INVESTIGATION ON THE EFFECT OF PCM LAYER THICKNESS IN DOUBLE GLAZED WINDOWS

A PROJECT REPORT

Submitted by

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REG. No: TKM21MEIR03

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in partial fulfilment of the requirements for the award of Degree

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in

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Specialization : ***Industrial Refrigeration and Cryogenic Engineering***

DEPARTMENT OF MECHANICAL ENGINEERING

T K M College of Engineering, Kollam

MAY 2023

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CERTIFICATE

This is to certify that the project report entitled **"INVESTIGATION ON THE EFFECTOF PCM LAYER THICKNESS IN DOUBLE GLAZED WINDOWS"** submitted by **AROMAL S SUDHARSANAN.**, Reg. No: **TKM21MEIR03** during **2021-2023** to the APJ Abdul Kalam Technological University in partial fulfilment of the requirements for the award of the Degree of Master of Technology in Industrial Refrigeration and Cryogenics Engineering, Department of Mechanical Engineering is a bonafide record of the project work caried out by him under our guidance and supervision.

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DECLARATION

I **Aromal S Sudharsanan,** hereby declare that this project report entitled **"INVESTIGATION ON THE EFFECTOF PCM LAYER THICKNESS IN DOUBLE GLAZED WINDOWS".** submitted for partial fulfilment of the requirements for the award of degree of Master of Technology of the APJ Abdul Kalam Technological University is a bonafide work done by me under the supervision of **Dr. K.A Shafi,** Professor, TKM College of Engineering Kollam. This submission represents my ideas in my own words and where ideas or words of others have been included. I have adequately and accurately cited and referenced the original sources. I also declare that I have adhered to ethics of academic honesty and integrity and have not misrepresented or fabricated any data or idea or fact or source in my submission. I understand that any violation of the above will be a cause for disciplinary action by the institute and/or the University and can also evoke penal action from the sources which have thus not been properly cited or from whom proper permission has not been obtained. This report has not been previously formed the basis for the award of any degree, diploma or similar title of any other university.

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ABSTRACT

Green building design is gaining popularity due to the environmental impact of today's energy sources, which rely heavily on fossil fuels. The construction and industrial facilities sector accounts for up to 40% of worldwide energy demand. Heating, ventilation, and air conditioning (HVAC) systems are responsible for more than 60% of overall energy usage in buildings, with glass windows being the primary source of heat load. Windows cannot be avoided in a structure, as they are an essential aspect of a building for obtaining natural light. This study investigates the effect of phase transition or melting temperatures of phase change materials (PCMs) when used in double-glazed windows and their impact on heat and light transfer characteristics, using experimental and numerical methods. The PCMs used for this study are OM42 and OM 50. PCMs acts as latent heat storage units and reduce the heat in leak to the inner space. The objective of this study is to limit the amount of heat transfer through the glass provided in windows. The developed experimental setup is having the provision to change the glass thickness and to fill different PCM's. Experiments were conducted by varying PCM layer thickness to determine the glazing's inner and outer surfaces temperatures in a controlled environment. ANSYS FLUENT software was used to conduct the numerical analysis and the results obtained were compared with the experimental results for validation. The main property taken for the study is the phase transition temperature of the PCM. In this study it is observed that the heat transfer through the window to the room is mitigated by PCM through its phase change, which in turn leads to the decrease in room temperature. Since the solidification of the liquid PCM happens slowly, the glazing's ability to transmit light is unaffected. This can be achieved by properly fixing the thickness of PCM. It is also observed that, the glass thickness is having significant effect on the performance of PCM's. This study explores the potential of PCM that can be used as a filler material for double-glazed windows to reduce the fluctuations of room temperature thereby increasing the comfort.

Keywords: Latent heat storage, Green building, PCM, Double glazed window, HVAC, Organic Material.

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ABBREVATIONS

CFD	Computational fluid dynamics
FDM	Finite Difference Method
FEM	Finite Element Method
FVM	Finite Volume Method
HVAC	Heating, ventilation, and air conditioning
OM	Organic material
PCM	Phase change material
TC	Thermo-Couple

CHAPTER 1

INTRODUCTION

Urbanisation in modern times is expanding quickly, which calls for infrastructure and construction development. With this development, energy consumption is rising as well. Buildings consume a substantial part of the energy in the globe, primarily through their HVAC systems. People, electrical equipment, and penetration through building materials like walls and windows are all parts of the HVAC systems' cooling or heating load. Due to its high susceptibility to heat transfer, windows or glazing contribute significantly to the HVAC load. However, windows are a crucial and unavoidable component of a building because they serve a variety of purposes, including letting in light, providing ventilation, and providing an aesthetically pleasing, visual link between the inside and outside worlds. The current methods of energy reduction through windows include metal coated glazing, double glazing, etc. However, in terms of energy economics, these alternatives are not entirely viable. By replacing standard windows with double-glazed ones that are filled with phase change material (PCM), a significant reduction in energy consumption can be achieved. When heat enters through a window from the outside, PCM absorbs it and holds it there until the phase transition has used all of the heat.

1.1 BACKGROUND

It is possible to save a lot of energy by switching to double-glazed windows with phase change material (PCM) loaded instead of standard windows. When heat enters through the window from the outside, PCM absorb it and won't let it out until the heat has been completely used for the phase transition.

1.2 PCM AND ITS CLASSIFICATIONS

A phase change material (PCM) is a substance which can absorb or discharge thermal energy to move from one state to another. PCM in the solid state absorbs energy and transforms into a liquid, whereas PCM in the liquid state releases heat and transforms back into a solid. Because this process occurs at a steady temperature, the latent heat is absorbed or released. In general, latent heat is substantially higher than perceptible heat. Ice, for example, takes 335 J/g to melt, whereas water only takes 4.18 J/g to raise its temperature by one degree. As a result, PCM can be employed as a heat storage material for both heating and cooling. Fig.1.1 depicts various PCM classifications.

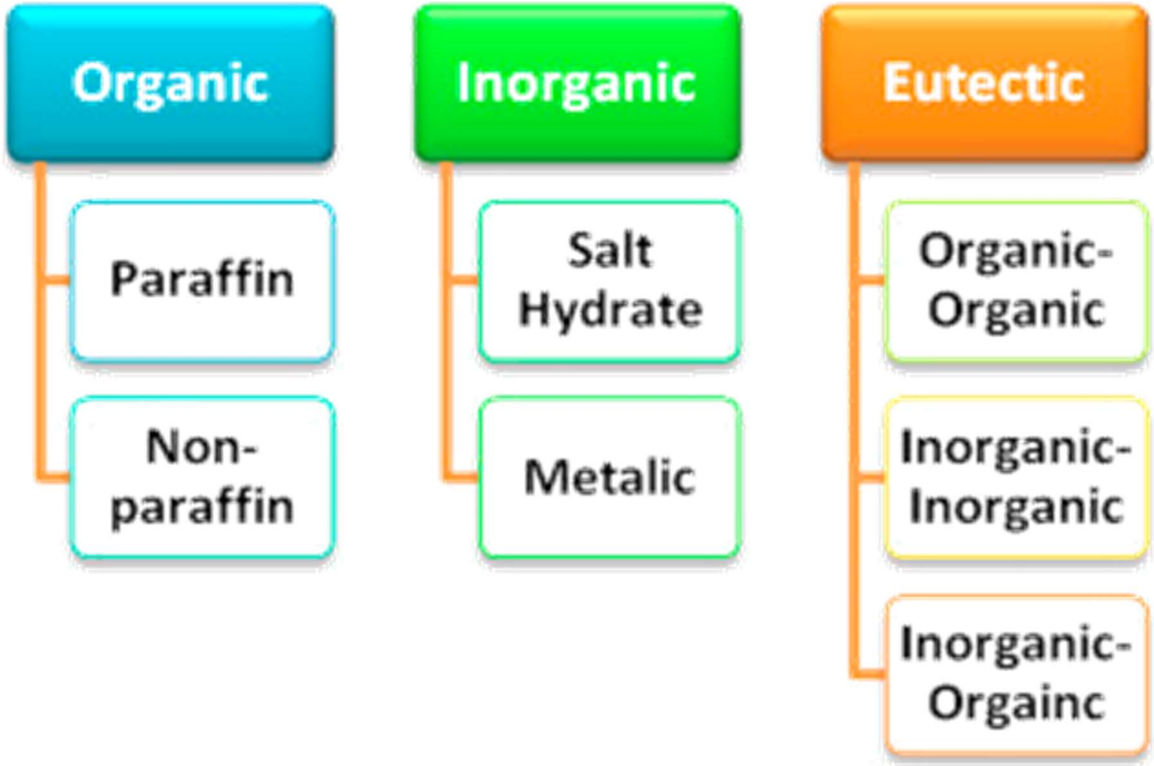


Fig.1.1 PCM classifications

1.1.1 Organic PCM:

Organic PCM includes paraffins and non-paraffins, for instance. They are inert both chemically and thermally. In general, organic PCMs have poor heat conductivity. They have little to no subcooling. Subcooling happens when a substance melts in one area while hardening in another, causing the effect to be unevenly spread. They are not corrosive in any way. Glycols, various non-paraffinic materials, including fatty acids and their esters are used as PCMs.

1.1.2 Inorganic PCM:

Inorganic PCMs consist of hydrated salts and metallic PCMs. Metallic materials are unsuitable for building applications because they do not operate within the acceptable temperature range and are excessively heavy. Natural salts are mixed with water to make a hydrated salt solution. To achieve the required temperature for phase change, the chemical makeup of the salts in the mixture is altered. 'Subcooling of inorganic PCMs complicates their application. High latent heat of fusion per unit volume, better thermal conductivity when compared to organic PCMs, less volume change, and convenient availability at a lower cost are all desirable properties of salt hydrates used as PCMs.

1.1.3 Eutectic PCM:

A eutectic system is a chemical combination. It solidifies at a lower temperature than any other composition containing the same constituents. The temperature at which it solidifies indicates the eutectic composition. Eutectics allows for the combination of organic-organic, organic-inorganic, and inorganic-inorganic substances. They melt and freeze without segregation because they freeze to a crystal mixture, which prevents the constituents from segregating. When both components are heated, they liquefy at the same moment. The ability of eutectic blends to produce certain qualities, such as a precise melting point or a better heat storage capacity per unit volume, is one advantage.

1.3 PROBLEM FORMULATION

The global expansion of energy thinking produces research to develop sustainable energy solutions. Because more people use cooling systems and air conditioning in general during the summer, there are higher summertime electricity peak needs. The need for safe, pollution-free refrigerants and economical energy is critical, as is the high cost of fossil fuels, environmental concerns, and environmental difficulties. Using PCM in between double-glazed windows can help to limit interior heat gain during the day.

1.4 THESIS OUTLINE

This thesis involves the experimental and numerical analysis on the effect of different PCMs filled between double glazed windows. This thesis is alienated in nine units.

- Chapter 1 Introduces the project topic and background.
- Chapter 2 Reviews recent development in PCM filled windows
- Chapter 3 Gives a brief introduction to Computational fluid dynamics
- Chapter 4 Presents the proposed experimental investigation.
- Chapter 5 Includes the experimental results.
- Chapter 6 The chapter deals with numerical analysis.
- Chapter 7 Presents the results of numerical analysis.
- Chapter 8 Discuss the comparison between Numerical and experimental results.
- Chapter 9 Summarizes the findings of the work.

CHAPTER 2

LITERATURE REVIEW

PCM materials can be used as an environmentally acceptable solution to lessen a building's interior heat load. However, studies on the thermal properties of the PCM material are required to determine its efficiency and effectiveness. This chapter highlights the findings of extensive study into the performance and impact of various PCMs in double-glazed windows.

2.1 STUDIES ON THE EFFECT OF PCM IN DOUBLE GLAZED WINDOWS

The recent developments in the field of PCM filled windows have been presented here in this section.

Ismail et al. (2008) compared PCM glass windows filled with gas-absorbent windows using statistical analysis. “A simple and effective radiation one-sided design is used to mimic a double-glazed window filled with PCM.” All heat gain coefficients are compared, and window heat transfer is determined electronically. A high-absorption gas mixture, a moderate gas absorption mixture, and a visible infrared radiation mixture were all used. The thermal conductivity of a double-glazed window filled with a suction gas mixture and using transparent glass ranges from 0.55 to 0.65. A double-glazed PCM-filled window has a thermal gain of 0.65 to 0.80.

Gasparella et al. (2011) investigated the effects of various polishing systems (double glazing), “size of windows (from 16 to 41 percent of the floor area covered by windows), the shape of a large window facade, and the internal benefits of winter and summer energy needs and loads at a high level of a well-installed residential building. For their climatic data, four regions in central and southern Europe were considered: Paris, Milan, Nice, and Rome. The data was statistically analysed to identify the most influential features. Thermal transport is crucial in both winter and summer settings, according to reversal research. Solar transmission appears to be the most critical for both summer loads as well as winter and summer energy needs. It is critical to advise preliminary preparation, for solar exposure, geometry,and solar and thermal structures of the glossy system’’.

According to Jian Qu et al. (2014), “single layer, waterborne, silicon-based, transparent heat insulation coatings were created for the fabrication of energy-efficient glazing items. The optical, thermal, and electrical properties of the coatings were examined. The new data can lead to the following conclusions: High surface resistivity, low haze, low far-infrared emissivity, high absorptance (low transmittance) in the near-infrared spectrum, and high visible light transmittance are all characteristics of the coatings. The haze of transparent heat insulation coatings was not affected by ATO concentration or coating thickness. It is thought that the ability of transparent heat insulation coatings to absorb near infrared light is what causes their thermal insulation effect. The surface resistance of the developed transparent heat insulation coatings is 11 orders of magnitude greater. The silicon emulsion provides the clear thermal insulation coatings with good artificially accelerated weathering resistance and high radio wave transmission, which decreases as ATO content and coating thickness increase’’.

Shuhong Li et al. (2014), “ In order to determine the effects of the phase change material filled glass window (PCMW) on building energy consumption in the hot summer and cold winter area of China, dynamic heat transfer process and heat transfer parameters of the PCMW and the hollow glass window (HW) exposed to different non-steady boundary conditions related to the climatic characteristic were investigated. The experiments and the numerical simulations in a representative sunny summer day were conducted, and the results were in good agreement. Then the validated numerical model was used to simulate the dynamic heat transfer processes of the two kinds of windows at more different weathers, the temperature and heat flux fluctuations on the interior surfaces were analyzed based on simulation results. It was concluded that in the representative sunny summer day, the peak temperature on the interior surface of the PCMW reduced by 10.2 °C, and the heat entered the building through the PCMW reduced by 39.5%, comparing with the HW. However, in the other representative days, the dynamic thermal performance of the PCMW was unsatisfactory as it cannot decrease the building energy consumption. The annual energy consumption of the air conditioning system and the heating system because of the heat transferred though the PCMW decreased 40.6% comparing with the HW applied”.

According to Rouhollah Ahmadi and Amir Shahcheraghian's (2015) research, phase change materials are a sort of substance that can be melted to achieve high latent heat capacity. By employing PCM in windows as a heating store, an attempt was made here to slow down the dispersion of heat flux into the structure. Heat flux diffusion via two distinct types of windows on a hot day in Tehran, Iran, was investigated in this study. Types I and II windows are composed of two layers of glass, one of which is filled with PCM. Heat flux diffusion into the room increases monotonically during the day, reaching 97 percent of the applied heat flux after 6 hours in type I. Type II, on the other hand, has been demonstrated to absorb the majority of the heat flow and keep it from diffusing into the room. According to Fluent's numerical simulation, PCM holds 86 percent of the external heat flux into the window for 9 hours in type II windows. As a result, using PCM in windows can generate a great thermal barrier for a building's windows in the summer.

According to Siddharth Lohia and Swati Dixit (2015) double glazed windows with an uPVC frame are ideal for Indian buildings and homes. However, it differs from triple-glazed windows in a few ways. But given the climate in India, it is the wisest and most cost-effective option. These kinds of high performance windows are used in India in places like the ITC Green Center in Gurgaon, the Wipro Technologies Center in Gurgaon, the Olympia Technological Park in Chennai, and many more to help reduce energy consumption and protect the environment.

Lechowska (2016)“Examples of reversed glazing have been examined using downward heat flow. In the Ansys Fluent CFD programme, a numerical 3D model of the glazing atvarious angles has been created. The modelling results were contrasted with measurements taken in a calorimetric chamber on a test stand set up to look at heat transfer through glazing at various angles. Assuming that the models produce accurateresults, additional CFD calculations were carried out for other glazing examples (4-16-4argon/air, 4-13-4 air, and 4-13- 4 argon/air). The calculation and measurement findingsfor the chosen glazing (4-16-4 with air filling) demonstrated satisfactory agreement. Afew changes to the EN 673 and ISO 15099 standards have been suggested after the setof findings for four glazing samples under various angles were obtained. The modifications apply to Rayleigh numbers Ra 104 and the computation of gas gap Nusselt numbers for glazing angles between 90° and 180° (horizontal glazing, upper heated side)”.

Hussein et al. (2016) conducted “a numerical analysis on the thermal performance of a PCM filled double glazing unit with various PCM thermo-physical characteristics" in North-East China. With the purpose of researching the thermal behaviour of a PCM-filled double-glazing unit, the impacts of density, specific heat capacity, latent heat, thermal conductivity, and PCM melting temperature were also explored. Solar transmittance of double-glazed units is quite low when the density of PCM is greater than 1275 kg/m3. Temperature lag increases as PCM density increases, time range of liquid PCM decreases, and melting time is postponed. The impact of PCM density on temperature drop is negligible. The effect of PCM density on temperature decrease is minor. When PCM has a thermal conductivity of more than 2.1 W/m K, increasing the thermal conductivity of the material is useless for improving the thermal performance of double-glazed units filled with PCM. The temperature time lag and time range of liquid PCM increase as the thermal conductivity of PCM exceeds 2.1 W/m K, but the temperature decrement decreases. When the thermal conductivity of PCM exceeds 2.1 W/m K, the effect of the thermal conductivity of PCM is reduced. When the specific heat capacity of PCM is less than 4460 J/kg K, increasing the specific heat capacity of PCM is ineffective in improving the thermal performance of PCM-filled double-glazed units. The temperature lag grows, the temperature gradient decreases, and the initial melting time decreases. To improve the thermal performance of double-glazed units filled with PCM, increasing the thermal conductivity of the material is ineffective when PCMhas a thermal conductivity of more than 2.1 W/m K When the thermal conductivity of PCM exceeds 2.1 W/m K, the temperature time lag and time range of liquid PCM rise,while the temperature decrement decreases. When the specific heatcapacity of PCM is less than 4460 J/kg K, increasing the specific heat capacity of PCMis not an effective way to improve the thermal performance of double-glazed units filled with PCM. The time lag in temperature increases, the temperature gradient lowers, theinitial melting time is delayed, and the time range of liquid PCM changes slightly as thespecific heat capacity of PCM increases. When the latent heat of PCM is less than 410 kJ/kg, increasing the latent heat is an effective way to improve the thermal performanceof double-glazed units filled with PCM. The time lag in temperature increases as the latent heat of PCM increases, and the temperature decrement decreases. The initial melting time of PCM is delayed as the latent heat of PCM increases, and the time rangeof liquid PCM is decreased; however, when the latent heat of PCM exceeds 1025 kJ/kg,the PCM does not melt in the working temperature range. Controlling the melting temperature of PCM is an efficient way to optimise the thermal performance of double-glazed units filled with the material, and it should be matched not only with the indoorand outdoor temperatures, but also with the solar transmittance of the units. The temperature decrement increases as the melting temperature of PCM rises. The impact of PCM melting temperature on temperature time lag is not consistent. The initial melting time of PCM is delayed as the melting temperature rises, and the temperature range of liquid PCM narrows. PCM 297–299 K has a melting temperature close to China's climatic conditions”.

Zheng et al. (2016) explored the thermal performance of a “PCM-filled double glazing unit with varied phase change material optical features using a mathematical model. The temperature of the interior surface of a double-glazed unit filled with PCM is very little impacted by the refractive index of the liquid and solid PCM, whereas the transmitted energy of the interior surface of a double-glazed unit filled with PCM is significantly impacted. As PCM's refractive index rises, both the overall transmitted energy and the solar energy of its inner surface in double glazing units decrease’’.

A numerical research for PCM-filled glass windows in hot summer and cold winter circumstances was conducted by Zhong et al. (2016). In this investigation, Na2SO4.10H2O and CaCl2.6H2O were used as PCMs. In this study, the thermal efficiency of insulated glass windows—double glass windows that have been sealed with sealing strips and filled with dry air—was compared to that of PCM-filled glass windows. A 3D unsteady model was made in FLUENT to capture the internal and external surface temperature fluctuations of these windows over the course of 48 hours. On overcast and rainy summer days, the phase transition process of CaCl2.6H2O takes 6 to 30 hours. The internal surface temperature of double glass windows filled with Na2SO4.10H2O was higher than that of insulated glass windows for the bulk of the operation due to its higher melting temperature. The temperature of the inside surface of the windows controls how much heat enters the space. Na2SO4.10H2O-filled double glass windows had a worse thermal performance. Thermal performance deteriorated within a certain time period of the entire process as internal and external surface temperatures changed. The temperature of the internal and external surfaces was maintained within the melting temperature range for the 10 to 25 hours that Na2SO4.10H2O was melting. Double glass windows filled with Na2SO4.10H2O altered smoothly in internal and external surface temperatures over the course of 48 hours, and they functioned better. Due to CaCl2.6H2O and Na2SO4.10H2O's phase change temperatures being higher than the surrounding temperature, there was no phase change in these PCM during the winter. Sensible heat was employed during the day to heat the PCM and release it at night. Daytime room heat gain caused by solar radiation from the window was minimised and the heating load was increased by double glass windows filled with PCM.

Phase-changing materials' commercialisation, toxicity, health risks, and energy storage were all examined by Chandel et al. (2017).The features and potential uses of various PCMs are discussed in this paper. Three categories of PCMs are defined: eutectic, inorganic, and organic. The study came to the conclusion that salt hydrates are safe when handled properly, unlike commercial grade paraffins, which are flammable and emit toxic fumes, and should only be used with extreme caution. Examining the commercial viability of PCM goods, this article demonstrates how these materials can be used for textiles, heat- or cold-storage during transportation, pain relief packs, vaccine and blood storage, as well as other scenarios where maintaining a particular temperature is crucial. Good PCMs should have the following qualities: a melting point within the appropriate working temperature range, high latent heat capacity, high specific heat, chemical stability, high thermal conductivity, non-toxicity, and non-flammability.

In an experimental study, Durakovic et al. (2017) investigated the performance of double-glazed windows filled with PCM and water. The PCM utilised in this experiment was Rubitherm RT 27.Air, water, and PCM were employed as filler materials in double glazing in a number of investigations. Without PCM glazing, there was about a 5oC difference in temperature between the interior and outside glass surfaces at peak temperature. The peak As a consequence, it was found that the inner glass surface experienced temperature oscillations of around 5°C, whereas the outside glass surface experienced extreme temperature changes of about 11°C.Because air has a low specific heat capacity, very little heat builds up in the space between the glazing. It takes an hour for a temperature change to be reflected on the interior glass surface when the outside air falls below room temperature. Due to water's significantly higher thermal conductivity, water filled glazing had the biggest temperature difference between the outer and inner glass surfaces at about 2°C. When compared to air-filledglazing, the outside glass surface temperature variance was around 2°C lower, but the inside glass surface temperature variation was about 4°C higher. Due to the water's somewhat larger specific heat capacity and ability to absorb heat,the exterior glazing's temperature was lowered by two degrees.

“The variance in the temperature of the internal glazing is compounded by the water's substantially stronger heat conductivity. Water is therefore an undesirable medium for storing energy between the glazings since the temperature change on the internal glass surface is more sensitive to the outside temperature change. It was discovered that the PCM filled glazing system significantly reduced temperature changes on the interior and exterior glass surfaces. Temperature fluctuations on the external and interior glass surfaces were found to be substantially lower with the PCM filled glazing system. By keeping the inner glass surface temperature lower, the heat is absorbed by the PCM as latent heat. By giving the longest time of almost uniform temperature on the inside glass surface, a temperature flatteningeffect over the melting and solidification period was seen. Because the stored latent heatin the PCM is able to maintain the interior glass surface temperature for about 4 hours after the outer air temperature falls below room temperature, the window is not sensitive to sudden external temperature changes. As a result, the PCM could be deemed a bettermaterial for energy storage and balance”.

According to Gorantla et al. (2017), "the thermal efficiency of buildings with various double glazing window glass material combinations in four different climate zones of India, including mild (Bangalore), composite (Hyderabad), hot and dry (Jodhpur), and warm and humid (Vishakhapatnam)," were studied. In order to conduct this study, four different double glazing window material combinations were selected: clear-clear, bronze-clear, green-clear, and grey-clear. A 10 mm unventilated air space was kept between the two glass layers. Four different types of glass were put to the test using the UV 3600 Shimadzu spectrophotometer at wavelengths between 300 and 2500 nm. 64 building models were made using Design Builder 4.3.0.039, and thermal analysis was done using the Energy Plus 8.1 simulation tools. According to the findings, concrete buildings with double grey-clear glass windows were found to be the most energy efficient in terms of least heat gain out of the sixty-four building models assessed across India's four climatic zones. The clear-clear double glazing window glass material gains the most heat when compared to the other three double glazing window glass materials.

Kim et al. (2017) used mathematical and experimental research to examine "the performance of vacuum glazing in office buildings in Korea. In terms of thermal efficiency, vacuum glazing outperforms double glazing. Additionally, vacuum glazing had a U-value that was up to 55% lower than double glazing. When low-e glass and an argon gas gap were added to double glazing, the U-value was reduced by a maximum of 27% as compared to triple glazing. The hoover glazed case only saved a maximum of 2.46 percent of energy when compared to a case with double glazing. Furthermore, double vacuum glazing only saved a maximum of 3.91 percent more energy than double glazing. On the other hand, energy use was higher than with the triple-glazed.

Bolteya et al. (2020) used experimental and numerical approaches to investigate "the thermal efficiency of PCM-filled double glazing units in Egypt. The RT28HC PCM was used for this project. The influence of PCM thicknesses on the thermal efficiency of double-glazing units (DGU) was investigated utilising fluent software using internal temperature, total transmitted energy, and liquid fractions. The temperature of the DGU internal surface decreased by 7.6°C when PCM was used in place of air, while CFD results showed that the interior surface temperature declined by 9.44°C and the total transmitted energy decreased by 223.9 W m-2 when PCM thickness was 50 mm as opposed to 4 mm. However, the liquid fraction of 50 mm thickness during the day did not reach larger than 0.57, indicating inadequate latent use of PCM for this thickness. PCM was completely melted at thicknesses ranging from 4 mm to 30 mm, suggesting a good usage ratio. The results showed that PCM may be used to manage indoor heat in substantially glazed structures, and PCM thicknesses up to 30 mm were advised.

According to Qudama Al-Yasiri and Marata Szabo (2021), "PCMs have a high potential to improve the building's energy when coupled with building materials. The following concepts can be applied to future research to direct further examination and development. The thermal behaviour and beneficial characteristics of PCM-incorporated structures in severe weather have not received much attention. Early in the day in particularly hot conditions, the PCM reaches its full melting condition. The instantaneous release of heat that has been stored is required to stop any malicious behaviour. In this case, the passive approach is insufficient, and the nocturnal ventilation technique is useless. An alternative discharge medium, such as geothermal energy, must be employed to get the PCM ready for the upcoming day cycle. The part of a structure that receives sunlight in cold areas passively accumulates heat throughout the day and releases it as the temperature drops. Since the solar radiation is frequently insufficient to reach the envelope layers in colder climates, the PCM cannot be heated. As a result, solar collectors must be used to actively use solar energy. The construction application has created the most concerns about PCM's thermal conductivity. Using plastic objects as macro encapsulation containers in warm climates seems like a clever idea. These materials may efficiently promote insulation by limiting heat from the outside. These elements affect PCM's inadequate heat conductivity. To guarantee efficient use, proper precautions should be implemented. There are few long-term studies that provide a good image of PCM performance during many years of service in buildings. There aren't many studies on whether applying PCM to entire structures is feasible. For technologies to be commercialised, these investigations are necessary.

2.2 SUMMARY

- To study analysis the effect of different PCM materials on double glazed windows.
- Selection of the PCM is done after characteristics study.
- The PCM materials will be tested experimentally and numerically to know whether the results of the experiment and simulation are comparable.
- Several methods have been investigated to reduce the heat load through glazed windows but rarely attended the heat load using latent heat storage.
- From available literature a very little studies compared the effect of different PCM materials on glazed windows for wide range of melting temperatures.

2.3 OBJECTIVES

- Conduct numerical studies to find the effect of PCM layer thickness on heat transfer characteristics of double glazed window using different PCM materials.
- Conduct experimental studies to find the effect of PCM layer thickness on heat transfer characteristics of double glazed window using different PCM materials.
- Validate the experimental results with the results obtained from numerical analysis.

2.4 METHODOLOGY

- Conduct literature survey for the selection of suitable PCM materials.

- Development of an experimental setup to study the effect of thickness of PCM on heat transfer.
- Conduct the numerical analysis to study the heat transfer characteristics.
  Validation of the experimental results.
- Analysing the findings of each publication.
- Identifying the research gap.
- Problem formulation

CHAPTER 3

COMPUTATIONAL FLUID DYNAMICS

3.1 INTRODUCTION TO CFD

Computational fluid dynamics (CFD) is a branch of fluid mechanics that employs numerical methods and algorithms to analyse and solve problems involving fluid flows. Computers provide the many calculations required to simulate how fluids and gases interact with the complicated surfaces used in engineering. CFD predicts mathematically what would happen with fluid flow, frequently with the complexity flow, frequently with of

- Heat is flowing simultaneously.
- Mass transfer
- Phase change
- Chemical reaction
- Mechanical movement
- Immersed solids' displacement and stress

3.2 CFD APPLICATIONS

- Lift and drag in aviation and vehicle aerodynamics
- Hydrodynamics of ships
- Power plants, gas turbines, and IC engine combustion
- Flow inside rotating passages, Turbo machinery
- Weather predictions, Metrology
- Wind loading; the external and internal environments of structures

3.3 NUMERICAL METHODS USED IN CFD

The methods used in CFD are

- Finite Difference Method (FDM)
- Finite Element Method (FEM)

- Finite Volume Method (FVM)

3.3.1 Finite Difference Method (FDM)

The heat/diffusion equation is solved using the finite difference method, which is the most simple numerical method. The method's fundamental notion is to substitute the multiple derivatives that come from the formal description of the issue with suitable approximations on a finite difference mesh of nodes. Taylor series are used in the simplest derivation of finite difference formulas. Any numerical method can be used to solve the final set of linear algebraic equations.

3.3.2 Finite Element Method (FEM)

The finite element method involves dividing the calculation domain into smaller elements, such as triangular rectangles, tetrahedrons, or rectangular parallelepipeds. These elements are considered interconnected at specific points called nodes. To estimate the fluctuation of the field variable within an element, a simple function can be used, with the field variable values at each node defining the approximation functions. The nodal points represent the locations of new unknowns in the field equations for the entire continuum. The values of the field variables at the nodes can be obtained by solving the field equations expressed as matrices. The combination of these approximation functions is used to define the field variable.

3.3.3 Finite Volume Method (FVM)

The conventional approach used in both research coding and commercial software is to discretize the computation domain into smaller elements using the finite element method. An alternative approach to discretization involves partitioning the computation domain into finite volumes, where each volume is represented as a line in 1D, an area in 2D, and a volume in 3D, with nodes serving as the computational values hub. In 2D rectangular Cartesian coordinates, the simplest finite volumes are rectangles, and discretization equations are obtained by integrating the initial partial differential equation across each finite volume. Nonlinear problems can be solved using iterative techniques to arrive at solutions of algebraic equations. This approach has an advantage over the finite difference method in that it can be used without a structured mesh, although one can be employed if desired. The finite volume method can handle asymmetrical geometry and conserve variables on a coarse mesh, which is particularly important in fluid problems.

3.4 ADVANTAGES OF CFD OVER EXPERIMENT METHODS

CFD research can significantly reduce the lead time and cost of developing new designs. It allows for the study of systems in risky situations and systems where controlled tests are difficult or impossible to conduct, providing detailed results. The cost of conducting experiments can be uneven due to the number of data points and tested configurations, which can lead to high facility or labor expenditures. In contrast, parametric analyses can be performed relatively inexpensively to optimize equipment performance. Additionally, CFD algorithms can generate vast amounts of findings with virtually no additional cost.

3.5 WORKING OF A CFD CODE

The foundation of CFD codes for solving fluid flow problems is the numerical algorithms. Commercial CFD software such as Phoenics, Flow3D, and Star CD incorporate three essential elements to provide easy access to the solving power: user interfaces for entering issue parameters and reviewing outcomes. These three elements are

- Pre-Processor
- Solver
- Post-Processor

3.5.1 Pre-processor

Pre-processing refers to the process of inputting a flow problem into a CFD application and converting it into a format that the solver can utilize. During the pre-processing stage, users perform activities such as defining the computational domain, which specifies the geometry of the region of interest.

- The geometry of the region of interest is defined by the computational domain.
- Creating a grid of cells or mesh by subdividing a larger area into multiple smaller, non-overlapping sub domains (control volumes or elements).
- Deciding which physical and chemical events are necessary for modelling.
- A description of fluid characteristics.

In addition to defining the computational domain, another activity during the pre-processing stage is specifying appropriate boundary conditions for cells that are adjacent to or in contact with the domain boundary. The solution of a flow problem is obtained at the nodes within each cell, and the accuracy of the CFD solution is directly related to the number of cells in each grid.

3.5.2 Solver

Three unique streams of numerical solution techniques are finite difference, finite element, and spectral methods. The operations described below are performed by the numerical methods that form the solver's foundation.

- Using basic functions to approximate the unknown flow variables.
- Discretization through further mathematical procedures that involve substituting approximations into the governing flow equations.
- The resolution of algebraic problems.

The approximate approximation of the flow variables and the discretization procedures are related to the main distinctions between the three distinct streams.

3.5.3 Post-processor

In CFD, post-processing refers to the analysis and visualization of the results obtained from the solver. With the increasing use of engineering workstations, which often have powerful graphics capabilities, the post-processing field has seen significant development activity. The best CFD systems now include a variety of tools for data visualization, such as:

- Grid display and domain geometry
- Vectograms
- Contour plots with lines and shade
- Surface plots in 2D ,3D
- Element monitoring
- View adjustment
- Output in colour.
- Colour postscript output.

These plots and contours helps us to visualize the problems to a great extent and a thorough understanding of the situation can be attained.

3.6 PROBLEM SOLVING WITH CFD

While tackling fluid current issues, it's important to remember that the fundamental physics is intricate that a CFD programme can only produce answers that are as accurate as the physics and chemistry they include, or worse, as accurate as its user. There are steps of identification and formulation of the flow crisis in terms of the physical and chemical processes which need to be taken into consideration before setting up and executing a CFD simulation. More than half of the time spent on a CFDproject in industry is spent on the definition of the domain geometry and grid generation.

3.7 COMPUTATIONAL FLUID DYNAMICS SIMULATION

In the chemical process industries, the design, scaling up, and operation of unit operations heavily depend on empirical data and correlations of overall parameters for non-ideal or non-equilibrium situations. Due to the complex nature of these processes, many current equipment designs are more of an art than a science, relying on the experience and intuition of professionals who use common sense to make decisions. Processes that are affected by local phenomena and reactant concentrations are particularly challenging to design or scale up because the existing correlations do not take into account the local effects. It is difficult, if not impossible, to forecast non-idealitiesthat result from scaling up lab or pilot scale equipment. computational fluid dynamics (CFD) are increasingly used by researchers, equipment designers, and process engineersto analyse the flow and performance of process equipment, such as chemical reactors, stirred tanks, fluidized beds, cyclones, combustion systems, spray dryers, pipeline arrays, and other equipment. CFD makes it possible to analyse in-depth the chemistry, local effects, and fluid mechanics of this kind of machinery, including combustion and turbulence. When experimental data or design correlations are unavailable, CFD can beused. It offers thorough information that is difficult to get through experimental studies.It emphasises the underlying cause rather than just the consequence, and numerous "what if" scenarios can frequently be examined quickly. As the models are based on basic physics and are scale-independent, this strategy reduces scale-up issues.

At its core, numerical algorithms are employed to solve mathematical equations that govern fluid movement, mass transfer, heat transfer, chemical reactions, and other relevant phenomena. This requires the integration of traditional theoretical and experimental scientific methods with contemporary numerical computation techniques.

The output of CFD analysis yields pertinent engineering data that is appliedto conceptual explorations of novel designs, in-depth product development, troubleshooting, and redesign. CFD has been shown to provide numerous benefits, including improved insight, better performance, increased dependability, more confident scale-up, improved product uniformity, and enhanced plant productivity.

Over the past fifty years, CFD has advanced extraordinarily. The tremendous advancements in the speed of digital computers have been a major factor in this advancement. Non-experts can now regularly utilise CFD as a design tool credit to the continuous and exponential rise in computer power, enhanced physical models in many CFD systems, and improved user interfaces. As a result, CFD has moved from being a mainframe-only technology to being used on high-end engineering workstations and even PCs and laptop. As it has in practically all human endeavours, the power of digital computing has revolutionised research and engineering, particularly in the subject of fluid mechanics.

3.8 PHASES OF MODELLING AND SIMULATION

In modelling and computer simulation, vocabulary and core ideas have been standardised for a very long time. Operations research pinpointed the key issues and debates 20 years ago, way before the CFD community was worried about this. The terms model, modelling, and simulation are used in many different areas. As a result, depending on the situation and the discipline, these expressions may mean different things. A replica is a depiction of how a physical system or process would appear, and it is designed to aid in understanding, foreseeing, or controlling its behaviour. The process of modelling involves creating or changing a model. Simulation is the use of a model in practise or in application. The community of operation researchers has identified the fundamental stages of modelling and simulation. Fig. 3.1depicts these fundamental steps and procedures. It distinguishes between two different models: conceptual models and computer models. The knowledge, mathematical equations and mathematical modelling data, and that explain the relevant physical system or processes are all included in the conceptual model. The process of observing and analyzing a physical system leads to the creation of a conceptual model in CFD. In this conceptual model, partial differential equations play a dominant role. A functional computer program that executes the conceptual model is known as a computer model. Nowadays, the term "computer code" is commonly used to refer to the computer model.

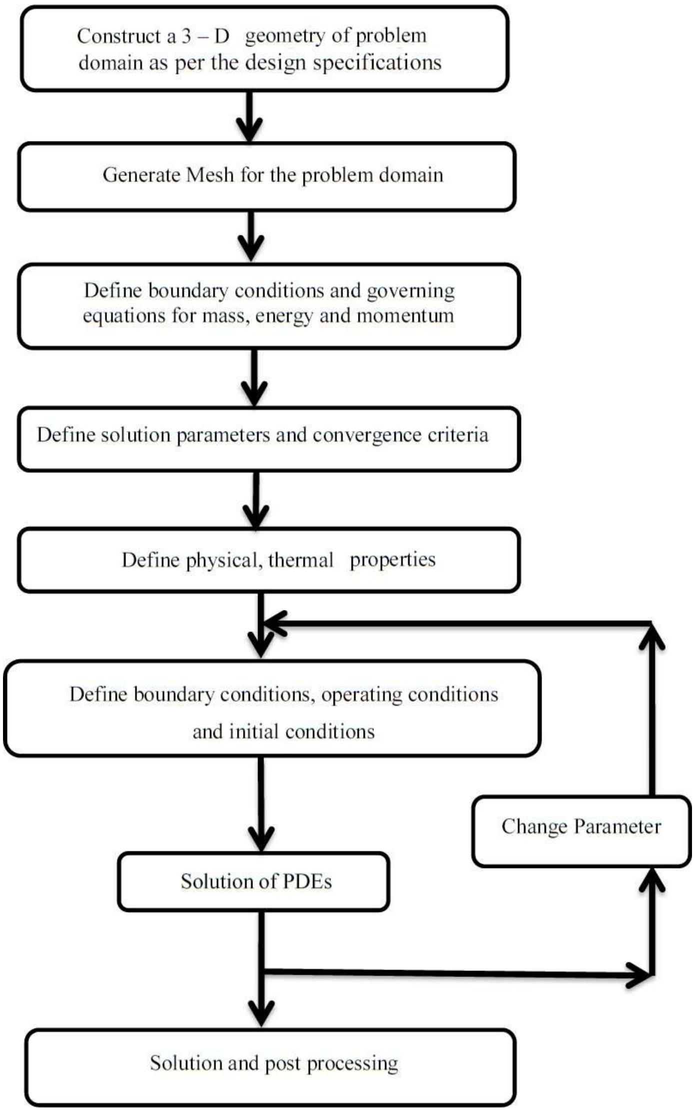


Fig 3.1 Phases of Modelling and simulation

Although CFD simulations are frequently employed in business, academia, and government, there is currently no agreement on how to assess their efficacy. There is no agreed benchmark for the accuracy or authenticity of CFD simulations. Various degrees of accuracy are necessary depending on the purposes that simulations are meant to fulfil. The two essential components needed to establish credibility are verification and validation.

Verification is a technique for ensuring that a computational simulation accurately portrays the conceptual portrayal of the model and its solution; it makes no assumptions about the simulation's relationship to reality.

The process of validating a computational simulation is evaluating how well it resembles reality from the perspective of the model's intended usage. The definitions of verification and validation both place a strong emphasis on accuracy evaluation. During verification efforts, accuracy is frequently assessed in comparison to benchmark solutions to difficulties with simplified models. Validation procedures are used to assess accuracy in respect to experimental data that accurately represents the real world. The main causes of the deterioration in modelling and simulation accuracy are uncertainty and error. A potential flaw in any stage or activity of the modelling process that arises from ignorance is what is meant by "indecision." Unawareness frequently results from incomplete knowledge of a physical characteristic or attribute Erroris defined as an observable inadequacy in any modelling and simulation phase or activity that is not brought on by a knowledge gap. There are two types of errors: acknowledged errors and unacknowledged errors. Two examples of acknowledged defects include round-off errors in digital computers and physical approximations intended to simplify the modelling of physical processes. Unaddressed errors include slip-ups and blunderslike programming errors.

The four main reasons for inaccuracy in CFD simulations are computer programming, insufficient spatial discretization convergence, insufficient temporal discretization convergence, and insufficient iterative convergence. The most important phase in verification testing is methodically altering the time step and grid size. Calculating the numerical solution's discretization error is the aim. As the grid size and time step decrease, the discretization error should asymptotically decrease until it approaches zero. Comparing the computational answer to an extremely accurate solution during verification operations is the most accurate and dependable method for determining the degree of error. But there are known, extremely accurate solutions to a relatively small number of simple problems.

3.9 CFD CALCULATION

The geometry of interest is first divided or discretized into a number of computational cells before being employed in CFD. The discretization method involves solving a set of algebraic equations for the variables at numerous discrete locations in space and time in order to approximate the differential equations. The grid or mesh is the phrase used to describe the distinct locations.

Discrete values have now taken the place of the continuous data from the accurate solution of the Navier-Stokes partial differential equations. A little, straightforward issue can have a few thousand cells, whereas a huge, intricate issue might have millions. Cells have a variety of forms. Quadrilateral and triangular cells are frequently employed in 2D issues. Hexahedral, tetrahedral, pyramidal, and prismatic cells can be used for 3D problems.

The use of structured grids with a single cell type, such as brick-shaped hexahedral components, in which the cells were organised in a regular way was previously required by CFD algorithms. Modern codes provide far greater geometric variety by allowing cells to be arranged in an irregular, unstructured way. The CFD analyst has versatility since a capable CFD code can accept hybrid grids, which combine several cell types to address complex geometries. Geometries are often built using computer-aided design (CAD) software. In order to generate the CFD-quality grid, the geometry is sent to the grid-generation programme as either a wireframe or a solid model.

A few software integrate mesh manufacturing and CAD geometry development into a single user interface. Once the grid has been formed, the boundary conditions, including pressures, velocities, mass fluxes, and scalars, have been characterised, and the physical properties have been set, the CFD calculations can start. The CFD algorithms will solve the necessary conservation equations iteratively for each grid cell. Examples of typical chemical process applications include enthalpy, turbulent kinetic energy, turbulent energy dissipation rate, chemical species concentrations, local reaction rates, and local volume fractions for multiphase problems. These applications can be used to solve for mass conservation (using a continuity equation), momentum conservation (using Navier Stokes equations), and more.

There are many commercial CFD software options available for modelling and assessing systems, including fluid flow, heat transfer, and related phenomena like chemical reaction. A few well-known CFD software packages are ANSYS, FLUENT, CFX, and PHOENICS. Each of these commercial CFD codes has three essential components: Pre-processor, Solver, and Post-processor. This study specifically focuses on simulating flow and mixing behaviour for industrial applications that involve chemicals and heat using the ANSYS software suite. However, comparisons with some of these well-known commercial CFD codes were also required to validate the results generated by the ANSYS CFD code.

3.10 CFD SOFTWARE PACKAGE

Total mesh freedom is provided by modelling flow and heat transfer in complex forms using a CFD software package, making it possible to generate unstructured meshes regarding complex geometries to address flow difficulties. A CFD code built on the finite-volume technique is used to solve the transport equation for the conservation of momentum, mass, and energy. The main goal of a finite-volume technique is an integral approximation of the integral form of the conservation law for each of the several contiguous control volumes across the area of interest. This domain is discretized into a finite number of computational cells as control volumes. There are several different mesh types that are supported, including body-fitted, block-structured meshes, Meshes that are 2D triangular or quadrilateral, 3D tetrahedral, or wedge-shaped. It makes use of unstructured meshes to speed up the mesh generation process, make geometry modelling and mesh generation simpler, represent morecomplicated geometries with multi-block ordered meshes, and quickly modify the meshto resolve flow-field character. In ANSYS, any mesh type can be adjusted in order to resolve significant gradient in the flow field. For each cell, the generic transport equation is,

$$\partial/_{\partial t}\int_{CV}\rho\emptyset dv+\oint_{A}\ \rho\emptyset u.dA=\oint_{A}\ \Gamma\nabla\emptyset.dA+\int_{CV}s\emptyset dV \qquad (3.1)$$

Where ϕ is a parameter, which is for the continuity equation, I stands for the energy equation, u for the X-momentum equation, v for the Y-momentum equation, w for the Z-momentum equation, and v for the X-momentum equation. An unstable state is accounted for by the first half of the equation on the left side, while convective behaviour is accounted for by the second component. The right side of the equation must first account for diffusive behaviour, and the creation of amount within the cell must then be taken into consideration. Each transport equation is then discretized and put into algebraic form. The discretized equations require field data (material properties, velocities, etc.) stored at cell centres as well as face values that are interpolated in terms of local and neighbouring cel values. An equation set is created by writing out the equation for each control volume in the domain. The flow field is then created by solving the set of equations.

3.11 SOLDIFICATION AND MELTING PROBLEM

PCM examines the processes of melting and solidification in this study. ANSYS Fluent can be used to tackle fluid flow issues whether melting and/or solidification occur at a single temperature (for example, in pure metals) or across a wide temperature range (for example, in binary alloys). Instead of explicitly following the liquid-solid front, ANSYS Fluent uses an enthalpy porosity model. In order to account for the pressure drop brought on by the presence of solid material, the liquid-solid mushy zone is considered as a porous zone with a porosity equal to the liquid% and corresponding momentum sink components are added to the momentum equations. In order to account for the decreased porosity in the solid parts, sinks are also included in the turbulence calculations. Calculation of liquid-solid solidification and melting in binary alloys.

3.11.1 Continuous casting process modelling (also known as "drawing" solid material out of the domain).

3.11.2 Modeling the thermal contact resistance between solidified substance andwalls, for instance because there is an air gap)

3.11.3 Modeling species movement with melting and solidification

3.11.4 Post-processing of amounts involved in melting or solidification (that is, liquid fraction and pull velocities)

ANSYS Fluent can simulate a variety of solidification/melting challenges, such as melting, freezing, crystal formation, and continuous casting, thanks to these modelling features. The solidification/melting process is simulated in ANSYS Fluent using enthalpy-porosity modelling. The melt interface is not precisely tracked by this method. Instead, a value known as the liquid fraction is assigned to each cell in the domain and represents the proportion of the cell's volume that is in liquid form. At each iteration, the liquid fraction is calculated using an enthalpy balance. The mushy region between 0 and 1 is where the liquid fraction can be found. The mushy zone is described as a "pseudo" porous medium where the substance's porosity decreases as it hardens, from 1 to 0. The porosity is zero when the substance has entirely solidified in a cell, and hence, the velocities are likewise zero

3.12 ANALYSIS

The research of heat transport in a double-glazed system has been conducted using CFD analysis. Following the identification of the problem's key characteristics, the subsequent procedural procedures must be carried out.

- Establish modelling goals.
- Create the grid and model geometry.
- Construct physical models and solvers.
- Computer and monitoring programme.
- Review and keep the outcomes.
- Take into account changing the physical or numerical model parameters.

3.12.1 Defining Modelling goals.

In the section we have to define our system needs so that the final goal is achieved.

3.12.2 Creating model geometry and grid

Is used to speed up mesh generation and make geometry modelling simpler. is capable of handling elements that are hexagonal and pyramidal in 3D and triangular and quadrilateral in 2D.

3.12.3 Setting up the solved and physical models, for a given problem, we need to,

- Import the grids and verify them.
- Decide on the calculator.
- Pick suitable physical models.
- Describe the characteristics of the substance.
- Establish operational and boundary conditions.
- Demonstrated initial fixes.
- Setup of flow fields.

3.12.4 Computing and monitoring the solutions.

- Relatively easy to solve the discretized conservation equations.
- When convergence occurs,

a) The solution variables don't change all that much from iteration toiteration.
b) Residuals offer a means for keeping an eye on this tendency.

c) Property preservation in general is accomplished.

- The accuracy of converged solutions depends upon,
  a) Correctness and approximation of models
  b) Resolution of grids
  c) Problem onset

3.12.5 Examining and saving results.

- Key flow aspects may be resolved and flow patterns can be shown using visualisation tools.
- You can calculate things like flex balances and the average heat transfer coefficient using numerical reporting tools..

3.12.6 Revising the model

The following inquiries are taken into account for examining the solutions once the solution has converged.

- Weather the physical models fitting
- Weather boundary conditions accurate
- Weather the grid passable

CHAPTER 4

EXPERIMENTAL INVESTIGATION

Typical multi-glazed windows have air or inert gases filled in the gaps to reduce convective and conductive heat transfer. This experiment characterised the performance of three separate PCMs with various phase transition temperatures. The experiment's purpose is to compare different PCM materials and measure the temperature difference between two double-glazed panes. The outcomes were contrasted with double-glazed, air-filled windows.

4.1 MATERIALS AND INSTRUMENTATION

4.1.1 Window glass:

For this experiment, transparent glass was chosen over other materials due to its excellent light transmission. Heat transfer is then minimised by using glass with a high light transmission.

Table 4.1: Properties of clear glass

Density (4mm* 2mm glass) (kg m^{-3})	Specific heat capacity (J kg^{-1} K^{-1})	Thermal conductivity (W m^{-1} K^{-1})
2080	590	0.65
1800	670	0.80

4.1.2 Window frame:

In this experiment, the glass is placed in a wooden frame because wood has a lower thermal conductivity and hence conducts heat less readily through window frame.

4.1.3 Phase change material:

The selection of PCM is influenced by its melting point, latent heat storage capability, and price. The phase transition temperature was the main factor for selecting two PCMs. The purpose of the study is to ascertain the effect of PCM phase transition temperature in double-glazed windows. The PCMs chosen are OM42 and OM50. The phase transition temperatures are 42 and 50 degrees C, respectively.

Table 4.2: Properties of Selected PCMs

Name	Temperature ($°c$)	Latent Heat (KJ/kg)		Density (kg/m^3)		Specific Heat (KJ/kgK)		Conductivity (W/mk)		Appearence
	Phase change	Melting	Freezing	Liquid	Solid	Liquid	Solid	Liquid	solid	
OM 42	42	199	190	863	903	2.78	2.71	0.1	0.19	White solid @25°C
OM 50	50	189	204	870	900	2.78	3.33	0.14	0.21	White Waxy solid @25°C

4.1.4 Thermocouples:

Type T thermocouples were used to measure the inner and outer surface temperature of the glazing. Four on each glass surfaces and one to measure the ambient temperature.

4.1.5 Heat flux sensors:

Heat flux sensor (Omega make) is used to measure heat flux falling on the glazing from the IR lamps. It generates electrical signal comparative to total heat rate applied to surface of sensor.

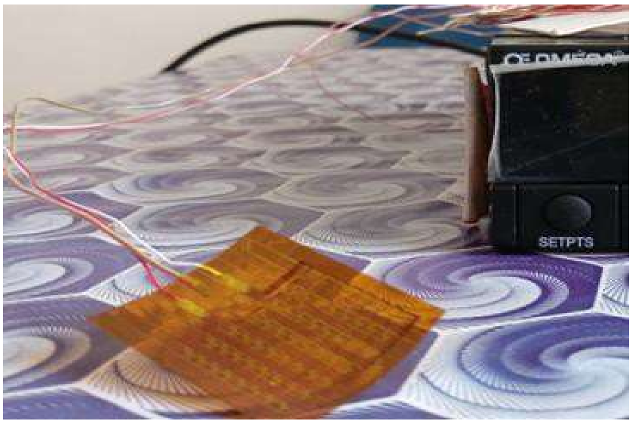


Fig 4.1: Heat flux sensor

4.1.6 Data acquisition system:

Data acquisition system (Agilent-34972A) is used for collecting and storing data from sensors that are attached to it. The data logger's software converts millivolt signals from thermocouples to temperature data directly. Data can be transferred from the software's native file format to the Microsoft Excel platform.

Fig 4.2: Data acquisition system

4.2 GLAZING UNIT

The glazing unit is made up of two 4 mm and 2mm thick glass panels with dimensions of 300 mm x 250 mm. These glasses can be put into the slots of a wooden frame with a 5mm,10mm and 15mm gap between them. So, when two glasses are inserted, there is a gap of 5mm,10mm and 15mm between them, which can be filled with air and different PCMs. The developed experimental setup is having the provision to change the glass thickness and to fill different PCM's. To prevent fillingmaterial leaking, the inserted glasses are secured to the frame with a silicon sealant andM seal. The glazing unit for the experiment is made up of glasses fitted into a wooden frame. The entire glazing unit is supported by a wooden support.

Fig 4.3: Glazing unit

Fig 4.4: Window frame profile

Fig 4.5: 2mm and 4mm glass

4.3 EXPERIMENTAL SETUP

Experiments have been conducted on double glazed window for its heat transfer characteristic using different PCM materials. The key parameters tested in the study was the temperature across the glazing. An experimental set up was fabricated and schematic diagram of the same is shown in fig.4.5. The experimental setup includes four major parts namely Double glazing unit , one IR Lamps, Data Acquisition system and thermo couple.

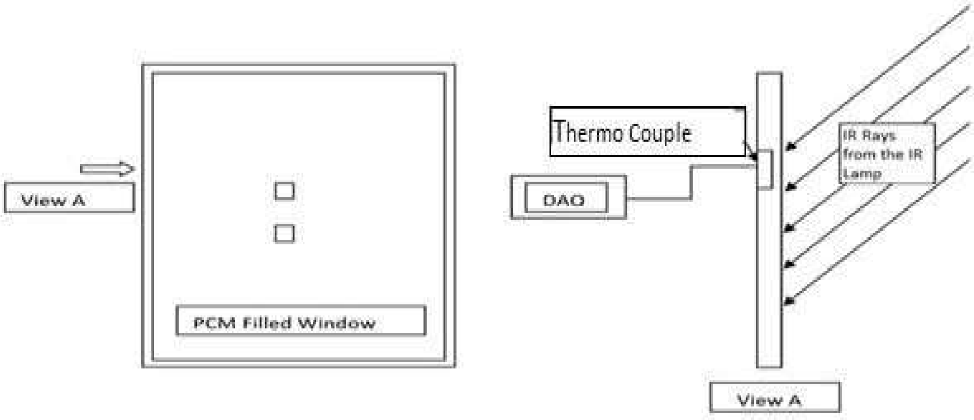


Fig 4.6: Schematic of experimental set up

The experiment was conducted inside a laboratory in a controlled environment the ambient temperature is maintained constant. One side of the window is called the outer side, which was exposed to one 150W IR lamps, while the other side is considered the inner side, which has convective heat transmission. The IR lamp, which is aimed at the outside, functions as a radiation source, raising the temperature was placed at a convenient distance from the glazing unit to assure radiation in all part of the glazing unit. The developed experimental setup is having the provision to change the glass thickness and to fill different PCM's. Experiments were conducted by varying PCM layer thickness to determine the glazing's inner and outer surfaces temperatures in a controlled environment.

Fig. 4.7 : Different PCM layer thickness

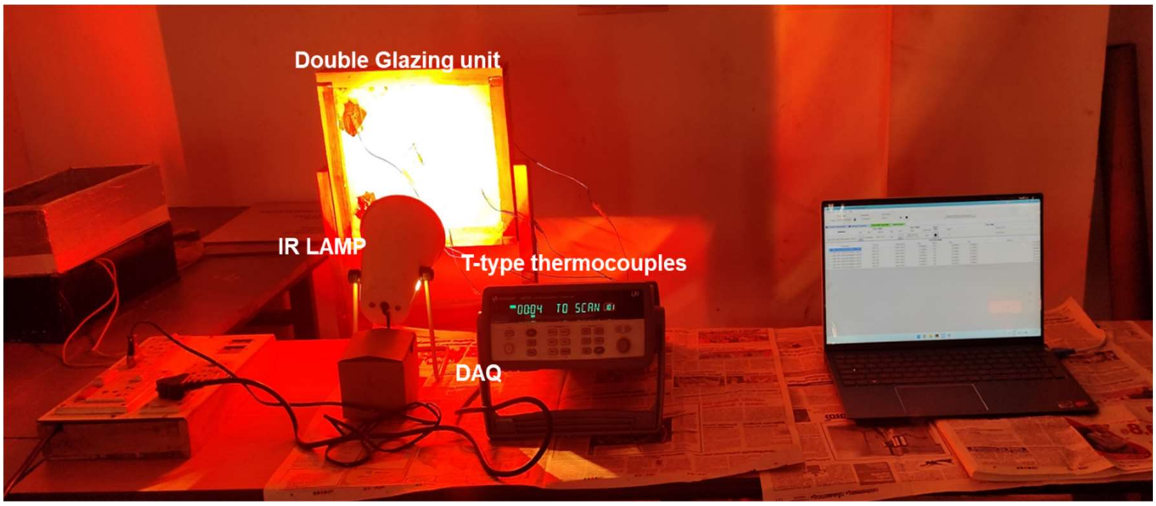


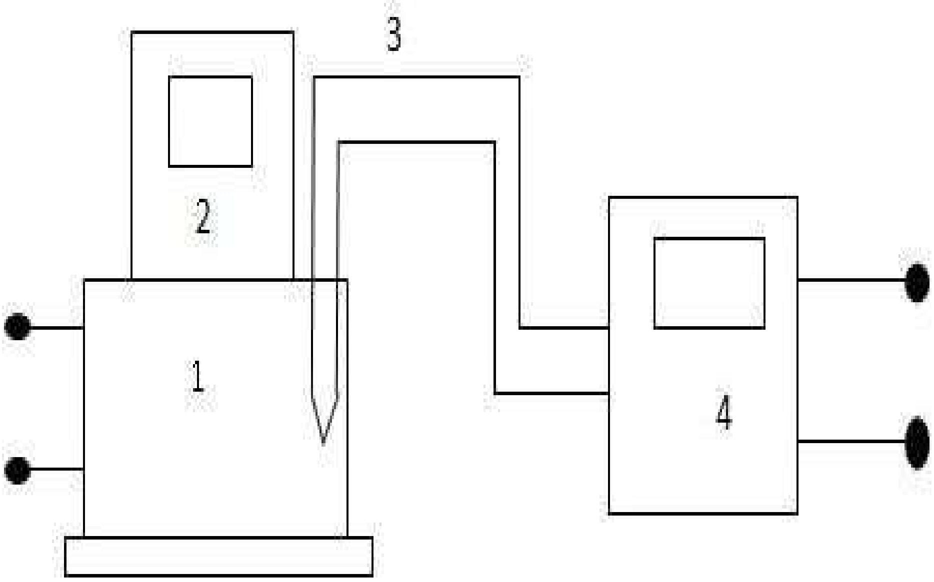
Fig 4.8: Experimental setup

Fig 4.9: PCM Filled Glazing unit

Fig 4.10 :Melting process of PCM in glass panel

4.4 CALIBRATION OF THERMOCOUPLE

Fig.4.8 depicts a schematic representation of the setup for calibrating the thermocouples used in the experiment. For the current experimental work, T-type thermocouples are employed. Gas welding is used to create the thermocouple bulbs. The thermocouple bulb is submerged in bath oil that is kept at a consistent temperature. A temperature scanner is attached to the thermocouple's opposite end. The bath is kept at a constant temperature, and the temperature measured by the temperature scanner is noted to a temperature scanner



1. Constant temperature bath 2. Temperature display 3. Thermocouple 4. Temperature scanner

Fig.4.11 Schematic layout of thermocouple calibration

Table 4.3 Calibration data for thermo-couple (TC-01)

Sl.No	Set Temperature (°C)	Observed Temperature (°C)	Error(%)
1	30	30.05	0.05
2	40	40.33	0.33
3	50	50.44	0.44
4	60	60.05	0.05
5	70	70.82	0.82

Table 4.4 Calibration data for thermo-couple (TC -02)

Sl. No	Set Temperature (°C)	Observed Temperature (°C)	Error(%)
1	30	30.06	0.06
2	40	40.34	0.34
3	50	50.43	0.43
4	60	60.04	0.04
5	70	70.83	0.83

Table 4.5 Calibration data for thermo-couple (TC -03)

Sl. No	Set Temperature (°C)	Observed Temperature (°C)	Error(%)
1	30	30.04	0.04
2	40	40.32	0.32
3	50	50.45	0.45
4	60	60.02	0.02
5	70	70.81	0.81

Table 4.6 Calibration data for thermo-couple (TC -04)

Sl.No	Set Temperature (°C)	Observed Temperature (°C)	Error(%)
1	30	30.03	0.03
2	40	40.34	0.34
3	50	50.46	0.46
4	60	60.03	0.03
5	70	70.86	0.86

Table 4.7 Calibration data for thermo-couple (TC -05)

Sl.No	Set Temperature (°C)	Observed Temperature (°C)	Error(%)
1	30	30.01	0.01
2	40	40.32	0.32
3	50	50.44	0.44
4	60	60.04	0.04
5	70	70.81	0.81

Table 4.8 Calibration data for thermo-couple (TC -06)

Sl.No	Set Temperature (ºC)	Observed Temperature (ºC)	Error(%)
1	30	30.04	0.04
2	40	40.33	0.33
3	50	50.45	0.45
4	60	60.03	0.03
5	70	70.84	0.84

Table 4.9 Calibration data for thermo-couple (TC -07)

Sl.No	Set Temperature (ºC)	Observed Temperature (ºC)	Error(%)
1	30	30.05	0.05
2	40	40.36	0.36
3	50	50.44	0.44
4	60	60.04	0.04
5	70	70.83	0.83

Table 4.10 Calibration data for thermo-couple (TC -08)

Sl.No	Set Temperature (ºC)	Observed Temperature (ºC)	Error(%)
1	30	30.03	0.03
2	40	40.34	0.34
3	50	50.43	0.43
4	60	60.02	0.02
5	70	70.84	0.84

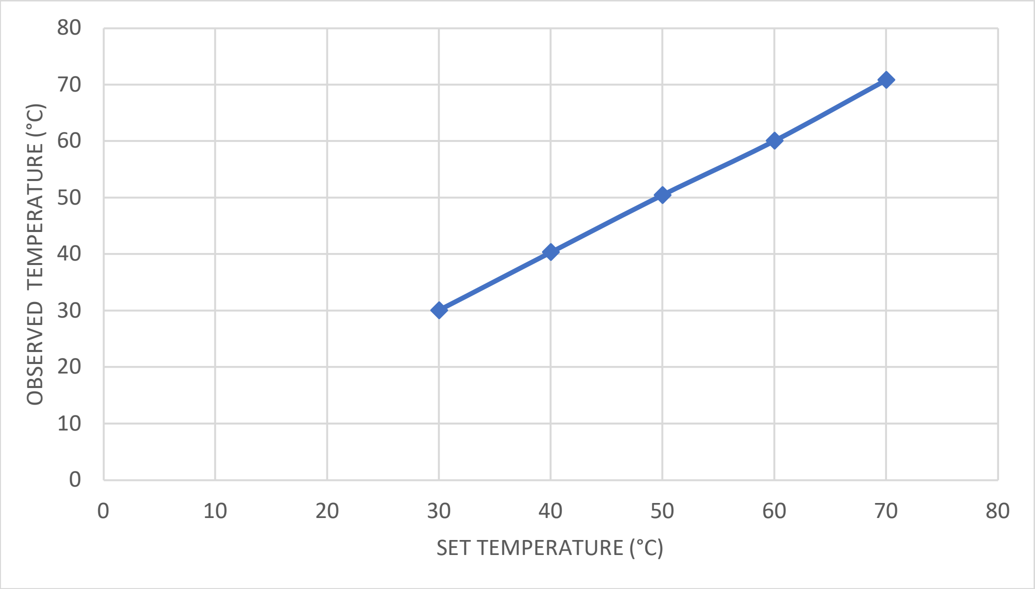


Fig.4.12 Thermocouple Calibration Curve

CHAPTER 5

EXPERIMENTAL RESULTS

5.1 EXPERIMENTAL PROCEDURE

The gap between the glazings was filled with air and the two designated PCMs on different experimentation days. T type thermocouples were mounted on the inner and outer glasses, four in the outer wall and four in the inner wall, and one for measuring the ambient temperature, to measure the temperature across these surfaces. Every 5 minutes, a data collection system recorded the readings from these sensors. To analyse the fluctuation of temperature while using various PCMs and without PCM, outside and inside temperatures were plotted along with ambient temperature.

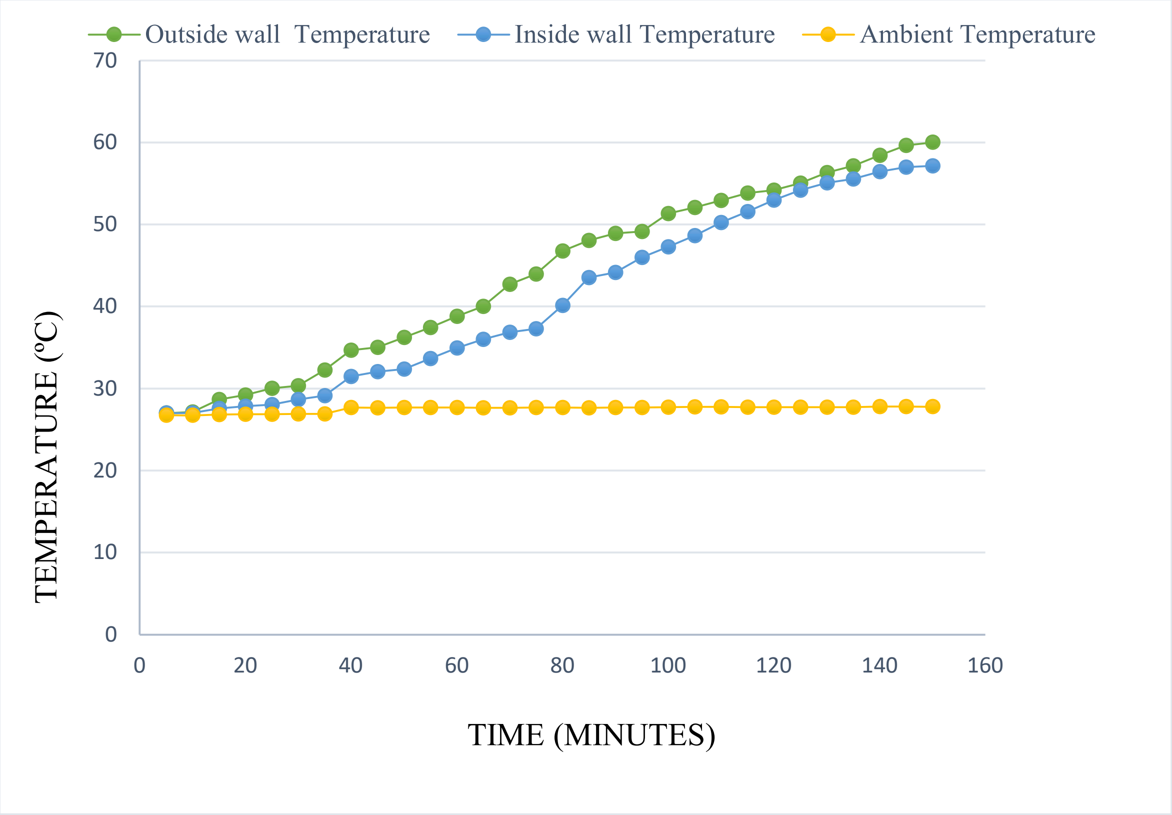


Fig 5.1 : Temperature Vs Time (Without PCM in double glazing)

From the above graph it can be concluded that air-filled double-glazed windows have a minimal temperature difference between the interior and exterior surface temperatures. This is because the air layer between the two glasses accumulates heat and does not shield the inner surface from incoming radiation. As a result, there may be an increased demand for refrigeration and higher electricity consumption in buildings with air-filled double-glazed windows. It is important for building designers and owners to consider the thermal properties of windows when making decisions about energy efficiency and reducing electricity consumption.

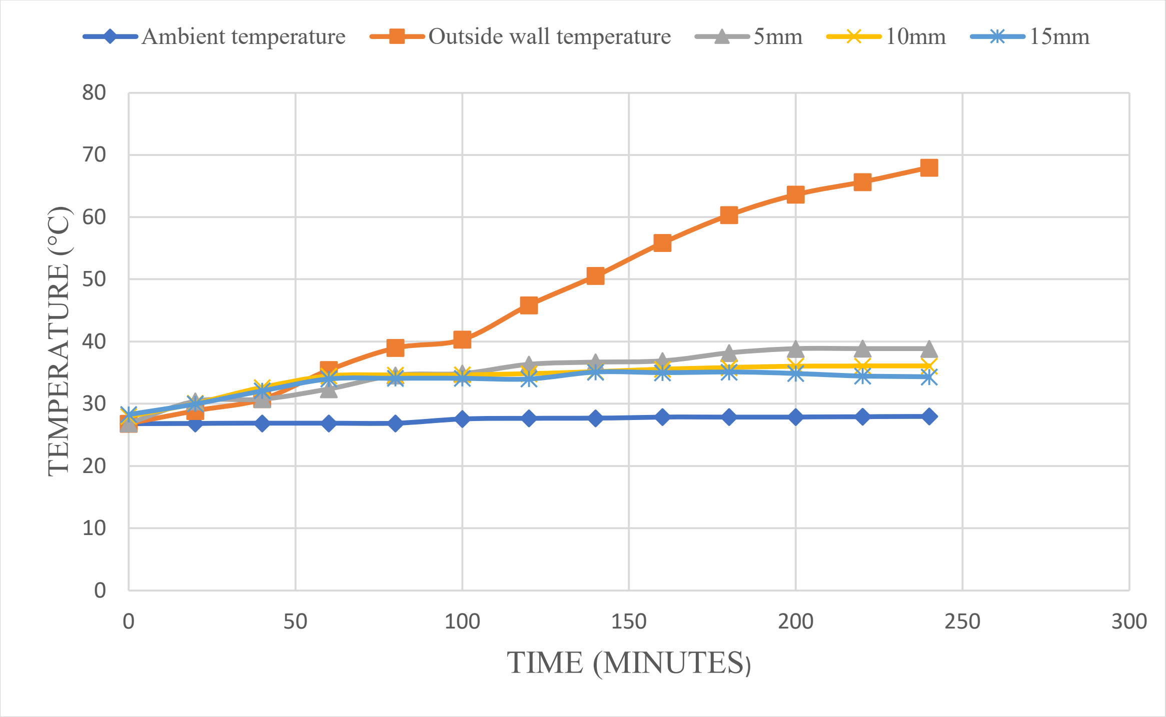


Fig 5.2 : Effect of OM 42 PCM layer thickness on inside wall temperature in 4mm glass

For PCM (OM 42) in 4mm glass Generally, thicker PCM layers (15mm) have a greater thermal mass and can store more thermal energy, which can lead to greater energy savings. In double glazing with PCM (OM42) filling, the melting temperature is 42°C. In the first 30 minutes, the temperature in the outer wall rises fast until it reaches the melting zone. During that period, conduction heat transfer between the outside and inner walls occurs. Because of this, the inner wall's temperature is somewhat higher than the surrounding air's temperature. The temperature rise is mostly brought on by conduction through the PCM material when the curve flattens out at 42 °C as the PCM material started to absorb latent heat. In this instance, the PCM is used to around 80% of its potential, with the remaining PCM functioning normally.

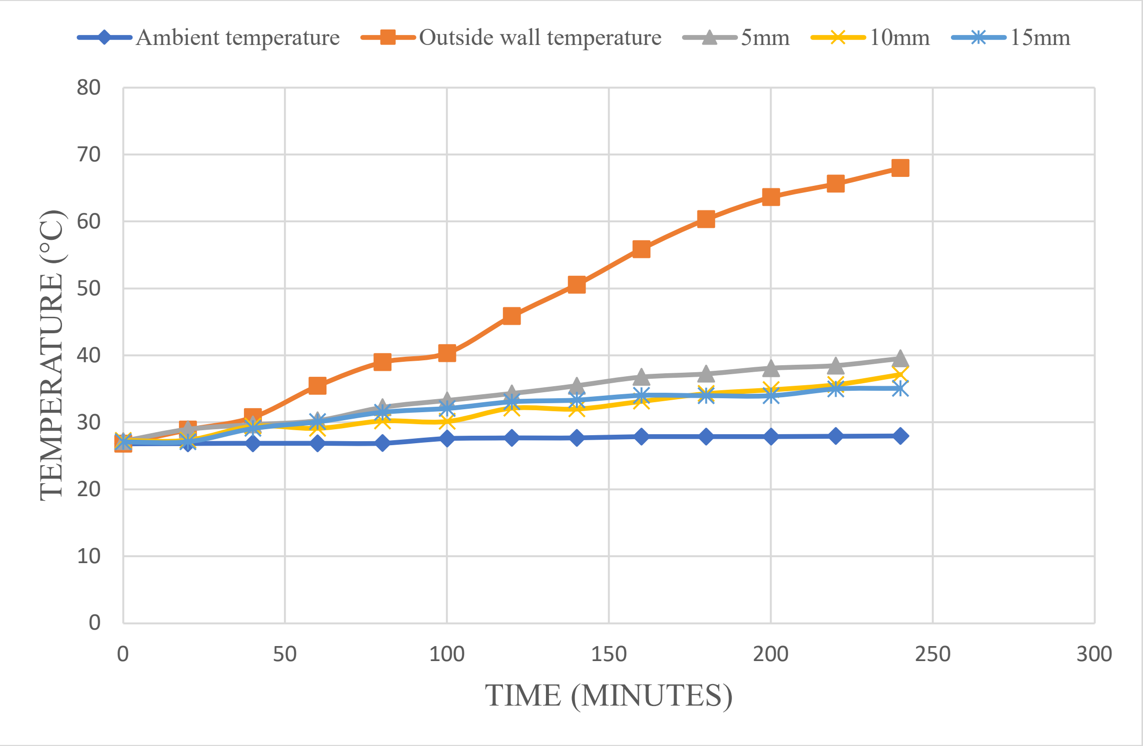


Fig 5.3 : Effect of OM 42 PCM layer thickness on inside wall temperature in 2mm glass

For PCM (OM 42) in 2mm glass Generally, thicker PCM layers (15mm) have a greater thermal mass and can store more thermal energy, which can lead to greater energy savings. In double glazing with PCM (OM42) filling, the melting temperature is 42°C. In double glazing with PCM (OM42) filling, the melting temperature is 42°C. In the first 30 minutes, the temperature in the outer wall rises fast until it reaches the melting zone. The inner surface temperature then begins to gradually increase but continues to be lower than the outer surface temperature. The inner surface temperature of the 4mm and 2mm glass in 15 mm PCM layer thickness ranges between 33°C and 35 °C since this is where PCM absorbs the latent heat and the phase change takes place. The ongoing increase in internal surface temperature is caused by the sensible heating of PCM that occurs after the phase change.

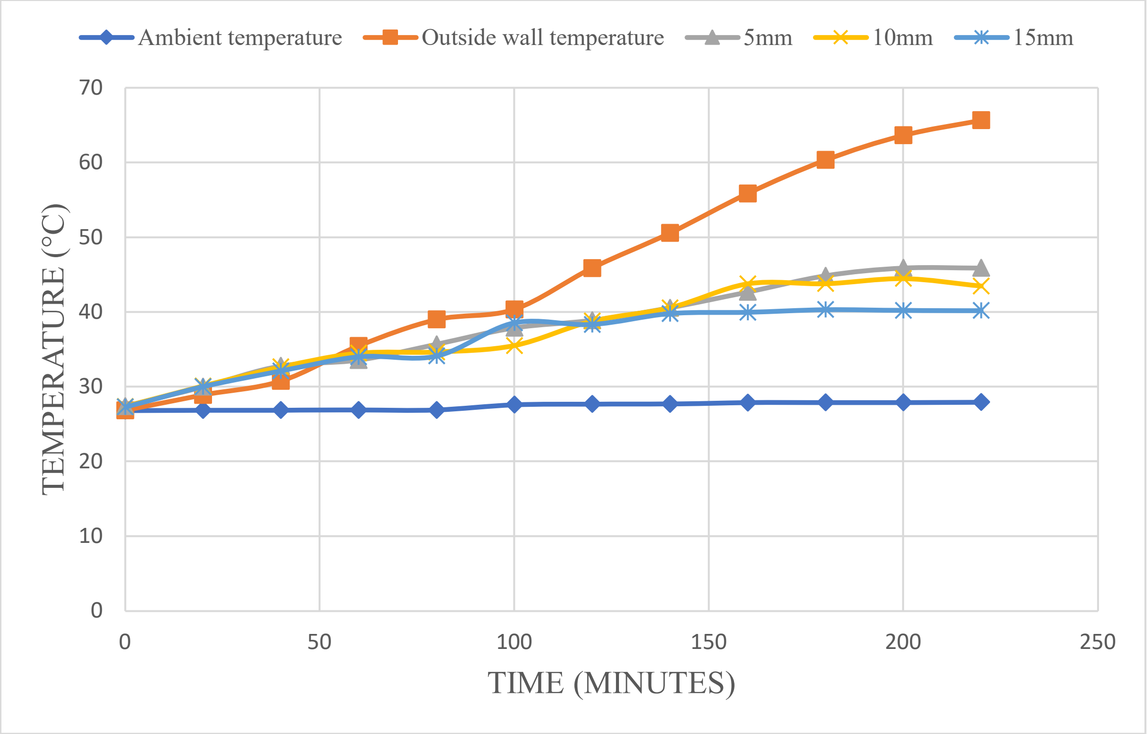


Fig 5.4 : Effect of OM 50 PCM layer thickness on inside wall temperature in 4mm glass

For PCM (OM 50) in 4mm glass Generally, thicker PCM layers (15mm) have a greater thermal mass and can store more thermal energy, which can lead to greater energy savings. PCM filled double glazing unit, we can see from the graph that during the initial stages of the experiment, the outer wall temperature rises steadily, much like in the prior example of PCM (OM42), until it reaches a range of 50°C. PCM OM 50 melts at a temperature of 50 °C after which the temperature remains stable for a while before rising steadily once more. Due to conduction through the PCM layer, the inner wall's wall temperature is continuously rising. The significant temperature difference between the inner and exterior walls of the glass causes this conduction heat transfer.

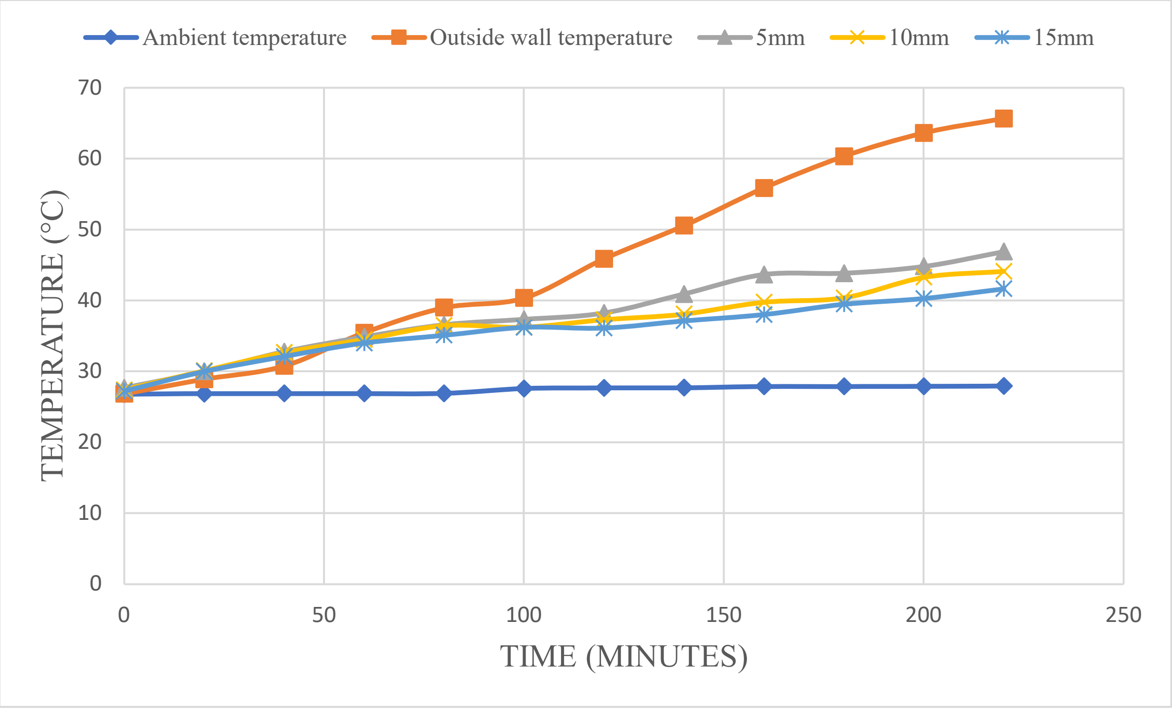


Fig 5.5 : Effect of OM 50 PCM layer thickness on inside wall temperature in 2mm glass

For PCM (OM 50) in 2mm glass Generally, thicker PCM layers (15mm) have a greater thermal mass and can store more thermal energy, which can lead to greater energy savings. In the first 30 minutes, the temperature in the outer wall rises fast until it reaches the melting zone. The inner surface temperature then begins to gradually increase but continues to be lower than the outer surface temperature. The inner surface temperature of the 4mm and 2mm glass in 15 mm PCM layer thickness ranges between 40°C and 42°C since this is where PCM absorbs the latent heat and the phase change takes place. The ongoing increase in internal surface temperature is caused by the sensible heating of PCM that occurs after the phase change.

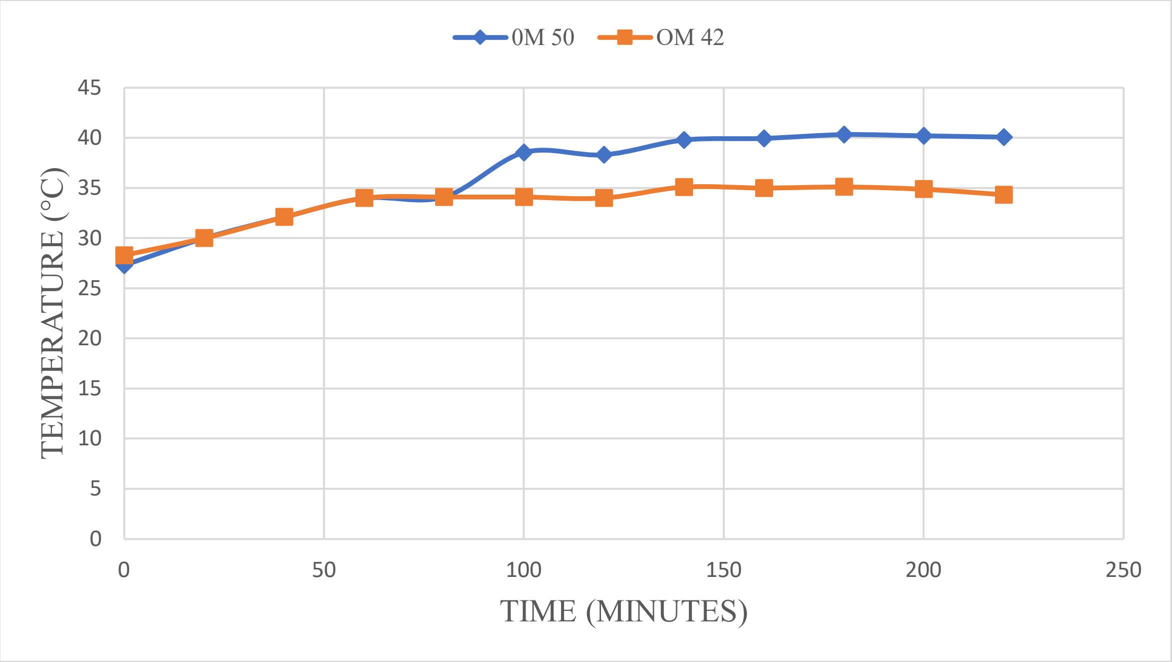


Fig 5.6 Variation of inside wall surface with time temperature for different PCM's in 4mm glass

From the above graph it can be concluded that the variation of OM 42 and OM 50 inside wall surface temperature in 15mm PCM layer thickness of 4mm glass. Then they compared in this two PCMs, the inner surface temperature then begins to gradually increase but continues to be lower than the outer surface temperature. The inner surface temperature of the OM 42 and OM 50 in 15 mm PCM layer thickness ranges between 34°C and 40°C since this is where PCM absorbs the latent heat and the phase change takes place.

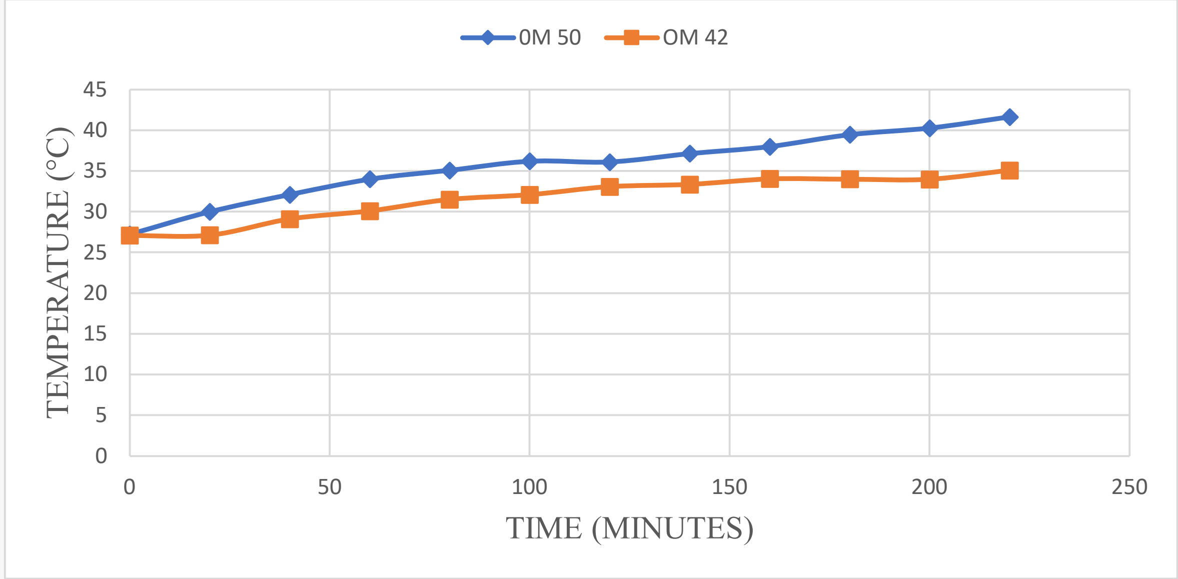


Fig 5.7 Variation of inside wall surface with time temperature for different PCM's in 2mm glass

From the above graph it can be concluded that the variation of OM 42 and OM 50 inside wall surface temperature in 15mm PCM layer thickness of 2mm glass. Then they compared in this two PCMs, the inner surface temperature then begins to gradually increase but continues to be lower than the outer surface temperature. The inner surface temperature of the OM 42 and OM 50 in 15 mm PCM layer thickness ranges between 35°C and 42°C since this is where PCM absorbs the latent heat and the phase change takes place. Experimental studies shows that PCM 42 having 15mm layer thickness in 4mm glass is showing best performance.

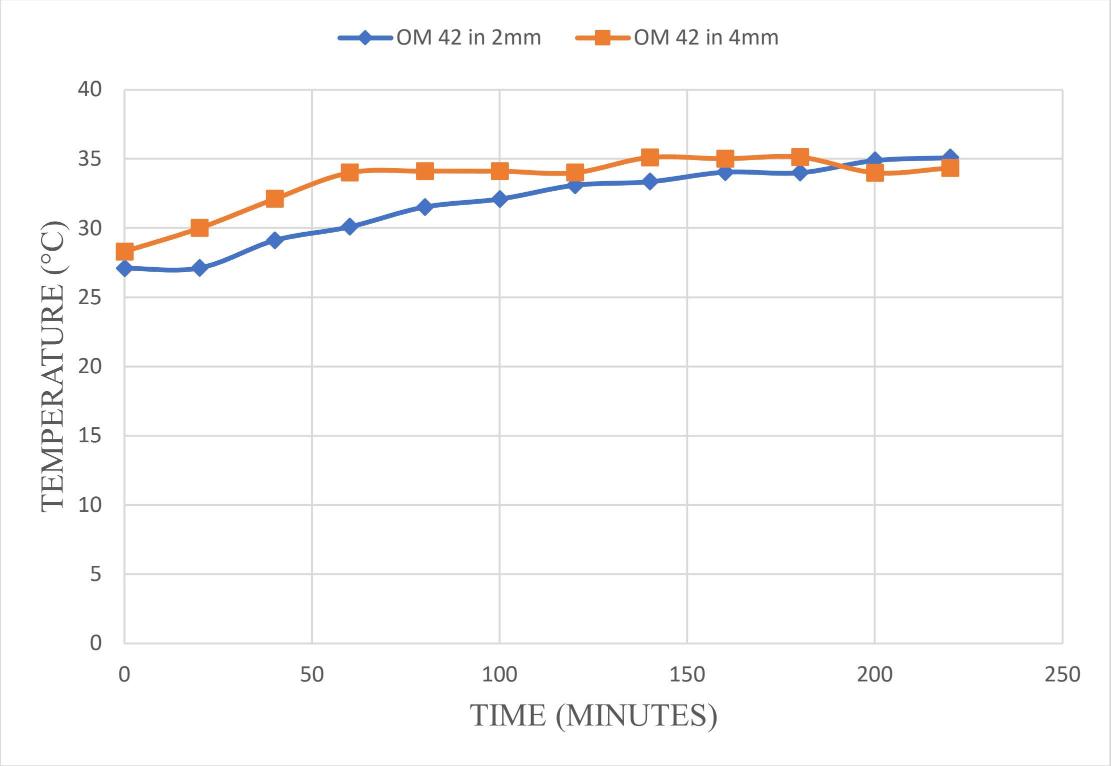


Fig 5.8 Effect of glass thickness on inside surface temperature

In general, thicker glass can provide better insulation and reduce heat transfer between the inside and outside of a building. This is because thicker glass has a lower thermal conductivity than thinner glass, which means it is better at resisting the flow of heat. But the selection of PCM and the layer thickness playsan important role in the proper functioning of the windows. To determine the PCM 42 having 15mm layer thickness in 4mm glass is showing best performance.

CHAPTER 6

NUMERICALANALYSIS

The creation of a geometric model of the problem domain is the initial stage in a CFD study. After being constructed, the geometric model is mesh to discretize it. After meshing, the input data must be specified, the material properties must be specified, and the boundary conditions must be specified. After initialising the solution setup, calculations are run for the specified number of seconds. Following the completion of the calculations, post processing is done to extract the data relevant to the important variables. In this study, post processing is not required because the desired outcome, inner surface temperature, is monitored and plotted during the calculation.

6.1 GEOMETRY MODELLING

The Modelling of window geometry is the first step in a CFD analysis, and in this work,it is the problem field. As a design tool, In ANSYS Workbench design modeler sectionis used for creating geometric models of physical problem domains. The two 4 mm and 2mm glass layers in the modeled glazing have a 5mm,10mm and 15 mm gap between them that can be filled with air, water, or PCM. The glazing measures 300 mm x 250 mm,when two glasses are inserted, there is a gap of 5mm,10mm and 15mm between them.

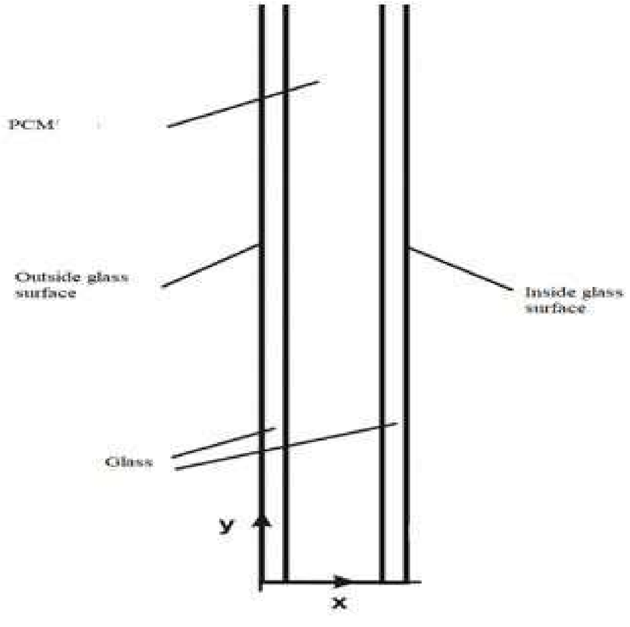


Fig 6.1: Schematic for the cross section of the glazing geometry

6.2 MESHING OF THE DOMAIN

The meshing of the computational region is the next step in the CFD analysis process after the geometric model has been created. The issue domain is split up into a great deal of tiny cells during mesh generation. The CFD application solves a number of equations for each cell in order to simulate physical events. The number of cells in the domain has a big impact on the simulation's outcomes. The domain needs to have enough cells in order to replicate the physical events. The time it takes the solver to find a solution increases as the number of cells does. As a result, it is crucial to identify the appropriate number of cells that would allow a simulation to run in a reasonable amount of time and still produce findings that are accurate enough. The optimal number of cells for a domain usually depends on the difficulty of the problem and the amount of simulation time available. For a precise CFD study, a high-quality mesh is required. For this work, a hexahedral mesh was used for discretization. Hexahedral meshing was used since windows' geometry only contains rectangular surfaces. Because there are no curved surfaces in the geometry of windows, the hexahedral sort of meshing is ideal for producing accurate results with little computational effort. For various numbers of elements, a grid independence test is conducted, and the inner surface temperature of double glazing is noted. It demonstrates that for 400000 elements, the temperature difference is minimal.

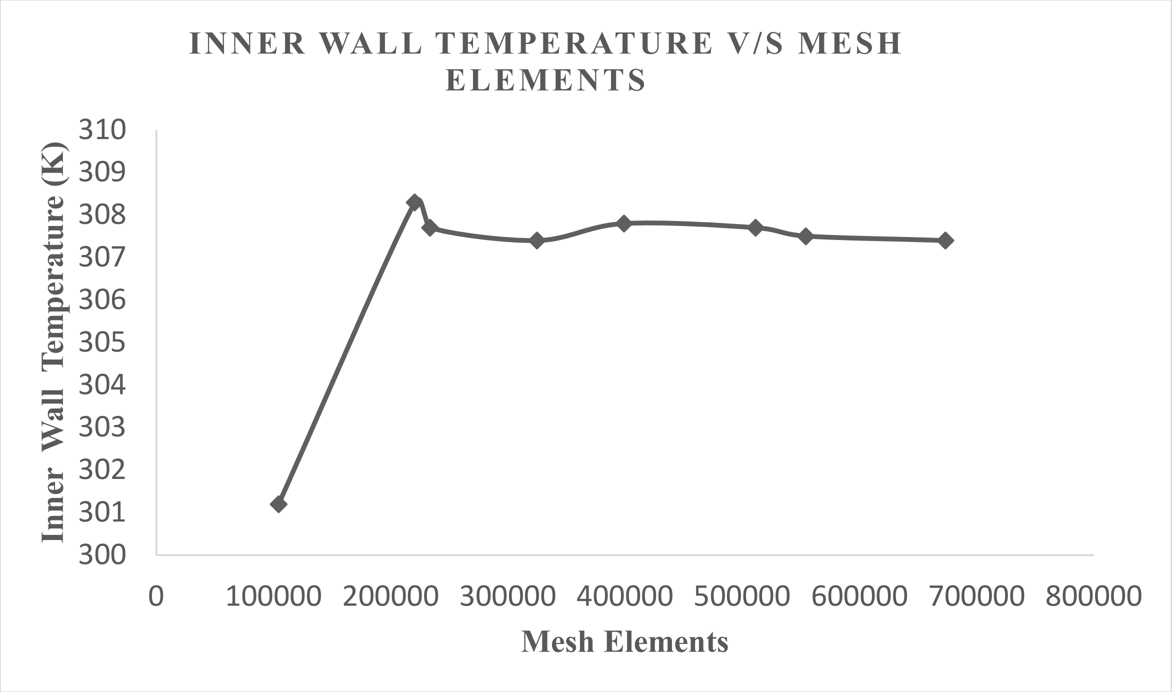


Fig 6.2: Grid independence test

Once the mesh has been created, it must be checked for quality.

In this work, two parameters—skewness and aspect ratio of the produced mesh—have been investigated. The skewness criteria perceive an element with a skewness value of 0 as perfect, while elements with a skewness value greater than zero are not thought to be of high quality. The general consensus is that an element with a skewness value of 1 is not feasible. A extremely small or negligible number of elements with a skewness value of 1 must exist in a well-meshed domain. An ideal mesh must always have an average skewness value of less than 0.3. The result is that it is less than 0.001.Aspect ratio is a comparable statistic for measuring how well a created mesh is done. A mesh should have an average aspect ratio of no greater than two. Aspect ratio is 1 in this case. This shows that the created mesh, which is primarily composed of hexahedron-shaped pieces, is a mesh of high quality in terms of skewness and aspect ratio.

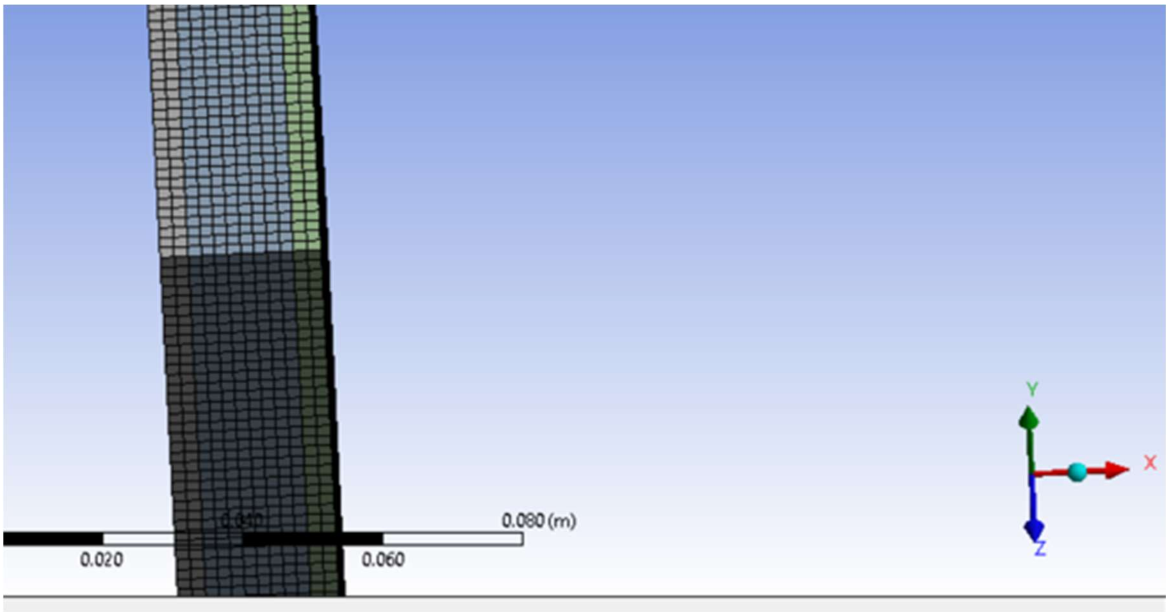


Fig 6.3: 3D view of grid

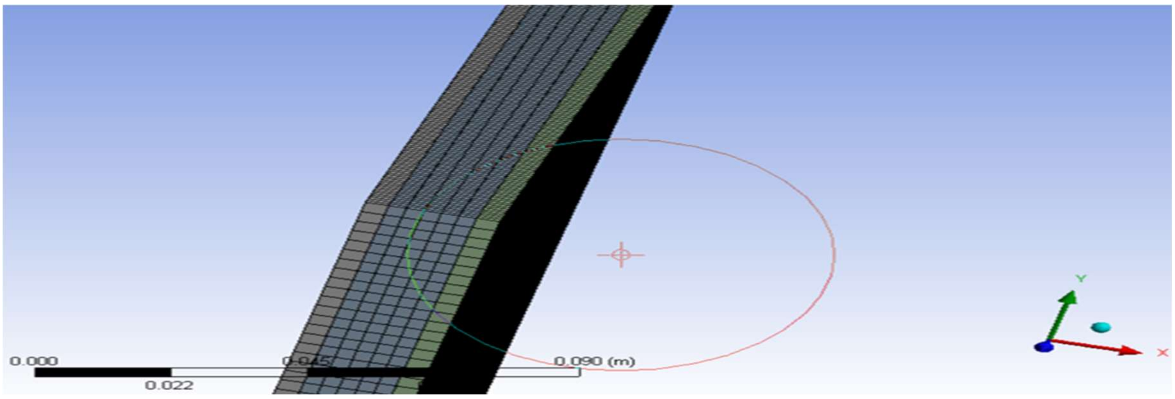


Fig 6.4 :Cross section of modeled glazing

6.3 BOUNDARY CONDITIONS

For an accurate solution to a fluid flow problem, it is crucial to define the appropriate boundary types and boundary conditions. While some boundary conditions are set by simulation software, the majority are defined by physical phenomena. The interfaces are configured to be thermally linked, and all of the window's side walls are assumed to be adiabatic. The experimentally determined glazing's outer surface temperature serves as the CFD model's outer surface's thermal condition.

6.4 INPUT PARAMETERS

Certain parameter values, such as material qualities and beginning parameter values must be entered as input parameters into the CFD tool. The table displays the thermo physical characteristics of the materials utilised for the CFD simulation of glazing, including density, thermal conductivity, and specific heat capacity. Other materials were chosen from a database contained within Fluent, with the exception of PCM and glass. Glass and PCM's characteristics were defined externally. The table contains the values for the additional input parameters.

Table 6.1: Input parameters

Function	**Specification**	
Solver	Type	Pressure -based
	Time	Transient
	Viscous model	Laminar
	Solidification & melting	On (for PCM)
Materials	Solid	Glass
	Fluid	PCM1/PCM2

6.5 NUMERICAL SOLVER USED

Two of the main numerical solvers offered by ANSYS FLUENT are the coupled solver and the segregated solver (implicit and explicit type) as already discussed in chapter 3.For both of these approaches. The governing integral equations for the conservation of mass, momentum, and energy are also solved using FLUENT. Each of the governing equations for the many variables, such as velocity, temperature, pressure, turbulent kinetic energy, etc., is solved separately and sequentially with an implicit type algorithm. Each governing equation is dissociated from the others while being solved.The separated algorithm is memory-efficient since only one discretized equationneeds to be stored at a time. Due to the solver's memory efficiency, the implicit approach has been taken into account in this case.

6.5.1 Solution technique

A discretization strategy is needed to solve the governing equations and scalar variables like temperature. For this work, two discretization schemes are pertinent: -

- First Order Upwind, in which the values of the cell faces are specified to be equal to those of the cell centres in cells upstream, and
- Second Order Upwind, where the Taylor Series expansion is used to determine the cell face values in order to enhance the range of the surroundingcells' influences.

A stable solution is provided by the First Order upwind solution method, which also exhibits a good rate of residual convergence. This plan's drawback is that the solution's accuracy could not be adequate. Therefore, where great precision is not the primary objective, the first order upwind technique can be employed. The Second Order upwind approach, on the other hand, delivers extremely precise simulation results. However, the amount of time needed for the simulation increases significantly when the second order upwind solution technique is used. Therefore, first order upwind solution method was used in the current study by taking into account for the calculation capability and the time available.

6.5.2 Convergence criteria

The solution's convergence is determined by the residuals' predetermined, stated values known as the convergence criteria. Relatives were watched as convergence was reached. The energy equation's convergence criteria is 10^{-6}.All other variables' convergence requirements are set at 10^{-3}.Convergence criteria are established under thepresumption that the solution would remain unchanged after convergence. One approach to the problem is the pressure-velocity coupling, which employs the SIMPLE system. The parameters were set in Fluent, and then the solution was initialised. Depending on how easily the convergence occurred and how long it took to obtain theresults, iterations were performed. Temperature at the interior surface was measured after running the problem for a period of 9000s.

CHAPTER 7

NUMERICAL ANALYSIS RESULT

The computational fluid dynamics (CFD) technique was used to numerically simulate the thermal properties of the current problem. For the current numerical investigation, ANSYS 21R2 is a commercial software package. The consequences of thermal expansion are not considered in this comparative study. The Ansys software is set up to converge, and once the iterations converged and it was run for the necessary time step, the results were shown for various PCMs.

EFFECT OF OM 42 PCM LAYER THICKNESS ON INSIDE WALL TEMPERATURE IN 4MM AND 2MM GLASS

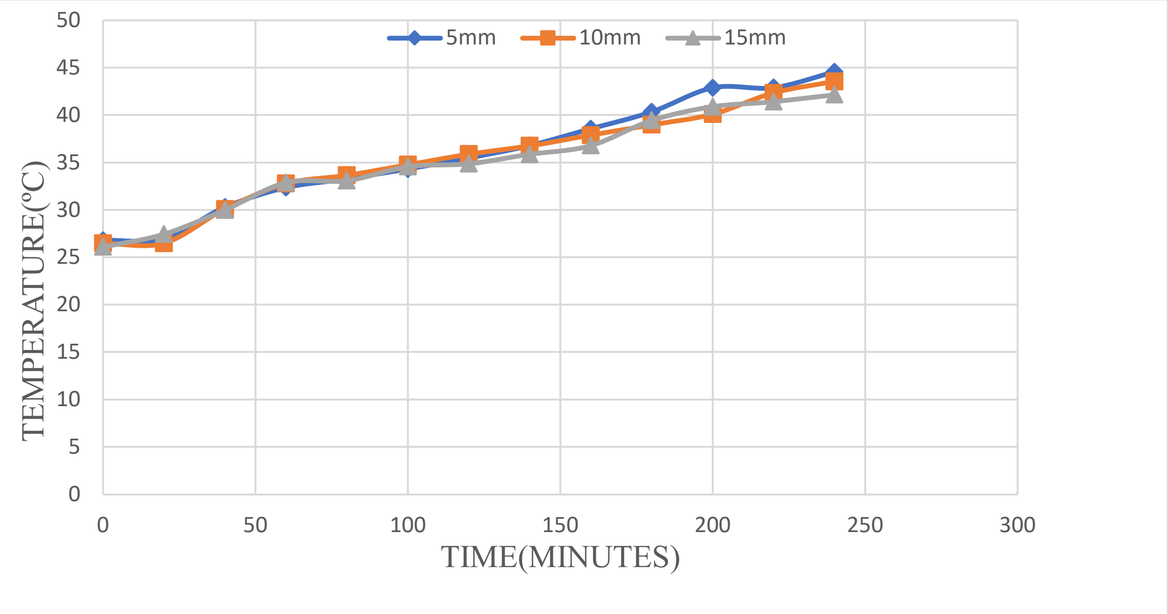


Fig. 7.1: Effect of OM 42 PCM layer thickness on inside wall temperature in 4mm glass

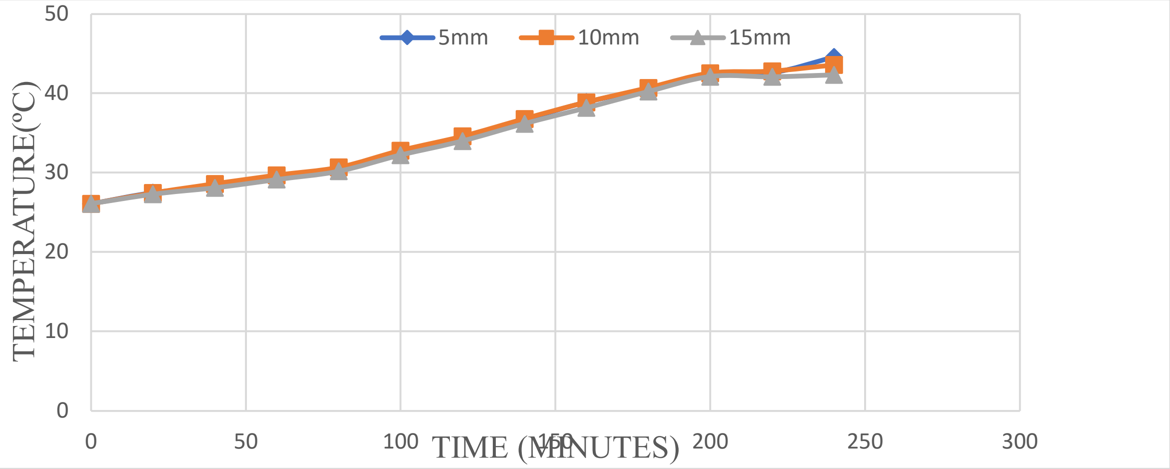


Fig.7.2: Effect of OM 42 PCM layer thickness on inside wall temperature in 2mm glass

From the above two graphs are the effect of PCM layer thickness on inside wall temperature of the OM 42 in 15 mm PCM layer thickness ranges between 41°C and 43°C since this is where PCM absorbs the latent heat and the phase change takes place. The thickness of an OM 42 PCM (Phase Change Material) layer can have an impact on the inside wall temperature in glass. OM 42 PCM is a type of material that undergoes a phase change (melting or solidifying) at a specific temperature, and it can be used to regulate temperature in buildings by absorbing or releasing heat as needed.

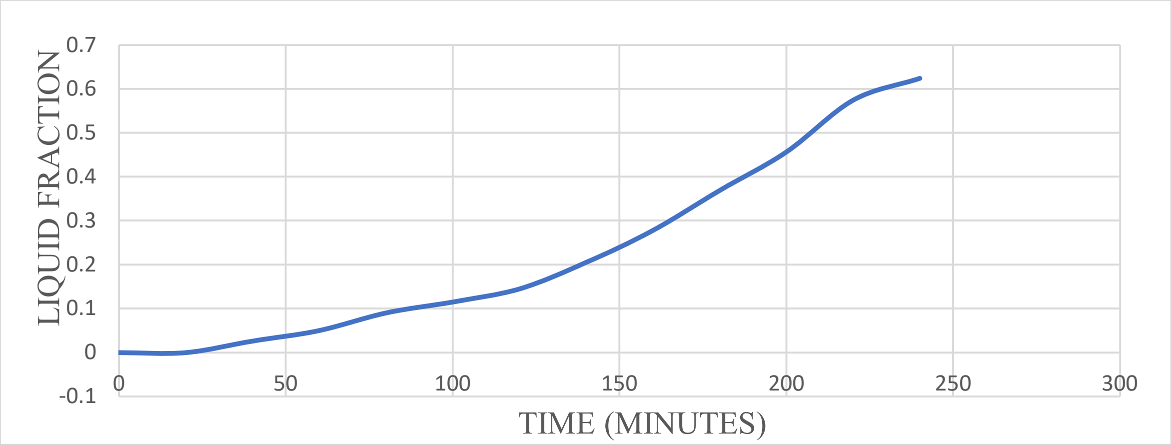


Fig.7.3: Liquid fraction Vs Time for PCM (OM42) filled double glazing

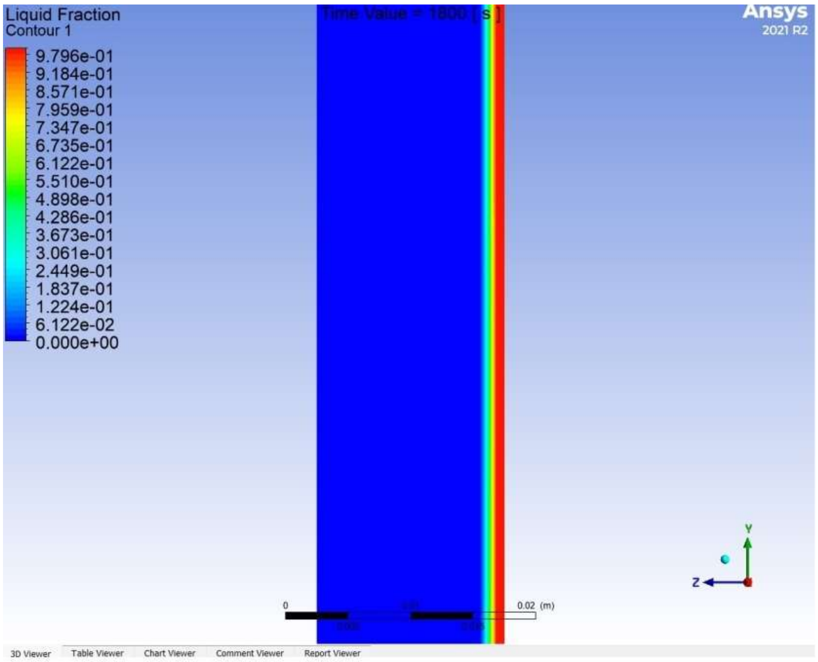


Fig.7.4: Liquid fraction Contour PCM (OM42) 1800s

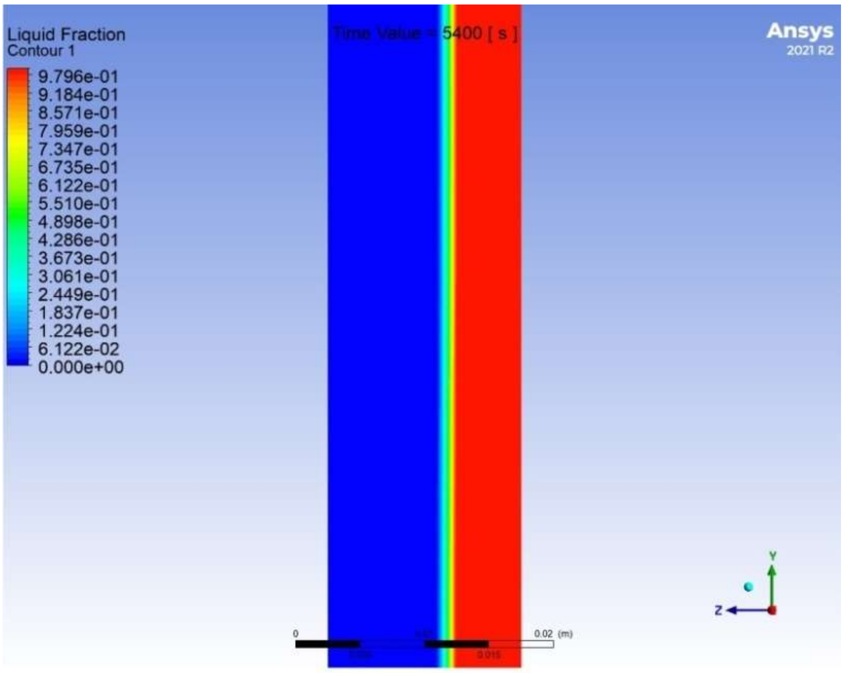


Fig.7.5: Liquid fraction Contour PCM (OM42) 5400s

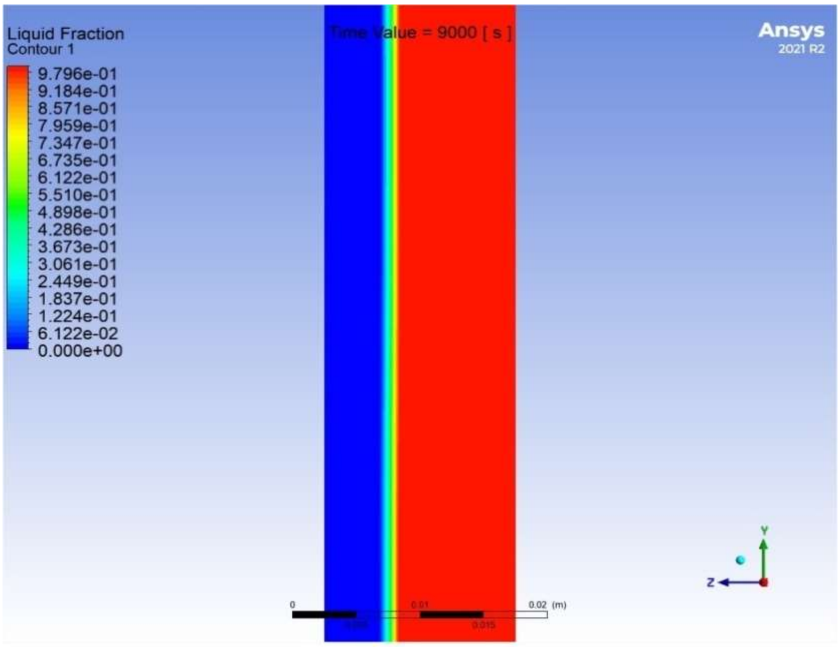


Fig.7.6: Liquid fraction Contour PCM (OM42) 9000s

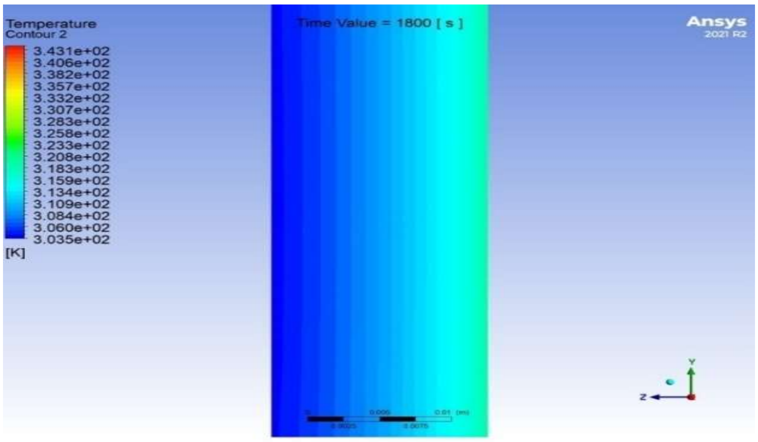


Fig.7.7: Temperature Contour PCM (OM 42) @ 5mm

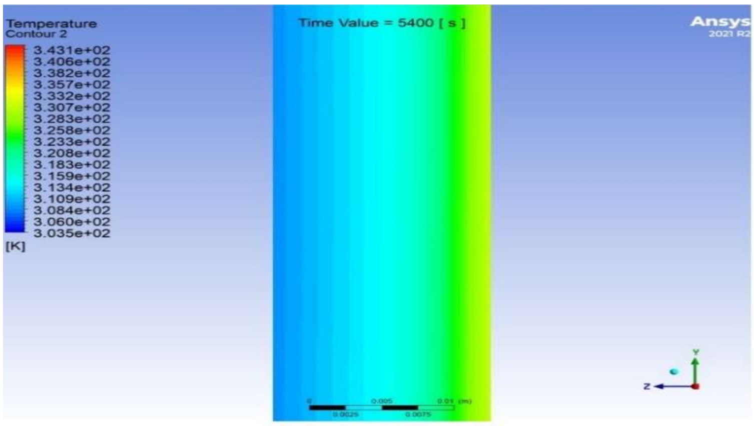


Fig.7.8: Temperature Contour PCM (OM 42) @ 10mm

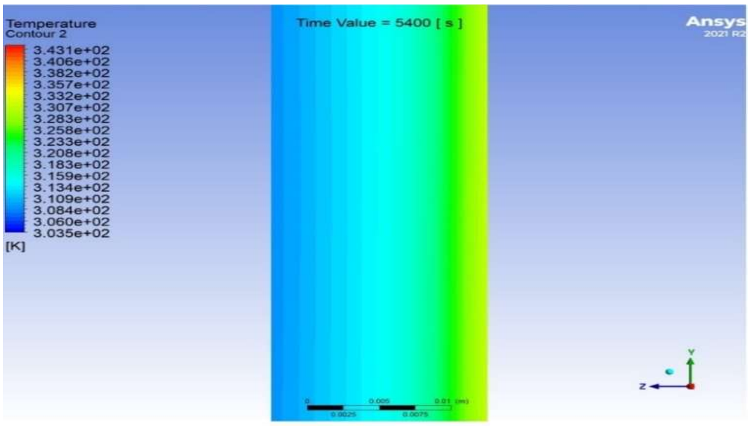


Fig.7.9: Temperature Contour PCM (OM 42) @ 15mm

EFFECT OF OM 50 PCM LAYER THICKNESS ON INSIDE WALL TEMPERATURE IN 4MM AND 2MM GLASS

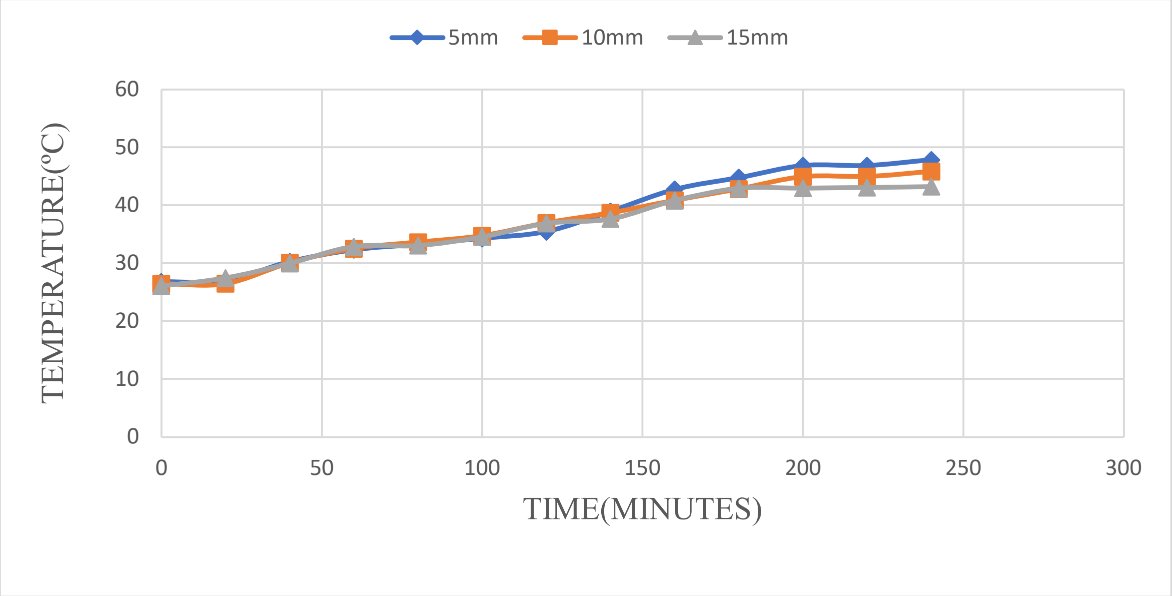


Fig. 7.10: Effect of OM 50 PCM layer thickness on inside wall temperature in 4mm glass

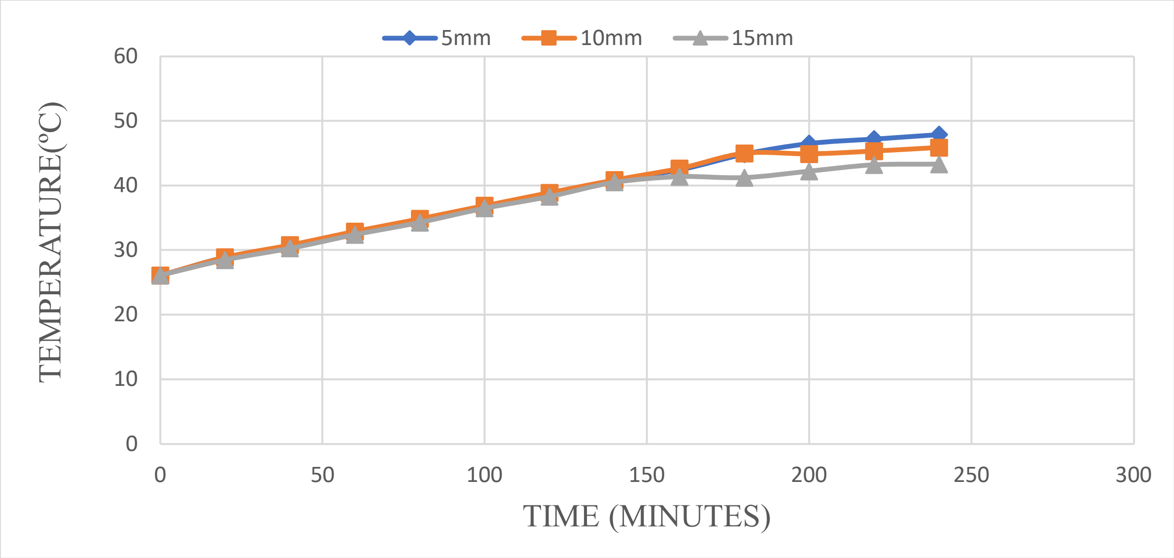


Fig. 7.11: Effect of OM 50 PCM layer thickness on inside wall temperature in 2mm glass

From the above two graphs are the effect of PCM layer thickness on inside wall temperature of the OM 50 in 15 mm PCM layer thickness ranges between 43°C and 45°C since this is where PCM absorbs the latent heat and the phase change takes place. OM 50 PCM is a type of material that undergoes a phase change (melting or solidifying) at a specific temperature, and it can be used to regulate temperature in buildings by absorbing or releasing heat as needed. The optimal thickness of the PCM layer will depend on the specific needs of the building and the desired level of temperature regulation.

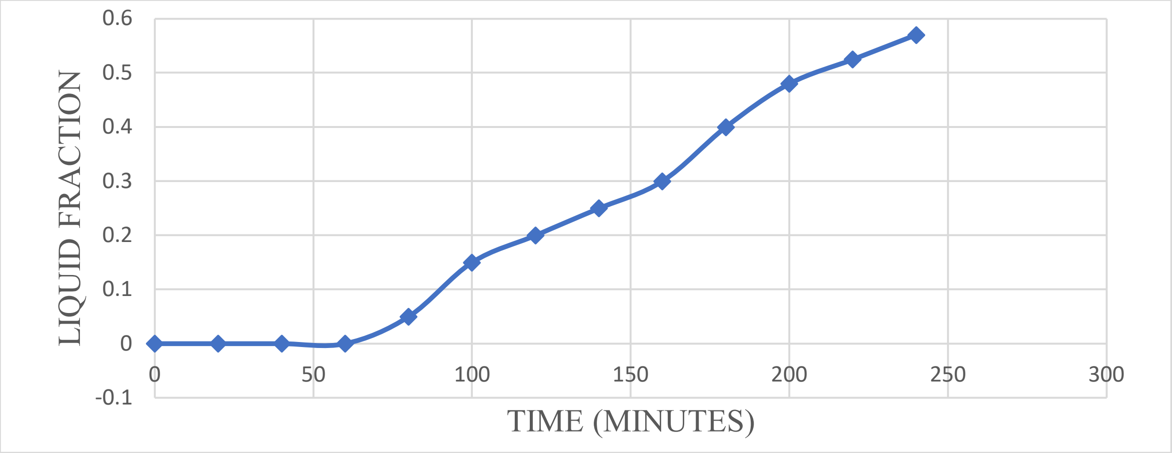


Fig.7.12: Liquid fraction Vs Time for PCM (OM50) filled double glazing

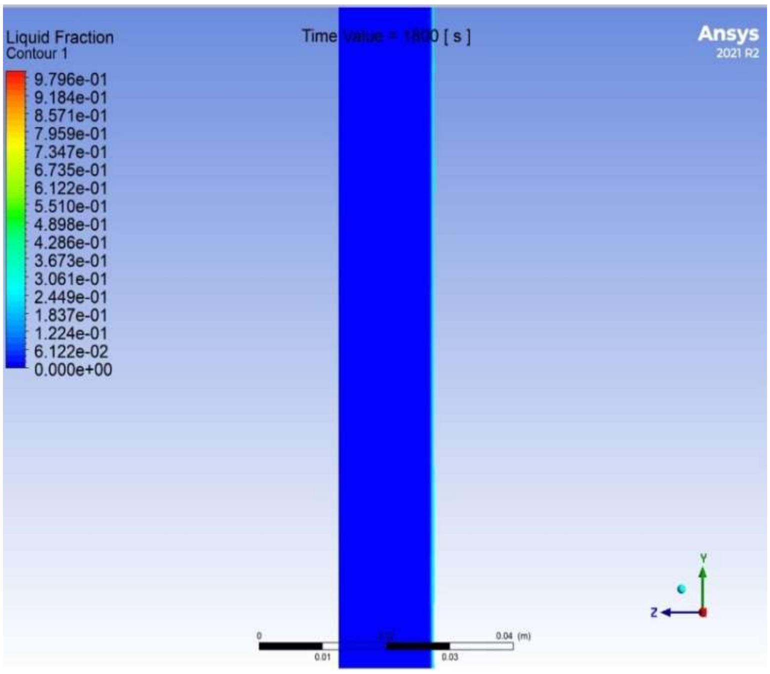


Fig.7.13: Liquid fraction Contour PCM (OM50) 1800s

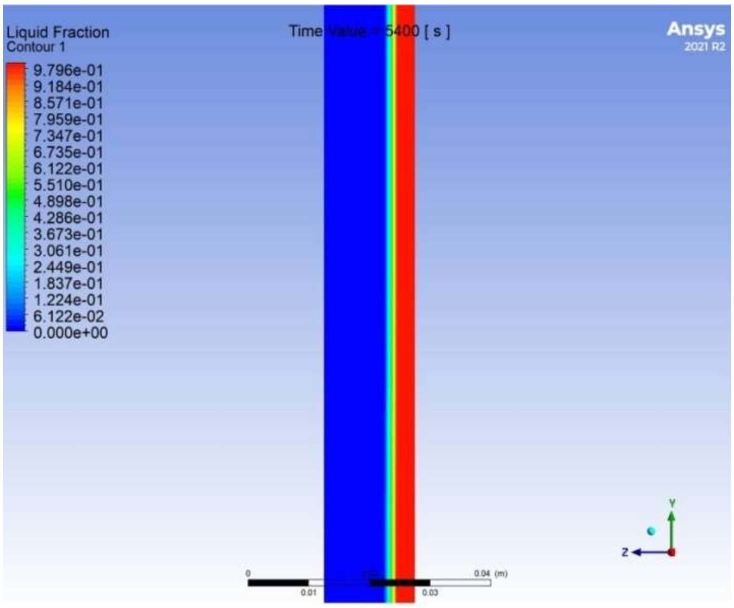


Fig.7.14: Liquid fraction Contour PCM (OM50) 5400s

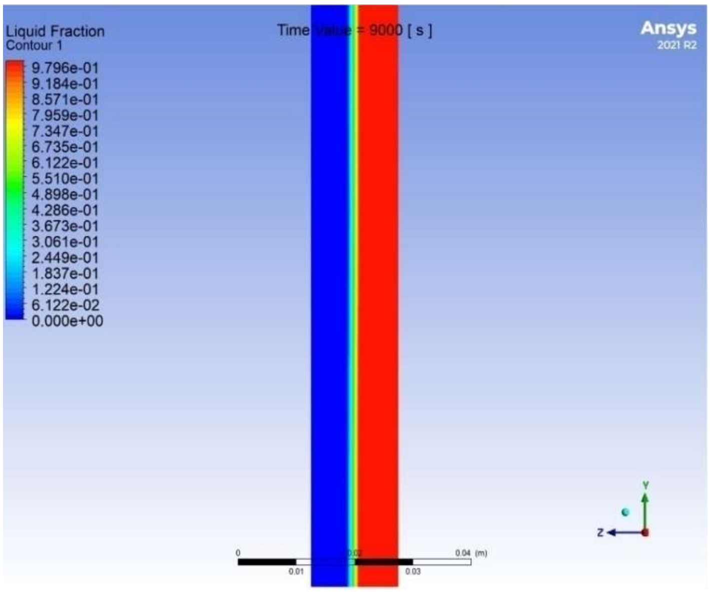


Fig.7.15: Liquid fraction Contour PCM (OM50) 9000s

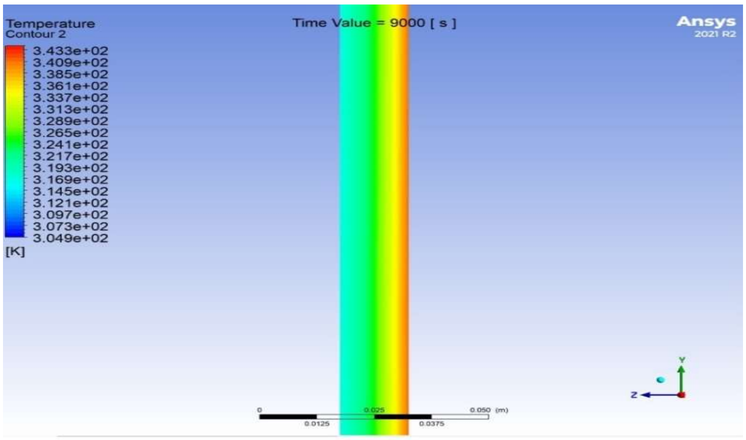


Fig.7.16: Temperature Contour PCM (OM 50) @ 5mm

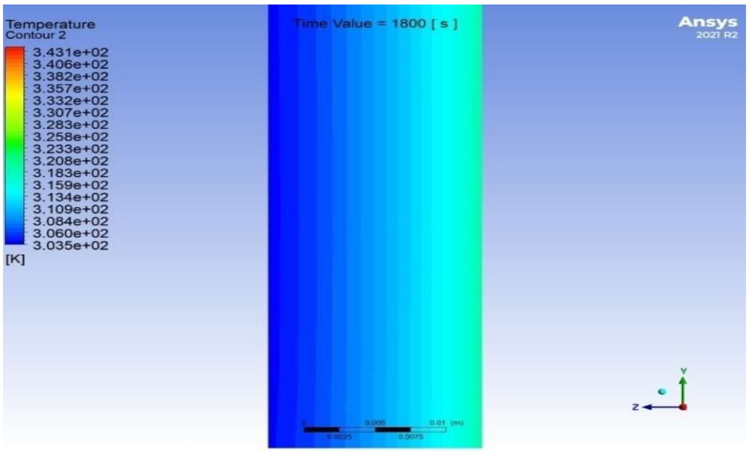


Fig.7.17: Temperature Contour PCM (OM 50) @ 10mm

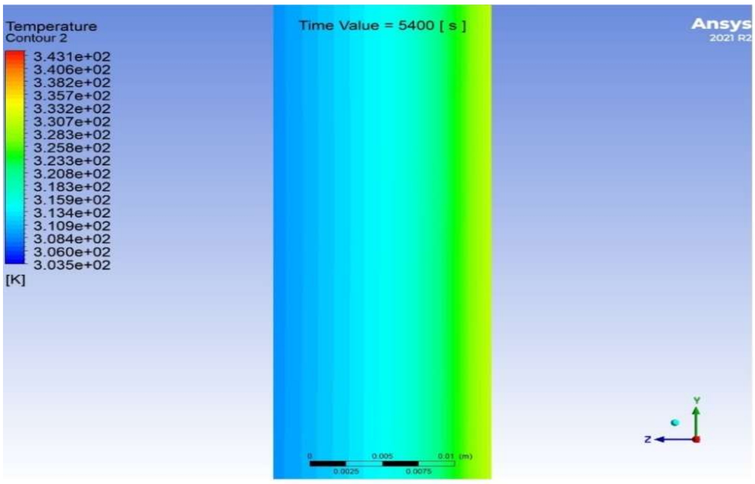


Fig.7.18: Temperature Contour PCM (OM 50) @ 15mm

VARIATION OF INSIDE WALL SURFACE WITH TIME TEMPERATURE FOR DIFFERENT PCM’s IN 4MM AND 2MM GLASS

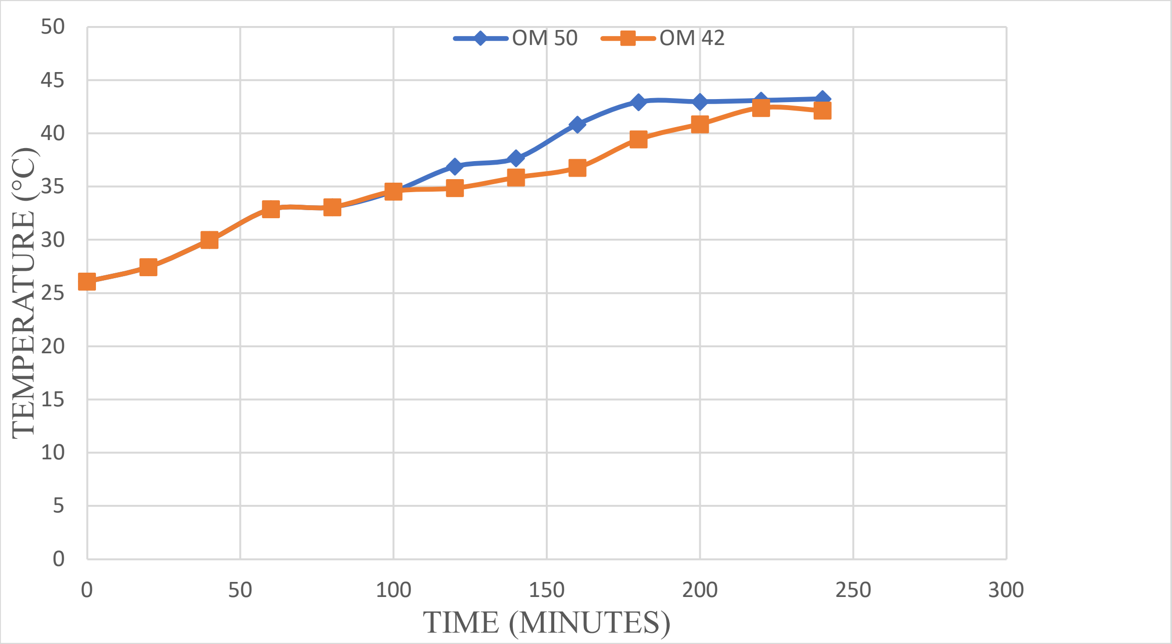


Fig.7.19: Variation of inside wall surface with time temperature for different PCM’s in 4mm glass

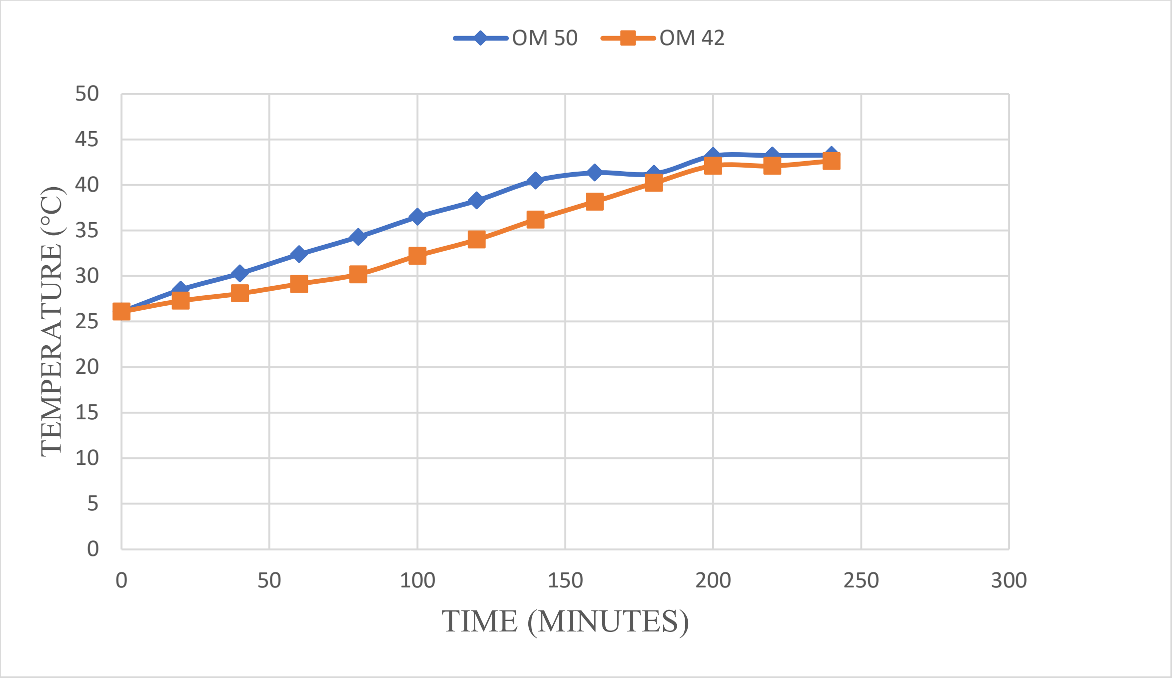


Fig.7.20: Variation of inside wall surface with time temperature for different PCM’s in 2mm glass

From the above two graphs are the Variation of inside wall surface with time temperature for different PCM's and layer thickness are noted . PCM's are a type of material that undergoes a phase change (melting or solidifying) at a specific temperature, and they can be used to regulate temperature in buildings by absorbing or releasing heat as needed. It clearly explains how the lower melting point PCM, or PCM(OM42), can be used to reach the highest efficiency with 15mm PCM layer thickness. It facilitates the long-term maintenance of a lower temperature in the inner glass wall. Due of the greater temperature difference, higher melting PCMs will experience conduction heat transfer between the outer and inner walls. Numerical studies shows that PCM OM 42 having 15mm layer thickness in 4mm glass is showing best performance.

EFFECT OF GLASS THICKNESS ON INSIDE SURFACE TEMPERATURE

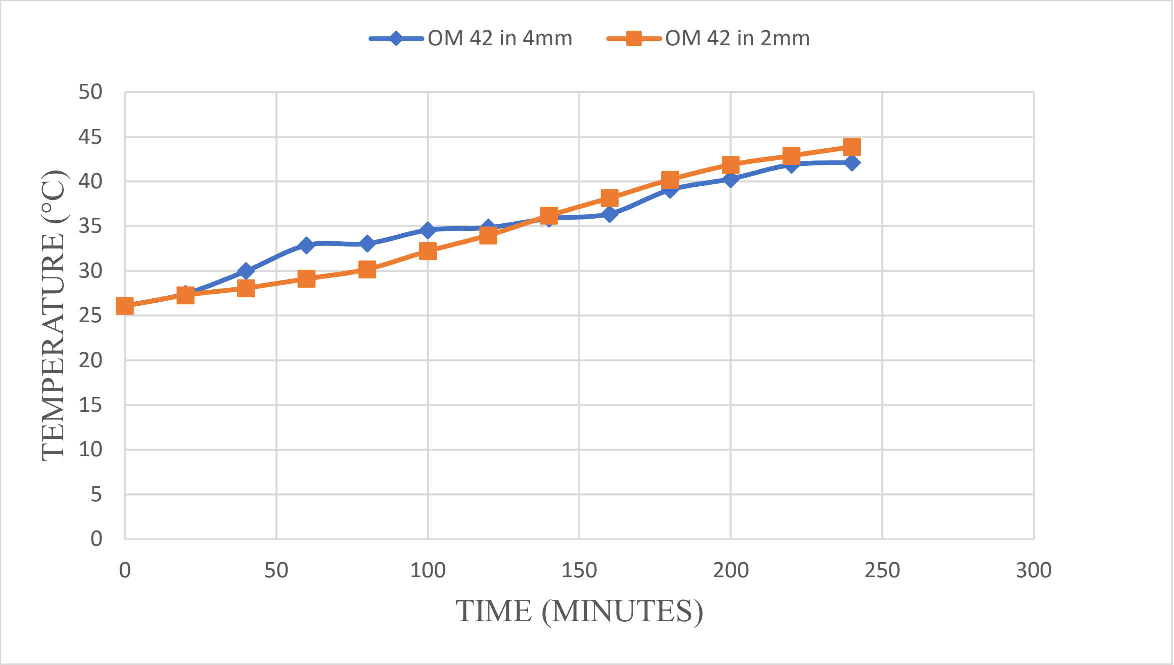


Fig.7.21: Effect of glass thickness on inside surface temperature

From the above results shows the effect of glass thickness on inside surface temperature of PCM,s in glass panel are noted. The thickness of glass can have an impact on the inside surface temperature of the glass. Thicker glass typically provides better insulation and reduces heat transfer, which can lead to lower inside surface temperatures. In contrast, thinner glass may allow more heat to pass through, resulting in higher inside surface temperatures. It's important to consider the desired level of temperature regulation and energy efficiency when selecting the thickness of glass for a building. The PCM utilization of PCM (OM42) is 80% and that of PCM (OM50) 60% respectively for a layer thickness of 15mm.It shows that PCM OM 42 having 15mm layer thickness in 4mm glass is showing best performance.

CHAPTER 8

COMPARISON BETWEEN EXPERIMENTAL AND NUMERICAL RESULTS

8.1 COMPARISON OF RESULTS

Table 8.1 Comparison of Experimental and Numerical Values for PCM (OM42)

Experimental Investigation(°C)	Numerical Investigation (°C)	Time (min)
32.005	27.456	20
34.043	30.007	40
34.110	32.890	60
34.107	33.867	80
34.008	34.028	100
35.105	35.105	120
35.008	35.008	140
35.123	35.123	160
34.990	34.990	180
34.478	34.478	200
34.400	34.400	220
34.342	34.342	240

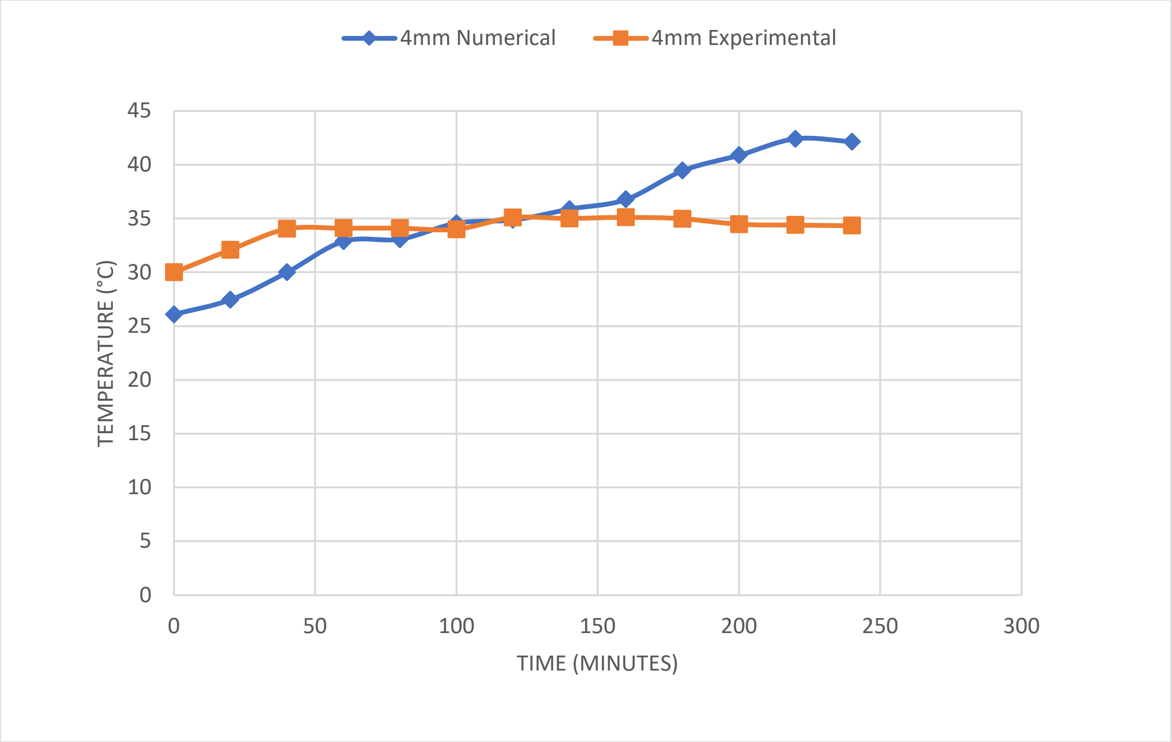


Fig 8.1: Average Inner surface Glass temperature of the double glazing Vs Time graph for PCM (OM42) filled double glazed window

It is obvious from the data above that the experimental values and numerical values correspond very well. Since the other window walls are assumed to be adiabatic in the simulation, it is discovered that the inner surface temperatures obtained using CFD simulation are greater than those of experimental values. In the experiment, however, there may be some heat loss through the walls that is not taken into account in the simulation. Since the surface temperature readings, not the ambient air temperature, are taken into account here, convection heat transfer in the outer side window need not be taken into account. The inner glass walls are taken into account for convection heat transfer, and a 27°C initial temperature is used for the solution.

8.2 REGRESSION ANALYSIS

The conditional explanation of the answer is typically thought to be an affine function of the values of the descriptive variables (or predictions); a conditional median or other quantile is occasionally used. Line regression, like all other types of regression analysis, concentrates on the likely distribution of conditional responses given predictable values rather than the distribution of the aggregate probability of all these variables, which is the domain of multivariate analysis. In this work, the agreement between test analysis and results was investigated using a straightforward linear regression model. Here, we wish to carry out a retrospective regression analysis in order to organise the numerical and test data as a scatter plot around the line structure that is based on the test result. Understanding the agreement between test data and numerical data is made easier by the variation from line to line.

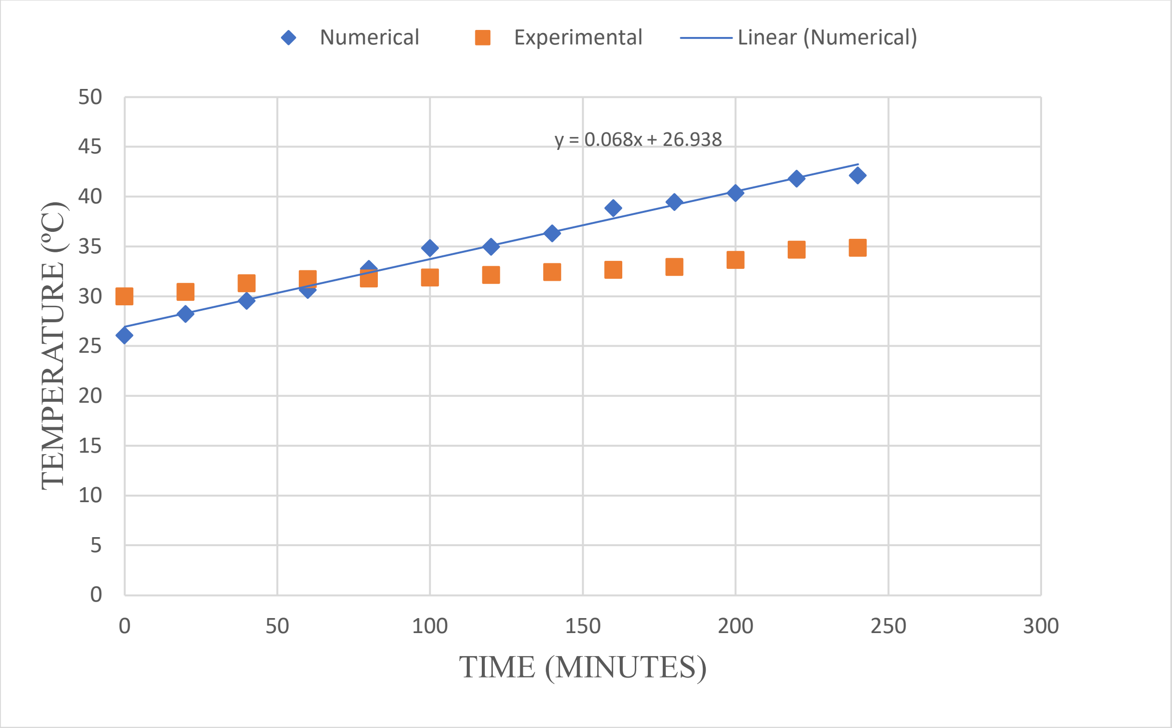


Fig.8.2: Scatter Plot Regression Trend line for PCM (OM42) filled double glazed window

In the analysis, it appears that the regression analysis has confirmed that the experimental data and the numerical analysis are in excellent agreement with each other. The fact that the values are very close to the linear line plotted with the experimental results indicates that there is only marginal variation above and below the line in all cases. This suggests that the numerical analysis is accurately predicting the experimental results and that the two sets of data are in agreement with each other.

CHAPTER 9

CONCLUSION

PCM is an effective substitute to traditional cooling systems, which is a practical application of the LHS concept, can there by act as a smart material to control the indoor temperature of a building. The results revealed the PCM potential for indoor thermal regulation of highly glazed buildings. Overall, the results of the study suggest that the use of PCM filled double glazing may be an effective way to reduce energy consumption and improve indoor comfort in buildings. However, the effectiveness of PCM technology may depend on various factors such as the type of PCM used, the thickness of the glass. PCM materials have the ability to absorb and release heat energy as they change phase from solid to liquid and vice versa. By filling the gap between double glazed windows with PCM material, the PCM can absorb excess heat during the day when temperatures are high and release it back into the room at night when temperatures are low. This process can help to regulate the indoor temperature, reducing the amount of heat that is transferred through the window and ultimately reducing the inner surface temperature of the window. The thickness of the glass can also impact the effectiveness of the PCM layer in regulating temperature, with thicker glass typically offering better insulation and reducing heat transfer. Since the values for the inner surface temperature obtained through experimentation and numerical analysis are consistent, numerical analysis performed on ANSYS FLUENT displays results that are comparable to those obtained through experimentation. Some of the differences reported in the numerical results can be accounted for by the assumptions made in the numerical analysis, such as neglecting heat loss through window margins and infiltration.

SCOPE FOR FUTURE WORK

Development of mathematical models to predict the thermal performance of PCM-based systems as a function of the PCM layer thickness.

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