Studies on Thermal Behaviour of Phase Change Material for Cooling of Buildings

Thesis submitted by

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Statement of Originality

I, **Ashish Kumar** registered on 30th October 2015, do hereby declare that this thesis entitled **"Studies on Thermal Behaviour of Phase Change Material for Cooling of Buildings"** contains literature survey, and original research work done by the undersigned candidate as part of Doctoral studies.

All information in this thesis have been obtained and presented in accordance with existing academic rules and ethical conduct. I declare that, as required by these rules and conduct, I have fully cited and referred all materials and results that are not original to this work.

I also declare that I have checked this thesis as per the "Policy on Anti Plagiarism, Jadavpur University, 2019", and the level of similarity as checked by iThenticate software is **3%.**

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This is to certify that the thesis entitled "**Studies on Thermal Behaviour of Phase Change Material for Cooling of Buildings**" submitted by **Mr. Ashish Kumar**, who got his name registered on 30th October 2015, for the award of Ph.D. (Engineering) degree of Jadavpur University is absolutely based upon his work under the supervision of Dr. Sudip Simlandi and Dr. Nilkanta Barman, and that neither his thesis nor any part of the thesis has been submitted for any degree or any other academic award anywhere before.

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Abstract

In our daily life, use of air conditioning in buildings increases greatly to satisfy human comfort level, which consumes a huge amount of electrical power, about 15% of the total power consumption. However, in the recent decades, use of the phase change material (PCM) spreads widely as a thermal energy storage towards cooling of the residential as well as commercial buildings, which is an economically beneficial technology and save use of the conventional energy. The PCM melts and stores energy during a day and releases the same in night to the ambient. Utilizing the phenomenon, maintaining human comfort is possible encapsulated or embedded PCMs on walls, or terrace of the buildings. Hence, the use of PCMs in buildings will possibly save consumption of electricity that supplied from fossil fuels based power plants. Indirectly, this method reduces the consumption of fossil fuels in power plants, hence reduces pollution in the environment-a reasonable remedy to reduce the global warming. Therefore, establishment of cooling of buildings using PCM is an important requirement and thrust area of research.

To incorporate the concept, this work considered placing of PCMs on terrace of buildings instead of tiles on walls as major portion of the heat in a sunny day enters into the room through the terrace only. Also spreading of PCMs over the terrace is difficult in handling; accordingly, preparation of a model brick filled with suitable PCM is adopted in this thesis for the cooling purpose.

In order to establish the above consideration, experimental behaviors for a model brick have been determined by carrying out mainly four successive experiments. In the experiments, two types of organic PCMs: OM-29 and OM-37 are selected because of their melting temperatures are closer to the human comfort zone, i.e., 29°C and 37°C, respectively. All experiments are conducted at the Heat Power Laboratory of Jadavpur University. In this thesis, accordingly, the day time situation is represented by two temperatures close to the terrace temperature of a sunny day using a copper heat exchanger connected to a constant temperature bath (CTB) set at two different temperatures, i.e., 55°C and 65°C. The night time situation is represented by a suitable ambient temperature at 20°C. Based on these conditions, four combinations of experiments are conducted: Case-I: OM-29 as PCM and 55°C at CTB, Case-II: OM-29 as

PCM and 65°C at CTB, Case-III: OM-37 as PCM and 55°C at CTB, and Case-IV: OM-37 as PCM and 65°C at CTB.

Out of the four experimental cases, it is observed that molten PCM of all cases solidifies back within end of the day, i.e., after 24 hours. Hence, recycling of the selected PCMs is possible for all cases. It is established that a minimum temperature at bottom of the model brick comes to 28.8°C when OM-29 is used as the PCM. Finally, it is concluded that room temperature of a building can be maintained at a temperature lower than 28.8°C in a moderate sunny day, and that may reaches to 33.3°C in a very sunny day.

The above experimental results are then validated with numerical work. In the numerical work, all transport phenomena are modelled using a set of governing equations include mass, momentum and energy conservations along with a consideration of volume average physical properties. The control volume method (CVM) is used to discretize these governing equations appropriately, and using the TDMA, all final linear simultaneous equations are solved with proper boundary conditions and morphology of solid-liquid interface occurs during melting and solidification of the phase change materials. Thereafter, a simulation code is developed on FORTRAN platform. The numerical results are compared with experimental predictions for all four cases. It is observed that a good agreement is found for all the cases of numerical predictions with experimental ones.

In brief, in this thesis, a model brick filled with a suitable PCM is established. Such model bricks are to be placed on terrace of the buildings for cooling purpose. On using of OM-29 as a PCM in such model bricks, room temperature of a building can be maintained at a temperature below of 28.8°C, which is under human comfort zone.

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Chapter I

Introduction and Literature Review

1.1 Introduction

In view of gracefulness of the modern technology and its recent development, which provide a wonderful lifestyle at present and expect much better in the near future. Through use of several equipment of such development, new technology has been providing many facilities in order to build a contented society. As of human daily-life, domestic appliances such as fans, computers, washing machines, televisions, air conditioning etc. is facilitating a comfortable daily life. Without these facilities, it is difficult to imagine a comfortable daily life as electricity is the requirement to power these machineries; which implies that these facilities are unable to use without electricity.

In concern to the air-conditioning systems those give us a good comfort in a room, but consume about 15% of the total supplied electricity [1] that indicates these air-condition systems consume a huge amount of electrical energy. This is well known that electrical energy comes out of the fossil fuel based conventional power stations. It is to be noted here that these power stations have many side effects; those increase environmental pollution as well as global warming. In order to maintain the pollution control norms [2] and related environmental issues those insist researchers to search alternatives of the air-conditioning systems for controlling environment pollution, global warming as well as electricity crisis of the present era by reducing the use of electricity.

1.2 Reduction of pollution in the environment by reducing the use of electricity

In concern to the environmental pollution, which is mainly caused by the power plants those supply electricity, is increased by different ways [3, 4] day-by-day. Construction and thus operation of the power plants is one of such causes, and construction and operation imply side impacts on the environment largely. The undesirable outcomes or consequences out of the power plants affect the environment either temporarily or permanently. It is noticed that a power plant and its related supporting infrastructure such as natural gas pipelines, water intakes and its discharge, coal delivery and necessary storage systems, new transmission lines, required waste disposal facilities etc. consume water resources at a large volume, occupy spaces on ground and in the air too, and certainly the power plant releases pollutant in nearby air [5, 6]. Footprint of such power plants on the earth prevents other people as well as animals to occupy or use such lands. A coal-fired based power plant has also several towering structures as well as exhaust stacks. The height of such infrastructures in the power plants raises safety issues for aeroplanes, or an obstruction to local people. In brief, there are many side effects in use of the lands, soils, and also to the animals present on the sites if such lands are utilized by power plants.

The power plants those burn fossil fuels or biomass produce exhaust gases and various by-products, pollutes the environment at large scale [7]. On the other hand, the water that is used to create steam must be treated and must be available in a huge amount from the adjacent rivers, lakes, or from underground water aquifers. In particular, this used water needs to be removed from the power plants. Thus power plants are polluting the surrounding water also [8]. There are also other variables to take into account including volume of discharged water, its temperature, and quantity of pollutants present in the discharged water.

The power plants also produce solid wastes in various forms, and these must be managed by the associated authority [9]. Ash is produced in burning of coals, and is a solid waste. Further, before releasing water into the surface waters, the power facilities use water either to produce steam or to cool, frequently needs to filter and purify. The filtered solids are the by-products those are to be properly disposed.

To remove heat from the condensers, cooling towers are used to circulate water for cooling purpose. In this case, million gallons of water per day in vapour form are carried into atmosphere by the air in cooling tower; as accordance, the atmospheric air has been warming day-by-day in the cooling towers. In other way, these power plants also consume a significant amount of water [10], which is obtained locally and is a cause of water crisis.

The community where a power plant is established may experience unpleasant impacts [11] as a result of power plant construction and its operation. Although relatively well-organized construction of power plant has been seen, the nearby landowners and other residents have an impact on their daily business. Costs for the public services including traffic control, emergency medical care, and fire protection is raised, and cost of water supply too as the related municipal water supply [10], wastewater handling, and solid-waste management systems need special additional standard treatment. Also, the coal or the fuel must be delivered into coal-fired power plants in an effective, dependable, and long-term manner, typically by the rail or barge. Such construction also results a rise in the local noise level, and together with power plant operation, generates huge noise and vibration.

All above are discussed as parts of environment pollution caused by the power plants built in order to generate and supply the demanded electricity. On the other way, it is noted that reduction in electricity utilization reduces the consumption of fossil fuels or coal; this may control additional emission of pollutants as well as the solid wastes by any power plant into the environment.

1.3 Reducing effect in global warming by reducing the use of electricity

Warming of the global atmosphere is currently one of the most pressing issues, facing by the planet and its ecosystem. Because of various human activities, a shift in composition of atmospheric air, i.e., an increase in the greenhouse gases is observed, which results an increase in the rate of global warming. Climate scientists agree [12] that the human activities such as burning of fossil fuels, contribute a huge to this problem.

The solar radiation is being absorbed into the atmosphere by an increased combination of the greenhouse gases, majority of which are formed when fossil fuels are burned, and the minute particles those are formed when combustion is not completed. The common greenhouse gases are CO_2, CH_4, NO, NO_2, etc.

Major of the power plants are running using the fossil fuels, and due to their burning, hazardous greenhouse gases emit in the environment that means indirectly any of the fossil fuel based power plants is one of the reasons for the global warming, which is a real threat to this planet. Thus, the consumption of more and more electricity in order to provide comfort to daily lives, more greenhouse gases are being released into the environment in operation of power plants – a spark to the threat of global warming. In concern to this, reduction in the use of electricity is one of the solutions.

1.4 Green buildings - an alternative to reduce the use of electricity

As of today, every human being lives in own building which is powered by the electricity.

The power plants are the sources where this electricity is being generated. In order to reduce reliance on the electricity, incorporation of green buildings is a necessity.

This green building is also known to us as a green construction or a sustainable building. In comparison to any conventional building, a green building consumes less water, maximises energy efficiency, protects natural resources, produces less waste, and gives occupants a better environment. Building of green buildings is a challenging method by designing an ecological friendly structure in a simple way, and a practical approach. Traditional and collaborative design methods, technology, and material application are all combined in the green buildings.

The features for different types of green buildings [13] are presented here:

- ***Structure design efficiency***: It is primary concerned to minimize overall negative impacts on the environment. It has most significant effect on both cost and performance of the structure.
- ***Energy efficiency***: The plan is to decrease amount of energy that is to be used in operation of buildings. Use of renewable energy sources like solar electricity, wind power, hydro power etc. can greatly reduce harmful effects that a building has on its surrounding environment.
- ***Material efficiency***: The components of a building should be made of eco-friendly, recyclable, and renewably sourced materials whichever possible. For instance, woods lumber, renewable plant materials such as bamboo and straw, and various other items, reusable, etc. are some examples. The use of phase change materials (PCMs) is one of such suitable options. This work mainly concerns about use of suitable PCMs in building construction.

1.5 Use of phase change materials (PCMs) for the cooling of buildings

Since past few decades, an interest has been growing in the use of phase change materials (PCMs) in building construction [14]. The PCMs are able to store and release both sensible and latent heat energy, which is an intriguing quality of the PCMs. These substances transform from their solid phase to liquid phase by absorbing heat at a constant temperature. Similarly, the substances turn from their liquid phase to solid phase by releasing heat to the ambient at a constant temperature. The phase change property of the PCMs makes them different from other materials. As latent heat value of suitable PCMs is comparably high, it is possible to store more heat or to release heat without rising or decreasing its temperature.

As an emerging research area, Osterman *et al*. [15] reported that the thermal energy storage using PCMs is suitable in cooling or heating of buildings by storing or releasing energy changing phase or PCMs, which is one of the technologies that helps to reduce energy usages. These PCMs are suitable devices, may be used for cooling or heating of any space including buildings or any electronic devices too.

In concern to the cooling of a building with the help of PCMs, mainly different ways are referred in which PCM can be set up to ensure that the buildings remain cool. Placing of PCM on top of the roof of buildings is one option, where PCM takes in heat or solar radiation during the day time, and then release that stored heat into the surrounding environment at night [16]. Because of the high latent heat value of such PCMs, the building is able to maintain a comfortable temperature owing to the process, i.e., the PCM absorbs or releases heat at constant temperature. It is noted here that inside temperature of any building mainly depends on the selection of PCMs. Tiles containing PCM can also be installed on side walls of the structures, and they will provide the same cooling effect, which is another option for cooling the buildings.

However, finding a suitable way to incorporate the PCMs in construction is still under investigation and an emerging issue in present day research. According, this work considers placing a layer of bricks filled with suitable PCM on terrace of buildings without disturbing the basic structure so that the concrete of terrace provides an additional resistance to the heat flow into the room.

1.6 Background of the present thesis

A typical condition of conventional building is shown in Fig. 1.1(a) in which, several air conditioning systems are utilised to maintain the room cool for daily comfort. People are more comfortable in their daily lives; thus, there has been a significant growth in the demand of electricity for air conditioning systems recently. This demand of air conditioning from commercial, industrial, and residential activities results in a significant electrical energy consumption both during day and at night. In a country with a hot climate, it has been found that a significant portion of the total power produced is used for air conditioning of spaces in buildings. For this luxury life with respect to using air condition systems, about 15% of the total energy produced is consumed [1]. As a large portion of energy in air conditioning systems is consumed for the sake of cooling of buildings, huge amount of electricity is also consumed. This electrical energy is coming from conventional energy sources specifically from the conventional power plants, and these sources cause the environment pollution at a large scale. In other way, it can be said that the cooling system using air-conditioning systems causes environment pollution.

To overcome such problems, moving towards alternative methods is the recent trends in order to save the energy or electrical energy as well as to overcome the harmful effect of using conversional energy sources. One of the most affordable methods that has the least negative environmental effects and maintains a balance between the supply and demand of energy, is the use of thermal energy storage systems in construction.

Recently, use of phase change materials (PCMs), which is an economically advantageous technology, has been introduced as a thermal energy storage device for cooling the residential and commercial buildings in order to save conventional energy (in terms of electrical energy). The latent heat value of the PCMs is relatively high. This property of the PCMs makes possible to store heat during the day without increasing its overall temperature during melting. Thus, a PCM based system may be installed on top of the terrace or side walls of buildings. This will absorb radiation throughout the day by melting of the PCM, and release the same during night to the ambient by solidifying. This work is a consideration of using PCM without disturbing basic structure of buildings made of concretes. The concretes oppose entering outside heat additionally into the rooms as the concretes behave as insulator.

To incorporate the concept of using PCM in cooling of buildings, PCM in a form of model bricks or tiles in the surroundings of building can be placed. As noted, Fig. 1.1 (a) is a conventional building cooling system with the help of air-conditioning systems. It is already known that there are numerous disadvantages in using air-conditioning. Accordingly, in the present work, a suitable alternative is proposed for cooling of buildings. Use of PCM is one of the best ways to cool the buildings. Fig. 1.1(b) represents a suitable cooling of buildings with the help of PCM. PCM can be used in the form of bricks on the terrace and/or as tiles on the walls. During the day time heat is absorbed by the PCM and in the night time, heat is released by the PCM to the atmosphere. Using this cooling system in buildings, it is possible to save the electricity. Moreover, installment of PCMs is a onetime investment. So the main focus of this work is to consider a suitable method for cooling of buildings using PCMs. This thesis prepares a model brick containing a suitable PCM and analyzes thermal behavior of the brick which includes mainly melting and solidification phenomena of the PCM. The bricks are to be placed on terrace of buildings with an aim to maintain a suitable room temperature of the buildings. The model bricks can save electricity which indirectly means a reduction in pollution so this model brick is named here as green brick.

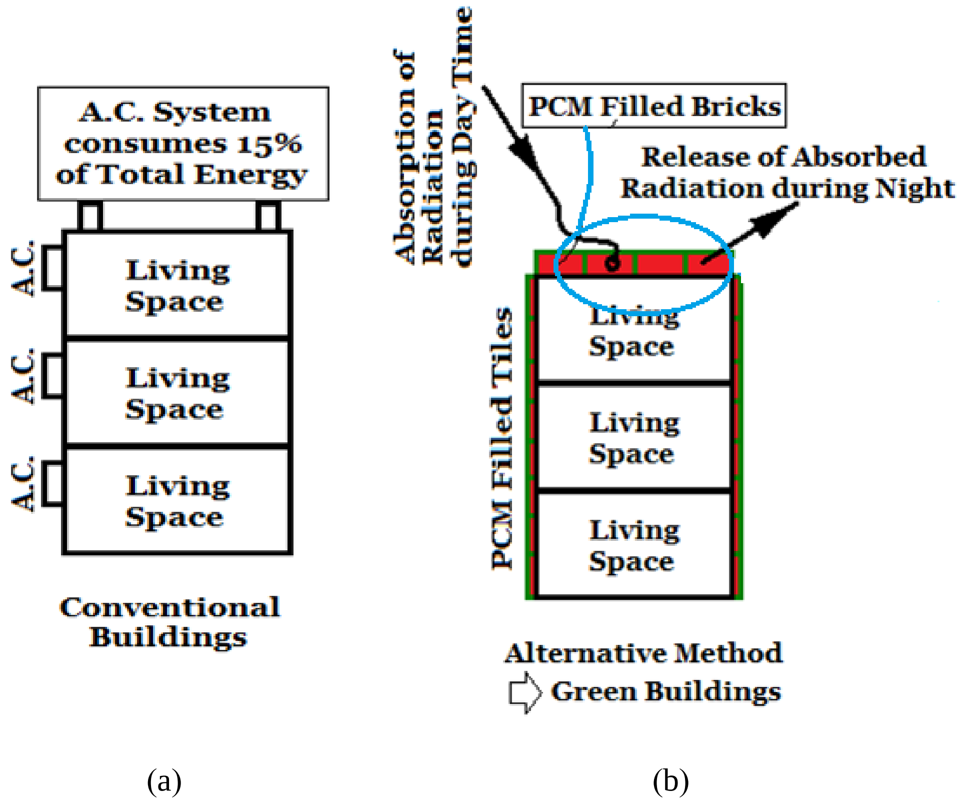

Figure 1.1: (a) Cooling of buildings using air conditioning, (b) cooling of buildings using PCMs

1.7 Literature review

For understanding of the basics of cooling using the phase change materials (PCMs), a thorough literature review has been conducted. A brief of the important research papers is presented here as a reference. Primarily this review covers research papers related to the establishment of methods for cooling of buildings using phase change materials, and then the review is extended for understanding thermal behavior of the phase change materials. Finally, the review includes presentation of related numerical works.

1.7.1 Literature related to establishment of the method of cooling the buildings using phase change materials

Out of the literature review, it is summerised that cooling of buildings using phase change materials is a recent trend, and limited literature on the issue has been cited accordingly. Some of the related literature are presented here.

Butala *et al*. [17] carried out an experimental work on free cooling with the help of PCM.They conducted an experiment using paraffin of melting point 22℃. Free-cooling is a technique for storing night time outdoor coolness and supplying daytime indoor cooling. They applied this concept in cold storage where PCM is kept in a duck. In their experiments, PCM is cooled down throughout the night, which enables the cold storage to maintain their desired state during the day. In their result analysis, they found that as the flow rate of the air increases, temperature inside the duct decreases due to placing of PCM.

Lazaro *et al*. [18] worked on the free cooling of the building using PCM. As the PCM stores and releases energy by changing its phase; to take this concept, they made a heat exchanger where they placed the PCM to cool room air in day time. For this experiment, they considered two prototypes using organic and inorganic PCMs, respectively, in alluminium panels. They concluded that prototype 2 is able to maintain cooling capacity more than 3KW.

Waqas *et al*. [19] reported a work on free cooling. In their experimental work, PCM is placed in a horizontal ventilated pannel, in which air flows with help of fan. In the day time, air becomes cool due to installation of PCM, and sends it into the room. In the night time, air takes heat from the PCM and sends it to the surroundings by changing its phase. In their research, the night time temperatures for the charging of PCM are considered as 20℃, 22℃ and 24℃ whereas during the discharging process, the temperatures are considered as 36℃, 38℃ and 40℃.

Jaworski [20] analysed a free cooling work by changing the PCM position. They mix the PCM with gypsum and placed it in horizontal ventilation system. They found that room temperature reached to human comfort zone. Temperature reduced to 3℃ as compare to surroundings.

Zeinelabdein *et al*. [21] conducted a work related to free cooling. For this work, they made a PCM panel. They found that the proposed system has a potential to cut cooling load a lot used by air conditioning system. This system has potential to keep the air temperature well within comfort zone of 25.5°C to 30°C.

For the recycling of the PCM, **Panchabikesan *et al*.** [22] used water spray system to solidify the PCM completely. They found that PCM is completely solidified for the use of next day. In this analysis, melting temperature of the PCMs is considered in the range of 27℃- 29℃.

Diaconu *et al*. [23] considered a multi-layer wall system to keep the place cool or hot. The multi-layer wall is made from PCM and insulating materials. With this system, they have shown that the energy saving using PCM is possible. About 35.4% reduction in cooling load is found in their study.

Thiele *et al*. [24] examined the annual energy and cost saving of a building by application of PCM embedded on concrete walls. This wall will prevent the heat to enter inside a room. They concluded that annual cooling load and electricity cost are reduced. It is found that the cooling load reduction in San Francisco and in Los Angeles is from 85% to 100% and 53% to 82%, respectively.

Jayalatt *et al*. [25] carried out a work in reducing the cooling and heating load of the building with use of PCM. They placed the PCM on side walls. They found that 39% annual cooling load and 12% heating load are reduced of the building.

Hasan *et al*. [26] conducted an experimental investigation where PCM incorporated into layers of walls and ceiling. PCM as insulating material decreases indoor temperature and reduces cooling load. They found that about Rs 110/ day in electricity bill is saved considering 1 cm thickness of PCM in wall.

Many buildings are having the metallic roof. In this case room temperature is increased in a large scale. To consider this case, **Boobalakrishnan** [27] conducted an experimental work. In his experimental work, he considered a room made of bricks and covered with plywood. Top of the system is covered with galvanic iron sheet. They placed PCM below of the sheet in the form of grid. They found that with the help of PCM, it is possible to reduce the room temperature.

Faraj *et al*. [28] conducted a review on cooling of building by using phase change materials. They found that PCM work good for the cooling of buildings by placing PCM in different ways with ceiling and walls. The main drawback is incomplete solidification of PCM in the night time.

In concern to cooling of building using cool roof, which works good in cooling process of buildings; because it reflects enough sun light during day time compare to conventional cases. Accordingly, **Saffari *et al*.** [29] combined PCM with cool roof, and that gives good results in cooling of buildings.

Vicente *et al*. [30] prepared a brick with combination of PCM, where PCM is macro-encapsulated in the brick cavity. Interior temperature compare to the normal brick wall is less. They found that thermal amplitude reduction is about 50% to 80%.

Wang *et al*. [31] conducted an experimental work to reduce a building temperature with the help of PCM containing in brick walls. With the application of PCM, containing brick wall is abled to reduce indoor surface temperature of the building. They found that reduction in cooling and heating load are 24.32% and 10-30% respectively.

Saxena *et al*. [32] carried out an experimental work by placing PCM in the brick cavity. Two PCMs, i.e., eicosane and OM-37 are considered in their work. They found that temperature reduction is 2.1℃ and 2.2 ℃ in case of eicosane and OM-37 brick model, respectively.

Garg *et al.*[33] carried out a experimental work with encapsulation of PCMs for cooling of building. They found that encapsulated phase change materials work as a heat exchanger and reduce heat gain to an approximate up to 50% and air temperature reduces around 6℃.

Alqallaf and Alawadhi [34] conducted a numerical and experimental work to reduce heat flux that enters inside of the room. They have used PCMs as vertical cylindrical holes made on the roof. They found possible heat reduction between 9% and 17.26%.

Elarga *et al.* [35] carried out experimental and numerical analysis on thermal performance of PCMs to reduce heat load in the building. They found that peak heat load reduction in between 13% and 59%.

Hichem *et al.* [36] conducted a numerical and experimental analysis of cooling of building using PCM in square hollow bricks. They found that PCM bricks improve cooling rate of building. They found a reduction in temperature of 3.8℃ in the inner wall of buildings. **Kong *et al.*** [37] also carried out similar work for cooling of buildings using PCMs and they focused on thermal energy storage.

Pashupathy and Vilraj [38] carried out a work on cooling of building over a year. In their work, they used double layers of PCMs for cooling of buildings for the two different seasons of the year.

Tokue *et al.* [39] conducted an experimental and numerical analysis on cooling of building with PCMs. They placed the PCMs as a flat plate. During their analysis, they considered thickness of the PCM in the range of 1cm to 5cm. They found that 2cm height of PCM in flat roof is suitable for cooling of building in Istanbul.

1.7.2 Literature related to understanding thermal behavior of the phase change materials (PCMs)

It is found that cooling of buildings using phase change materials (PCMs) is suitable and acceptable in order to save electricity, which intends toward construction of green buildings. However, implementation of the technology depends on the thermal behaviour of phase change materials. In order to understand basics of thermal behavior of PCMs, a through literature review has been incorporated. Some of the important literatures are presented here.

A review on experimental and computational investigations for improving thermal conductivity of PCMs is carried out by **Fan *et al***. [40]. They found that a variety of materials including copper, aluminium, nickel, stainless steel, and carbon fibre, are frequently utilised to enhance heat conductivity of the PCMs.

Stritih [41] examined the enhancement of heat transport in a phase change material in laboratory. Paraffin was considered as PCM with a melting point of 30°C. A heat exchanger was used to transport heat in phase-change material from water. They found that presence of fins increases heat transmission during solidification.

Choubuneh *et al*. [42] used PCM to extract excess amount of heat from system. They placed PCM below of absorber plate. As a result, they found that average temperature on back side of a photovoltaic panel is decreased by 4.3℃ and 3.6℃ through natural and forced convection, respectively.

Kandasamy *et al*. [43] examined the most effective strategy for cooling of electronic devices. They found that PCM is capable of effectively dispersing heat that is generated by electronic gadgets.

Fang *et al*. [44] prepared a new PCM, i.e., novel composite phase change material. They prepared the PCM with the help of blending of organice PCM, RT20 and organic modified montmorillolite. They found that the new PCM has the properties close to RT20. It has good performance stability and heigher heat tranfer rate as compare to the RT20.

Kong *et al*. [45] prepared a shape-stabilised PCM particle (PCMP) with the help of liquid paraffin and expanded pearlite (EP) in a vaccume heating rolling box. With the help of this PCMP along with styrene acrylic emulsion and glass fibers, they prepared the composite phase change material wallboard (CPCMW). The melting point and latent heat value of CPCMW were 25.22℃ and 85.63J/g respectively. They found that with the use of CPCMW in cooling of building provides good results compare to the PCMP .

Sari and Keygusuz [46] reported an experemental study to understand thermal performaence of palmitic acid (PCM). They found that palmitic acid is good for domestic solar water heating. They observed average heat storage efficiency as 53.3%.

Nagano *et al*. [47] worked with a new PCM that is $Mn(NO_3)_2.6H_2O$. They prepared a cylindrical test vessal for the experiments where they placed the PCM in inside of a jacket whereas in outer of the jacket, water flows as a cooling or heating agent. Range of melting point temperature of PCM is taken as 15℃-25℃. They found that this new PCM provide a good result in the cooling process.

Sharma *et al*. [48] made a new PCM with different compositions of a eutectic based PCM which is fatti acid. Carpic acid (CA), lauric acid (LA), myristic acid (MA), palmitic acid (PA) and stearic acid (SA), belong to the category of fatti acid. With the different weight percentage of PCM, they prepared the new PCM. In their experiment, they prepared thirty six eutectic samples by mixing different fatti acids.

Jeong *et al*. [49] combined PCM with silica fume. Due to its strong early compressive strength, high tensile and flexural strength, and high bond strength, silica fume has been utilized as a substitute for cement. They found that, PCM can improve thermal storage performance of the material.

Wu *et al*. [50] prepared a synthesis phase change humidity control material (PCHCM) by using hygroscopic material and microencapsulated phase change material (MPCM). They found that the PCHCM provides good results to reduce temperature as well as humidity with 18% energy saving.

Thaib *et al*. [51] reported an experimental analysis on the comparison of cooling effect of photovoltaic (PV) shell with beeswax PCM and paraffin wax PCM. Beeswax PCM provide more cooling effect compare to paraffin wax. They found that the range of efficiency become 6.1%-6.5% and 7.0%-7.8% without PCM and with PCM respectively.

1.7.3 Literature related to numerical works on cooling of buildings using phase change materials

The present work is a consideration of identifying a suitable energy saving method in order to cool buildings using phase change materials experimentally. However, in this work, it is considered to compare experimental outcomes with numerical ones. The literature has been reviewed, accordingly, and some important literature are presented here.

Zwanzig *et al*. [52] performed a numerical investigation for the energy saving by placing PCM containing in wallboard and roof of a building. They found that the annual cooling load and heating load is reduced by using PCM.

Ravikumar *et al*. [53] conducted a numerical investigation for cooling of buildings using PCM. They found heat entering inside a room is reduced, and cooling of building also takes place.

Peippo *et al*. [54] conducted a numerical simulation. They used PCM in plasterboard in passive solar heating. PCM works as a heat storage system. With the use of PCM, plasterboard saves about 5-20 % of energy.

Navarro *et al*. [55] performed a work for cooling of building using PCM. They found that 15 -20% energy saving is possible.

In a numerical investigation of cooling of building by **Mukharjee *et al*.** [56], they reported that, by keeping a layer of PCM above concrete, there is a reduction in room temperature. They have considered 24 hours of heating and cooling process. As reported , at end of the day, solidification of the PCM was incomplete.

Kumar *et al*. [1] worked on cooling of buildings using PCM. They considered 24 hours of heating and cooling process also. During the cooling process of PCM, aluminium is used with PCM to enhance its thermal conductivity. They found that room temperature is reduced with the use of PCM and the recycling of the PCM is possible. Maximum indoor temperature is recorded as 31.5°C.

Rucevskis *et al*. [56] conducted a numerical simulation-based study for the cooling of a room. To perform this, they selected a room model and placed PCM in between concrete ceiling slab and finishing layer of the ceiling. They found that the average indoor air temperature was reduced by 6.8°C.

Schossig *et al*. [58] carried out a work with micro-encapsulation of PCM in interior plaster. They encapsulated the PCM with gypsum plaster. In their simulation, they focused on ventilation so that stored heat can be easily dispersed. They found that with use of PCM, plaster provides more cooling compare to the case wihout use of plaster.

Kunzik *et al*. [59] conducted a numerical investigation for a wood house, where a wallboard is composed with PCM. The wallboard has different layers : wood, insulating material, PCM and plaster. With the use of PCM, they found that indoor temperature decreases.

Zhu *et al*. [60] reported a numerical work for the cooling of buildings. For this they considered a double layered PCM wallboard. They found that cooling and heating load is reduced 9% and 15 % respectively with the use of the PCM.

Gracia [61] performed a work on cooling of building using a concept of dynamic use of phase change material. In their dynamic use, they moved PCM from one place to another. The reason behind this was to complete solidification of the PCM, which allows more coolness. As a result, they found that dynamic PCM wall system provides better result compare to static PCM wall system and 37.9% of cooling load is reduced by the use of PCM.

Lizana *et al*. [62] reported a work with PCM for cooling of building. They found that use of PCM decreases room temperature of buildings. Without the use of air conditioning, discomfort hours are reduced by 65% with the use of PCM based system.

Farajollahi *et al*. [63] conducted a work on reducing heating and cooling energy during cold and hot environment with the help of phase change material (PCM). In their numerical work, they placed the PCM in wall cavity. They found that with the application of the PCM, reduction in thermal energy and cooling load are 20.8% and 22.6% respectively.

Arumugam *et al*. [64] carried out a work on optimum positioning of PCM or insulating materials in building envelope for reducing cooling load. For this work, they considered different models, combination of wall, plaster and PCM. They found that use of PCM reduces indoor temperature as well as cooling energy demand in Bangalore, Delhi, Pune, Jodhpur and Guwahati reduced by 64%, 61%, 63%, 57% and 58% respectively.

Kant *et al*. [65] performed a numerical investigation of brick containing PCM. In his numerical domain, PCM is placed inside a cylindrical cavity of brick model. PCM used by them is carpic acid, paraffin and RT-25. Heat reduction is possible more in case of carpic acid. They found that heat flux reduction is 1.198% by using multiple PCM.

Li *et al*. [66] worked for cooling of building for both summer and winter seasons with the help of composite phase change material wall. They prepared the wall with the help of PCM composition. They found good results in cooling of buildings using phase change materials and recommended PCM having melting point temperature range of 28℃- 33℃.

Bhamare *et al.* [67] discuss on selection of PCMs through the concept of the measuring key response index, in this regard, thermo-physical properties of the PCMs with different climatic zone are integrated at a glance.

Alawadhi and Alqallaf [68] performed a numerical study for cooling of building by placing PCM in conical holes of the roof. They found that n-Eicosane PCM provide good result. They found that entering of heat flux reduces up to 39%.

Triano-Juarez *et al.* [69] carried out a numerical analysis for cooling of buildings using PCM. They found that PCM with a thickness of 2 cm is used in concrete roof, which provides a good reduction of the room temperature. Maximum reduction in the temperature reported at the interior wall is 6.4℃.

Yu *et al.* [70] conducted a numerical analysis for cooling of building using PCM on the roof. They found that a height of 3 cm foe the PCM is good in order to minimize the temperature inside of the room. They found a reduction in the inner roof surface temperature as 3.7℃.

1.8 Conclusion out of literature review

Out of the above literature review, it may be concluded that the cooling of spaces in residential buildings is possible using phase change materials (PCMs), which is a onetime investment. This method reasonably saves the energy, i.e., in the form of electricity. Saving electricity reduces the pollution in environment, and accordingly, it can be said that such cooling system using suitable PCMs is an environment friendly method. This alternative method of building cooling is in the establishing stage, and requires a systematic study. Accordingly, objectives of the present thesis are planned and explained in the next section.

1.9 Objectives of the present thesis

There are many research reported on the field of cooling of building using phase change materials, which is an emerging field in this present era. However, implementation of this method is in the establishing stage, and requires a systematic study in order to implement the method. Accordingly, this work primarily considered a study on the method of cooling the buildings using suitable PCMs. While reviewing the literature, it is found that the maximum of research works is related to numerical works. In view of its practical implementation, related experimentation is to be conducted in systematic way. Accordingly, in this thesis work, development of a model brick filled with PCM is considered, and such bricks are to be placed on terrace in order to cool the buildings. Thus, the thesis primarily includes experimental works, and finally compared the work with numerical work. Out of other controlling parameters, height of the PCMs or model brick is major one for recycling. In this research work, accordingly, an optimum height of the model brick for placing above the roof in the form of green brick is estimated. This green brick model is experimentally studied inside Heat Power Laboratory of Jadavpur University. During experiments, thermal behavior of the PCM is also determined. In Fig. 1.2, a model of green brick is shown where PCM is placed inside an insulated plexiglass cover whose top surface is made of a thin metal plate. By using model green bricks on the terrace of buildings, it is possible to cool the buildings.

The major challenges included in this thesis are as follows:

- ***Selection of the PCM***: To conduct the experiment, the first challenge is to select a suitable PCM. However, different types of PCMs are available in market. The PCM should be selected in such a way that its melting temperature is near to the human comfort zone and its latent heat value should be high enough. Apart from this, handling of the PCM must be comfortable. It should be nonflammable, non-toxic and ecofriendly.
- ***Placing of PCM on terrace or on wall***: In the literature review, it has been found that most of the literature considered placing of PCMs on walls of the buildings, rarely any literature considered placing of PCMs on terrace which is a suitable method. Accordingly, this work considers placing of PCMs on the terrace of buildings. While conducting experiments, it is difficult to place PCM over wide area of the terrace. To overcome this difficulty, it is decided to place the PCM inside a model brick as shown in Fig. 1.2. This model brick can be easy placed above the terrace.

- ***PCM thickness***: PCM thickness is one of the major parameters, as it is a deciding factor for recycling of the PCM includes absorbing heat by melting in day and releasing heat to the ambient in night by complete solidifying to initial state. The PCM height should be in such a way that it must be fully solidified for the next day. If it is not solidified completely after each of the full day, then after few days or month, liquid fraction of PCM will be present inside bricks and further cooling is not possible.

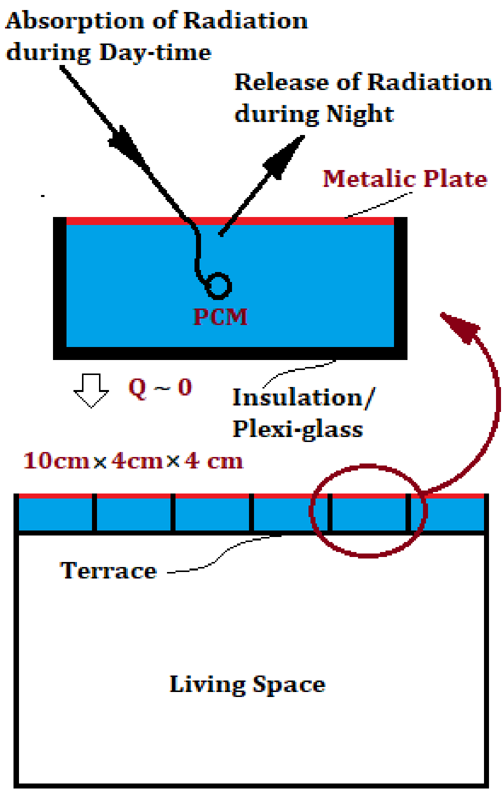

Figure 1.2: A schematic of model green brick

1.10 Summary of the chapter

Cooling of spaces in buildings is always a challenge for the researchers. Many research works have been reported to find a suitable solution. After going through the literature review, it is found that cooling of spaces in buildings using phase change materials (PCMs) is one of the suitable methods, but maximum reported research works are related to numerical analysis, and rarely any systematic experimental work has been reported for cooling of spaces in buildings.

Therefore, the main focus of this work is to consider a method for cooling of buildings using PCMs. Accordingly, this work prepares a model brick containing a suitable PCM and analyzes thermal behavior of the model brick includes mainly melting and solidification phenomena of PCM placed inside of the brick in order to maintain a suitable room temperature of the buildings. As model brick is able to save electricity, indirectly a reduction in pollution is also possible. Thus, the proposed model brick is named as a green brick.

1.11 Organization of the thesis

Organization of the thesis is presented as follows:

- **Chapter 2**: Development of experimental setup for a green brick. Consideration of two different types of PCMs with different melting temperatures. For different time intervals, photographs of melting and solidification of the PCM have been captured. Temperature of the PCM inside the green brick is also noted down.
- **Chapter 3**: A numerical model is developed for comparison with the experimental work.
- **Chapter 4**: Conclusion of the thesis and future scopes of the work.

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Chapter II

Experimental Investigation on Thermal Behaviour of a Model Brick-Green Brick

2.1 Introduction

The present work is a consideration of placing a suitable phase change material (PCM) on terrace of building in order to cool it without disturbing conventional design and construction. The terrace of a building is usually made of concrete which is primarily an insulator. Till, the major of heat during a sunny day enters into a room through terrace. Heat entering to the room through its walls is not considered in the present work. Accordingly, in order to cool the building, the phase change materials may be spread over the terrace with a minimum height or green bricks filled with suitable PCM are to be placed over the terrace. The PCM will absorb solar radiation during the day time by melting and that will be released to the ambient during the night consequential to its solidification. This cycle of melting and solidification is able to resist in entering of the day radiation into the room. Using the green bricks, the room in the buildings may remain in comfortable zone based on selection of a suitable phase change material.

This chapter mainly involves experimentations in order to prepare a model brick (green brick) filled with phase change materials. The experiments include determination of the relevant shape and size of such green bricks.

2.2 Description of the physical problem

Nowadays, use of phase change material (PCM) as an economically advantageous technology has been introduced as a thermal energy storage for cooling of residential as well as commercial buildings in order to save conventional energy, in terms of electrical energy. The latent heat value of the PCMs is relatively high. This property of the PCMs makes possible to store heat during the day without increasing its overall temperature during melting. Thus, a PCM based system may be installed on top of the terrace or side walls of the buildings. This will absorb radiation throughout the day by melting of the PCM, and release the same during night to the ambient by solidifying. Hence, this work is a consideration of using PCM without disturbing the basic structure of buildings made of concretes.

To incorporate the concept of using PCM in cooling of buildings, the PCM can be placed in the form of green bricks or tiles on surroundings of building. As noted, Fig. 1.1 (a) is a conventional building cooling system with the help of air-conditioning systems. But, many disadvantages are incorporated in using air-conditioning. Use of PCM is one of the best alternatives to cool the buildings. Fig. 1.1(b) represents a suitable method for cooling of buildings with help of PCM. PCM can be used in the form of bricks on the terrace and/or as tiles on the walls. Using this cooling system in buildings, it is possible to save electricity. Moreover, installment of PCMs is a onetime investment. So the main focus of the present work is a consideration of cooling the buildings using PCMs. Hence, this work prepares a model brick consist of a suitable PCM for placing over the terrace of any building, and analyzes thermal behavior of the brick including melting and solidification phenomena of the PCM.

2.3 Necessary parts/accessories for preparing the experimental setup

2.3.1 Plexiglass

Usually acrylic plastic sheet is called as plexiglass. It is a lightweight, crystal clear material with transparency, highly impact resistant, chemically resistant, and thermo-formable [71, 72]. The plexiglass sheets are flexible and used in several applications in home, business, industry, and professions. This work considered plexiglass to prepare shell of the green brick; however, top surface of the shell is made of metal plate in order to allow transfer heat. Inside of the shell, a suitable PCM can be filled. Being an insulator, it resists entering heat into the green brick from all sides, except top surface which is made of metal plate; and due to its transparency, melting and solidification phenomena of the PCM can be visualized, and necessary snap shots can be captured using a SLR digital camera.

2.3.2 Thermocouples

A thermocouple is known as thermo-electrical thermometer, which works on the Seebeck effect. Thermocouple is a transducer that joins wires made of various metals to create junctions, and transforms heat energy into electrical energy. A voltage will be generated, when there is a change in temperature within the junctions. Types C, E, T, N, J, and K are the common thermocouples used in day to day engineering. The base metals for these thermocouples are iron, copper, nickel, platinum, rhodium, and chromel [73, 74]. For the present experiments, K-type thermocouples are used; those are made of chromel and alumel. Its working temperature range is -200°C to 1250°C. In present experiments, temperature range is 20°C to 65°C.

2.3.3 Phase change materials (PCMs)

In the past decades, interest in the use of phase change materials (PCMs) in the cooling of building increases. PCM can store both sensible and latent heat energy. Utilization of

PCM in construction is a research topic, nowadays. PCM can store as well as release large amounts of thermal energy by its phase change. Thus, with integration of PCM, there is a significant reduction in the use of electricity. Accordingly, this work considered use of PCM in cooling of buildings. However, there are different types of PCMs available in the market. The common classification of the PCMs is presented in Fig. 2.1.

Organic PCM

There is a large diversity in organic PCMs, but pure n-alkanes, fatty acids, and esters are widely use as the latent heat storage because these have good latent heat capacity, stable physical and chemical properties. However, pure organic PCMs have low heat conductivity (often less than 0.2W/m^{2}K [75]). Paraffin and non-paraffin are the major two types of the organic PCMs. Paraffins are blending of straight chain alkanes (CH_3-(CH_2)-CH_3). The non-paraffin PCMs are fatty acids, alcohols, esters, and glycols. As organic PCMs have less corrosive properties and reasonably low melting points; this work considered organic PCMs. For use of PCMs in building applications, some organic PCMs are presented in Table 2.1.

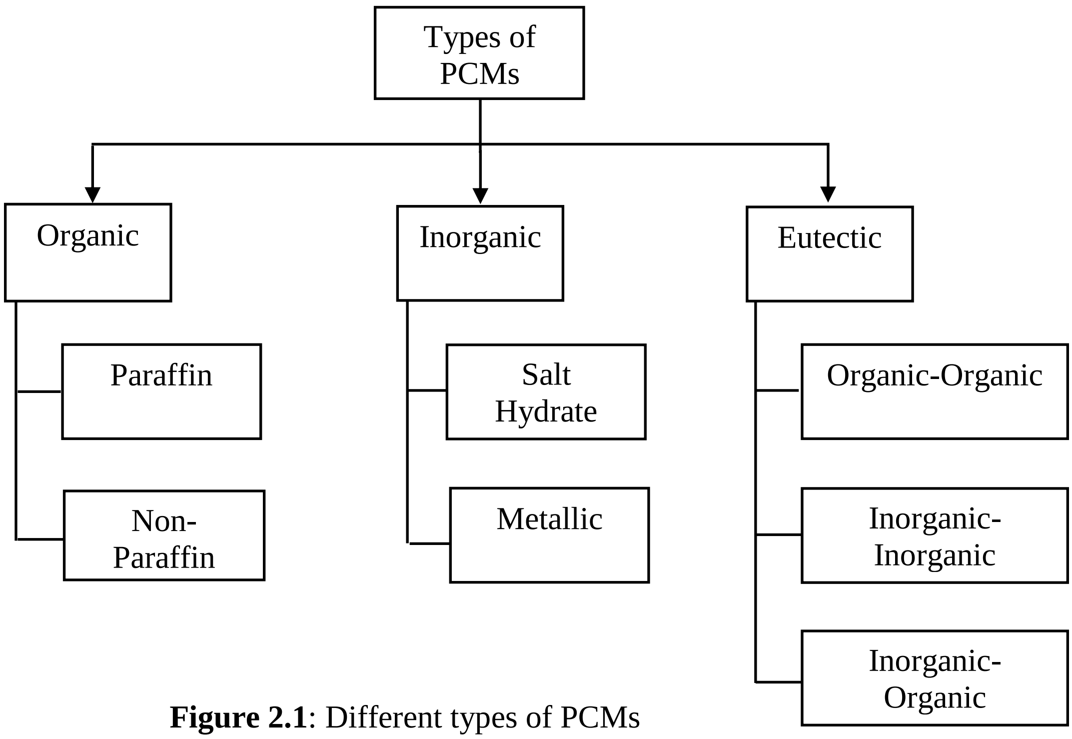


Figure 2.1: Different types of PCMs

Table 2.1: Some organic PCMs along with melting points and latent heat values [76–81]

S. No.	Materials	Melting Point (^oC)	Latent Heat (kJ/kg)
1	Glycerine	17.9	198.7
2	Paraffin C16	18.2	238
3	Paraffin C17	21.7	213
4	Paraffin C18	28	244
5	Capric acid	29.62	139.8
6	Methyl Palmitate	29	205

Inorganic PCM

Inorganic PCM is less expensive. Apart from this, it is corrosive in nature. Salt hydrates are the well-known type in this category. This group contains salt solutions and metals. They have high thermal conductivity (about 0.5 W/mK [82]), but lower cost compared to organic PCMs. Some inorganic PCMs are presented in Table 2.2.

Table 2.2: Some inorganic PCMs with melting points and latent heat values [76, 78–80]

S. No.	Materials	Melting Point (^oC)	Latent Heat (kJ/kg)
1	$KF.4H_2O$	18.5	231
2	$Mn (NO_3)_2.6H_2O$	25.5	148
3	$LiBO_2.8H_2O$	25.7	289
4	$LiNO_3.2H_2O$	30	296
5	$LiNO_3.3H_2O$	30	189
6	$CaCl_2.6H_2O$	29	191

Eutectic PCM

Eutectic PCMs are made up by mixing of at least two or more PCMs [83, 84]. This mixture may be the combination of organic with organic, organic with inorganic, and inorganic with inorganic components. Some eutectic PCMs are presented in Table 2.3.

Selection of PCM

For the present experiments, two organic PCMs: OM-29 and OM-37 are selected where OM stands for organic mixture. These PCMs are selected because of their availability in the market, easy to handle, and chemically inert. In addition, these PCM have low melting point temperature – towards the human comfort zone. Thus, both the PCMs from market are procured; sample cover of the OM29 is shown in Fig. 2.2. The necessary thermo-physical properties of these PCMs are listed in Table 2.3.

Table 2.3: Some eutectic PCMs with melting points and latent heat values [76–80]

S. No.	Materials	Melting Point (^oC)	Latent Heat (kJ/kg)
1	Capric + Lauric acid	21	143
2	Methyl stearate + Cetyl stearate	22.2	180
3	Methyl stearate + Methyl palmitate	23.9	220
4	Triethylolethane + Urea	29.8	218
5	Capric acid + Stearic acid	24.7	178.6

Figure 2.2: Packet for PCM OM-29

Table 2.4: Thermo-physical properties of the selected PCMs [84]

Name of Properties	**OM-29**	**OM-37**
Melting Temp. (°C)	29	37
Freezing Temp. (°C)	26	36
Latent Heat (kJ/kg)	194	179
Liquid Density (kg/m^3)	870	860
Solid Density (kg/m^3)	976	973
Liquid Specific Heat (kJ/kgK)	2.71	2.63
Solid Specific Heat (kJ/kgK)	2.32	2.55
Liquid Thermal Conductivity (W/mK)	0.172	0.13
Solid Thermal Conductivity (W/mK)	0.293	0.16

2.3.4 Representation of the day and night conditions by consideration of a heat exchanger

During a day time, solar radiates over the terrace mostly. Due to this radiation, temperature of building terrace reaches to a limit between 45°C to 60°C, whereas in the night time, the ambient temperature reaches towards 20°C [85]. In present experiments, the variation of temperature during day and night time is presented using a heat exchanger, and its temperature is maintained as per the ambient conditions. Thus, present experiments are conducted inside of the laboratory; the necessary temperature range inside the heat exchanger is maintained with help of a constant temperature bath (as explained in subsection 2.3.5).

Related heat exchanger used in the present experiments is shown in Fig. 2.3. The body of the heat exchanger is made of plexiglass for insulation, except one side which is made of copper plate in order to transfer heat. Inside the heat exchanger, one copper tube is placed from which hot or cold fluid will pass. In the Fig. 2.3, the inlet and outlet fluid flow through the copper pipe is clearly shown. Inside the heat exchanger, water is placed which gets heated when hot fluid passes through the copper pipe. Heat of the water is extracted when cold fluid passes through the pipe. The bottom surface of the heat exchanger that is made of copper plate, works like a heating and cooling source for the model brick (as discussed in section 2.4).

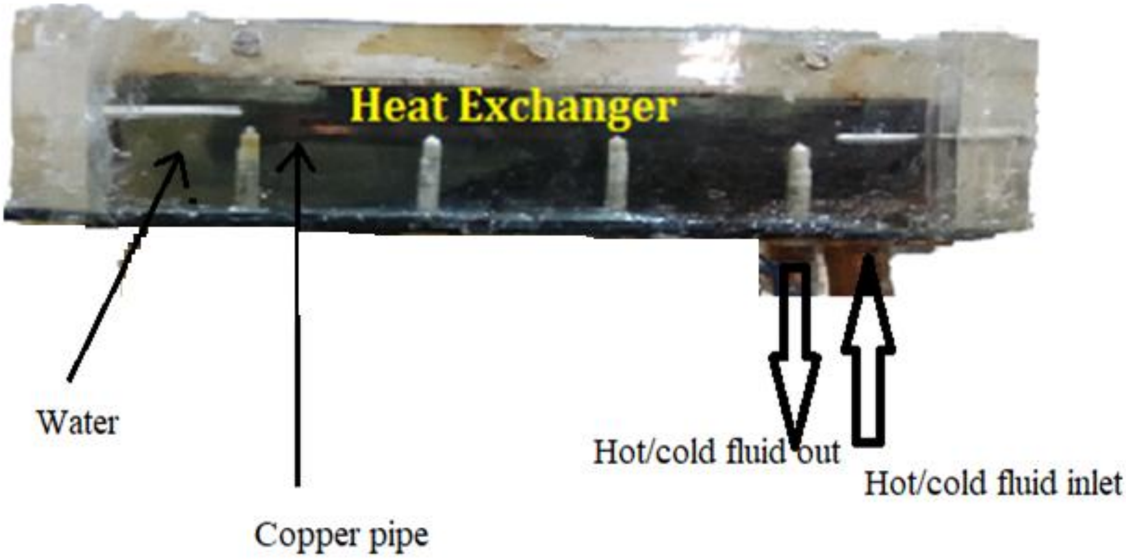


Figure 2.3: Heat exchanger

2.3.5 Constant temperature bath (CTB)

For working of heat exchanger, a constant temperature adjustable fluid flow system is used, i.e., a constant temperature bath (CTB). Constant temperature bath (CTB) is a device which provides constant temperature fluid flow. In the present experimental work, a precise CTB is used, made of Julabo, Germany.

Fig. 2.4 represents the Julabo CTB, where '1' indicates where working fluid is placed inside of the system and '2' indicates digital display and control unit from where it is possible to set required temperature limits. Point '3' is on/off switch of the system.

In case of water as working fluid, the temperature range of the CTB lies between 10°C to 70°C. But, on changing working fluid from water to ethanol; its range changes to low temperatures.

Fig. 2.5 shows a display unit of the CTB in which, '1' represents the display unit, where it is possible to visualize working fluid temperature. In this figure, it is showing 55°C. Setting of temperature range is possible by the '2', '3'- buttons, in order to increase and decrease temperature of the working fluid.

Figure 2.4: Constant temperature bath (Julabo, Germany)

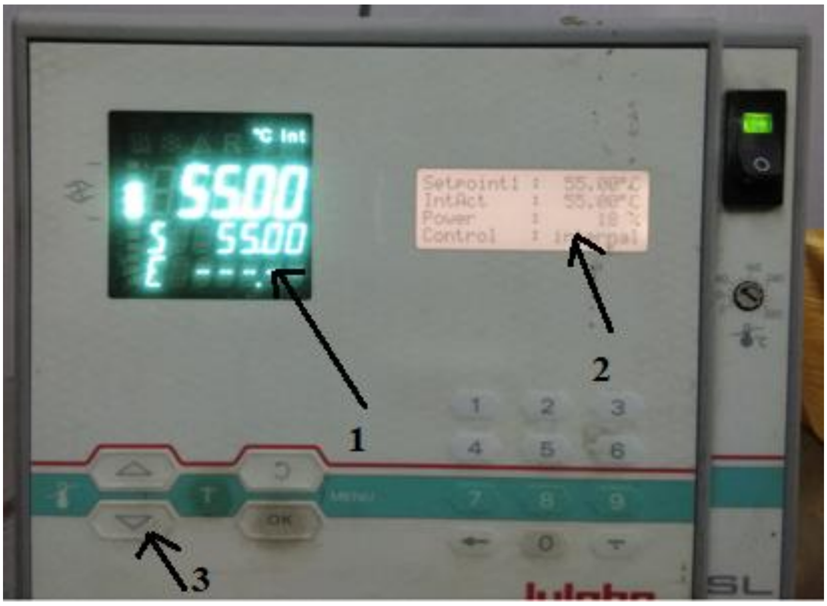


Figure 2.5: Display unit of CTB

2.4 Preparation of model/green brick

Ashish *et al.* [85] conducted a numerical analysis for cooling of building using PCMs placed on the roof. In their analysis, approximate height of the brick varies between 4cm to 5cm in order to continue receiving the whole day heat by full melting of the PCMs. In order to easy handling of the bricks, a suitable size of the brick is considered as 10 cm × 4 cm × 4 cm in present experiment.

The green brick is made of plexiglass material with top surface made of the copper plate. Fig. 2.6 represents the brick cavity which is made of plexiglass. Inside the cavity, K-type thermocouples are placed. These thermocouples are connected with a thermocouple display where readings are recorded. Fig. 2.7 is the front view of green brick, where the position of thermocouples can be seen. In this cavity, molten PCM is poured and let the PCM to solidify. Fig. 2.8 represents the top surface layer of the model brick that is made of copper plate. Above the copper plate, copper dust is placed to avoid the air gap which is shown in the Fig. 2.9. After solidification of the PCM inside the model brick, it is ready for experiments, which is shown in Fig. 2.10.

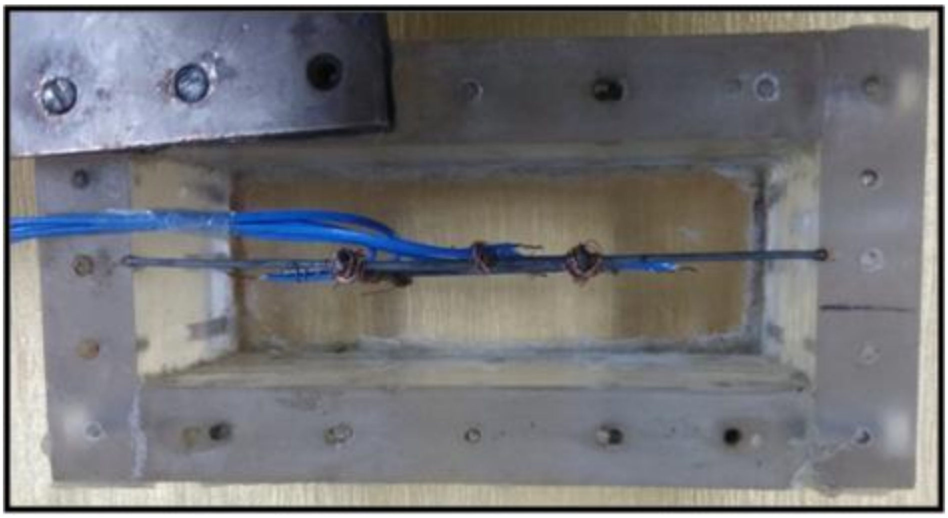


Figure 2.6: Empty model brick with K-type thermo couples

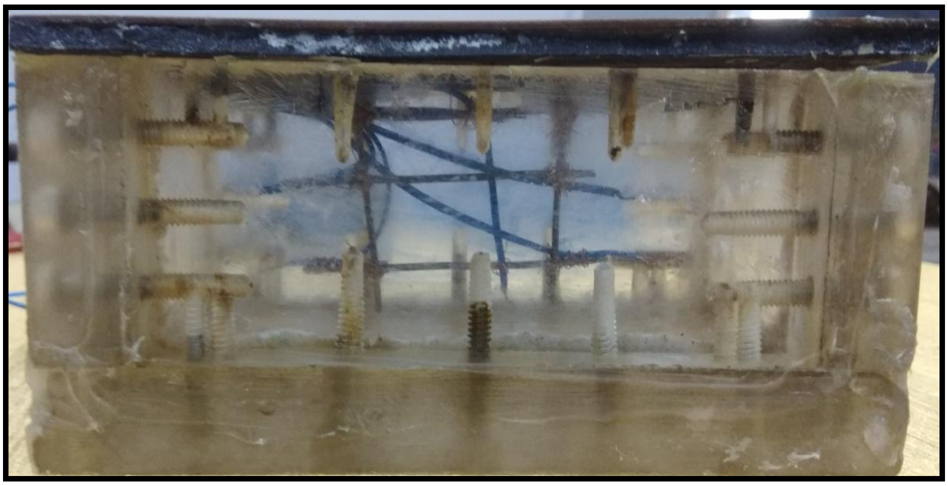


Figure 2.7: Front view of empty model brick

Figure 2.8: Top surface of the model brick made of copper plate

Figure 2.9: Copper dust placed over the copper plate

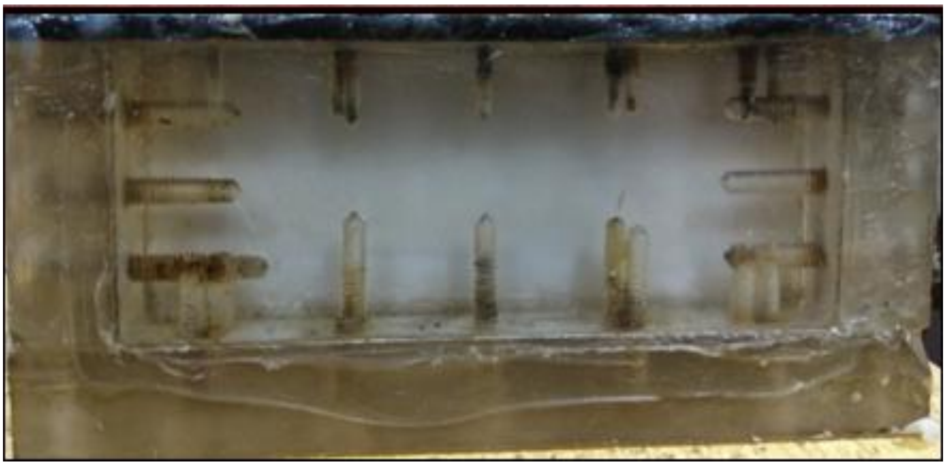


Figure 2.10: After filling of PCM, the model brick is ready for experiments

2.5 Schematic of experimental setup

The above sections discuss about heat exchanger, constant temperature bath, model brick and thermocouples. To conduct the experiments, these components are connected to each other. The arrangement and connections are shown in Fig. 2.11 (a), (b) and (c). Fig. 2.11 (a) represents schematic of the experimental setup. A proper line diagram of the experimental setup is shown in the figure. In order to measure temperature within the PCM, K-type thermocouples are kept on a skeleton placed vertically symmetrically at the middle of the brick. The letter 'A' denotes the location of a thermocouple to measure temperature of the top surface of the PCM or brick. The letter 'F' denotes the location of a thermocouple to measure the temperature of the bottom surface of the PCM. The letters

'B, C, D and E' in Fig. 2.11 (a) show the different locations of the thermocouples within the PCM. The PCM undergoes melting while hot water passes through the copper heat exchanger placed on top of the PCM, and solidification while cold water passes through the heat exchanger. A transparent scale is placed on the right side of the setup to measure the height of the melted and solidified portion of the PCM. As all side walls are made of plexiglass that is transparent in nature, images of melting and solidification of the PCM are captured by a SLR camera (Sony α A68, DSLR, 18-55mm Single Lens, maximum resolution 24.2 MP, minimum aperture 5.6).

Fig. 2.11 (b) represents a flow chart of the experimental setup, in which it is clearly shown the connection of heat exchanger with constant temperature bath (CTB) , and that with the thermocouples along their display unit. Fig. 2.11 (c) represents the actual experimental setup in the laboratory.

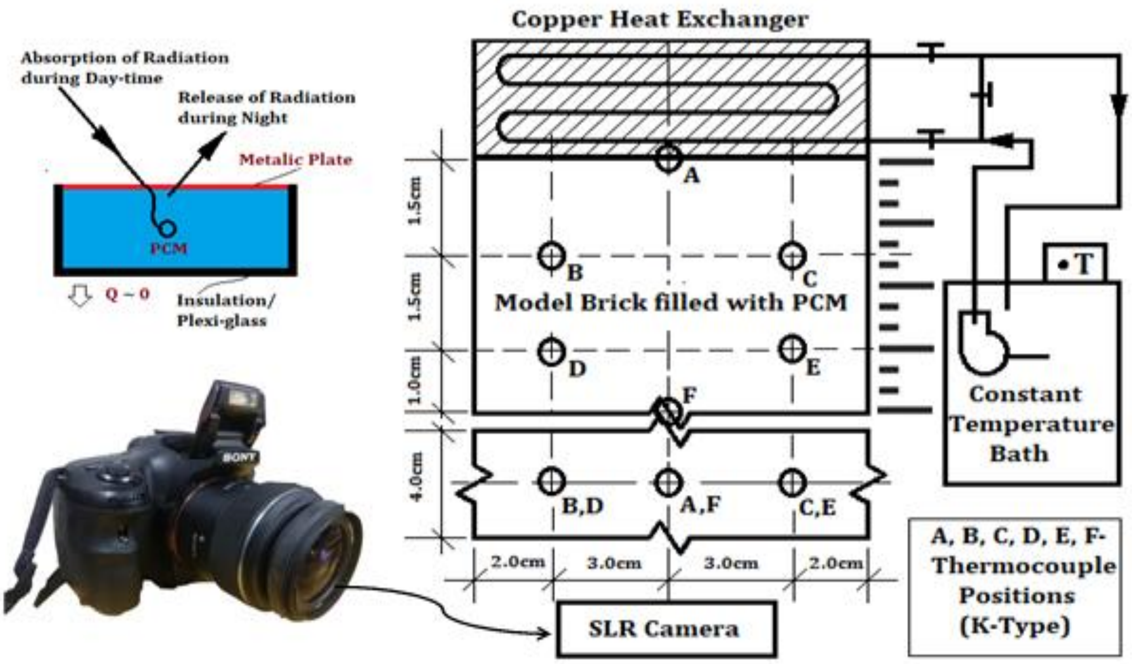


Figure 2.11 (a): Schematic of experimental setup

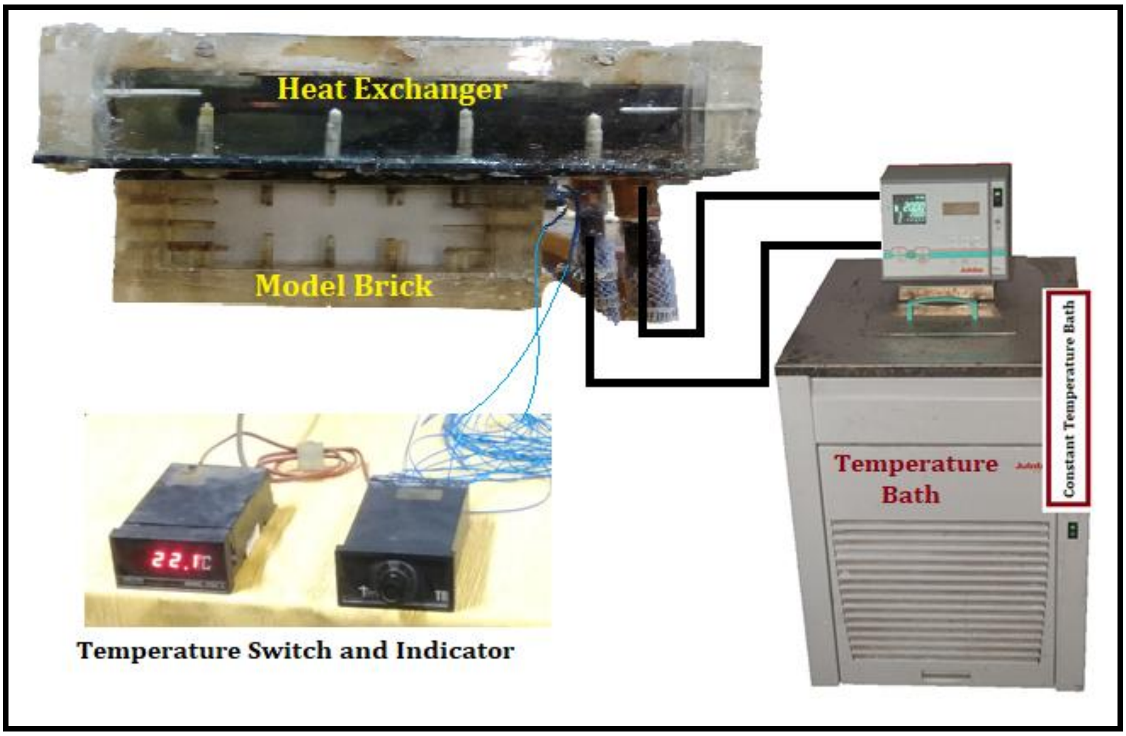


Figure 2.11 (b): Flow chat of experimental setup

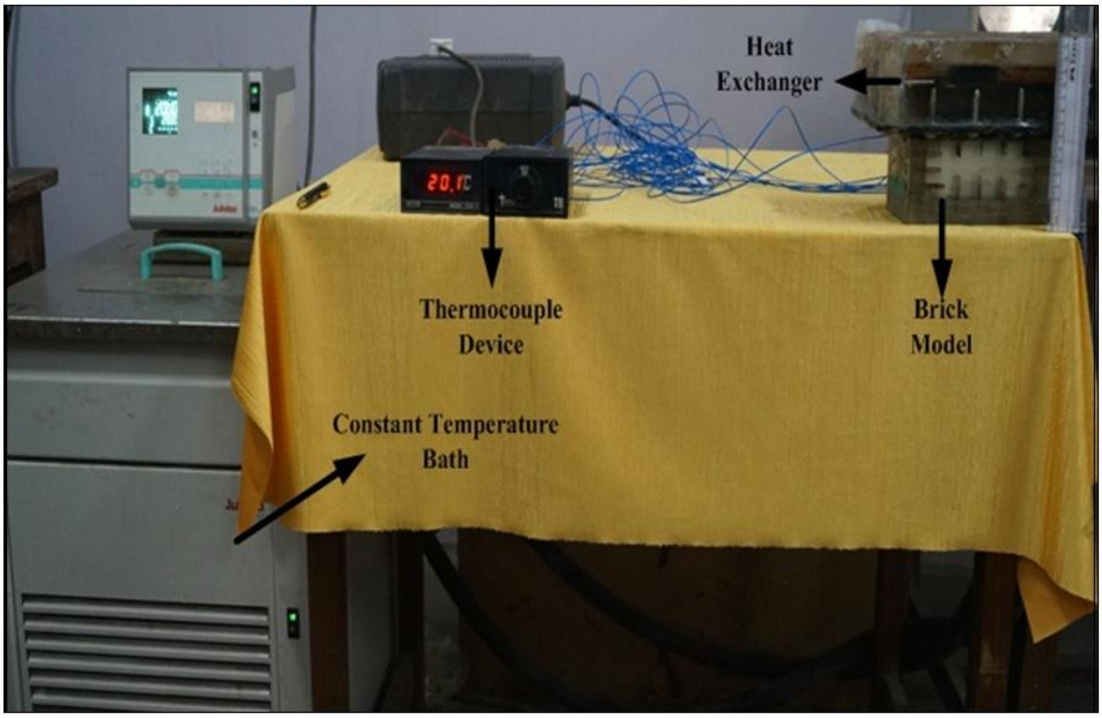


Figure 2.11 (c): Actual experimental setup

2.6 Working procedure of the experiments

In the period of experiments, temperature in constant temperature bath (CTB) is set to the desired temperature, and accordingly it supplies hot or cold fluid to the heat exchanger through a copper tube. The heat exchanger is filled with water mixing of copper dust to transfer heat from the bath fluid to the phase change material or phase change material to bath fluid. Accordingly, heat is transferred into the PCM in model brick, which causes PCM to melt. At each of the distinct locations, a thermocouple of type 'K' is positioned in order to take temperature readings. Each single reading has been noted at a particular time interval. During the heating process, hot fluid passes through the heat exchanger, which causes the PCM to melt. After the heating process, cold fluid passes through the heat exchanger, which causes the PCM to solidify. Throughout the experiments, images are captured at different time intervals.

2.7 Results and discussion for experiments conducted under various cases

For present experiments, two types of organic PCMs: OM-29 and OM-37 are selected because of their melting temperature is close to human comfort zone, i.e., 29°C and 37°C, respectively. The melting and solidification of these PCMs will take place at their melting temperature only. In this work, the day time situation is represented by two temperatures close to the terrace temperature in a sunny day. Accordingly, the constant temperature bath (CTB) is set at two different temperatures, i.e., 55°C and 65°C. The night time situation is represented by ambient temperature at 20°C. Based on the situation, the following four combinations of experiments are considered.

Case-I: OM-29 as PCM and 55°C at CTB
Case-II: OM-29 as PCM and 65°C at CTB
Case-III: OM-37 as PCM and 55°C at CTB
Case-IV: OM-37 as PCM and 65°C at CTB

The details of experiments and results are discussed one-by-one for each of the four cases.

2.7.1 Case-I (OM-29 and bath temperature is 55°C)

In this case, OM-29 is used as PCM and CTB is set at the temperature of 55°C. During experiment, the readings of all thermocouples are noted. It is noted here that the hot fluid from the bath passes through a tube to the heat exchanger. Since hot fluid has higher temperature than the ambient, a heat loss is incorporated from the tube and, thus, a lower temperature is recorded at the surface of the heat exchanger. Fig. 2.12 is a graph represents variation of temperature for the heat exchanger, where time is represented towards X-axis and variation of the temperature is represented towards Y-axis. It is seen from the Fig. 2.12 that the maximum temperature reaches to 43.5°C which presenting a sunny day with a moderate solar radiation, and minimum temperature reaches to 20°C which presenting the ambient condition at night. During the experiment, the higher temperature is maintained for 15 hours in order to find the maximum melting of PCM and to incorporate additional heat absorption based on the condition of a sunny day. After completion of heating, a sudden drop in temperature is set in CTB to represent the night condition.

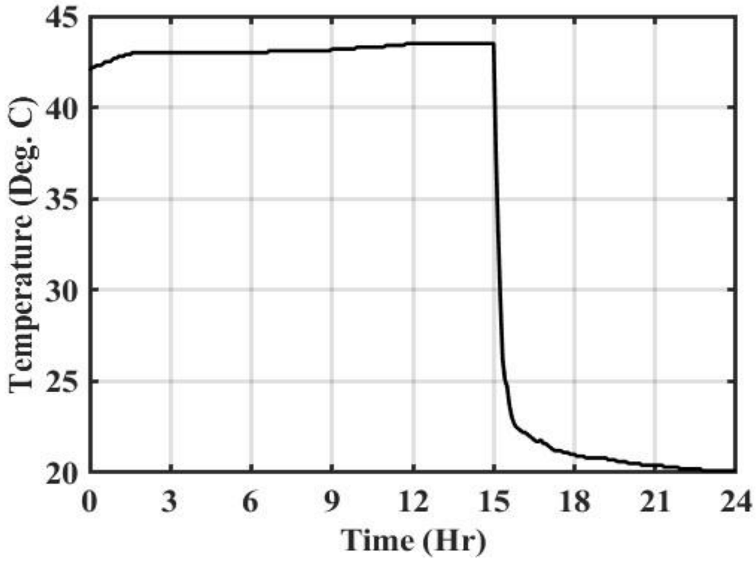


Figure 2.12: Variation of heat exchanger temperature

Melting temperature of OM-29 is 29°C whereas the top surface temperature changes from 43.5°C to 20°C. Accordingly, melting and solidification of the PCM is occurred inside transparent plexiglass of model brick by exchanging heat from and to the heat exchanger. Due to the transparency of walls, pictures are captured during melting and solidification of the PCM at different time intervals using a SLR camera. Fig. 2.13 (a), (b) and (c) are sample pictures captured during melting process of the PCM. From these pictures, it is easily seen that, during heating corresponds to the day time, after 7 hours, 12 hours and 15 hours, the heights of molten PCM from the top surface are 2.2 cm, 3cm and 3.2 cm, respectively. Similarly, Fig. 2.14 (a), (b) and (c) are the pictures captured during solidification process of the PCM. From these pictures, it is easily seen that during the cooling process corresponds to the night time, after 16:30 hours, 16:50 hours and 24 hours, the heights of the solidified PCM from the top surface are 1 cm, 1.1 cm and 3.2 cm, respectively. Fig 2.14 (c) indicated that after 24 hours of a day cycle, the total PCM is solidified that is, recycling or readiness for the next day is possible.

In order to note the variation of temperatures at different locations within the PCM during experiment, the readings of all thermocouples are recorded. Fig. 2.15

represents corresponding variation of temperatures with PCM during melting and solidification at different locations. With a reference to the Fig. 2.11(a), in the graph of Fig. 2.15, the curve-A represents variation of temperature at top surface of the PCM within the model brick. Temperature of the surface increases to a maximum of 40°C during heating, after sudden change in temperature of the CTB, the temperature decreases to almost 20°C. Curve-B and curve-C follow the same pattern. Since points B and C are at same horizontal plane, i.e., 1.5cm below of the top surface, their temperature variations are almost same. It is found that the maximum temperature of the PCM at this horizontal plane reaches to 33.8°C. Two thermocouples are placed on a horizontal plane which is 3cm below of the top surface; the variation of temperatures at this height or plane is shown by the curve-D and curve-E. It is seen that at this height maximum temperature reaches after 15 hours to 29.8°C. This implies, as the height of the PCM increases from top surface, the temperature at bottom of the PCM almost remain unchanged. Thermocouple for curve-F is placed at bottom of the model brick. At that point, maximum temperature reaches to 29.6°C. It is concluded from the graph that, after using PCM, the room temperature should be less than 29.6°C even after the terrace temperature reaches to 43.5°C to 55°C.

For the whole day, the melting and solidification height of the PCM for different time intervals are recorded in order to plot the variation in a graph. Fig. 2.16 is the related graph plotted variation of molten PCM height with respect to the time. In the graph, it is seen that 3.2 cm is the maximum height of PCM melted after 15 hours of the heating, and 3.2 cm height of PCM is solidified within 9 hours of cooling. At the end of the day, i.e., after 24 hours, the height of molted PCM is zero implies recycling of the PCM is possible.

(a) Picture representing molten PCM at time t =7 hours during heating

(b) Picture representing molten PCM at time t =12 hours during heating

(c) Picture representing molten PCM at time t =15 hours during heating

Figure 2.13: (a), (b), and (c) are the pictures representing melting process

(a) Picture representing molten PCM at time t =16:30 hours during cooling

(b) Picture representing molten PCM at time t =16:50 hours during cooling

(c) Picture representing molten PCM at time t =24 hours during cooling

Figure 2.14: (a), (b), and (c) are the pictures representing solidification process

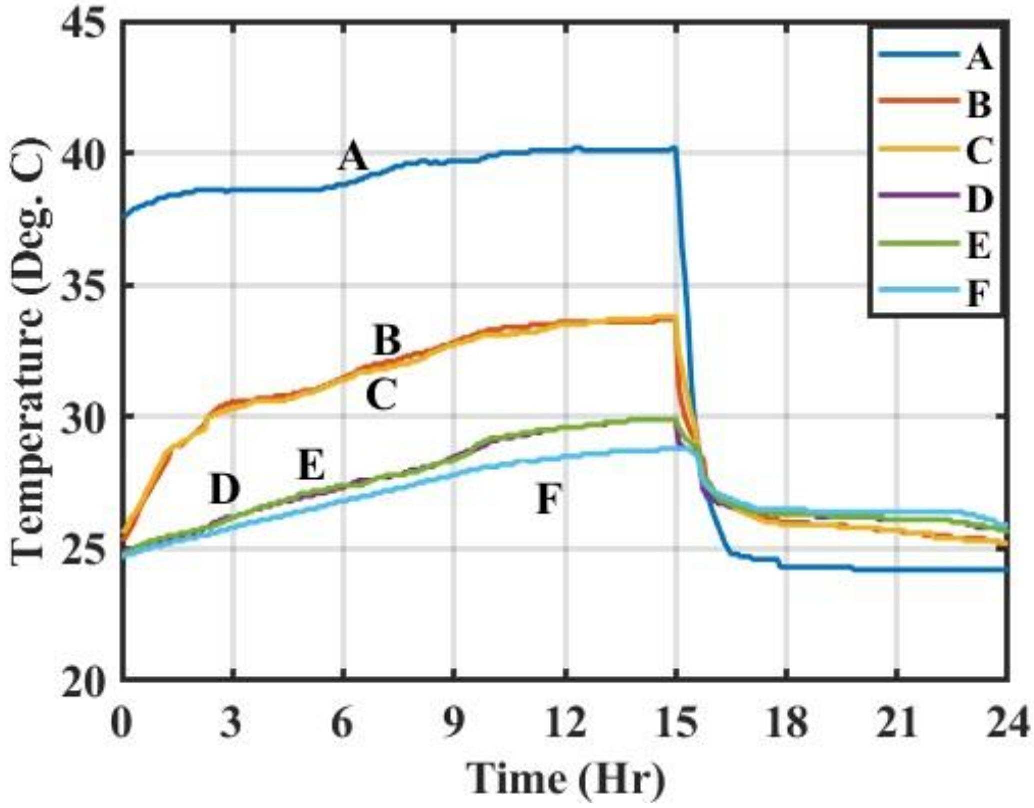


Figure 2.15: Temperature variation at various locations within PCM with time

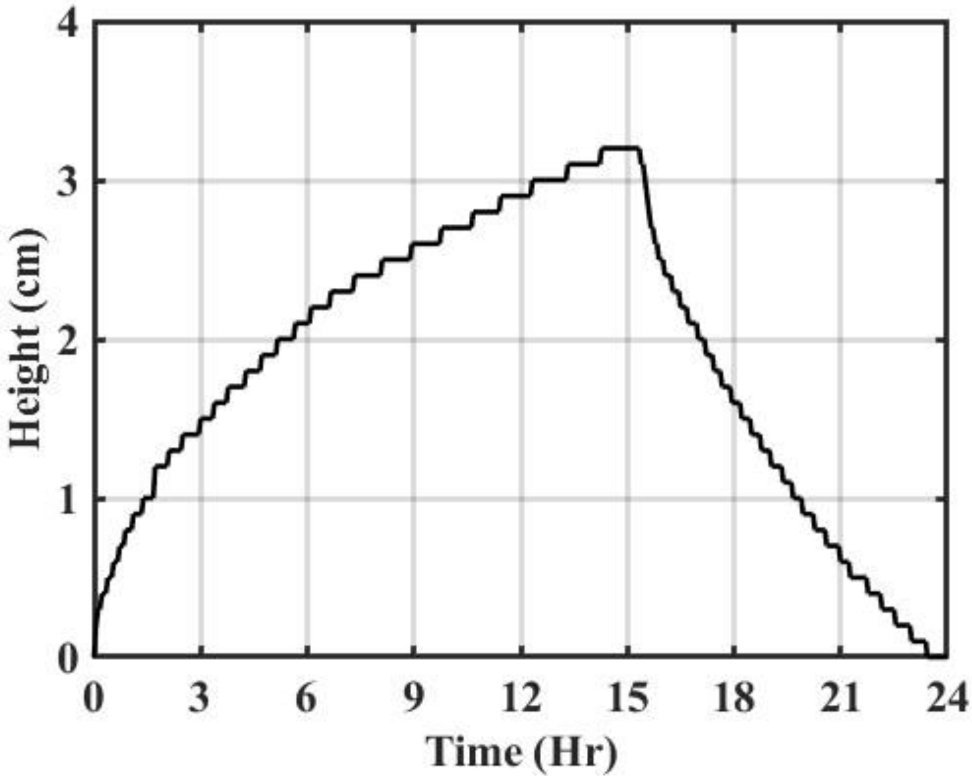


Figure 2.16: Variation of the average height of the molten PCM with time

Conclusion out of the Case-I:

1. Total heating period is 15 hours in order to accommodate the additional day radiation and high temperature of terrace. The maximum height of the molten PCM is 3.2 cm. This implies out of considered 4cm height PCM, 0.8 cm PCM is not utilized.
2. Total cooling period of 9 hours is considered. It is observed that total molten PCM of 3.2 cm height is fully solidified within this 9 hours period. That is a clear indication that recycling of the PCM is possible and ready for the next day.
3. The maximum temperature at bottom of the brick reaches to 28.8℃ (curve-F). This indicates that when model bricks are used on terrace of building for its cooling, in that case, the room temperature will be less than 28.8 ℃ which comes under the human comfort zone.

2.7.2 Case-II (OM-29 and bath temperature is 65℃)

In the case-I, temperature of the constant temperature bath is set to 55℃, corresponding maximum temperature at heat exchanger reaches to 43.5 ℃. However, based on the situation of a day, the intensity of solar radiation may varies and increase. Accordingly, a higher temperature at the constant temperature bath is set. To increase temperature in the heat exchanger, the temperature of constant temperature bath is changed from 55℃ to 65 ℃. By changing this temperature, the maximum temperature rises in the heat exchanger to 50℃, variation of which is shown in the Fig. 2.17. Here, 50℃ temperature of terrace represents a very sunny day. The minimum temperature recorded is 20℃ which represents the night ambient temperature. From the Fig. 2.17, it is noted that, a total of 13:40 hours is considered for heating process and 10:20 hours is considered for cooling process. The additional hour in heating (13:40 hours> 12 hours) is considered to incorporate additional radiation and high temperature corresponds to maximum melting of the PCM.

Fig. 2.18 (a), (b) and (c) presents melts fraction of the PCM at the different time intervals. From these pictures, it is easily seen that, during heating process after 1:20 hours, 3:50 hours and 7:30 hours, the heights of molten PCM from the top surface are 1.3 cm, 2.2 cm and 3 cm, respectively. Fig. 2.19 (a), (b), and (c) are the pictures correspond to solidification of PCM during cooling. From these pictures, it is observed that during this cooling process after 14:40 hours, 15:10 hours and 24 hours, the heights of the solidified PCM from the top surface are 0.6 cm, 0.9 cm and 4 cm, respectively. The whole molten PCM solidified after 24 hours.

In order to determine the temperature variation within PCM of the model brick, thermocouples are placed at the different locations too. During heating and cooling, all the temperature readings are noted down. Fig. 2.20 shows the temperature profiles at the different locations of the PCM with time. With a reference to the Fig. 2.11(a), in the graph of Fig. 2.20, curve-A represents the temperature variation at the top surface of the model brick. Curve-B and curve-C represent the temperature variations at the 1.5 cm below of the top surface of the brick. It is seen that the B and C curves follow same pattern as these two locations are at the same level or both thermocouples are placed at same horizontal plane. Similarly, D and E curves follow same pattern as they are placed at the same horizontal level. In the graph, it is seen that up to 13:40 hours, slope of all the temperature profiles increases and then it decreases due to sudden drop in temperature at constant temperature bath, hence in the heat exchanger.

Fig. 2.21 shows the variation of molten PCM height with respect to the time. Here, it is noticed that, as compare to the case-I, the height of the molten PCM is more and reaches to 4cm, this is due to the increase of temperature at constant temperature bath to 65 °C. This 4 cm height of molten PCM is obtained after 13:40 hours, and which is solidified fully within 10:20 hours of cooling. This also indicates that at end of the day or after the 24 hours process, solid form of the PCM is restored that means a recycling possibility of the PCM.

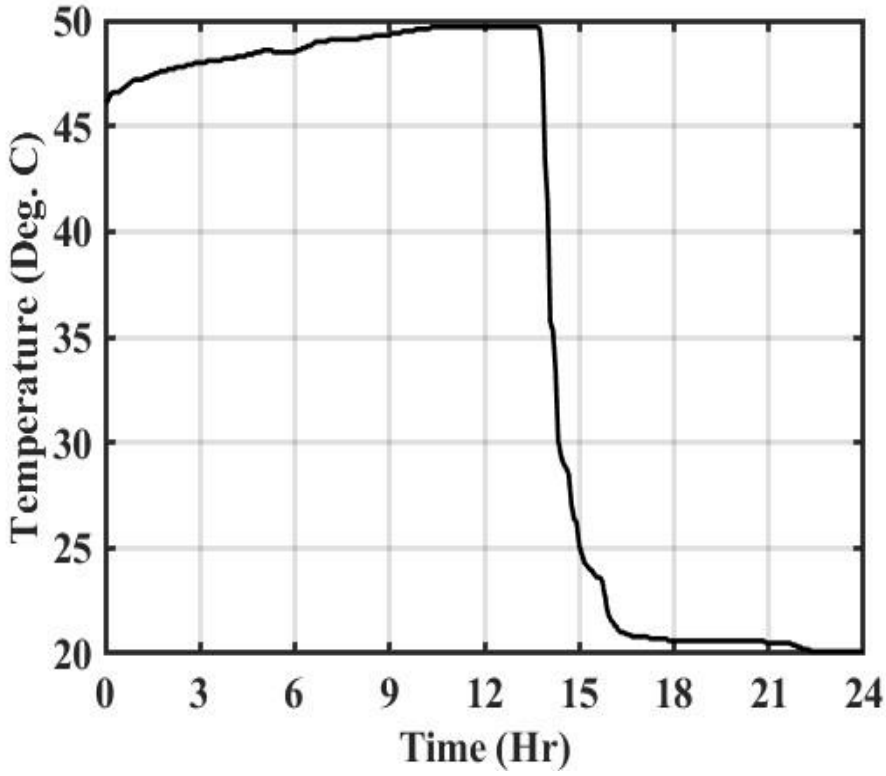


Figure 2.17: Variation of heat exchanger temperature

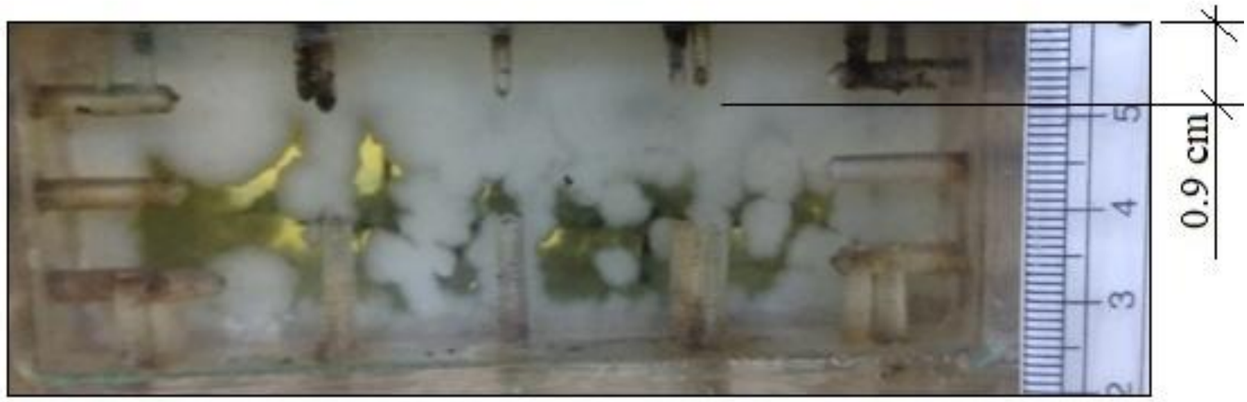
(a) Picture representing molten PCM at time t =1:20 hours during heating

(b) Picture representing molten PCM at time t =3:50 hours during heating

(c) Picture representing molten PCM at time t =7:30 hours during heating

Figure 2.18: (a), (b), and (c) are the pictures captured during heating process

(a) Picture representing molten PCM at time t =14:40 hours during cooling



(b) Picture representing molten PCM at time t =15:10 hours during cooling

(c) Picture representing molten PCM at time t =24:00 hours during cooling

Figure 2.19: (a), (b), and (c) are the pictures captured during cooling process

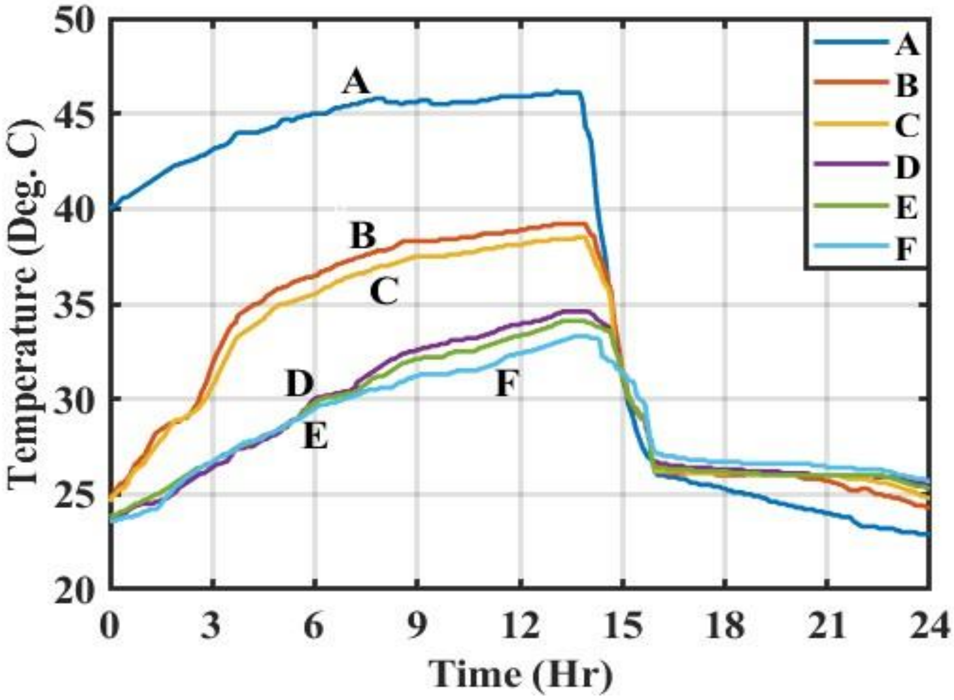


Figure 2.20: Temperature variation at various locations within the PCM during heating and cooling process

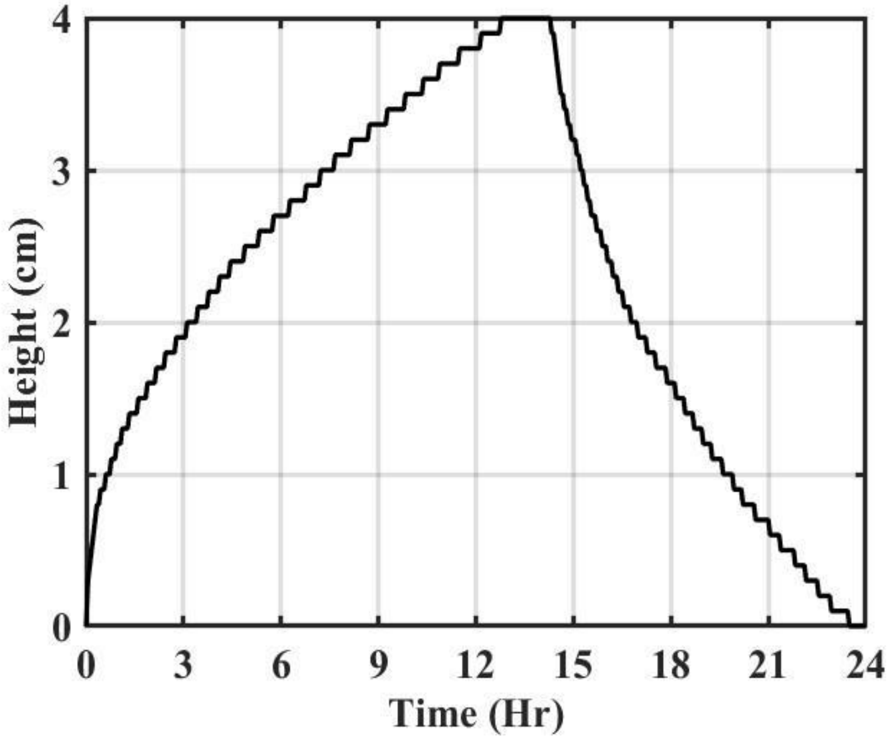


Figure 2.21: Variation of the average height of the molten PCM with time

Conclusion for the Case II:

1. In this case, a total of 13:40 hours heating to the PCM is considered. Since high temperature of the heat exchanger is considered, a height of 4 cm of the PCM is found after the 12:30 hours of heating, i.e., the PCM is melted fully. The additional time of heating is considered to incorporate additional radiation and high temperature of the terrace

2. In next 10:20 hours of cooling, this 4 cm height of molten PCM is fully solidified. That indicates that recycling of the PCM is possible for the next day too.

3. After the heating process, the maximum temperature at bottom of the brick reaches to 33.3°C. That indicates that when this system (model PCM bricks) is used in cooling of buildings, the room temperature will be less than 33.3°C which is also comfortable in a very sunny day correspond to a terrace temperature of 50°C to 65°C.

Comparison of the Case I and Case II

Fig. 2.22 represents a comparison of the height of molten PCM during heating and cooling process for the OM-29 PCM for two constant temperature bath temperatures: 55°C and 65°C. In the figure, it is seen that for different time intervals, height of molten PCM melts is different, like at time t = 3 hours, for case I the molten PCM height is 1.5 cm. On the other hand, for Case-II, molten PCM height is 2 cm. This is due rise in temperature in the Case-II. Accordingly, the maximum height of molten PCM is 3.2 cm for the Case-I whereas full PCM (4cm height) is melted in Case-II. But, both the cases, the molten PCM is solidified within 24hours, i.e., recycling is possible even the terrace temperature reaches to about a temperature of 65°C. A reasonable conclusion of present investigation includes placing of present model bricks on the terrace of buildings. The model bricks are to be filled with OM-29 up to a height of 4 cm. In such conditions, the room temperature remains within 28.8°C to 33.3°C.

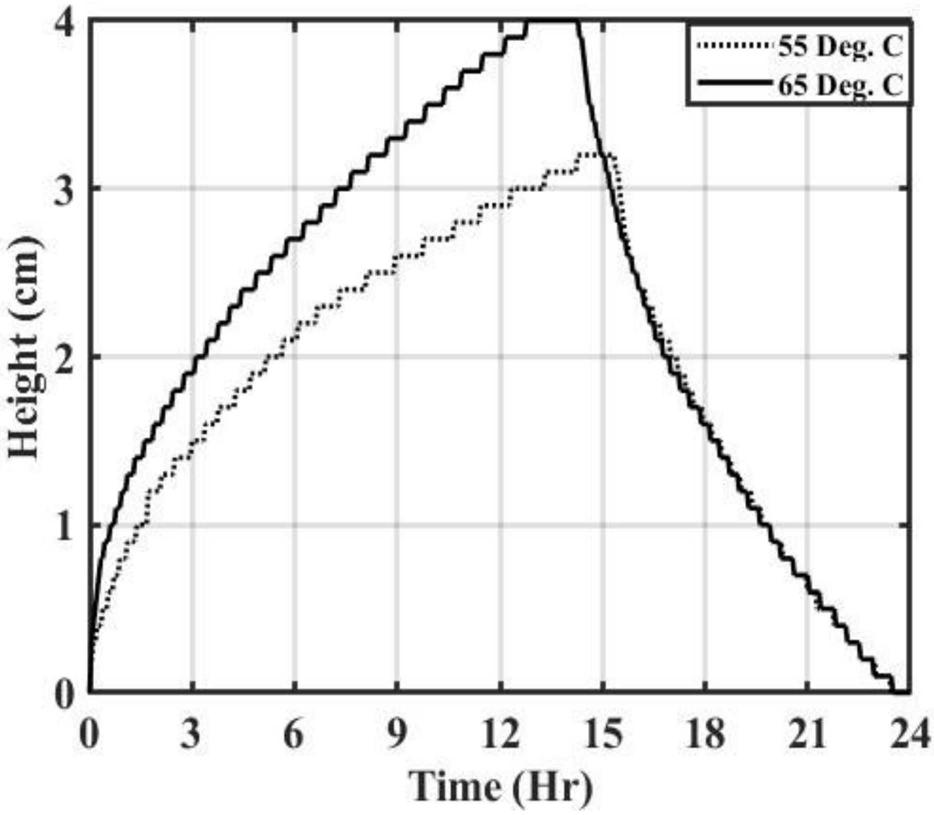


Figure 2.22: Variation of the average height of molten PCM with time

2.7.3 Case-III (OM-37 and bath temperature is 55°C)

In the Case-I and Case-II, OM-29 is used as PCM which has a melting temperature of 29°C. In this Case-III, OM-37 is chosen in place of OM-29. OM-37 has a melting temperature of 37°C. In this case, constant temperature bath (CTB) is set at 55°C. After setting temperature in CTB at 55°C, it is found that the heat exchanger temperature reaches to a maximum of 45°C. Fig. 2.23 represents the variation of temperature in heat exchanger with time. It is clear that the total heating process is 12:30 hours and total cooling process is 11:30 hours. After 12:30 hours of heating, there is a sudden drop in temperature due to the change of CTB temperature from 55°C to 20°C. As found, the maximum temperature of heat exchanger reaches to 45°C and the minimum temperature of the heat exchanger is 20°C.

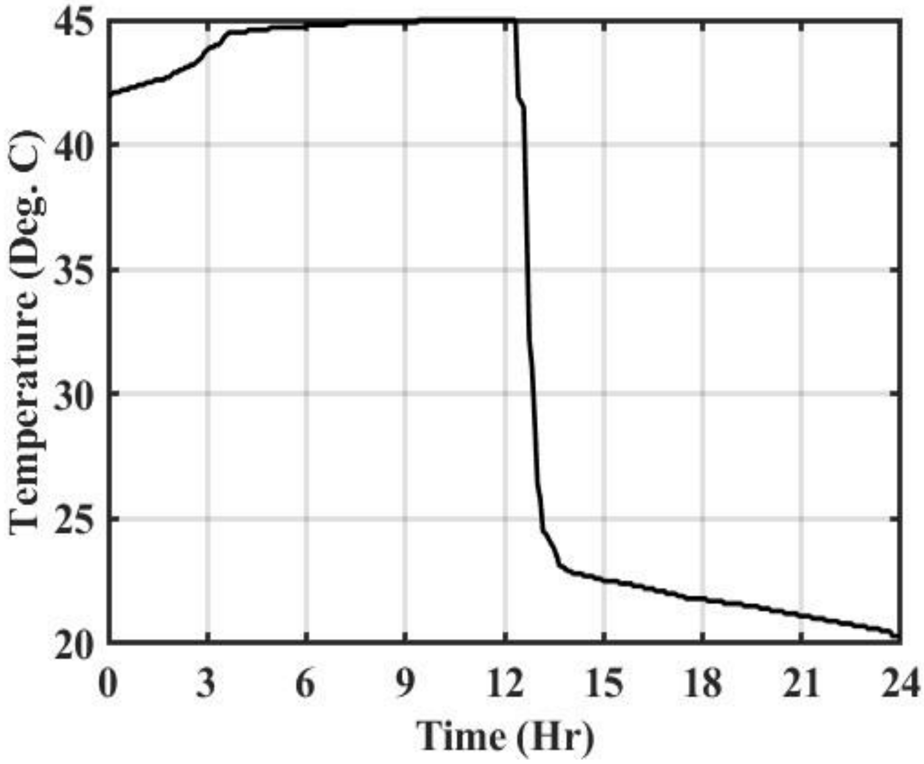


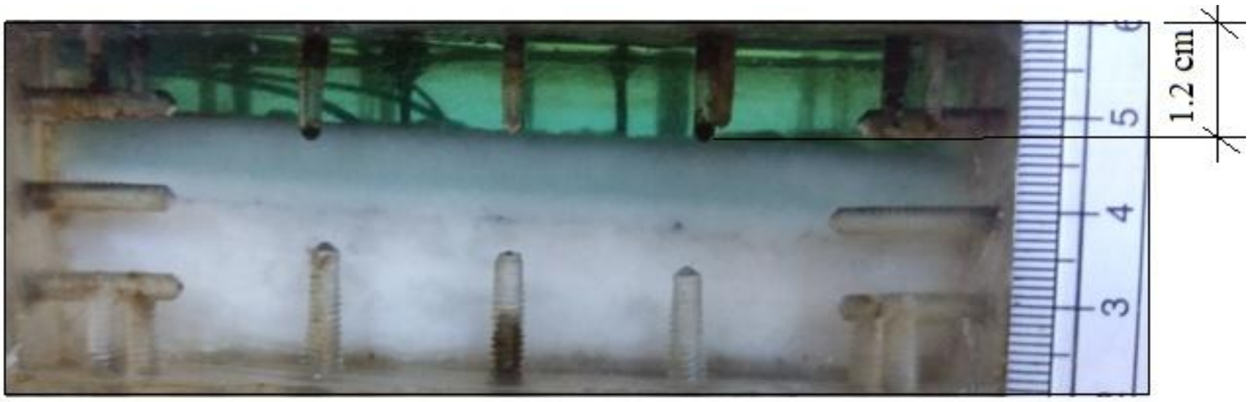
Figure 2.23: Variation of heat exchanger temperature

Fig. 2.24 (a), (b) and (c) represents the captured pictures with molten fraction of the PCM at the different time intervals. At the time of 1:30 hours, it is seen that 0.6 cm height of the PCM is melted. As the time passes, PCM melts more as shown in Fig 2.24(b), at time 5:30 hours; the PCM of 0.9 cm height is melted. Similarly, at the time 12:30 hours, 1.2 cm height of the PCM is melted.

In Fig. 2.25 (a), (b) and (c), progress of solidification process of the PCM is shown during cooling. Here, it is seen that at the time of 13:30 hours, 0.4 cm height of the PCM is solidified. As the time passes, more and more PCM solidifies. At the time 13:45 hours, 0.6 cm height of the PCM is solidified. At end of the day, i.e., after 24 hours of the cooling, the total molten PCM is solidified as shown in the Fig. 2.25 (c).

(a) Picture representing molten PCM at time t =1:30 hours during heating

(b) Picture representing molten PCM at time t =5:30 hours during heating

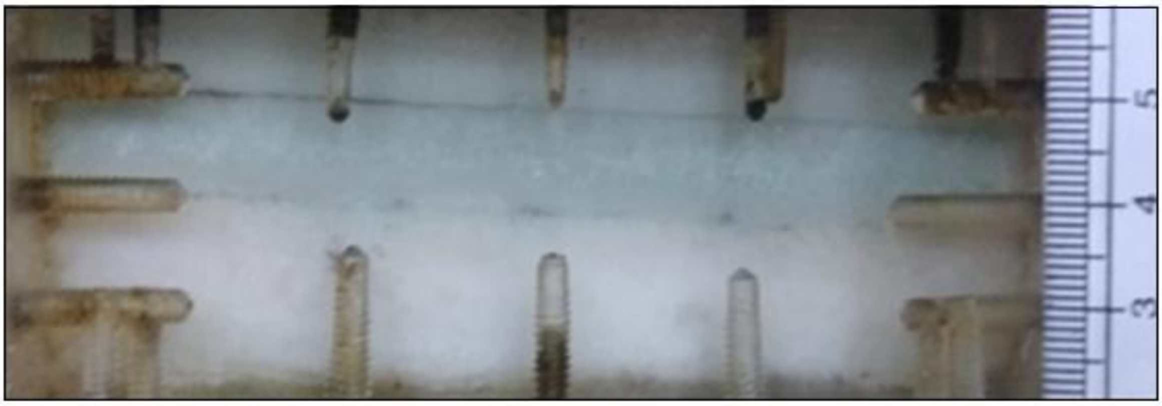


(c) Picture representing molten PCM at time t =12:30 hours during heating

Figure 2.24: (a), (b), and (c) are the pictures captured during heating process

(a) Picture representing molten PCM at time t =13:30 hours during cooling

(b) Picture representing molten PCM at time t =13:45 hours during cooling



(c) Picture representing molten PCM at time t =24:00 hours during cooling

Figure 2.25: (a), (b), and (c) are the pictures captured during solidification process

Similar to the Case-I and Case-II, here also thermocouples are placed within PCM of the model brick at different locations, through these thermocouples, the temperature readings are noted. Fig. 2.26 presents the temperature profiles at different locations within the PCM. With a reference to the Fig. 2.11(a), in the graph of Fig. 2.26, curve-A represents the temperature variation at top surface of the brick. Curve-B and curve-C represent the temperature variations at a horizontal plane which is 1.5 cm below of the top surface of the brick. It is seen that B and C curves follow same pattern as these two locations are at same level. Similarly, D and E curves follow same pattern in the graph as they are also at the same level. From the graph, it is seen that F follows almost same pattern as D and E as F is at 1 cm below from the D and E thermocouple positions where effect of the heating is insignificant. In the graph, it is seen that up to the 12:30 hours, the slope of all temperature profiles increases, thereafter the slope decreases due to sudden drop in set temperature. After 13 hours, it is seen that B and C temperature profiles follow almost same graph. Similarly, D, E and F follow almost same path. Out of the temperature record throughout of the day period, the maximum temperature of the bottom surface (curve-F) of the brick is 34°C.

Figure 2.27 shows the variation of the average height of molten PCM with time. Out of the Fig. 2.26, it is clear that maximum molten PCM height is 1.2 cm only. This is due to the high melting temperature of the PCM, which is 37°C. As seen, 1.2 cm height of the PCM is melted within 12:30 hours, and it is solidified within 11:30 hours. This indicates that at end of the day, i.e., after 24 hours, solid form of the PCM is restored again for recycling of the PCM towards next day.

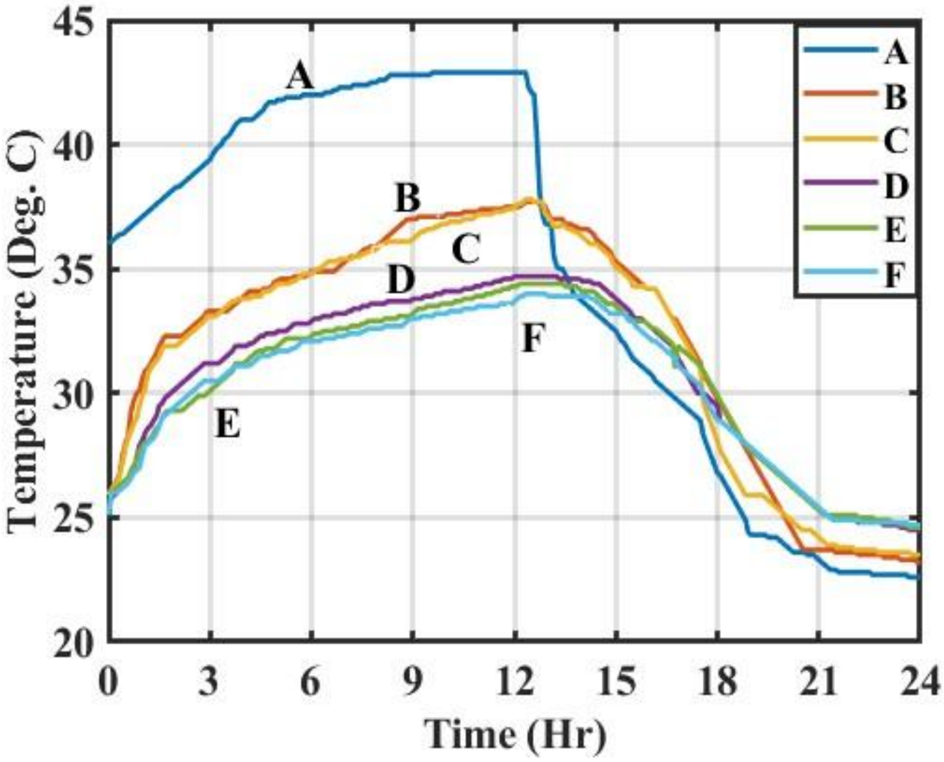


Figure 2.26: Temperature variation at different locations within the PCM

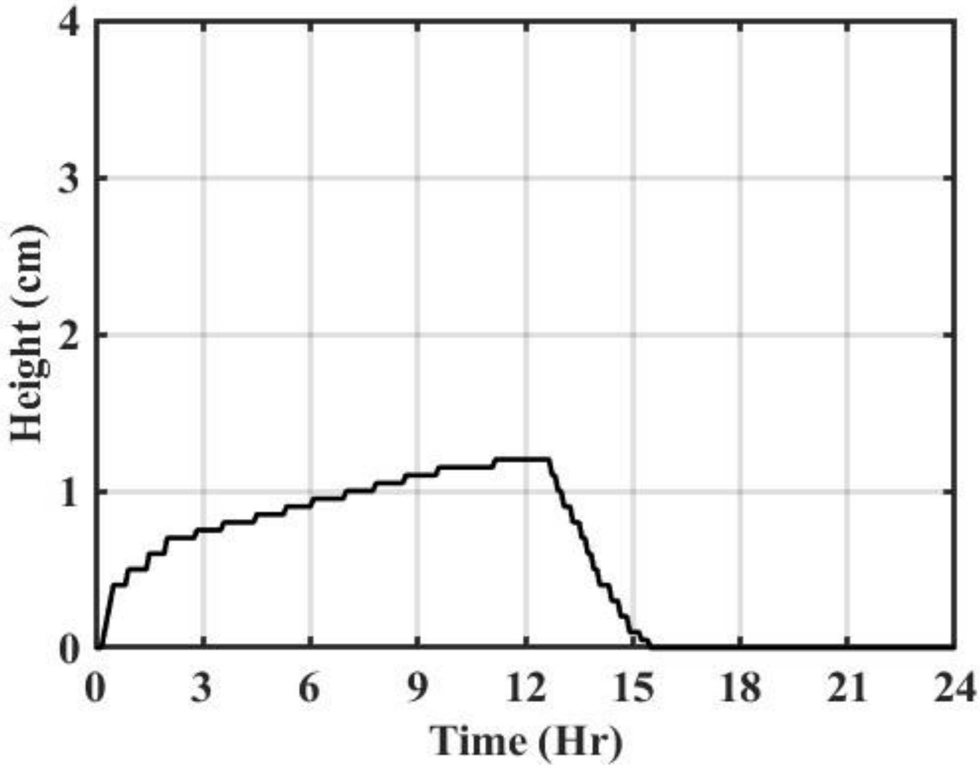


Figure 2.27: Variation of the average height of the molten PCM with time

Conclusions of the Case-III:

1. In about 12:30 hours of heating; 1.2 cm height of the PCM is melted.
2. Within 11:30 hours of cooling, the 1.2 cm height of molten PCM is fully solidified, which means recycling of the PCM is possible within a day.
3. Maximum temperature at bottom surface (node F) of the brick reaches to about 34°C.

2.7.4 Case-IV (OM-37 and bath temperature is 65°C)

In the case-III, temperature of the constant temperature bath is set to 55°C, corresponding maximum temperature at heat exchanger reaches to 45°C. However, based on the situation of a day, the intensity of solar radiation may varies and increase. Accordingly, a higher temperature at the constant temperature bath is set. To increase temperature in the heat exchanger, the temperature of constant temperature bath is changed from 55°C to 65°C. By changing this temperature, the maximum temperature rises in the heat exchanger to 51°C, variation of which is shown in the Fig. 2.28. Here, 51°C temperature represents terrace day time temperature. The minimum temperature recorded is 20°C which represents the night ambient temperature. From the Fig. 2.28, it is noted that, a total of 14:20 hours is considered for heating process and 9:40 hours is considered for cooling process. The additional hours in heating (14:20 hours> 12 hours) are considered to incorporate additional radiation and high temperature corresponds to maximum melting of the PCM.

Fig. 2.29 (a), (b) and (c) represent melts fraction of the PCM at the different time intervals. From these pictures, it is easily seen that, during heating process after 3:30 hours, 5 hours and 14:20 hours, the heights of molten PCM from the top surface are 1.1 cm, 1.6 cm and 2.2 cm, respectively. Fig. 2.30 (a), (b), and (c) are the pictures correspond to solidification of PCM during cooling. From these pictures, it is observed that during this cooling process after 15 hours, 15:40 hours and 24 hours, the heights of the solidified PCM from the top surface are 0.3 cm, 0.7 cm and 2.2cm, respectively. The whole molten PCM is solidified after 24 hours.

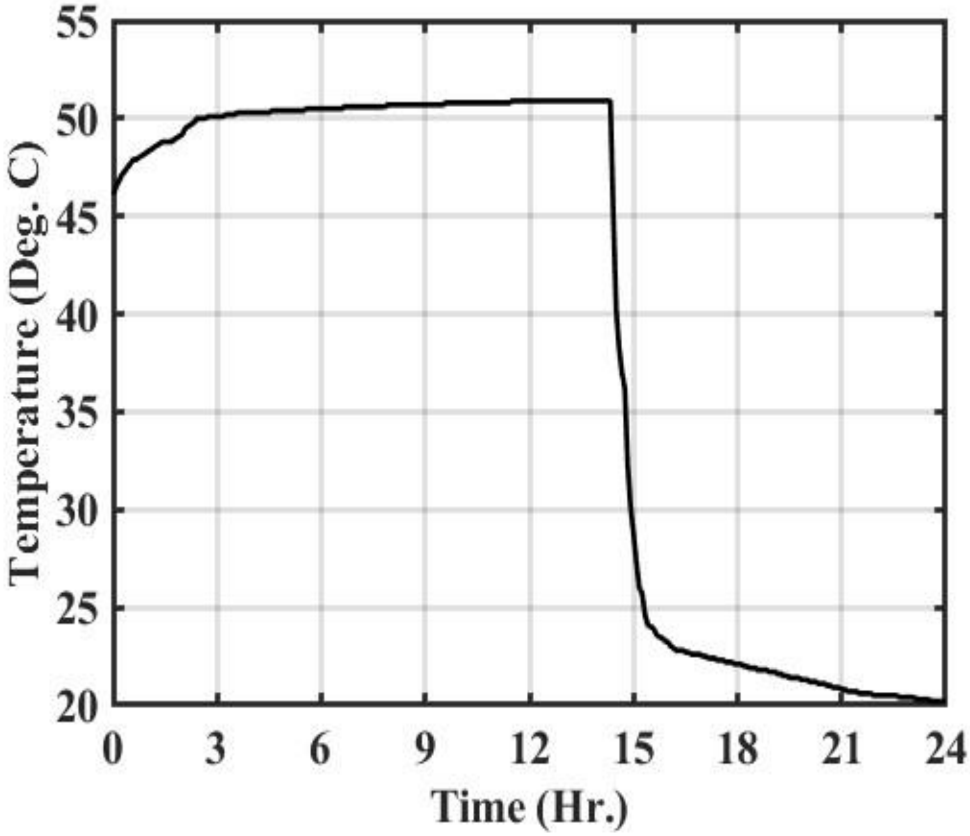
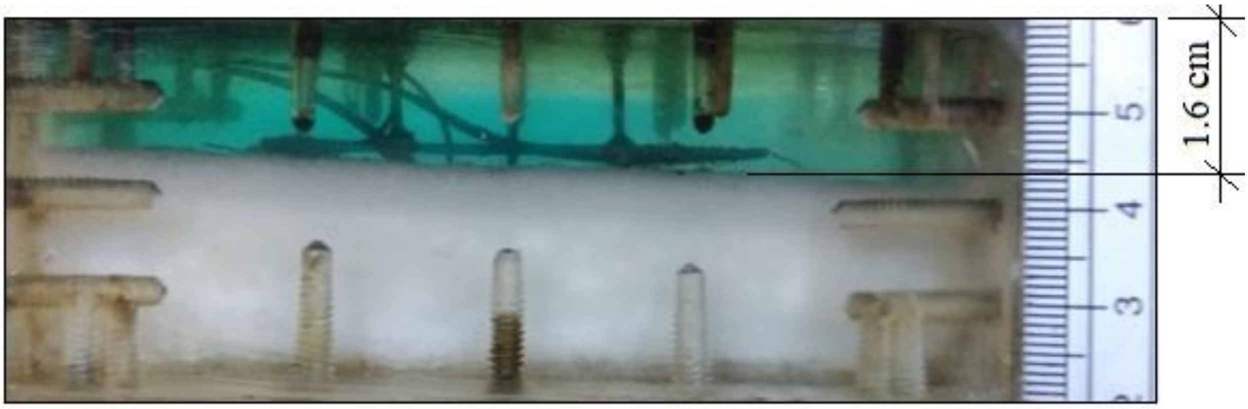


Figure 2.28: Variation of heat exchanger temperature

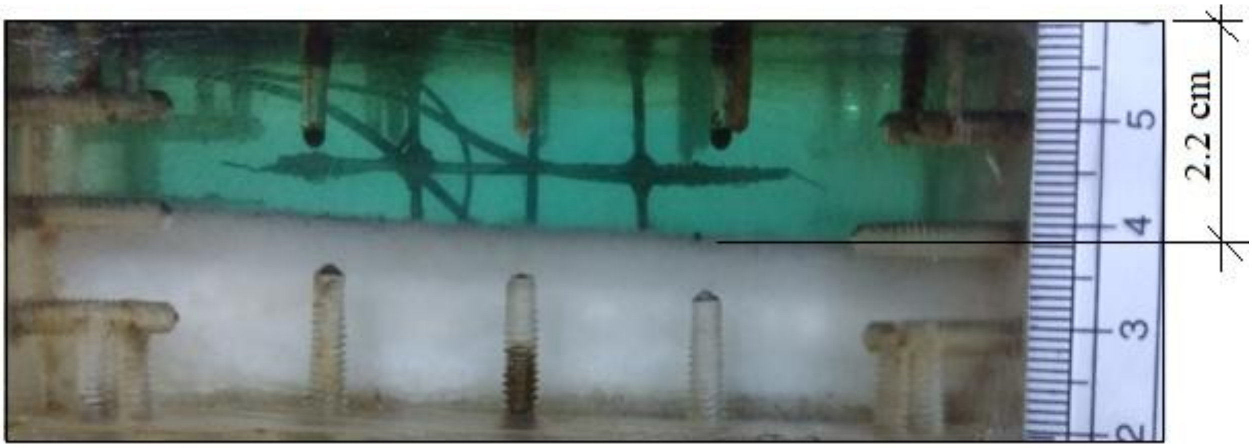
In order to determine the temperature variation within PCM of the model brick, thermocouples are placed at the different locations. During heating and cooling, all the temperature readings are noted down. Fig. 2.31 shows the temperature profiles at the different locations of the PCM with time. With a reference to the Fig. 2.11(a), in the graph of Fig. 2.31, curve-A represents the temperature variation at the top surface of the model brick. Curve-B and curve-C represent the temperature variations at the 1.5 cm below of the top surface of the brick. It is seen that the B and C curves follow same pattern as these two locations are at the same level or both thermocouples are placed at same horizontal plane. Similarly, D and E curves follow same pattern as they are placed at the same horizontal level. In the graph, it is seen that up to 14:20 hours, slope of all the temperature profiles increases and then it decreases due to sudden drop in temperature at constant temperature bath, hence in the heat exchanger.

Fig. 2.32 shows the variation of molten PCM height with respect to the time. Here it is noticed that, as compare to the case-III the height of the molten PCM is more, this is due to the temperature rise in constant temperature bath from 55°C to 65°C. This 2.2 cm height of molten PCM is obtained after 14:20 hours, and which is solidified fully within 9:40 hours of cooling. This also indicates that at end of the day or after the 24 hours process, solid form of the PCM is restored that means a recycling possibility of the PCM.

(a) Picture representing molten PCM at time t =3:30 hours during heating

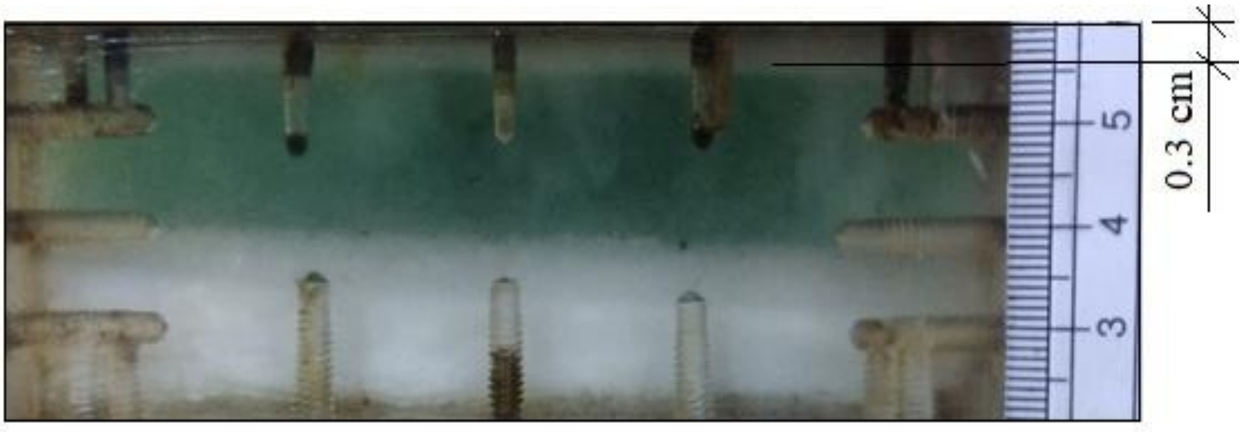


(b) Picture representing molten PCM at time t =5:00 hours during heating



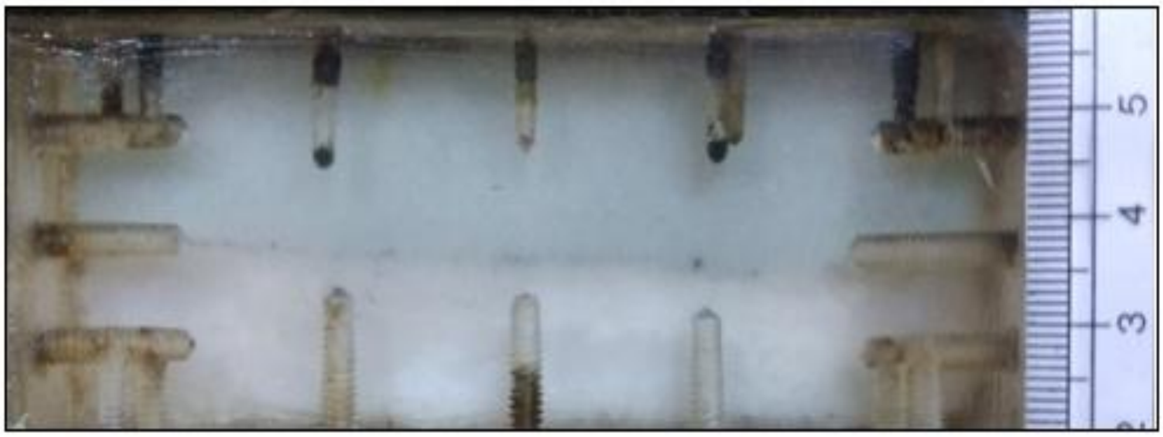
(c) Picture representing molten PCM at time t =14:20 hours during heating

Figure 2.29: (a), (b), and (c) are the pictures captured during heating process



(a) Picture representing molten PCM at time t =15:00 hours during cooling

(b) Picture representing molten PCM at time t =15:40 hours during cooling



(c) Picture representing molten PCM at time t =24:00 hours during cooling

Figure 2.30: (a), (b), and (c) are the pictures captured during cooling process

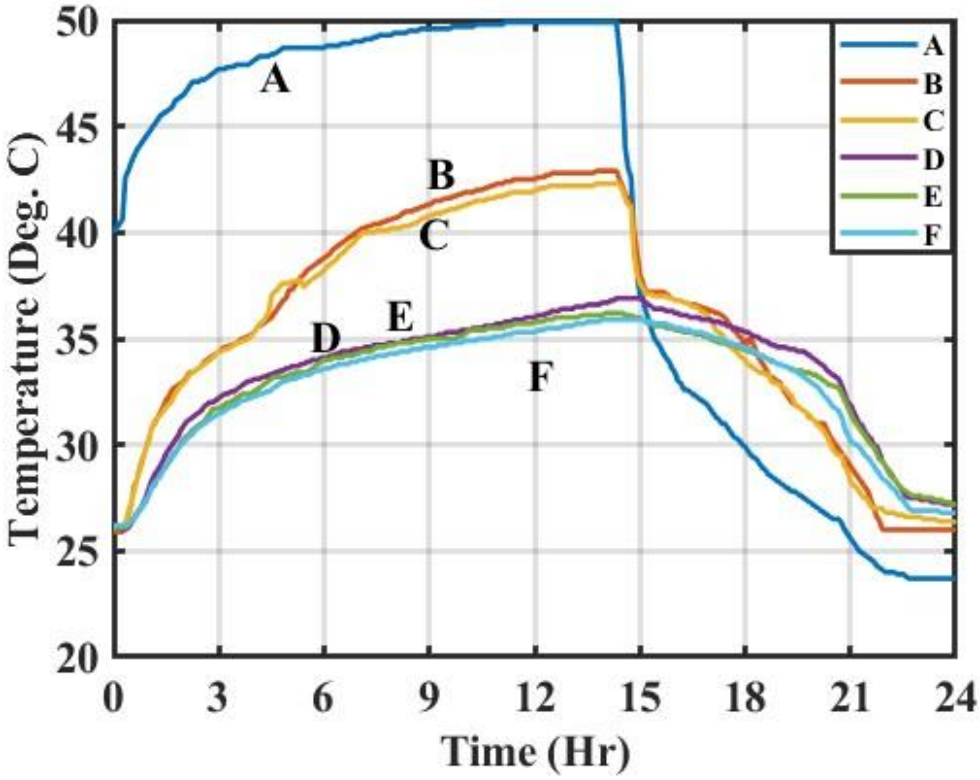


Figure 2.31: Temperature variation at various locations within the PCM

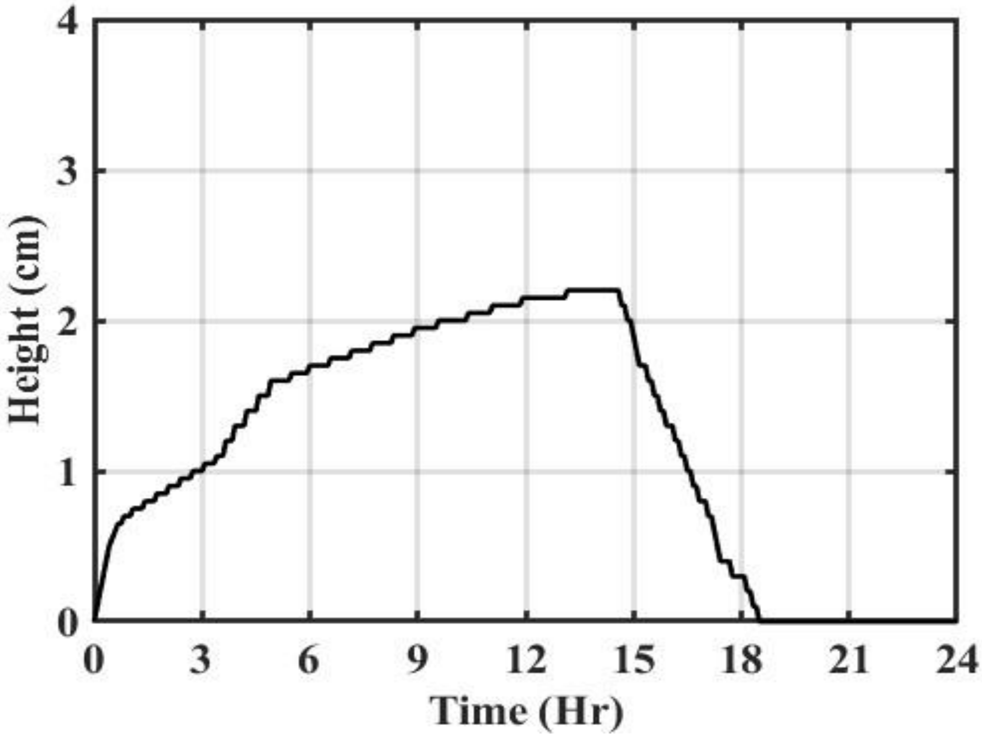


Figure 2.32: Variation of the average height of the molten PCM with time

Conclusions of the Case-IV:

1. In this case, total heating period is 14:20 hours. The maximum height of the molten PCM is 2.2 cm only. This implies out of considered 4cm height PCM, 1.8 cm PCM is not utilized. This is due to the high melting point of the PCM.
2. Total cooling period of 9:40 hours is considered. It is observed that total molten PCM of 2.2 cm height is fully solidified within this 9:40 hours period. That is a clear indication that recycling of the PCM is possible and ready for the next day.
3. The maximum temperature at bottom of the brick reaches to 35.9°C (curve-F). This indicates that when model brick is used on terrace of building for its cooling, in that case, the room temperature will reached to 35.9°C.

<u>Comparison of Case III and Case IV</u>

Fig. 2.33 represents a comparison of the height of molten PCM during heating and cooling process for the OM-37 PCM for two constant temperature bath temperatures: 55°C and 65°C. In the figure, it is seen that for different time intervals, height of molten PCM melts is different, like at time t = 3 hours, for case III the molten PCM height is 0.8 cm. On the other hand, for Case-IV, molten PCM height is 1 cm. This is due rise in temperature in the Case-IV. Accordingly, the maximum height of molten PCM is 1.2cm for the Case-III whereas in case Case-IV it is 2.2cm. But, both the cases, the molten PCM is solidified within 24 hours, i.e., recycling is possible even the terrace temperature reaches to about a temperature of 65°C. A reasonable conclusion of present investigation includes placing of present model bricks on the terrace of buildings. The model bricks are to be filled with OM-37 up to a height of 4 cm. In such conditions, the room temperature remains within 34°C to 35.9°C.

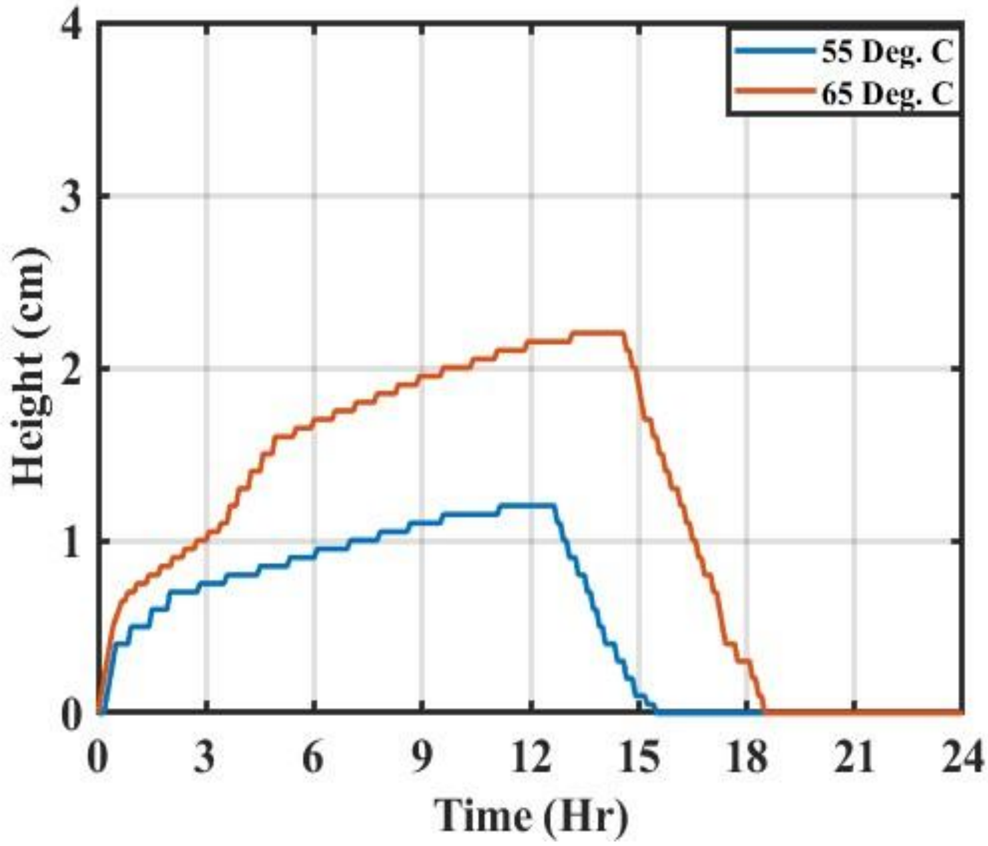


Figure 2.33: Variation of the average height of the molten PCM with time

2.8 A summary for all four cases

Table 2.5 represents a summary of all four cases which are discussed above. From the table, it is seen that, the heat exchanger temperature varying within a temperature range from 43.5°C to 51°C out of all four cases while the range of the set temperature for constant temperature bath from 55°C to 65°C. A maximum molten PCM height is 4 cm when OM-29 is used as PCM, and corresponding temperature in the heat exchanger is 50°C. It is also observed that the minimum height of molten PCM is 1.2 cm when OM-37 is used as PCM and corresponding temperature in heat exchanger is 45°C, this is due to high melting point temperature of the PCM. In all four cases, it is observed that the molten PCM solidifies back within end of the day, i.e., after 24 hours. Hence, recycling of the PCM is possible for all the cases. From the table, it is also clear that a minimum temperate at the bottom of the model brick is 28.8℃ when OM-29 is used as PCM. It is summarized out of all the four cases that on use of PCM, the room temperature may be maintained at 28.8 ℃ for a moderate sunny day and that can reach to 33.3℃ on a very sunny day when OM-29 is used as PCM.

Table2.5: Comparison of different cases (Case I to IV)

PCM	CTB TEMP (°C)	Heat Exchanger temperature during melting(°C)	Heat Exchanger temperature during solidification(°C)	Max. Height of Molten PCM (cm)	Max. Temperature at Bottom (Node F) of Brick (°C)
OM-29	55/20	43.5	20	3.2	28.8
OM-29	65/20	50	20	4	33.3
OM-37	55/20	45	20	1.2	34
OM-37	65/20	51	20	2.2	35.9

2.9 Summary of the chapter

In this chapter, cooling of buildings using PCM is considered. Accordingly, a model brick is prepared in order to place on terrace of the building to maintain the human comfort zone temperature inside a building. For fabricating the model brick; plexiglass, copper plate and K-type thermocouples are used. To maintain day and night time condition on the terrace, an equivalent temperature of the terrace is considered through considering a heat exchanger, which is connected with a constant temperature bath. Constant temperature bath provides the required temperature in the heat exchanger through passing fluid through it. In the experiments, PCMs used are OM-29 and OM-37. To maintain a terrace temperature of sunny day, the temperatures at constant temperatures bath are set at

55°C and 65°C assuming different conditions of sunny days. Similarly, to present the night ambient temperature, 20°C temperature is set at constant temperature bath.

In the experiments, all temperature readings are recorded from the temperature device at different time intervals as well as the pictures of melting and solidification of the PCM captured with a SLR camera. It is found that in all cases, recycling of the PCM is possible, but the maximum height of molten PCM and bottom surface temperature of the PCM are different for different cases. As found, OM-29 is suitable in order to cool the buildings and the optimum height of the brick will be 4.0 cm maximum. After placing the model bricks on the terrace the buildings, the indoor temperature would be less than 28.8°C that comes under the human comfort zone.

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Chapter III

Numerical Validation of the Experimental Predictions

3.1 Introduction

It is well established that the use of phase change materials (PCMs) spreads widely as a thermal energy storage device towards cooling of residential as well as commercial buildings, which is an economically beneficial technology and save the use of conventional energy. Hence, recycling of PCMs is very essential for successful cooling of buildings. Also, a detailed study is required towards study of the complex transport phenomena during cooling. It is seen that the experimental analysis is very costly and time consuming. Therefore, in this chapter an effort is given on numerical analysis for recycling of PCM and room temperature during cooling of building using PCMs. Few existing literature on numerical study for cooling of buildings using PCMs are reviewed in Chapter – 1 (Section 1.7.3). The experimental predictions as discussed in the Chapter-2 are compared with the numerical predictions for validation. In this context, all transport phenomena are modeled using a set of governing equations include mass, momentum and energy conservations in consideration of volume average physical properties. The finite volume method (CVM) is used to discretize these governing equations appropriately, and using the TDMA, final linear simultaneous equations are solved with the proper boundary conditions and morphology of the solid-liquid interface occurs in melting and solidification of the phase change materials. Accordingly, a simulation code is developed on FORTRAN platform. The details of necessary mathematical and numerical modeling are described in the thesis [85] reported by the candidate and same has been considered for the present thesis also.

3.2 Consideration of a suitable numerical domain

The size of experimental cavity is 100mm×40mm×40mm. For simplicity in describing the problem, a 2-D rectangular cavity is considered as shown in Fig. 3.1. Except the top surface, all other walls are made of plexiglass which is an insulating material in nature. Accordingly, all side walls of the 2-D cavity are represented as the adiabatic walls. In case of momentum transfer, no slip boundary conditions are considered. The cavity is filled with phase change material (PCM). The top surface of the cavity is made of copper plate and over it, a heat exchanger is placed. The heat exchanger is maintained at a temperature ($T_{H.E.}$). Accordingly, top surface temperature (T) is set to a temperature equal to the heat exchanger temperature.

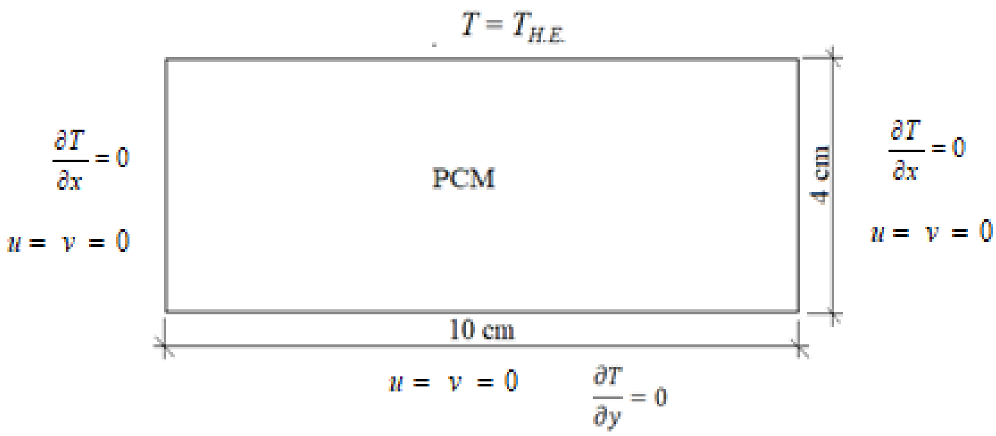


Figure 3.1: Numerical domain of the present problem

3.3 Mathematical modeling

The present problem involves mass, momentum and energy transfer together. In addition, this problem involves phase transformation of PCM involves evolution of the latent heat. Accordingly, this work considered the volume average properties in modeling of the problem. The related governing equations for present problem are the mass, momentum and energy conservations equations illustrated below in details. Following assumptions are considered during modeling of the governing equations:

i. Incompressible fluid
ii. No shrinkage during solidification
iii. Boussinesk approximation
iv. Volume average properties

3.3.1 Conservation of mass

The conservation of mass equation is presented as:

$$\frac{\partial(\rho u)}{\partial x} + \frac{\partial(\rho v)}{\partial y} = 0 \quad \text{(i)}$$

In the above equation, ρ denotes the volume average density, u and v denote velocity in x- and y-direction, respectively [86].

3.3.2 Conservation of momentum

For present analysis, the following equations for conservation of momentum are used.

$$\frac{\partial(\rho u)}{\partial t} + u\frac{\partial(\rho u)}{\partial x} + v\frac{\partial(\rho u)}{\partial y} = -\frac{\partial p}{\partial x} + \nabla.(\mu \nabla u) + S_u \quad \text{(ii)}$$

$$\frac{\partial(\rho v)}{\partial t} + u\frac{\partial(\rho v)}{\partial x} + v\frac{\partial(\rho v)}{\partial y} = -\frac{\partial p}{\partial y} + \nabla.(\mu \nabla v) + S_v + \rho\, g\, \beta\left(T - T_{ref}\right) \quad \text{(iii)}$$

In the problem, during heating and cooling of the PCM, melting or solidification of PCM occurs. Accordingly, the molten front thickness is modeled as a porous region. Accordingly,

S_u and S_v are the source terms added in the momentum equations in order to provide an additional frictional resistance toward the fluid flow [87], and those are represented as

$$S_u = Au$$

$$S_v = Av$$

where A is defined as

$$A = -\frac{C(1-f_l)^2}{f_l^3 + b} \quad \text{(iv)}$$

In the equation (iv), C is a morphological constant and which has a sufficiently large value ($\sim 1.6\times10^6$). In the equation, the term '*b*' is a computational constant presented to avoid division of a value by zero. As noticed from the above equation, Zero value occurs to this additional frictional resistance in case of liquid phase ($f_l=1$) and that varies from zero to a very high value in case of solid phase ($f_l=0$).

3.3.3 Conservation of energy

In modeling of the present problem, following conservation of energy equation is used.

$$\frac{\partial(\rho c_p T)}{\partial t} + u\frac{\partial(\rho c_p T)}{\partial x} + v\frac{\partial(\rho c_p T)}{\partial y} = \nabla.(k\nabla T) + S_h \quad \text{(v)}$$

In equation (v), S_h is the source term and represents absorption of latent heat during melting or evolution of latent heat during solidification of the PCM. The corresponding latent heat source term (S_h) is given as

$$S_h = -\frac{\partial(\rho\Delta H)}{\partial t} \quad \text{(vi)}$$

where

$$\Delta H = 0 \qquad T < T_{melt}$$

$= L_a \qquad T > T_{melt}$

where ΔH is the enthalpy value. In each of iterations in simulation, the enthalpy value is updated based on the enthalpy update scheme [87] as

$$[\Delta H_P]^{n+1} = [\Delta H_P]^n + \frac{a_P}{a_P^0}\lambda \left[\{H_p\}^n - c_p F^{-1}\{\Delta H_p\}^n\right] \qquad \text{(vii)}$$

In equation (vii), ΔH_P represents latent heat content at the P_{th} node point of the computational domain, n is iteration number, $a_p^o = \rho \Delta V / \Delta t$, a_p is coefficient of T_p, in the discretized energy equation [66], λ is a relaxation factor, c_p is specific heat and F^{-1} is inverse latent heat function. In the present work, PCM is considered as a pure substance, thus F^{-1} equals to T_{melt}. Based on latent heat content (ΔH), fraction of liquid at any of the cells in computational domain is calculated as

$$f_l = \frac{\Delta H}{L_a}$$

$$f_s = 1 - f_l$$

In the numerical model considered average properties (i.e., density, thermal conductivity, specific heat etc.) of the PCM and represented as

$$\rho = f_l \rho_l + f_s \rho_s$$

$$k = f_l k_l + f_s k_s$$

$$c_p = f_l c_{pl} + f_s c_{ps}$$

where,

ρ : density of the PCM

ρ_l : density of the PCM in liquid state

ρ_s : density of the PCM in solid state

k : thermal conductivity of the PCM

k_l : thermal conductivity of the liquid PCM

k_s : thermal conductivity of the solid PCM

c_p: specific heat of the PCM

c_{pl} : specific heat of the liquid PCM

c_{ps}: specific heat of the solid PCM

However, in this thesis, same values of properties for liquid and solid have been considered.

Boundary conditions

Boundary conditions are important in numerical analysis of any problem. For the present numerical work, the boundary conditions are represented as

Top face:

u = 0, v =0

$T= T_{H.E.}$

In present case, top surface is made of copper place and attached with the heat exchanger. Accordingly, top surface temperature (T) is made equal to the temperature of heat exchanger (T_{HE}).

Bottom face:

u = 0, v =0

$$\frac{\partial T}{\partial y} = 0$$

Left and right faces:

u = 0, v =0

$$\frac{\partial T}{\partial x} = 0$$

Since other than the top surface, all other walls of the cavity are made of plexiglass which is an insulator, all side and bottom walls are considered as adiabatic.

3.4 Numerical modeling

In present numerical modeling, all governing equations (eqns. i to v) are discretised on standard of the semi-implicit finite volume method (FVM) using power law scheme [86]. Then, in order to solve related discretized linear equations, this work adopted the SIMPLER algorithm, and in respect to solver, the TDMA: tri-diagonal matrix solver is used. For all variables, a convergence criteria is considered as $\left|(\phi-\phi_{old}) / \phi_{max}\right| < 10\text{-}5$ where ϕ stands for related solved variables at a grid point at its current iteration level, ϕ_{old} represents corresponding value at its previous iteration level and ϕ_{max} is maximum value of related variable at its current iteration level in the entire numerical domain. The work conducted a comprehensive grid-independence study, initially. It is found that a 102 × 82 uniform grid is suitable for present simulation, and a time step of 0.1s offers a suitable convergence.

3.5 Results and discussion

Initially, the numerical model is validated against a benchmark problem solved by Brent *et al*. [87] where melting of a pure gallium in a side heated rectangular cavity is considered. Corresponding comparison of the present numerical prediction with the prediction of Brent *et al*. [87] is presented in Fig. 3.2. As observed, a good agreement between the numerical results is found. Therefore, the present numerical code is extended for analysis of present work.

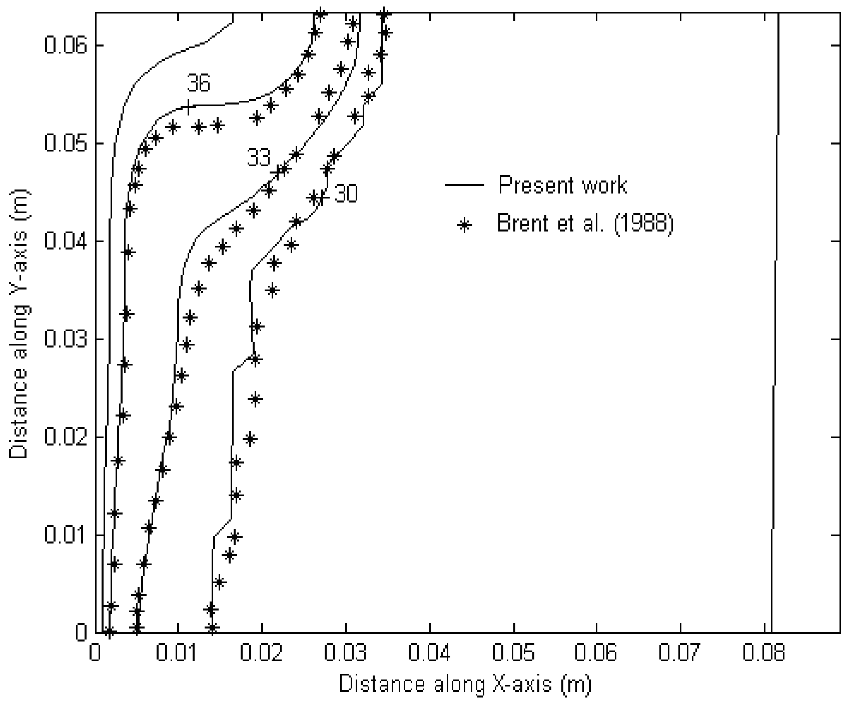


Figure 3.2: Temperature distribution of the 2-D melting of gallium

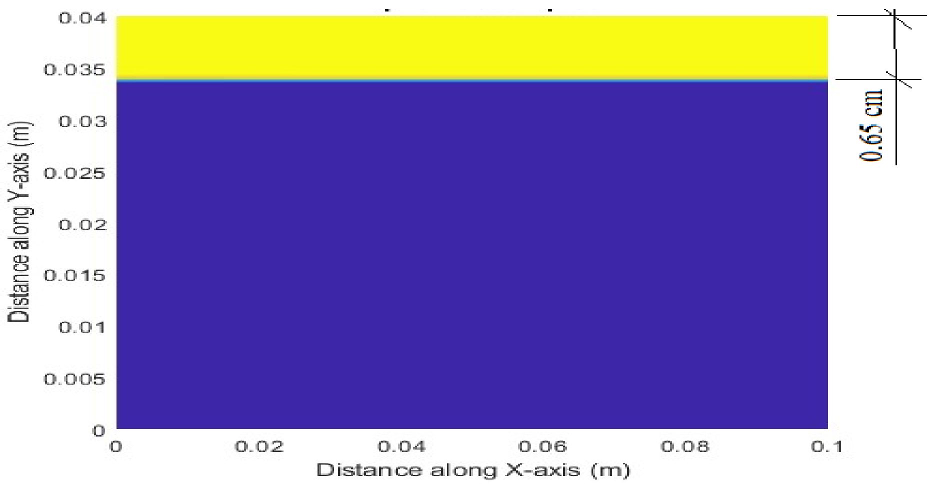
After preliminary validation of present numerical code, it is extended to for validating the experiments conducted in the Chapter-II. As discussed in the Chapter-II, the experiments are conducted for four different cases. Validation for each of the cases is presented below in details.

3.5.1 Case I (OM-29 and bath temperature is 55°C)

In this case, OM- 29 is used as PCM and temperature of the top surface or heat exchanger is set at 43.5°C. The properties and related data of the PCM those are feed into the numerical simulation are considered from the Table. 2.4. Based on the numerical outcomes, Fig. 3.3 (a) is a sample numerical presentation of melt fraction of the PCM within the domain of interest at time t = 0:30 hours. Fig. 3.3 (b) is corresponding melt fraction picture captured at the time t = 0:30 hours. From both the figures, it is seen that the height of the molten PCM in experimental case is 0.5 cm whereas in case of numerical analysis, height of the molten

PCM is 0.65 cm for corresponding time. However, the comparison shows a good agreement.

Fig. 3.4 shows variation of the average height of the molten PCM with time based on experimental and numerical results. In the figure, it is clear that both curves follow same pattern with almost closer values.



(a) Melt fraction of the PCM, numerically predicted at t =0:30 hours

(b) Melt fraction of the PCM, captured on experiment at t =0:30 hours

Figure 3.3: (a) and (b) are the melt fraction of the PCM at time t =0:30 hours

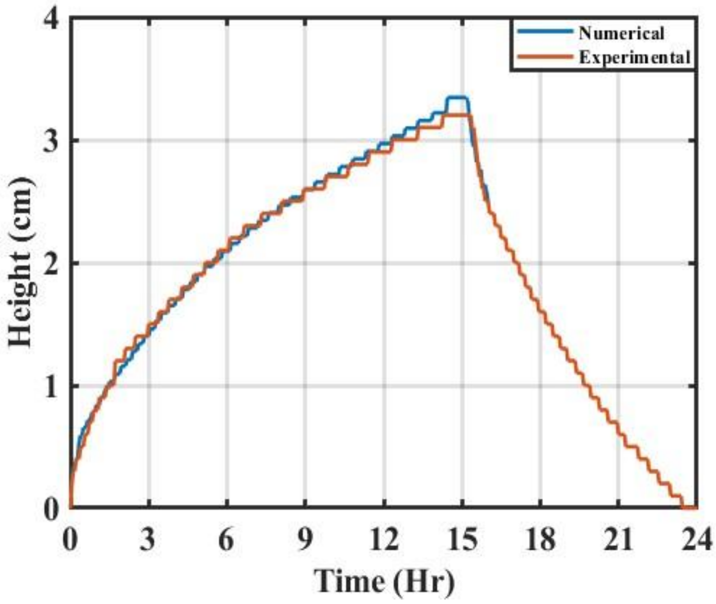
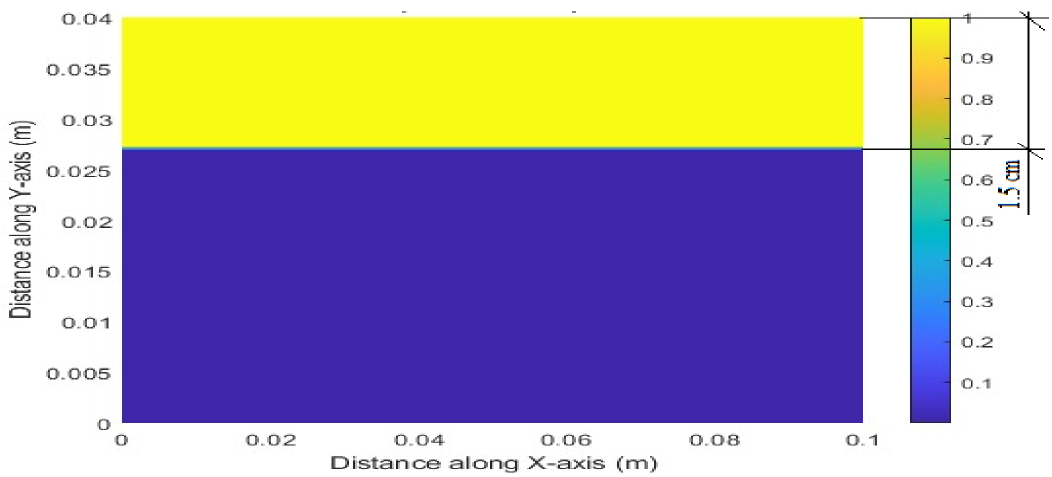


Figure 3.4: Comparison between experimental and numerical work

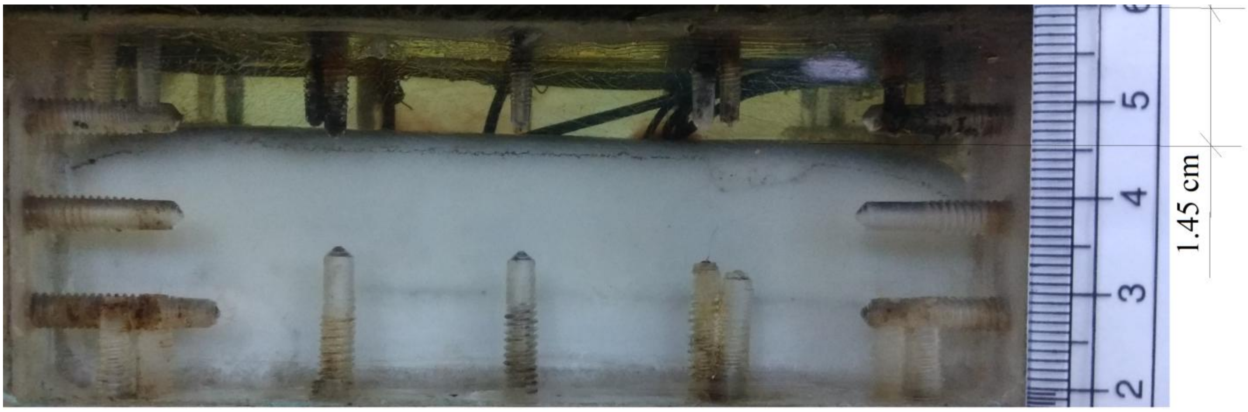
3.5.2 Case II (OM-29 and bath temperature is 65°C)

In this case, OM- 29 is used as PCM and temperature of the top surface or heat exchanger is set at 50°C. The properties and related data of the PCM those are feed into the numerical simulation are considered from the Table. 2.4. Based on the numerical outcomes, Fig. 3.5 (a) is a sample numerical presentation of melt fraction of the PCM within the domain of interest at time t = 1:30 hours. Fig 3.5 (b) is corresponding melt fraction picture captured at the time t = 1:30 hours. From both the figures, it is seen that the height of the molten PCM in experimental case is 1.45 cm whereas in case of numerical analysis, height of the molten PCM is 1.5 cm for corresponding time. However, the comparison shows a good agreement.

Fig. 3.6 shows variation of the average height of the molten PCM with time based on experimental and numerical results. In the figure, it is clear that both curves follow same pattern with almost closer values.



(a) Melt fraction of the PCM, numerically predicted at t =1:30 hours



(b) Melt fraction of the PCM, captured on experiment at t =1:30 hours

Figure 3.5: (a) and (b) are the melt fraction of the PCM at time t =1:30 hours

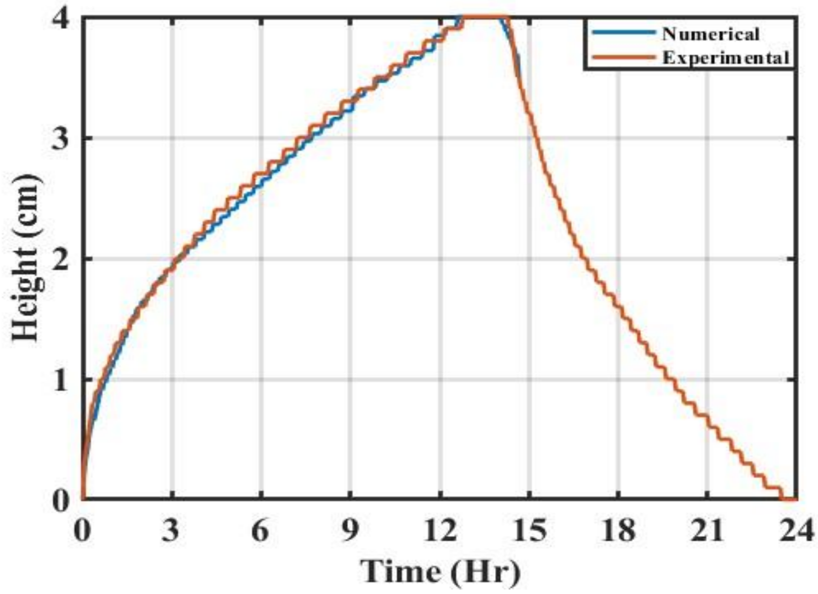
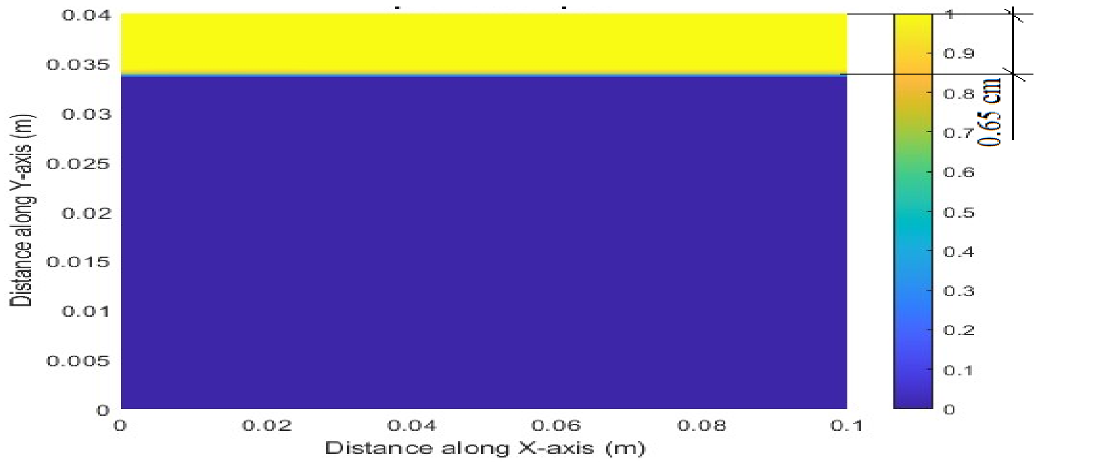


Figure 3.6: Comparison between experimental and numerical work

3.5.3 Case III (OM-37 and bath temperature is 55°C)

In this case, OM- 37 is used as PCM and temperature of the top surface or heat exchanger is set at 45°C. The properties and related data of the PCM those are feed into the numerical simulation are considered from the Table. 2.4. Based on the numerical outcomes, Fig. 3.7 (a) is a sample numerical presentation of melt fraction of the PCM within the domain of interest at time t = 1:30 hours. Fig. 3.7 (b) is corresponding melt fraction picture captured at the time t = 1:30 hours. From both the figures, it is seen that the height of the molten PCM in experimental case is 0.6 cm whereas in case of numerical analysis, height of the molten PCM is 0.65 cm for corresponding time. However, the comparison shows a good agreement.

Fig. 3.8 shows variation of the average height of the molten PCM with time based on experimental and numerical results. In the figure, it is clear that both curves follow same pattern with almost closer values.



(a) Melt fraction of the PCM, numerically predicted at t =1:30 hours

(b) Melt fraction of the PCM, captured on experiment at t =1:30 hours

Figure 3.7: (a) and (b) are the melt fraction of the PCM at time t =1:30 hours

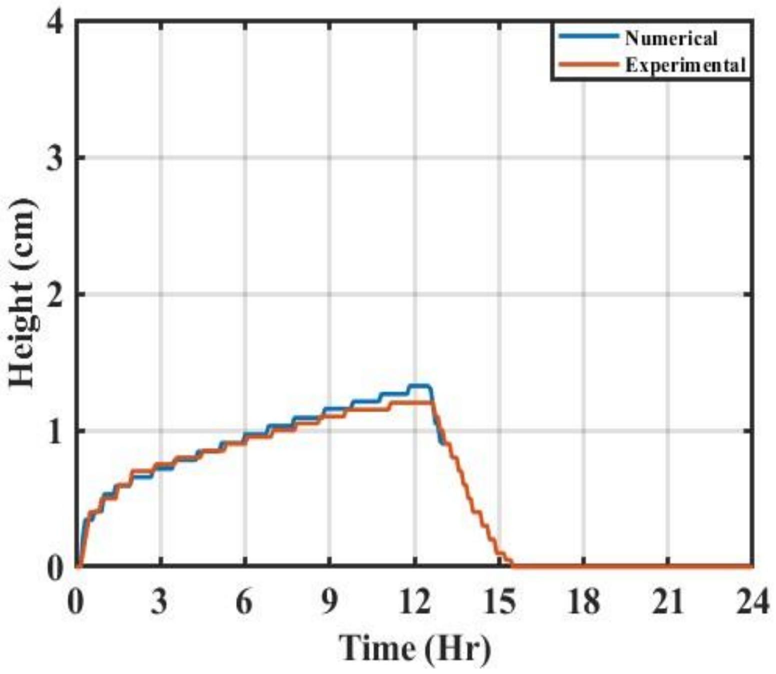
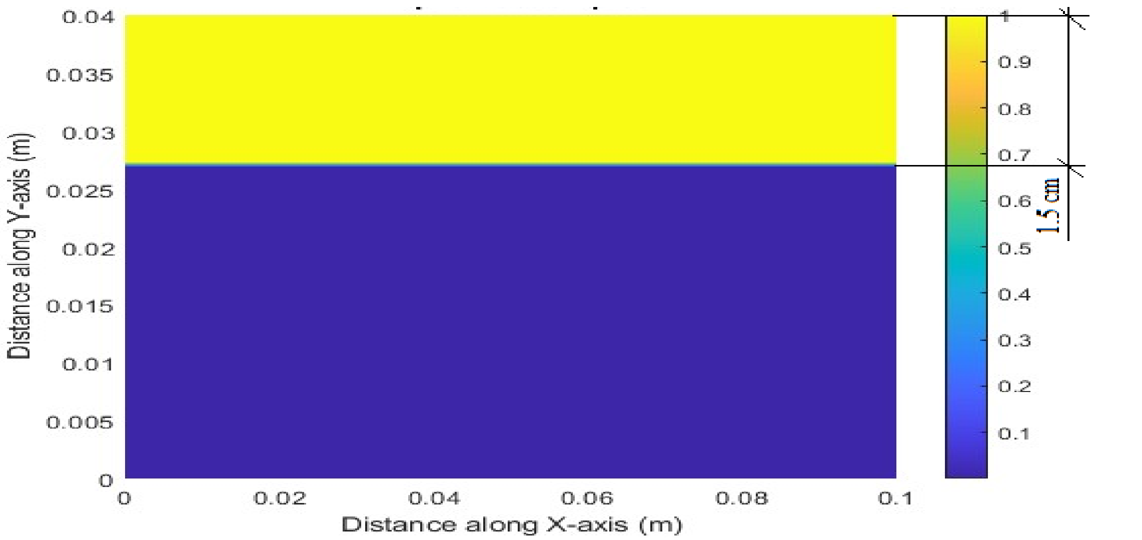


Figure 3.8: Comparison between experimental and numerical work

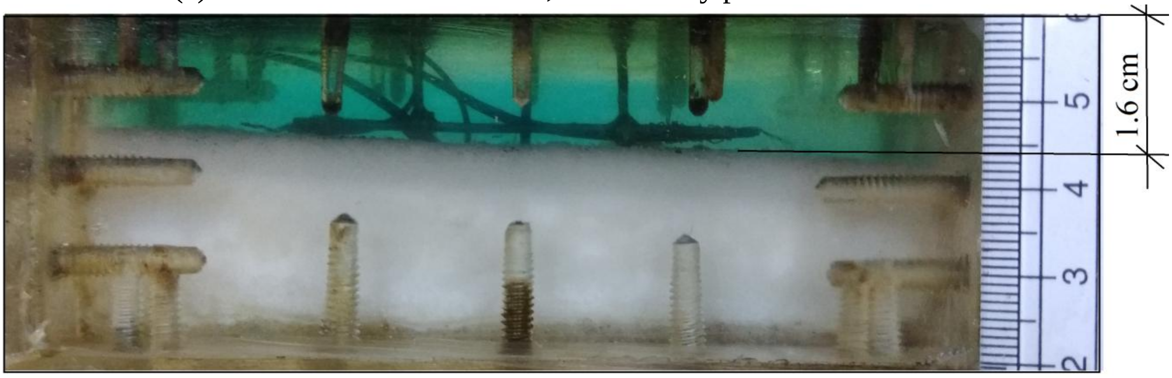
3.5.4 Case IV (OM-37 and bath temperature is 65°C)

In this case, OM- 37 is used as PCM and temperature of the top surface or heat exchanger is set at 51°C. The properties and related data of the PCM those are feed into the numerical simulation are considered from the Table. 2.4. Based on the numerical outcomes, Fig. 3.9 (a) is a sample numerical presentation of melt fraction of the PCM within the domain of interest at time t = 5 hours. Figure 3.9 (b) is corresponding melt fraction picture captured at the time t = 5 hours. From both the figures, it is seen that the height of the molten PCM in experimental case is 1.6 cm whereas in case of numerical analysis, height of the molten PCM is 1.5 cm for corresponding time. However, the comparison shows a good agreement.

Fig. 3.10 shows variation of the average height of the molten PCM with time based on experimental and numerical results. In the figure, it is clear that both curves follow same pattern with almost closer values.



(a) Melt fraction of the PCM, numerically predicted at t =5 hours



(b) Melt fraction of the PCM, captured on experiment at t =5 hours

Figure 3.9: (a) and (b) are the melt fraction of the PCM at time t =5 hours

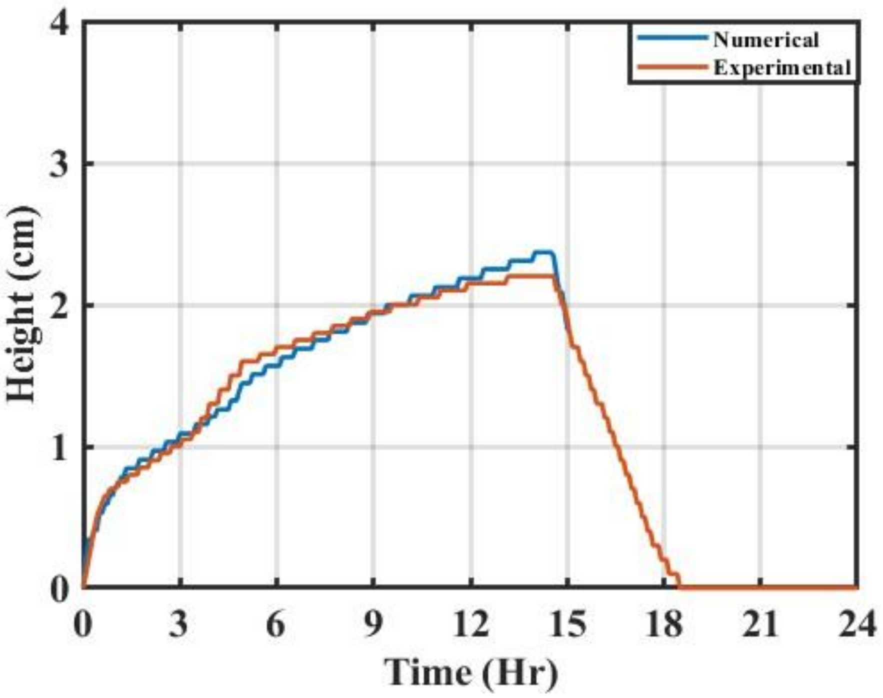


Figure 3.10: Comparison between experimental and numerical work

3.6 Summary of the Chapter-III

In Chapter-II, a model brick is prepared filled with phase change material (PCM) and established the model experimentally for cooling of buildings in the summer seasons. The model brick has been established through consideration of four successive experiments (Case-I to Case-IV). In this chapter, a numerical model is considered to compare and validate all of the experiments conducted and discussed in the Chapter-II. The numerical predictions are compared with the experimental predictions. It is observed that a similar variation for all predictions in numerical case is found in comparison to the experimental results.

Reference

[86] Patankar, S. V., 1980, “Numerical Heat Transfer and fluid flow’’, Hemisphere Publications, New York

[87] Brent AD, Voller VR, Reid KJ. Enthalpy-porosity technique for modeling convection-diffusion phase change: Application to the melting of a pure metal. Numerical heat transfer 1988; 13:297-318

Chapter IV

Conclusion and Scope of Future Work

4.1 Summary of the thesis

Use of PCMs in cooling of buildings possibly saves about 15% consumption of the total electricity supplied by fossil fuels based power plants. To incorporate the concept of using PCMs in cooling of buildings, the PCMs can be placed in a form of model bricks or tiles in surroundings of the building. In the present work, placing of PCMs on the terrace of the buildings instead of wall tiles is considered as major portion of the heat in a sunny day enters into the room through terrace only. Since spreading of PCMs over the terrace is difficult in handling, this work considers preparation of a model brick filled with suitable PCMs to be placed on the terrace of the buildings for cooling purpose. The present cooling method will indirectly reduce consumption of the fossil fuels, polluting environment etc. which directly implies a reasonable reduction in the global warming. Therefore, establishment of present method for cooling of buildings is an important requirement.

In order to establish the method, experimental study using model brick has been considered through carrying out four successive experiments (Case-I to Case-IV). For the experiments, two types of organic PCMs: OM-29 and OM-37 are selected because of their melting temperature is close to human comfort zone, i.e., 29℃ and 37℃, respectively. In this thesis, the day time situation is represented by two temperatures close to the terrace temperature in a sunny day. Accordingly, the constant temperature bath

(CTB) is set at two different temperatures, i.e., 55°C and 65°C. The night time situation is represented by ambient temperature at 20°C. Based on the situation, following four combinations of experiments are conducted:

Case-I: OM-29 as PCM and 55°C at CTB

In this case, total heating period is 15 hours in order to accommodate the additional day radiation and high temperature of terrace. The maximum height of the molten PCM is 3.2 cm. This implies out of considered 4cm height PCM, 0.8 cm PCM is not utilized. Subsequently, total cooling period of 9 hours is considered. It is observed that total molten PCM of 3.2 cm height is fully solidified within this 9 hours period. That is a clear indication that recycling of the PCM is possible and ready for the next day. It is found that the maximum temperature at bottom of the brick reaches to 28.8°C (curve-F). This indicates that when the use of model brick on terrace of building for its cooling, in that case, the room temperature will be less than 28.8 °C which comes under the human comfort zone.

Case-II: OM-29 as PCM and 65°C at CTB

In this case, a total of 13:40 hours heating to the PCM is considered. Since high temperature of the heat exchanger is considered, a height of 4 cm of the PCM is found after the 12:30 hours of heating, i.e., the PCM is melted fully. The additional time of heating is considered to incorporate additional radiation and high temperature of the terrace. In next 10:20 hours of cooling, this 4 cm height of molten PCM is fully solidified. That indicates that recycling of the PCM is possible for the next day too. It is noticed that the heating process, the maximum temperature at bottom of the brick reaches to 33.3°C. That indicates that when the use of this system (model PCM bricks) in cooling of buildings, the room temperature will be less than 33.3°C which is also comfortable in a very sunny day correspond to a terrace temperature of 50°C to 65°C.

Case-III: OM-37 as PCM and 55°C at CTB

In about 12:30 hours of heating; 1.2 cm height of the PCM is melted. Within 11:30 hours of cooling, the 1.2 cm height of molten PCM is fully solidified, which means recycling of the PCM is possible within a day. It is seen that maximum temperature at bottom surface (node F) of the brick reaches to about 34°C.

Case-IV: OM-37 as PCM and 65°C at CTB

In this case, total heating period is 14:20 hours. The maximum height of the molten PCM is 2.2 cm only. This implies out of considered 4cm height PCM, 1.8 cm PCM is not utilized. This is due to the high melting point of the PCM. Total cooling period of 9:40 hours is considered. It is observed that total molten PCM of 2.2 cm height is fully solidified within this 9:40 hours period. That is a clear indication that recycling of the PCM is possible and ready for the next day. The maximum temperature at bottom of the brick reaches to 35.9°C (curve-F). This indicates that when the model brick is used on terrace of building for its cooling, in that case, the room temperature will reached to 35.9°C.

Out of the four cases, it is observed that any of the molten PCM solidifies back within end of the day, i.e., after 24 hours. Hence, recycling of the PCM is possible for all the cases. It is found that a minimum temperate at the bottom of the model brick is 28.8°C when OM-29 is used as PCM. It is concluded that the room temperature may be maintained at 28.8 °C for a moderate sunny day and that to be reached to 33.3°C on very sunny day when OM-29 is used as PCM.

The experimental predictions as discussed above are compared with the numerical predictions for validation. In this context, all transport phenomena are modeled using a set of governing equations include mass, momentum and energy conservations in consideration of volume average physical properties. The control volume method (CVM) is used to discretize these governing equations appropriately, and using the TDMA, final linear simultaneous equations are solved with the proper boundary conditions and morphology of the solid-liquid interface occurs in melting and solidification of the phase change materials. Accordingly, a simulation code is developed on FORTRAN platform. The numerical predictions are compared with all experimental predictions. It is observed that a similar variation for all predictions in numerical case is found in comparison to the experimental results.

The model brick filled with suitable PCM, to be placed on the terrace of the buildings, has been established well in order to cool the buildings. On using OM-29 as PCM in the model brick, the room temperature can be maintained below 28.8°C which is within human comfort level.

The use of PCM bricks is an indication of a reasonable reduction in consumption of electricity; indirectly it reduces environmental pollution and subsequently reduces the global warming. Therefore, this technology has a novelty in terms of reducing use of electricity.

4.2 Scope of future work

Thermal storage property of the PCM make it valuable from the others, i.e., it is used in the different places as per the requirements.

Future work:

1. In the present work, the brick model filled with suitable PCM is established. In the future work, this model bricks can be placed physically above the terrace in the cooling of a building.
2. The inside room temperatures of the building at different heights and positions need to be monitored.

Appendix-I

```
!=================================================================
!===> A  2-D CODE DEVELOPED ON FORTRAN-90
!=================================================================
!===>   GLOBAL DECLARATIONS **************************************
!=================================================================
 MODULE GLOBAL
 IMPLICIT NONE
 INTEGER,PARAMETER :: NI=82
 INTEGER,PARAMETER :: NJ=102
 INTEGER,PARAMETER :: NIJ=102
 INTEGER,PARAMETER :: NFMAX=10
 INTEGER,PARAMETER :: NP=11
 INTEGER,PARAMETER :: NFX3=NFMAX+1
 INTEGER,SAVE :: L1,L2,L3,M1,M2,M3,NF,NRHO,NGAM,NGRID
 INTEGER,SAVE ::IST,JST,ITER,ISTP,IPREF,JPREF,MODE,ITERL
 INTEGER,SAVE :: ISTP2,ISTP3,NTIME,ITLL,itimestep,index,timep
 REAL,SAVE,DIMENSION(500000) :: ptime,uu,vv,tt
 REAL,SAVE :: XL,YL,DT,TLAST
 REAL,SAVE :: TINT,THOT,TCOLD,TMELT,G,BETA,VISCOSITY,TREF
 REAL,SAVE :: RHOREF,arelax,alatent,epmean,const
 REAL,SAVE :: SMAX,SSUM,FLOW,DIFF,ACOF,DIFF1
 REAL,SAVE :: AMIU,TK,CP,epsiinitial
```

```
REAL,SAVE :: TINITIAL,RHOCON,TIME

REAL,SAVE :: DELTMX,DELUMX,DELVMX,ERT,ERU,ERV,RHOMX

REAL,SAVE,DIMENSION(NI) :: X,XU,XDIF,XCV,XCVS,FV,FVP,FX,FXM

REAL,SAVE,DIMENSION(NI) :: XCVI,XCVIP

REAL,SAVE,DIMENSION(NJ) :: Y,YV,YDIF,YCV,YCVS,YCVR,YCVRS,ARX

REAL,SAVE,DIMENSION(NJ) :: ARXJ,ARXJP

REAL,SAVE,DIMENSION(NJ) :: R,RMN,SX,SXMN,FY,FYM

REAL,SAVE,DIMENSION(NIJ) :: PT,QT

REAL,SAVE,DIMENSION(NI,NJ) :: U,V,PC,T,P,RHO,GAM,CON,Ui,Vi,tamb

REAL,SAVE,DIMENSION(NI,NJ) :: AIP,AIM,AJP,AJM,AP,AP0,AP1,AP2

REAL,SAVE,DIMENSION(NI,NJ) :: DU,DV,delh,delho,epsi,epsio

REAL,SAVE,DIMENSION(NI,NJ) :: TO,UO,VO,TOLD,UOLD,VOLD,UHAT,VHAT

REAL,SAVE,DIMENSION(NI,NJ) ::UHAT1,VHAT1,UHAT2,VHAT2

REAL,SAVE,DIMENSION(NI,NJ,6) :: COFU,COFV,COFP,COF

REAL,SAVE,DIMENSION(NFX3) :: RELAX

INTEGER,SAVE,DIMENSION(NFX3) :: NTIMES

CHARACTER(LEN=4),DIMENSION(NFX3) :: TITLE

LOGICAL,SAVE,DIMENSION(NFX3) :: LSOLVE,LPRINT,LBLK

LOGICAL,SAVE :: LSTOP,LCONV

END MODULE GLOBAL
```

```
!=================================================================
!===>   PROGRAM MAIN    ****************************************
!=================================================================
PROGRAM MAIN
USE GLOBAL
IMPLICIT NONE
WRITE(*,*)"PROGRAM RUNNING"
CALL GRID
CALL GEOMET
CALL START
MAINLOOP: DO WHILE(.NOT.LSTOP)
CALL DENSE
CALL BOUND
CALL OLDVAL
CALL COEFF
END DO MAINLOOP
WRITE(*,*)"PROGRAM FINISHED"
END PROGRAM MAIN
```

```
!==============================================================

!THIS SUBROUTINE CALCULATES DISCRETIZATION EQN COEFFS AS PER

!===>   POWER LAW.   *******************************************

!==============================================================

SUBROUTINE DIFLOW

USE GLOBAL

IMPLICIT NONE

REAL :: TEMP

ACOF=DIFF

IF(FLOW.EQ.0.) RETURN

TEMP=DIFF-ABS(FLOW)*0.1

ACOF=0.

IF(TEMP.LE.0.) RETURN

TEMP=TEMP/DIFF

ACOF=DIFF*TEMP**5

END SUBROUTINE DIFLOW

!==============================================================

!===>   THIS SUBROUTINE SOLVES DISCRETISATION EQUATIONS BY

!===>   'LINE BY LINE TDMA'.   **********************************

!==============================================================

SUBROUTINE SOLVE

USE GLOBAL

IMPLICIT NONE

INTEGER :: I,J,II,JJ,N,NT,ISTF,JSTF,IT1,IT2,JT1,JT2

REAL :: BL,BLP,BLM,BLC,BLC1,TEMP,DENOM
```

```
REAL,DIMENSION(NI,NJ) :: F
SELECT CASE(NF)
       CASE(1)
        F = U
       CASE(2)
        F = V
       CASE(3)
        F = PC
       CASE(4)
        F = T
 CASE(NP)
        F = P
END SELECT

!-----------------------------------------------------------------
ISTF=IST-1
JSTF=JST-1
IT1=L2+IST
IT2=L3+IST
JT1=M2+JST
JT2=M3+JST
!-----------------------------------------------------------------
DO 999 NT=1,NTIMES(NF)
N=NF
!-----------------------------------------------------------------
```

```
      IF(.NOT.LBLK(NF)) GO  TO 10
      PT(ISTF)=0.
      QT(ISTF)=0.
      DO 11 I=IST,L2
      BL=0.
      BLP=0.
      BLM=0.
      BLC=0.
      DO  12 J=JST,M2
      BL=BL+AP(I,J)
      IF(J.NE.M2)  BL=BL-AJP(I,J)
      IF(J.NE.JST) BL=BL-AJM(I,J)
      BLP=BLP+AIP(I,J)
      BLM=BLM+AIM(I,J)
      BLC1=BLC+CON(I,J)+AIP(I,J)*F(I+1,J)+AIM(I,J)*F(I-1,J)
      BLC=BLC1+AJP(I,J)*F(I,J+1)+AJM(I,J)*F(I,J-1)-AP(I,J)*F(I,J)
 12  END DO
      DENOM=BL-PT(I-1)*BLM
      IF(ABS(DENOM/BL).LT.1.E-10) DENOM=1.E30
      PT(I)=BLP/DENOM
      QT(I)=(BLC+BLM*QT(I-1))/DENOM
 11  END DO
      BL=0.
      DO 13 II=IST,L2
      I=IT1-II
```

```
   BL=BL*PT(I)+QT(I)
   DO 13 J=JST,M2
13  F(I,J)=F(I,J)+BL
   PT(JSTF)=0.
   QT(JSTF)=0.
   DO 21 J=JST,M2
   BL=0.
   BLP=0.
   BLM=0.
   BLC=0.
   DO 22  I=IST,L2
   BL=BL+AP(I,J)
   IF(I.NE.L2) BL=BL-AIP(I,J)
   IF(I.NE.IST) BL=BL-AIM(I,J)
   BLP=BLP+AJP(I,J)
   BLM=BLM+AJM(I,J)
   BLC1=BLC+CON(I,J)+AIP(I,J)*F(I+1,J)+AIM(I,J)*F(I-1,J)
   BLC=BLC1+AJP(I,J)*F(I,J+1)+AJM(I,J)*F(I,J-1)-AP(I,J)*F(I,J)
22  END DO
   DENOM=BL-PT(J-1)*BLM
   IF(ABS(DENOM/BL).LT.1.E-10) DENOM=1.E30
   PT(J)=BLP/DENOM
   QT(J)=(BLC+BLM*QT(J-1))/DENOM
21  END DO
   BL=0.
```

```
   DO  23 JJ=JST,M2
   J=JT1-JJ
   BL=BL*PT(J)+QT(J)
   DO 23 I=IST,L2
23  F(I,J)=F(I,J)+BL
10  CONTINUE
   !----------------------------------------------------------------
   DO 90 J=JST,M2
   PT(ISTF)=0.
   QT(ISTF)=F(ISTF,J)
   DO 70 I=IST,L2
   DENOM=AP(I,J)-PT(I-1)*AIM(I,J)
   PT(I)=AIP(I,J)/DENOM
   TEMP=CON(I,J)+AJP(I,J)*F(I,J+1)+AJM(I,J)*F(I,J-1)
   QT(I)=(TEMP+AIM(I,J)*QT(I-1))/DENOM
70  END DO
   DO 80 II=IST,L2
   I=IT1-II
80  F(I,J)=F(I+1,J)*PT(I)+QT(I)
90  END DO
   !----------------------------------------------------------------
   DO 190 JJ=JST,M3
   J=JT2-JJ
   PT(ISTF)=0.
   QT(ISTF)=F(ISTF,J)
```

```
    DO 170 I=IST,L2
    DENOM=AP(I,J)-PT(I-1)*AIM(I,J)
    PT(I)=AIP(I,J)/DENOM
    TEMP=CON(I,J)+AJP(I,J)*F(I,J+1)+AJM(I,J)*F(I,J-1)
    QT(I)=(TEMP+AIM(I,J)*QT(I-1))/DENOM
170  END DO
    DO 180 II=IST,L2
    I=IT1-II
180  F(I,J)=F(I+1,J)*PT(I)+QT(I)
190  END DO
    !-----------------------------------------------------------------
    DO 290 I=IST,L2
    PT(JSTF)=0.
    QT(JSTF)=F(I,JSTF)
    DO 270 J=JST,M2
    DENOM=AP(I,J)-PT(J-1)*AJM(I,J)
    PT(J)=AJP(I,J)/DENOM
    TEMP=CON(I,J)+AIP(I,J)*F(I+1,J)+AIM(I,J)*F(I-1,J)
    QT(J)=(TEMP+AJM(I,J)*QT(J-1))/DENOM
270  END DO
    DO 280 JJ=JST,M2
    J=JT1-JJ
280  F(I,J)=F(I,J+1)*PT(J)+QT(J)
290  END DO
    !-----------------------------------------------------------------
```

```
    DO 390 II=IST,L3
    I=IT2-II
    PT(JSTF)=0.
    QT(JSTF)=F(I,JSTF)
    DO 370 J=JST,M2
    DENOM=AP(I,J)-PT(J-1)*AJM(I,J)
    PT(J)=AJP(I,J)/DENOM
    TEMP=CON(I,J)+AIP(I,J)*F(I+1,J)+AIM(I,J)*F(I-1,J)
    QT(J)=(TEMP+AJM(I,J)*QT(J-1))/DENOM
370  END DO
    DO 380 JJ=JST,M2
    J=JT1-JJ
380  F(I,J)=F(I,J+1)*PT(J)+QT(J)
390  END DO
    !-----------------------------------------------------------------
999  END DO
    SELECT CASE(NF)

        CASE(1)
         U = F
        CASE(2)
         V = F
        CASE(3)
         PC = F
        CASE(4)
```

```
    T = F
   CASE(NP)
    P = F
END SELECT
CALL RESET
END SUBROUTINE SOLVE

!=================================================================
!===>   THIS SUBROUTINE RESETS 'ap' AND 'con' TO zero  **********
!=================================================================
SUBROUTINE RESET
USE GLOBAL
IMPLICIT NONE
INTEGER :: I,J
DO J=2,M2
DO I=2,L2
CON(I,J)=0.
AP(I,J)=0.
END DO
END DO
END SUBROUTINE RESET


!=================================================================
```

```
!THIS SUBROUTINE GENERATES THE CONTROL VOLUMES&VARIOUS RELATED-
!===>   GEOMETRICAL PARAMETERS.  ******************************
!===============================================================
SUBROUTINE GEOMET
USE GLOBAL
IMPLICIT NONE
INTEGER :: I,J,IM4,IM5
1 FORMAT(//15X,'COMPUTATION  IN  CARTESIAN  COORDINATES')
2 FORMAT(//15X,'COMPUTATION FOR AXISYMMETRIC SITUATION')
3 FORMAT(//15X,'COMPUTATION   IN   POLAR   COORDINATES')
4 FORMAT(14X,40(1H*),//)
!---------------------------------------------------------------
NRHO=NP+1
NGAM=NRHO+1
L2=L1-1
L3=L2-1
M2=M1-1
M3=M2-1
X(1)=XU(2)
DO 5 I=2,L2
5 X(I)=0.5*(XU(I+1)+XU(I))
X(L1)=XU(L1)
Y(1)=YV(2)
DO 10 J=2,M2
10 Y(J)=0.5*(YV(J+1)+YV(J))
```

```
      Y(M1)=YV(M1)
      DO 15 I=2,L1
15    XDIF(I)=X(I)-X(I-1)
      DO 18 I=2,L2
18    XCV(I)=XU(I+1)-XU(I)
      DO 20 I=3,L2
20    XCVS(I)=XDIF(I)
      XCVS(3)=XCVS(3)+XDIF(2)
      XCVS(L2)=XCVS(L2)+XDIF(L1)
      DO 22 I=3,L3
      XCVI(I)=0.5*XCV(I)
22    XCVIP(I)=XCVI(I)
      XCVIP(2)=XCV(2)
      XCVI(L2)=XCV(L2)
      DO 35 J=2,M1
35    YDIF(J)=Y(J)-Y(J-1)
      DO 40 J=2,M2
40    YCV(J)=YV(J+1)-YV(J)
      DO 45 J=3,M2
45    YCVS(J)=YDIF(J)
      YCVS(3)=YCVS(3)+YDIF(2)
      YCVS(M2)=YCVS(M2)+YDIF(M1)
      IF(MODE.NE.1) GO TO 55
      DO 52 J=1,M1
      RMN(J)=1.0
```

```
52  R(J)=1.0
    GO TO 56
55  DO 50 J=2,M1
50  R(J)=R(J-1)+YDIF(J)
    RMN(2)=R(1)
    DO 60 J=3,M2
60  RMN(J)=RMN(J-1)+YCV(J-1)
    RMN(M1)=R(M1)
56  CONTINUE
    DO 57 J=1,M1
    SX(J)=1.
    SXMN(J)=1.
    IF(MODE.NE.3) GO TO 57
    SX(J)=R(J)
    IF(J.NE.1) SXMN(J)=RMN(J)
57  END DO
    DO 62 J=2,M2
    YCVR(J)=R(J)*YCV(J)
    ARX(J)=YCVR(J)
    IF(MODE.NE.3) GO TO 62
    ARX(J)=YCV(J)
62  END DO
    DO 64 J=4,M3
64  YCVRS(J)=0.5*(R(J)+R(J-1))*YDIF(J)
    YCVRS(3)=0.5*(R(3)+R(1))*YCVS(3)
```

```
      YCVRS(M2)=0.5*(R(M1)+R(M3))*YCVS(M2)
      IF(MODE.NE.2) GO TO 67
      DO 65 J=3,M3
      ARXJ(J)=0.25*(1.+RMN(J)/R(J))*ARX(J)
65    ARXJP(J)=ARX(J)-ARXJ(J)
      GO TO 68
67    DO 66 J=3,M3
      ARXJ(J)=0.5*ARX(J)
66    ARXJP(J)=ARXJ(J)
68    ARXJP(2)=ARX(2)
      ARXJ(M2)=ARX(M2)
      DO 70 J=3,M3
      FV(J)=ARXJP(J)/ARX(J)
70    FVP(J)=1.-FV(J)
      DO 85 I=3,L2
      FX(I)=0.5*XCV(I-1)/XDIF(I)
85    FXM(I)=1.-FX(I)
      FX(2)=0.
      FXM(2)=1.
      FX(L1)=1.
      FXM(L1)=0.
      DO 90 J=3,M2
      FY(J)=0.5*YCV(J-1)/YDIF(J)
90    FYM(J)=1.-FY(J)
      FY(2)=0.
```

```
      FYM(2)=1.
      FY(M1)=1.
      FYM(M1)=0.
      !--------------------------------------------------------------
      IM4=M1-3
      IM5=M1-4
117  FORMAT(5E10.4)
      IF(MODE.EQ.1) PRINT 1
      IF(MODE.EQ.2) PRINT 2
      IF(MODE.EQ.3) PRINT 3
      PRINT 4
      END SUBROUTINE GEOMET
      !=================================================================
      !****** THIS SUBROUTINE FORMS COEFFS. FOR DISCRETISATION EQNS. **
      !=================================================================
      SUBROUTINE COEFF
      USE GLOBAL
      IMPLICIT NONE
      INTEGER :: I,J,K,N
      REAL :: ZERO,REL,FL,FLM,FLM1,FLP,GM,GM1,GMM,GH,VOL,APT,AREA
      REAL :: SXT,SXB,ARHO,TMX,UMX,VMX,DELT,DELU,DELV !,BTIME
      REAL::APT1,APT2
      !COEFFICIENTS FOR THE U EQUATION.
      ITERL=1
      ZERO=0.0
```

```
      LCONV = .FALSE.
 99  CONTINUE
      CALL RESET
      !-----------------------------------------------------------------
      NF=1
      IF(.NOT.LSOLVE(NF)) GO TO 500
      IST=3
      JST=2
      CALL GAMSOR
      REL=1.-RELAX(NF)
      DO 102 I=3,L2
      FL=XCVI(I)*V(I,2)*RHO(I,1)
      FLM=XCVIP(I-1)*V(I-1,2)*RHO(I-1,1)
      FLOW=R(1)*(FL+FLM)
      DIFF=R(1)*(XCVI(I)*GAM(I,1)+XCVIP(I-1)*GAM(I-1,1))/YDIF(2)
      CALL DIFLOW
102  AJM(I,2)=ACOF+AMAX1(ZERO,FLOW)
      DO 103 J=2,M2
      FLOW=ARX(J)*U(2,J)*RHO(1,J)
      DIFF=ARX(J)*GAM(1,J)/(XCV(2)*SX(J))
      CALL DIFLOW
      AIM(3,J)=ACOF+AMAX1(ZERO,FLOW)
      DO 103 I=3,L2
      IF(I.EQ.L2) GO TO 104
      FL=U(I,J)*(FX(I)*RHO(I,J)+FXM(I)*RHO(I-1,J))
```

```
      FLP=U(I+1,J)*(FX(I+1)*RHO(I+1,J)+FXM(I+1)*RHO(I,J))
      FLOW=ARX(J)*0.5*(FL+FLP)
      DIFF=ARX(J)*GAM(I,J)/(XCV(I)*SX(J))
      GO TO 105
104   FLOW=ARX(J)*U(L1,J)*RHO(L1,J)
      DIFF=ARX(J)*GAM(L1,J)/(XCV(L2)*SX(J))
105   CALL DIFLOW
      AIM(I+1,J)=ACOF+AMAX1(ZERO,FLOW)
      AIP(I,J)=AIM(I+1,J)-FLOW
      IF(J.EQ.M2) GO TO 106
      FL=XCVI(I)*V(I,J+1)*(FY(J+1)*RHO(I,J+1)+FYM(J+1)*RHO(I,J))
      FLM1=XCVIP(I-1)*V(I-1,J+1)
      FLM=FLM1*(FY(J+1)*RHO(I-1,J+1)+FYM(J+1)*RHO(I-1,J))
      GM1=GAM(I,J)*GAM(I,J+1)
      GM=GM1/(YCV(J)*GAM(I,J+1)+YCV(J+1)*GAM(I,J)+1.0E-30)*XCVI(I)
      GH=GAM(I-1,J)*GAM(I-1,J+1)
     GMM=GH/(YCV(J)*GAM(I-1,J+1)+YCV(J+1)*GAM(I-1,J)+1.E-30)*XCVIP(I-1)
      DIFF=RMN(J+1)*2.*(GM+GMM)
      GO TO 107
106   FL=XCVI(I)*V(I,M1)*RHO(I,M1)
      FLM=XCVIP(I-1)*V(I-1,M1)*RHO(I-1,M1)
      DIFF=R(M1)*(XCVI(I)*GAM(I,M1)+XCVIP(I-1)*GAM(I-1,M1))/YDIF(M1)
107   FLOW=RMN(J+1)*(FL+FLM)
      CALL DIFLOW
      AJM(I,J+1)=ACOF+AMAX1(ZERO,FLOW)
```

```
    AJP(I,J)=AJM(I,J+1)-FLOW
    VOL=YCVR(J)*XCVS(I)
    APT=(RHO(I,J)*XCVI(I)+RHO(I-1,J)*XCVIP(I-1))/(XCVS(I)*DT)
    AP(I,J)=AP(I,J)-APT
    CON(I,J)=CON(I,J)+APT*UO(I,J)
    AP2(I,J)=(-AP(I,J)*VOL+AIP(I,J)+AIM(I,J)+AJP(I,J)+AJM(I,J))
    AP(I,J)=AP2(I,J)/RELAX(NF)
    !porous update
            const=1.e3 !1.6e6 !
           !-----source term
            epmean = fx(i)*epsi(i,j) + fxm(i)*epsi(i-1,j)
            ap(i,j)=ap(i,j)+1.*const*(1.-epmean)*vol* &
                    & (1.-epmean)/(epmean*epmean*epmean+1.e-6)
     !--------------------
          CON(I,J)=CON(I,J)*VOL+REL*AP(I,J)*U(I,J)
    DU(I,J)=VOL/(XDIF(I)*SX(J))
    DU(I,J)=DU(I,J)/AP(I,J)
103  CONTINUE
    COFU(:,:,1) = CON(:,:)
    COFU(:,:,2) = AIP(:,:)
    COFU(:,:,3) = AIM(:,:)
    COFU(:,:,4) = AJP(:,:)
    COFU(:,:,5) = AJM(:,:)
    COFU(:,:,6) = AP(:,:)
    !-------------------------------------------------------------
```

```
      !COEFFICIENTS FOR THE  V  EQUATION.
      NF=2
      CALL RESET
      IST=2
      JST=3
      CALL GAMSOR
      REL=1.-RELAX(NF)
      DO 202 I=2,L2
      AREA=R(1)*XCV(I)
      FLOW=AREA*V(I,2)*RHO(I,1)
      DIFF=AREA*GAM(I,1)/YCV(2)
      CALL DIFLOW
202   AJM(I,3)=ACOF+AMAX1(ZERO,FLOW)
      DO 203 J=3,M2
      FL=ARXJ(J)*U(2,J)*RHO(1,J)
      FLM=ARXJP(J-1)*U(2,J-1)*RHO(1,J-1)
      FLOW=FL+FLM
      DIFF=(ARXJ(J)*GAM(1,J)+ARXJP(J-1)*GAM(1,J-1))/(XDIF(2)*SXMN(J))
      CALL DIFLOW
      AIM(2,J)=ACOF+AMAX1(ZERO,FLOW)
      DO 203 I=2,L2
      IF(I.EQ.L2) GO TO 204
      FL=ARXJ(J)*U(I+1,J)*(FX(I+1)*RHO(I+1,J)+FXM(I+1)*RHO(I,J))
      FLM1=ARXJP(J-1)*U(I+1,J-1)
      FLM=FLM1*(FX(I+1)*RHO(I+1,J-1)+FXM(I+1)*RHO(I,J-1))
```

```
      GM1=GAM(I,J)*GAM(I+1,J)
      GM=GM1/(XCV(I)*GAM(I+1,J)+XCV(I+1)*GAM(I,J)+1.E-30)*ARXJ(J)
      GH=GAM(I,J-1)*GAM(I+1,J-1)
     GMM=GH/(XCV(I)*GAM(I+1,J-1)+XCV(I+1)*GAM(I,J-1)+1.E-30)*ARXJP(J-1)
      DIFF=2.*(GM+GMM)/SXMN(J)
      GO TO 205
204   FL=ARXJ(J)*U(L1,J)*RHO(L1,J)
      FLM=ARXJP(J-1)*U(L1,J-1)*RHO(L1,J-1)
     DIFF=(ARXJ(J)*GAM(L1,J)+ARXJP(J-1)*GAM(L1,J-1))/(XDIF(L1)*SXMN(J))
205   FLOW=FL+FLM
      CALL DIFLOW
      AIM(I+1,J)=ACOF+AMAX1(ZERO,FLOW)
      AIP(I,J)=AIM(I+1,J)-FLOW
      IF(J.EQ.M2) GO TO 206
      AREA=R(J)*XCV(I)
      FL=V(I,J)*(FY(J)*RHO(I,J)+FYM(J)*RHO(I,J-1))*RMN(J)
      FLP=V(I,J+1)*(FY(J+1)*RHO(I,J+1)+FYM(J+1)*RHO(I,J))*RMN(J+1)
      FLOW=(FV(J)*FL+FVP(J)*FLP)*XCV(I)
      DIFF=AREA*GAM(I,J)/YCV(J)
      GO TO 207
206   AREA=R(M1)*XCV(I)
      FLOW=AREA*V(I,M1)*RHO(I,M1)
      DIFF=AREA*GAM(I,M1)/YCV(M2)
207   CALL DIFLOW
      AJM(I,J+1)=ACOF+AMAX1(ZERO,FLOW)
```

```
AJP(I,J)=AJM(I,J+1)-FLOW

VOL=YCVRS(J)*XCV(I)

SXT=SX(J)

IF(J.EQ.M2) SXT=SX(M1)

SXB=SX(J-1)

IF(J.EQ.3) SXB=SX(1)

APT1=(ARXJ(J)*RHO(I,J)*0.5*(SXT+SXMN(J)))

APT2=(ARXJP(J-1)*RHO(I,J-1)*0.5*(SXB+SXMN(J)))

APT=(APT1+APT2)/(YCVRS(J)*DT)

AP(I,J)=AP(I,J)-APT

CON(I,J)=CON(I,J)+APT*VO(I,J)

AP2(I,J)=(-AP(I,J)*VOL+AIP(I,J)+AIM(I,J)+AJP(I,J)+AJM(I,J))

AP(I,J)=AP2(I,J)/RELAX(NF)

                    const=1.e3 !1.6e6 !

          !porous update

          !-----source term

            epmean = fy(i)*epsi(i,j) + fym(i)*epsi(i-1,j)

            ap(i,j)=ap(i,j)+1.*const*(1.-epmean)*vol* &

                     & (1.-epmean)/(epmean*epmean*epmean+1.e-6)

         CON(I,J)=CON(I,J)*VOL+REL*AP(I,J)*V(I,J)

DV(I,J)=VOL/YDIF(J)

DV(I,J)=DV(I,J)/AP(I,J)

203  CONTINUE

 COFV(:,:,1) = CON(:,:)

 COFV(:,:,2) = AIP(:,:)
```

```
 COFV(:,:,3) = AIM(:,:)
 COFV(:,:,4) = AJP(:,:)
 COFV(:,:,5) = AJM(:,:)
 COFV(:,:,6) = AP(:,:)
 !--------------------------------------------------------------
 !CALCULATE UHAT AND VHAT.
 DO J=2,M2
 DO I=3,L2
UHAT1(I,J)=(COFU(I,J,2)*U(I+1,J)+COFU(I,J,3)*U(I-1,J))
UHAT2(I,J)=(COFU(I,J,4)*U(I,J+1)+COFU(I,J,5)*U(I,J-1)+COFU(I,J,1))
 UHAT(I,J)=(UHAT1(I,J)+UHAT2(I,J))/COFU(I,J,6)
END DO
END DO
DO J=3,M2
DO I=2,L2
      VHAT1(I,J)=(COFV(I,J,2)*V(I+1,J)+COFV(I,J,3)*V(I-1,J))
VHAT2(I,J)=(COFV(I,J,4)*V(I,J+1)+COFV(I,J,5)*V(I,J-1)+COFV(I,J,1))
VHAT(I,J)=(VHAT1(I,J)+VHAT2(I,J))/COFV(I,J,6)
END DO
END DO
!COEFFICIENTS FOR THE PRESSURE EQUATION.
NF=3
CALL RESET
IST=2
JST=2
```

```
      CALL GAMSOR
      DO 410 J=2,M2
      DO 410 I=2,L2
      VOL=YCVR(J)*XCV(I)
410   CON(I,J)=CON(I,J)*VOL
      DO 402 I=2,L2
      ARHO=R(1)*XCV(I)*RHO(I,1)
      CON(I,2)=CON(I,2)+ARHO*V(I,2)
402   AJM(I,2)=0.
      DO 403 J=2,M2
      ARHO=ARX(J)*RHO(1,J)
      CON(2,J)=CON(2,J)+ARHO*U(2,J)
      AIM(2,J)=0.
      DO 403 I=2,L2
      IF(I.EQ.L2) GO TO 404
      ARHO=ARX(J)*(FX(I+1)*RHO(I+1,J)+FXM(I+1)*RHO(I,J))
      FLOW=ARHO*UHAT(I+1,J)
      CON(I,J)=CON(I,J)-FLOW
      CON(I+1,J)=CON(I+1,J)+FLOW
      AIP(I,J)=ARHO*DU(I+1,J)
      AIM(I+1,J)=AIP(I,J)
      GO TO 405
404   ARHO=ARX(J)*RHO(L1,J)
      CON(I,J)=CON(I,J)-ARHO*U(L1,J)
      AIP(I,J)=0.
```

```
405  IF(J.EQ.M2) GO TO 406
     ARHO=RMN(J+1)*XCV(I)*(FY(J+1)*RHO(I,J+1)+FYM(J+1)*RHO(I,J))
     FLOW=ARHO*VHAT(I,J+1)
     CON(I,J)=CON(I,J)-FLOW
     CON(I,J+1)=CON(I,J+1)+FLOW
     AJP(I,J)=ARHO*DV(I,J+1)
     AJM(I,J+1)=AJP(I,J)
     GO TO 407
406  ARHO=RMN(M1)*XCV(I)*RHO(I,M1)
     CON(I,J)=CON(I,J)-ARHO*V(I,M1)
     AJP(I,J)=0.
407  AP(I,J)=AIP(I,J)+AIM(I,J)+AJP(I,J)+AJM(I,J)
403  CONTINUE
     DO 421 J=2,M2
     DO 421 I=2,L2
     AP(I,J)=AP(I,J)/RELAX(NP)
421  CON(I,J)=CON(I,J)+(1.0-RELAX(NP))*AP(I,J)*P(I,J)
     !---------------------------------------------------------------
     COFP(:,:,2) = AIP(:,:)
     COFP(:,:,3) = AIM(:,:)
     COFP(:,:,4) = AJP(:,:)
     COFP(:,:,5) = AJM(:,:)
     !---------------------------------------------------------------
     NF=NP
     CALL SOLVE
```

```
!COMPUTE U* AND V*.
NF=1
IST=3
JST=2
DO 550 K=1,6
DO 550 J=JST,M2
DO 550 I=IST,L2
550  COF(I,J,K)=COFU(I,J,K)
!---------------------------------------------------------------
CON(:,:) = COF(:,:,1)
AIP(:,:) = COF(:,:,2)
AIM(:,:) = COF(:,:,3)
AJP(:,:) = COF(:,:,4)
AJM(:,:) = COF(:,:,5)
AP(:,:) = COF(:,:,6)
!---------------------------------------------------------------
DO 551 J=JST,M2
DO 551 I=IST,L2
551   CON(I,J)=CON(I,J)+DU(I,J)*AP(I,J)*(P(I-1,J)-P(I,J))
CALL SOLVE
NF=2
IST=2
JST=3
DO 552 K=1,6
DO 552 J=JST,M2
```

```
      DO 552 I=IST,L2
552   COF(I,J,K)=COFV(I,J,K)
      !------------------------------------------------------------
      CON(:,:) = COF(:,:,1)
      AIP(:,:) = COF(:,:,2)
      AIM(:,:) = COF(:,:,3)
      AJP(:,:) = COF(:,:,4)
      AJM(:,:) = COF(:,:,5)
      AP(:,:) = COF(:,:,6)
      !------------------------------------------------------------
      DO 553 J=JST,M2
      DO 553 I=IST,L2
553   CON(I,J)=CON(I,J)+DV(I,J)*AP(I,J)*(P(I,J-1)-P(I,J))
      CALL SOLVE
      !COEFFICIENTS FOR THE PRESSURE CORRECTION EQUATION.
      NF=3
      CALL RESET
      IST=2
      JST=2
      DO 554 K=2,5
      DO 554 J=JST,M2
       DO 554 I=IST,L2
554    COF(I,J,K)=COFP(I,J,K)
       !-----------------------------------------------------------
          AIP(:,:) = COF(:,:,2)
```

```
        AIM(:,:) = COF(:,:,3)
        AJP(:,:) = COF(:,:,4)
        AJM(:,:) = COF(:,:,5)
    !-----------------------------------------------------------------
    CALL GAMSOR
    SMAX=0.
    SSUM=0.
    DO 510 J=2,M2
    DO 510 I=2,L2
    VOL=YCVR(J)*XCV(I)
510  CON(I,J)=CON(I,J)*VOL
    DO 502 I=2,L2
    ARHO=R(1)*XCV(I)*RHO(I,1)
    CON(I,2)=CON(I,2)+ARHO*V(I,2)
502  END DO
    DO 503 J=2,M2
    ARHO=ARX(J)*RHO(1,J)
    CON(2,J)=CON(2,J)+ARHO*U(2,J)
    DO 503 I=2,L2
    IF(I.EQ.L2) GO TO 504
    ARHO=ARX(J)*(FX(I+1)*RHO(I+1,J)+FXM(I+1)*RHO(I,J))
    FLOW=ARHO*U(I+1,J)
    CON(I,J)=CON(I,J)-FLOW
    CON(I+1,J)=CON(I+1,J)+FLOW
    GO TO 505
```

```
504  ARHO=ARX(J)*RHO(L1,J)
     CON(I,J)=CON(I,J)-ARHO*U(L1,J)
505  IF(J.EQ.M2) GO TO 506
     ARHO=RMN(J+1)*XCV(I)*(FY(J+1)*RHO(I,J+1)+FYM(J+1)*RHO(I,J))
     FLOW=ARHO*V(I,J+1)
      CON(I,J)=CON(I,J)-FLOW
      CON(I,J+1)=CON(I,J+1)+FLOW
      GO TO 507
506   ARHO=RMN(M1)*XCV(I)*RHO(I,M1)
      CON(I,J)=CON(I,J)-ARHO*V(I,M1)
507   AP(I,J)=AIP(I,J)+AIM(I,J)+AJP(I,J)+AJM(I,J)
      PC(I,J)=0.
      SMAX=AMAX1(SMAX,ABS(CON(I,J)))
      SSUM=SSUM+CON(I,J)
503   CONTINUE
      CALL SOLVE
      !COME HERE TO CORRECT THE VELOCITIES.
      DO 521 J=2,M2
      DO 521 I=2,L2
      IF(I.NE.2) U(I,J)=U(I,J)+DU(I,J)*(PC(I-1,J)-PC(I,J))
      IF(J.NE.2) V(I,J)=V(I,J)+DV(I,J)*(PC(I,J-1)-PC(I,J))
521   CONTINUE
500   CONTINUE
      !COEFFICIENTS FOR OTHER EQUATIONS.
      CALL RESET
```

```
      IST=2
      JST=2
      DO 600 N=4,NFMAX
      NF=N
      IF(.NOT.LSOLVE(NF)) GO TO 600
      CALL GAMSOR
!
      REL=1.-RELAX(NF)
      DO 602 I=2,L2
      AREA=R(1)*XCV(I)
      FLOW=AREA*V(I,2)*RHO(I,1)
      DIFF=AREA*GAM(I,1)/YDIF(2)
      CALL DIFLOW
602   AJM(I,2)=ACOF+AMAX1(ZERO,FLOW)
      DO 603 J=2,M2
      FLOW=ARX(J)*U(2,J)*RHO(1,J)
      DIFF=ARX(J)*GAM(1,J)/(XDIF(2)*SX(J))
      CALL DIFLOW
      AIM(2,J)=ACOF+AMAX1(ZERO,FLOW)
      DO 603 I=2,L2
      IF(I.EQ.L2) GO TO 604
      FLOW=ARX(J)*U(I+1,J)*(FX(I+1)*RHO(I+1,J)+FXM(I+1)*RHO(I,J))
      DIFF1=ARX(J)*2.*GAM(I,J)*GAM(I+1,J)
      DIFF=DIFF1/((XCV(I)*GAM(I+1,J)+XCV(I+1)*GAM(I,J)+1.0E-30)*SX(J))
      GO TO 605
```

```
604  FLOW=ARX(J)*U(L1,J)*RHO(L1,J)
     DIFF=ARX(J)*GAM(L1,J)/(XDIF(L1)*SX(J))
605  CALL DIFLOW
     AIM(I+1,J)=ACOF+AMAX1(ZERO,FLOW)
     AIP(I,J)=AIM(I+1,J)-FLOW
     AREA=RMN(J+1)*XCV(I)
     IF(J.EQ.M2) GO TO 606
     FLOW=AREA*V(I,J+1)*(FY(J+1)*RHO(I,J+1)+FYM(J+1)*RHO(I,J))
     DIFF1=AREA*2.*GAM(I,J)*GAM(I,J+1)
     DIFF=DIFF1/(YCV(J)*GAM(I,J+1)+YCV(J+1)*GAM(I,J)+1.0E-30)
     GO TO 607
606  FLOW=AREA*V(I,M1)*RHO(I,M1)
     DIFF=AREA*GAM(I,M1)/YDIF(M1)
607  CALL DIFLOW
     AJM(I,J+1)=ACOF+AMAX1(ZERO,FLOW)
      AJP(I,J)=AJM(I,J+1)-FLOW
603  CONTINUE
     !--------------------------------------------------------------
     DO 349 I=1,L1
     DO 349 J=1,M1
     VOL=YCVR(J)*XCV(I)
     APT=RHO(I,J)/DT
     AP(I,J)=AP(I,J)-APT
     IF(NF.EQ.4) CON(I,J)=CON(I,J)+APT*TO(I,J)
     AP1(I,J)=(-AP(I,J)*VOL+AIP(I,J)+AIM(I,J)+AJP(I,J)+AJM(I,J))
```

```
      AP(I,J)=AP1(I,J)/RELAX(NF)

      IF(NF.EQ.4) CON(I,J)=CON(I,J)*VOL+REL*AP(I,J)*T(I,J)

      IF(NF.EQ.NP) CON(I,J)=CON(I,J)*VOL+REL*AP(I,J)*P(I,J)

      !-----------------------------------------------------------------

            IF(NF.EQ.4) TOLD(I,J)=T(I,J)

      !-----------------------------------------------------------------

   349  CONTINUE

      !________________________m_________________________________________________

!**************************************************************************

!**************************************************************************

          if (nf.eq.4) then          !enthalpy-porosity-source-term

!print*,nf

    ! arelax=0.05

    do i=2,l2 !2,l2

            do j=2,m2 !2,m2           m


            vol=ycv(j)*xcv(i)*1.0

            ap0(i,j)=rho(i,j)*vol/dt

            delh(i,j)=delh(i,j)+(ap(i,j)*cp*arelax*(t(i,j)-tmelt))/ap0(i,j)

            !prevent overshoot or undershoot

            if(delh(i,j).le.0.) delh(i,j)=0.0

           if(delh(i,j).gt.alatent) delh(i,j)=alatent

       epsi(i,j)=delh(i,j)/alatent

            !con(i,j)=con(i,j)-rho(i,j)*(delh(i,j)*epsi(i,j)-delho(i,j)*epsio(i,j))/(cp(i,j)*dt)

            !IF(epsi(i,j).le.0.0)epsi(i,j)=0.000001
```

```
    enddo

    enddo

         endif     !enthalpy-porosity-source-term

!**************************************************************************

!**************************************************************************


           CALL SOLVE

     !---------------------------------------------------------------

 600  END DO


     !CONVERGENCE CRITERIA.

         TMX = MAXVAL(ABS(T))

         UMX = MAXVAL(ABS(U))

         VMX = MAXVAL(ABS(V))

         RHOMX = MAXVAL(ABS(RHO))


         DELT = MAXVAL(ABS(T-TOLD))

         DELU = MAXVAL(ABS(U-UOLD))

         DELV = MAXVAL(ABS(V-VOLD))


         IF(TMX.GT.0.) THEN

         DELTMX=DELT/TMX

         ELSE

         DELTMX=0.

         END IF
```

```
      IF(UMX.GT.0.) THEN
      DELUMX=DELU/UMX
      ELSE
      DELUMX=0.
      END IF
      IF(VMX.GT.0.) THEN
      DELVMX=DELV/VMX
      ELSE
      DELVMX=0.
      END IF
      IF(TIME.LT.TLAST) THEN
  WRITE(*,*)'TIME=',TIME,'ITERL=',ITERL,'TMX=',TMX
  WRITE(*,*)'UMX=',UMX,'VMX=',VMX,'RHOMX=',RHOMX
  ! 678 FORMAT(f10.5,1x,i6,1x,3f15.8)
  ! WRITE(*,*)'\n','TIME=',TIME,'ITERL=',ITERL,'TMX=',TMX, &
  !       & 'UMX=',UMX,'VMX=',VMX
  !     WRITE(*,*)'\n',ITERL,'TMX=',TMX,'DELT=',DELTMX, &
  !     & 'UMX=',UMX,'DELU=',DELUMX,'VMX=',VMX,'DELV=',DELVMX
      END IF

 !    IF(ITERL.GT.100) THEN
      IF((DELT.LT.ERT).AND.(DELU.LT.ERU).AND.(DELV.LT.ERV)) THEN
        LCONV=.TRUE.
      END IF
 !      END IF
```

```
        IF(LCONV) GOTO 59
        IF(DELTMX.GT.ERT) GOTO 51
        IF(DELUMX.GT.ERU) GOTO 51
        IF(DELVMX.GT.ERV) GOTO 51
        GOTO 59
51  IF(ITERL.EQ.ISTP) THEN
         WRITE(*,*)'EXCEEDED MAX. NO. OF ITERATIONS'
         GOTO 59
         STOP
        ENDIF
40  FORMAT(I5,6F10.6,2X,2F12.4)
        ITERL=ITERL+1
        DO I=2,L1
        DO J=2,M1
      UOLD(I,J)=U(I,J)
      VOLD(I,J)=V(I,J)
    END DO
        END DO
        CALL BOUND
        GOTO 99
59  ITLL=ITLL+1
        !!BTIME=TIME+DT
        TIME=TIME+DT
    iTimeStep=iTimeStep+1
      !index=0
```

```
  if(mod(itimeStep,10)==0) then
      index=index+1
      ptime(index)=time
  !ptime(0)=0.0
  !uu(0)=0.0
  !vv(0)=0.0
  uu(index)=u(38,5)
      vv(index)=v(38,5)
      tt(index)=t(38,5)
      endif
      !tt(0)=TINITIAL
  !=============================================================
IF (mod(iTimeStep,100)==0) THEN
!IF(TIME.GE.TLAST) THEN
CALL VECT_PLOT
      CALL PRINTOUT
END IF


!=============================================================
     !!CALL ENRBAL
     !!ITER=ITER+1
     CALL BOUND
 IF(TIME.GE.TLAST) LSTOP=.TRUE.
     DO I=2,L1
     DO J=2,M1
```

```
        UOLD(I,J)=U(I,J)
        VOLD(I,J)=V(I,J)
      END DO
      END DO
END SUBROUTINE COEFF
!===============================================================
!=THIS SUBROUTINE STORES INITIAL VALUES FOR THE COMING TIMESTEP
!===============================================================
SUBROUTINE OLDVAL
USE GLOBAL
IMPLICIT NONE
INTEGER :: I,J
DO I=1,L1
DO J=1,M1
TO(I,J)=T(I,J)
TOLD(I,J)=T(I,J)
UO(I,J)=U(I,J)
VO(I,J)=V(I,J)
 epsio(i,j)=epsi(i,j)
          delho(i,j)=delh(i,j)
                    epsi(i,j)=epsiinitial
 END DO
 END DO
 END SUBROUTINE OLDVAL
```

```
!==============================================================
!===>   THIS SUBROUTINE GENERATES UNIFORM GRID *****************
!==============================================================
      SUBROUTINE UGRID
      USE GLOBAL
      IMPLICIT NONE
      INTEGER :: I,J
      REAL :: DX,DY
      XU(2)=0.
      DX=XL/FLOAT(L1-2)
      DO 1 I=3,L1
 1    XU(I)=XU(I-1)+DX
      YV(2)=0.
      DY=YL/FLOAT(M1-2)
      DO 2 J=3,M1
 2    YV(J)=YV(J-1)+DY
      END SUBROUTINE UGRID
!==============================================================
!===>   THIS SUBROTINE CHECKS OVERALL ENERGY BALANCE  **********
!==============================================================
      SUBROUTINE ENRBAL
      USE GLOBAL
      IMPLICIT NONE
      END SUBROUTINE ENRBAL
```

```
 !==============================================================
!THIS SUBROUTINE DIRECTLY GIVES MATLAB PLOTS OF PROBLEM VARIABLES
!================================================================
 SUBROUTINE PRINTOUT    !!!! Postprocessing
 USE GLOBAL
 CHARACTER :: FNAME*20
 !OUPUT IN MATLAB FORMAT:
! OPEN(UNIT=OUT,FILE="output.m")
 integer:: out
 out=REAL(itimestep)*DT
 write(fname,7000) out
7000   format('validation',i5.5,'.m')
 open(unit=out,file=fname,form="formatted")
 write(*,*)"file=",fname
 !!********
   !!tt(0)=TINITIAL
 WRITE(*,*)"CURRENT TIME IS",TIME
 WRITE(OUT,*) "x=["
  DO I=1,L1
 WRITE(OUT,*) X(I)
 END DO
 WRITE(OUT,*)"];"
 WRITE(OUT,*) "y=["
 DO J=1,M1
 WRITE(OUT,*) Y(J)
```

```
END DO
WRITE(OUT,*)"];"
    !FOR ISOTHERMAL CONTOURS:
WRITE(OUT,*) "t=["
DO I=1,L1
WRITE(OUT,111) (T(I,J),J=1,M1),";"
111 FORMAT(<M1>(f15.8),1a)
      !111  FORMAT(' ',(f15.8),1a)
END DO
WRITE(OUT,*)"];"
WRITE(OUT,*)"cs=contour(y,x,t);"
WRITE(OUT,*)"clabel(cs);"
WRITE(OUT,*)"xlabel('Distance along Y-axis (m)')"
WRITE(OUT,*)"ylabel('Distance along X-axis (m)')"
!WRITE(109,*)"grid on"
WRITE(OUT,*)"title('Isotherms plot');"
!FOR VELOCITY VECTOR FIELD:
WRITE(OUT,*) "u=["
DO I=1,L1
WRITE(OUT,111) (Ui(I,J),J=1,M1),";"
END DO
WRITE(OUT,*)"];"
WRITE(OUT,*) "v=["
DO I=1,L1
WRITE(OUT,111) (Vi(I,J),J=1,M1),";"
```

```
END DO
WRITE(OUT,*)"];"
WRITE(OUT,*)"figure(2);"
WRITE(OUT,*)"quiver(y,x,v,u);"
WRITE(OUT,*)"xlabel('Distance along Y-axis (m)')"
WRITE(OUT,*)"ylabel('Distance along X-axis (m)')"
!WRITE(109,*)"grid on"
WRITE(OUT,*)"title('Velocity vector plot');"
!***********************************************************
write(out,*) "time=["
    do j=1,index
    write(out,*) ptime(j),";"
    end do
    write(out,*) "];"
 write(out,*) "uu=["
    do j=1,index
    write(out,*) uu(j)*1000,";"
    end do
    write(out,*) "];"
    write(out,*) "tt=["
    do j=1,index
    write(out,*) tt(j),";"
    end do
    write(out,*) "];"
    write(out,*) "figure(3);"
```

```
   write(out,*) "plot(time,uu);"

   write(out,*) "hold on"

   write(out,*) "plot(time,tt);"

   WRITE(out,*)"xlabel('Time (s)');"

   WRITE(out,*)"ylabel('V-Velocity (mm/s)');"


         !******************************************


                  WRITE(out,*) "epsi=["

DO I=1,L1

  WRITE(out,111) (epsi(I,J),J=1,M1),";"

  !111 FORMAT(<L1>(f15.8),1a)

END DO

WRITE(out,*)"];"

         WRITE(out,*)"figure(4);"

WRITE(out,*)"cs=contour(y,x,epsi);"

WRITE(out,*)"clabel(cs);"

WRITE(out,*)"xlabel('Distance along Y-axis (m)')"

WRITE(out,*)"ylabel('Distance along X-axis (m)')"

!WRITE(out,*)"grid on"

WRITE(out,*)"title('Liquid fraction plot');"

         WRITE(out,*)"figure(5);"

         write(out,*)" pcolor(y,x,epsi);"

          WRITE(out,*)"xlabel('Distance along X-axis (m)')"

WRITE(out,*)"ylabel('Distance along Y-axis (m)')"
```

```
!WRITE(out,*)"grid on"
WRITE(out,*)"title('Liquid fraction plot');"
        write(out,*)"shading interp;colorbar"
  CLOSE(OUT)
  END SUBROUTINE PRINTOUT


  !===============================================================
  !===>   USER PART BEGINS HERE **********************************
  !===============================================================
  !THIS SUBROUTINE INITIALISES DIFFERENT VARIABLES AND READS
  !===>  INPUT DATA.  ********************************************
  !===============================================================
  SUBROUTINE GRID
  USE GLOBAL
  IMPLICIT NONE
  INTEGER :: I,J
  IPREF=1
  JPREF=1
  MODE=1
  RELAX = 0.5
  RELAX(1)=0.5
  RELAX(2)=0.5
  RELAX(3)=0.6
  RELAX(4)=0.9
  LSOLVE = .FALSE.
```

```
LSOLVE(1)=.FALSE. !.TRUE. !

LSOLVE(2)=.FALSE. !.TRUE.   !

LSOLVE(3)=.FALSE. !.TRUE. !

LSOLVE(4)=.TRUE.

LSOLVE(6)=.FALSE.

LSOLVE(11)=.FALSE. !.TRUE.  !

LSTOP=.FALSE.

 DO I=1,NFX3

 NTIMES(I)=1

 LBLK(I)=.FALSE.

 END DO

 TIME=0.

 TITLE(1)='UVEL'

 TITLE(2)='VVEL'

 TITLE(4)='TEMP'

 !=================================================================

 !********************* INPUT DATA HERE ***********************

 XL=0.05        ; YL=0.130          ; L1=NI       ; M1=NJ

 NTIME=1        ; NGRID=1           ; ISTP=1000

 RHOCON=923.0    ; TK=0.2325          ; CP=2515.0    ;TCOLD=0.0

 RHOREF=923.0    ; VISCOSITY=1.81E-3   ; G=9.81       ; BETA=1.05E-4

 TINT=22.0       ; THOT=50.0          ; DT=2        ; TLAST=90000.0

 ERU=0.0001      ; ERV=0.0001         ; ERT=0.0001   ; TINITIAL=22.0

 TREF=29.0      ; arelax=0.05       ; TMELT=29.0            ; alatent=194000

          epsiinitial=0.0
```

```
!=============================================================
ITER=0
R(1)=0.0
CALL UGRID
!CON,AP,U,V,RHO,PC AND P ARRAYS ARE INITIALIZED HERE
DO J=1,M1
DO I=1,L1
U(I,J)=0.
 V(I,J)=0.
 PC(I,J)=0.
 T(I,J)=TINITIAL !0.
 P(I,J)=0.
 RHO(I,J)=RHOCON
  DU(I,J)=0.
   DV(I,J)=0.
    UOLD(I,J)=0.
    VOLD(I,J)=0.
    AIP(I,J)=0.
   AIM(I,J)=0.
  AJM(I,J)=0.
 AJP(I,J)=0.
CON(I,J)=0.
AP(I,J)=0.
AP0(I,J)=0.
AP1(I,J)=0.
```

```
TOLD(I,J)=0.
END DO
END DO
COFU = 0.0
COFV = 0.0
COF = 0.0
COFP = 0.0
END SUBROUTINE GRID

!===============================================================
!=THIS SUBROUTINE GIVES INITIAL CONDITIONS FOR THE PROBLEM *****
!===============================================================
SUBROUTINE START
USE GLOBAL
IMPLICIT NONE
INTEGER :: I,J
DO I=1,L1
DO J=1,M1
U(I,J)=0.0
V(I,J)=0.0
T(I,J)=TINITIAL
TOLD(I,J)=T(I,J)
TO(I,J)=T(I,J)
RHO(I,J)=RHOCON
        delh(I,J)=0.0
```

```
index=0
END DO
END DO
END SUBROUTINE START
!===============================================================
!===>    THIS SUBROUTINE CALCULATES THE DENSITY ****************
!===============================================================
SUBROUTINE DENSE
USE GLOBAL
IMPLICIT NONE
INTEGER :: I,J
DO I=1,L1
DO J=1,M1
!IF(T(I,J).LE.10)THEN
!RHO(I,J)=106.273748*(TO(I,J)+273.15)-7218.26287 &
!& -0.517050664*(TO(I,J)+273.15)**2 &
!& +0.0011246302*(TO(I,J)+273.15)**3 &
!& -9.25648144*1E-7*(TO(I,J)+273.15)**4
!ELSE
RHO(I,J)=RHOCON
!END IF
END DO
END DO
END SUBROUTINE DENSE
```

```
!=================================================================
!=THIS SUBROUTINE GIVES BOUNDARY CONDITIONS FOR THE PROBLEM ****
!=================================================================
SUBROUTINE BOUND
USE GLOBAL
IMPLICIT NONE
INTEGER :: I,J
!VELOCITY BOUNDARY CONDITIONS
DO J=1,M1
 U(2,J)=0.0   !bottom
 U(L1,J)=0.0  !top
 END DO
 DO J=2,M1
 V(1,J)=0.0    !bottom
 V(L1,J)=0.0   !top
 END DO
 DO I=2,L1
 U(I,1)=0.0   !right
 U(I,M1)=0.0  !left
 END DO
 DO I=1,L1
 V(I,2)=0.0   !right
 V(I,M1)=0.0  !left
 END DO
```

```
!TEMPERATURE BOUNDARY CONDITIOMS
DO J=1,M1
T(1,J)=T(2,J) !THOT !T(2,J)      !bottom
CALL TOPTEMP
                 T(L1,J)=tamb(L1,J)    !top
END DO
DO I=1,L1
T(I,1)=T(I,2)  !right
T(I,M1)=T(I,M2)      !left
END DO
END SUBROUTINE BOUND
!===========================================================
!===>   THIS SUBROUTINE GIVES DIFF. COEFF.& SOURCE TERMS FOR
!===>   DISCRETISED EQNS.  ************************************
!===========================================================
SUBROUTINE GAMSOR
USE GLOBAL
IMPLICIT NONE
INTEGER :: I,J
REAL :: TMEAN !,TMIN
 IF(NF.LE.2) THEN
 DO J=1,M1
 DO I=1,L1
 GAM(I,J)=VISCOSITY
 END DO
```

```
END DO
END IF
IF(NF.EQ.1) THEN
DO J=1,M1
    DO I= 1,L1
          ! TMEAN=FY(J)*T(I,J)+FYM(J)*T(I,J-1)
           TMEAN=FX(I)*T(I,J)+FXM(I)*T(I-1,J)
    CON(I,J)=RHOREF*G*BETA*(TMEAN-TMELT)
    !! Source term for accounting free convection
          END DO
    END DO
END IF
IF(NF.EQ.4) THEN
 DO J=1,M1
 DO I=1,L1
 GAM(I,J)=TK/CP
                con(i,j)=con(i,j)-rho(i,j)*(delh(i,j)*epsi(i,j)-delho(i,j)*epsio(i,j))/(cp*dt)
 END DO
 END DO
END IF
END SUBROUTINE GAMSOR
```

```
!===========================================================
!===>   THIS SUBROUTINE FOR VECTOR PLOT  ********************
!===========================================================
SUBROUTINE VECT_PLOT
USE GLOBAL
IMPLICIT NONE
INTEGER :: I,J
!INTERNAL GRID POINTS
 DO J=2,M2
 DO I=2,L2
 Ui(I,J)=(U(I,J)+U(I+1,J))/2.0
 Vi(I,J)=(V(I,J)+V(I,J+1))/2.0
 END DO
 END DO
 !LEFT BOUNDARY (EXCLUDING CORNER GRIDS)
 DO J=2,M2
  Ui(1,J)=U(2,J)
  Vi(1,J)=(V(1,J)+V(1,J+1))/2.0
   END DO
!BOTTOM BOUNDARY (EXCLUDING CORNER GRIDS)
DO I=2,L2
Ui(I,1)=(U(I,1)+U(I+1,1))/2.0
Vi(I,1)=V(I,2)
END DO
```

```
!RIGHT BOUNDARY (EXCLUDING CORNER POINTS)
DO J=2,M2
Ui(L1,J)=U(L1,J)
Vi(L1,J)=(V(L1,J)+V(L1,J+1))/2.0
END DO
!TOP BOUNDARY (EXCLUDING CORNER POINTS)
DO I=2,L2
 Ui(I,M1)=(U(I,M1)+U(I+1,M1))/2.0
 Vi(I,M1)=V(I,M1)
END DO
! ALL CORNER POINTS
!LEFT  BOTTOM CORNER POINT
Ui(1,1)=U(2,1)
Vi(1,1)=V(1,2)
!LEFT TOP CORNER POINT
Ui(1,M1)=U(2,M1)
Vi(1,M1)=V(1,M1)
!RIGHT BOTTOM CORNER POINT
Ui(L1,1)=U(L1,1)
Vi(L1,1)=V(L1,2)
!RIGHT TOP CORNER POINT
Ui(L1,M1)=U(L1,M1)
Vi(L1,M1)=V(L1,M1)
END SUBROUTINE VECT_PLOT
```

```
!*****************************************************************

SUBROUTINE TOPTEMP

USE GLOBAL

IMPLICIT NONE

INTEGER :: J

!real::timer

timep=time/60

DO J=1,M1

IF(timep.lt.820)tamb(L1,J)=-5E-05*timep*timep+0.0076*timep+46.659

IF(timep.ge.820.and. timep.lt.825)tamb(L1,J)=-0.02*timep+65.99

IF(timep.ge.825.and. timep.lt.845)tamb(L1,J)=-
0.0166*timep*timep+26.982*timep-10912.25

IF(timep.ge.845.and. timep.lt.850)tamb(L1,J)=-0.08*timep+102.3

IF(timep.ge.850.and. timep.lt.890)tamb(L1,J)=0.0049*timep*timep-
8.7522*timep+3933.8

IF(timep.ge.890.and. timep.lt.895)tamb(L1,J)=-0.02*timep+43.4

IF(timep.ge.895.and. timep.lt.975)tamb(L1,J)=0.0002*timep*timep-
0.4181*timep+239.43

IF(timep.ge.875.and. timep.lt.980)tamb(L1,J)=21.9

IF(timep.ge.980.and. timep.lt.1435)tamb(L1,J)=-3E-
06*timep*timep+0.0048*timep+20.1

IF(timep.ge.1435)tamb(L1,J)=-3E-06*timep*timep+0.0048*timep+20.1


END DO

END SUBROUTINE TOPTEMP
```

```
!==============================================================
!====>   END OF THE CODE *************************************
!==============================================================
!===>    HAVE A NICE TIME ***********************************
!==============================================================
```