EXPERIMENTAL AND NUMERICAL STUDY ON THE IMPACT OF THERMAL CHARACTERISTICS OF DIFFERENT PCM IN DOUBLE GLAZED WINDOWS

A PROJECT REPORT

Submitted by

RAHUL RAJEEV

REG.No:TKM20MEIR12

to

The APJ Abdul Kalam Technological University

in partial fulfillment of the requirements for the award of degree of

Master of Technology

in

Industrial Refrigeration and Cryogenic Engineering

DEPARTMENT OF MECHANICAL ENGINEERING

T K M College of Engineering, Kollam

JULY 2022

DEPARTMENT OF MECHANICAL ENGINEERING T.K.M COLLEGE OF ENGINEERING, KOLLAM

CERTIFICATE

This is to certify that the project report entitled ***"Experimental and Numerical Study on the Impact of Thermal Characteristics of Different PCM in Double Glazed Windows"*** submitted by **RAHUL RAJEEV.**, Reg. No: **TKM20MEIR12** during **2020-2022** to the APJ Abdul Kalam Technological University in partial fulfillment 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 carried out by him under our guidance and supervision.

Project Guide:

Dr. K.A. Shafi

Professor
Dept. of Mechanical Engineering
T K M College of Engineering, Kollam

P.G Coordinator:
Dr. K.A. Shafi,
Professor
Dept. of Mechanical Engineering
T K M College of Engineering, Kollam

Dr. P.N. Dileep,
Professor & Head
Dept. of Mechanical Engineering
T K M College of Engineering, Kollam

DECLARATION

I, Rahul Rajeev., hereby declare that this project report entitled "**Experimental and Numerical Study on the Impact of Thermal Characteristics of Different PCM in Double Glazed Windows**", submitted for partial fulfillment 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, T K M 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.

Rahul Rajeev

Reg.No.TKM20MEIR12 of the year 2020-22

Dr. K.A. Shafi
Professor
Dept. of Mechanical Engineering
T K M College of Engineering, Kollam

Dr. P.N. Dileep,
Professor & Head
Dept. of Mechanical Engineering
T K M College of Engineering, Kollam

July 2022

ACKNOWLEDGEMENT

I take this opportunity to express my deep sense of gratitude and sincere thanks to all who helped me to complete the project successfully.

Firstly, I would like to express my heartfelt thanks to my guide **Dr. K.A Shafi**, Professor, Department of Mechanical Engineering for his selfless support, guidance, motivation, great encouragement, and valuable comments during the course of project and during the preparation of this report.

I am extremely thankful to **Dr. T.A. Shahul Hameed,** Principal TKM College of Engineering for providing excellent experimental facilities at TKM Engineering College from bottom of my heart for lending me all facilities and support for the completion of project.

I express my gratefulness to my PG coordinator **Dr. K.A Shafi**, Professor, Department of Mechanical Engineering and **Dr. P.N. Dileep**, Professor & Head of Department, Mechanical Engineering for rendering their valuable suggestions, timely advice, and support throughout the work.

I expresses my deep sense of gratitude to thank **Dr. Mohammed Sajid N.K**., Professor and former Head of Department and **Dr. Mohammed Sadhikh**, Professor, former PG Co-ordinator, Department of Mechanical Engineering, TKM College of Engineering from bottom of heart for the support they have rendered during my project.

I thank **Dr. Reby Roy K.E** Department of Mechanical Engineering for allowing me to conduct my experimental procedure in Space Technology lab. I also extend my regards to **Sigi Kumar**, **Aravind J** and **Manu M** Research scholars, Department of Mechanical Engineering for their constant support during the proceedings of my project.

I also mark my deep gratitude to all the faculty of Department of Mechanical Engineering and my beloved classmates for their support and constructive intervention.

Rahul Rajeev

ABSTRACT

Green building designs are gaining traction in the current scenario, as today's energy source has a significant environmental impact due to its reliance on fossil fuels. Furthermore, fossil fuel sources are depleting at the same time as energy demand is quickly increasing. The construction or 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. Because windows are an essential aspect of a building's system for obtaining natural light, they cannot be overlooked when designing a structure. The present work investigates the effect of the phase transition or melting temperature of PCMs when used in double-glazed windows. Its impact on the heat and light transfer characteristics were analyzed using experimental and numerical methods. The PCM acts as latent heat storage and reduces the heat in leak to the inner space. The goal of this study is to limit the amount of heat that is conveyed to the inside through the glass. An experiment was conducted for each PCM material with different phase transition temperatures to determine the glazing's inner and outer surface temperatures in a controlled environment. To validate the experimental results ANSYS FLUENT software was utilized to conduct the numerical analysis. Windows with PCM filled between two glazing's were discovered to efficiently reduce the inner surface temperature of the glazing along with reduction in heat transfer. The main parameter that was taken into consideration in this work is the phase transition temperature. PCMs having different melting temperatures are used to establish that the phase transition temperature plays an important role in the proper usage of PCM in double-glazed windows. In the investigation, it was observed that the utilization of PCMs diminishes as phase transition temperatures rise. We must choose the right width for the double glazing to make up for this. The solidification of the liquefied PCM happens slowly and the glazing's ability to transmit light is unaffected if the PCM's melting temperature and thickness of the PCM layer is selected based on the atmospheric condition.

Keywords: Green building; PCM; latent heat storage; double glazed windows; HVAC.

CONTENTS

LIST OF TABLES

LIST OF FIGURES

ABBREVATIONS

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

CHAPTER 1

INTRODUCTION

Urbanization is quickly expanding these days, necessitating construction and infrastructure development. As a result of this progress, energy consumption is also rising. Buildings consume a lion part of the world's energy, primarily through the building's HVAC system. The inhabitants, electrical equipment, and infiltration via the building envelope, including walls and windows, are all components of the cooling or heating load in an HVAC system. Because it is highly susceptible to heat transfer, windows or glazing contribute significantly to HVAC load. However, windows are an essential and unavoidable feature of any structure since they serve a variety of services such as light transmission, ventilation, aesthetics, and a visual interface between the interior and outside environments**.** Tinted, metal coated glass, double glazing, and other options for energy reduction through windows are now being used. But, in terms of energy and economics, these options are not entirely viable.

1.1 BACKGROUND

Using Phase change material (PCM) loaded double glazed windows instead of conventional windows can result in significant energy savings. PCM absorb incoming heat from the outside through the window and do not allow it to pass through until the heat has been completely consumed for 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.

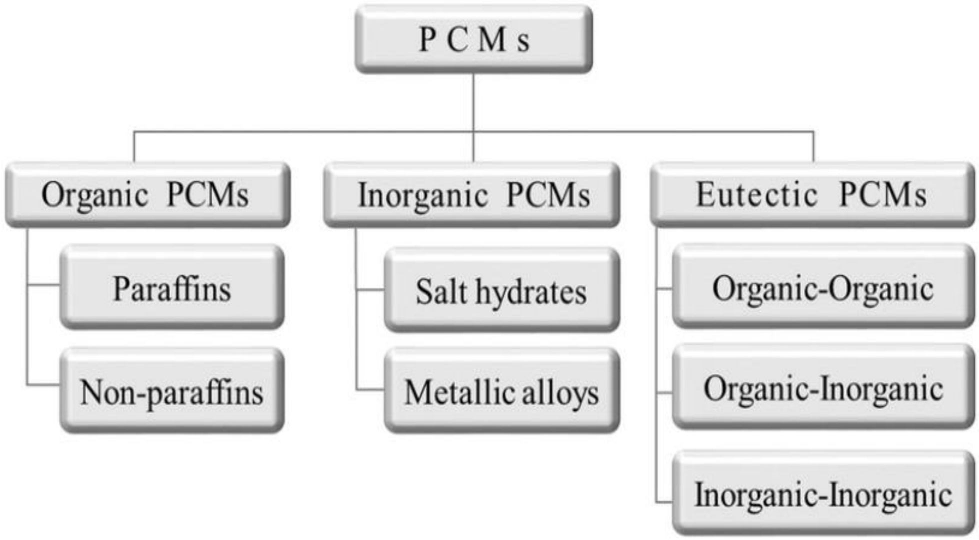


Fig 1.1 Classification of PCM (Guijun et al., 2019)

1.1.1 Organic PCM:

Paraffins and non-parrafins are examples of organic PCM. Chemically and thermally, they are inert. Organic PCMs have low heat conductivity in general. They don't have much, if any, subcooling. Subcooling occurs when one section of a substance melts while another hardens, causing the effect to be unevenly distributed. They have no corrosive properties. Fatty acids and their esters, glycols, and other non-paraffin’s are employed as PCMs.

1.1.2 Inorganic PCM:

Hydrated salts and metallic PCMs make up inorganic PCMs. Metallic materials are inappropriate for construction applications because they do not operate within the necessary temperature range and are extremely heavy. Natural salts are combined with water to create a hydrated salt solution. To attain the needed temperature for phase transition, the chemical composition of salts in the mixture is altered. 'Subcooling of inorganic PCMs offers a difficulty to their uses. High latent heat of fusion per unit volume, greater thermal conductivity when compared to organic PCMs, little volume change, and convenient availability at a reduced cost are all desirable qualities of salt hydrates utilised as PCMs.

1.1.3 Eutectic PCM:

A mixture of chemical substances or components called a eutectic system. It solidifies at a lower temperature than any other composition made up of the same elements. The eutectic composition is identified by the temperature at which it solidifies. Organic-organic, organic-inorganic, and inorganic-inorganic chemicals are all possible combinations in Eutectics. They melt and freeze without segregation because they freeze to a crystal mixture, preventing the components from segregating. Both components liquefy at the same time when they are heated. One benefit of eutectic blends is their propensity to generate certain properties, such as a precise melting point or a higher heat storage capacity per unit volume.

1.3 PROBLEM FORMULATION

Research to identify sustainable energy solutions is produced by the global expansion of energy thinking. Because more people use cooling systems and air conditioning in general throughout the summer, there are higher summertime electricity peak needs. The necessity for safe, pollution-free refrigerants and affordable energy are crucial, as are the high cost of fossil fuels, environmental concerns, and environmental issues. By using PCM in between double glazed window can reduce the internal heat gain during day time.

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

The PCM materials can act as environmental friendly alternative to reduce the internal heat load in a building. However studies have to be conducted on the thermal characteristics of the PCM material to know its efficiency and its effectiveness. This chapter summarises the results of considerable research into the performance and the effect of different 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) performed statistical analysis and compared PCM glass windows filled with gas-absorbent windows. “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 calculated electronically. High-absorption gas mixture, moderate gas absorption mixture, and visible infrared radiation mixture were all used. The thermal conductivity of a double glazed window filled with a mixture of suction gas and the use of clear glass is a distance of 0.55 to 0.65. The temperature gain of a double-glazed PCM-filled window is in the range of 0.65 to 0.80”.

Gasparella et al. (2011) examined the effects of different 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 high level of well-installed residential building. Four regions of central and southern Europe were considered for their climate information: Paris, Milan, Nice, and Rome. Data were analyzed statistically to determine the most influential features. Reversal analysis shows that thermal transfer is important for strength and high loads in both winter and summer conditions. For both summer loads and winter and summer energy needs, solar transmission seems to be the most important. It is important to suggest the initial preparation for solar exposure, geometry, and solar and thermal structures of the glossy system due to the effects from computer simulations made on the various types of structures currently in use. The top of the windows does not seem to touch the energy requirements of the winter".

Jian Qu et al. (2014) summarised that for "the production of energy-efficient glazing goods, single layer, waterborne, silicon-based, transparent heat insulation coatings were developed. The coatings' optical, thermal, and electrical properties were investigated. The following conclusions may be drawn from the new data: The coatings have high surface resistivity, low haze, low far-infrared emissivity, high absorptance (low transmittance) in the near-infrared range, and high visible light transmittance. The ATO concentration and coating thickness had no effect on the haze of transparent heat insulation coatings. The transparent heat insulation coatings' ability to absorb near infrared light is thought to be the cause of their thermal insulation effect The developed transparent heat insulation coatings have a surface resistance that is 11 orders of magnitude higher. The silicon emulsion gives the transparent thermal insulation coatings good artificially accelerated weathering resistance and high radio wave transmission, which diminishes with increasing ATO content and coating thickness".

Rouhollah Ahmadi and Amir Shahcheraghian (2015) in their study concluded that Phase change materials are a type of substance that can be melted to implement high latent heat capacity. Here, an attempt was made to slow down the dispersion of heat flux into the structure by using PCM in windows as a heating store. In this study, heat flux diffusion via two different types of windows on a hot day in Tehran, Iran was studied. Windows of types I and II are made of two layers of glass with one of those layers filled with PCM. In type I, heat flux diffusion into the room rises monotonically during the day, reaching 97 percent of applied heat flux after 6 hours. On the other hand, type II is shown to absorb the majority of heat flux and prevent it from diffusing into the room. In type II windows, PCM holds 86 percent of the external heat flux into the window for 9 hours, according to Fluent's numerical simulation. Thus, it can be said that employing PCM in windows can create an excellent thermal barrier in summer for a building's windows.

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 at various 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 accurate results, additional CFD calculations were carried out for other glazing examples (4-16-4 argon/air, 4-13-4 air, and 4-13- 4 argon/air). The calculation and measurement findings for the chosen glazing (4-16-4 with air filling) demonstrated satisfactory agreement. A few changes to the EN 673 and ISO 15099 standards have been suggested after the set of 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)”.

In North-East China, Hussein et al. (2016) did “a numerical analysis on the thermal performance of a PCM filled double glazing unit with various PCM thermo-physical characteristics. The effects of density, specific heat capacity, latent heat, thermal conductivity, and PCM melting temperature on the thermal behaviour of a PCM-filled double-glazing unit were also investigated with the goal of investigating the thermal behaviour of a PCM-filled double-glazing unit. When the density of PCM is larger than 1275 kg/m^3, the solar transmittance of double-glazed units is quite low. The time lag in temperature increases as the density of PCM grows, the time range of liquid PCM decreases, and the melting time is delayed. The effect of PCM density on temperature decrease is minor. To improve the thermal performance of double-glazed units filled with PCM, increasing the thermal conductivity of the material is ineffective when PCM has 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 PCM's thermal conductivity exceeds 2.1 W/m K, the effect of PCM's thermal conductivity is reduced. When the specific heat capacity of PCM is less than 4460 J/kg K, increasing the specific heat capacity of PCM is 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, the initial melting time is delayed, and the time range of liquid PCM changes slightly as the specific 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 performance of 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 range of 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 indoor and 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 temporal range of liquid PCM narrows.PCM 297–299 K has a melting temperature range that is close to China's climatic conditions".

Zheng et al. (2016) used a "numerical model to explore the thermal performance of a PCM-filled double glazing unit with various phase change material optical characteristics. The refractive index of liquid and solid PCM has a minor effect on the temperature of the interior surface of a double-glazed unit filled with PCM, but it has a significant impact on the transmitted energy of the interior surface of a double-glazed unit filled with PCM. The total transmitted energy and solar energy of the inner surface of a double glazing unit filled with PCM decrease as the refractive index of liquid and solid PCM increases".

Zhong et al. (2016) carried out "a numerical study for PCM-filled glass windows in hot summer and cold winter conditions. The PCMs utilised in this study are $Na_2SO_4.10H_2O$ and $CaCl_2.6H_2O$.This study compared the thermal performance of PCM-filled glass windows to insulated glass windows (double glass windows filled with dry air and sealed with sealing strips).To acquire the internal and external surface temperature changes of these windows in 48 hours, a 3D unsteady model was created in FLUENT. The phase transition process of $CaCl_2.6H_2O$ takes 6 to 30 hours on gloomy and rainy summer days. However, because of its greater melting temperature, the internal surface temperature of double glass windows filled with $Na_2SO_4.10H_2O$ was higher than that of insulated glass windows over the majority of the operation. The heat flow into the room is determined by the windows inside surface temperature. The thermal performance of $Na_2SO_4.10H_2O$ -filled double glass windows was not as good. In a specific period of the complete process, mutations of the internal and external surface temperatures emerged, and thermal performance weakened. During the 10–25 hours when $Na_2SO_4.10H_2O$ was melting, the temperature of the internal and external surfaces was kept within the melting temperature range. In 48 hours, the internal and external surface temperatures of double glass windows filled with $Na_2SO_4.10H_2O$ changed smoothly, and they performed better in hot summer days. There was no phase change in these PCM in the winter because the phase change temperature of $CaCl_2.6H_2O$ and $Na_2SO_4.10H_2O$ was higher than the ambient temperature. During the day, sensible heat was used to store heat in PCM, which was then released at night. In the daytime, double glass windows filled with PCM reduced room heat gain induced by solar radiation from the window, and the heating load was raised".

Chandel et al. (2017) investigated the present level of research on energy storage, toxicity, health risks, and commercialisation of phase-changing materials. "The paper describes the features of several PCMs as well as their possible uses. It defines the three types of PCMs: organic, inorganic, and eutectic PCMs. The study found that salt hydrates are safe if handled cautiously, whereas commercial grade paraffin's, which are combustible and emit poisonous vapours, are a possible health danger and should be used with caution. The economic potential of PCM goods is discussed, demonstrating that these materials can be used in textiles, heat or cold storage during transportation, pain relief packs, vaccine and blood storage, and other applications where maintaining a critical temperature is crucial. Melting point in the appropriate working temperature range, high latent heat capacity value, high specific heat value, chemically stable, high thermal conductivity, non-toxicity, and non-flammability are all desirable features for selecting a good PCM".

An experimental investigation was undertaken by Durakovic et al. (2017) to investigate the performance of water and PCM filled double glazed windows. "The PCM utilised in this experiment was Rubitherm RT 27.Air, water, and PCM were used as filler materials in double glazing in a series of tests. At peak temperature, the temperature differential between the inner and exterior glass surfaces for without PCM glazing was roughly

5^{o}C.Low air conductivity, which acts as a thermal insulator, accounts for the large temperature differential. As a result, high temperature fluctuations on the outer glass surface (about 11^{o}C) were detected, while the temperature oscillation on the inner glass surface was around 5^{o}CBecause air has a low specific heat capacity, the amount of heat that accumulates between the glazing is negligible. When the outside air temperature drops below room temperature, it takes an hour for the change to be reflected on the interior glass surface. The highest temperature differential between the outside and inner glass surfaces was roughly 2^{o}C in the case of water filled glazing, which was due to the water's comparatively higher thermal conductivity. When compared to air-filled glazing, the outside glass surface temperature variance was around 2^{o}C lower, but the inside glass surface temperature variation was about 4^{o}C higher. The water's somewhat higher specific heat capacity allows it to absorb heat, resulting in a two-degree reduction in the temperature of the outside glazing".

"The significantly higher heat conductivity of water causes increased variance in interior glazing temperature. As a result, the temperature change on the internal glass surface is more susceptible to the outside temperature change, making water an unfavourable medium for energy storage between the glazings. 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 flattening effect over the melting and solidification period was seen. Because the stored latent heat in 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 better material for energy storage and balance".

Gorantla et al. (2017) investigated "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).Four double glazing window material combinations were chosen for this study: clear-clear, bronze-clear, green-clear, and grey-clear. Between the two glass layers, a 10 mm unventilated air space was maintained.. The UV 3600 Shimadzu spectrophotometer was used to test the spectral optical characteristics of four glass materials at wavelengths ranging from 300 nm to 2500 nm. Design builder 4.3.0.039 was used to create a total of 64 building models and the Energy plus 8.1 simulation tools was used to conduct thermal analysis. According to the findings, of the sixty-four building models tested in India's four climatic zones, concrete buildings with double grey-clear glass windows were determined to be the most energy efficient in terms of least heat gain. When compared to the other three double glazing window glass materials, clear-clear double glazing window glass material gains the maximum amount of heat".

Kim et al. (2017) investigated "the performance of vacuum glazing in office buildings in Korea by a modelling and experimental investigation. Vacuum glazing has a superior thermal performance than double glazing. Furthermore, when compared to double-glazing, the U-value of vacuum glazing was reduced by up to 55 percent. The low-e glass and argon gas gap added to double glazing resulted in a maximum 27 percent reduction in U-value compared to triple glazing. When compared to a case with double glazing, the vacuum glazed case saved a maximum of 2.46 percent in energy consumption. Furthermore, when compared to double glazing, the energy saved with double vacuum glazing was a maximum of 3.91 percent. Energy usage, on the other hand, was higher than with the triple-glazed case".

Bolteya et al. (2020) studied "the thermal efficiency of PCM-filled double glazing units in Egypt using experimental and numerical methods. For this project, the PCM was RT28HC.Internal temperature, total transmitted energy, and liquid fractions were used to study the influence of PCM thicknesses on the thermal efficiency of double-glazing unit (DGU) using fluent software. When filled with PCM instead of air, the temperature of the DGU internal surface reduced by 7.6^0C, while CFD findings showed that the interior surface temperature decreased by 9.44^0C, and the total transmitted energy decreased by 223.9 W m^{-2} when the PCM thickness was 50 mm compared to 4 mm. PCM was entirely melted at thicknesses ranging from 4 mm to 30 mm, suggesting a good usage ratio, 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. The findings demonstrated PCM's potential for indoor heat management in heavily glazed structures, with PCM thicknesses of up to 30 mm being recommended".

Qudama Al-Yasiri and Marata Szabo (2021) concluded that "when fitted with building materials, PCMs have a strong potential to improve the building's energy. The following ideas can be used in future research to guide additional analysis and advancements. Little emphasis has been paid to the thermal behaviour and advantageous qualities of PCM-incorporated structures in severe weather. The PCM reaches its full melting condition in the early hours of the day in extremely heated environments. To prevent any malevolent behaviour, immediate release of stored heat is necessary. The passive method is insufficient in this situation, and the nocturnal ventilation technique is worthless. To prepare the PCM for the following day cycle, an alternative discharge medium must be used, such as geothermal energy. In frigid climates, the building component that receives sunlight passively absorbs heat during the day and releases it as the temperature drops. The PCM cannot be heated since the solar radiation is often low in colder places and cannot reach the envelope layers. Consequently, it is necessary to use solar energy actively by using solar collectors. The biggest issue with PCM's thermal conductivity that has been raised in the construction application. It sounds like a creative idea to use plastic products as macro encapsulation containers in hot climes. These materials may limit the heat from the outside; supporting insulation more effectively. These substances have an impact on PCM's poor heat conductivity. So proper care should be taken to ensure efficient use. There is a dearth of long-term research that offers a clear picture of PCM performance throughout many years of service in buildings. Studies on the viability of applying PCM to entire buildings are likewise few. These investigations are required for the commercialization of technologies".

2.2 SUMMARY

- Glazed windows are main source of heat load in high raise buildings.
- 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.
- In this study an attempt to compare the effect of phase transition temperature of different PCM materials in double glazed windows.

2.3 OBJECTIVES

- Develop an experimental setup to conduct the study in a controlled environment.
- Conduct experimental studies on double glazed window for its heat transfer characteristic using PCM materials of different phase transition temperature.
- Conduct numerical study to validate the experimental result.

2.4. METHODOLOGY

- Literature review and market survey of different PCM materials.
- Analysing the findings of each publication
- Identifying the research gap.
- Problem formulation
- Selection of suitable PCM materials based on phase transition temperature.
- Conduct the experiment to obtain the required parameters.
- Conduct the numerical validation of the experiment.
- Comparison of the results.

CHAPTER 3

COMPUTATIONAL FLUID DYNAMICS

3.1 INTRODUCTION TO CFD

One area of fluid mechanics called computational fluid dynamics (CFD) makes use of numerical techniques and algorithms to solve and examine issues involving fluid flows. The countless computations needed to simulate how fluids and gases interact with the intricate surfaces utilised in engineering are carried out by computers.CFD forecasts quantitatively what will occur with fluid flow, frequently with the complexities 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 finite difference method is the most straightforward numerical technique used in the heat/diffusion equation's solution. The basic idea behind the method is to replace the numerous derivatives that result from the formal description of the problem with appropriate approximations on a finite difference mesh of nodes. The simplest derivation of finite difference formulas makes use of Taylor series. The final set of linear algebraic equations can be solved using any numerical technique.

3.3.2 Finite Element Method (FEM)

The calculation domain is separated into elements using the finite element method, such as triangular rectangles, tetrahedral, or rectangular parallelepipeds .At specific joints known as nodes, these elements are regarded as interconnected. Here, a straightforward function can be taken for estimating the fluctuation of the field variable inside a finite element. The values of the field variables in each node serve as the definition for these approximation functions. The nodal points are where the new unknowns are located when field equations are constructed for the entire continuum. The node values of the field's variables can be attained by resolving the field equations, which are typically expressed as matrices. Once understood, approximation functions use the combination of these to define the field variable.

3.3.3 Finite Volume Method (FVM)

In both research coding and commercial software, this is the traditional or conventional approach that is most frequently employed. A different approach to discretization is related on the notion that the computation domain can be partitioned to a number of finite volumes. This method represents each finite volume as a line in 1D, an area in 2D, and a volume in 3D. Each finite volume's nodes serve as the hub for computational values. The simplest finite volumes in 2D rectangular Cartesian coordinates are rectangles. The rectangle faces are created for each node by drawing perpendiculars via the midpoints of neighbouring nodes.. The initial partial differential equation is integrated across each finite volume to provide the discretization equations. Nonlinear issues can readily be solved using this approach. Iterative techniques are used to arrive at the solutions of algebraic equations.

This approach has one advantage over FDM: it can be used without a structured mesh, albeit one can be employed. The FVM may deal with issues with asymmetrical geometry. The fact that this method can readily conserve the variables on a coarse mesh is another benefit it has over FEM. This is a crucial aspect of the fluid problem.

3.4 ADVANTAGES OF CFD OVER EXPERIMENT METHODS

The lead time and cost of a new design are significantly decreased as a result of CFD research. Both studying systems in risky situations and studying systems where controlled tests are hard or unfeasible to conduct are possible. It offers essentially infinitely detailed results.

The amount of data points and tested configurations directly relates to the uneven cost of an experiment in terms of facility appoint or labour expenditures. Contrarily, parametric analyses can be performed for relatively little money, for example to optimise equipment performance, and CFD algorithms can generate extraordinarily huge volumes of findings with essentially no additional cost.

3.5 WORKING OF A CFD CODE

The numerical algorithms that can be used to solve fluid flow issues are the foundation of CFD codes. Three essential elements are incorporated in all commercial CFD software (Phoenics, Flow3D, and Star CD) to enable easy access to the solving power. These user interfaces allow issue parameters to be entered and outcomes to be reviewed. The three elements are

- Pre-Processor
- Solver
- Post-Processor

3.5.1 Pre-processor

Pre-processing is the process of entering a flow problem into a user-friendly CFD application and then transforming this input into a format that the solver can use. User activities during the pre-processing stage include, The computational domain defines 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.

- Specifying suitable border criteria for cells that are next to or in contact with the domain boundary.

The solution of a flow problem is found at the nodes inside each cell. The precision of a CFD solution is dependent on 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

Similar to pre-processing, the post-processing field has recently seen a significant amount of development activity. The best CFD systems now include a variety of tools for data visualisation due to the increasing use of engineering workstations, many of which have great graphics capabilities. These consist of.

- 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 CFD project in industry is spent on the definition of the domain geometry and grid generation.

3.7 COMPUTATIONAL FLUID DYNAMICS SIMULATION

The design, scaling up, and operation of unit operations in the chemical process industries significantly rely on empiricism and correlations of overall parameters for non-ideal or non-equilibrium circumstances. Many current equipment designs are more akin to art than science because they are built on the knowledge of professionals applying common sense. Processes that are susceptible to local phenomena and reactant concentrations are usually difficult to design or scale up since the design correlations do not account for local impacts. It is difficult, if not impossible, to forecast non-idealities that result from scaling up lab or pilot scale equipment. computational fluid dynamics (CFD) are increasingly used by researchers, equipment designers, and process engineers to 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 be used. 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.

Fundamentally, numerical algorithms are used to solve the mathematical equations governing fluid movement, mass, heat transfer, chemical reactions, and other related phenomena. It is the combination of the traditional theoretical and experimental scientific departments with the addition of a contemporary numerical computation component. The output of CFD analysis yields pertinent engineering data that is applied to conceptual explorations of novel designs, in-depth product development, troubleshooting, and redesign. CFD frequently results in better insight, better performance, better dependability, more confident scale-up, improved product uniformity, and increased 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

The quest to standardise nomenclature and fundamental ideas in modelling and computer simulation has a long history. The operation research community started to pinpoint the fundamental issues and disagreements two decades ago, long before there was any concern in the CFD community. There are many disciplines that employ the words model, modelling, and simulation. As a result, these phrases might signify different things depending on the context and the discipline. A replica is a picture of how a physical system or process could seem, and it's made to help us comprehend, forecast, or manage its behaviour. Building or modifying a model is the process of modelling. Simulation is the practise of or application of a model. The community of operation researchers has identified the fundamental stages of modelling and simulation. Fig. 3.1 depicts 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. Observing and analyzing the physical system results in the conceptual model. Partial differential equations dominate the conceptual model in CFD. A functional computer programme that carries out a conceptual model is the computer model. The computer model is referred to as computer code in modern terms.

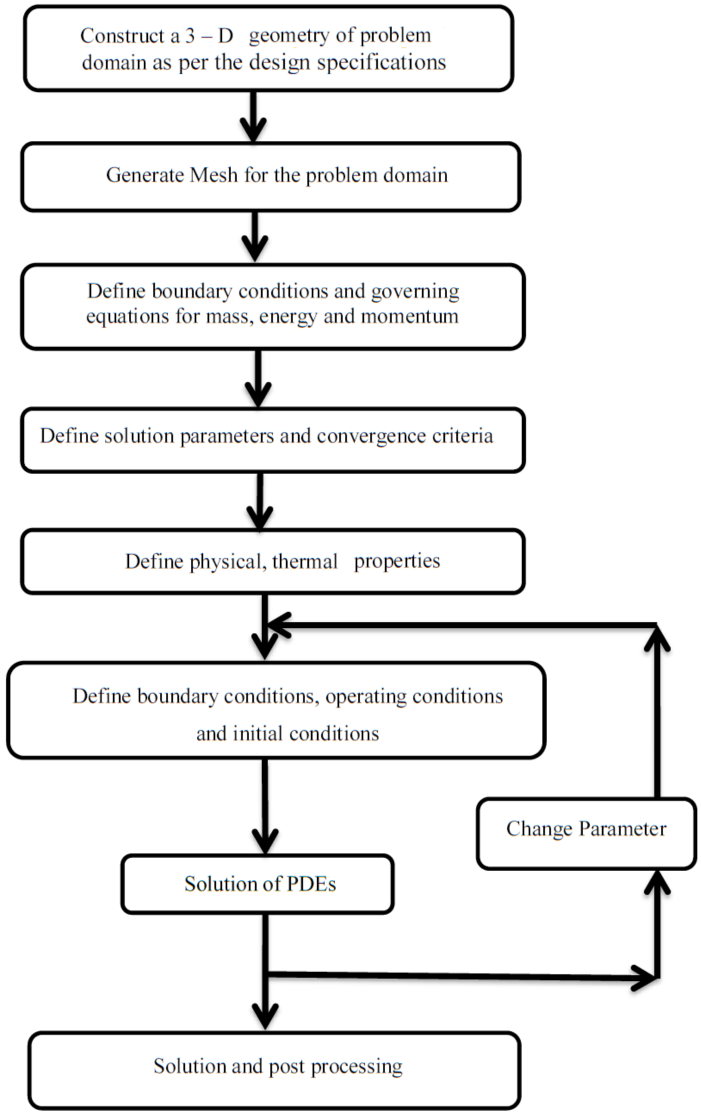


Fig 3.1 Phases of Modelling and simulation

Even though CFD simulations are often used in business, academia, and government, there are currently little consensus on how to evaluate its effectiveness. There is no universally accepted standard of veracity or correctness for CFD simulations. Depending on the uses that simulations are intended to serve, different levels of accuracy are required. Verification and validation are the two key elements required for determining credibility.

Verification is the method of verifying whether a computational simulation precisely depicts the conceptual portrayal of the model and the solution to the model; nevertheless, there is no say made regarding the simulation's association to reality.

From the standpoint of the model's intended usage, the process of validating a computational simulation involves determining how effectively it represents reality. The evaluation of accuracy is also emphasised in the definitions of verification and validation. Accuracy is typically evaluated in relation to benchmark solutions of simplified model issues during verification activities. Accuracy is evaluated through validation activities in relation to experimental data, which mirrors reality. Uncertainty and error are the two main categories that are often linked with the decline in modelling and simulation accuracy. The definition of indecision is a potential defect in any step or activity of the modelling process that results from ignorance. Incomplete knowledge of a physical trait or parameter is a typical cause of unawareness. The intricacy of a physical process, like in the case of turbulent combustion, can also contribute to ignorance. Error is 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 blunders like programming errors.

Computer programming, insufficient spatial discretization convergence, insufficient temporal discretization convergence, and insufficient iterative convergence are the four main causes of inaccuracy in CFD simulations. Verification testing's most crucial task is methodically adjusting the time step and grid size. The goal is to calculate the discretization error of the numerical solution. The discretization error ought to asymptotically go closer to zero as the grid size and time step get lesser. The most precise and reliable technique to quantify the inaccuracy in the computational solution is to compare it to a very accurate solution during verification activities. But for a comparatively small number of straightforward issues, there exist known highly precise solutions.

3.9 CFD CALCULATION

Before being used to CFD, the geometry of interest is first divided or discretized into a number of computational cells. In order to approximate the differential equations, the discretization method entails solving a number of algebraic equations for the variables at various discrete locations in space and time. The term used to denote the distinct locations is the grid or mesh.

The continuous data from the exact solution of the Navier-Stokes partial differential equations has now been replaced by discrete values. A simple problem might have a few thousand cells, while a very large and complex one might have millions. The shapes of cells vary. In 2D problems, cells that are triangular and quadrilateral are typically used. For 3D problems, cells with hexahedral, tetrahedral, pyramidal, and prismatic shapes can be employed.

CFD algorithms previously required the usage of structured grids with a single cell type, such as brick-shaped hexahedral components, in which the cells were organised in a regular way. By allowing cells to be organised in an irregular, unstructured manner, modern codes give much more geometric variety. Additionally, a competent CFD code can accept hybrid grids that combine various cell types to handle complex geometries, giving the CFD analyst flexibility. Software for computer-aided design (CAD) is frequently used to construct geometries. The geometry is provided to the grid-generation software in the form of either a wireframe or a solid model in order to create the CFD-quality grid.

A few programmes combine the creation of CAD geometry and mesh production into a single user interface The CFD calculations can begin once the grid has been established, the boundary conditions, such as pressures, velocities, mass fluxes, and scalars, have been described, and the physical characteristics have been defined. The required conservation equations will be solved iteratively by the CFD algorithms for every grid cell. Examples of typical chemical process applications include solving for mass conservation (using a continuity equation), momentum conservation (using Navier Stokes equations), enthalpy, turbulent kinetic energy, turbulent energy dissipation rate, chemical species concentrations, local reaction rates, and local volume fractions for multiphase problems.

For modelling and evaluating systems including fluid flow, heat transport, and related phenomena like chemical reaction, there are numerous commercial CFD software available. Popular CFD software programmes include ANSYS, FLUENT, CFX, and PHOENICS. Pre-processor, Solver, and Post-processor are the three key components of each of these commercial CFD codes. In particular, this study focuses on using the ANSYS software package to reproduce flow and mixing behaviour for industrial applications that involve chemicals and heat. However, in order to validate the outcomes produced by the ANSYS CFD code, It was also necessary to make comparisons with some of these well-known commercial CFD codes.

3.10 CFD SOFTWARE PACKAGE

Modelling flow and heat transfer in complicated shapes using a CFD software suite offers total mesh freedom, allowing for the relatively simple generation of unstructured meshes about complex geometries to solve flow issues. For the purpose of solving the transport equation of conservation of momentum, mass, and energy, a CFD code based on the finite-volume approach is used. An integral approximation of the integral form of the conservation law for each of the several contiguous control volumes across the area of interest is the primary objective of a finite-volume technique. The domain in this instance is discretized as control volumes into a finite number of computational cells. 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 more complicated geometries with multi-block ordered meshes, and quickly modify the mesh to 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,

$$\frac{\partial}{\partial t}\int_{CV}\rho\phi dV + \oint_{A}\rho\phi u.\, dA = \oint_{A}\Gamma\nabla\phi.\, dA + \int_{CV}s_{\phi}dV \qquad \textbf{(3.1)}$$

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

In this study PCM works on solidification and melting process. Whether melting and/or solidification take place at a single temperature (for example, in pure metals) or across a broad temperature range, ANSYS Fluent can be utilised to handle fluid flow problems (for example, in binary alloys). ANSYS Fluent does not explicitly follow the liquid-solid front; instead, an enthalpy porosity model is employed. The liquid-solid mushy zone is viewed as a porous zone with a porosity equal to the liquid % and matching momentum sink factors are added to the momentum equations in order to account for the pressure decrease caused by the presence of solid material. Sinks are also incorporated into the turbulence equations to account for the decreased porosity in the solid portions. Calculation of liquid-solid solidification/melting in pure metals as well as in binary alloys

- Continuous casting process modelling (also known as "drawing" solid material out of the domain).
- Modeling the thermal contact resistance between solidified substance and walls, for instance because there is an air gap)
- Modeling species movement with melting and solidification
- Post-processing of amounts involved in melting or solidification (that is, liquid fraction and pull velocities)

These modelling capabilities enable ANSYS Fluent to mimic a range of solidification/melting issues, including melting, freezing, crystal formation, and continuous casting. Enthalpy-porosity modelling is used in ANSYS Fluent to simulate the solidification/melting process. This approach does not specifically track the melt interface. Instead, the percentage of the cell's volume that is in liquid form is represented by a value called the liquid fraction that is assigned to every cell in the domain. The liquid fraction is determined using an enthalpy balance at each iteration.The liquid fraction can be found in the mushy zone between 0 and 1. The mushy zone is modelled as a "pseudo" porous medium in which the substance's porosity goes from 1 to 0 as it hardens. When the substance has fully solidified in a cell, the porosity is zero, and as a result, the velocities are also 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 to iteration.

  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

To limit convective and conductive heat transfer, traditional multi-glazed windows have their gaps filled with air or inert gases. The performance of three distinct PCMs with differing phase transition temperatures was characterized in this experiment. The goal of the experiment is to determine the temperature difference between the two panes of double glazing while using different PCM materials. The results were compared to those of double-glazed air-filled windows.

4.1 MATERIALS AND INSTRUMENTATION

4.1.1 Window glass:

In compared to other options, clear glass was chosen for this experiment because of its great light transmission. Glass with a strong light transmission is chosen, and then heat transfer is reduced.

Table 4.1: Properties of clear glass

Density ($kg\ m^{-3}$)	Specific heat capacity ($J\ kg^{-1}\ K^{-1}$)	Thermal conductivity ($W\ m^{-1}\ K^{-1}$)
2530	700	0.75

4.1.2 Window frame:

In this experiment, a wooden frame is utilized to insert the glass since wood has a lower thermal conductivity and hence reduces heat transmission through the window frame.

4.1.3 Phase change material:

The latent heat storage capacity, melting point, and cost of PCM are all factors in its selection. Three PCMs were chosen, with the phase transition temperature serving as the primary criterion. The study's goal is to determine the impact of PCM phase transition temperature in double-glazed windows.OM29, OM42, and OM50 are the PCMs chosen. The phase transition temperatures are 29, 42, and 50 degrees ^{0}C, respectively.

Table 4.2: Properties of Selected PCMs

Name	Temperature (^{0}C)	Latent Heat (KJ/kg)		Density (kg/m^3)		Specific Heat (KJ/kgK)		Conductivity (W/mK)		Appearance
	Phase Change	Melting	Freezing	Liquid	Solid	Liquid	Solid	Liquid	Solid	
OM29	29	194	188	870	976	2.71	2.32	0.172	0.293	White Waxy solid @25 °C
OM42	42	199	190	863	903	2.78	2.71	0.1	0.19	White solid @25 °C
OM50	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.

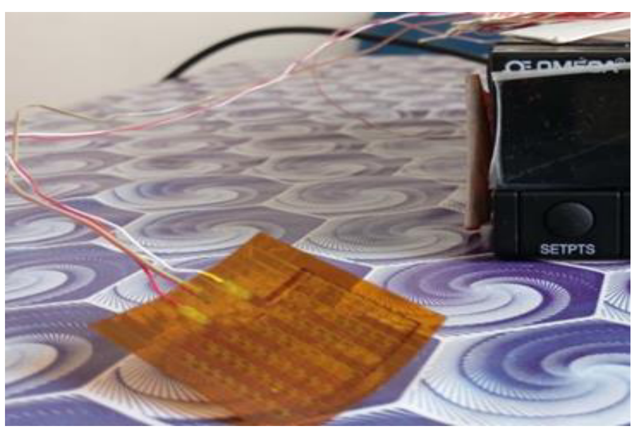


Fig 4.1: Heat flux sensor

4.1.6 Data acquisition system:

The Agilent-34972A Data Acquisition Unit collects and stores data from sensors that are attached to it. The data logger's software converts mill volt 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 thick glass panels with dimensions of 500 mm x 500 mm. These glasses can be put into the slots of a wooden frame with a 15-millimeter gap between them. So, when two glasses are inserted, there is a gap of 15 mm between them, which can be filled with air and different PCMs. To prevent filling material leaking, the inserted glasses are secured to the frame with a silicon sealant and M 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

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 , two IR Lamps, Data Acquisition system and thermo couple.

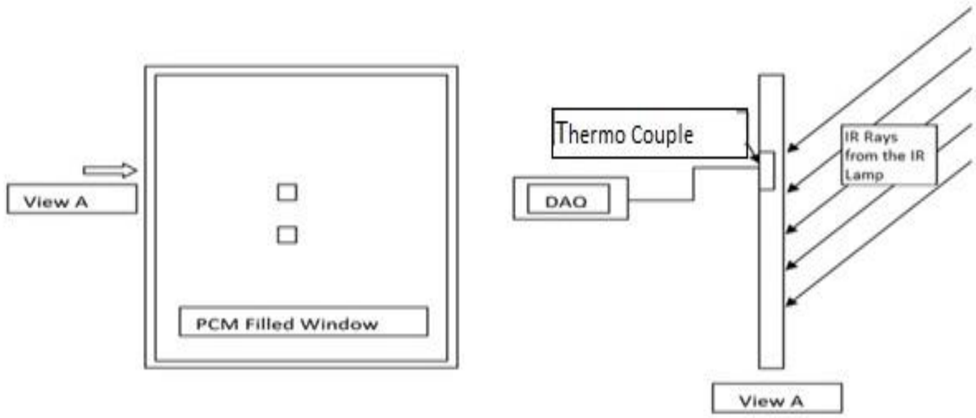


Fig 4.5: Schematic of experimental set up

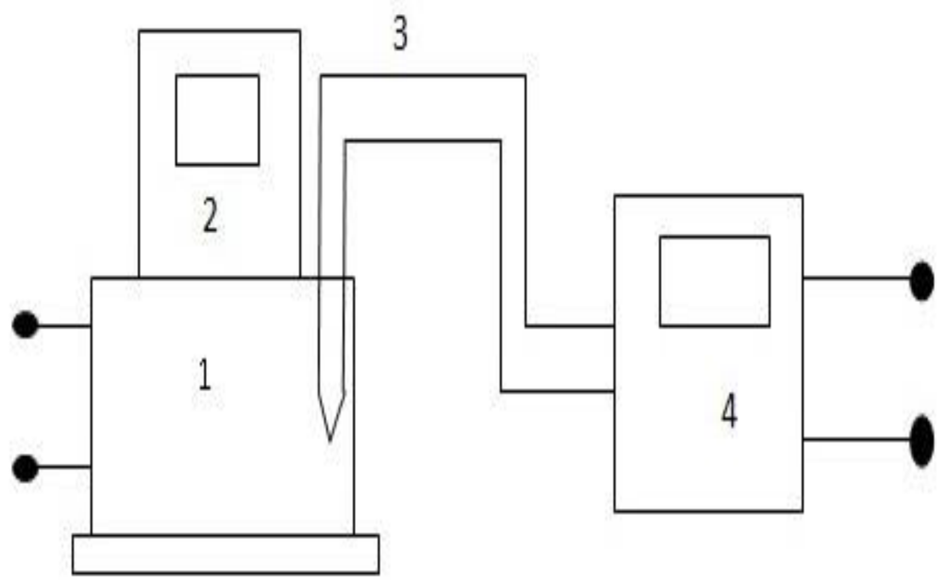
The experiment was conducted inside a laboratory in a controlled environment the ambient temperature is maintained constant. One side of the window is called the outer side, which was exposed to two 150W IR lamps, while the other side is considered the inner side, which has convective heat transmission. 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.

Fig 4.6: Experimental setup

Fig 4.7: PCM Filled Glazing unit

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.4.8 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	25	25.05	0.05
2	35	35.66	0.66
3	45	45.14	0.14
4	55	54.87	-0.13
5	65	64.82	-0.18

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

Sl.No	Set Temperature (C)	Observed Temperature (C)	Error
1	25	25.02	0.02
2	35	35.64	0.64
3	45	45.13	0.13
4	55	54.87	-0.13
5	65	64.80	-0.20

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

Sl.No	Set Temperature (C)	Observed Temperature (C)	Error
1	25	25.03	0.03
2	35	35.61	0.61
3	45	45.14	0.14
4	55	54.84	-0.16
5	65	64.75	-0.25

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

Sl.No	Set Temperature (C)	Observed Temperature (C)	Error
1	25	25.05	0.05
2	35	35.60	0.60
3	45	44.11	0.11
4	55	54.90	-0.10
5	65	64.75	-0.25

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

Sl.No	Set Temperature (C)	Observed Temperature (C)	Error
1	25	25.06	0.06
2	35	35.59	0.59
3	45	45.16	0.16
4	55	54.90	-0.10
5	65	64.77	-0.23

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

Sl.No	Set Temperature (C)	Observed Temperature (C)	Error
1	25	25.01	0.01
2	35	35.67	0.67
3	45	45.14	0.14
4	55	54.91	-0.09
5	65	64.81	-0.19

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

Sl.No	Set Temperature (C)	Observed Temperature (C)	Error
1	25	25.02	0.02
2	35	35.64	0.64
3	45	45.13	0.13
4	55	54.88	-0.12
5	65	64.80	-0.20

Table 4. Calibration data for thermo-couple (TC-08)

Sl.No	Set Temperature (C)	Observed Temperature (C)	Error
1	25	25.03	0.03
2	35	35.61	0.61
3	45	45.13	0.13
4	55	54.86	-0.14
5	65	64.77	-0.23

Table 4.11 Calibration data for thermo-couple (TC-09)

Sl.No	Set Temperature (C)	Observed Temperature (C)	Error
1	25	25.04	0.04
2	35	35.62	0.62
3	45	45.12	0.12
4	55	54.89	-0.11
5	65	64.79	-0.21

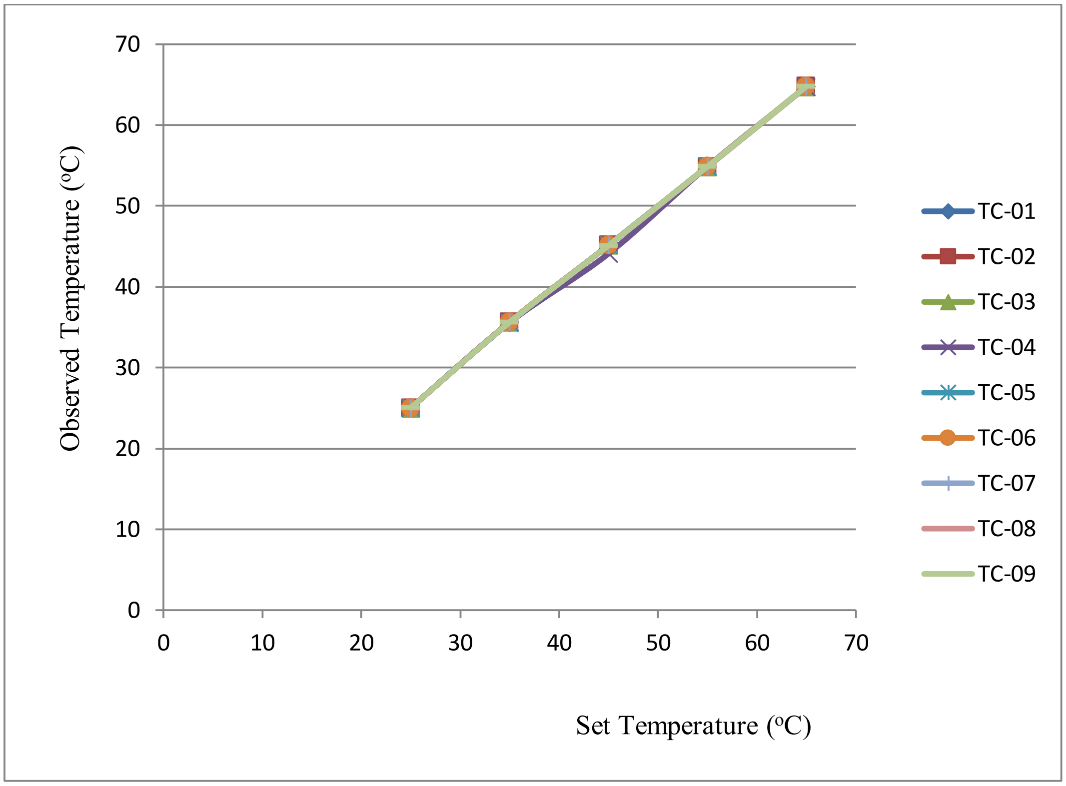


Fig.4.9 Thermocouple Calibration Curve

\

CHAPTER 5

EXPERIMENTAL RESULTS

5.1 EXPERIMENTAL PROCEDURE

On separate days of the experiment, the gap between the glazing's was filled with air and the three specified PCMs. To measure the temperature across these surfaces, T type thermocouples were installed on the inner and outer glasses four in the outer wall and four in the inner wall and one for measuring the ambient temperature. The measurements from these sensors were captured every 5 minutes using a data gathering system. Outside and inside temperatures were plotted along with ambient temperature to study the variation of temperature while using different PCMs and without PCM.

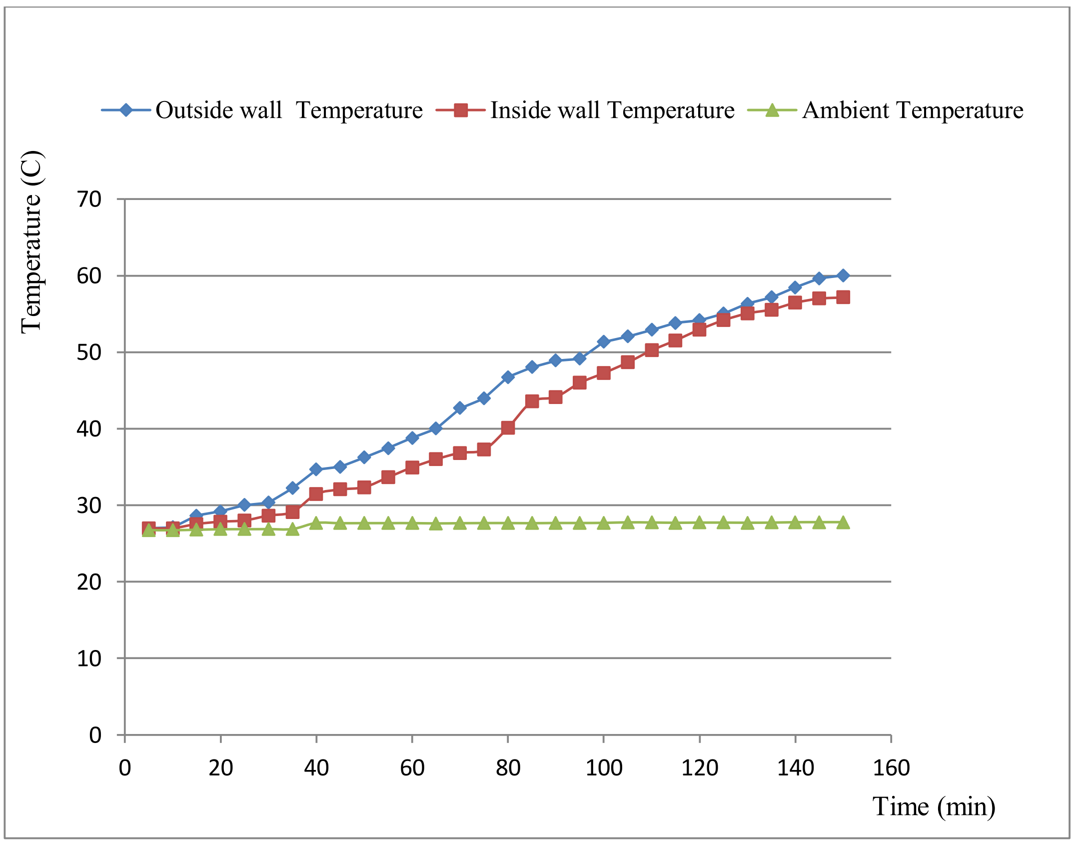


Fig 5.1: Average Temperature Vs Time (Without PCM double glazing)

From the above graph it clear that an air-filled double-glazed window's interior surface temperature matches the exterior surface temperature to a greater extent. The gaps between these curves are modest and nearly constant throughout because of the buildup of heat in the layer between the two glasses and the inability of air to shield the inner surface from incoming radiation. The outcome demonstrates that the inside surface temperature is nearly identical to the external temperature. The building's internal refrigeration load will grow as a result, which could result high electricity consumption.

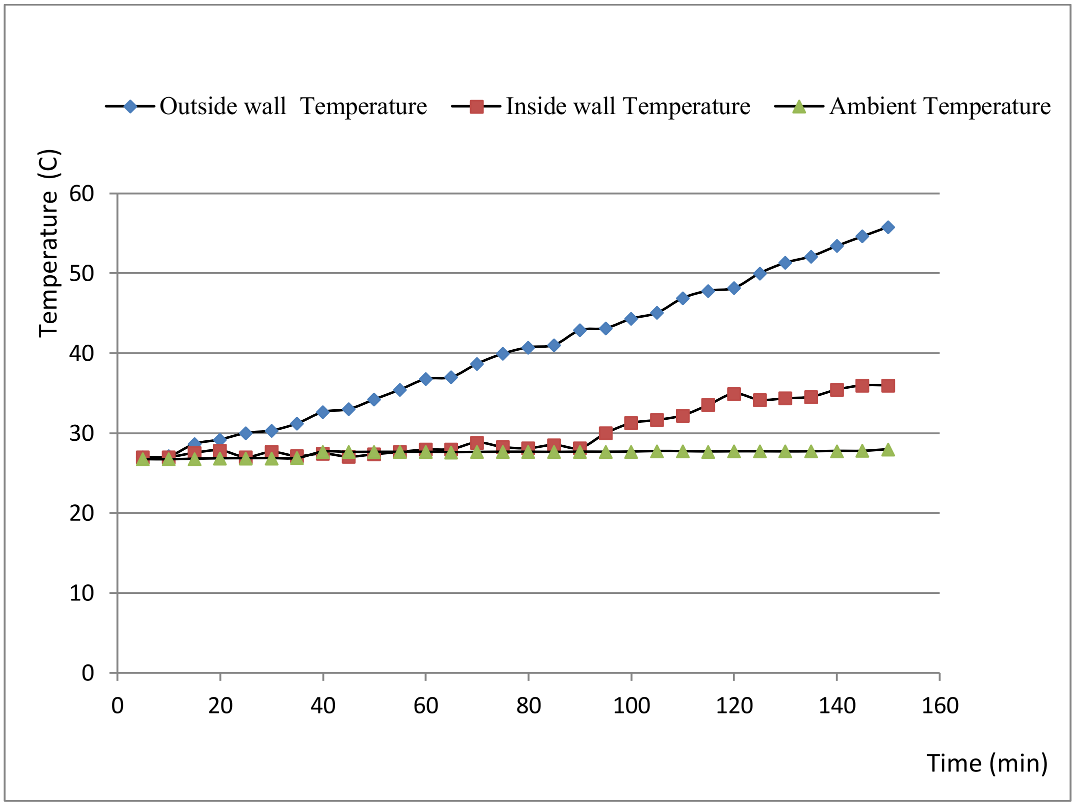


Fig 5.2: Average Surface Temperature Vs Time for PCM1 (OM29) filled double glazing

The plot shows the effect of PCM1 (OM29) filled between the glazing. It is clearly shown that the inner surface temperature of double-glazed windows with PCM filling is lower than the outside surface temperature. Inner surface temperature and ambient temperature are perfectly combined in the first half. After that, the inner surface temperature gradually rises but remains below the outer surface temperature. Since this is where PCM absorbs the latent heat and phase transition occurs, the inner surface temperature in the first half is practically constant and between 27 ^{o}C and 30^{o}C. The sensible heating of PCM following the phase transition is what is responsible for the constant rise in internal surface temperature. PCM-filled glazing appears to be excellent in the first half, but when all of the PCM turns liquid, the PCM layer conducts heat from the outside wall to the inner wall, causing the inner glass temperature to steadily rise.

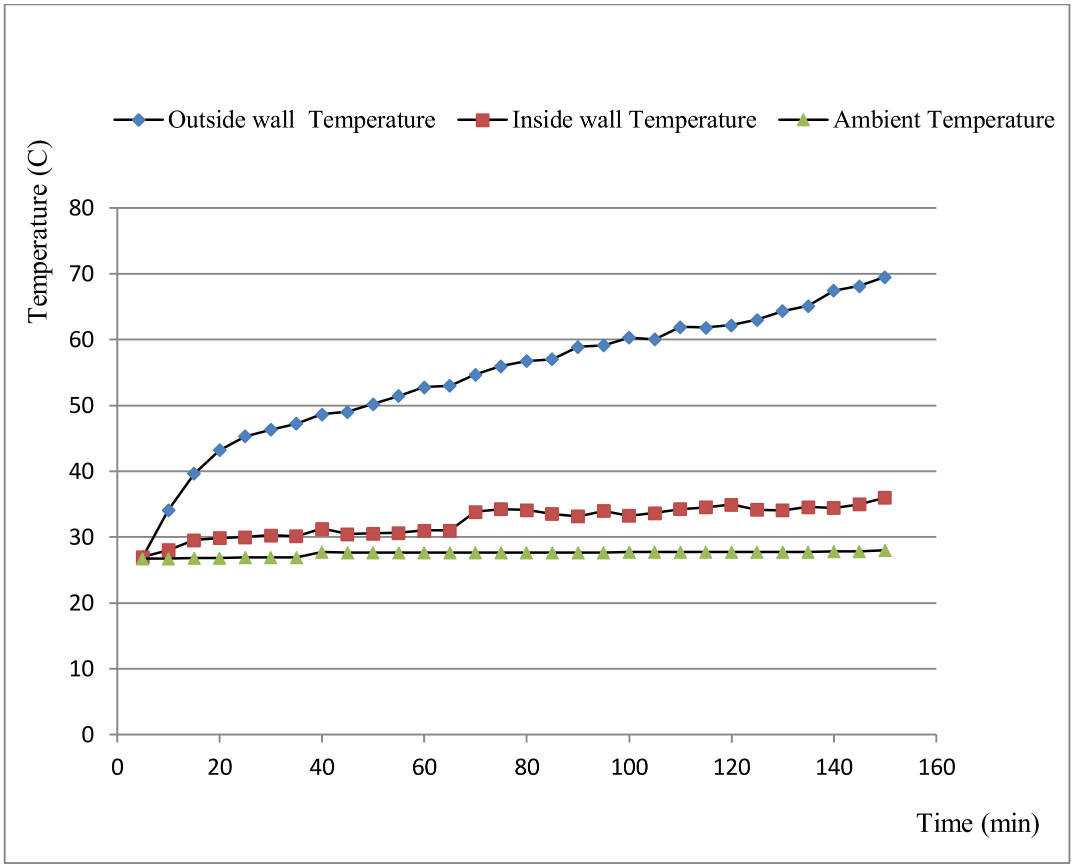


Fig 5.3: Average Surface Temperature Vs Time PCM2 (OM42) filled double glazing

For PCM2 (OM42) filled double glazing, the melting temperature is 42 °C in the first 20min the temperature in the outer wall raises rapidly till it reaches to the melting zone during that time conduction heat transfer happens between the outer and inner wall happens. Due to which there is slight increase in the temperature of the inner wall when compared to the ambient temperature. After reaching 42 °C the curve flattens as the PCM material began to absorb latent heat and the temperature of the inner wall the temperature rise is mainly due to conduction through the PCM material. The PCM utilization in this case approximately 65% and the rest of the PCM remain as solid. This can impact the light transmission capability of the windows. So we can say that while using higher melting temperature PCM we have to reduce to thickness of the PCM layer so that the complete utilization of the PCM can be achieved.

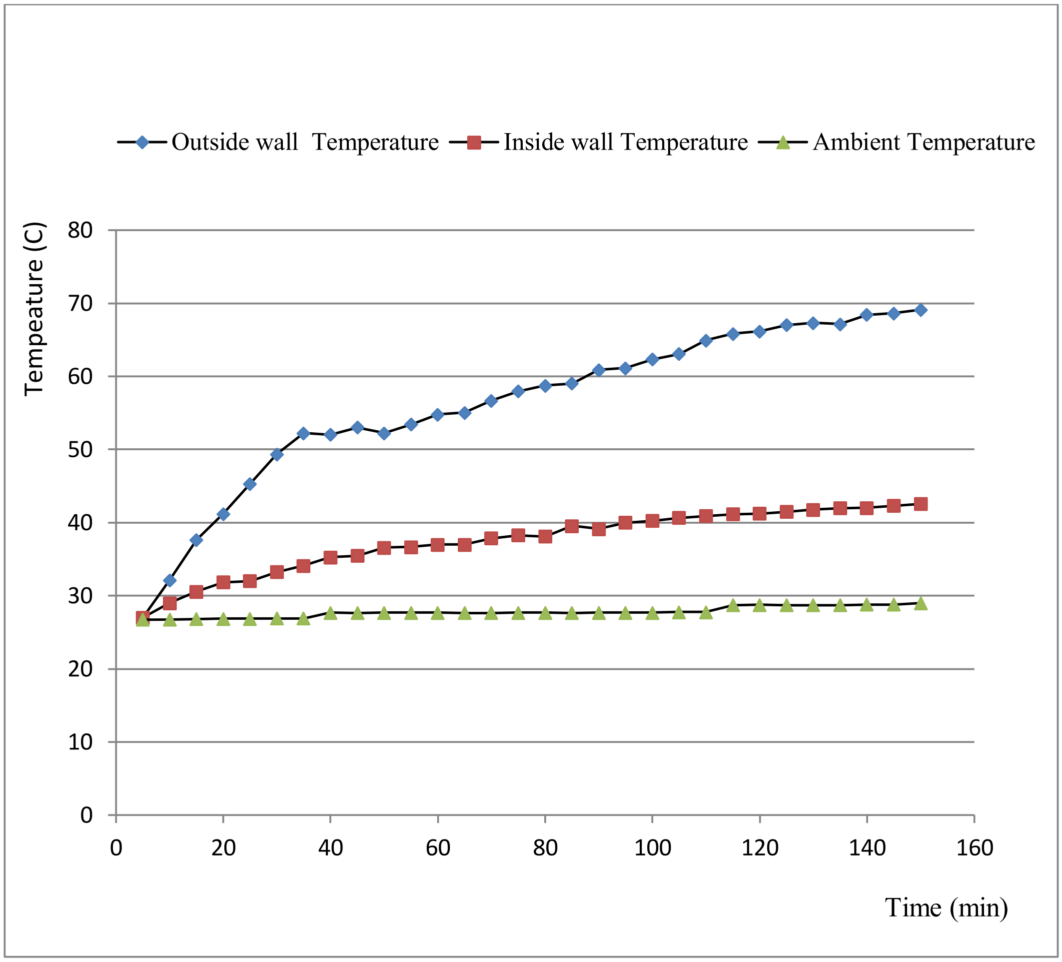


Fig 5.4: Average Surface Temperature Vs Time PCM3 (OM50) filled double glazing)

In the case of PCM3 (OM50) filled double glazing unit we can see from the graph that in the first phase of the experiment there is a constant increase in the outer wall temperature similar to the earlier case of PCM2 (OM420 till it reaches to the range of 50 ºC. The melting point of PCM3 is 50 ºC after that the melting happens and the temperature remains constant for some time and again rises at a constant rate. In case of inner wall there is a constant increase of wall temperature as a result of conduction through the PCM layer. This conduction heat transfer occurs due to high temperature difference between the inner and outer wall of the glazing. The PCM utilization in these cases is similar to PCM2 and is less than 60% due to its high melting temperature. Here also we can say that by decreasing the PCM layer thickness we can provide maximum utilization of the PCM. Using higher melting point PCM can increase the conduction heat transfer between the outer and the inner wall.

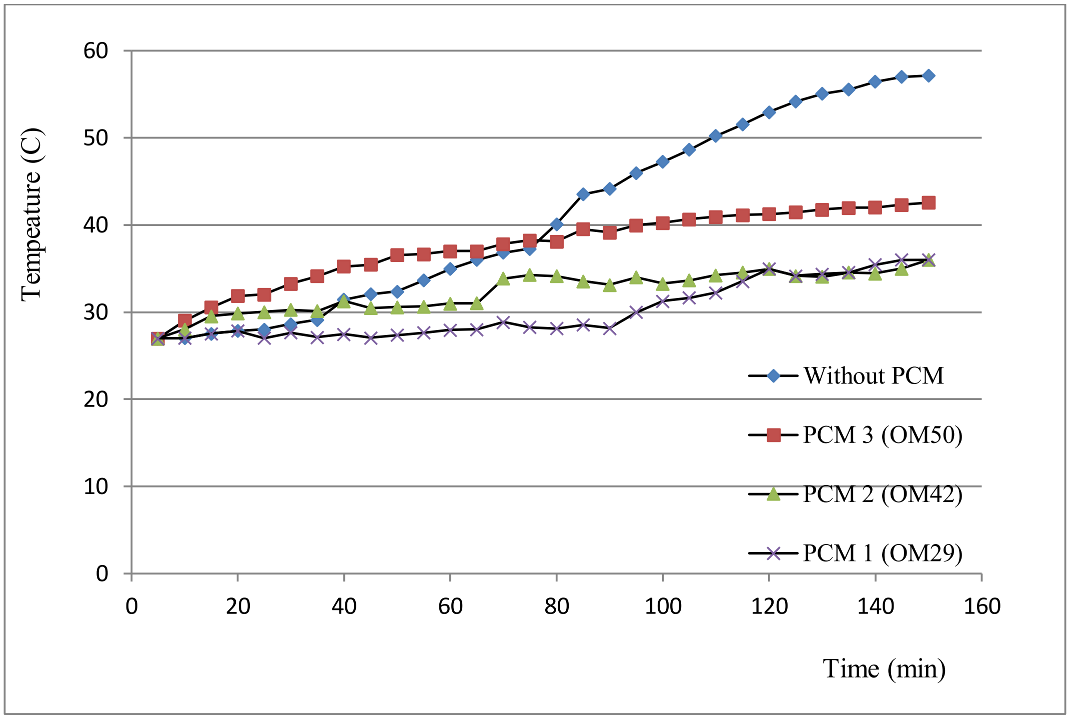


Fig 5.5: Comparison between average inner surface temperatures of glazings Vs Time

When comparing the inner surface temperature of different glazings, it can be seen that the PCM1 and PCM2 filled glazing have the lowest inner surface temperature .The inner surface temperature is PCM3 is comparatively high because of the conduction heat transfer through the PCM layer. Without PCM glazing unit shows the highest inner temperature and PCM1 maintain lower inner wall temperature for a long period of time and the PCM utilization of the PCM1 is 100% due to its lower melting temperature. So we can say that use of PCM between double glazings can decrease the inner surface temperature to a greater extent. But the selection of PCM and the layer thickness plays an important role in the proper functioning of the windows. If the PCM utilization is not 100% then it can greatly affect the performance and functioning of the windows.

CHAPTER 6
NUMERICAL ANALYSIS

The first step in CFD analysis is to create a geometric model of the issue domain. The geometric model is created, and then it is meshed to discretize it. Specifying the input data, defining the material qualities, and defining the boundary conditions are done after meshing. The solution setup is then initialized, and computations are carried out for the designated amount of time. After the calculations are finished, post processing is carried out to extract the data pertaining to the key variables. Since the desired result, inner surface temperature, is monitored and plotted during the calculation, post processing is not necessary in this study.

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 section is used for creating geometric models of physical problem domains. The two 4 mm glass layers in the modeled glazing have a 15 mm gap between them that can be filled with air, water, or PCM. The glazing measures 500 mm x 500 mm on the outside and is 23 mm thick overall.

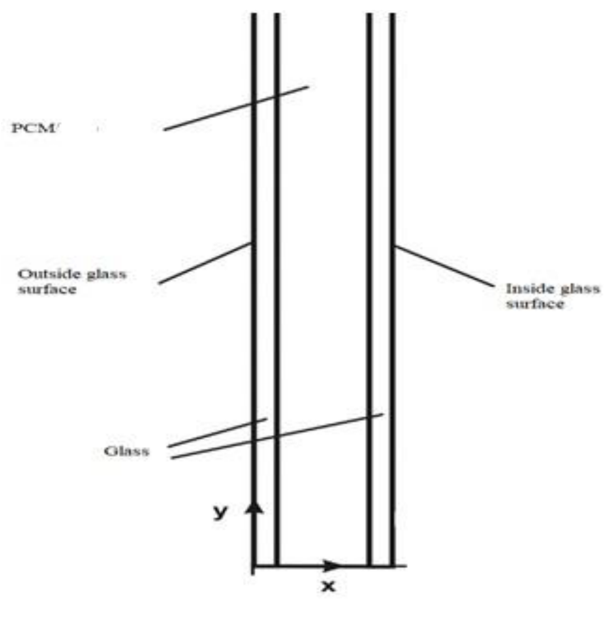


Fig 6.1: Schematic for the cross section of the glazing geometry

6.2 MESHING OF THE DOMAIN

After the geometric model has been developed, the following stage in CFD analysis is to build the meshing of the computational area. During mesh creation, the problem domain is divided into a large number of tiny cells. To mimic physical events, the CFD application solves multiple equations for each cell. The results of the simulation are significantly influenced by the number of cells in the domain. To imitate the physical occurrences, the domain must have a sufficient number of cells. As the number of cells rises, so does the amount of time it takes the solver to discover a solution. Therefore, it is always important to determine the ideal number of cells that can run a simulation in a reasonable amount of time while still producing results that are sufficiently accurate. The best number of cells for a domain typically relies on how challenging the problem is and how much simulation time is available. A high-quality mesh is necessary for a precise CFD analysis. Hexahedral mesh was chosen for discretization in this work. Because the geometry of windows has only rectangular surfaces, the hexahedral type of meshing was chosen. The hexahedral kind of meshing is best suited because the geometry of windows does not include any kind of curved surfaces and can produce precise results with only a modest amount of calculation time. 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 1029000 elements, the temperature difference is minimal.

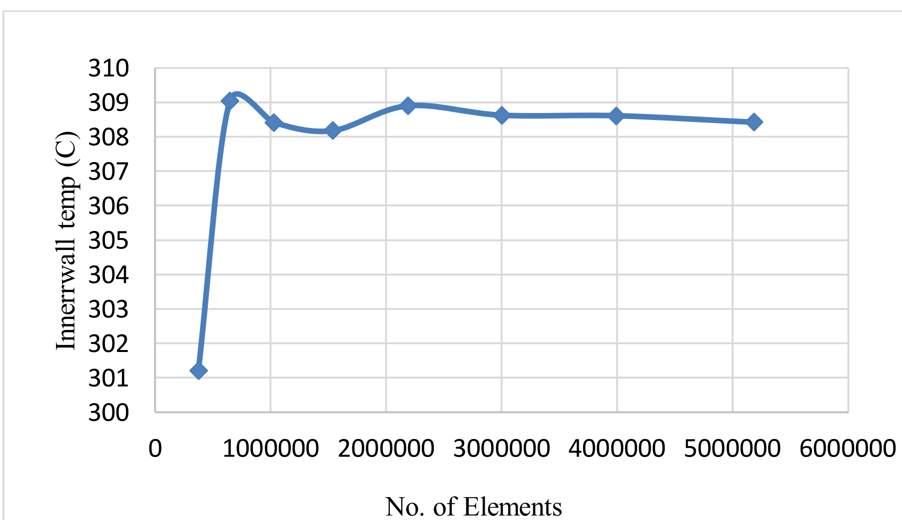


Fig 6.2: Grid independence test

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

The skewness and aspect ratio of the generated mesh have been studied in this work as two parameters. An element with a skewness value of 0 is considered perfect by the skewness criteria, while elements having a skewness value greater than zero are not regarded as being of high quality. An element with a skewness value of 1 is typically regarded as being unviable. In a well-meshed domain, there must be a very tiny or negligible number of elements having a skewness value of 1. The average skewness value for a mesh of excellent quality must always be less than 0.3.It is found to be less than 0.001.Another metric used to assess how well a produced mesh is done is aspect ratio, which is comparable to this. An acceptable mesh should have an aspect ratio of no more than two on average. Here, the aspect ratio is 1.This demonstrates that the produced mesh, which is made up mostly of hexahedron pieces, is a mesh of goodquality in terms of skewness and aspect ratio.

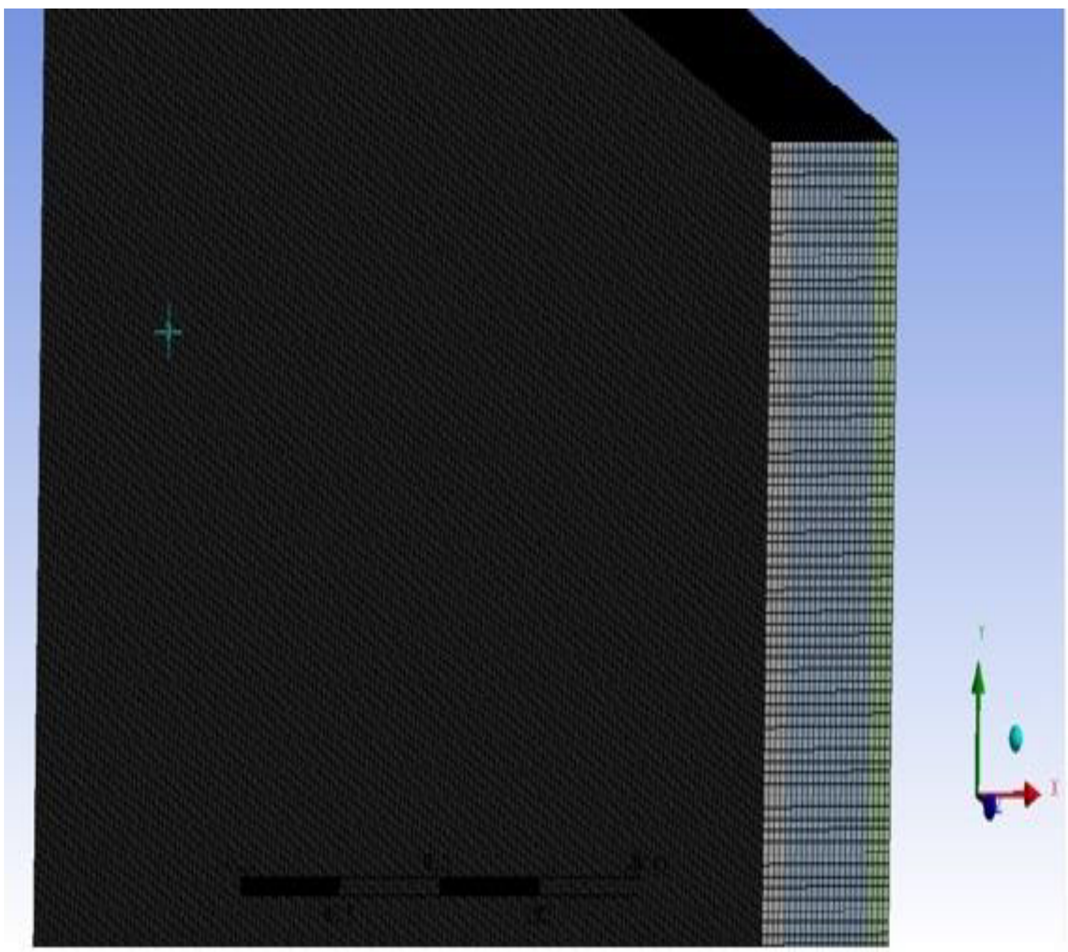


Fig 6.3: 3D view of grid

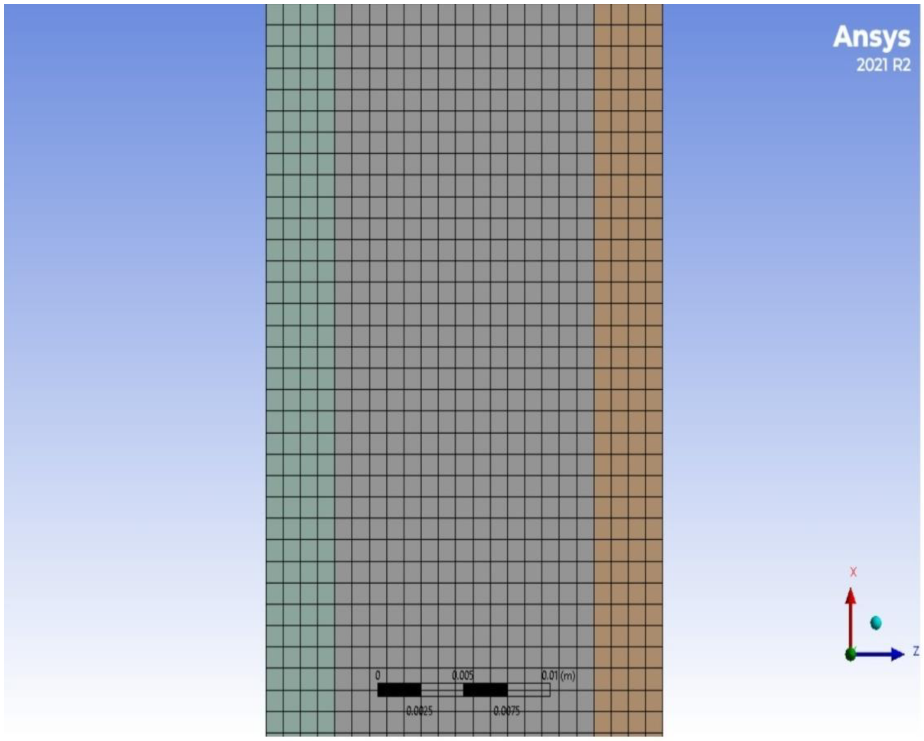


Fig 6.4: Cross section of modeled glazing – lower segment

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/PCM3

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 equation needs 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 surrounding cells' 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 the presumption 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 the results, 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 thermal characteristics of the present problem were numerically simulated by computational fluid dynamics (CFD) technique. Commercial package ANSYS 21R2 is used for the present numerical study. In this comparative study the effects of thermal expansion is neglected. The setup is provided to converge in the Ansys software, and after the convergence of the iterations and running it for the required time step, the results were plotted for different PCMs.

PCM1 (OM29)

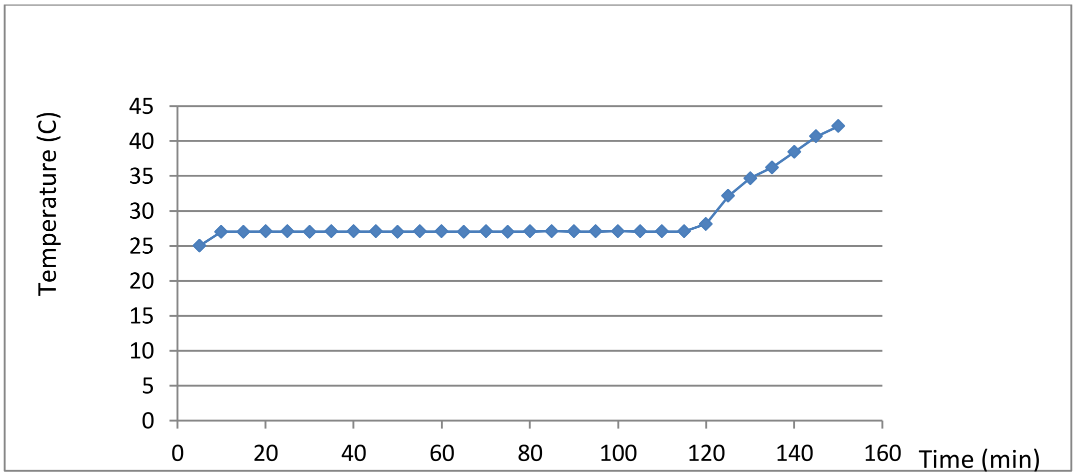


Fig.7.1 Average Inner glass Surface Temperature Vs Time for PCM1 (OM29) filled double glazing

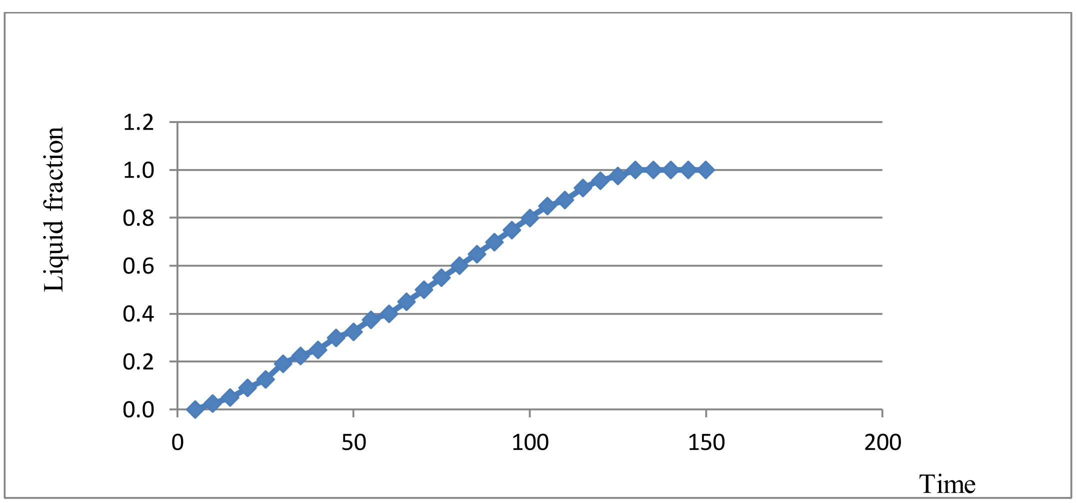


Fig.7.2 Liquid fraction Vs Time for PCM1 (OM29) filled double glazing

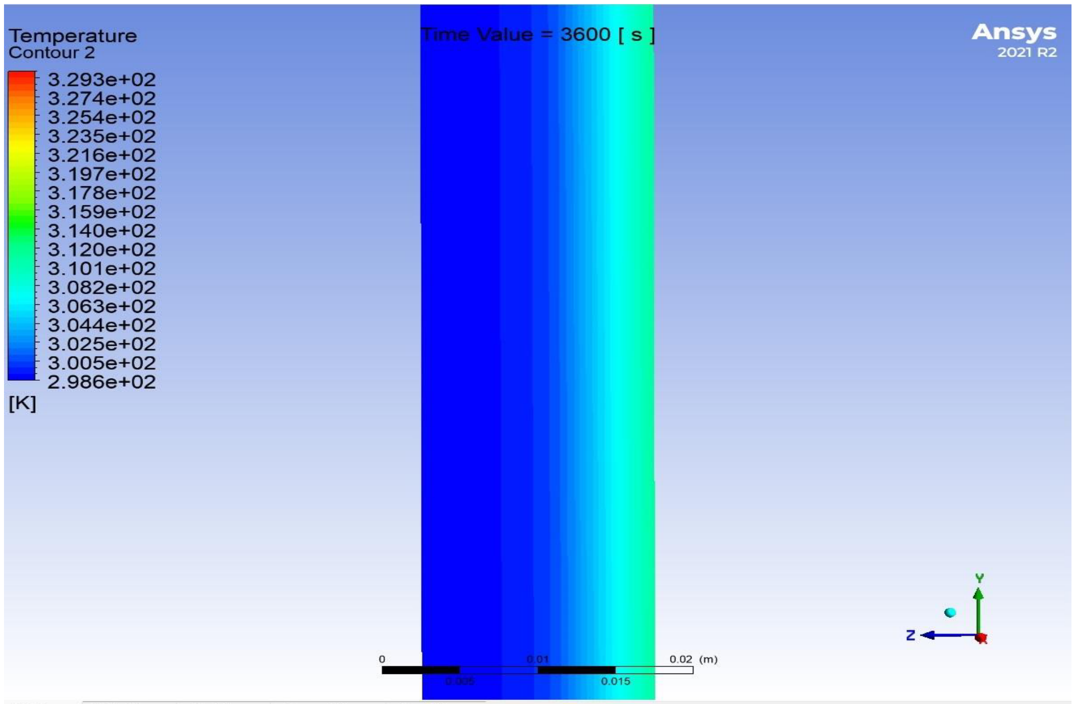


Fig.7.3 Temperature Contour PCM1 (OM29) 3600s

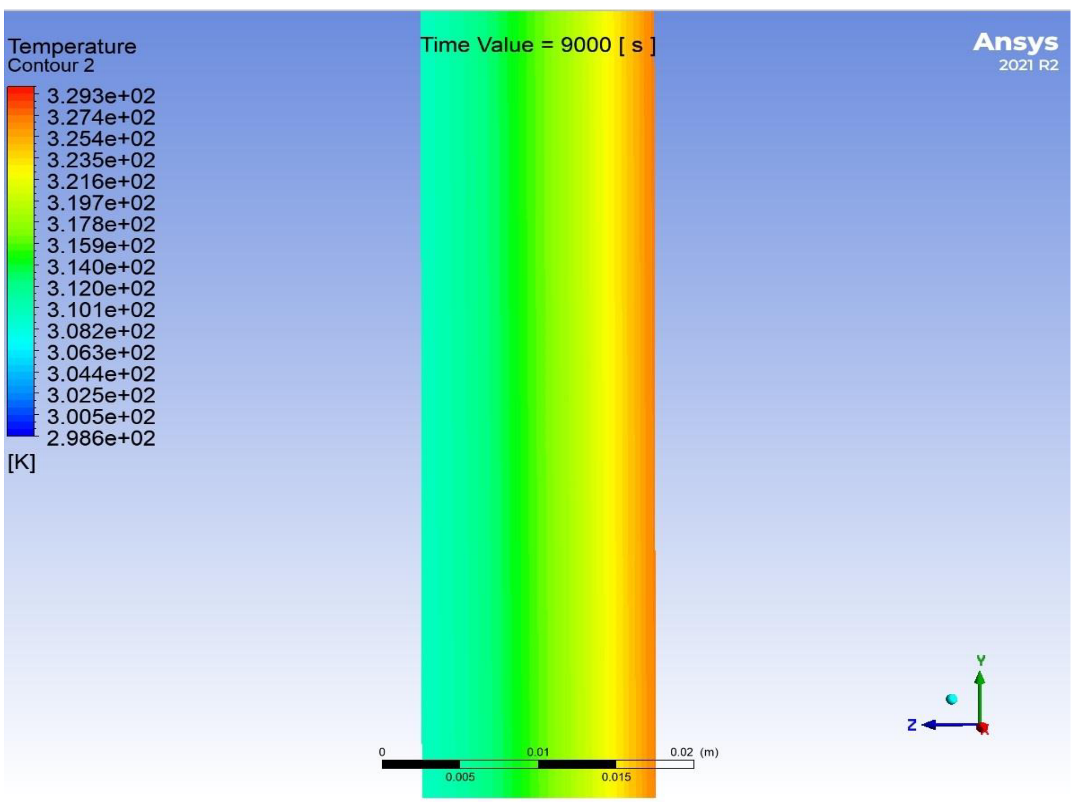


Fig.7.4 Temperature Contour PCM1 (OM29) 9000s

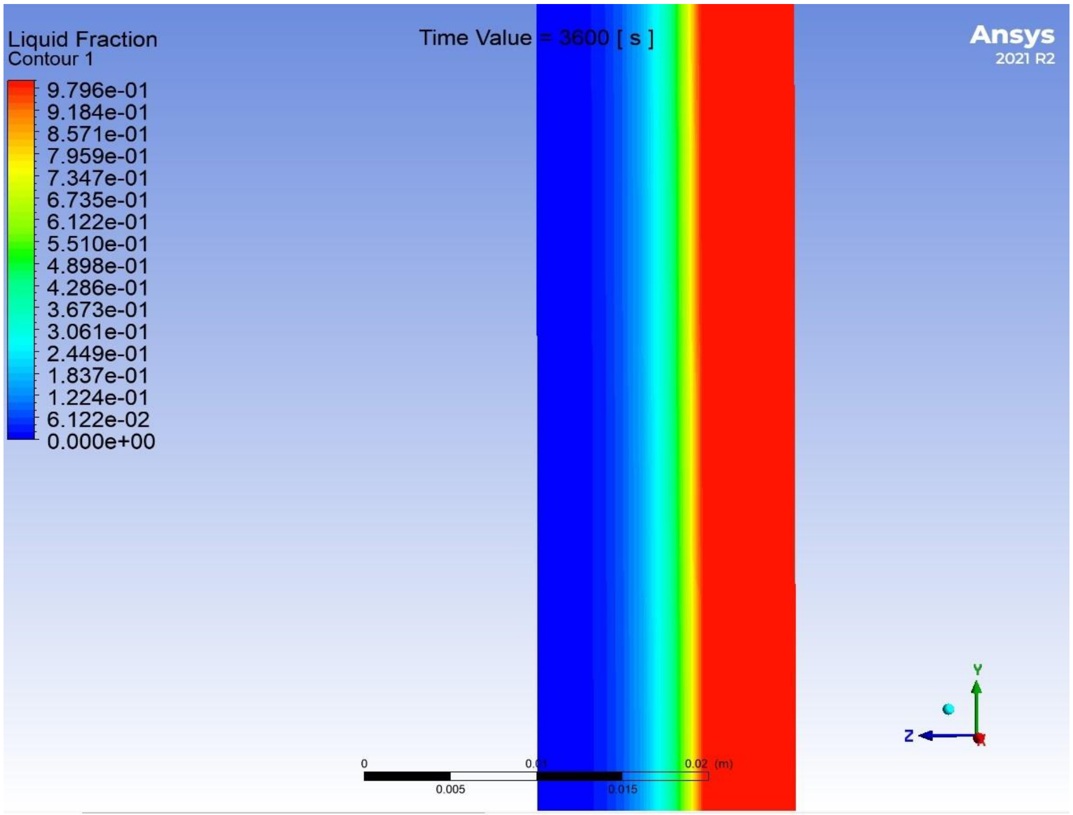


Fig.7.5 Liquid fraction Contour PCM1 (OM29) 3600s

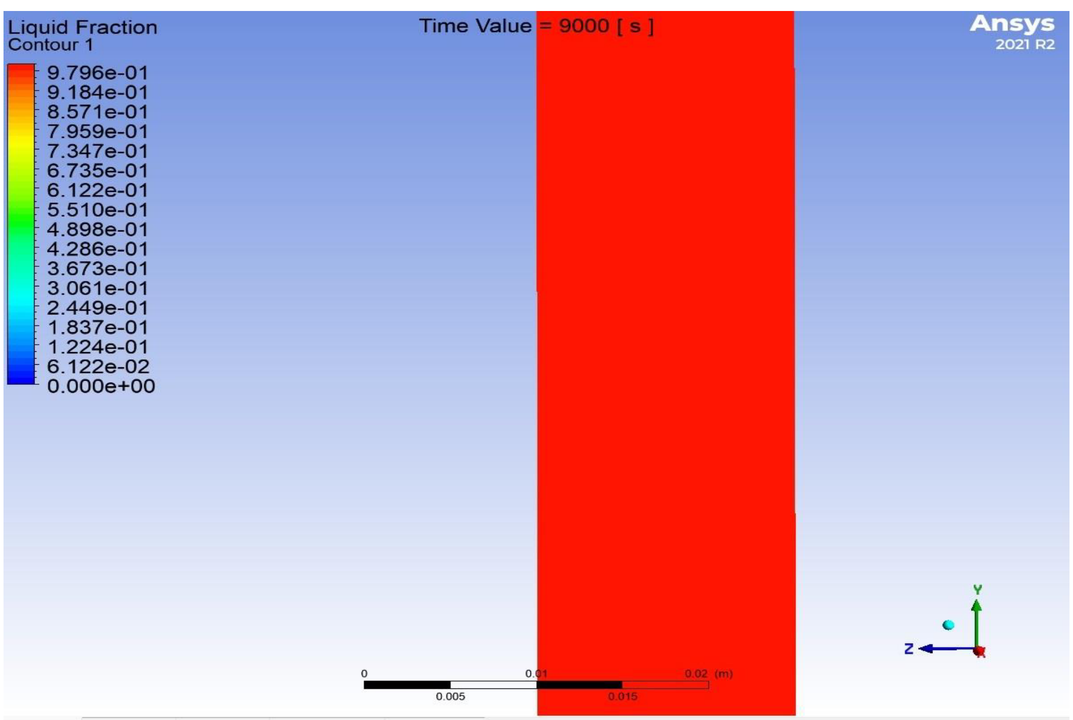


Fig.7.6 Liquid fraction Contour PCM1 (OM29) 9000s

PCM 2 (OM42)

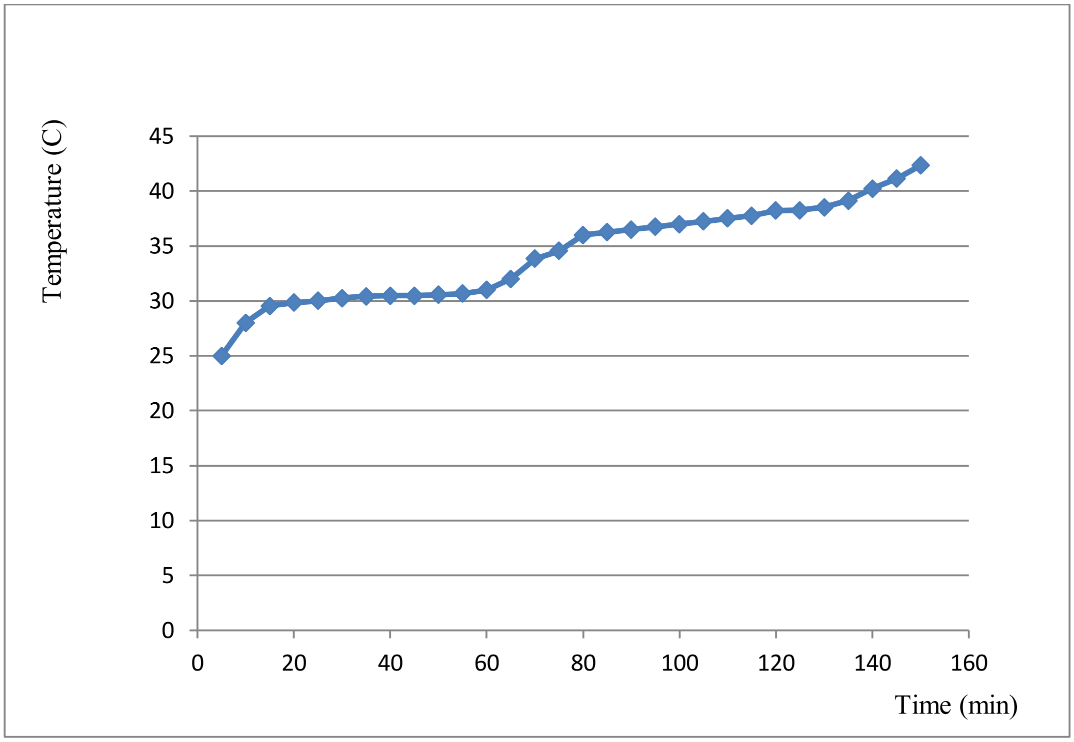


Fig.7.7 Average Inner glass Surface Temperature Vs Time for PCM 2 (OM42) filled double glazing

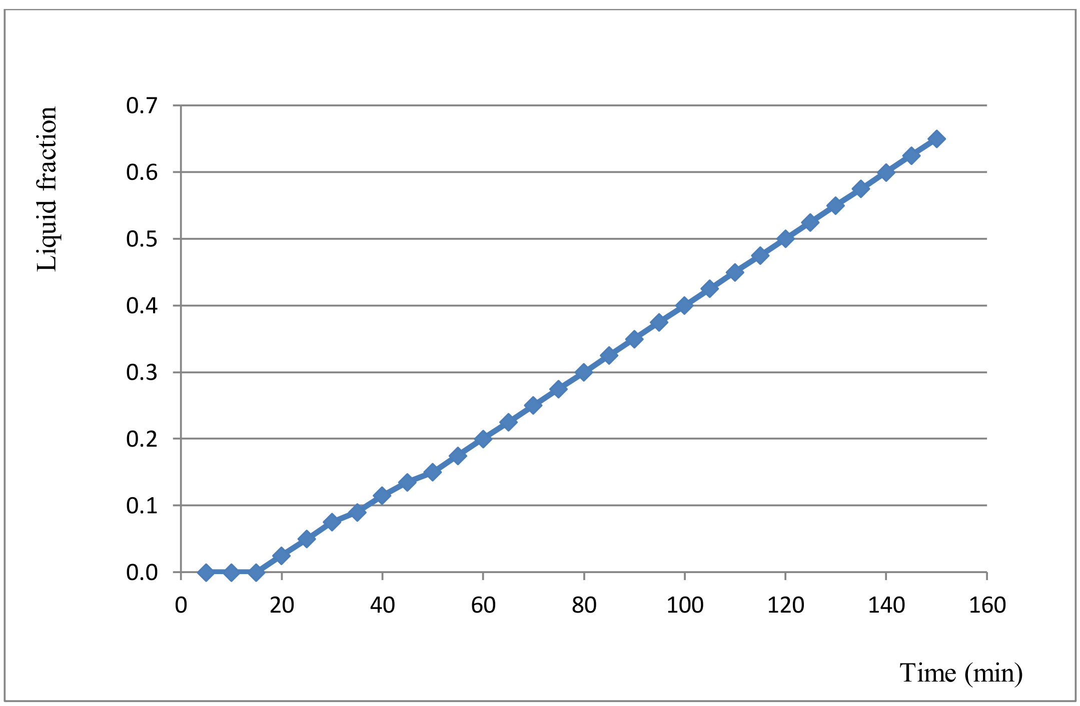


Fig.7.8 Liquid fraction Vs Time for PCM 2 (OM42) filled double glazing

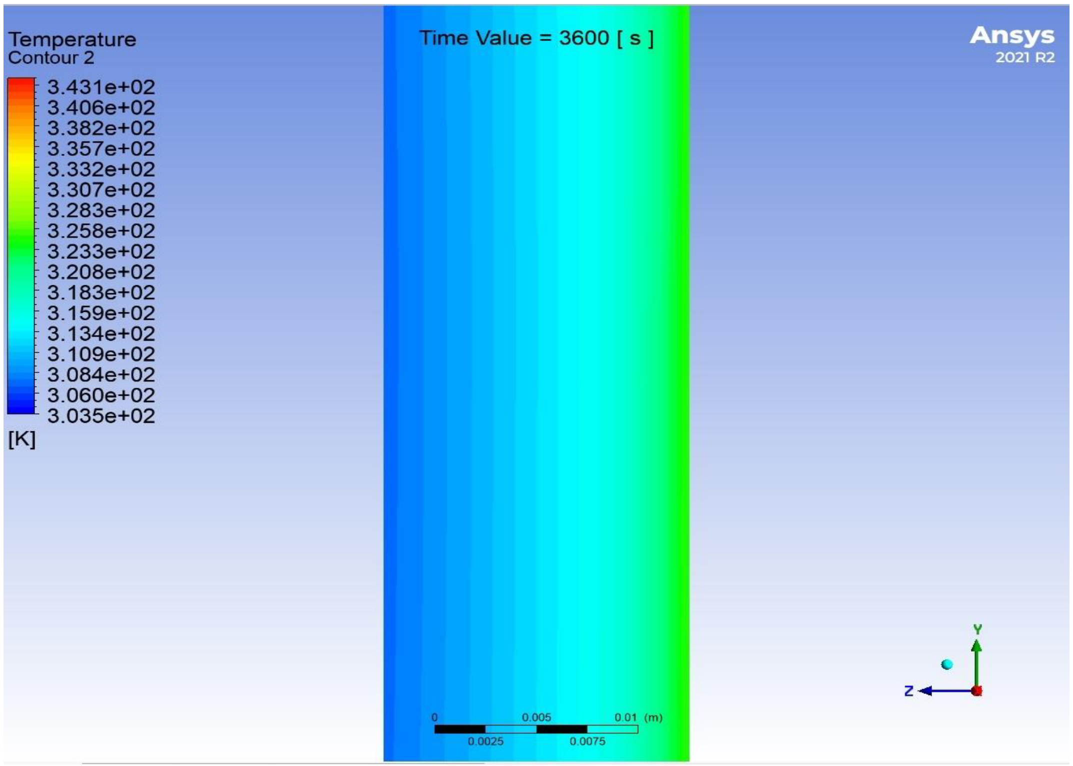


Fig.7.9 Temperature Contour PCM 2 (OM42) 3600s

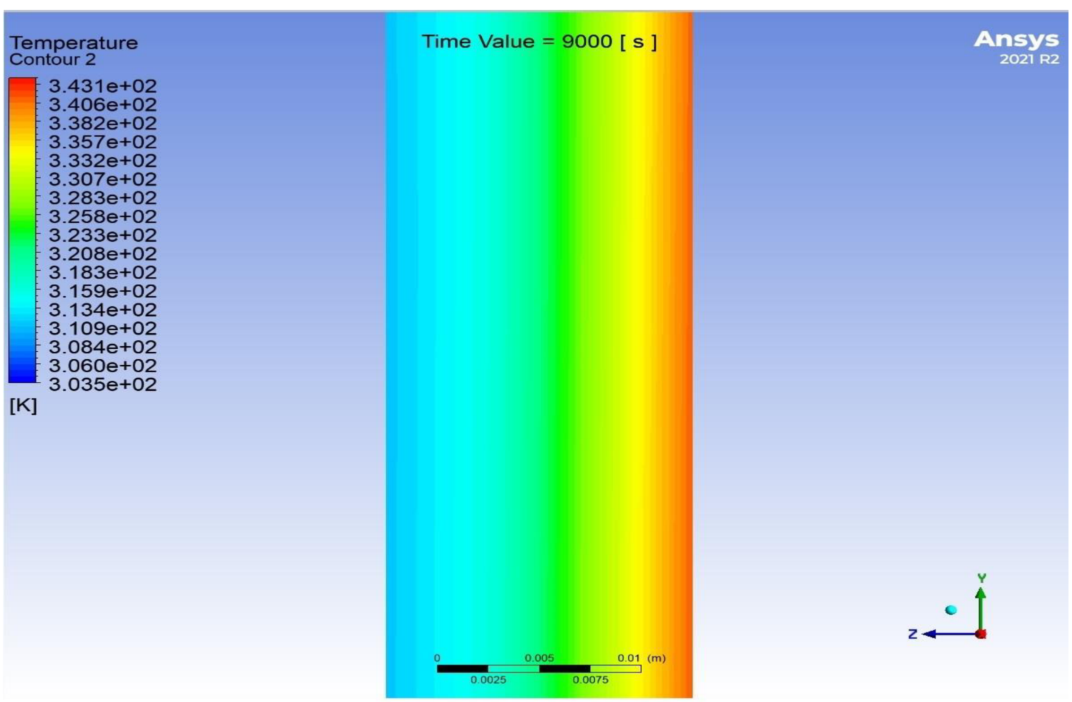


Fig.7.10 Temperature Contour PCM 2 (OM 42) 9000s

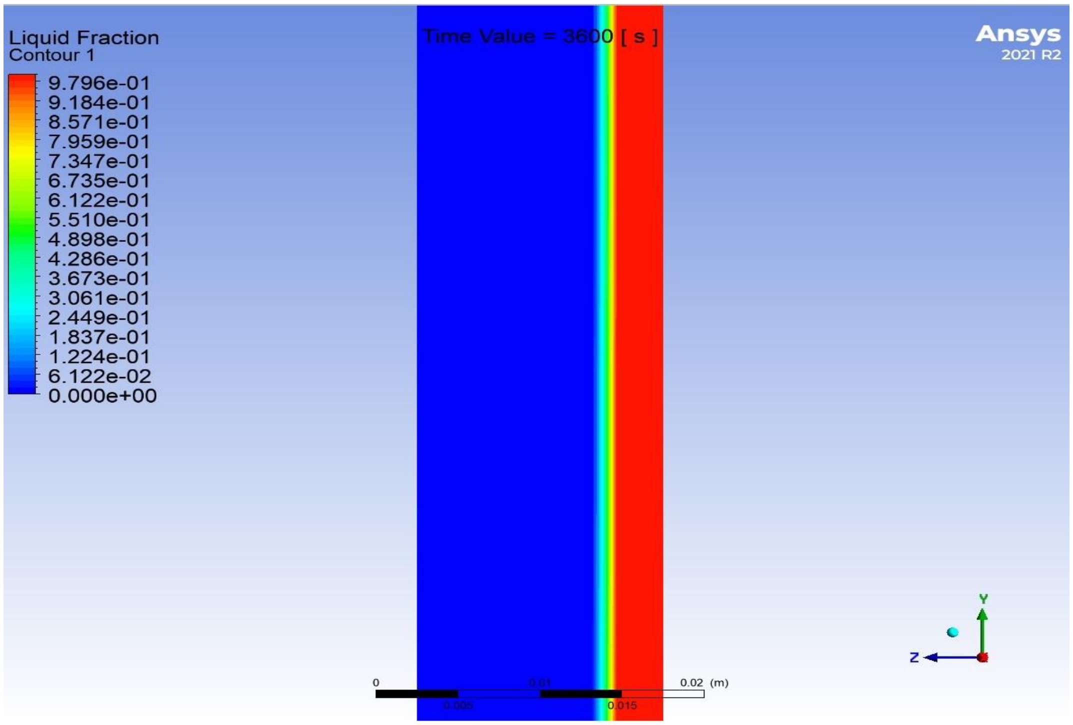


Fig.7.11 Liquid fraction Contour PCM 2 (OM42) 3600s

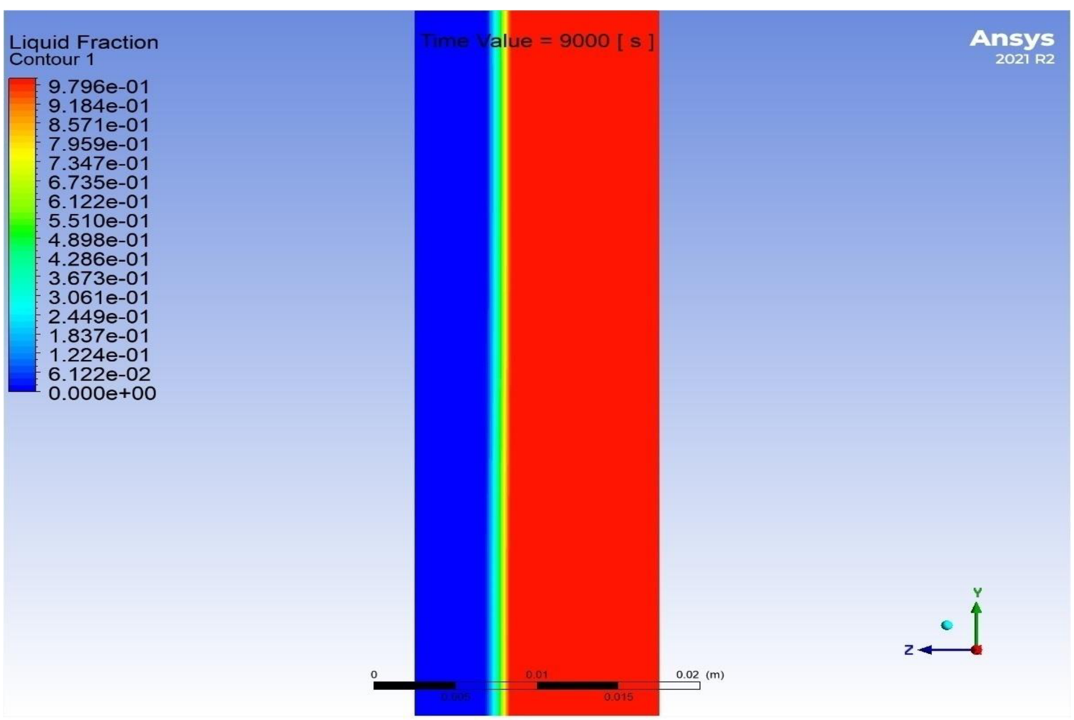


Fig.7.12 Liquid fraction Contour PCM 2 (OM42) 9000s

PCM 3 (OM50)

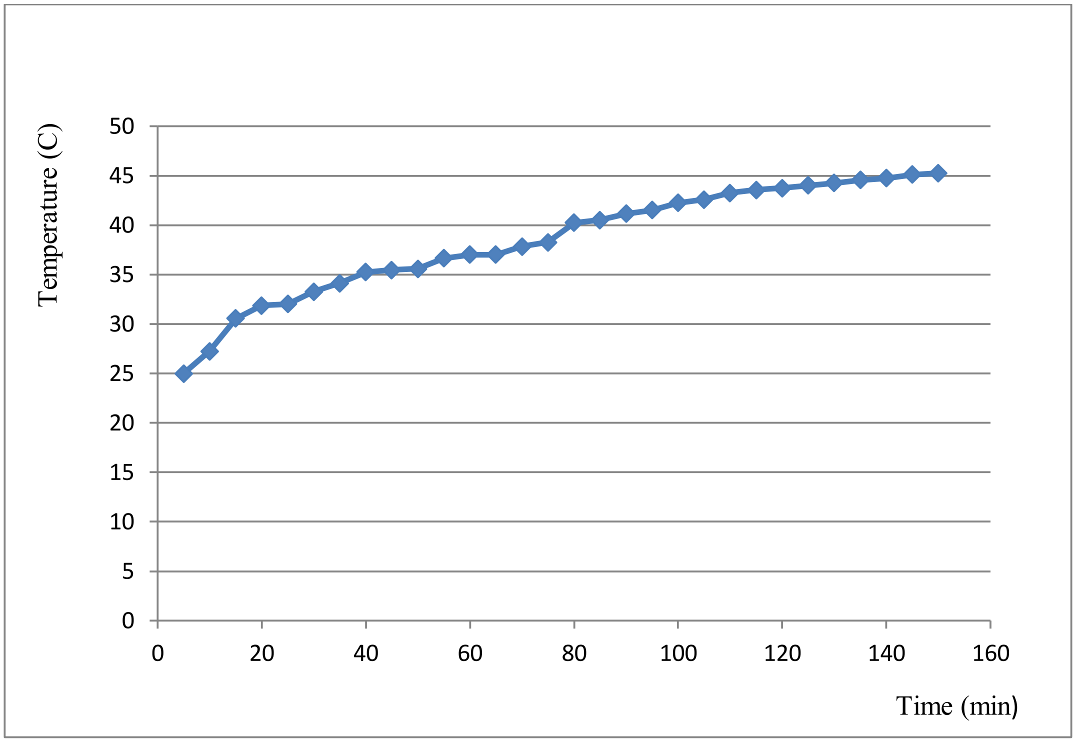


Fig.7.13 Average Inner glass Surface Temperature Vs Time for PCM 2 (OM42) filled double glazing

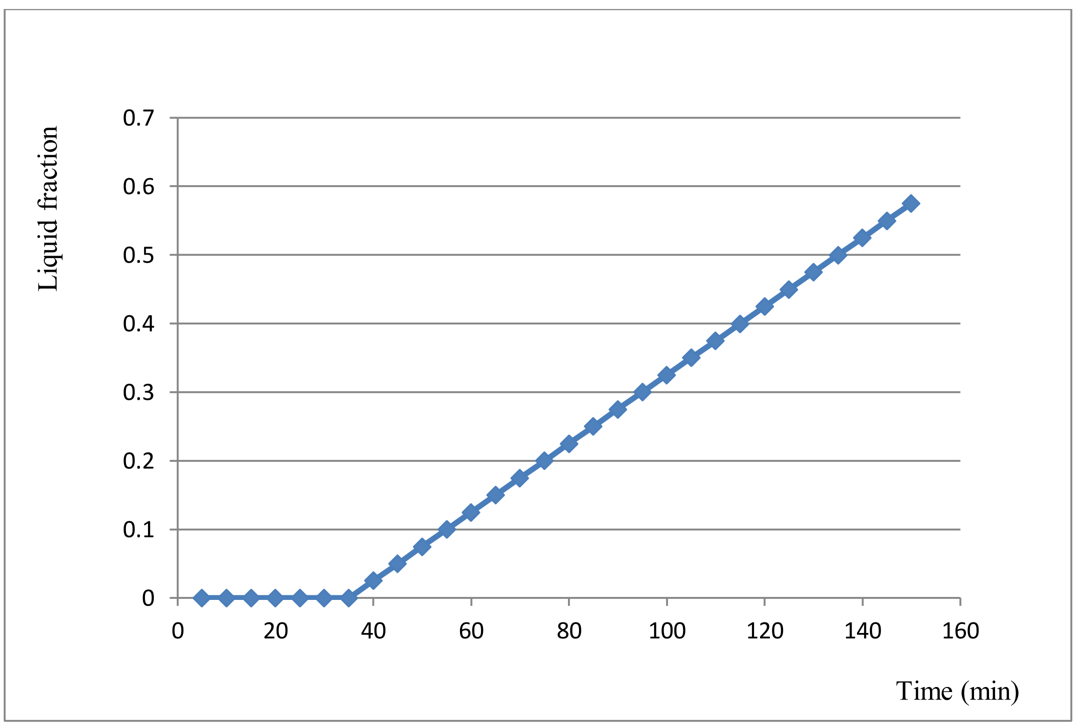


Fig.7.14 Liquid fraction Vs Time for PCM 3 (OM50) filled double glazing

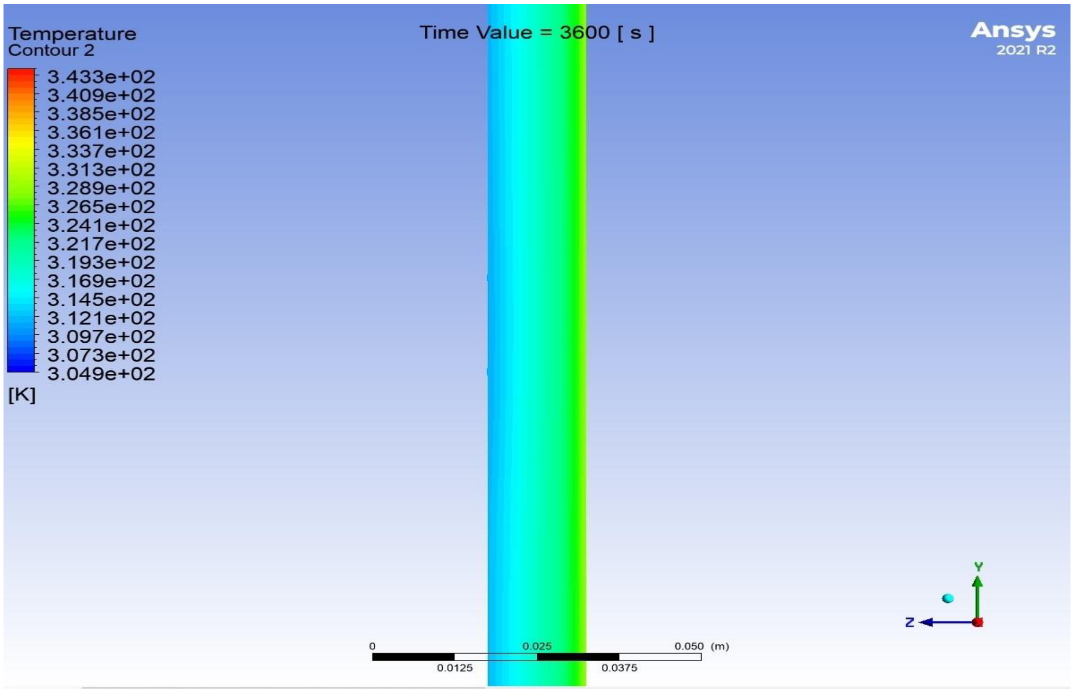


Fig.7.15 Temperature Contour PCM 3 (OM50) 3600s

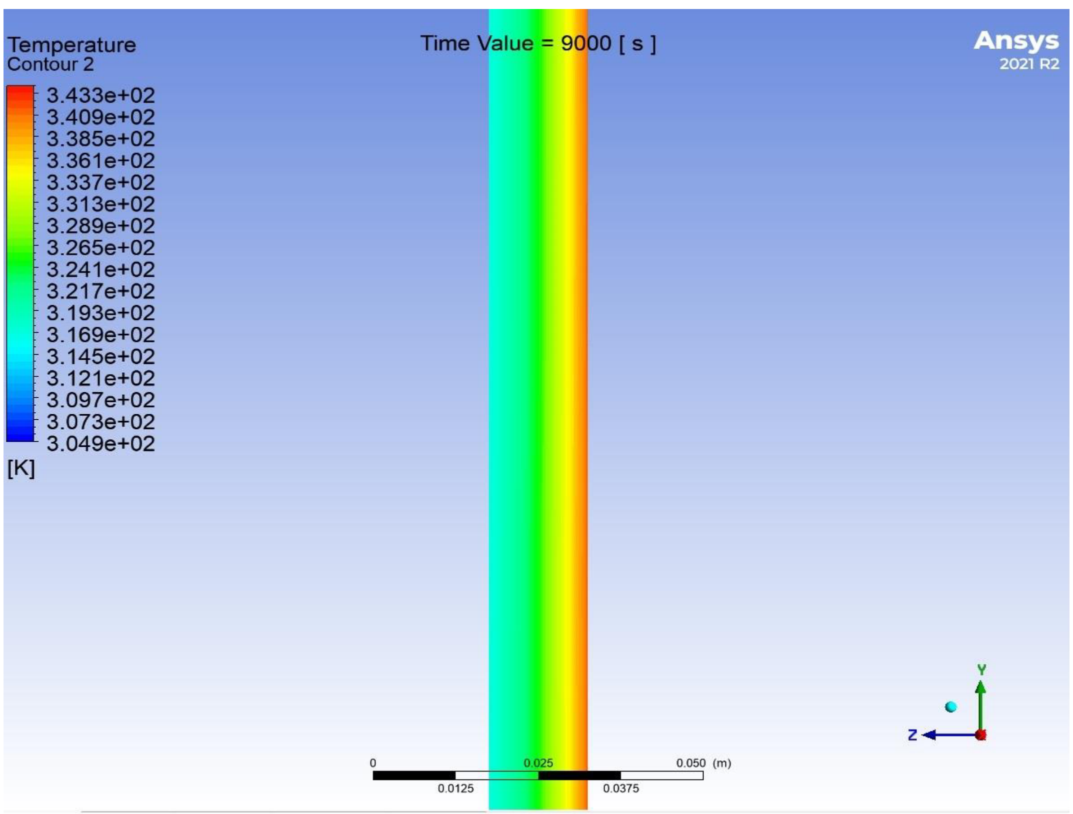


Fig.7.16 Temperature Contour PCM 3 (OM50) 9000s

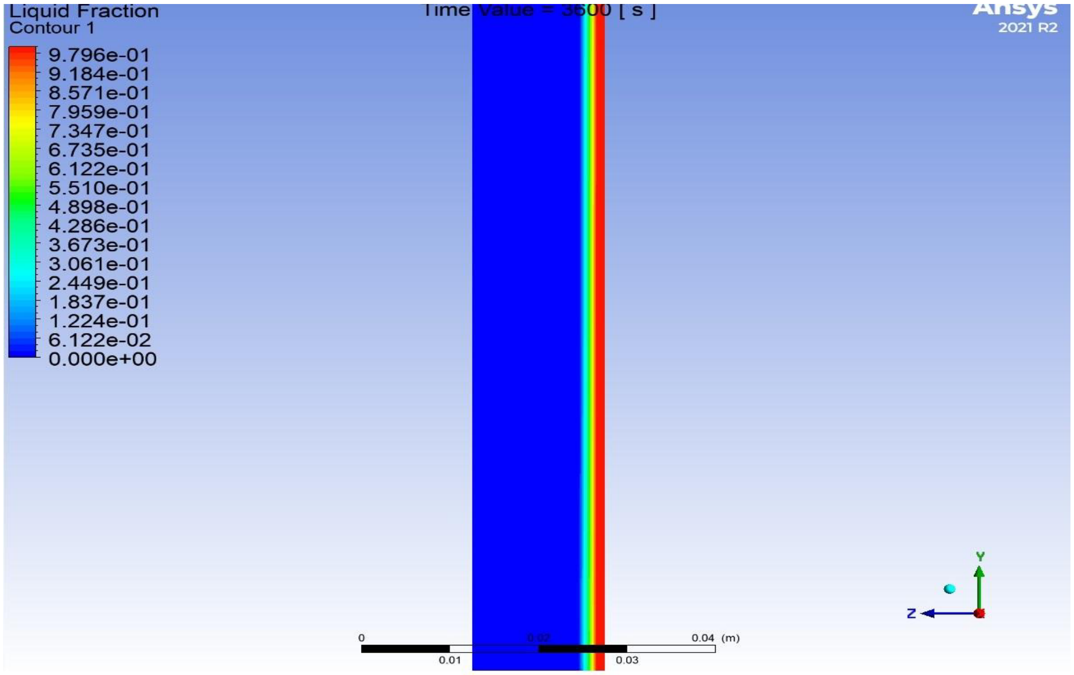


Fig.7.17 Liquid fraction Contour PCM 3 (OM50) 3600s

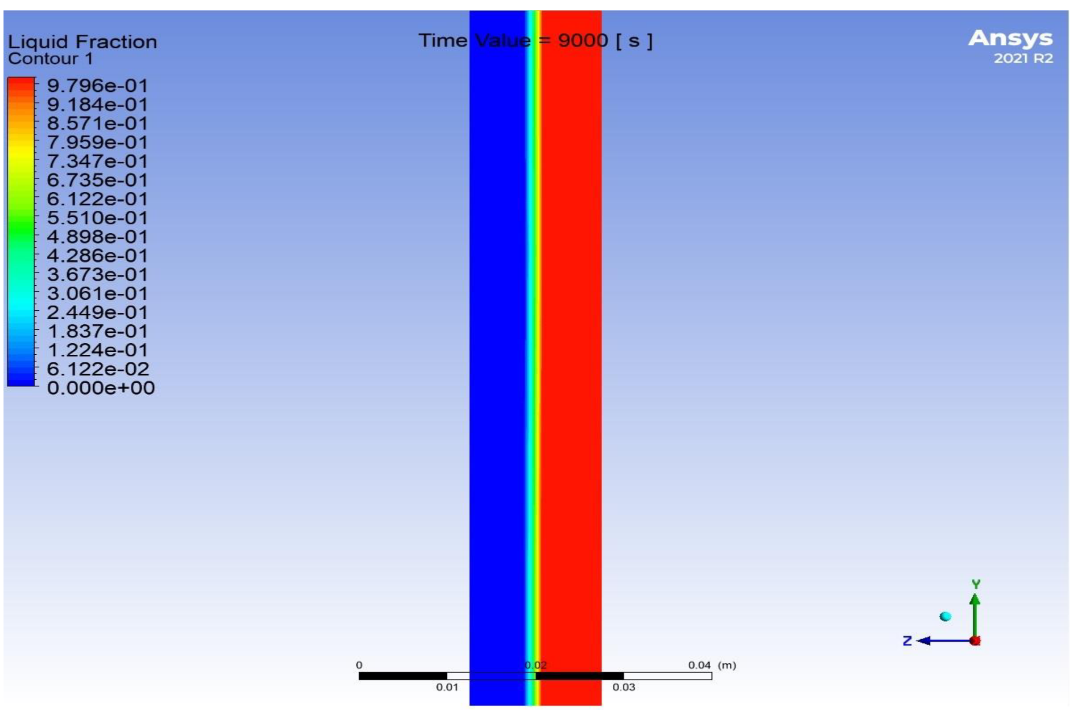


Fig.7.18 Liquid fraction Contour PCM 3 (OM50) 9000s

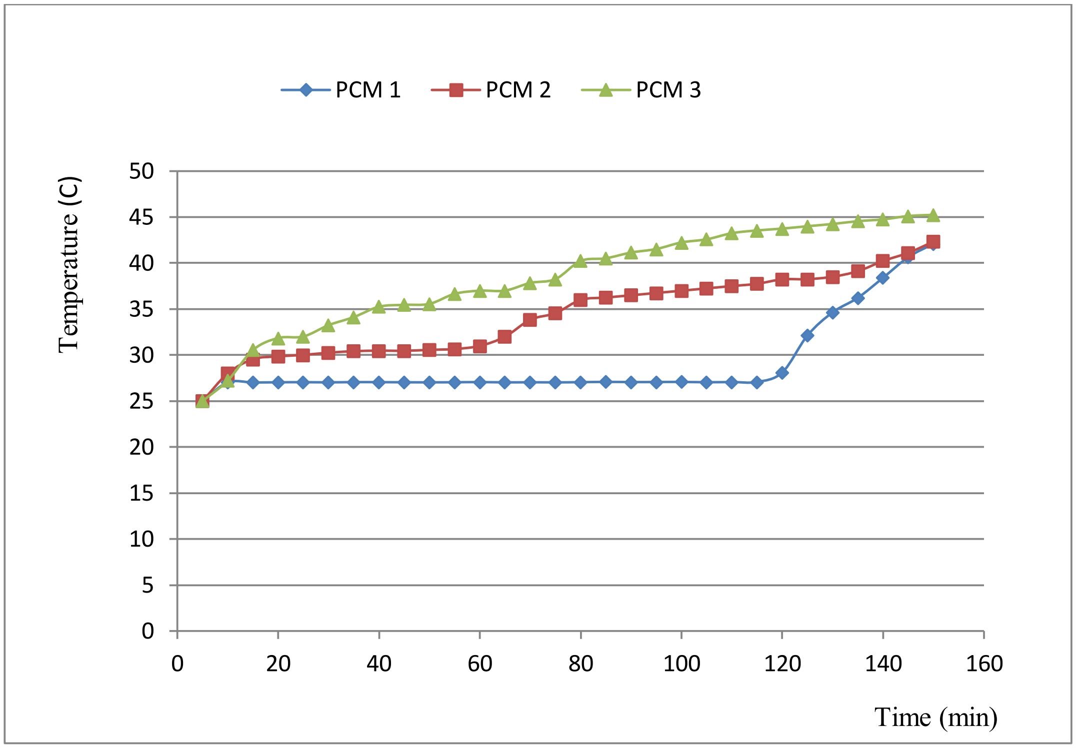


Fig.7.19 Comparison between average inner surface temperatures of different glazings Vs Time

The figures from 7.1 to 7.19 show the counters and plots of different PCMs when filled between double glazed windows. It very well explain that the maximum effectiveness with 15mm PCM layer thickness can be achieved by the lower melting point PCM i.e. PCM1(OM29). It helps to maintain a lower temperature in the inner glass wall for a long period of time. For higher melting PCMs there will be conduction heat transfer between the outer and inner wall due to higher temperature difference. The PCM utilization can be obtained from the liquid fraction plots and counters. The PCM utilization of PCM1 (OM29) is 100% and that of PCM2 (OM42) and PCM3 (OM50) are 65% and less than 60% respectively for a layer thickness of 15mm.

CHAPTER 8

COMPARISON BETWEEN EXPERIMENTAL AND NUMERICAL RESULTS

8.1 COMPARISON OF RESULTS

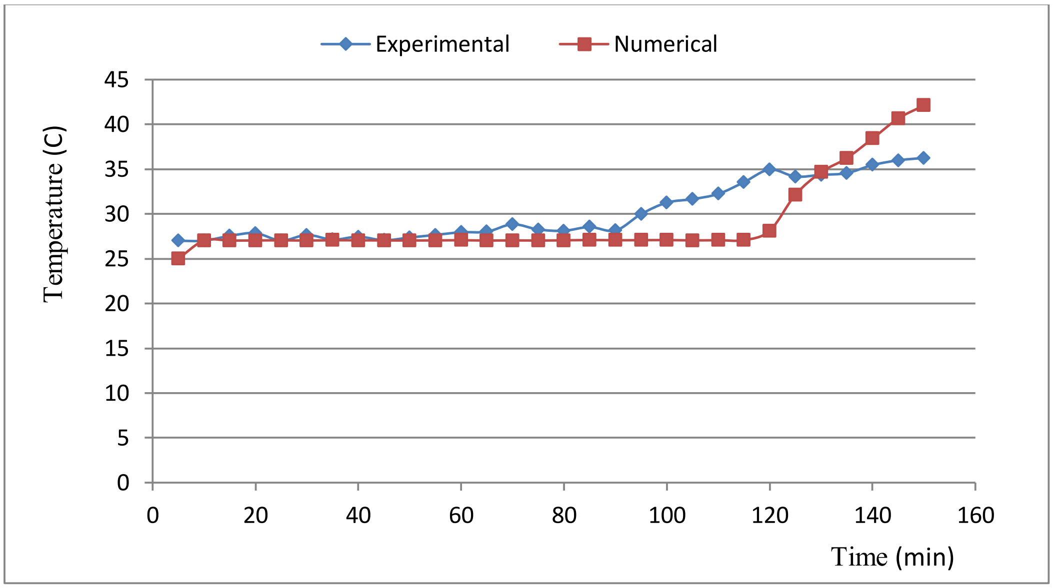


Fig 8.1: Average Inner surface Glass temperature of the double glazing Vs Time graph for PCM1 (OM29) filled double glazed window

Table 8.1 Comparison of Experimental and Numerical Values for PCM1 (OM29)

Experimental Investigation (C) (Average Temperature)	Numerical Investigation (C) (Area Weighted Average Temperature)	Time (min)
27.657	27.032	30
27.065	27.047	45
27.954	27.063	60
28.263	27.073	75
28.149	27.080	90
31.653	27.087	105
34.954	28.121	120
35.987	40.654	145
35.995	42.113	150

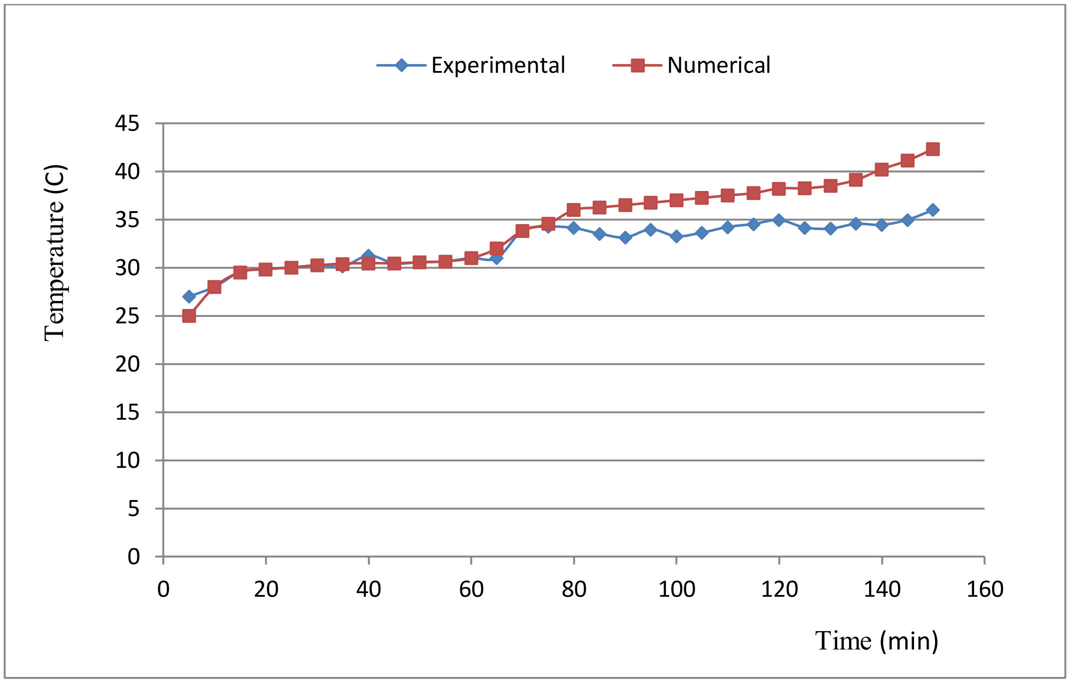


Fig 8.2: Average Inner surface Glass temperature of the double glazing Vs Time graph for PCM2 (OM42) filled double glazed window

Table 8.2 Comparison of Experimental and Numerical Values for PCM2 (OM42)

Experimental Investigation (C) (Average Temperature)	Numerical Investigation (C) (Area Weighted Average Temperature)	Time (min)
30.262	30.257	30
30.473	30.485	45
31.001	31.012	60
34.265	34.563	75
33.152	36.502	90
33.653	37.252	105
34.954	38.235	120
34.559	39.124	145
36.225	42.335	150

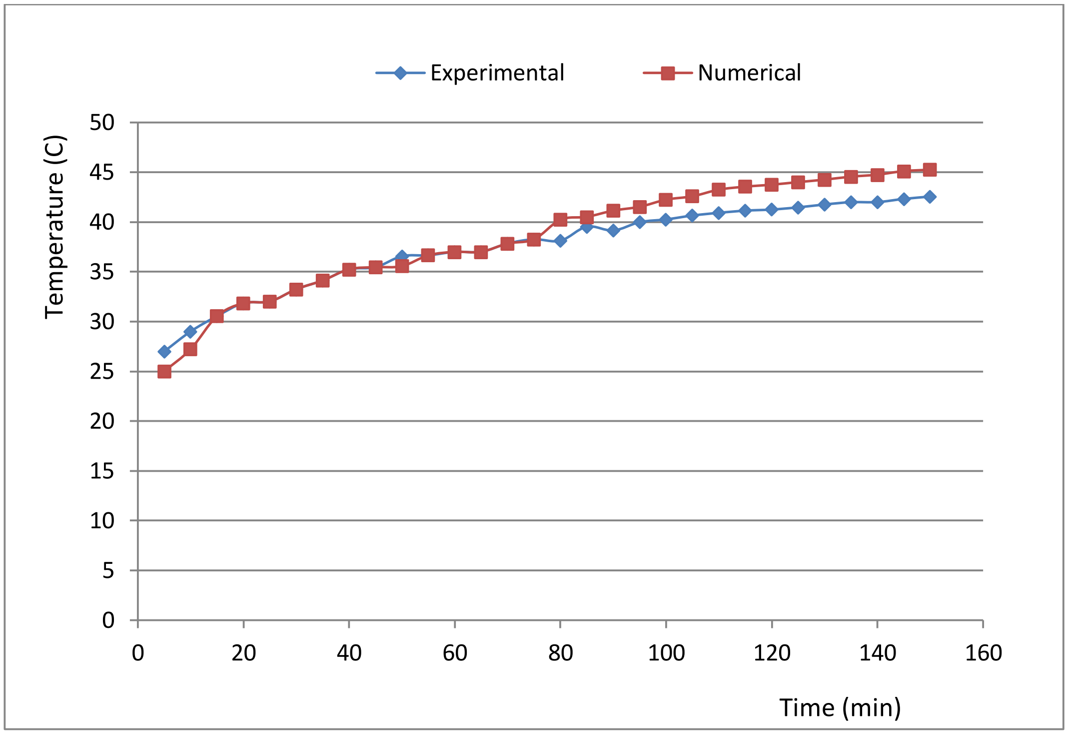


Fig 8.3: Average Inner surface Glass temperature of the double glazing Vs Time graph for PCM3 (OM50) filled double glazed window

Table 8.3 Comparison of Experimental and Numerical Values for PCM3 (OM50)

Experimental Investigation (C) (Average Temperature)	Numerical Investigation (C) (Area Weighted Average Temperature)	Time (min)
33.257	33.268	30
35.465	35.531	45
37.002	37.121	60
38.263	38.321	75
39.149	41.151	90
40.653	42.587	105
41.254	43.753	120
41.993	44.558	145
42.559	45.252	150

From the above results it is clear that the experimental values are in excellent agreement with numerical values. Inner surface temperatures obtained using CFD simulation are found to be higher than that of experimental values, since all other walls of window are considered to be adiabatic in simulation and in experiment there may be some heat loss through the walls, that is not considered in the simulation. Convection heat transfer in outer side window need not to be considered since the surface temperature values, not the surrounding air temperature, is considered here. Convection heat transfer is considered in the inner glass walls and the solution is initialized with 25°C initial temperature.

8.2 REGRESSION ANALYSIS

When you compare the correlation between a response and one or more descriptive variables in mathematics, linear regression is a linear method (also known as dependent and independent variables). Simple line rotation is used when there is a single descriptive variable; more line regression is used when there are multiple descriptive variables. In contrast to the multivariate linear regression, which predicts the relative dynamics associated with a single scale variation, this expression is very common. In linear regression, line prediction functions are used to model relationships, and anonymous model parameters are measured in data. These models are called straight models. The conditional explanation of the response is generally considered to be an affine function of the values of the descriptive variables (or predictions); a conditional median or other quantile is occasionally used. As with all other types of regression analysis, line regression focuses on the probable distribution of conditional response given predictable values instead of the distribution of the combined probability of all these variables, which is the purview of multivariate analysis. In this study a simple linear regression model was used to study the agreement between test analysis and numbers. Here we want to perform a retrospective regression analysis so that the line structure is based on the test result and the numerical and test data is organized as a scatter chart around this line structure. The variance from line to line helps to understand the agreement between test data and numerical data.

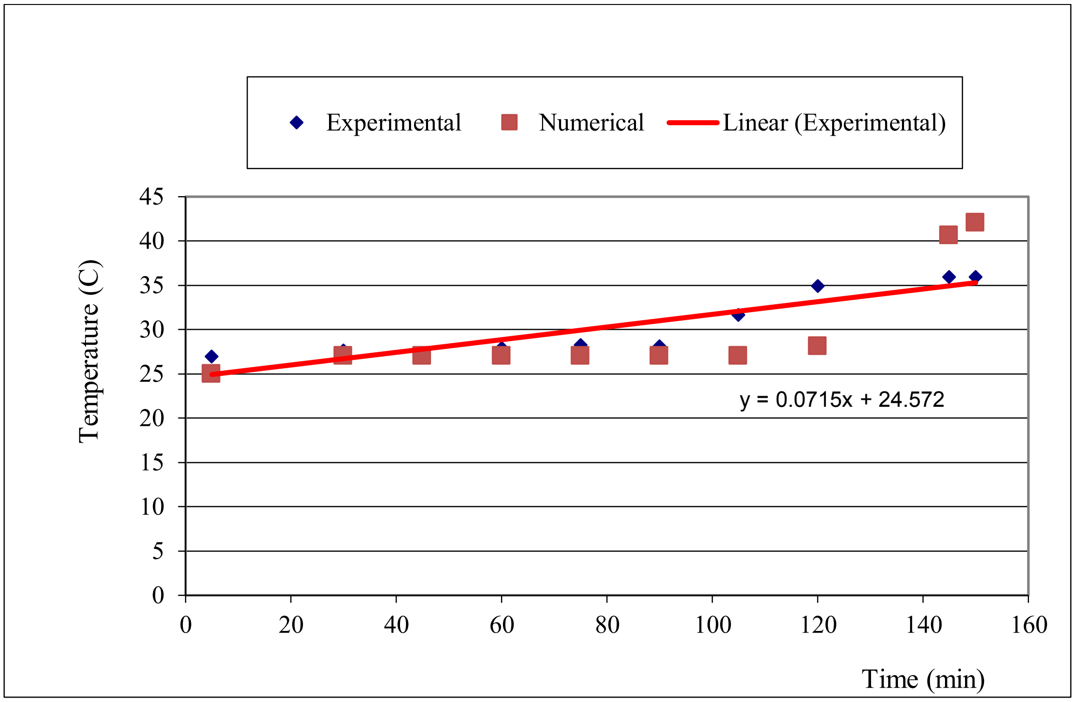


Fig 8.4: Scatter Plot Regression Trend line for PCM1 (OM29) filled double glazed window

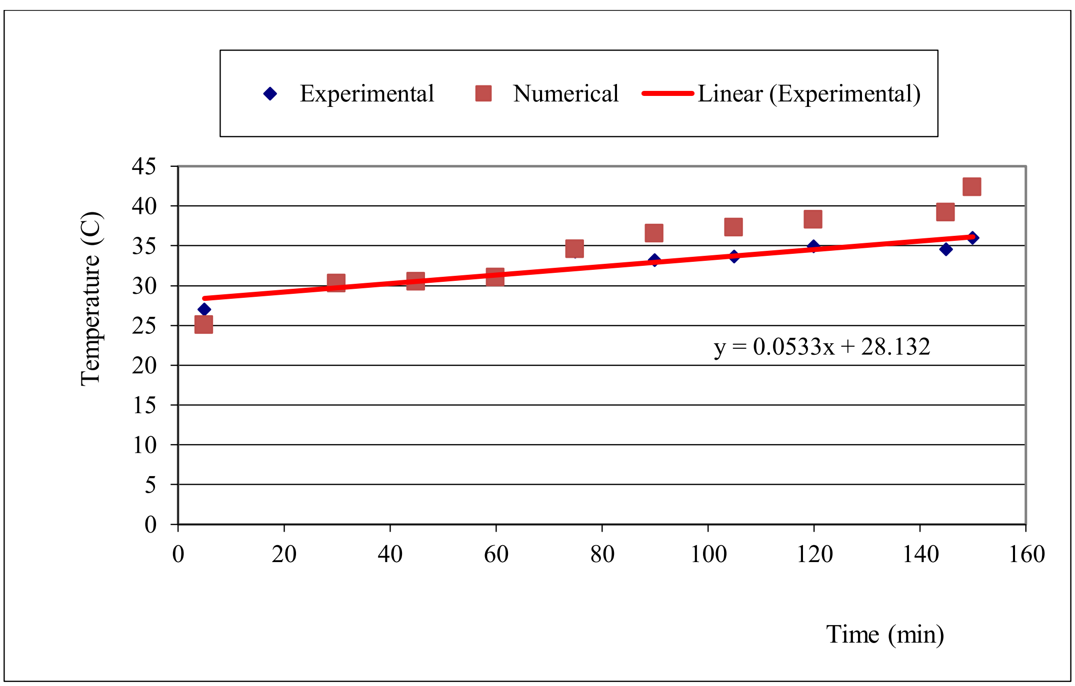


Fig 8.5: Scatter Plot Regression Trend line for PCM2 (OM42) filled double glazed window

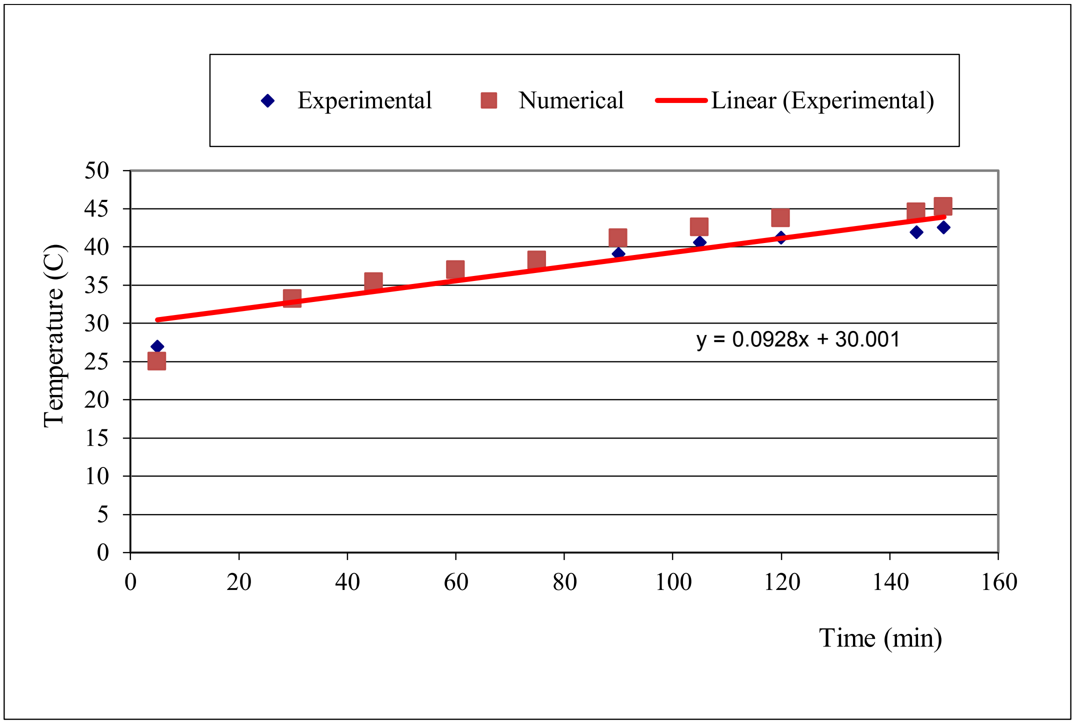


Fig 8.6: Scatter Plot Regression Trend line for PCM3 (OM50) filled double glazed window

The regression analysis also confirms that the experimental data are in excellent agreement with the numerical analysis as all the values are very close to the linear line plotted with the experimental results. Here we can see that there is only marginal variation above and below the linear line in all the three cases.

CHAPTER 9

CONCLUSION

An experimental study has been conducted to understand the heat transfer characteristics of PCM filled double glazing along with without PCM double glazing. The results show that PCM filled between the gaps of double glazing can effectively reduce the inner surface temperature of window when compared to without PCM double glazed windows. The temperature difference between the outer and inner glass wall in without PCM double glazing is 2.88^{o}C after two and a half hours of experiment. But in the case of PCM filled windows for PCM1, PCM2 and PCM3 the temperature difference are 19.82^{o}C, 33.52^{o}C and 26.56^{o}C respectively. The study mainly focused on the phase transition or melting temperature of the PCM and the results shows that with increase in the phase transition temperature there is a large difference between outer and inner wall temperature but at the same time PCM utilization decrease. It is also noted that there is temperature buildup in the outer glass wall due to the increased phase transition temperature. The melting temperature and PCM thickness should be selected based on the average atmospheric temperature to make sure its complete utilization. If the PCM layer is not completely utilized then it can affect the light transmission capacity of the windows. Numerical study, done on ANSYS FLUENT, displays outcomes that are comparable to those obtained through experimentation since the inner surface temperature values obtained through experimentation and numerical analysis are congruent. The assumptions employed in the numerical analysis, such as ignoring heat loss via the margins of windows and infiltration can be used to offset some of the variances shown in the numerical results.

SCOPE FOR FUTURE WORK

- Study on varying thickness of double glazing unit can be done for different PCMs.

REFERENCES

Ahmadi, R., and Shahcheraghian, S. **(2015)**, Energy saving in building using PCM in windows,*14th Conference of International Building Performance Simulation Association, Hyderabad*

ANSYS fluent software package: user's manual, 21R1, (**2021)**

Bolteya, M., Elsayad, A., & Belal, M. **(2020)**, Thermal efficiency of PCM filled double glazing units in Egypt, *Ain Shams Engineering Journal*, 12(2), 1523-1534

Cho, S & Kim, S. (**2017**). Analysis of the Performance of Vacuum Glazing in Office Buildings in Korea: Simulation and Experimental Studies. *Sustainability*, *9*(6),1-15

Dixit, S. and Lohia, S. (**2015**), Energy Conservation using Window Glazing in India, *International Journal Of Advanced Research In Electrical, Electronics And Instrumentation Engineering*, *4*(11), 8645-8654

Durakovic, B., and Torlak, M. **(2017)**, Simulation and experimental validation of phase change material and water used as heat storage medium in window applications, *Journal of Materials and Environmental Sciences*, 8(5), 1837-1846

Gasparella, A., Pernigotto, G., Cappelletti, F., Romagnoni, P., & Baggio, P. (**2011**), Analysis and modelling of window and glazing systems energy performance for a well insulated residential building, *Energy And Buildings*, *43*(4), 1030-1037

Gorantla, K., Shaik, S., &Setty, A. (**2017**). Effect of Different Double Glazing Window Combinations on Heat gain in Buildings for Passive Cooling in Various Climatic Regions of India. *Materials Today: Proceedings*, *4*, 1910-1916.

Hussein, A.K., Li, D., Li, Z., Zheng, Y., Liu, C.,., & Liu, X. **(2016)**, Thermal performance of a PCM-filled double-glazing unit with different thermos-physical parameters of PCM, *Solar Energy*, 133, 207–220

Ismail, A.R., Salinas, C.T., Henriquez, R.J. **(2008)**, Comparison between PCM filled glass windows and absorbing gas filled windows, *Energy and Building*, 40, 710–719

JianQu et al. (**2014**), Transparent thermal insulation coatings for energy efficient glass windows and curtain walls*, Energy and Buildings 77, 1–10*

Lechowska, A. **(2016)**, A CFD study and measurements of double glazing thermal transmittance under downward heat flow conditions, *Energy and Building*, 122, 107-119

Li, D., Ma, T., Liu, C., Zheng,Y., Wang,Z., & Liu, X. **(2016)**, Thermal performance of a PCM-filled double glazing unit with different optical properties of phase change material, *Energy and Buildings*, 119, 143–152

Li, S., Zhou, Y., Zhong, K., Zhang, X., and Jin, X. **(2016)**, Thermal analysis of PCM-filled glass windows in hot summer and cold winter area*, International Journal of Low-Carbon Technologies,* 11, 275–282

Qudama Al-Yasiri and Marta Szabo **(2021),** Incorporation of phase change materials into building envelope for thermal comfort and energy saving: A comprehensive analysis .*Journal of Building Engineering* 36 (2021) 102122

Sharma, V., Sharda, A., & Kumar, V. (**2016**), Simulation Thermal Analysis of Double Glazed Window with InterpaneChik Blind, *International Journal Of Engineering Research And Technology*, *05*(07)

Shuhong Li et al **(2014),** Comparative study on the dynamic heat transfer characteristics of PCM-filled glass window and hollow glass window , *Energy and Buildings* 85 (2014) 483–492

Sigi Kumar, T.S, Rijo Jacob ,T., Mohammed Sajid, N.K, & Shafi, K.A (**2018**). Experimental Analysis of Glazed Windows for Green Buildings. 2018 *2nd International Conference on Green Energy And Applications (ICGEA) conducted at Nanyang Technological University*

Taheri, M., and Foroughian, S. (**2017**), Comparative Study of Single-glazed and Double-glazed Windows in Terms of Energy Efficiency and Economic Expenses. *Journal of History Culture and Art Research*, *6*(3), 879-893

Taniya, A., and Chandel, S. (**2017**), Review of current state of research on energy storage, toxicity, health hazards and commercialization of phase changing materials, *Renewable and Sustainable Energy Reviews,* 67, 581–596

Vigna, I., Bianco, L., Goia, F., and Serra, V. (**2018**), Phase Change Materials in Transparent Building Envelopes: A Strengths, Weakness, Opportunities and Threats (SWOT) Analysis, *Energies*, 11, 1-19

Zhang, C., Gang, W., Wang, J., Xu, X., & Du, Q. **(2019)**, Numerical and experimental study on the thermal performance improvement of a triple glazed window by utilizing low-grade exhaust air. *Energy*, 167, 1132-1143

Zhang, W., Qu, J., Song, J., Qin, J., Song, Z., & Shi, Y. et al. (**2014**), Transparent thermal insulation coatings for energy efficient glass windows and curtain walls, *Energy And Buildings*, *77*(1), 1-10

Zsembinszki, G., Fernández, A.G., and Cabeza, L.F. **(2020),** Selection of the Appropriate Phase Change Material for Two Innovative Compact Energy Storage Systems in Residential Buildings, *Applied science,* 10, 1-14