Investigation on the Melting Performance of Phase Change Material in a Horizontal Modified Shell and Tube Thermal Energy Storage using Longitudinal Fins

Thesis

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Pantnagar
March, 2022

(Baldev Kumar)
Author

CERTIFICATE-I

This is to certify that the thesis entitled **“Investigation on the Melting Performance of Phase Change Material in a Horizontal Modified Shell and Tube Thermal Energy Storage using Longitudinal Fins’’** submitted in partial fulfillment of the requirements for the degree of **Master of Technology** in Mechanical Engineering with major in **Thermal Engineering** of the College of Post-Graduate Studies, G. B. Pant University of Agriculture and Technology, Pantnagar, is a record of *bona fide* research carried out by **Mr. Baldev Kumar,** Id. No. **55318** under my supervision and no part of the thesis has been submitted for any other degree or diploma.

The assistance and help received during the course of this investigation and source of literature have been duly acknowledged.

(Prashant Verma)
Chairman
Advisory Committee

Pantnagar
March 2022

CERTIFICATE-II

We, the undersigned, members of the Advisory Committee of **Mr. Baldev Kumar,** Id. No. **55318,** a candidate for the degree of **Master of Technology** in Mechanical Engineering with major in **Thermal Engineering**, College of Post-Graduate Studies, G. B. Pant University of Agriculture and Technology, Pantnagar, agree that the thesis entitled **“Investigation on the Melting Performance of Phase Change Material in a Horizontal Modified Shell and Tube Thermal Energy Storage using Longitudinal Fins”** may be submitted in partial fulfillment of the requirements for the degree.

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ABBREVIATIONS

α : Volume of thermal expansivity
β : Volume of liquid fraction
η : Thermal energy storage efficiency
ρ : Density
μ : Dynamic viscosity
C_p : Specific heat capacity
C_{ps} : Specific heat capacity of solid PCM
C_{pl} : Specific heat capacity of liquid PCM
CFD : Computational fluid dynamics
D : Diameter of inner tube
dt : Change in temperature
D : Diameter of outer shell
E : Heat energy storage
Exp : Experimental
E_R : Enhancement ratio
L_f : Liquid fraction
fig : Figure
g : Acceleration due to gravity
H : Enthalpy
ΔH : Latent heat of fusion
HTF : Heat transfer fluid
K : Kelvin
kW : kilo-Watt
LHTES : Latent heat thermal energy storage
LPM : Litre per minute
m : Mass
min : Minute
num : Numerical
M_f : Frozen masses on finned tube
M_{uf} : Frozen masses on un-finned tube
A_f : Surface area of the finned tube

A_{uf} : Surface area of un-finned tube

M_{scf} : Melting fraction of PCM in semi-circular shell with finned tube

M_{sc} : Melt fraction of PCM in semi-circular shell with un-finned tube

N : Number of grids

PCM : Phase change material

Q : Heat storage

R : Radius

T : Temperature

T_i : Initial temperature

T_f : Final temperature

T_m : Melting temperature

T_{pcm} : Temperature of the PCM

Ts : Solidus temperature

T_l : Liquidus temperature

TES : Thermal energy storage

sec : Seconds

St : Stefan number

SHTES : Sensible heat thermal energy storage

Introduction

Chapter 1 INTRODUCTION

Energy conversion is an important aspect of technology advancement and hence its efficient generation and use is important in today’s scenario. It is obvious that the society is very much dependent on energy consumption and its rate is also increasing day by day, and since the annual population growth rate of the world is more than 2% **(Dincer, 2000)** it leads to the global demand of the world to increase by 1.5 to 3 times by the year 2050 **(Dincer, 1998).** There is a large gap between demand and supply and it is difficult to meet the demand. There is also concern about the environmental effects like air pollution, forest destruction, ozone depletion, global warming, etc. **(Dincer *et al.*, 1997)**. Scientific evidence shows that the impact of all these effects is going to be severe if society continues to degrade the environment **(Rosen *et al.*, 2000)**. There are two kinds of energy sources renewable and non-renewable sources. In the case of non-renewable sources, fossil fuel (coal of different grades) and crude oil products like petrol, diesel. The consumption of non-renewable sources of energy are the main cause behind environmental pollution.

Energy is the main factor that must be considered while discussing sustainable development. Sustainable development can be defined as “development that meets the needs of the present without compromising the ability of future generations to meet their own needs” and in this regard thermal energy storage (TES) utilization is important. There is an intimate connection between energy, the environment and sustainable development and to seek sustainable development we must utilize that source of energy which has no environmental impact. In this regard, renewable energy sources are one of the advantageous solutions. It is known that there are no such energy sources available that do not negatively impact the environment other than renewable energy sources. A strong correlation exists between energy efficiency and environmental impact since, for the same services or products, less resource utilization and pollution are normally associated with higher efficiency processes. Based on the current environmental problem few solutions are identified which include the use of renewable energy technology and increased efficiency. TES is one the technology with the help of which the goal of sustainable development can be achieved according to which the use of currently available sources of energy in such a manner that in the long term it is easy and sustainable available at low cost and can be utilized without affecting the environment. In the context of sustainable development, TES plays a very important role. **(Dincer and Rosen, 2002)**

TES system contributes significantly to fulfil society demand more efficiently particularly in the field of building heating and cooling and in power generation. It reduces energy consumption which results in following significant environmental impacts:

a) It helps to conserve fossil fuels through efficiency increment and fuel substitution

b) It helps to reduce the emission of pollutants such as SO_2, CO_2, NO_x, and CFCs.

The energy shortage has increased the use of TES technologies and their applications which are advantageous in many cases. The engineer and designer have to achieve the maximum benefits of TES by considering the reliability and economics of the TES. TES is an emerging and effective method that is available at present. Adopting TES in any application leads to a better economy, reliability of the system and increase in an overall efficiency of the system, it has various advantages like pollution reduction and also reduction in emission of CO_2, SO_2, NO_x, and CFCs. TES not only bridges the gap between energy supply and demand but also improves the performance and reliability of the system.

1.1. Thermal energy storage

Thermal energy storage can be defined as the temporary storage of thermal energy at high or low temperatures. TES have the potential to minimize the mismatch between energy supply and the energy demand and another big advantage of using thermal energy storage devices is that although primarily it is used for the storage of solar energy TES is not restricted only to solar energy but it can also be used to store surplus energy coming out from different power plants or as a waste heat recovery system such as the energy that is going to waste in any industrial process. TES work as a sink in which waste energy can be rejected **(Socaciu, 2012**).

In TES unit energy can be stored and later that stored energy can be used for heating or cooling application, the source of which is the solar energy or may be any other source of energy. Solar energy primarily is used for energy storage purposes because of the ease of availability of the solar energy. Thermal energy storage system is one in which PCM (phase change material) can be used as thermal energy storage material, which on changing its phase stores energy during melting and solidification. The stored energy is discharged and it completes one cycle of charging and discharging. TES is the future of energy storage systems because these devices have the scope to enhance their storage capacity by using a different technique of enhancing heat transfer rate. Technique to improve heat storage capacity and further research work is going on to improve the performance and the efficiency of these storage systems which can also be implemented in the power plants by which the fuel requirement in any of the fuel consuming industry can be reduced. A good TES system has the following characteristics:

a) The capacity of a storage system indicates the energy stored in the system which depends on the size of the system and the process employed for the storage purpose.

b) The power of a TES system shows how fast the system is charging and discharging.

c) The efficiency of TES is defined as the ratio of the amount of energy provided to the system to the energy needed to the system for the charging process. It also incorporates the losses which happen during the charging and discharging process.

d) The storage period indicates about how long the energy is stored and lasts (i.e., months, hours, days, weeks, and months for seasonal storage).

e) The charging and discharging time indicate that how much time is needed to charge and discharge the TES system.

f) The cost refers to the capacity and the power of the storage system which depends on the capital investment and running cost of the system **(Sarbu and Sebarchievici, 2018).**

1.2. Classification of thermal energy storage devices:

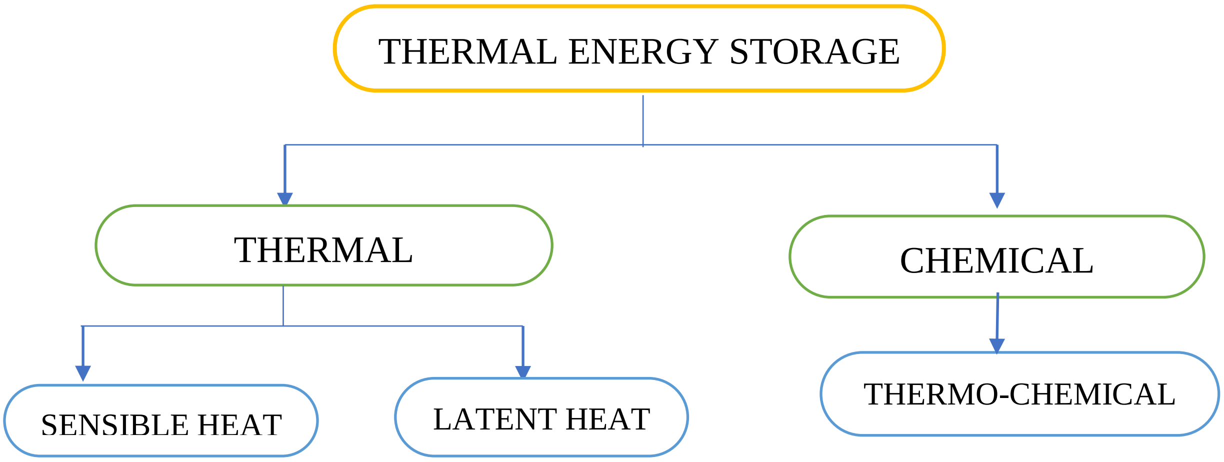


Fig 1.1 Classification of thermal energy storage

1.2.1. Sensible heat storage

In a sensible heat storage system, the energy is stored or extracted by heating or cooling a liquid or solid during which it does not change its phase in this process. This includes liquid like water, heat transfer oils, inorganic molten salt, and solid like rocks, pebbles. As most of the solids are porous in which heat is extracted by the flow of gas or liquids through these pores or voids during the extraction process these materials do not change their phase. The most common material that can be used for a sensible heat storage system is water because of having its high specific heat, higher the specific heat higher the heat storage, heat storage depends not only on the specific heat of the materials but also on the amount of material used. A sensible heat storage system utilizes sensible heat and changes in temperature in the storage materials during the charging and discharging process. In SHS water is used when the temperature level is below 100ºC. The only drawback of SHS is they are generally bigger and cannot deliver energy at a constant temperature. This is the reason sensible heat storage system are not in much use. The basic equation of sensible heat storage;

$$\text{sensible heat Q} = \int_{T_i}^{T_f} \text{m.}\,\text{c}_p.\,\text{dt}$$

Where, T_i is the initial temperature of the storage material and T_f is the final temperature of the storage material, m is the mass of the material cp is the total heat capacity of the material and it is the function of temperature and to determine the amount of stored thermal energy the above equation can be used. sensible storage systems are easy to design but have a big disadvantage in that they are bigger and do not store or deliver energy at a constant temperature.

1.2.2. Latent heat energy storage (LHES)

In the latent heat storage system heat is stored when the storage material melts and the heat is extracted when the material solidifies, heat storage depends on latent heat of the storage materials.

$$\text{Latent heat} = \int_{T_i}^{T_m} m.\,c_p.\,dt + \Delta\text{m.h}_\text{m} + \int_{T_m}^{T_f} m.\,c_p.\,dt$$

Among all thermal energy storage device latent heat energy storage devices are most widely used for the purpose and using latent heat thermal energy devices over sensible heat thermal energy devices have so many advantages like it store energy almost at a constant temperature during the phase change process and the heat storage capacity of the latent heat thermal energy storage devices are 6 to 14 times greater than the sensible heat energy storage devices and the very best part of LHTES even with the small volume of PCM this system can store a greater amount of thermal energy compared to SHTES. Fig 1.2 shows the heating of a substance in which there is an increase in temperature during sensible heating and a change in phase during latent heat. According to the diagram from point O to A sensible heating starts which leads to an increase in the temperature of solid from initial point O, sensible heating is followed by phase change process which takes place during region A to B, the latent heating of substance changing phase from solid to liquid then again sensible heating of liquid from B to C then phase change process again from C-D from liquid to liquid-vapour and sensible heating of vapor in region D-E.

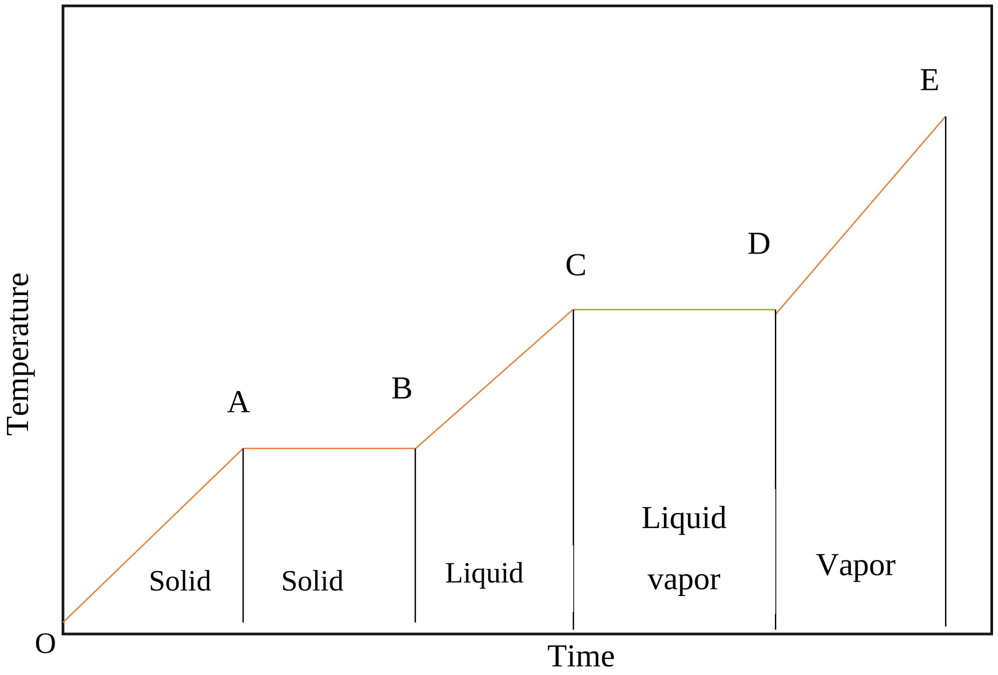


Fig 1.2 Temperature vs time graph for heating of a substance

The total heat during the process can be written as

$$Q = m \cdot \left[\int_{To}^{TA} C_{ps}(T)dT + q_t + \int_{TB}^{TC} C_{pl}(T)dT + q_i + \int_{TD}^{TE} C_{pv}\,(T)dT \right]$$

Where C_{ps} = Specific heat of solid; C_{pl} = Specific heat of liquid; C_{pv}= Specific heat of vapor; q_t and q_i are the latent heat associated during the phase change.

1.2.3. Thermochemical storage

This is another type of thermal energy storage system in which an endothermic and exothermic chemical reaction takes place the basic principle of this system is during the endothermic process the charging process will take place in which reactant AB absorbs the thermal energy AB break down into two component A and B, and during exothermic process, the reverse process or say that discharging process is applied during which AB recombine and release some thermal energy which was stored during the charging process. During the charging process, it may be possible that simultaneous process of discharge can happen so to avoid such condition during charging process both resultant A and B are advised to collect separately, if both the resultant A and B are different phase form for example A is in solid form and B is in liquid form it is more convenient to implement reverse reaction for thermochemical storage media, well separation of resultant A and B provides stable and long-term storage feature to the system.

$$\text{Endothermic Reaction,} \qquad \mathrm{AB} + \text{Heat Energy}(\downarrow) \rightarrow \mathrm{A} + \mathrm{B}$$

$$\text{Exothermic Reaction,} \quad \mathrm{A} + \mathrm{B} \rightarrow \mathrm{AB} + \text{Heat energy}(\uparrow)$$

The must condition for thermochemical storage is as follow:

a. The reaction in the process should run near the equilibrium condition.

b. The energy stored in the system must be large enough.

c. The storages system based on chemical reaction has negligible losses.

d. The reactant used for the purpose should be cheap and easily available.

1.3. Phase change materials (PCM)

Phase-changing materials are most widely used for heat storage systems. The PCM is primarily selected based on the temperature range of application and secondly based on the following properties:

a) The PCM material should have a high value of latent heat of fusion for unit mass, the higher the value lesser the amount of material required for storage of given thermal energy.

b) PCM of higher thermal conductivity is generally preferred so that the temperature gradient required for charging the PCM will be small.

c) The PCM that is selected should have a small volume change during phase transition so that the container is going to use and the heat exchanger geometry will be simple.

d) The PCM should exhibit little or no sub-cooling during freezing.

e) The density of the PCM material must be small so that a small volume container can hold the material.

f) The melting of the material is required at desired operating temperature.

g) The PCM must not be inflammable, non-poisonous, non-explosive, and non-corrosive to the construction material.

h) There should be no chemical decomposition so that latent heat storage system life is assured.

1.4. Classification of phase change material:

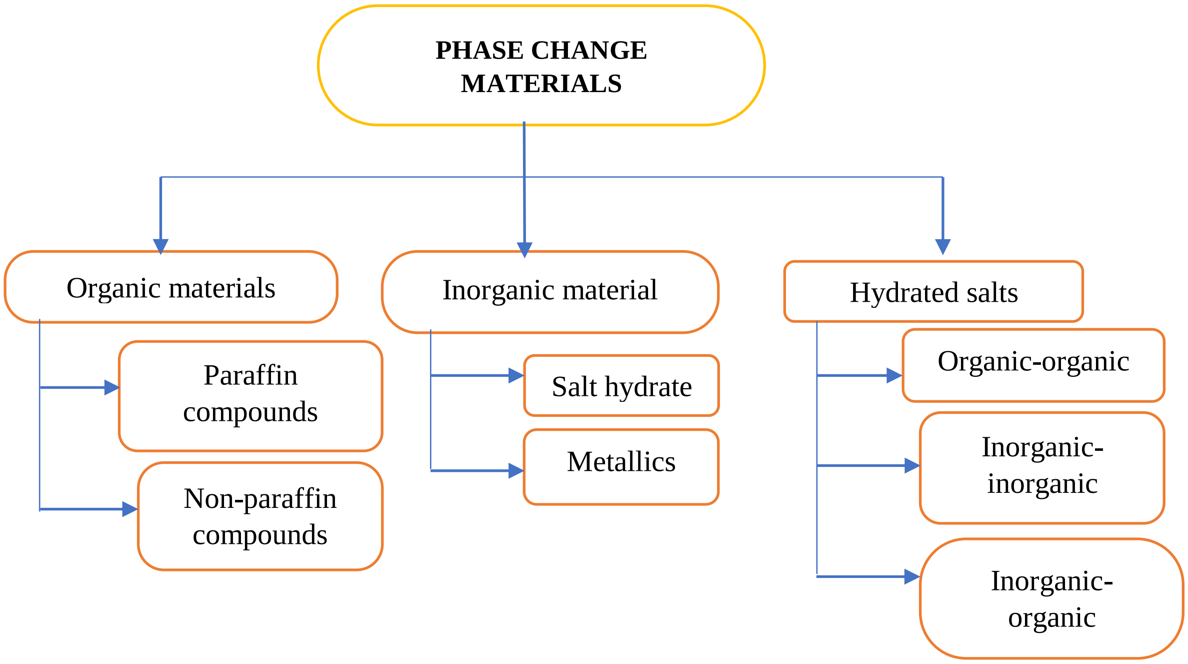


Fig 1.3 Classification of phase change material

Organic material PCM: Generally obtained from agricultural and food processing industries, as well as hydrocarbon processing industries, such as fatty acids, wax, oil, and so on, these materials are abundant and have very little environmental impact. These materials are inexpensive and easy to use in thermal applications. Organic PCMs are widely used and commercially available materials because of their properties like non-corrosiveness and good thermal stability. Organic PCM includes paraffin and non-paraffin PCM. The distinguishing feature between them is their melting temperatures. Fatty acid (non-paraffin) has a lower melting temperature than paraffin PCM and is hence used in building and textile applications.

Paraffin: Heptadecane, Octadecane, Polyethylene etc.

Fatty acid: Caprylic acid, Lauric acid, Palmitic acid etc.

Inorganic Material PCM: It includes salts, salt hydrates, and metals. Inorganic PCMs confer applicability over a wider range of temperatures and higher volumes of volumetric energy storage capacities, as well as higher values of thermal conductivity, compared to those of organic PCMs. Inorganic PCM has greater advantages because of its higher thermal conductivity and higher energy storage density, but also has disadvantages like corrosion thermal instability.

Salts and salt hydrates: lithium Nitrate ($LiNO_3$), Potassium Nitrate (KNO_3), Magnesium Chloride ($MgCl_2$) etc.

1.5 Designing of heat exchanger

For the study of latent heat thermal energy storage systems, various shapes of shell and tube heat exchangers have been used till now for the study. The present work is based on modifications in the outer shell geometry for the analysis of heat transfer in the PCM with the help of longitudinal fins attached to the inner copper tube. Present work is focused on investigating the melting performance of PCM numerically as well as experimentally. The main objective behind the project is to enhance the rate of heat transfer for which there are various methods to enhance the rate of heat transfer. Some of them are as follows: (**Kumar and Verma, 2020).**

a) As the thermal conductivity of PCM is low, the very first method focused on enhancing the thermal conductivity of the PCM, is use of nano-additives such as carbon nano-tube, copper metal foam, nano-graphite, and the addition of nano-particles, which reduces the thermal resistance, because of which the rate of heat transfer increases and hence the melting rate increases.

b) Arranging the multiple PCM longitudinally, PCM are arranged in decreasing order of melting point from HTF entry to HTF exit, which aids PCM during charging and discharging.

c) Increasing the heat transfer area with the help of fin. Attaching fins on tube improve the heat transfer performance compared to the bare tube.

Adding fins to the tube determined to be the best approach for increasing the rate of heat transfer since it is easy to fabricate and is less expensive than the other two methods. Adding fins not only aids in melting of PCM but also in the solidification process.

1.6 Organization of thesis

- Chapter 2 gives a thorough review of the literature on heat transfer enhancement mechanisms for horizontal shell (semi-circular in shape) and tube LHTES systems of various configurations. In the field of LHTES systems, this chapter covers both experimental and computational study.
- Chapter 3 provides thorough information on the preparation and operation of the experimental setup. It also explains the numerical simulation solution methodologies for a better understanding of the experimental results.
- Chapter 4 describes the detailed study of results obtained through experimental and numerical work, as well as the validation of numerical results with experimental results.
- Chapter 5 presents the summary and conclusion of the present work.

Review of Literature

Chapter 2 REVIEW OF LITERATURE

Latent heat thermal energy storage systems are the effective thermal heat energy storage devices among all other types of heat storages devices, with many advantages over different types of energy storages devices in terms of heat storage, heat transfer rate, and efficiency. In this chapter, a thorough review of various research works in the field of thermal energy storage systems is conducted, with the current work focusing on storage devices in which natural convection plays a vital role during the melting of PCM, as well as conduction, which is beneficial during solidification. The goal of the research is to improve the heat transfer rate and the storage capacity of PCM in a short amount of time.

Sparrow *et al*. (1981) various experiments were performed to study the freezing on a finned vertical tube for either conduction when solid controls the heat transfer or when liquid is at its fusion temperature and natural convection controls when the liquid temperature is above fusion value, the phase change medium that used in the experiment is n-eicosane paraffin, 99% pure, the freezing point of which has been measured to 36.4ºC. A quantitative relationship between the two freezing configurations is given as

$$M_f/M_{uf} = 2.90/(\Delta T_i)^{0.134}$$

Where; M_f and M_{uf} are frozen masses on finned and un-finned tubes respectively.

And the area ratio is defined as a dimensionless parameter as the ratio of the surface area of the finned tube with the surface of the un-finned tube

$$\text{Area ratio} = A_f/A_{uf}$$

Where A_f and A_{uf} are the surface area of the finned tube and un-finned tube respectively.

When conduction controls the freezing due to fin, there is an enhancement in the frozen mass when the frozen layer found thin and then decreases as the frozen layer grows and become thick and the degree of enhancement found to be less than the surface area ratio when convection control the freezing there is an enhancement in the freezing due to finning and it is assumed to be proportional to the surface area of the fins, the comparison is done between conduction control heat transfer and convention control heat transfer during freezing in which there is the degradation of the heat transfer due to natural convection as time increases and the degradation are lower at lower temperature difference. For conduction control the enhancement of freezing has been recorded, which is less than the area ratio of finned tubes, whereas the enhancement is very nearly equal to the area ratio when natural convection control freezing.

Sasaguchi *et al.* (1986) experimentally studied the heat transfer characteristics of the latent heat storage unit with finned tube and the results were compared with the un-finned tube, and the effect of non-dimensional parameters like NTU(the number of transfer unit), Biot number and Stephan number and the effectiveness on solidification and melting is shown in the paper, the experimental setup of latent heat transfer storage contains three tubes first one un-finned copper tube and other two finned copper tube having 4 and 8 longitudinal fins, water is used as a working fluid and the phase change material used in the experiment is n-Eciconsan the chemical for which is $C_{20}H_{42,}$ results shows that the effectiveness of fined tube was large in both solidification and melting processes and the heat flux for the finned tube found very much greater than the heat flux associated with the un-finned tube. A tube having 8 longitudinal fins is having heat flux 2.5 times as in case of without fin. Furthermore, the relation between non-dimensional parameters has been examined and found that in the case of finned tubes the effect of Stephan number is small as compared to a bare tube and for the bare tube the Biot number and NTU fairly affect the heat transfer characteristics.

Lacroix (1993) studied the heat transfer characteristic of the latent heat thermal storage unit with a finned tube and prepared a theoretical model for analyses and predicting the behavior of shell and tube storage unit with PCM working as a heat storage fluid. In which PCM S present on the shell side and the heat transfer fluid is circulating inside the tube, the numerical data is validated with experimented data. the effect of shell radius mass flow rate and the inlet temp of heat transfer fluid and the behavior of fins attached to inner tubes was observed. Results shows that on adding fins to the inner tube the thermal behavior of the system becomes effective for moderate mass flow rates and lower inlet temperature of heat transfer fluid.

Velraj *et al*. (1997) experimentally and numerically investigated the inward solidification of a finned vertical tube for a latent heat storage unit, for the enhancement in the rate of heat transfer by using internal longitudinal fins in a vertical tube in which the V-shaped encloser which is the region of analyses for a given tube, gives the maximum benefit to the fin arrangements. In the work numerical data is validated with the experimental data. As the PCM materials have a very poor thermal conductivity which is the major disadvantage of PCM, using V-shaped encloser of the tube results were improved the generalized H-T relationship, developed in the work which accommodates materials having either constant range of phase change temperatures. Overall, the heat transfer with fins is several folds as compared to the case with no fin, this design makes the system more attractive for latent heat storages system and also for solar applications.

Ismail (2001) studied the solidification of PCM around vertical axially finned isothermal tube experimentally as well as numerically so that it can be used in thermal energy storages devices. The model was purely based on the conduction mechanism of heat transfer and also on enthalpy formulation and control volume approach, the effect of fin thickness fin length no of fin, the degree of superheating and the aspect ratio of annular spacing is found to influence the time for complete solidification. The results show that by using fins it delays the undesirable effects of the natural convection during the phase change process. Results shows that the effect of fin thickness in solidification is not of great extent whereas the fin length and the number of fins greatly enhance the solidification time. It is reported that fin thickness is just equal to the tube wall thickness whereas the number of fins recommended is three to four having constant thickness and the radial length is around the twice the diameter of the tube.

Sari and kaygusuz (2002) studied the heat transfer characteristics by using lauric acid in a latent heat storage system experimentally in a vertical double pipe energy storage system, the experiment focused to :

a) To determine the temperature distribution and temporal temperature variation of PCM during the entire phase change process in radial and axial distances.

b) To determine the thermal characteristic of lauric acid like total melting and solidification time, the nature of heat transfer during melting and solidification.

c) The effect of Reynolds and Stefan number as inlet heat transfer fluid conditions on the phase transition parameter.

Based on experimental work it has been found that lauric acid melts and solidifies at an isothermal temperature range of 41ºC-42ºC and it is observed that there is no subcooling during freezing, and the melting front is mostly governed by convection heat transfer during melting and due to the bouncy effects. In case of solidification front the heat transfer is controlled by conduction and slowed due to increase in the formation of the solid-liquid interface.

The effect of Reynolds and Stefan number found almost constant during melting and solidification of PCM. Based on the work it is suggested to use lauric acid with 95 % purity, having an isothermal phase transition temperature range of (41-43) ºC having all desirable heat transfer characteristics and suitable for thermal energy storage devices.

Akgun *et al.* (2007) conducted an experimental study to investigate the melting and solidification of the paraffin (PCM) wax in a shell and tube vertical heat exchanger. The study focused on the enhancement in the heat transfer by varying the inlet temperature and the mass flow rate of the heat transfer fluid (HTF) where water is used as HTF and the effect of both charging and discharging is observed. Paraffin has been selected as a PCM because of its low cost and ease of availability high energy storage capacity and large-scale availability.

Seeniraj (2008) enhanced the thermal performance of solar dynamic LHTS module which contain fin as well as multiple PCM numerically and the LHTS unit has been studied for charging only, in which enthalpy-based formulation of the energy equations governing the behavior of LHTS system is made. In the physical system of LHTES system of shell and tube having the single tube in which 5 different PCM are arranged longitudinally in such a way that decreasing order melting point PCM are arranged during charging and increasing order of their melting point during discharging process, which are equally spaced and having 4 external radial fins arranged and the distance between two consecutive fins are called cell and these cells are considered for analysis throughout the experiment. Based on that it is found that the multiple PCM model results in a notable change in the thermal energy storage in the form of latent heat storage unit compared to single PCM model.

Agyenim *et al.* (2010) reviewed and investigate the development of latent heat thermal energy storage systems which includes the investigation of LHTES systems that were done in the last three decades for the enhancement of heat transfer of LHTES. Also examined the geometry and configuration of the PCM storage container, various numerical and experimental conducted for determining the effect of inlet temperature and mass flow rate of the heat transfer fluid. The review suggested that to enhance the rate of heat transfer adding fin to the tube is one of the best methods because of its simplicity, ease of fabrication, and low cost of construction followed by impregnation of the metal matrix in PCM having high thermal conductivity like carbon fiber also concluded that the numerical approach is one of the good approaches to solve the problem associated with the phase change in 1-D or 2-D model because of its simplicity of equation solving, numerical approach for the solution of phase change material is good for the 2-D system due to complexity of the equation involved.

Zhong *et al*. (2010) studied the heat transfer enhancement of paraffin wax by using graphite foam for a thermal storage unit in which mesophase pitch based graphite foams having different thermal properties and pore size are used to enhance the thermal properties of the paraffin wax and experimentally thermal diffusivity and latent heat is measured and the influence of the structure on thermal behavior has been recorded and found that there are different methods for enhancing the rate of heat transfer in a thermal energy storage device such as the introduction of fin, or by introducing the nanoparticle in the PCM, or by using graphite foam all other methods except graphite foaming increases the weight of the thermal storage unit so one of the methods to improve the heat transfer rate is by using graphite foam which greatly enhances the thermal diffusivity of the PCM material. Among four samples of a paraffin-GF sample, B shows the greater enhancement in the thermal diffusivity as well as in heat storage capacity. As per that the pore size and ligament thickness play an important role, the high thermal storage capacity and high thermal diffusivity can be obtained by using thicker ligament and large pores size.

Denge *et al.* (2013) studied the thermal performance for a finned double tube latent heat thermal storage device with fin and without fin aiming to find the most efficient arrangement of fins by considering different factors such as fin no (N), dimensionless fin length (l), the temperature of heat transfer fluid, and the material of outer shell of the tube. For which a 2d model is prepared which was based on finite volume method considering natural convection playing an important role during melting of the PCM. Based on previous study longitudinal fins are found appropriate for cylindrical PCM containers generally the shape of the fin taken is longitudinal and to improve the performance of the longitudinal fin many novel shapes were developed like triangular structure, tree-shaped structure, v-shaped structure, and topology structure but only longitudinal fin shows a greater difference in melting time compared to other shapes of the fin, that’s why longitudinal fins are preferred for LHTES system. A term defined called enhancement ratio which shows enhancement in the performance of PCM and saved time in melting based on the number of fins can be written as

Enhancement ratio

$$\mathrm{E_m} = \frac{\mathrm{t(NO\ fins) - t(Fins)}}{\mathrm{t(NO\ fins)}} \times 100\%$$

Where t (No fins) = complete time of melting of PCM without a fin,

t(fin)= complete melting time of PCM with fin on that basis using fin no N≤6 the optimum arrangement for lowered fin at which the dimensionless length taken is l=0.75, whereas for angled fin N>6 for which the dimensionless length for optimization equals 0.5-0.95.

A.Al-abidi *et al.* (2013) reviewed the CFD(computational fluid dynamics) application for latent heat thermal energy storage based on previous studies, in which CFD is used for numerical modeling of phase change material to study the heat transfer phenomena. The mathematical model for solidification and melting depends on the enthalpy porosity technique and finite volume methods. The use of CFD software for designing LHTES is believed to be an effective way to save money and time to deliver optimization tools for maximum efficiency of STEAs. The numerical solution for PCM phenomena is more accurate than any analytical solution different CFD software are used for PCM modeling but the most widely used software for the analysis is ANSYS fluent software. The use of CFD software for PCM modeling is a feasible method because of its accuracy in the result.

Kurnia *et al*. (2013) developed a numerical model to improve the design for heat transfer performance of novel phase change material in which different models were developed for the analysis which includes various configurations of the PCM TES devices like U-tube, U-tube with in-line and U-tube with staggered fins and a novel festoon design. For numerical modulation computational fluid dynamic approach by utilizing enthalpy porosity formulation is used. Based on which it is found that novel u-tube with staggered fins shows the highest rate of heat transfer compared to the other two models, on other hand by using multiple PCM having different melting point enhance the performance of the TES by putting the PCM of having a higher melting point to the inlet of the TES and then the other one having a lower melting point at the exit and the one having intermediate melting point used in between this PCM.

A.Al-Abidi *et al.* (2014) experimentally investigated the melting and solidification of triplex tube heat exchangers with internal and external fins for the system working as a thermal energy storage device. Various experiments were conducted for charging of PCM at different inlet temperatures under steady and unsteady heat transfer of fluid and also the influence of mass flow rate in the melting was analyzed. The effect of temperature gradient in radial and axial directions analyzed thoroughly. Results show a greater influence of inlet temperature in PCM melting compared to the mass flow rate of HTF. The charging time in the case of HTF inlet temperature is reduced by 86% whereas for a different mass flow rate of HTF the charging time is reduced by 58%.

Rathod *et al.* (2015) in a vertical shell and tube thermal energy storage system, experiments are carried to improve the overall thermal characteristics of a phase change material. To increase the heat transfer surface area, three longitudinal fins are added on the exterior surface of the heat transfer fluid tube. As a thermal storage medium, stearic acid is used. The time required for melting and solidification at varied inlet temperatures and heat transfer fluid flow rates has been investigated to improve the thermal performance of a heat exchanger.

According to the results of the experiments, the input temperature of HTF is a more reliable parameter for heat transfer enhancement than flow rates of HTF. Installing three longitudinal fins for specific HTF operating parameters increases solidification rate more than melting rate.

Seddegh *et al.* (2016) studied horizontal and vertical shell and tube arrangement for melting and solidification in which the numerical model validated with already present published experimental data based on a literature review during which the following assumptions are taken:

1. All the thermophysical properties of material do not change during the melting and solidification process with respect to temperature.
2. The motion of PCM during the liquid state is assumed to be laminar, incompressible, and unsteady.
3. Viscous dissipation is negligible and no viscous stress and convective flux at the pipe outlet.

The concluded results are, the horizontal shell and tube arrangement has better heat transfer performance compared to the vertical arrangement as during the charging process convective heat transfer is dominating part as the upper half melts completely the convective effect is lowered down for the lower half of the horizontal shell and tube arrangement. Whereas for solidification of PCM conduction is the dominating part and for both horizontal and vertical arrangement shows very significant behavior.

Bose (2016) reviewed the thermal conductivity enhancement of paraffin wax as latent heat thermal energy storage material .according to which the performance of most of the PCM on latent heat energy storage is limited due to its poor thermal conductivity various methods can be adopted to enhance the thermal performance which includes application of fins, the inclusion of nanoparticle by mixing these particles with PCM material, encapsulation of PCM and the last one by using multiple PCM, each method has its benefit and loss among all the mixing of nanoparticle with PCM observed which is having significant enhancement in the thermal properties of the paraffin wax. Greater the concentration of nanoparticles in the PCM is greater the enhancement in the thermal properties but the mixing concentration of nanoparticle limited to a certain value beyond which addition of nanoparticle results in an increase in density and viscosity and decrease in the latent heat and of melting and hence decrease in the storage capacity. So, the optimum value of concentration is selected at which the value of thermal conductivity is maximum and the latent heat degradation is minimum.

Wang *et al.* (2016) numerically analyzed the impact of fin geometry which includes the fin length, fin ratio, and the angle between neighbor fins and also the effect of thermal conductivity of the outer tube to determine the influence of natural convection in shell and tube geometry in which longitudinal fins were attached to the inner tube the whole work is based on the fact that the thermal conductivity of the phase change material is very poor and the heat transfer associated with it also very poor, based on that the work is focused to enhance the rate of heat transfer with the application of fins. The results show that by considering the effect of both shell conductivity and the angle between fins the melting time reduced by 49.1% at the optimal value of fin angle of 60º and 90º for 3 full-scale fins. The effect of natural convection had a great impact on the melting for the configuration when fin at an angle of 60º & 90º. Based on the analysis it is recommended that if fins are attached to the outer tube internally the material for the tube must be of high thermal conductivity because the thermal conductivity of outer material had a greater impact on the melting process.

Darzi *et al*. (2016) conducted a numerical study to enhance the melting and solidification of PCM with the help of radial fins and nanoparticles in three different horizontal cylindrical annuli along with tube, in these three configurations the first tube was circular second tube was elliptical and the third one was finned circular tube these tubes are investigated in term of aspect ratio, the orientation of the elliptical tube and the no of fin for the finned tube. To examine the effect of the nanoparticles on the heat transfer rate different volume fraction of the copper nanoparticle is added to the base PCM. By adding nano-particles enhances the rate of melting and solidification but does not eliminate the stable heat transfer at the bottom section of the annulus whereas using fins shows better results compared to the case when using nano-particle alone. During melting of the PCM it is observed that natural convection and heat conduction plays a dominant role during melting and in the first 40 min, the top PCM melted completely whereas the bottom PCM remain un-melted it is all because of the region that the liquid layer of PCM behave like a thermal barrier since the thermal conductivity of the liquid PCM is lower than the solid PCM and as the PCM melts it grows and become thicker and results in the lower down of the heat conduction this is the region why the lower PCM remains un-melted during first 40 min. so to reduce the heat conduction dominated region two vertically oriented elliptical tubes with different aspect ratios were used instead of inner circular tubes considering that elliptical tubes have areas identical to the circular tube and the volume of PCM going to melt remain constant irrespective of the tube configuration, among these configurations the vertically oriented elliptical tube having highest melting rate and the PCM melts in minimum time.

To investigate the effect of nanoparticles in the melting of PCM the sample of Cu-nano particles with different volume fractions were used and observed that using

NEPCM sample engenders a faster growth of the solid-liquid interface. By insertion of 2 % and 4 % of nanoparticles, the melting time reduces by 25 % and 46 % respectively. It is concluded that nano-particles do not improve the melting process and undesirable effect of the heat transfer in the dominant zone. The melting performance of the tube with fin is found the better as compared to all other cases. And during the time of solidifying the liquid PCM, it is found that the number of fins helps to solidify PCM faster because as the number of fins increases it suppresses the effect of convection, and during the solidification, conduction plays an important role. And it is noted that solidification time reduces by 28 %, 62 %, 75 %, 85 % by using 4,10, 15, and 20 fins respectively. But the only drawback with the number of fins is during melting it blocks the melted PCM and suppresses the natural convection.

Kazemi *et al.* (2017) studied latent heat storage system and improvement in the heat storage system with the help of longitudinal fins and the optimum angle of a fin is found for maximum heat transfer rate and minimum melting time and also Simulated and compared triplefin with double fin for different angles. Based on the result it is found that the addition of fin affects more in the case of solidification compared to melting it is because, during melting, the fins restrict the path of naturally driven streams produced during melting of PCM. In the case of the triplefin case, the optimum angle of fin obtained was 60° at which the melting rate found higher. According to the study putting fins in the lower half is more effective for reduction in total melting time. similarly to a case of a double fin in which the length of an upper fin is equally divided to bottom fins in which the length of each fin becomes 3h/2 from h, the optimum result obtained at 45° increasing the angle beyond 45° results in the blockage of natural convection streams whereas reducing the angle prevents the vortices formation between two fins and reduces the melting time.

Tao *et al.* (2017) studied the effect of the arrangement of PCM and natural convection on the charging and discharging of the latent heat transfer unit. As it is a well-known fact that the thermal conductivity of the PCM material is very low which affects the charging and discharging process of the latent heat storage system. so, for improving the performance effective approach is required, for which a 3D simulation model with and without natural convection effect is constructed to investigate the melting performance for shell and tube LHS unit. When compared to the widely used shell and tube LHS unit with PCM in the shell side, the findings reveal that the LHS unit with PCM in the tube side can improve heat storage rate under the same operating conditions. Natural convection has a major impact on charging performance, especially when the PCM is in the tube. With PCM placed on the tube side, PCM melting time can be lowered by 25.4 %and latent heat storage rate can be increased by 36.6 % when natural convection is ignored. With PCM organized in tube side, PCM melting time may be shortened by 34.4 %, and latent heat storage rate can be increased by 54.2 % when natural convection is considered. Natural convection, on the other hand, does not affect discharging performance, for the case when PCM is in the tube side.

Yang *et al.* (2017) conducted a numerical study on the thermal performance of shell and tube latent heat storage unit with annular fin. In the study, the phase change material (PCM) takes commercial-grade paraffin, while the heat transfer fluid is water (HTF). The impacts of fin number, height, and thickness on the phase change process are investigated using numerical simulations based on the finite-volume method (FVM). The role of local natural convection in the overall phase shift process is given special consideration. The findings indicate that by adding annular fins into PCM, the whole melting time can be decreased by up to 65 %. Based on investigation, an optimal group fin parameter (fin number N = 31, thickness t/l = 0.0248, and interval l/L = 0.0313) is recommended to maximize thermal performance.

Kousha *et al*. (2017) the influence of inclination angle on melting and solidification speeds studied experimentally and took into account four different inclination angles: 0°, 30°, 60°, and 90°. Horizontal configuration is represented by 0°, whereas vertical configuration is represented by 90°. Got the same results as with the charging process. It has been the horizontal design is found to be the best for the charging process on the other hand, a vertical configuration is found best for the discharging process to produce a higher heat output rate of transfer.

Dhaidan and Khodadadi (2017) analyzed the PCM based latent heat energy storage system to improve the performance of the latent heat energy storages system utilizing the high thermal conductivity fins and reviewed analytically and experimentally the main objective of using fin the LHTES system is to overcome the drawback associated with the poor thermal conductivity of the PCM, the experiment is done with a variety of PCM including paraffin, carbonate mixtures, polyethylene glycol, stearic acid and lauric acid having a different melting point the performance of the energy storage system is greatly dictated by length and number of fins in comparison to their thickness which plays a marked role during thawing. Concluded that for selection and designing of fins one should consider opposing trends between improving the thermal conductivity of the storage media and weaker buoyancy effect.

Kalapala (2018) studied the design parameter and the influence of these parameters on the performance of PCM based thermal energy storage device on the finned and plain tube and observed complete melting with longitudinal fin as compared to the circular fin and recommended wider and longer longitudinal fin with fin number restricted to 3 or 4, the number of fins selected in such a way that it will not affect storage capacity. Shell to tube dia ratio(R) is another design parameter that can be written as

$$R = (Diameter\ of\ shell)/(Diameter\ of\ tube)$$

that must be considered while designing the shell and tube heat exchanger the effect of the ratio of shell to tube diameter plays an important role in energy storage density by observing the behavior concerning the ratio the optimum value that can be considered while designing must lie in between 3.5 to 4.

Cao *et al.* (2018) investigated the optimum no of longitudinal fins in a horizontal annular shell and tube phase change unit by taking different no(n) of fins n= 4,6,8,10 at five different wall temperatures and comparing the result with the case of a tube having no fin. To investigate the correlation between the number of fins and the wall temperature PCM has been examined numerically based on the enthalpy porosity model. based on the results it shows that increasing the number of fins accelerates the rate of heat transfer and reduces the melting time. If the value of no. of fins exceeds the optimum value it will lead to a decrease in heat transfer coefficient so for average wall temperature the fin number must be optimized which is 10 in this case.

Deng *et al*. (2019) studied finned tubes for improving the melting performance of finned circular tubes by using local double fins at a different angle for which a 2-D transient model was developed aimed to enhance the rate of heat transfer and to study the melting characteristics of lauric acid, lauric acid is the suitable PCM for LHTES system because of its property of non-corrosiveness, non-toxicity, negligible supercooling and constant temperature phase change process and having good thermal and chemical stability during phase change process .concluded that the complete melting is greatly enhanced by using an optimum θ can be saved by 66.7 % when the dimensionless fin length increases from 0.05 (optimum at θ=30) to 1 (optimum at θ = 120). The dimensionless length is defined as $l = \frac{L}{r_o - r_i - 1}$ where, L is the length of the fin in meter

r_o = inner radius of the outer tube.

r_i = inner radius of the inner tube.

And the melting time decreased by 53.1 % when the temperature of heat transfer fluid increases from 333.15 K to 353.15 K under l= 1.00 and θ=120.

Kumar and Verma (2020) investigated the melting properties of lauric acid numerically and experimentally in a horizontal shell and finned tube LHTES storage unit. As we know phase change materials (PCMs) have a low thermal conductivity, to increase heat transfer an attempt has been made to include a finned tube in the storage container to improve the heat transfer rate between the heat transfer fluid (HTF) and PCM for 3 different eccentric positions (e = 12 mm, 18 mm, and 24 mm) of a finned HTF tube from the center of the outer tube in concentric configuration (e = 12 mm, 18 mm, and 24 mm). The research focuses on using a minimum fin length of 36 % of the annular length of a concentric arrangement to improve the melting rate of a phase change material (PCM), to optimize natural convection while keeping conduction effects intact. The melting rate of PCM in an annular is investigated at different eccentric positions of the inner tube at angles of 60^o, 120^o, and 180^o degrees between fins in the bottom annulus of the storage unit. Numerical computations yielded results that matched those gained through experimentation. The melting rate of PCM has been improved, and it has been discovered that the melting rate is 21 % higher at the maximum eccentric annulus compared to the concentric configuration, owing to increased domination area for natural convection effects, which also improves temperature distribution uniformity in PCM. In a fin arrangement with a 60º angle between the fins in the bottom annulus, eccentric behavior for improved melting performance has been accomplished. The melting rate of PCM is increased when the Stefan number is increased, regardless of the eccentric position of the inner tube, and the heat storage rate in an eccentric annulus is 18.7 % higher than in a concentric annulus.

Kumar *et al*. (2022) studied the melting characteristic of PCM to enhance the heat transfer rate numerically and experimentally in a semi-circular and circular shell and tube arrangement. In the work the PCM material in circular shell present in the lower half is confined to upper half by changing the configuration conventional circular shape to semi-circular shape. The melting performance of PCM investigated by changing the tube position with respect to bottom surface at three different position and it has been found that better melting performance observed when the tube is placed near the bottom surface. The results obtained with semicircular shell and tube compared with circular arrangement, on comparing it is found that the semicircular shell and tube takes approximately half the time to melt as taken by circular arrangement, semi-circular shell and tube stores 25 % higher thermal energy as compared to the circular TES system.

2.1 Gap and objectives of the research work

Based on available literature reviewed it is found that most of the research work done is focused on circular geometry of the outer shell and inner tube in which the circular tube shape is modified to elliptical tube with different aspect ratio to analyze the performance but the outer shell geometry modification with finned tube has not been focused for the study of melting performance enhancement of PCM. Hence it has been decided to modify the outer shell geometry to the semi-circular geometry and in order to enhance the heat transfer rate longitudinal fins have been attached to the inner tube. Attaching fins to the inner tube increases the surface area for heat transfer and is one of the effective techniques because of its easiness with which longitudinal fins are attached at three different angles of 60º, 90° and 120°.

Present research work involves numerical and experimental investigation of a PCM filled shell and tube LHTES system to enhance the rate of melting and heat storage capacity with the application of fins on tube. The above mentioned three configurations of fins have been analyzed numerically for enhanced melting performance of PCM for a particular fin angle configuration and then the obtained results have been validated experimentally for that particular fin configuration. The study for melting performance of PCM in LHTES system has been primarily carried out to estimate the following;

1. To determine the rate of heat transfer for the semicircular shell having finned tube.
2. To determine effect of natural convection on thermal characteristics of PCM.
3. Comparison of the results of the finned tube with the un-finned tube LHTES unit.
4. To determine the increase in the heat storage capacity of the LHTES unit with the application of fin.
5. To estimate the effect of angle of fin for which the LHTES system shows improved thermal performance.
6. To determine the effect of different inlet temperature heat transfer fluid on charging of PCM.

Materials and Methods

Chapter 3 MATERIALS AND METHODS

This chapter discusses the method and materials utilized in the research work, which comprises numerical and experimental work. The numerical study includes the development of a 2-D model, mesh generation, model selection, and melting of PCM using available ANSYS fluid fluent software. In this chapter, experimental work includes the fabrication of heat transfer units, the selection of phase change material and numerous components used in the experiment. The materials used are listed, along with their properties.

3.1 Numerical study

The numerical study is one of the techniques that gives precise and accurate results and is always preferred to obtain the best results. Computational fluid dynamics (CFD) in ANSYS fluid fluent is one of the numerical methods to analyze the present problem. In actuality, it could be difficult to examine a problem experimentally because it is time-consuming and requires manpower. As a result, numerical methods are one of the best options for performing repeated analyses without wasting material that could be used in real life. The use of CFD software for LHTES analysis has increased in popularity over the last few decades. The Navier-Stokes equations are used in CFD to calculate fluid flow and heat transfer.

3.1.1 Domain of computation

The computational domain includes three-domain which are:

1. Inner pipe
2. PCM region
3. Outer pipe

The configuration of semi-circular shell and tube storage units, as well as the CFD domain for numerical simulation, are depicted. The geometric parameters and the zones of the shell and tube LHTES system, namely the inner pipe, fins, PCM region, and outer pipe, are depicted in Figure 3.1

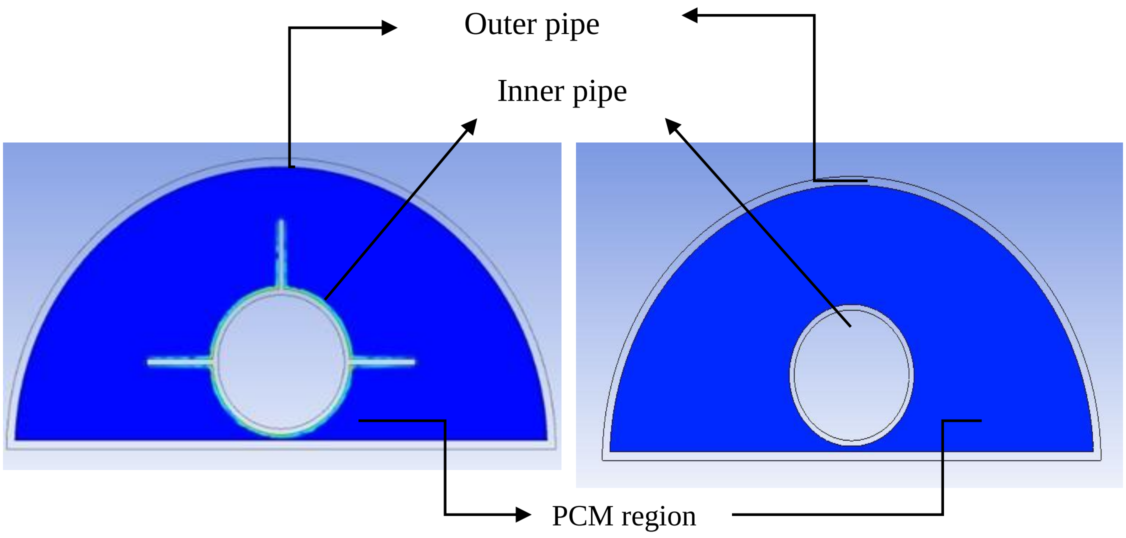


Fig 3.1 Representation of computational domain

In the present study semi-circular shell and tubes with longitudinal fins are used in which fins mainly attached to the inner tube are studied for three configurations of fin angle shown in fig 3.2. fins angled at 60°, 90°, and 120° are evaluated numerically for the melting performance of the PCM. Copper chosen for the inner tube and fins material because it has high thermal conductivity, making PCM melting easier. For the current investigation, a semi-circular shell is used, with steel as the shell material. Phase changing material having desirable properties as required and because of availability of the same is considered for the study named as lauric acid the one organic non-paraffin PCM. The thermophysical characteristics of lauric acid were extracted from Kumar and Verma (2020). The following are the geometric parameters: inner (copper) and outer (stainless steel) tubes have inner radiuses of 11.5mm and 48.5mm, respectively, with thicknesses of 1mm and 1.5mm.

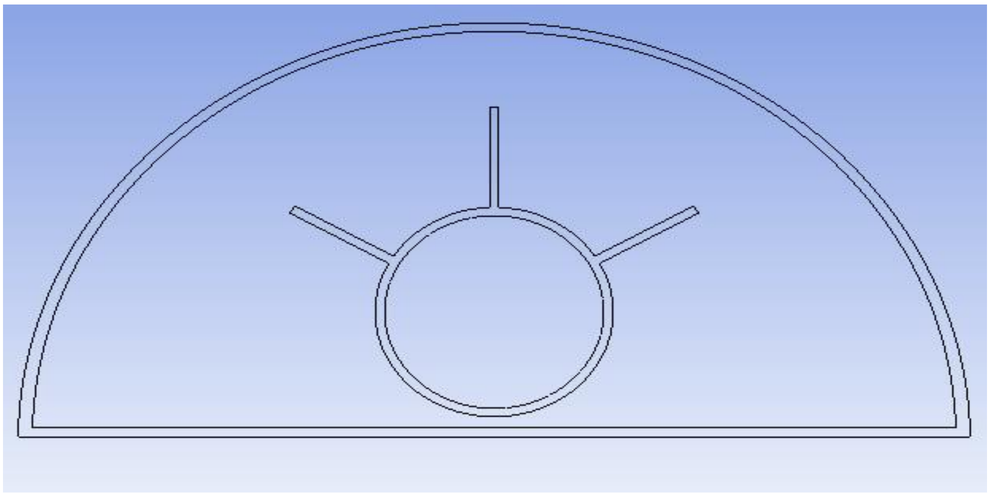


Fig3.2 (a) Fins at an angle of 60°

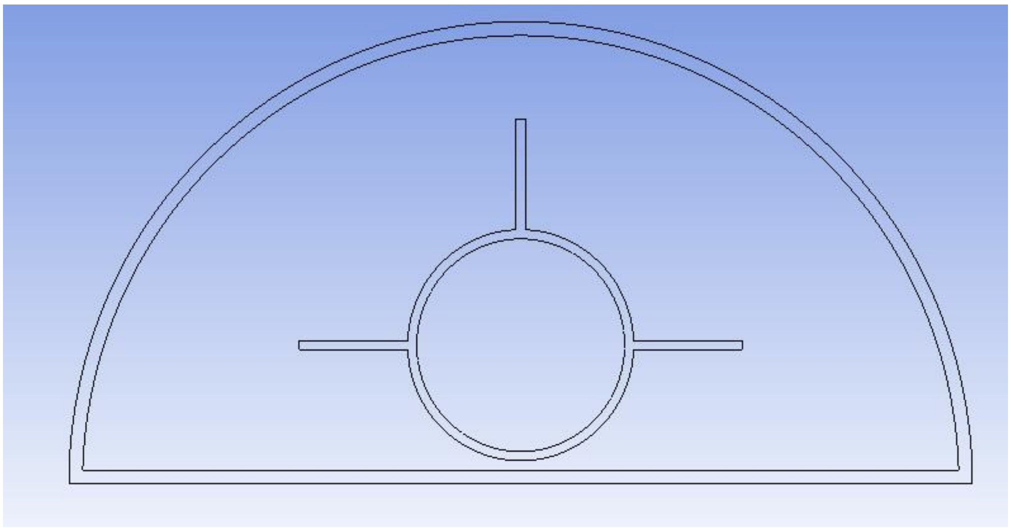


Fig 3.2(b) Fins at an angle of 90°

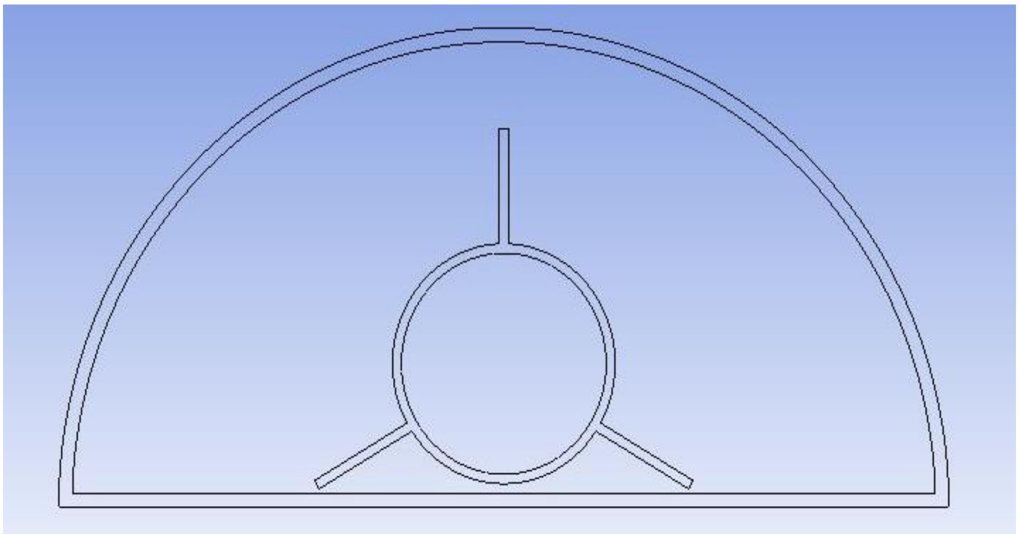


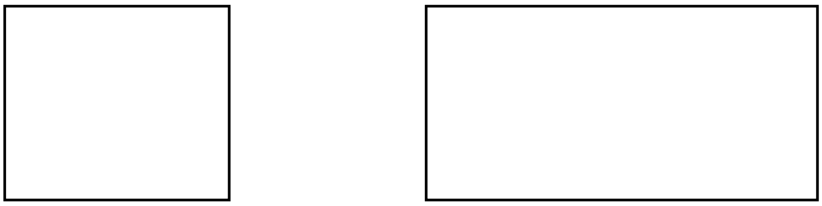
Fig 3.2 (c) Fins at an angle of 120˚

3.1.2 Mesh generation or grid generation

For numerical analysis of the physical model, mesh generation is one of the key steps to get accurate results. Ansys workbench helps to create geometry generating the mesh, problem setup, solution, and evaluate results. The quality of mesh decides the accuracy and convergence of the results better the quality of mesh generated better the results we will get. So, during mesh or grid generation following parameters must be considered which are helpful for the quality of the mesh generated and kept under the desired limit.

3.1.2.1 Aspect ratio

The stretching capability of the meshed cell is defined by its aspect ratio. And aspect ratio is also defined as the ratio of the longest side of the meshed cell to the shortest side of the meshed cell. The value of which is equal to 1 in the ideal scenario, but it should be close to 1 in multidimensional analysis.



Aspect ratio 1 Highest aspect ratio cell

Fig 3.3 Diagram of aspect ratio

3.1.2.2 Element quality

The mesh element quality should be 1 or close to 1, resulting in a perfect cube in the 3-D case and a perfect square in the 2-D case. The mesh element's quality spans from 0 to 1. Where 0 denotes poor mesh quality and 1 denotes excellent mesh quality.

For 2-D quadrilateral element

$$\text{Quality}= \mathbf{c}\left[\frac{\boldsymbol{Area}}{\sum(\boldsymbol{Edge\ length})^2}\right]$$

3.1.2.3 Skewness factor

One of the most crucial indicators of mesh validity and quality is the skewness factor. Higher skewness factors impact the accuracy of inserted areas by breaking the equiangular behavior of cells. The cell with the value of 0 is considered the best, while the cell with the value of 1 is considered the worst.

$$\text{skewness} = \max\left[\frac{\theta_{max} - \theta_e}{180° - \theta_e}, \frac{\theta_e - \theta_{min}}{\theta_e}\right]$$

θ_{max} = largest face angle of the cell θ_{min} = smallest face angle of the cell

θ_e = equiangular cell angle

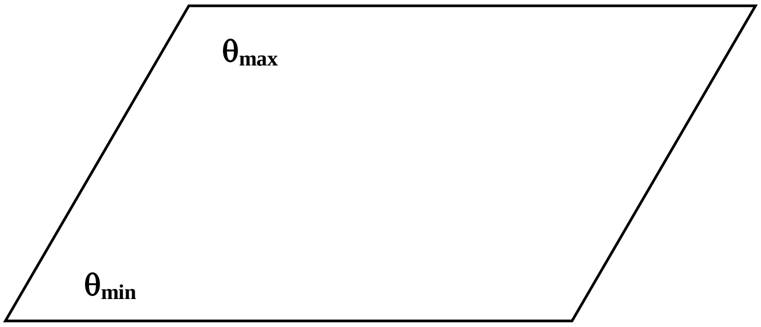


Fig 3.4 Skewness of quadrilateral

3.1.2.4 Orthogonality

In meshing, orthogonality refers to the ratio of angles between nearby element faces. Orthogonality is a generated mesh that ranges from 0 to 1, with 0 indicating the worst and 1 indicating the best.

3.2 Grid (N) independent test

The grid-independent test shows independence in the size of the grid in which the size of the grid is refined to a smaller value and the solution obtained after refinement is compared with the coarse grid mesh solution. Once the solution becomes independent of the mesh refinement process, stop the test and consider the respective number of grids for the solution to the problem. Four grid systems are investigated to make sure grids for independent solutions i.e., 24202, 28448, 32655, 35868 for the grid-independent test boundary condition kept the same for all four-grid systems as shown in fig 3.5.

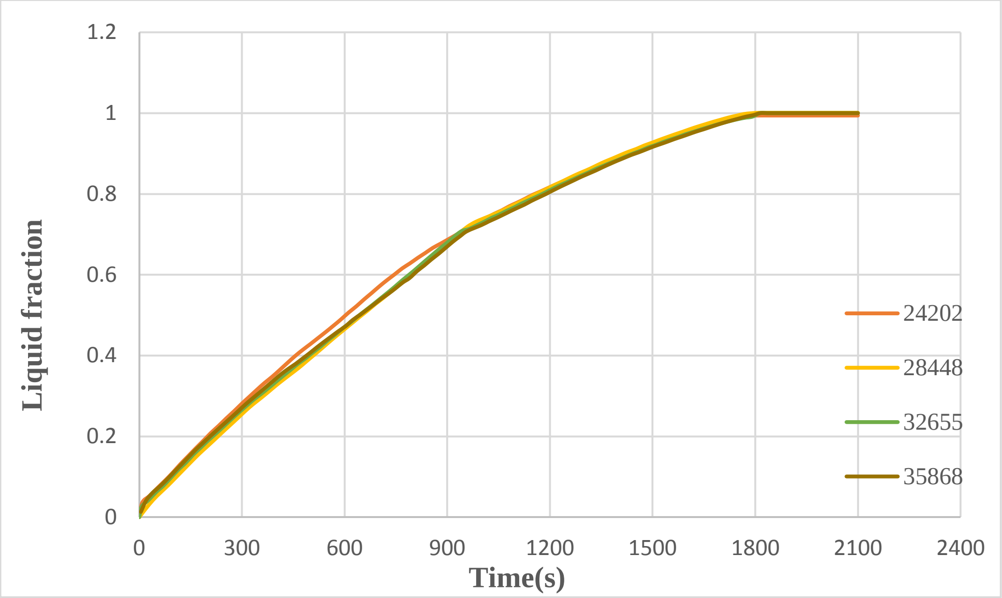


Fig 3.5 Variation of liquid fraction with time for different grid size for semi-circular shell and finned tube

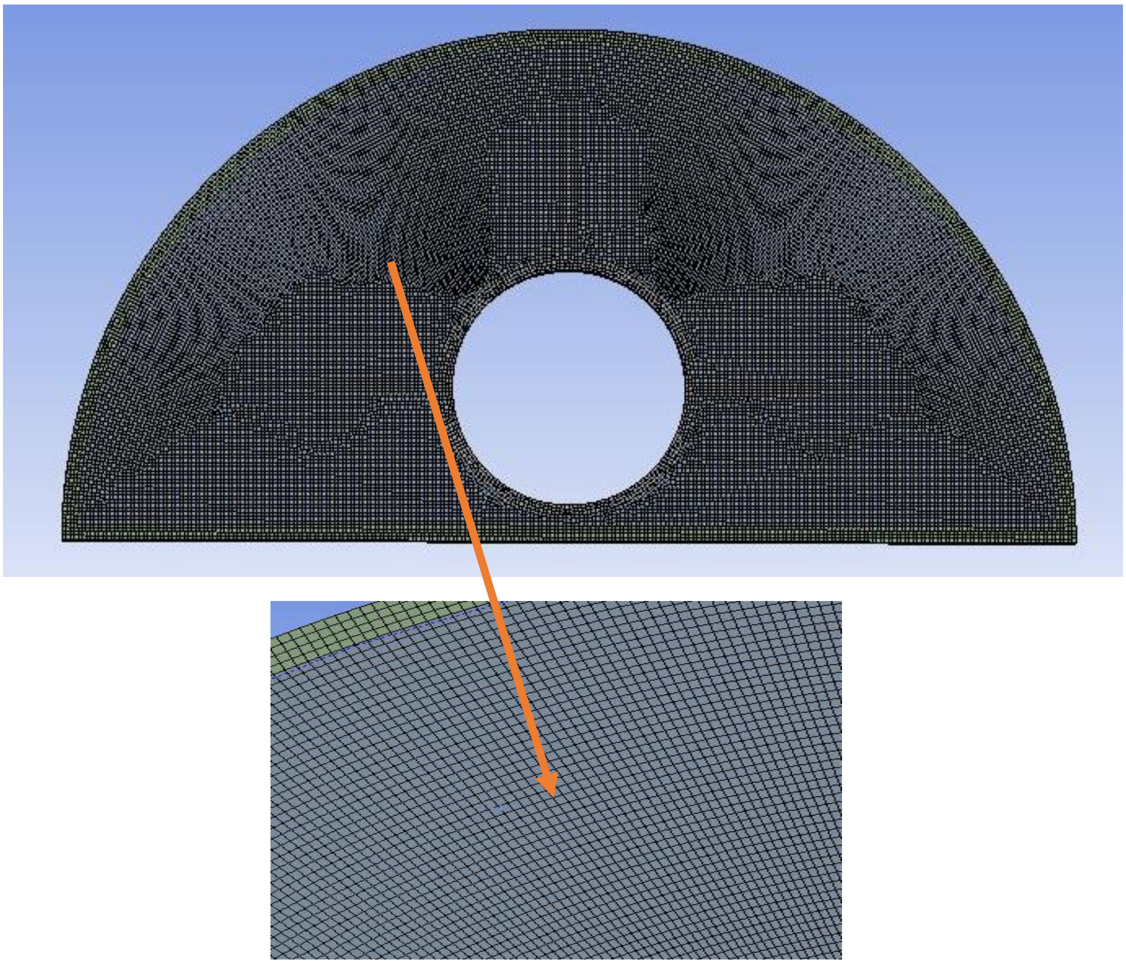


Fig 3.6 Picture of 2-D model with grid

3.3 Time independent test

Time independent test is done to make sure that the obtained results in the numerical study do not dependent on the time step size, it is a necessary step before going to solution because it saves computational time. In this work, choosing multiple time steps and if the computational results come out similar for these time steps, then there has a choice of selecting the time step size that fits the convergence requirements and also saves a lot of computational time. In the present numerical study, four distinct time step sizes 0.02, 0.04, 0.05, 0.08 were investigated. The mesh size, initial and boundary conditions are kept the same for all time step size during the investigation, fig 3.7 represents the results of a time-independent test, the graph plotted between liquid fraction vs time, as for all time step size liquid fraction curve overlaps, which indicates that our model is independent of time step size to achieve the convergence criteria while simultaneously reducing computation time 0.05-time step size has been chosen in a subsequent calculation.

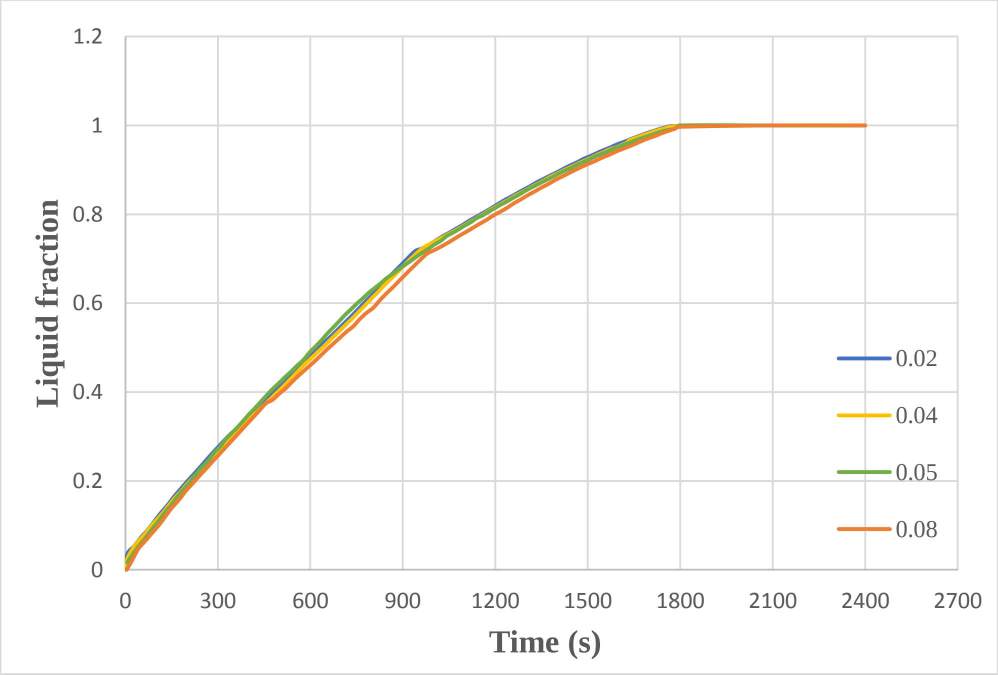
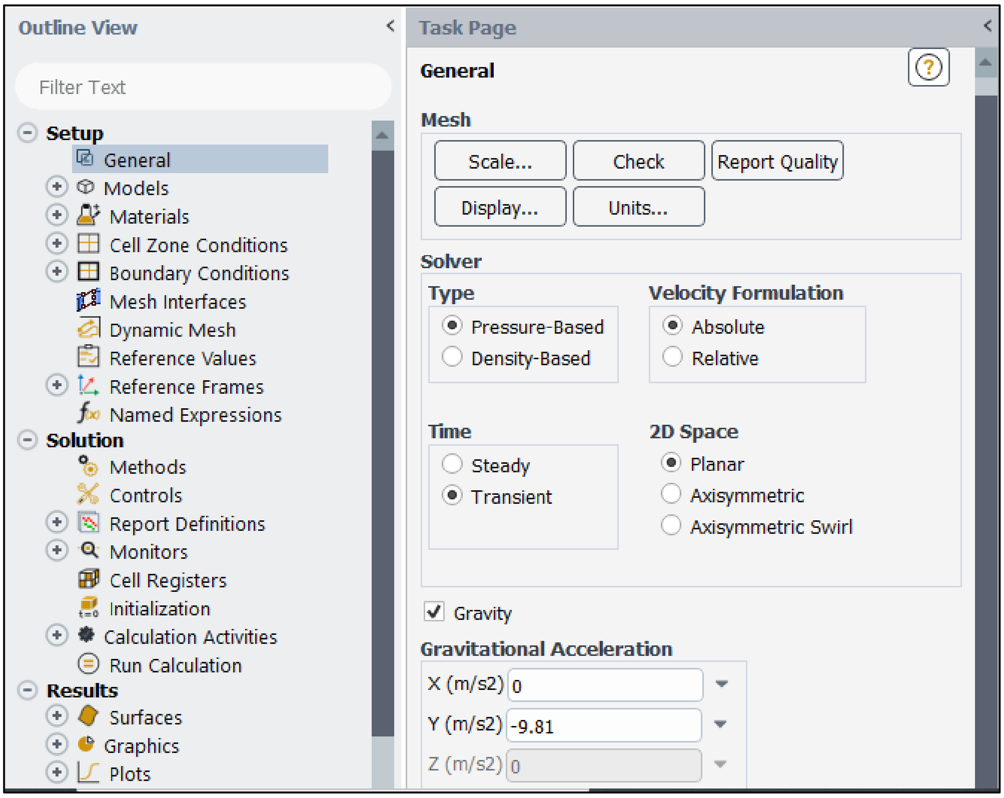


Fig 3.7 Liquid fraction vs time for different time step size for semi-circular shell and finned tube

3.4 Fluid fluent setup

The step in the process of solving equations that govern the melting process follows the modeling of geometry and grid generation. Problem setup, solution, and results are the three sections of the Ansys fluent solver. Model details, computational domain materials, boundary conditions, dynamic mesh, and reference values are all part of the problem setup.

3.4.1 Problem set up (General)



General

Solver

Type
● Pressure-Based
○ Density-Based

Velocity Formulation
● Absolute
○ Relative

Time
○ Steady
● Transient

2D Space
● Planar
○ Axisymmetric
○ Axisymmetric Swirl

☑ Gravity

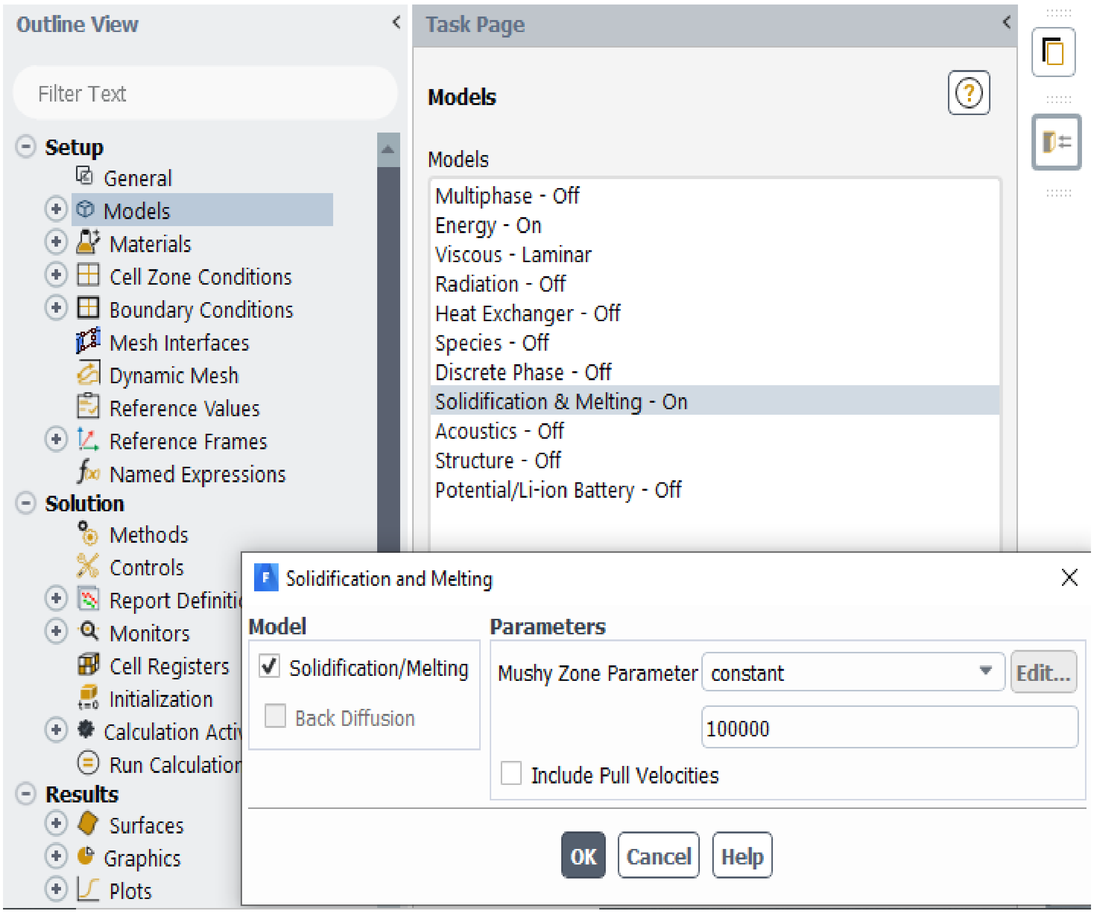
Gravitational Acceleration

X (m/s2) 0
Y (m/s2) -9.81
Z (m/s2) 0

Fig 3.8 General settings in Ansys fluid fluent

The preceding settings in Ansys fluid fluent set-up are applied to a 2-D representation of the present work. Fig 3.9 demonstrates a simplified 2-D computational domain based on planar symmetry for a pressure-based transient analysis with zero relative velocities.

3.4.2 2-D Numerical model



Models

Multiphase - Off
Energy - On
Viscous - Laminar
Radiation - Off
Heat Exchanger - Off
Species - Off
Discrete Phase - Off
Solidification & Melting - On
Acoustics - Off
Structure - Off
Potential/Li-ion Battery - Off

☑ Solidification/Melting
☐ Back Diffusion
Mushy Zone Parameter constant
100000
☐ Include Pull Velocities

Fig 3.9 Model setting in Ansys fluid fluent

During the melting process due to the involvement of natural convection and latent heat energy, the heat transfer process exhibits non-linear behavior during this process. In this process a solid-liquid interface is formed which separates the liquid from the solid part of the PCM, this interface starts growing with an increase in the volume of the PCM concerning time in storage annulus, as a result, it behaves as a moving boundary problem. For which there is an inbuilt characteristic in Ansys fluent software represented in the fig 3.9 as solidification and melting.

It's the enthalpy porosity model, which considers the natural convection mode of heat transfer in the solid-liquid interface and is commonly used for solidification and melting processes.

3.5 Materials and governing equation

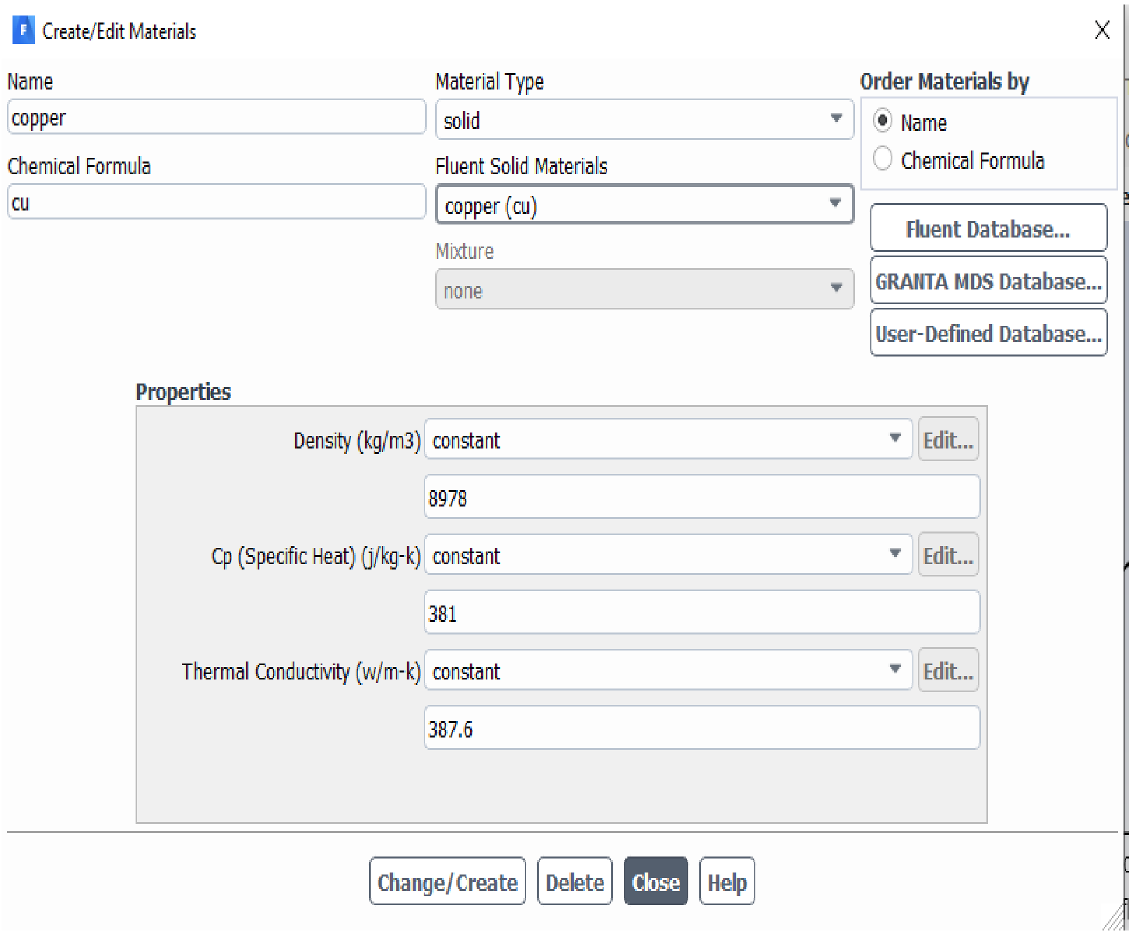
In the Present work the three computational domains are considered for the numerical solution, for different zones different materials are selected and used for the analysis selection of material is based on the previous study done by the different researchers which are discussed below:

The inner tube (copper)

The outer shell (stainless steel)

Pcm region (lauric acid)

Properties of copper and stainless steel are already available in the fluent database and on that basis the numerical calculations proceeds.



Name: copper

Chemical Formula: cu

Material Type: solid

Fluent Solid Materials: copper (cu)

Mixture: none

Order Materials by: ● Name ○ Chemical Formula

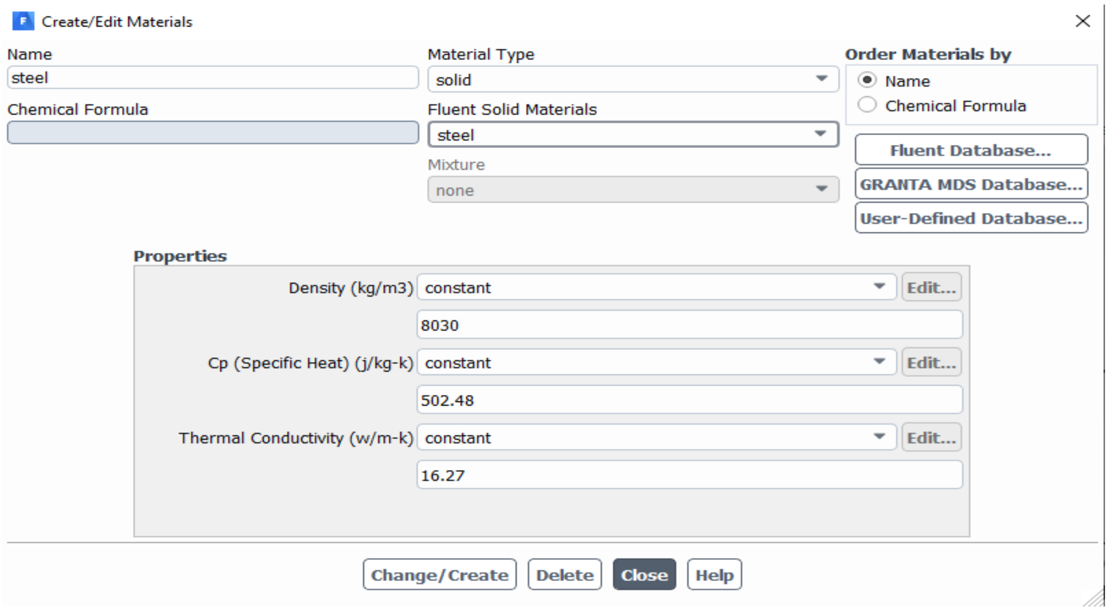
Properties

Density (kg/m3): constant — 8978

Cp (Specific Heat) (j/kg-k): constant — 381

Thermal Conductivity (w/m-k): constant — 387.6

Fig 3.10 Ansys fluent database copper properties


Create/Edit Materials

Name: steel

Chemical Formula:

Material Type: solid

Fluent Solid Materials: steel

Mixture: none

Order Materials by
● Name
○ Chemical Formula

Properties

Density (kg/m3): constant
8030

Cp (Specific Heat) (j/kg-k): constant
502.48

Thermal Conductivity (w/m-k): constant
16.27

Fig 3.11 Ansys fluent database stainless steel properties

Table 3.1 Thermophysical properties of lauric acid

Properties	**Lauric acid**	**Copper**	**Stainless steel**
Density	862 kg/m^3	8978kg/m^3	8030kg/m^3
Specific heat capacity C_p	2300 kJ/kg	381kJ/kg	502.48KJ/kg
Thermal conductivity	0.147 w/m^2-k	387.6w/m^2-k	16.27w/m^2-k
Thermal expansion	0.000615m^{-1}	NA	NA
Dynamic viscosity	0.005336Nsm^{-2}	NA	AN
Latent heat of fusion	177.4 kJ/kg	NA	NA
Solidus temperature	316.65K	NA	NA
Liquidus temperature	321.35K	NA	NA

3.5.1 Assumption and governing equation

Assumptions that are made to solve the numerical model are as follow:

a) The laminar, transient, and incompressible flow is considered for the melted PCM.

b) The variation in the temperature of the heat transfer fluid is negligible.

c) The nature of thermophysical properties of PCM in the working range of the temperature is constant.

d) For density variation Boussinesq approximation is undertaken.

e) Radiative heat losses, viscous dissipation, and change in volume during phase change are neglected.

The continuity equation, momentum equation, and energy conservation are used to define the fluid flow and heat exchange models in 2-D planer symmetry. (Ansys fluid fluent)

3.5.2 Continuity equation

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

3.5.3 Momentum equation

$$\frac{\partial(\rho u)}{\partial t} + \frac{\partial(\rho uu)}{\partial x} + \frac{\partial(\rho vu)}{\partial y} = -\frac{\partial p}{\partial x} + \frac{\partial}{\partial x}\left(\mu\frac{\partial u}{\partial x}\right) + \frac{\partial}{\partial y}\left(\mu\frac{\partial u}{\partial y}\right) + Su$$

$$\frac{\partial(\rho v)}{\partial t} + \frac{\partial(\rho uv)}{\partial x} + \frac{\partial(\rho vv)}{\partial y} = -\frac{\partial p}{\partial y} + \frac{\partial}{\partial x}\left(\mu\frac{\partial v}{\partial x}\right) + \frac{\partial}{\partial y}\left(\mu\frac{\partial v}{\partial y}\right) + Sv + \rho g\alpha(T - T_m)$$

Where ρ, μ, αand T_m are density, dynamic viscosity, the volume of thermal expansivity, and melting temperature point of the PCM, respectively and g is the acceleration due to gravity.

The enthalpy-porosity model treats the mushy zone as a porous medium that acts as a partially solidified region, with porosity referring to the volume of liquid fraction in a grid cell. The velocity of fluid flow in this region is annihilated as a result of this phenomenon. the descending nature of momentum is due to the diminished porosity in the mushy region. The momentum sink terms are denoted as S,

$$S = \frac{(1-\beta)^2}{(\beta^3 + \varepsilon)} A_{mush}(v - v_P)$$

Where β presents a volume of liquid fraction, ε is a small number (0.001) to avoid division by zero, A_{mush} is the mushy zone constant, and v_p is the pull velocity required for pulling out solidified material from the domain. In this numerical model solidified material is not being pulled from the domain, $v_p = 0$.

$$S = \frac{(1-\beta)^2}{(\beta^3 + \varepsilon)} A_{mush}(v)$$

The mushy zone constant signifies the damping amplitude and the higher value, which can cause a sharp transition of the velocity of material to zero as it solidifies. Very large values may disrupt the stability of the solution.

3.5.4 Energy equation

The enthalpy of the material is computed as the sum of the sensible enthalpy, h, and the latent heat, ΔH:

$$H = h + \Delta H$$

Where;

$$h = h_{ref} + \int_{T_{ref}}^{T} C_P dT$$

and

h_{ref} = reference enthalpy

T_{ref} = reference temperature

Cp = specific heat at constant pressure

The liquid fraction, β, can be defined as

$\beta = 0$ if $T < T_{solidus}$

$\beta = 1$ if $T > T_{liquidus}$

$\beta = \frac{T - T_{solidus}}{T_{liquidus} - T_{solidus}}$ if $T_{solidus} < T < T_{liquidus}$

latent heat content can now be written in terms of the latent heat of the material, L:

$$\Delta H = \beta L$$

The latent heat content can vary between zero (for a solid) and L (for a liquid). For solidification/melting problems, the energy equation is written as

$$\frac{\partial}{\partial t}(\rho H) + \nabla.(\rho\ v\ H) = \nabla.(k\nabla T) + S$$

Where, H = enthalpy, ρ = density, v = fluid velocity, S = source term

The solution for temperature is essentially an iterative technique between the energy and liquid fraction equations. In Ansys fluid fluent, the method proposed by Voller and Swaminathan in 1987 is used to upgrade the liquid fraction.

3.5.5 Initial and boundary condition

Boundary conditions are essential and are required to solve the problem, in the present work there are three computational regions which are inner pipe, PCM region, and outer pipe.

- Initial condition for the computational region

  t = 0, $T(x,y) = T_o = 298.15K$

- boundary condition for the computational region

  r = r_i = 12.5mm T=Tw= 333.15, 343.15, 353.15K.

the semi-circular shell outer wall is assumed to be purely adiabatic, no loss of heat from the outer wall have adiabatic boundary condition is

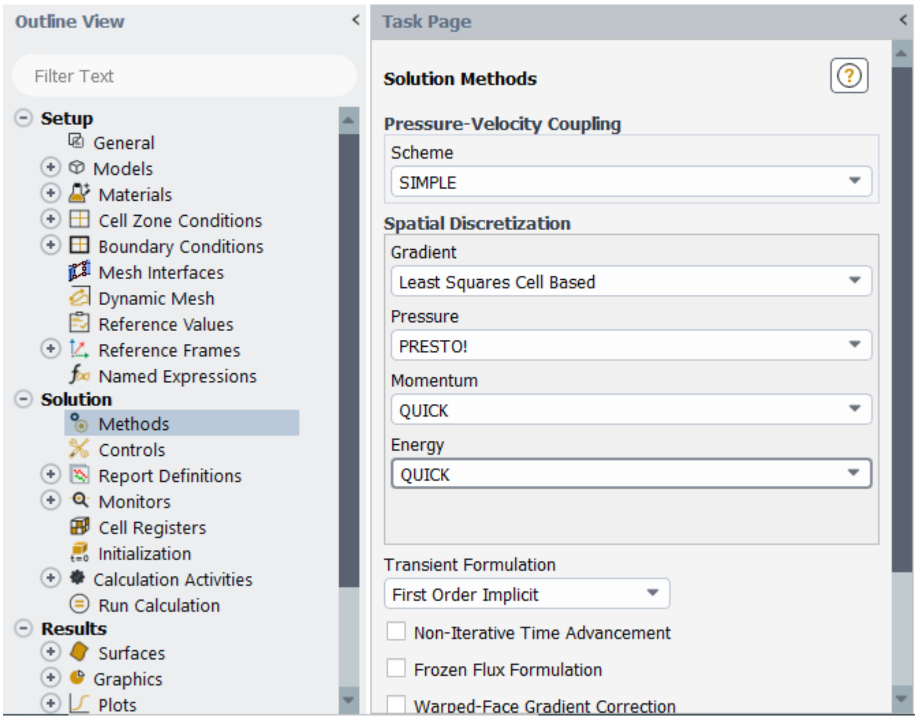
r = r_o= 50mm, $\frac{\partial T}{\partial r} = 0$,

The coupled boundary condition for the inner pipe outer wall and outer pipe inner wall is

$$u = v = 0,\ T_s = T_{PCM},\ -k_s\left(x\frac{\partial T_s}{\partial x} + y\frac{\partial T_s}{\partial y}\right) = -k_{PCM}\left(x\frac{\partial T_{PCM}}{\partial x} + y\frac{\partial T_{PCM}}{\partial y}\right)$$

The couple boundary condition signifies those values of the parameters at a nodal point of the outer wall of the inner tube will act as input values for the nodal points in the solid surface of PCM.

3.6 Solution method



Solution Methods

Pressure-Velocity Coupling

Scheme: SIMPLE

Spatial Discretization

Gradient: Least Squares Cell Based

Pressure: PRESTO!

Momentum: QUICK

Energy: QUICK

Transient Formulation: First Order Implicit

☐ Non-Iterative Time Advancement

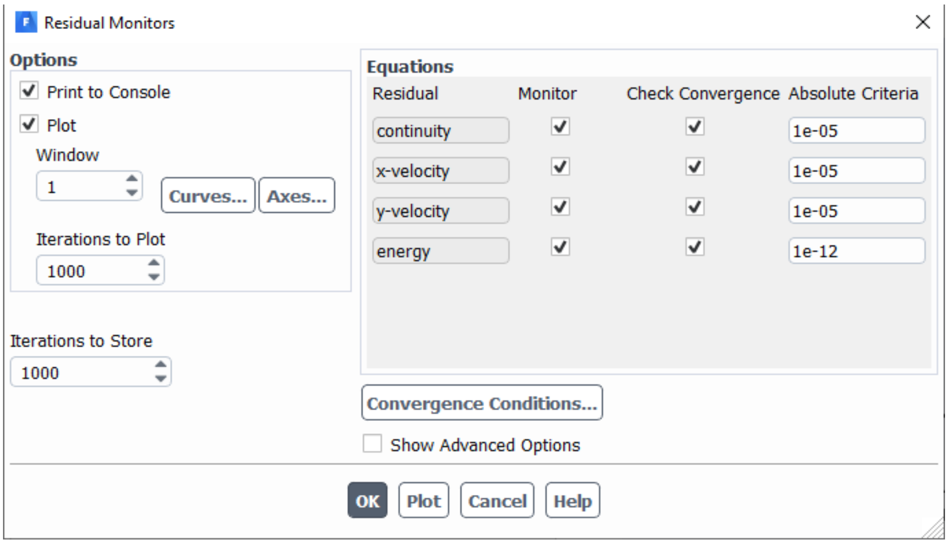
☐ Frozen Flux Formulation

☐ Warped-Face Gradient Correction

Fig 3.12 Schemes and solution method used for solving the governing equation

The SIMPLE (semi-implicit method for pressure-linked equations) approach is employed to solve the governing equations used in this heat transfer energy storage model. Prof. Brian Spalding and Suhas Patankar created the SIMPLE method in the 1970s to solve the fundamental governing equations of fluid mechanics. Individual convective terms in energy and momentum equations are deduced using the QUICK differencing model [Y. Pahamli 2016]. The pressure values at the cell faces are calculated using the PRESTO (Pressure Staggering Option) scheme and the momentum equation.

The 1e-05 convergence criteria have been used for flow equations, and the 1e-12 convergence criteria are used for energy equations, as illustrated in fig 3.13. Temperature data are recorded at various locations under the surface monitoring (shown in fig 3.14). Under the volume monitor, the melting rate or liquid fraction is tracked.



Residual Monitors

Options

☑ Print to Console

☑ Plot

Window: 1

Iterations to Plot: 1000

Iterations to Store: 1000

Equations

Residual	Monitor	Check Convergence	Absolute Criteria
continuity	☑	☑	1e-05
x-velocity	☑	☑	1e-05
y-velocity	☑	☑	1e-05
energy	☑	☑	1e-12

☐ Show Advanced Options

Fig 3.13 Convergence criteria tab in the residual monitor tab

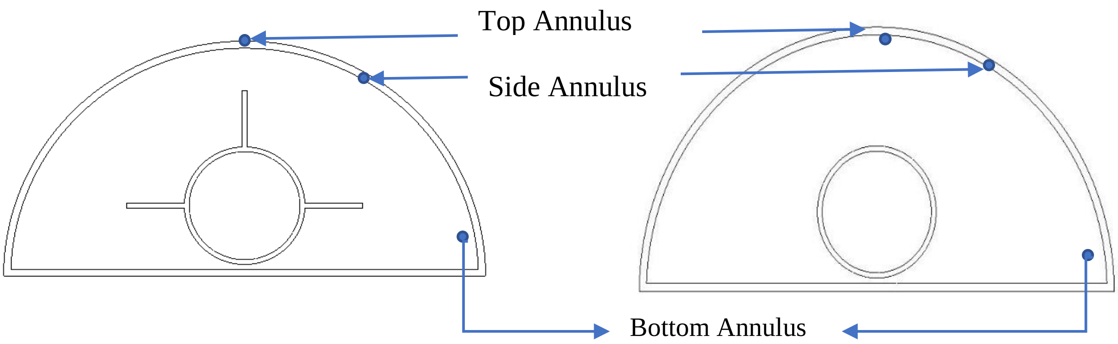


Fig 3.14 Temperature monitor at different annulus position semi-circular shell and finned tube

The temperature is measured at three different annulus positions top, side, and bottom as shown in the figure 3.14.

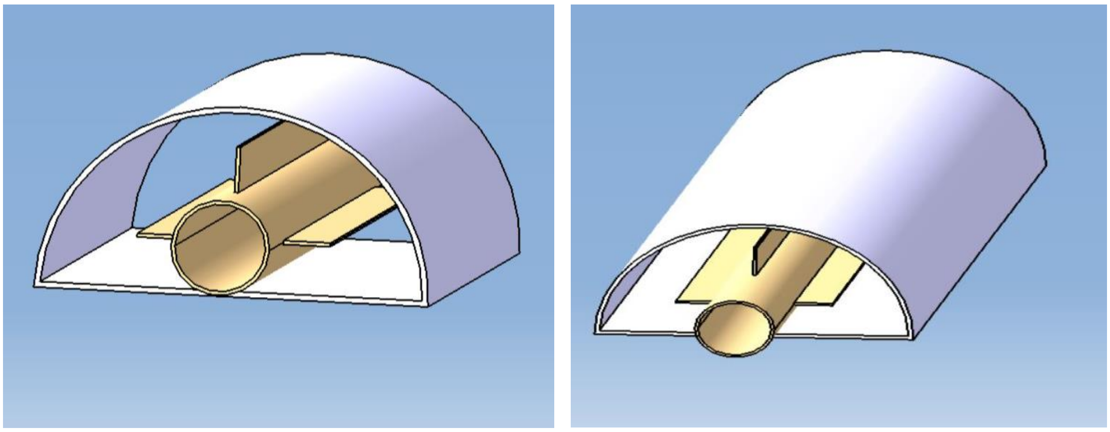


Fig 3.15 3-D View of fins attached to the inner tube semi-circular shell

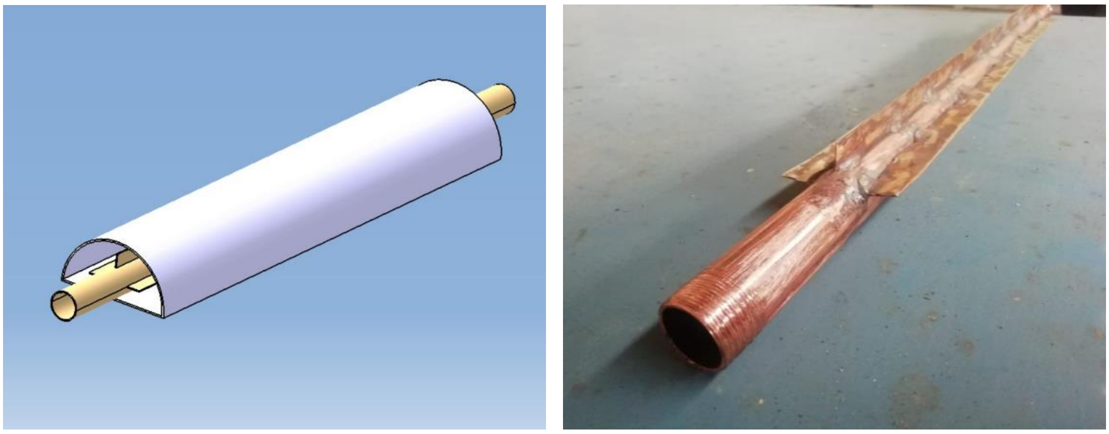


Fig 3.16 3-D View of semi-circular shell and finned tube (θ = 90°)

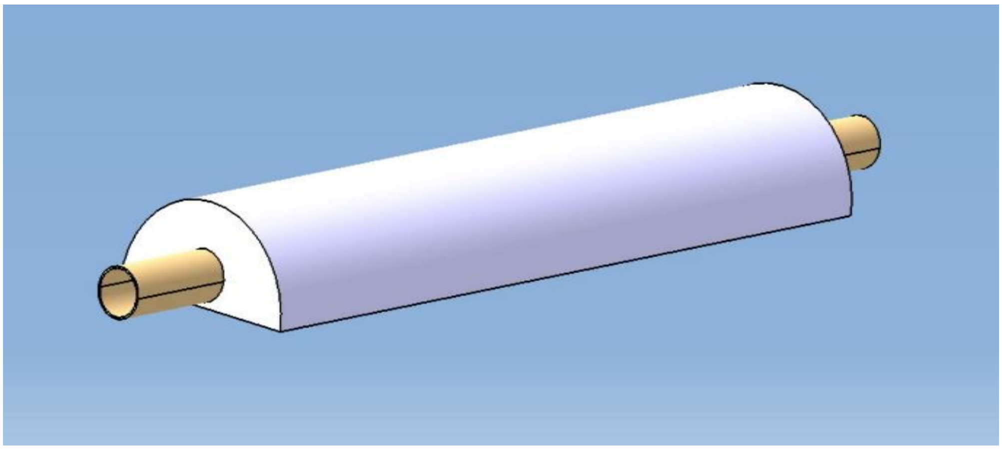


Fig 3.17 3-D View of semi-circular shell with un-finned tube

3.7 Experimental work

The experimental work involves the fabrication of a thermal storage unit, 2-D model of which first numerically simulated for three configurations of fin angle 60º, 90º, 120º, based on that the best result for the 90º fin angle configuration found best, so to validate the numerical results an experimental set up fig 3.18 present in the laboratory which is consist of the hot water bath, circulation pump, rotameter, thermocouple, primary and secondary HTF loops. All components are in good condition which helps to get an error-free result. The experimental study is done at T= 80ºC, T= 70ºC, T= 60ºC at mass flow rate of 4 liter per minute.

Fig 3.18 Experimental setup

3.7.1 Thermal energy storage unit

A thermal storage unit is the one on which the whole work depends the size of the unit can vary but in present work, the TES unit dimensions are similar to kumar and verma 2021, the inner tube of copper material and the outer shell is of steel pipe materials selected based on previous research work. Three longitudinal fins are attached to the inner tube, to enhance the rate of heat transfer and hence the melting performance of the thermal storage unit. The storage unit is filled with lauric acid and the outer shell is covered with glass wool of thermal conductivity 0.04W/m-K which reduces the heat loss and maintains the temperature of the heat transfer fluid constant. Fig 3.19 shows the geometric dimension of the thermal energy storage unit.

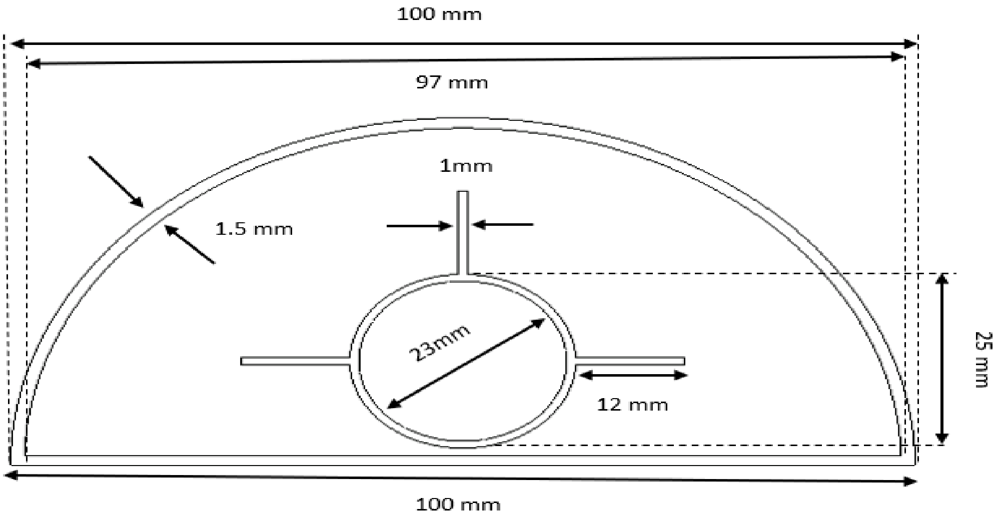


Fig 3.19 Geometric dimensions

Fig 3.20 Thermal storage unit

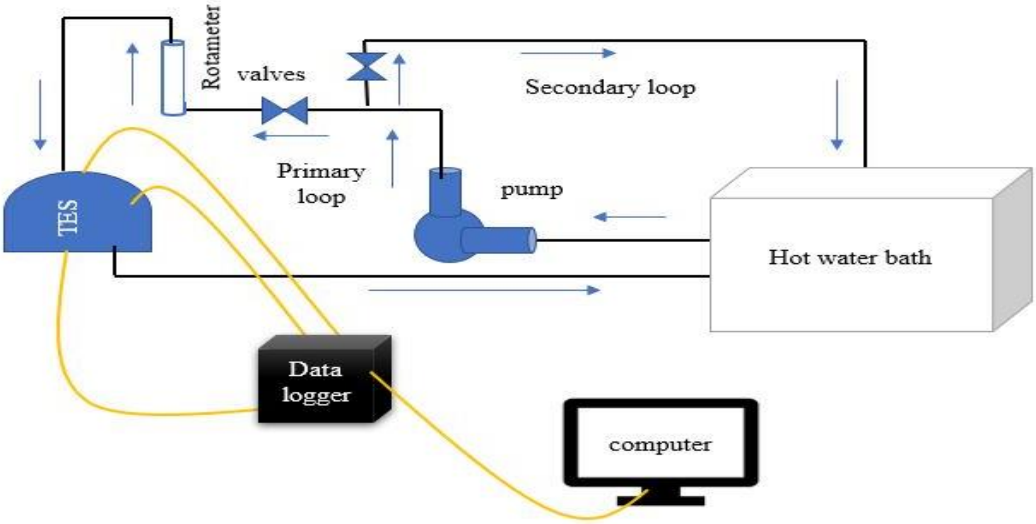


Fig 3.21 Schematic representation of an experimental setup

The set-up consists of data measuring instrument primary and secondary loop of for circulating heat transfer fluid, as the experiment is based on charging process so to deliver constant temperature fluid hot water bath is used here and to regulate the flow rate rotameter is used. As thermocouples are attached to TES at different annulus positions as shown in fig these thermocouples are connected to the data logger which records the data (temperature) at a regular period say 1 minute.

The annulus region of the heat exchanger has been filled with molten PCM with no leakage detected the melting process begins. The temperature of solid PCM is assumed (26-27°C) equivalent to the ambient temperature. During the melting process, a hot water bath maintains the temperature of the HTF constant. The experiments are been carried out at two different heat transfer fluid (HTF) charging temperatures (Ti= 70°C and 60°C), whereas numerical simulations are carried out run at three different HTF charging temperatures (Ti= 80°C, 70°C, and 60°C). The corresponding Stefan number, for three HTF inlet temperatures, is determined based on the equation mentioned in which the changing HTF inlet temperature (Ti) is a varying parameter.

$$\text{Stefan number} = \frac{\text{specific heat}}{\text{latent heat}}$$

Which can also be written as $\text{Ste} = \frac{\mathbf{Cp(Ti-Tm)}}{\mathbf{L}}$

Where, every term has its usual meaning C_p, L, T_m specific heat, latent heat of fusion, and the mean melting temperature PCM respectively.

$\mathbf{T_m} = \frac{(Ts+Tl)}{2}$ where Ts is solidus temperature and T_l is liquidus temperature of PCM, which tells about the melting temperature range of the HTF, the Stefan number for three different charging temperatures of HTF is Ste1=0.45, Ste2= 0.32 and Ste3= 0.18 for inlet temperature of 80°C, 70°C, 60°C respectively.

3.7.2 Hot water bath

Hot water bath having capacity of 15 L with a heating element of 1.5 KW as shown in the figure, the accuracy of the water bath(BS1515) is ± 0.05 ºC for regulating the temperature of the heat transfer fluid in the range of 0ºC to 100ºC. Distilled water is used as heat transfer fluid the purpose of using distilled here is to prevent the heating element from rusting.

Fig 3.22 Picture of hot water bath

3.7.3 Water circulating Pump

It has a 0.5-horsepower motor with a discharge rate of 33 LPM. It has a completely metal body with a voltage range of 180V to 220V.

Fig 3.23 Picture of water circulating pump

3.7.4 Rotameter

The pump's discharge capacity is 33 LPM, which is too high for this investigation, so a rotameter is employed to measure the flow rate of HTF. It has a measurement range of 0 to 20 LPM. Its entire body is constructed of acrylic material having the property to withstand a temperature of 80ºC. The rotameter utilized in this study is depicted in Figure 3.24.

Fig 3.24 Picture of flow meter

3.7.5 Temperature data scanner

It’s an 8-channel microprocessor-based thermocouple system with linear behavior for J/K/R thermocouples. It saves a significant amount of data, which can be simply transferred to a USB pen drive or directly stored in an MS Excel compatible file on a USB pen drive as needed. The data can be saved at any time step. The voltage difference at the thermocouple’s tail end is used to represent the value of standard temperature in digital form. Figure 3.25 depicts a universal data logger, which is used in this experimental study.

Fig 3.25 Picture of data logger

3.7.6 Thermocouple

Thermocouples are temperature sensors that work on the principle of the see-back effect. The thermocouples used in this study are type-k probe thermocouples with a probe diameter of 0.06 inches and a length of 0.4 inches, as indicated in the fig 3.26. The thermocouple used in this study is mineral-insulated wire with a larger temperature range resistance. The thermocouple used in the study has a temperature range of 0ºC to 1250°C.

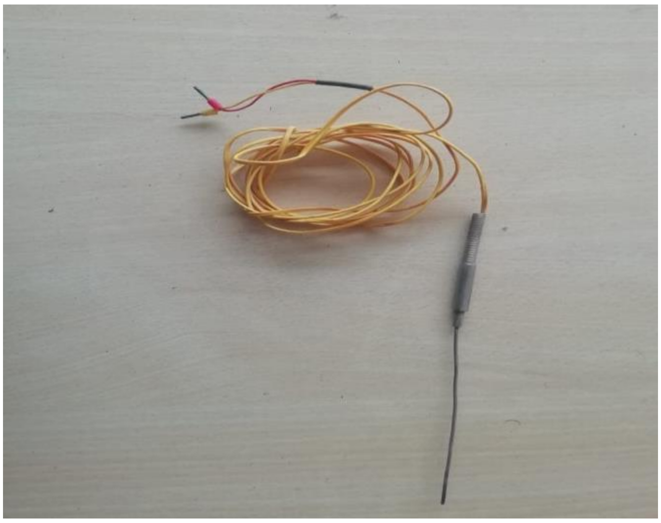


Fig 3.26 Picture of thermocouple

3.7.7 Calibration of thermocouple

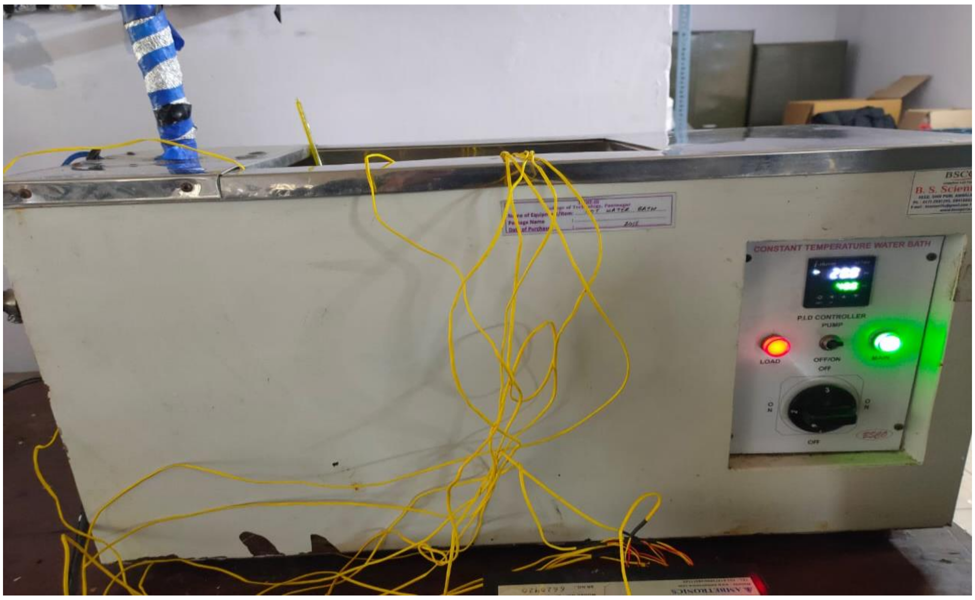


Fig 3.27 Picture of thermocouple calibration

As illustrated in the figure 3.27, thermocouple calibration has been performed using a thermometer and a digital temperature scanner. The constant temperature hot water bath is utilized for higher temperature calibration from 25ºC to 95ºC. the very First in calibration is to fix the temperature of the hot water bath and then the temperature of the hot water inside it is measured by thermometer and thermocouple. for Every 5ºC increase in the temperature of the water in the hot water bath, the temperature of the thermometer and thermocouple is measured until the temperature reaches 95ºC. Lower temperature ranges are calibrated using crushed ice cubes, which are placed in a glass beaker with a thermocouple and thermometer, and the temperature is monitor.

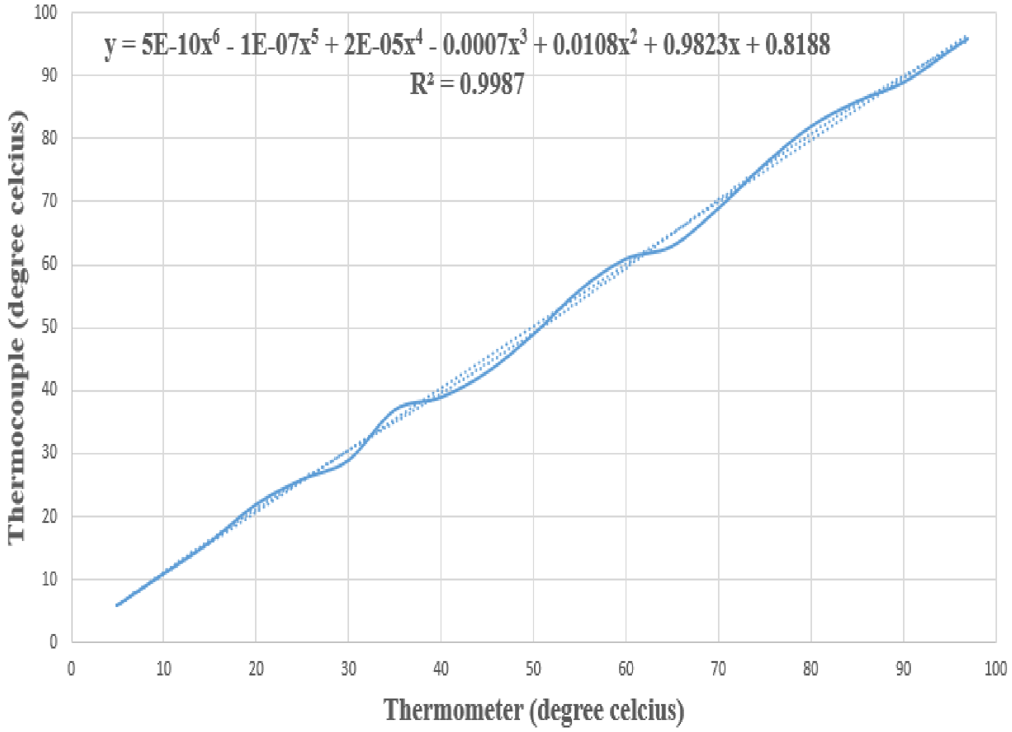


Fig 3.28 Calibration of the thermocouples

Results and Discussion

Chapter 4 RESULTS AND DISCUSSION

The present chapter deals with numerical and experimental results obtained during project work. The work includes investigation of the melting performance of PCM with the finned tube, and then the results obtained are compared with that of semicircular shell and tube unit without a fin. The experimental work is done primarily for the validation of the numerical work. It is also observed during the numerical analysis that the tube having fin at 90° angle shows better performance as compared to other considered angels of fin, so for experimental setup, the tube having longitudinal fins at 90° fin angle has been considered. The experimentally charging process is run for the temperature of 80°C of heat transfer fluid at 4 liter per min.

4.1 Validation of numerical results with the experimental results

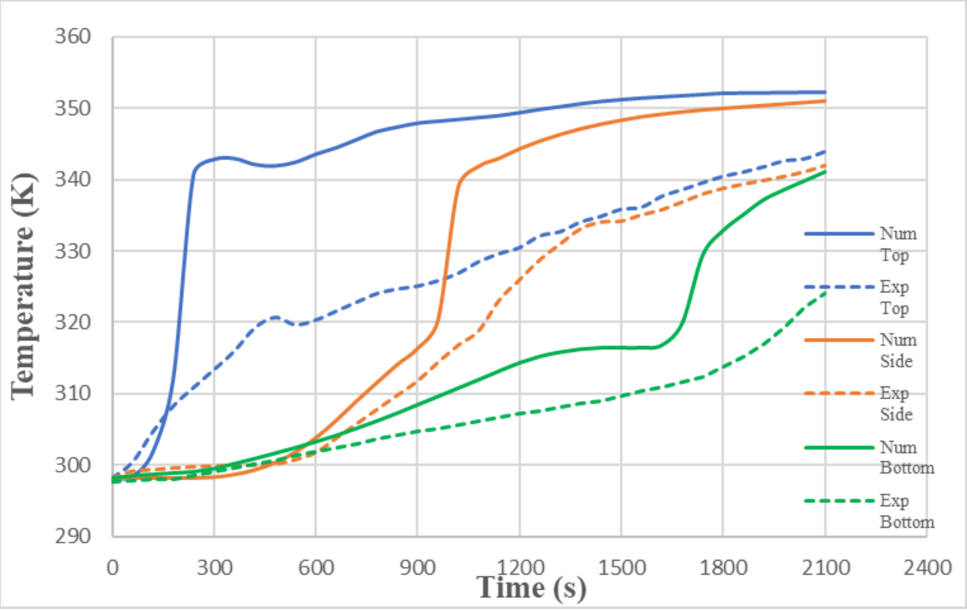


Fig 4.1 Temperature at different annulus region in numerical and experimental study of LHTES system T_{HTF} = 80°C with respect to time

The present work involves numerical simulation for the melting performance of the phase change material in a semicircular shell and finned tube LHTES system. The simulations are run at three different temperatures of HTF for three different orientations based on numerical results the better result is taken into consideration for further analysis and then that numerical model is validated experimentally for the same inlet temperature as taken in numerical simulations as shown in the fig 4.1.

As in the numerical simulation used 2-D model of the LHTES which consider all ideal condition because of that there is no energy or heat loss to the surroundings but in case of actual experimental model there are not only losses that incorporates the error in the results but also there are other reasons also behind it which causes error in the experiment and numerical results, for example in numerical results it is assume that the outer surface of the shell is completely adiabatic but this is not possible in the actual experiments though there is thermal insulation but there is still some loss of heat to the surroundings which results in source error. The formulae used to calculate error;

$$\%\ \text{Error} = \left|\frac{\text{Experinmental value} - \text{accepted value}}{\text{accepted value}}\right| \times 100$$

On the basis of the formulae mentioned above the error calculated at top, side and bottom annulus points are 4.79 % ,2.52 % & 2.03 % respectively. Hence the maximum average error occurred in the work is 4.79 % which is in the acceptable range the numerical model has been considered for further analysis of the LHTS unit.

4.2 Variation of temperature at different annulus positions of semi-circular LHTES system with the finned tube.

The present work is focused on three fin angles 60°, 90° and 120° attached to the tube of the semi-circular shell filled with phase change material, and the numerical study is conducted to investigate the melting performance of the material filled. Numerical study of LHTES system shows that the fin angle at 90° shows the enhanced performance compared to the other fin arrangement, as the heat transfer process proceeds melting fronts start growing as fins are attached to the inner tube of the semi-circular shell the amount of PCM is now in direct contact with an increased surface area of the heat transfer surface. On adding three longitudinal fins the heat transfer contact area is increased and, in our case, the fin covers 49.8 % of the total area of heat transfer surfaces. Due to which the melting performance of the LHTES system enhances.

As melting fronts temperature increases the solid PCM filled in the shell starts melting, the phase change process takes place the fraction of solid converting into liquid due to an increase in temperature, which results in density difference as the density of liquid PCM is lower than the solid PCM at this moment buoyance force acts and the liquid PCM rises because of its lower density and the process continues, in the process the natural convection heat transfer dominates. Heat transfer takes place from HTF to PCM due to the natural convection effect and buyout force the melted PCM always rises so, because of which the temperature of the top annulus region is always higher as compared to the bottom annulus region.

The conduction mode of heat transfer dominates at the start of the melting process then the convection mode of heat transfer dominates once, the considerable amount of PCM melts, throughout the melting process conduction heat transfer occur for a very short duration of time afterward the natural convection mode dominates the heat transfer. It is the melting front that separates the liquid PCM from solid PCM and grows rapidly in the upward direction, the liquid PCM nearer to the pipe wall and fin surfaces gains heat from these surfaces this heat then transfer from liquid PCM to melting front then to the solid PCM which takes time because of the lower conductivity of the PCM. The PCM present near to the pipe and fin surfaces have a higher temperature than the PCM present near the melt front which causes the temperature difference and hence the density difference due to which recirculation of the liquid PCM starts and natural convection dominates and because of which the upper region temperature is always higher than other region and melts faster compared to bottom and side region.

4.3 Effect of fin angle on the melting performance of the PCM in semi-circular shell and finned tube for LHTES system

The melting performance of PCM in semi-circular shells and finned tube LHTES has been investigated for three fin angle arrangements 60°, 90°, and 120° respectively.

In the present work, the tube is placed at an eccentric position having an eccentric ratio e = 0.20 as **Kumar *et al.* (2022)** found that the eccentric position of tube at this position the gap between the inner tube and the bottom surface of the semi-circular shell is 1mm, this minimum gap has been chosen in the present study also because keeping 1mm gap in semi-circular shell and un-finned tube arrangement gives a quit good result and continued for further study on adding fins to the inner tube of the arrangement for enhancing the melting performance of the LHTES arrangement.

For the first 60 seconds of melting, the melting starts consistently in all directions and increases outward radially for all fin angle arrangements, after some time the uniformity is disrupted, the melted PCM rises as the fins are attached to the inner tube of the shell and tube arrangement. The temperature rise of the PCM, in this case is rapid compared to un-finned tube arrangement as it can be seen from the fig 4.2 that the temperature rise for the top region is rapid and the upper region of the semicircular arrangement melts before 240 sec and the temperature rise of the upper region is continuous till the PCM in the LHTES unit melts completely, as it can be seen from the fig 4.2 that the temperature rise for fin angle 60° arrangement is greater for top annulus region because for this fin arrangement all three fins are nearest to the top selected point this is the reason because of which for fin angle 60° the top temperature of the top annulus is always higher throughout the melting performance. The top temperature rises for 90° fin arrangement is higher compared to 120° fin arrangement because of the nearness of the top annulus point from the fin surface and hence the melting rate of the top annulus region is higher in this order 60°, 90° and then 120°.

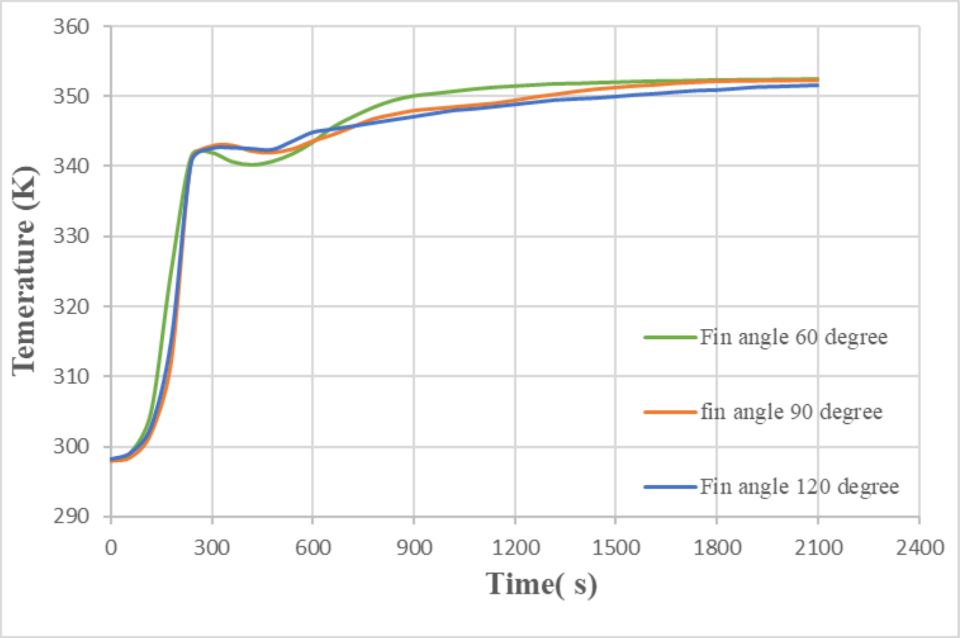


Fig 4.2 Comparison of temperature for different fin angle at top annulus point

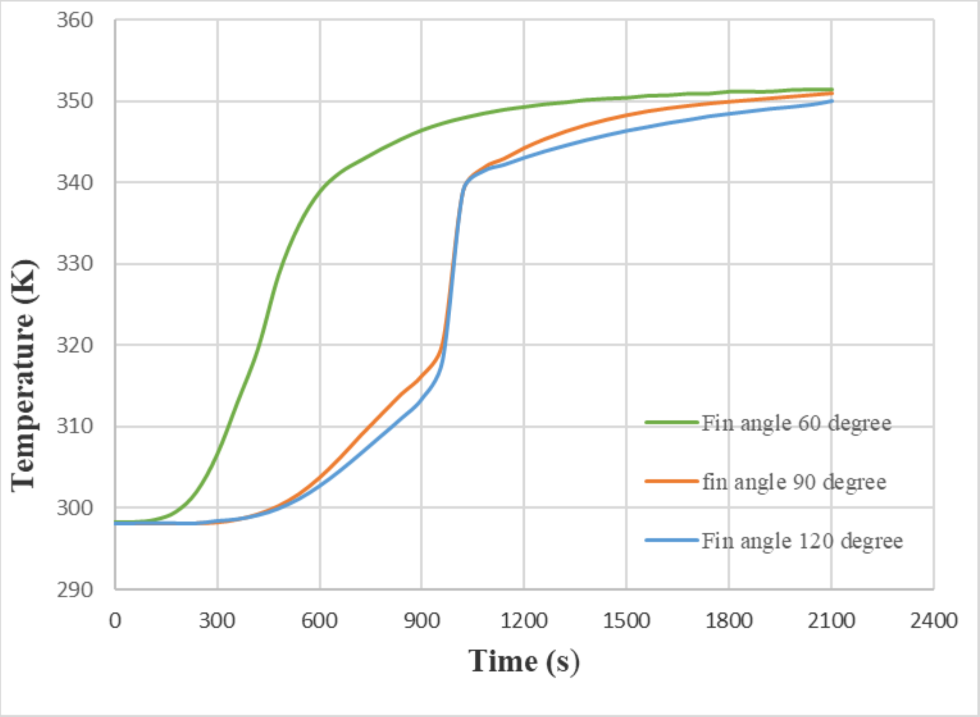


Fig 4.3 Comparison of temperature for different fin angle at side annulus point

The fig 4.3 shows the comparison of the temperature at side annulus point for three fin angle arrangements 60°, 90°and 120°. As it has been discussed that the top annulus temperature of the fin arrangement of 60° is higher due to which the upper region melts and gains a sufficiently high temperature. This melted PCM transfers heat to the side annulus region having un-melted PCM because of which the PCM present in the side annulus region gains higher temperature earlier as compared to the other fin arrangement. Fin arrangement of 90° and 120° shows quite similar behavior for side annulus region though the 90° fin arrangement having a little higher temperature compared to 120° fin arrangement as the fins for 90° configuration are arranged symmetrical and covers each annulus point symmetrically because due to which the side annulus PCM melts uniformly and quickly.

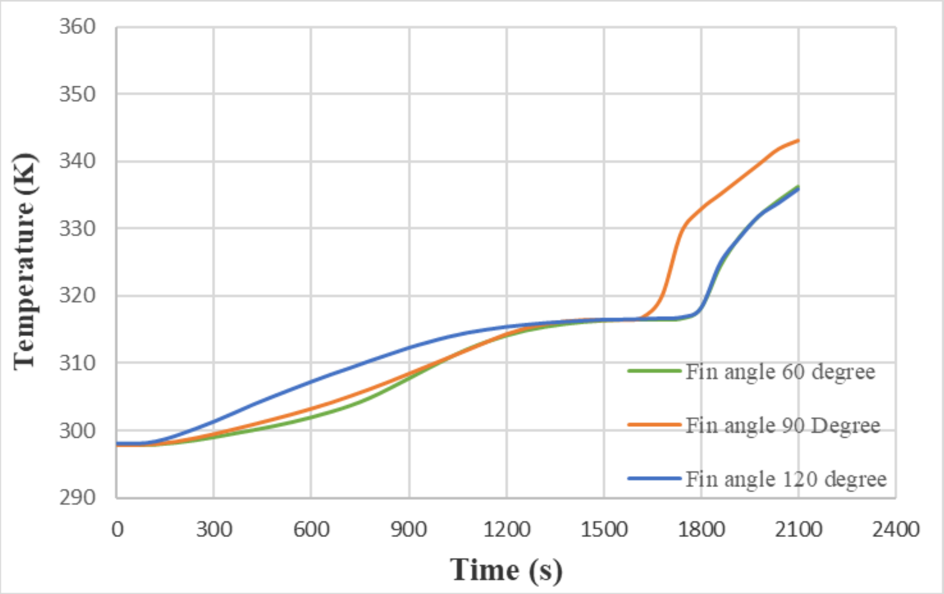


Fig 4.4 Comparison of temperature for different fin angle at bottom annulus point

The fig 4.4 shows the melting behavior and comparison of the bottom annulus region for three fin arrangements 60°, 90° and 120°. The PCM in these configurations melted in the top and side annulus region first because natural convection dominates in these regions and finally the un-melted PCM left in the lower region which takes time because of recirculation effect that arises due to buoyant force which always acts upward it is one of the reasons because of which the PCM at lower annulus melts at the end. The same is the case with present work as there are three fin arrangements for fin angle 90° the bottom annulus temperature reaches its melting point very fast compares to the other fin arrangement once the bottom annulus PCM melted completely it can be conclude that the whole PCM present in the LHTES unit melted completely so from fig 4.4 it is clear that for fin angle 90° the bottom annulus PCM melted completely for which the melting time is minimum and if talk about other fin arrangements 60° & 120° respectively, as for fin angle 60° the top and side annulus region melted quickly but the bottom annulus region is little farther so because of which it takes time to melt bottom annulus PCM. In case of 120° fin angle upper and side annulus regions are taking time so because of which the bottom annulus region is also taking time to melt completely. The net effect for the fin angles of 60° and 120° is the same that is the reason with these arrangements LHTES takes the almost same time having 1 min difference in to melt completely.

4.4 Effect of variation of fin angle on the melting performance of PCM in semi-circular shell and finned tube arrangement.

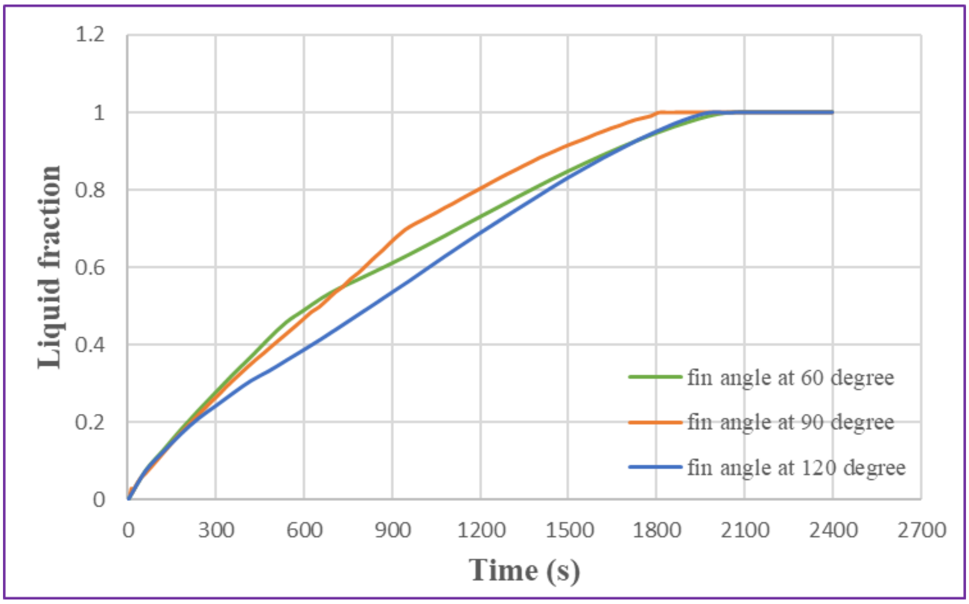
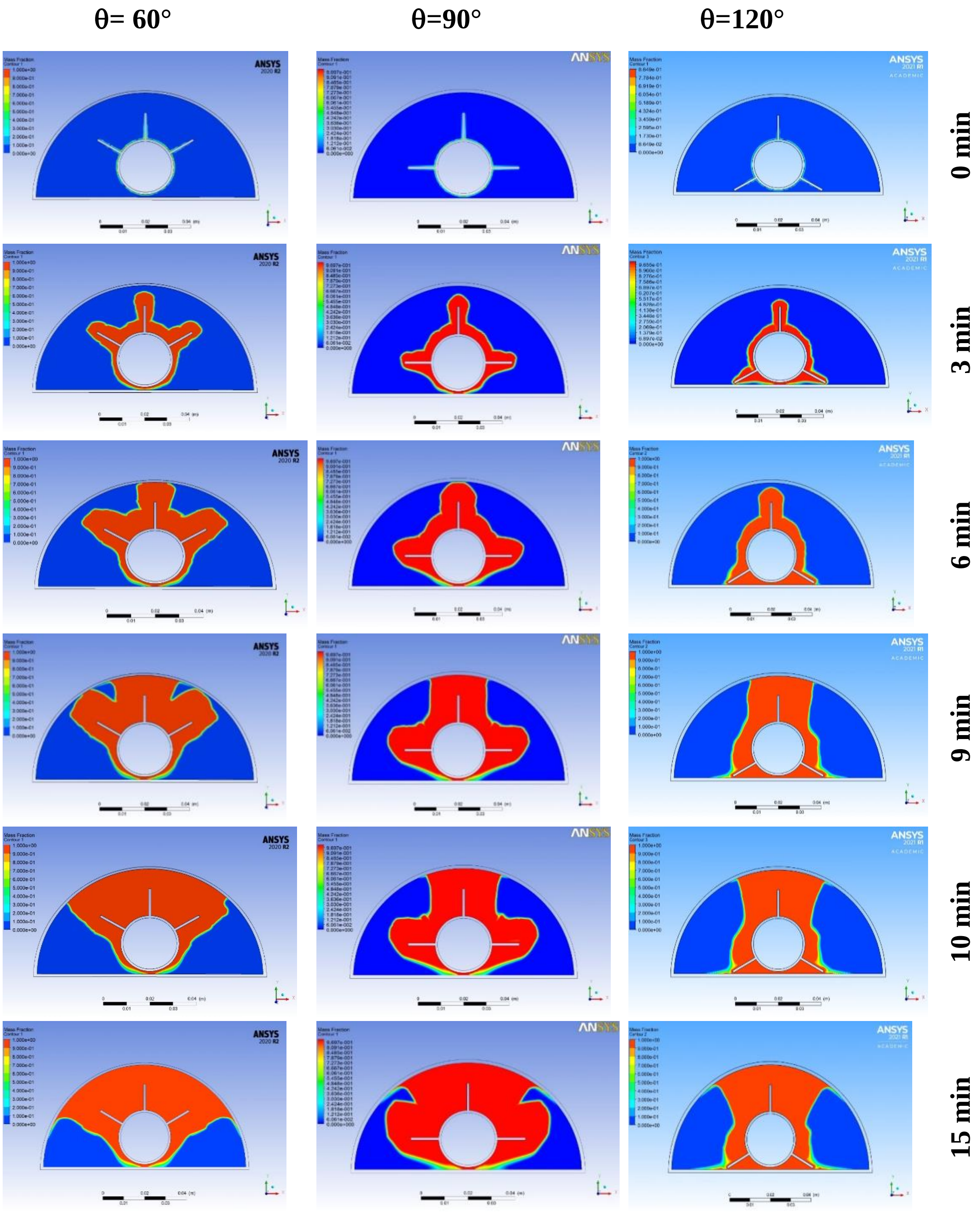


Fig 4.5 Comparison of liquid fraction for different fin arrangement

Present research work is focused on three different arrangements of fin 60°, 90°, 120° in which the melting performance of PCM is investigated numerically as fig 4.5 represents the LHTES unit having fin angle of 90° shows minimum melting time which is around 1800 second that is due to the symmetric arrangement of the fin which helps in uniform melting of the PCM present in the semicircular shell. Similarly, for fin angle 60° and 120° LHTES unit the melting time comes out to be 2040 second and 1980 second. When the inlet temperature of the heat transfer fluid is 353.15K, as for 60° fin angle arrangement upper region melts at a faster rate because the fin effect is more dominant in the upper region and less dominant in the lower region and if consider the fin arrangement of 120° for this case the fins effect is not that much dominant to the upper region because it takes time to melt the PCM in the upper region whereas for this arrangement the fin effect is dominant for bottom region hence the PCM present in the bottom region melts faster, once the PCM present in the top and side annulus region melts completely for fin arrangement of 120°.

So, on the basis of numerical results, for three fin arrangement the melting performance for fin having 90° angle is found having lower melting time of 1800 seconds which is 11.76 % and 10 % less as compared to 60° and 120° fin arrangement respectively. The present work deals with the melting performance of the PCM for which the melting time of the PCM in LHTES unit is the major parameter and the aim is to minimize the melting time or to minimize the charging time because this parameter has greater impact on energy storage.



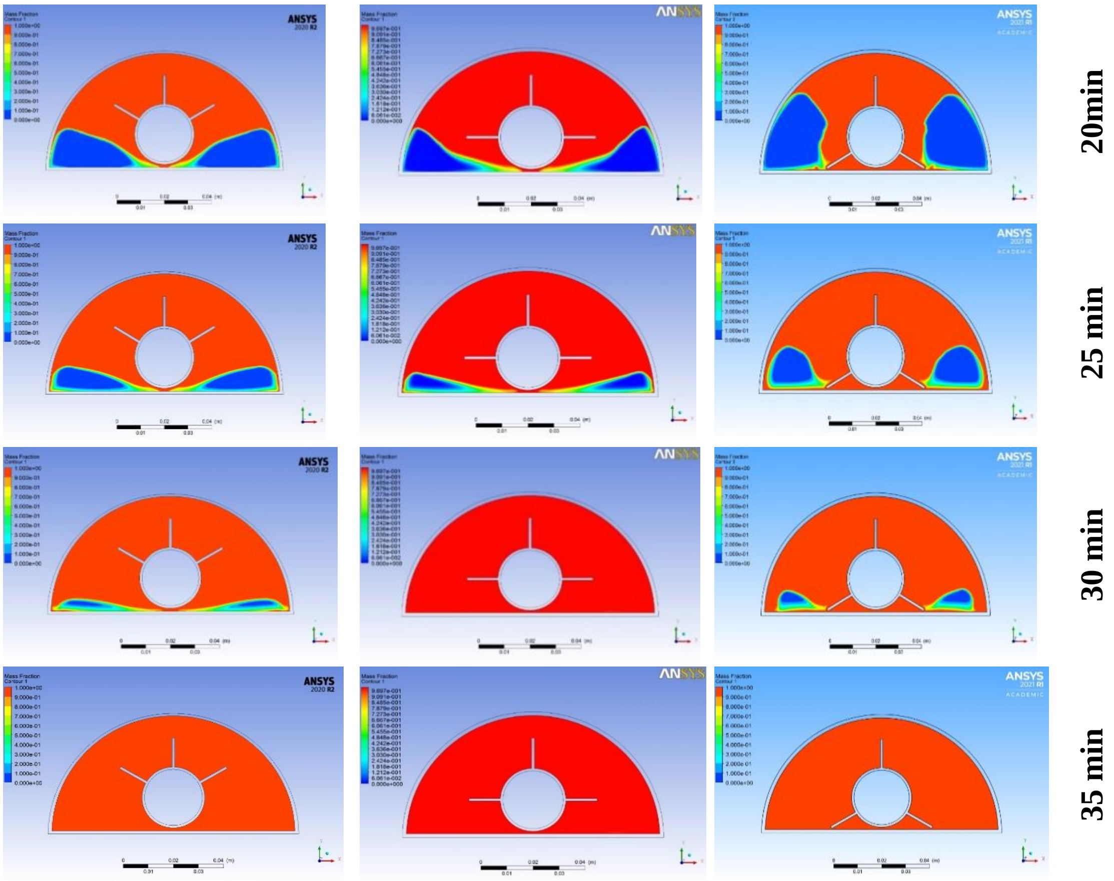
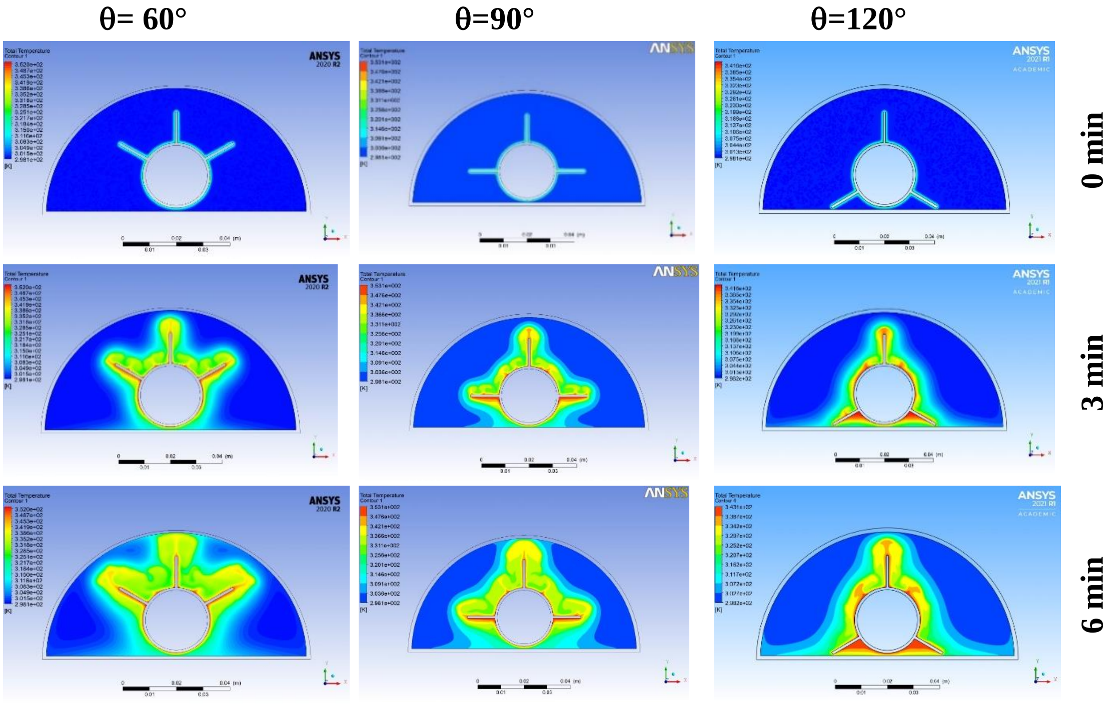


Fig 4.6 Liquid fraction contour for semi-circular shell with finned tube arrangement



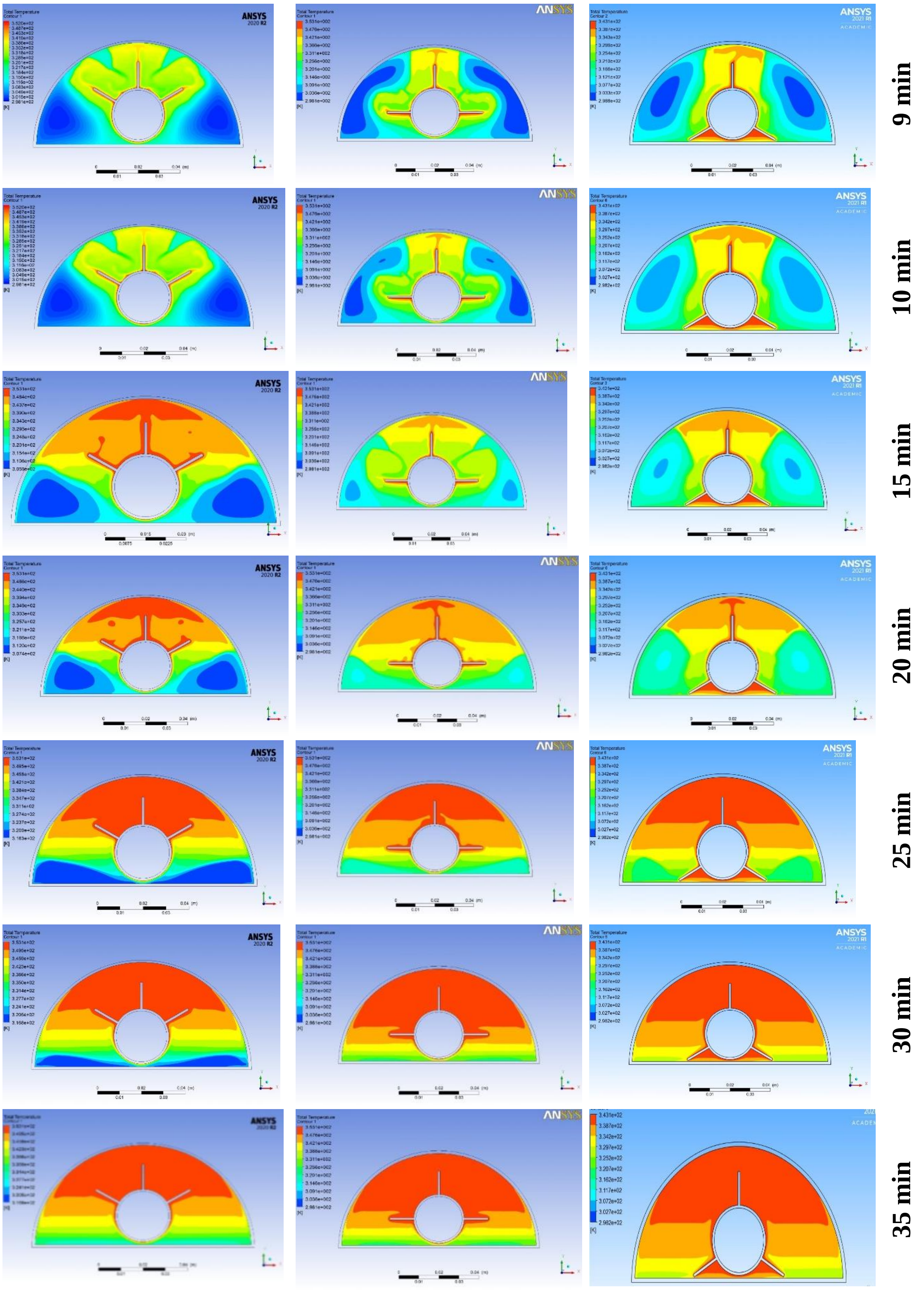


Fig 4.7 Temperature contour for semi-circular shell with finned tube arrangement for LHTES system

4.5 Comparison of melting performance of PCM in a semi-circular shell having an un-finned tube and finned tube separately.

The result obtained for three different fin arrangement shows different melting performance, among them fin angle θ= 90° shows the better melting performance based on that this fin arrangement is taken into consideration for the estimation of melting performance of PCM. In addition to this finned tube LHTES system is also compared with un-finned tube LHTES system.

From 2-D numerical analysis it can be the melting time for finned tube arrangement is 34.78 % lower as compared to the un-finned tube arrangement. The thermal conductivity of the PCM is low due to which in case of un-finned tube it takes time to melt the PCM , so to reduce this melting time using fin is one of the melting rate enhancement methods. In present work three longitudinal fins arranged at θ=90°.Using the fin arrangement the heat transfer area is increased by 91.8 % and the fin covers 49.8 % of the total area from where heat transfer takes place. With the help of which natural convection rate found quite high because of these reasons the melting rate is high and hence the melting time for the arrangement is 30 min for finned tube and 46 min for un-finned tube arrangement .

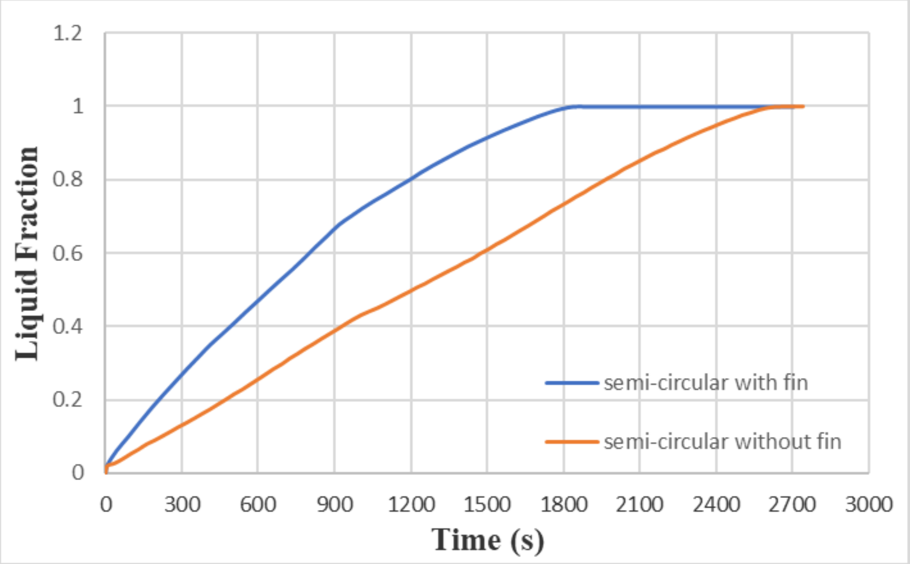
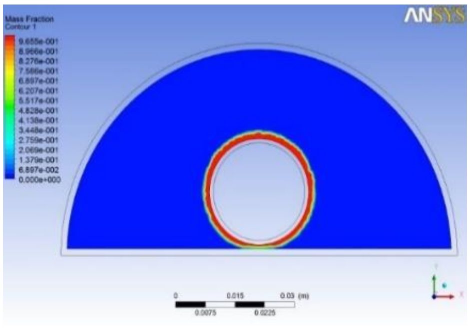


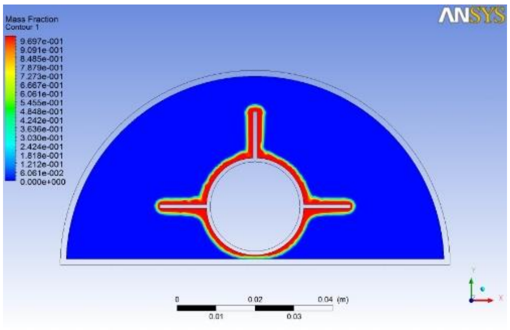
Fig 4.8 Comparison of liquid fraction semi-circular shell with finned tube and un-finned tube

Semi-Circular without fin

Semi-Circular with fin at θ = 90°

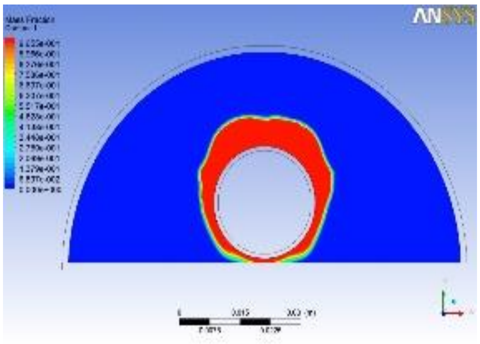


β = 3.52%

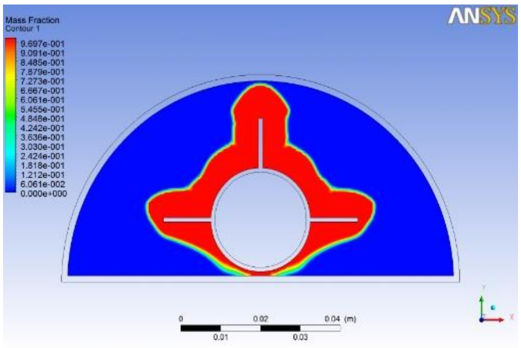


β = 7.49%

1 min

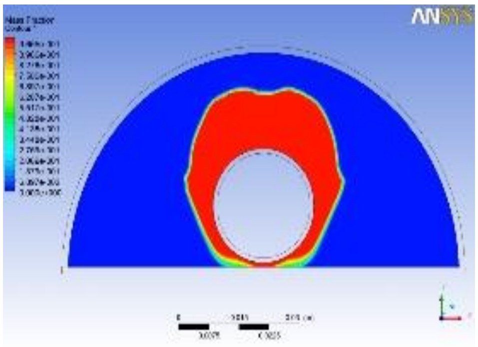


β = 12.99%

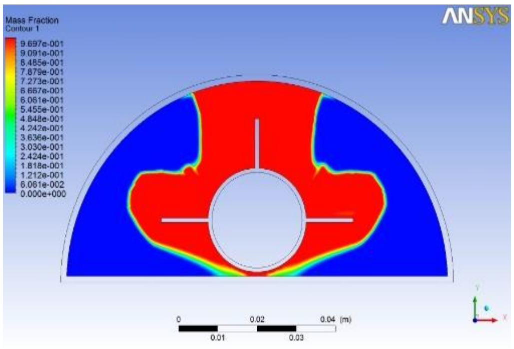


β = 26.94%

5 min

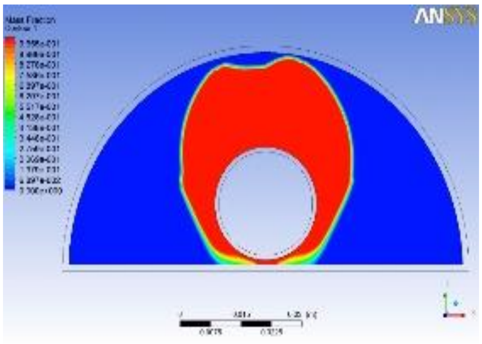


β = 25.57%

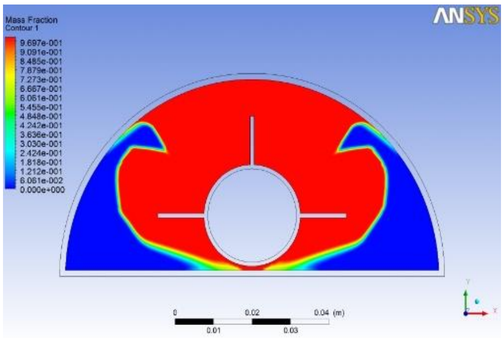


β = 47.13%

10 min

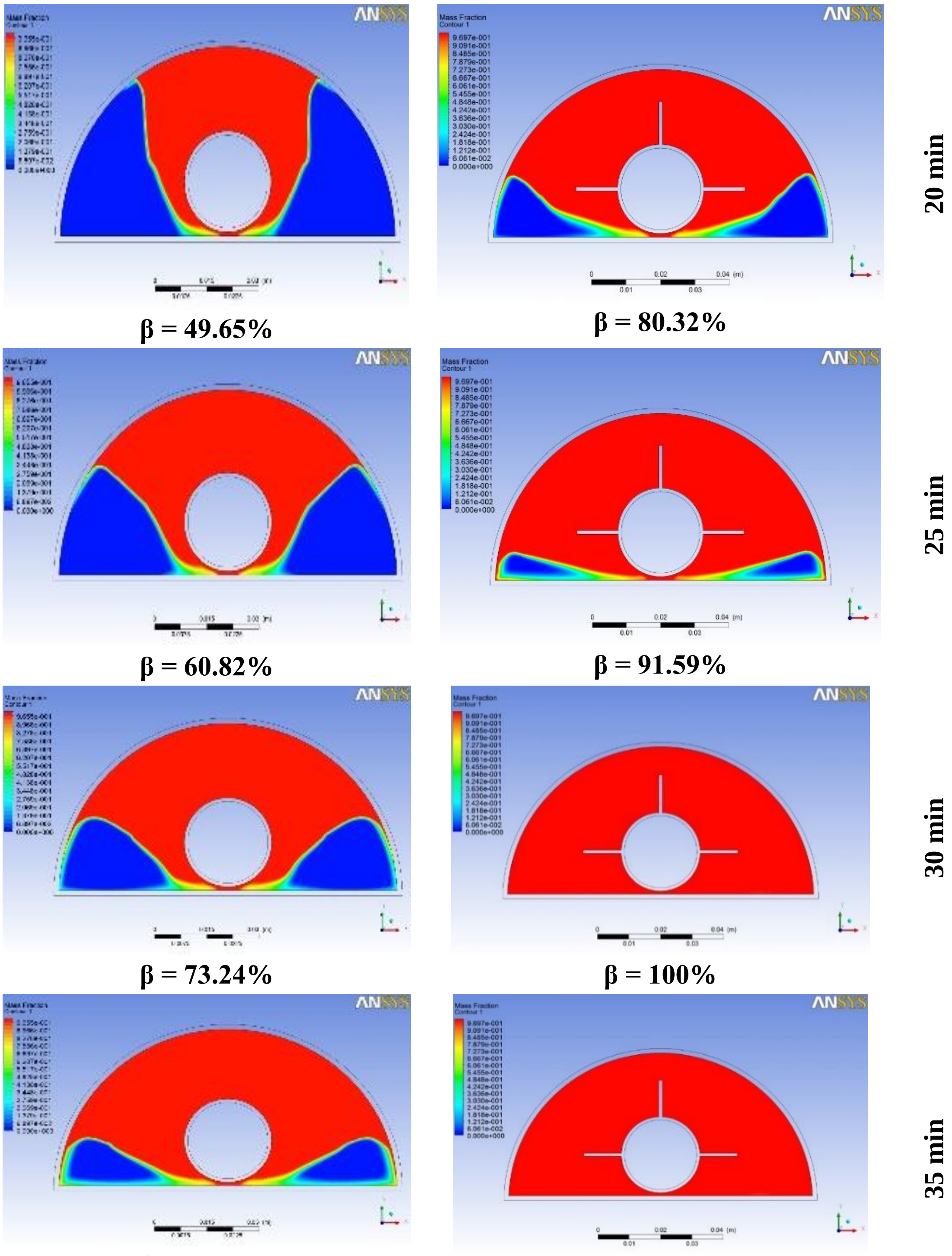


β = 38.73%



β = 66.72%

15 min



β = 49.65% β = 80.32%

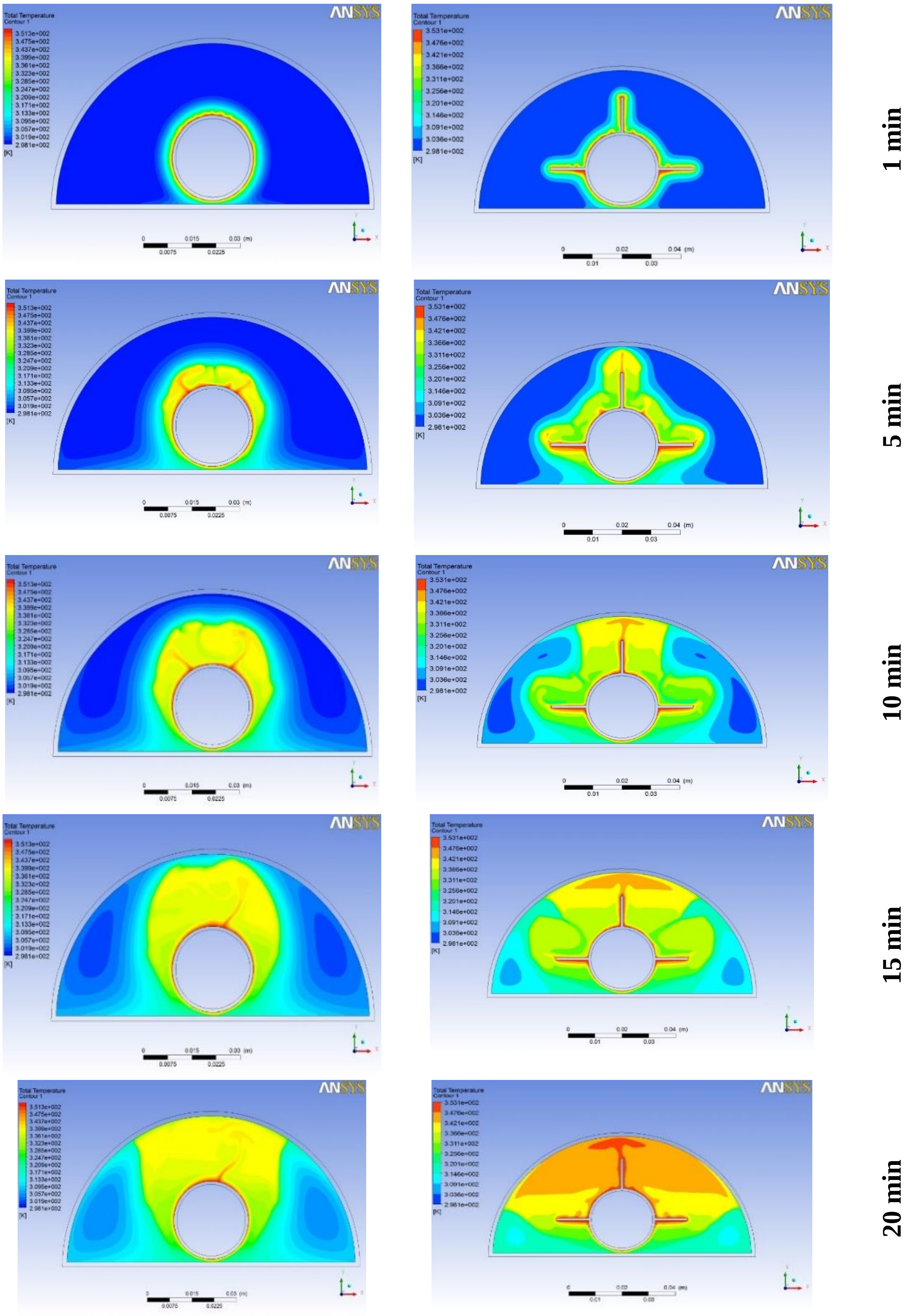
β = 60.82% β = 91.59%

β = 73.24% β = 100%

β = 85.12% β = 100%

Fig 4.9 Liquid fraction contours of semi-circular shell and tube without fin and with fin at θ=90°for LHTES system

Semi-Circular without fin **Semi-Circular with fin at θ = 90°**



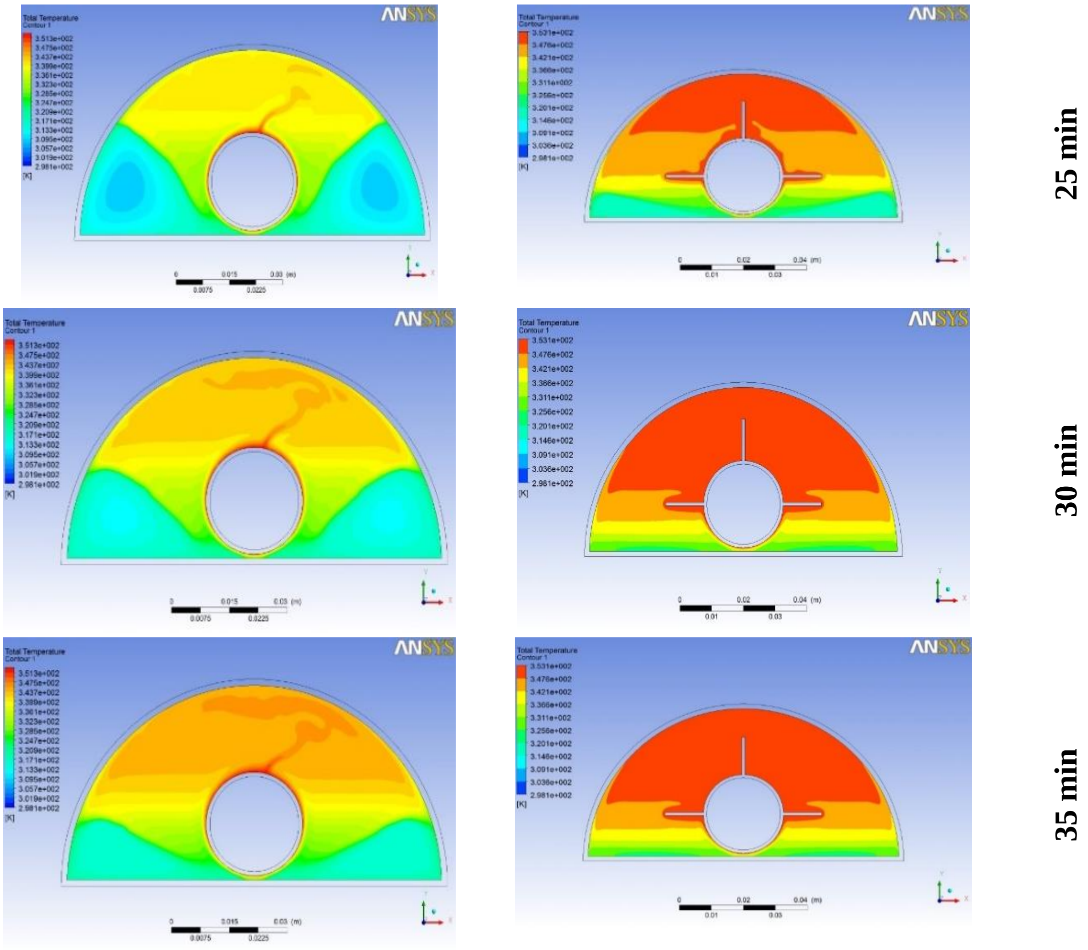


Fig 4.10 Temperature contours of semi-circular shell and tube without fin and with fin at θ=90°for LHTES system

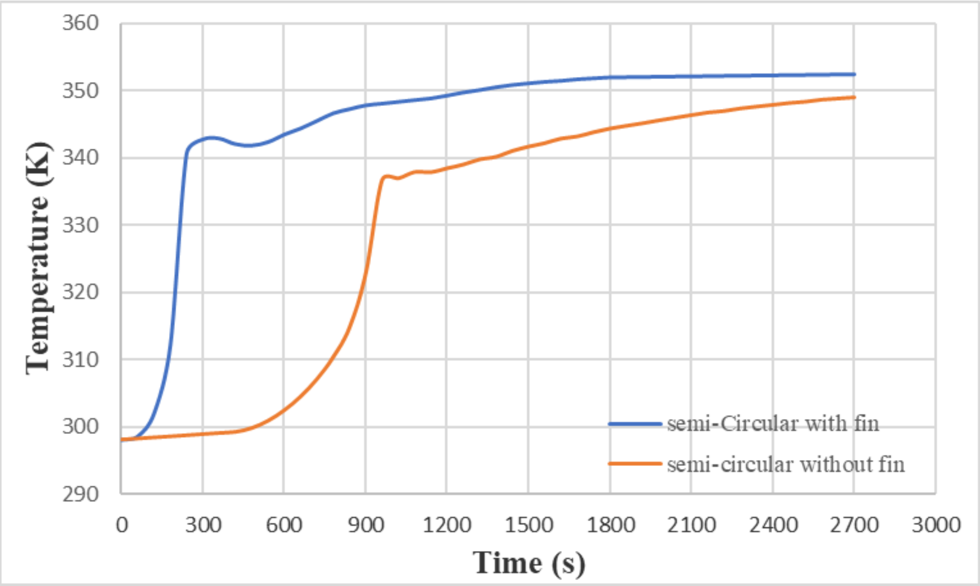


Fig 4.11 Top temperature comparison for semi-circular shell and tube with fin and without fin for LHTES system

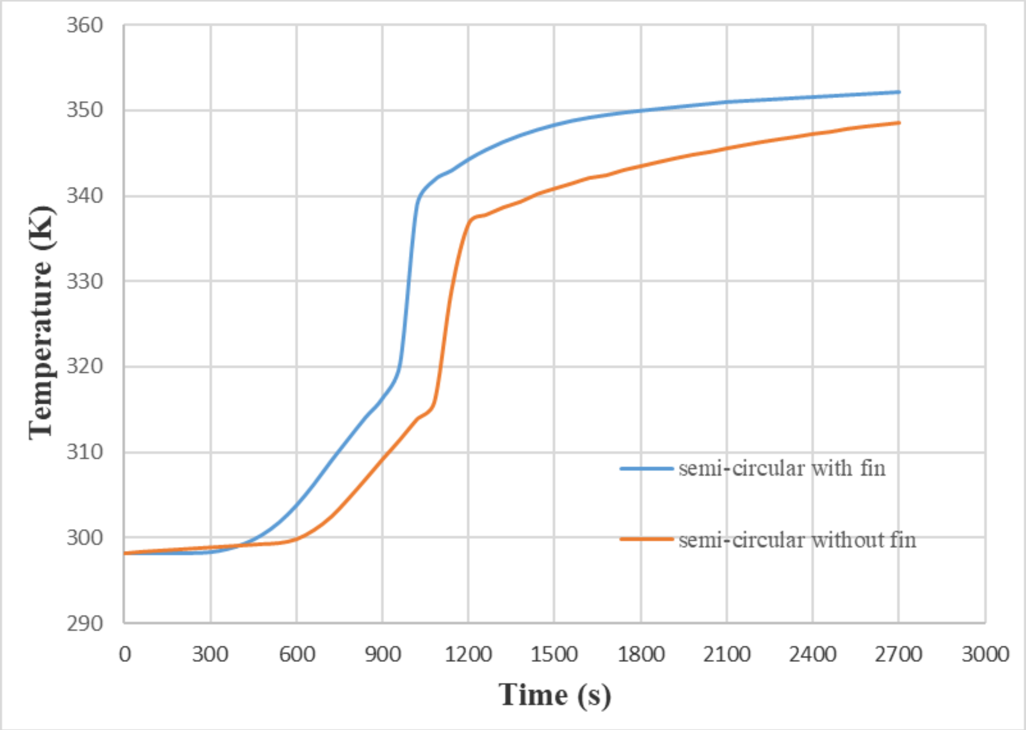


Fig 4.12 Side temperature comparison for semi-circular shell and tube with fin and without fin for LHTES system

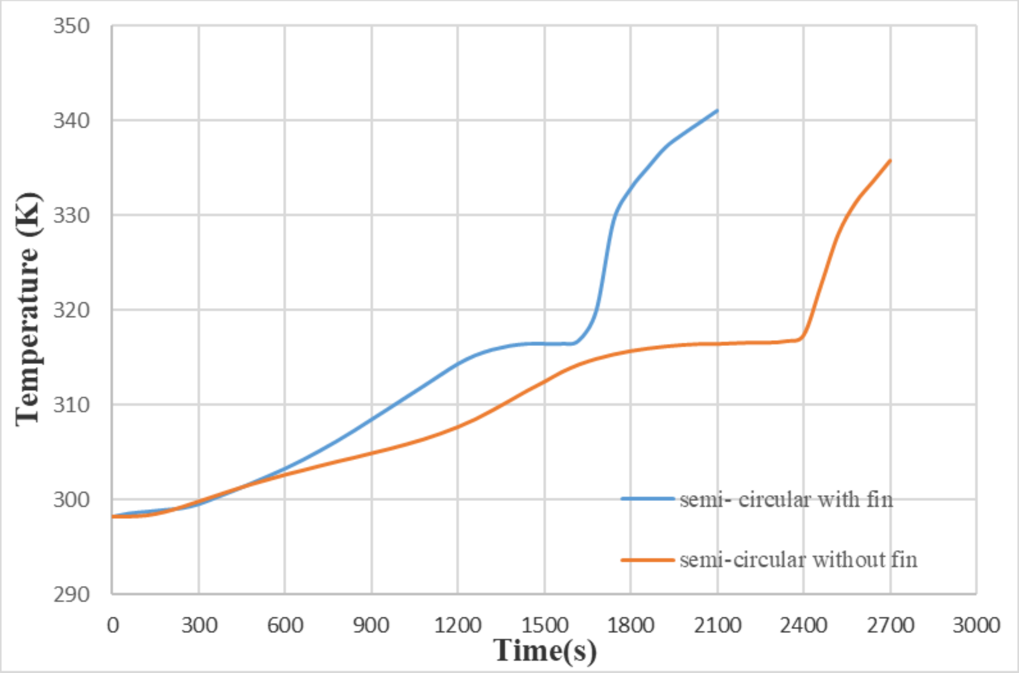


Fig 4.13 Bottom temperature comparison for semi-circular shell and tube with fin and without fin for LHTES system

Fig 4.11, 4.12, 4.13 shows the behavior of temperatures at three different annulus location namely top, side and bottom for shell and tube LHTES unit with and without fin. The temperature profile shown in figure 4.11, 4.12, 4.13 shows that the finned tube arrangement is having higher temperature throughout for all three-annulus region, as because of application of fin the PCM present in top annulus gains sufficient high temperature for melting in very short time duration as compared to un-finned tube arrangement. The finned tube LHTES system reaches to its melting point earlier as compared to un-finned tube LHTES system fig 4.11, 4.12, 4.13.

Comparing the temperature profile of semi-circular shell with and without fin it is found that the temperature for PCM in finned tube LHTES system is higher and gains its melting point temperature earlier as compared to un-finned tube LHTES system.

The PCM melting continuously due to density difference or due to buoyant force between liquid PCM and solid PCM the liquid PCM rises upward as the process continues the natural convection dominates because of which the top region melted quickly after gaining sufficient heat this region transfers heat to the solid PCM present in the shell because of which there is small dip after 600 second as shown in fig 4.11. This heat transfer from top region to un-melted region helps to melt PCM quickly. The PCM in un-finned tube LHTES system also follows the same trend but takes time to transfer heat from top region to the other region because of these reasons the finned tube LHTES performs better as compared to the un-finned tube LHTES system.

4.6 Thermal energy storage capacity of PCM in semi-circular shell with finned tube and without fin tube for LHTES System

Thermal energy storage capacity is one of the important parameters related to the LHTES unit. Fig 4.14 here shows the comparison of thermal energy storage between semi-circular shell with finned and un-finned tube. In case of semi-circular shell with finned tube the temperature of PCM considered is almost equal to the room temperature 25°C and the temperature of HTF is 80°C as the difference is large, the heat transfer take place from outer surface of finned tube to the PCM. It is known that the thermal conductivity of the phase change material is low due to that the heat transfer from the outer surface takes more time and the temperature of the PCM rises slowly so considering the thermal conductivity the fins attached to the tube play an important role here. The fins attached provides the increased surface area for heat transfer which enhances the rate of heat transfer and for the un-finned tube LHTES System the rate of heat transfer is lower as compared to the finned tube. Fins attached to the tube helps to achieve the temperature of higher values as compared to the to that of un-finned tube as shown in fig 4.11, 4.12,.4.13.

The thermal energy is calculated by using following formula:

$$Q_t = L_f \, \mathrm{m} \, \Delta \mathrm{H} + \mathrm{m} \, C_p \left(T_{pcm} - T_i\right)$$

Where;

$\mathrm{Q_t}$ = Total thermal energy stored by the phase changing material (PCM)

L_f = Fraction of liquid that is already melted

M = Mass of the PCM

$\Delta\mathrm{H}$ = Latent heat of fusion of PCM

$\mathrm{C_p}$ = Specific heat of the PCM in kJ

$\mathrm{T_{pcm}}$ = Temperature of the PCM

$\mathrm{T_I}$ = Initial temperature of the PCM

The thermal energy storage process of the PCM stores primarily latent heat as the process continues the temperature of the PCM increases and reaches to melting point of the PCM at the melting point phase of the PCM is changed to liquid and the energy stored by the PCM before melting is sensible heat after that the latent heat storge dominates the process. On comparing the heat storage capacity of the finned and un-finned LHTES system described the one with finned tube always stores more thermal energy because it melts at faster rate as the fraction of melted liquid for any instant of time is always more as shown in fig 4.8. and once the liquid fraction reaches to the 1 or say the PCM melted completely it stores sensible heat.

Based on the melting behaviour and the temperature profile of the PCM the thermal energy storage follows the trend, initially at a slower rate and then increases gradually once the sufficient amount of PCM melts and then remains almost constant when the temperature reaches nearly equal to the inlet temperature. The LHTES unit with finned tube stores energy for 2700 sec is 409.32 kJ and that without fin stores 368.54 kJ which result in a significant increase in overall thermal energy storage about 11.06 % as compared to the un-finned tube which is possibly due to more melting fraction available for all the time duration for the finned tube arrangement (Fig 4.14).

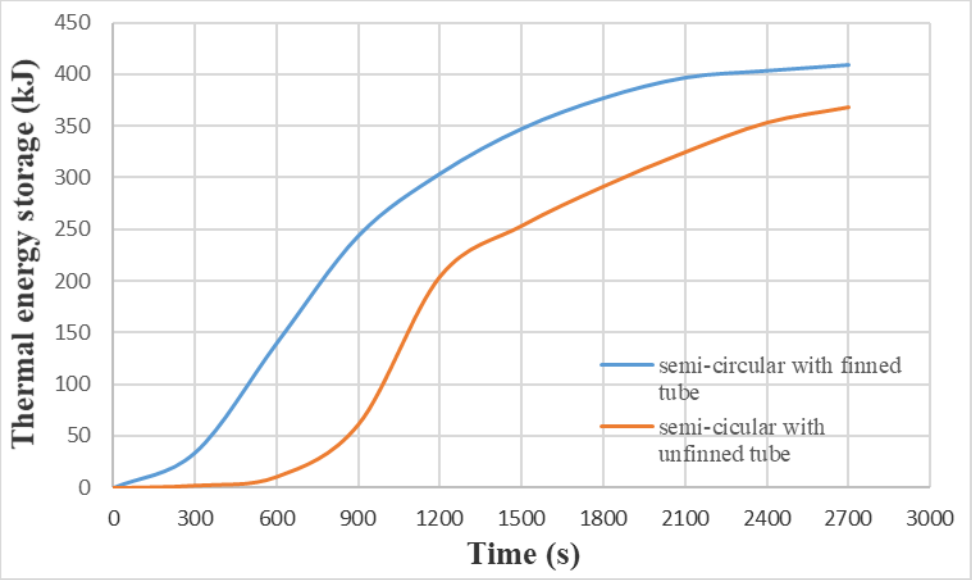


Fig 4.14 Comparison of thermal energy storage between finned tube and un-finned tube for LHTES system

4.7 Thermal energy storage rate of semi-circular shell with finned tube and without fin tube for LHTES system

Thermal energy storage rate is defined as energy stored per unit time fig 4.15 shows the variation of thermal energy storage for two different arrangements i.e., semi-circular with finned tube and un-finned tube. The fig 4.15 shows for finned tube the rate of energy storage is quite higher as compared to un-finned tube the only reason behind it is adding fins to the tube helps PCM to achieve higher temperature value and hence higher rate of thermal energy storage.

As the figure 4.15 shows that the rate of storage initially is steep and then reaches to the maximum value and afterwards starts decreasing because of the temperature difference between HTF and PCM, initially the PCM is considered at room temperature and the inlet temperature of the HTF is high as the process continues this temperature difference becomes lower as time proceeds and hence the rates slower down once it reached to the maximum value. Discussing about thermal storage rate of two different arrangements semi-circular with finned and un-finned tube the former is having higher storage rate as compared to the later one. The un-finned tube arrangement gains the maximum value equal to 0.16 kW and the arrangement with finned tube gains the maximum value equal to 0.27 kW which is around 68.75 % more when compared with maximum value of un-finned tube case.

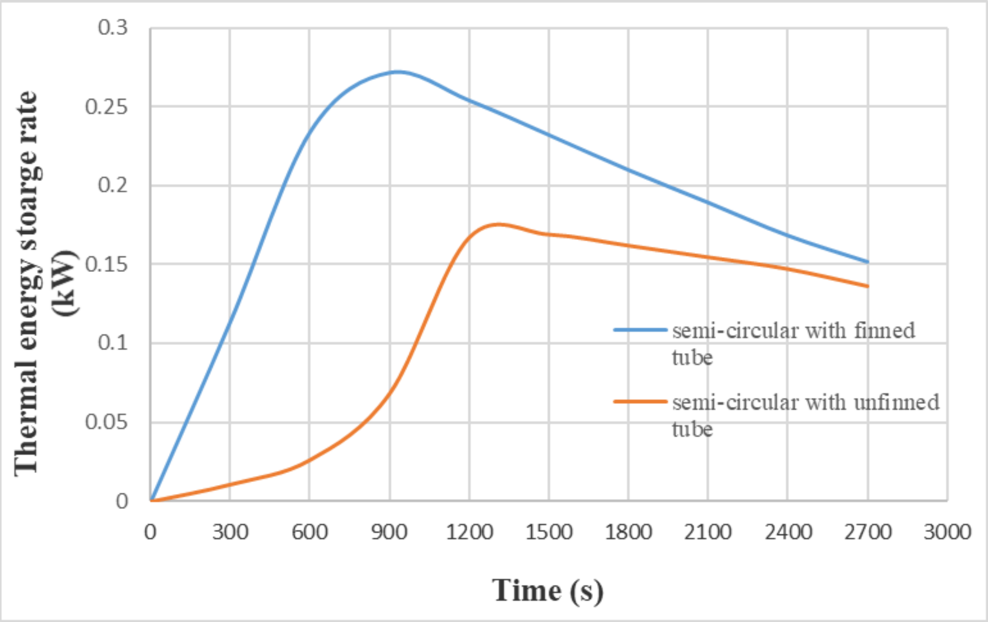


Fig 4.15 Variation of thermal energy storage rate for semi-circular shell with finned and un-finned tube

4.8 Enhancement ratio of liquid fraction of phase change material

Enhancement ratio is formulated as

$$Enhancement\ ratio = \frac{M_{scf} - M_{sc}}{1} \times 100$$

Where M_{scf} = melting fraction of the semicircular shell with finned tube

M_{sc} = melting fraction of the semi-circular shell with un-finned tube

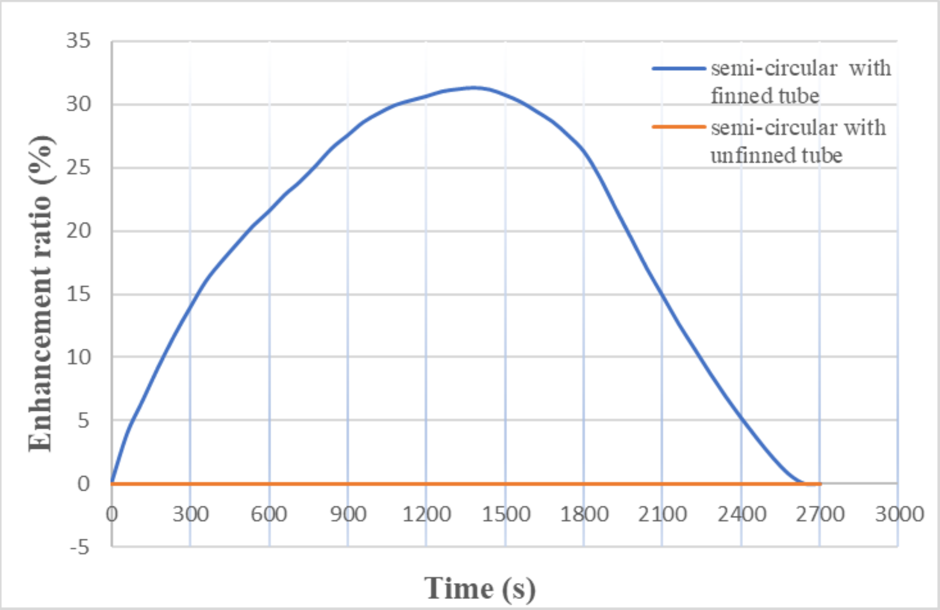


Fig 4.16 Melting enhancement ratio of PCM of semi-circular with finned tube with respect to semi-circular un-finned tube

The fig 4.16 shows enhancement in liquid fraction of PCM with in semi-circular shell with finned tube with respect to un-finned tube arrangement and for that enhancement ratio has been estimated.

The curve of enhancement ratio shows that finned tube arrangement reaches its maximum enhancement value of 31.24 % in 1500 sec which initially gradually increases up to 1500 sec during which the conduction effects dominate. As the melting of PCM proceeds the solid PCM changes to liquid as the convection effect comes into the picture and dominates over the conduction effect, which helps the liquid PCM to transfer heat from liquid PCM to solid PCM results into melting of PCM at a faster rate.

Hence, it can be concluded that the enhancement ratio curve first increases reach to maximum value and then starts decreasing.

4.9 Thermal energy storage efficiency

The thermal energy storage efficiency (TES) is defined as the ratio of total energy stored by the phase change material to the maximum amount of energy it can store and formulated as below

$$\eta = \frac{Q_t}{Q_{max}}$$

Where; Q_t = Total energy stored during the process

Q_{max} = Maximum energy that it can store

$$Q_{max} = m\,\Delta H + m\,C_p(T_{inlet} - T_i)$$

M = mass of the PCM in kg

H = Latent heat of Fusion in kJ/kg

T_{inlet} = Inlet temperature of the HTF

T_i = initial temperaure of the PCM

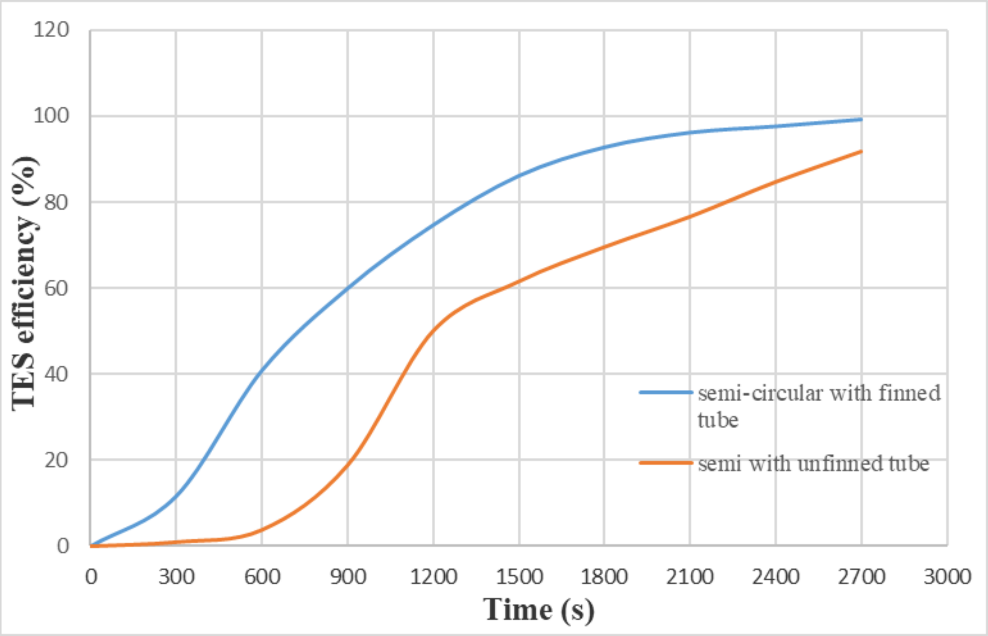


Fig 4.17 TES efficiency for semi-circular with finned tube and un-finned tube

The fig 4.17 represents the TES efficiency for semi-circular shell with finned and un-finned tube and it clearly shows that the former one achieves the higher value of the efficiency compared to the later one. As the storage of thermal energy and its rate totally depends on the temperature difference of the inlet fluid temperature and the initial temperature of the PCM. In the same way the TES efficiency follows the same path.

As the PCM melted completely it can only store the sensible energy and the rate of storages reduces as the temperature difference is not enough to drive the process at faster rate. Referring to fig 4.17 it can be clearly seen that semi-circular with finned tube is having high thermal efficiency as compared to the semi-circular with un-finned tube throughout the process.

4.10 Effect of HTF inlet temperature (or Stefan number) on the melting performance of PCM in Semi-circular shell with finned tube annulus LHTES system

The numerical study is conducted on three different inlet temperature of the HTF (water in our case) 60° ,70°, 80° C and their corresponding Stefan number are 0.18, 0.32, 0.45 respectively. Stefan number is already discussed in the last chapter. It is found that the melting performance of the PCM in LHTES unit improves when the inlet temperature of the HTF or Stefan number increases.

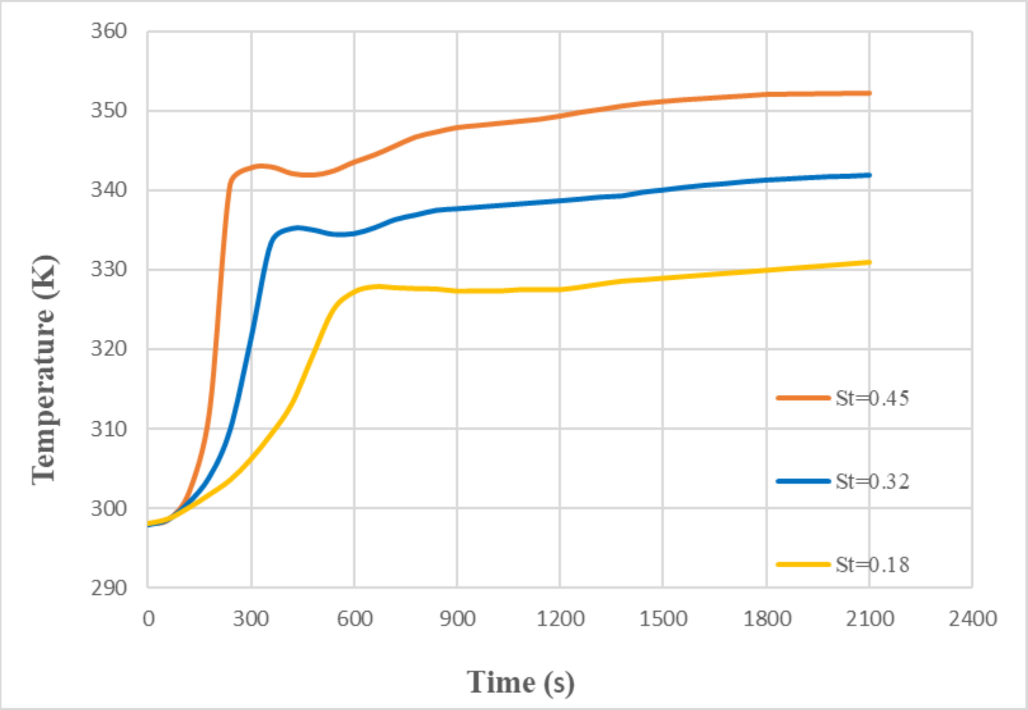


Fig 4.18 Comparison of temperature at top annulus position of semi-circular shell with finned tube for LHTES system for different value of Stefan number (St)

The temperature of PCM at different locations of semi-circular shell with finned tube LHTES is always higher for higher value of Stefan number, as it is shown by fig 4.18 , the reason behind it is that on increasing the inlet temperature of the heat transfer fluid the value of Stefan number also increases which results into increase in the temperature difference between HTF and PCM and thus the driving potential for the heat transfer. As a result of which the heat transfer rate increases with increase in Stefan number and hence the temperature at different thermocouple location rises quickly.

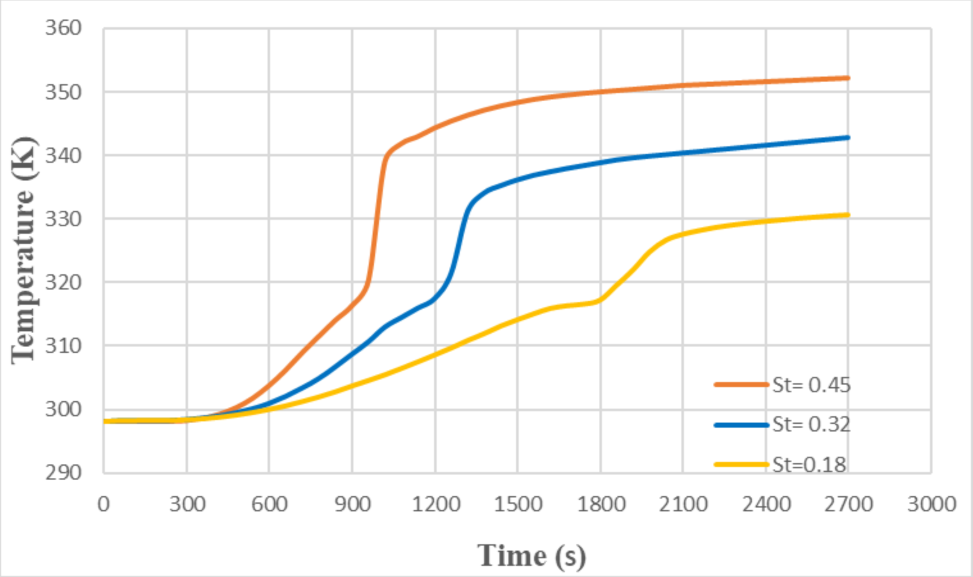


Fig 4.19 Comparison of temperature at side annulus position of semi-circular shell with finned tube for LHTES system for different value of Stefan number (St)

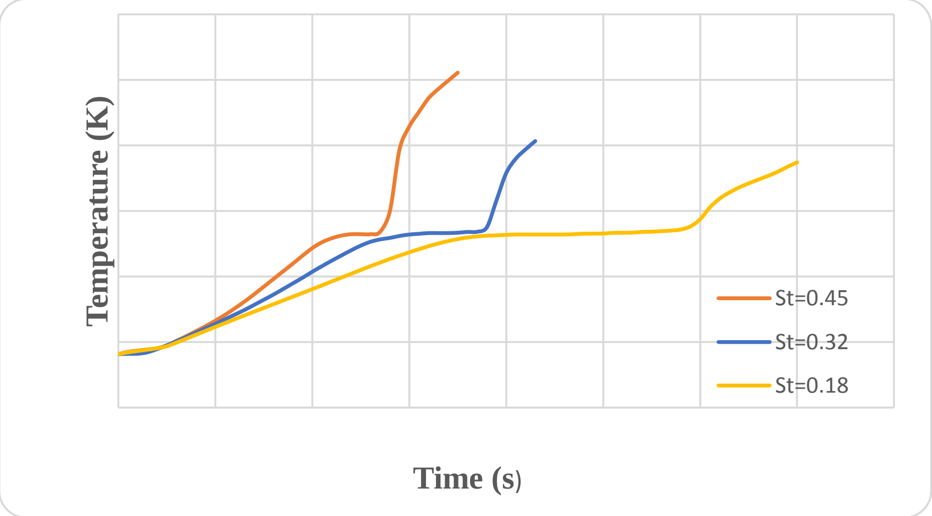


Fig 4.20 Comparison of temperature at bottom annulus position of semi-circular shell with finned tube for LHTES system for different value of Stefan number (St)

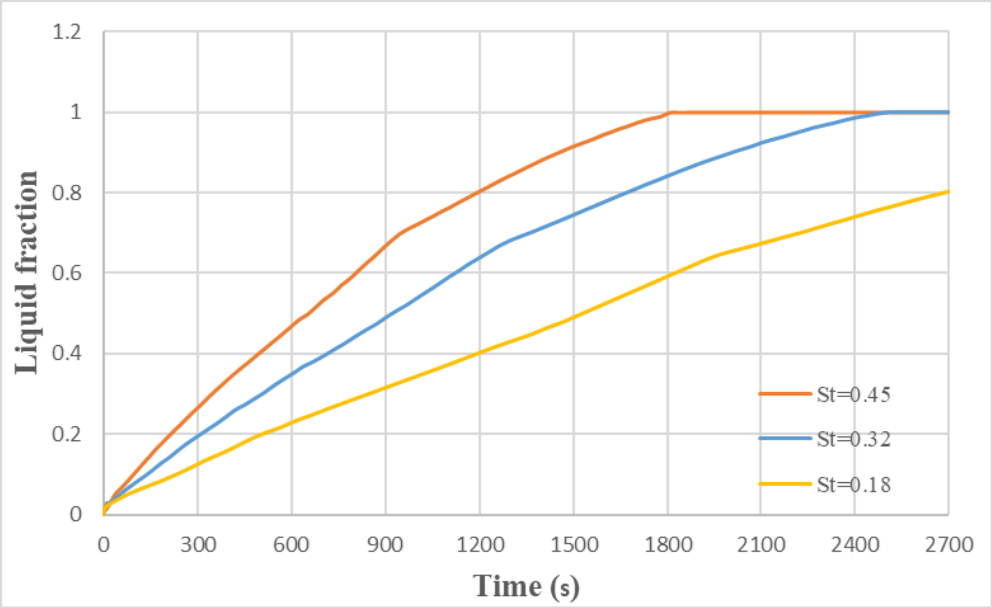


Fig 4.21 Comparison of the liquid fraction of semi-circular shell with a finned tube for LHTES system at different Stefan number (St)

From fig 4.21 total melting of PCM present in the shell occurs earlier for higher value of the Stefan number and it takes time for lower value of Stefan number, for Stefan numbers St = 0.45, 0.32, 0.18 the Liquid fraction of phase changing material in semi-circular shell with finned tube unit is 1 for 1800 sec when the Stephan number is 0.45 and 1 for 2100 sec when the Stefan number is 0.32 and 0.81 for Stephan number is 0.18 for time of 2700 sec.

Summary and Conclusions

Chapter 5 SUMMARY AND CONCLUSIONS

The present work is focused on the melting performance of phase change material in a shell which has been modified to a semi-circular shape from circular shape and has a tube with longitudinal fins. The PCM selected for the analysis is lauric acid & its selection is based upon literature review and ease of availability of the material. To analyse the thermal performance a numerical and experimental study is conducted. For the numerical study a 2-D model of LHTES is developed in Ansys computational fluid dynamics (CFD) fluid fluent software for three different angles (θ = 90°, 60°, 120°) of the fins. The numerical results are obtained for the best fin arrangement and to validate it experimentally an experimental actual model has been fabricated with a finned tube and semi-circular shell & PCM filled in it. The temperature at three different annulus positions namely top, side, bottom of shell and liquid fraction of PCM gives the percentage of total mass melted at a certain interval of time enables to estimate the thermal energy stored, rate of thermal energy stored, enhancement ratio, and the efficiency of the thermal energy storage system. The results have been compared with a semi-circular shell with the un-finned tube for the melting performance of PCM. It can be concluded that;

1. The semi-circular shaped shell with a tube having fin at three different angles θ = 60°, θ = 90°, θ =120°, we found that by increasing the fin angle from 60° to 90° the melting time of PCM is reduced by 11.76 % whereas on increasing the angle from 90° to 120° the melting time of PCM is increased by 10 %. the minimum melting time of 1800 sec (30 min) is found for the fin angle 90° and hence considered for further analysis and fabrication of shell and tube LHTES unit for experimental validation.
2. The numerical model has been validated with the experimental set up and the result are found fairly in agreement. It is observed that the PCM in finned tube LHTES system has a total melting time of 30 min whereas the PCM in un-finned tube LHTES system has meting time of 46 min. It is found that the finned tube model reduces the melting time by 34.78%.

3. Thermal energy stored in the finned tube LHTES system is 409.32 kJ and with an un-finned tube LHTES system it is 368.54 kJ. The thermal energy stored in finned tube LHTES system is estimated 11.06 % more as compared to an un-finned tube for 2700 sec. It is also found that the thermal energy storage rate for un-finned shell and tube system is 0.16 kW and for finned tube is 0.27 kW which is 68.75% more as compared to un-finned tube system.
4. The enhancement in the melting is found for a finned tube LHTES system which is 31.24% higher with respect to un-finned tube LHTES system for time of 1500 sec. It is also found that the finned tube LHTES system shows greater TES efficiency over un-finned tube LHTES system which is 7% higher for finned tube as compared to un-finned tube LHTES system.
5. Melting performance on increasing the Stefan number from 0.18 to 0.45 is found for finned tube LHTES system. The liquid fraction is 0.81 for 0.18 Stefan number for time of 2700 sec, 1 for 0.32 Stefan number for 2100 sec and 1 for 0.45 Stefan number for time of 1800 sec. For Stefan numbers 0.32 and 0.45 the liquid fraction is 19% more compared to Stefan numbers 0.18 when the time of 2700 sec is considered for all Stephan number.

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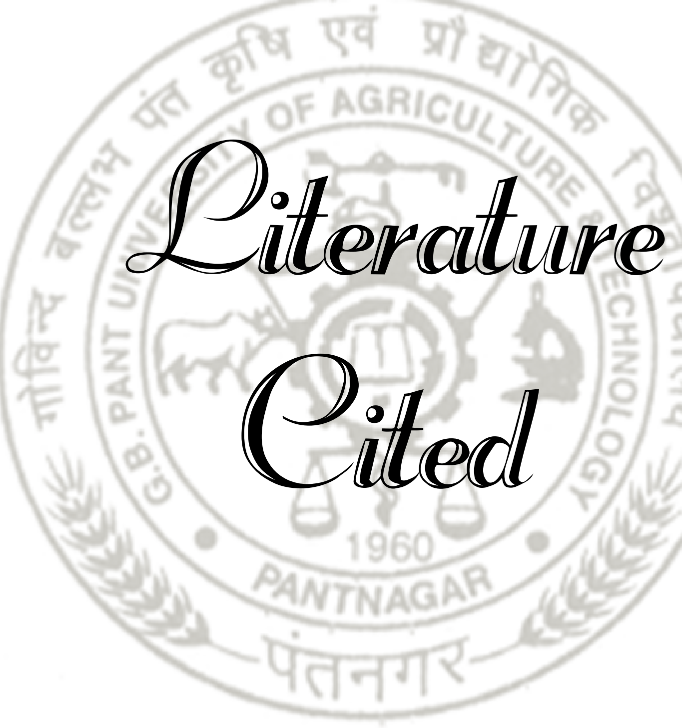

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ABSTRACT

Energy conversion is an essential aspect of technology advancement, and hence its efficient generation and use are important in today's scenario. In present scenario, there is a large gap between demand and supply, and it is difficult to meet the current energy requirement. Thermal energy storage devices enable us to attain energy demand while simultaneously minimizing pollution. This modified geometry having semi-circular shaped shell with finned tube has not been studied much for the melting performance of the phase change material in recent available literature. Hence it has been decided to investigate the melting performance of PCM numerically and experimentally for semi-circular shell having finned tube latent heat thermal energy storage (LHTES) system.

Enhancement of melting performance of lauric acid in a semi-circular shell with three longitudinal fins attached to the inner tube has been done for a two-dimensional numerical model in Ansys fluid fluent. The temperature obtained at different locations of shell from the numerical data has also been validated with experimental results. Since the phase change materials have low thermal conductivity so adding fins is one of the effective performance enhancement techniques used in the analysis to enhance the melting rate. Therefore, three different fin arrangements at different fin angles ($\theta = 60^\circ, 90^\circ, 120^\circ$) have been investigated for the melting performance of the PCM. It has been found that the melting rate of PCM for fin angle of 90° is higher, as compared to other fin arrangements. PCM melting performance is also investigated for different values of inlet temperature of heat transfer fluid for fin angle of 90°. It is observed that on increasing the Stefan number improves the melting rate of PCM in the semi-circular shell finned tube LHTES system.

The results for a semi-circular shell with a fin angle of 90° for the LHTES system are found better as the thermal energy storage rate of finned tube LHTES system is 0.27 kW, which is 68.75 % higher as compared to an un-finned tube LHTES system. The semi-circular shell with finned tube LHTES melts the PCM completely in 1800 seconds (30min) which is 34.78 % less in time than the un-finned tube LHTES system. The thermal energy stored in PCM for the shell with finned tube LHTES system is 409.32 kJ, which is 11.06 % more than that of un-finned tube LHTES for the same time duration of 2700 sec. The thermal energy storage efficiency of semi-circular with finned tube LHTES unit has been found 7 % higher than that of un-finned tube LHTES.

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शोध का शीर्षक : "क्षैतिज संशोधित शेल और ट्यूब ऊष्मीय ऊर्जा भंडारण में अनुदैर्ध्य फिनो का उपयोग करके चरण परिवर्तन सामग्री के पिघलने के प्रदर्शन पर जांच"

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सारांश

ऊर्जा रूपांतरण प्रौद्योगिकी उन्नति का एक अनिवार्य पहलू है, और इसलिए इसका कुशल उत्पादन और उपयोग आज के परिदृश्य में महत्वपूर्ण है। वर्तमान परिदृश्य में, मांग और आपूर्ति के बीच एक बड़ा अंतर है, और वर्तमान ऊर्जा आवश्यकता को पूरा करना मुश्किल है। ऊष्मीय ऊर्जा भंडारण उपकरण हमें प्रदूषण को कम करने के साथ-साथ ऊर्जा की मांग को प्राप्त करने में सक्षम बनाते हैं। हाल ही में उपलब्ध साहित्य में चरण परिवर्तन सामग्री के पिघलने के प्रदर्शन फिनेड ट्यूब के साथ अर्ध-गोलाकार आकार के खोल वाले इस संशोधित ज्यामिति का अधिक अध्ययन नहीं किया गया है। इसलिए फिनेड ट्यूब लेटेंट हीट थर्मल एनर्जी स्टोरेज (एल0एचटी0ई0एस0) प्रणाली वाले अर्ध-गोलाकार खोल के लिए संख्यात्मक और प्रयोगात्मक रूप से पी0सी0एम0 के पिघलने के प्रदर्शन की जांच करने का निर्णय लिया गया है।

आंतरिक ट्यूब से जुड़े तीन अनुदैर्ध्य फिनो के साथ अर्ध-गोलाकार खोल में लॉरिक अम्ल के पिघलने के प्रदर्शन में वृद्धि Ansys द्रव धाराप्रवाह में दो-आयामी संख्यात्मक मॉडल के लिए किया गया है। संख्यात्मक आंकड़े खोल के विभिन्न स्थानों पर प्राप्त तापमान को प्रयोगात्मक परिणामों के साथ मान्य किया गया है। चूंकि चरण परिवर्तन सामग्री में कम तापीय चालकता होती है, इसलिए पिघलने की दर को बढ़ाने के लिए विश्लेषण में उपयोग की जाने वाली प्रभावी प्रदर्शन वृद्धि तकनीकों में से एक, फिन जोड़ना है। इसलिए, पीसीएम के पिघलने के प्रदर्शन के लिए अलग-अलग फिन कोण (θ= 60°, 90°, 120°) पर तीन अलग-अलग फिन व्यवस्थाओं की जांच की गई है। यह पाया गया है कि 90° के फिन कोण के लिए पी0सी0एम0 की पिघलने की दर अन्य फिन व्यवस्थाओं की तुलना में अधिक है। 90° के फिन कोण के लिए ऊष्मा हस्तांतरण द्रव के इनलेट प्रवेश तापमान के विभिन्न मूल्यों के लिए पी0सी0एम0 पिघलने के प्रदर्शन की भी जांच की जाती है। यह देखा गया कि स्टीफन संख्या बढ़ाने से अर्ध-गोलाकार खोल फिनेड ट्यूब एल0एच0टी0ई0एस0 प्रणाली में पी0सी0एम0 की पिघलने की दर में सुधार होता है।

एल0एच0टी0ई0एस0 प्रणाली के लिए 90° के फिन कोण वाले अर्ध-गोलाकार खोल के परिणाम बेहतर पाए जाते हैं क्योंकि फिनेड ट्यूब एल0एच0टी0ई0एस0 प्रणाली की ऊष्मीय ऊर्जा भंडारण दर 0.27 kW है, जो कि अन-फिनेड ट्यूब एल0एच0टी0ई0एस0 प्रणाली की तुलना में 68.75% अधिक है। फिनेड ट्यूब एल0एच0टी0ई0एस0 प्रणाली के साथ अर्ध-गोलाकार खोल पी0सी0एम0 को पूरी तरह से 1800 सेकंड (30 मिनट) में पिघला देता है जो कि बिना फिन वाले ट्यूब एल0एच0टी0ई0एस0 प्रणाली की तुलना में समय में 34.78% कम है। फिनेड ट्यूब एल0एच0टी0ई0एस0 प्रणाली के साथ खोल के लिए पीसीएम में संग्रहित तापीय ऊर्जा 409.32 kJ है, जो 2700 सेकंड की समान अवधि के लिए अन-फिनेड ट्यूब वाले एल0एच0टी0ई0एस0 प्रणाली की तुलना में 11.06% अधिक है। फिनेड ट्यूब एल0एच0टी0ई0एस0 यूनिट के साथ अर्ध-गोलाकार की ऊष्मीय ऊर्जा भंडारण दक्षता अन-फिनेड ट्यूब एल0एच0टी0ई0एस0 की तुलना में 7% अधिक पाई गई है।

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