53.8 ^{o}c. it perform as second insulator to glass wool.

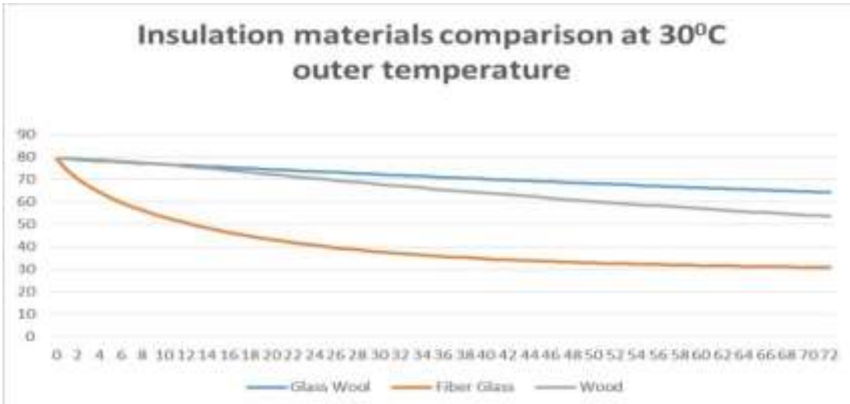

Figure 5.43 Insulation materials comparison at 30 ^{o}c outer temperature

Figure 5.43 this graph is showing the comparison of performance of insulation material at 30 ^{o}c were fiber glass losses temperature than wood and glass wool insulators.

Results show that thermal performance of the solar water heater is highly dependent on the insulation materials used, water flow rate and external temperature. Wood and glass wool insulators provide the best heat retention, while fiber glass is less effective. Simulation also highlights the importance of customizing water flow rates to balance temperature increase and practical water availability. These findings are particularly relevant to the changing climate, where solar water heaters can play an important role in providing permanent hot water solutions.

At an external temperature of 30 ° C, the thermal performance of the insulation material was further enhanced, representing a warm area, but remained relative differences between them. Fiber Glass Insulation: Fiber Glass Insulation maintained high temperatures within the tank with minimal heat loss. Its better thermal properties make it the best option for warm climate. Glass wool also performed well at 30 ° C, with stable temperatures and efficient heat retention. It is a cost -effective option for warm climate. Wood insulation showed better performance at 30 ° C, but it can still not match the efficiency of fiber glass or glass wool. Its use in hot climate is limited by its lower thermal resistance.

Chapter 6: Conclusion

6.1 Limitations

While this study provides valuable insight into the thermal performance of the solar water heater under the changing climate, it is important to accept its boundaries:

1. Simplified beliefs: simulations were based on ideal conditions, such as similar solar radiation and constant water flow rate. The real-world situation may vary due to factors such as cloud cover, seasonal change and water pressure fluctuations.
2. Limited insulation material: Only three insulation materials (wood, glass wool, and glass fibers) were evaluated. Other materials, such as polyurethane foam or aircraft, may offer better performance, but were not involved in this study.
3. Climate variability: Simulation focused on three specific external temperatures (17 ° C, 25 ° C, and 30 ° C) to represent cold, medium and warm areas. However, Rwanda may vary greatly within the climatic regions, and the results cannot catch these variations completely.
4. Economic and Social Factors: The study did not consider the economic viability or social acceptance of various insulation materials and system designs. Cost, availability and cultural priorities can affect the adoption of solar water heaters in Rwanda.
5. Long -term durability: Simulation focuses on short -term thermal performance. Long term durability, maintenance requirements and erosion of insulation materials were not addressed.

6.2 Summary of Findings

The study achieved its objectives by simulating the thermal performance of a solar water heater under various operating conditions and insulation materials. Major findings have been summarized:

1. Solar Collector Performance:

- ❖ The water flow rate greatly affects the thermal performance of the solar collector. The flow rate of 0.02 kg/s provides a good balance between the increase in temperature and the availability of water, making it suitable for domestic use.

- ❖ Insulation materials play an important role in heat retention. Glass fiber and glass wool insulation perform better than wood, with glass fiber best offers thermal performance.

2. Solar Tank Performance:

- ❖ Thermal performance of the solar tank varies with external temperature and insulation materials. Fiber glass and glass wool insulation maintained a stable temperature in all tested conditions (17 ° C, 25 ° C and 30 ° C), while wood insulation struggled to maintain heat, especially in cold climate.
- ❖ Placement of outlet pipes in the solar tank is important to ensure easy access to hot water. Hot water, being less dense, rises at the top, while the cold water sinks to the bottom.

3. Regional Adaptations:

- ❖ In cold areas (17 ° C), fiber glass or glass wool insulation is necessary to reduce heat loss.
- ❖ In moderate (25 ° C) and warm (30 ° C) areas, these materials continue to perform well, but costs can be considered in warm areas if the cost is a significant obstruction.

6.3 Policy Recommendations

Based on the findings of this study, the following policy recommendations are proposed to adopt a solar water heater in Rwanda and promote adaptation:

1. Promote High-Performance Insulation Materials:

Government and industry stakeholders should encourage the use of high-demonstration insulation materials such as glass fiber and glass wool in solar water heating systems. These materials provide better thermal efficiency and can significantly improve the performance of the system.

2. Subsidies and Incentives:

To make the solar water heater more accessible, the government can provide subsidy or tax incentives for homes and businesses investing in high efficiency systems. This will help offset high early costs of materials such as glass fiber.

3. Public Awareness Campaign:

Public awareness campaigns should be organized to educate citizens about the benefits of solar water heater, including energy savings, environmental stability and better quality of life.

4. Standard and Rules:

The government should set up standards and rules for the design and installation of solar water heaters to ensure optimal performance and safety. This includes guidelines for insulation materials, water flow rates and tank design.

-5. Regional Adaptation:

Policies should take into account regional climate variations. For example, in cold areas, additional assistance can be provided for the installation of high-demonstration insulation materials to reduce heat loss.

6.4 Future Research

To build the findings of this study, the following sectors are recommended for future research:

1. Economic viability analysis:

Future studies should evaluate the economic viability of various insulation materials and system designs, considering factors such as initial costs, maintenance and long -term savings.

2. Long -term durability and maintenance:

In particular, in the climate, the long -term durability and maintenance requirements of the solar water heater require research to assess the requirements. This involves studying the erosion of insulation material over time.

3. Integration with Renewable Energy Systems:

- Future work can detect integration of solar water heaters with other renewable energy systems, such as photovoltaic panels or wind turbines, to create hybrid energy solutions.

4. impact of Seasonal Variations:

- The effect of solar radiation and seasonal variations in temperature should be examined on the performance of solar water heaters. This will provide a more comprehensive understanding of the performance of the system throughout the year.

5. Social and Cultural Factors:

- Research should examine social and cultural factors that affect the adoption of solar water heaters in Rwanda. This involves studying user preferences, perceptions and adoption obstacles.

6. Advanced Simulation Techniques:

- Future studies can employ more elaborate and realistic performance data to capture more advanced simulation techniques such as transient analysis or computational fluid mobility (CFD).

6.5 Final Remarks

This study has demonstrated the capacity of solar water heaters to provide sustainable and efficient warm water solutions in Rwanda. By optimization of water flow rates and selecting proper insulation materials, thermal performance of these systems can be greatly improved. Conclusions provide a foundation for the design and implementation of the solar water heater in Rwanda, with a significant implication for energy stability, environmental protection and economic development. Future research and policy initiatives should be constructed on these conclusions to ensure widely adopting and successful solar water heating systems.

References

[1] M. Azzouzi and U.- Asia, “Control of solar water heater design,” 2011.

[2] H. M. Dbouk, R. A. Ali, M. Ghamlouch, and I. H. Elhajj, “Temperature Control for Residential Solar Water Heating Systems,” IEEE EUROCON 2019 -18th Int. Conf. Smart Technol., pp. 1–6, 2019.

[3] E. H. Achouyab, “Design , I mplementation and T esting of a S olar W ater H eater G lazed F lat P late D etector,” no. 5, pp. 9–11, 2015.

[4] Z. Chuancheng and L. Haijun, “The thermal insulation properties for wall material with various water contents,” pp. 5–7, 2010, doi: 10.1109/ICICTA.2010.414.

[5] M. Edwin, U. Arunachalam, R. Rakesh, M. S. Srinivas, and A. Santhanakumar, “Performance Analysis of Spiral tube solar water heater using concrete / sand absorbers for domestic use,” pp. 1–5, 2016.

[6] N. A. Badhan and F. M. Ela, “Evacuated Tube Solar Water Heater,” pp. 3–6.

[7] E. Nshimyumuremyi and W. Junqi, “Thermal efficiency and cost analysis of solar water heater made in Rwanda,” 2018, doi: 10.1177/0144598718815240.

[8] T. Urmee, E. Walker, P. A. Bahri, G. Baverstock, S. Rezvani, and W. Saman, “Solar water heaters uptake in Australia – Issues and barriers,” Sustain. Energy Technol. Assessments, vol. 30, no. August, pp. 11–23, 2018, doi: 10.1016/j.seta.2018.08.006.

[9] R. L. Shrivastava, V. Kumar, and S. P. Untawale, “Modeling and simulation of solar water heater: A TRNSYS perspective,” Renew. Sustain. Energy Rev., vol. 67, pp. 126–143, 2017, doi: 10.1016/j.rser.2016.09.005.

[10] K. Yaman and G. Arslan, “Modeling, simulation, and optimization of a solar water heating system in different climate regions,” J. Renew. Sustain. Energy, vol. 10, no. 2, 2018, doi: 10.1063/1.5004069.

[11] V. Madadi Avargani, B. Norton, A. Rahimi, and H. Karimi, “Integrating paraffin phase change material in the storage tank of a solar water heater to maintain a consistent hot water output temperature,” Sustain. Energy Technol. Assessments, vol. 47, no. December 2020, p. 101350, 2021, doi: 10.1016/j.seta.2021.101350.

[12] F. Eze, M. Egbo, U. J. Anuta, O.-B. R. Ntiriwaa, J. Ogola, and J. Mwabora, “A review on solar water heating technology: Impacts of parameters and techno-economic studies,” Bull. Natl.

Res. Cent., vol. 48, no. 1, pp. 1–22, 2024, doi: 10.1186/s42269-024-01187-1.