

NUMERICAL HEAT TRANSFER ANALYSIS OF ENCAPSULATED PHASE CHANGE MATERIALS FOR USE IN HIGH TEMPERATURE THERMAL ENERGY STORAGE APPLICATIONS

Submitted in partial fulfilment of the requirements for the award of
Bachelor of Engineering Degree in
Mechanical Engineering

By

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**DEPARTMENT OF MECHANICAL ENGINEERING
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SATHYABAMA

**INSTITUTE OF SCIENCE AND TECHNOLOGY
(DEEMED TO BE UNIVERSITY)**

Accredited with Grade "A" by NAAC

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APRIL - 2021



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BONAFIDE CERTIFICATE

This is to certify that this Project Report is the bonafide work of AVULAPATI SRIHARI (Reg no: 37150702) and ANTONY SHELTON (Reg no: 37150701) who carried out the project entitled "**NUMERICAL HEAT TRANSFER ANALYSIS OF ENCAPSULATED PHASE CHANGE MATERIALS FOR USE IN HIGH TEMPERATURE THERMAL ENERGY STORAGE APPLICATIONS**" under our supervision from October 2020 to April 2021.

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DECLARATION

We, AVULAPATI SRIHARI (Reg no: 37150702) and ANTONY SHELTON (Reg no: 37150701) hereby declare that the Project Report entitled “**NUMERICAL HEAT TRANSFER ANALYSIS OF ENCAPSULATED PHASE CHANGE MATERIALS FOR USE IN HIGH TEMPERATURE THERMAL ENERGY STORAGE APPLICATIONS**” done by us under the guidance of **Mr. V JAYAPRAKASH, M. Tech., (Ph.D.,)** is submitted in partial fulfillment of the requirements for the award of Bachelor of Engineering Degree in Mechanical Engineering.

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ACKNOWLEDGEMENT

I am pleased to acknowledge my sincere thanks to Board of Management of **SATHYABAMA** for their kind encouragement in doing this project and for completing it successfully. I am grateful to them.

I convey my thanks to **Dr. S. Prakash, M.E., Ph.D., Dean, School of Mechanical Engineering** and **Dr. G.ArunKumar, M.E., Ph.D., Head of the Department, Department of Mechanical Engineering** for providing me necessary support and details at the right time during the progressive reviews.

I would like to express my sincere and deep sense of gratitude to my Project Guide **Mr. V. Jayaprakash, M. Tech., (Ph.D.,)** for his valuable guidance, suggestions and constant encouragement paved way for the successful completion of my project work.

I wish to express my thanks to all Teaching and Non-teaching staff members of the Department of **Mechanical Engineering**, who were helpful in many ways for the completion of the project.

ABSTRACT

Many heat transfer studies in phase change material (PCM) based thermal energy storage (TES) systems have been carried out to investigate PCM activity at high temperatures. In general, the study did not take into account of voids inside the PCM encapsulated shell. The work's main goal is to investigate multi-phase heat transfer in encapsulated PCM under controlled conditions. The enthalpy-porosity method will be used to capture the dynamic multi-phase heat transfer that occurs inside the capsules during the study.

The effect of an internal void on overall heat transfer was investigated further by considering three limiting cases: an upper void, a central void, and random void distributions, where the upper void is located opposite the gravitational vector's orientation. Since the PCM for the central void distribution is in direct contact with the entire capsule shell during the initial melting stages, it has the highest heat transfer rate, resulting in a melting period that is 22 percent and 39 percent faster than the random and upper void distributions, respectively. In an ideal world, the hole will be placed as close to the middle of the capsule as possible. The three cases studied show how an internal void has a significant impact on the solid-liquid interface's temporal and spatial evolution.

The performance of pilot-scale EPCM-based latent heat thermal energy storage (TES) system was evaluated to supplement the findings from a single EPCM capsule. During the charging process, the melting front in the capsules evolved in a predictable pattern. The numerical results for the temperature in the EPCM capsule furthest downstream were compared to experimentally recorded values.

Finally, studies on the use of metallic oxides as new novel PCMs were carried out. The eutectic compounds in the paraffin wax system were studied in particular because they give higher energy storage densities at melting temperatures comparable to the nitrate and chloride salts previously studied. The substance that developed during the sample preparation, however, was not a eutectic compound. The difference between theoretical and experimental energy storage was shown to be within the calorimeter system's 2% uncertainty until the initial composition of the material was

established. Although the preliminary findings are positive, additionally before these metallic oxides can be incorporated into EPCM-based systems, further research is required. TES devices with latent heat as a superior alternative to the commonly used nitrate and salts of chloride.

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LIST OF SYMBOLS AND ABBREVIATIONS

- | | |
|------------------|--|
| 1. TES | – Thermal energy storage |
| 2. PCM | – Phase change material |
| 3. EPCM | – Encapsulated phase change material |
| 4. HTF | – Heat transfer fluid |
| 5. PV | – Photovoltaic |
| 6. CSP | – Concentrating solar power |
| 7. C_nH_{2n+2} | – Paraffin wax molecular formula |
| 8. Re | – Reynolds number |
| 9. LHTES | – Latent heat thermal energy storage |
| 10. PTFE and FEP | – Fluorinated ethylene propylene and polytetrafluoroethylene |
| 11. VOF | – Volume of fluid |
| 12. SEM | – Scanning electron microscopy |
| 13. DSC | – Differential scanning calorimetry |
| 14. XRD | – <i>X-ray diffraction</i> |
| 15. VOID | – Volume of free space |

CHAPTER 1

INTRODUCTION

Preceding the approach of coal-based force during the modern insurgency, all energy was delivered through sustainable methods. The improvement of petroleum product-based force age delivered these sustainable methods for energy wasteful. For a very long time the expense and wealth of petroleum derivatives made the idea of utilizing sustainable power uneconomical and in this manner, research zeroed in on methods of improving the innovation behind non-renewable energy source-based influence. Notwithstanding, the world has gone to the acknowledgment that petroleum derivative assets are truth be told restricted, prodding a re-visitation of sustainable force age. Notwithstanding this recovery, framework scale power age through sustainable methods is essentially not expense serious with the presently working non-renewable energy source power plants.

Consequently, while the idea of utilizing hydro, wind, and sun-oriented energies as methods for power are not new ones, further examination into improving their proficiency is required. Of the different sustainable assets, sun-based force is especially appealing in light of the fact that while its power may change it is accessible across the globe. There are two different ways to create power from sunlight-based radiation either using photovoltaic (PV) cells or at sun oriented nuclear energy stations, for example, concentrating sun-based force (CSP) plants.

PV cells straightforwardly convert the sun's beams into power by using the photovoltaic impact of a material. At a CSP plant, the sun's beams are utilized to warm a warm liquid that is then used to drive a force age cycle, for example, the Brayton or Rankine cycle. Both of these ways to deal with power age need to conquer the transient idea of sunlight-based radiation. This outcome in sun-oriented force plants having a low limit factor (18%) when contrasted with petroleum derivative plants (85%).

The limit factor 5 is a proportion of the level of a plant's potential yield that is really yield throughout some undefined time frame. One can improve the limit factor of sunlight-based force plants if a method for energy stockpiling was utilized. Since electrical energy can't be put away straightforwardly, abundance electrical energy

should be changed over into one or the other warmth, mechanical, or synthetic energy to be put away. This transformation brings about energy misfortunes during the capacity cycle as well as during energy recovery, and lessens the adequacy of the capacity interaction and accordingly restricts the measure of energy that can be recovered. This is the place where sun oriented nuclear energy has a benefit over most different types of sustainable power; it can undoubtedly incorporate capacity in the methods for nuclear power without exorbitant discussion measures. This utilizes CSP plants with Thermal Energy Storage (TES) an exceptionally alluring type of lattice scale power age.

1.1 Thermal Energy Storage (TES)

Heat storage systems, also known as thermal energy storage (TES), are a form of technology that stores thermal energy by heating or cooling a storage medium and then using it later, either directly or indirectly. The amount of energy stored is determined by the material's heat capacity and the temperature difference applied to it. Though sensible heat storage systems need large temperature differences to store energy, Can store more latent heat storage systems. To reduce the cost of the storage system, a material with a high energy storage density should be used. Of the three types of TES, thermochemical systems have the maximum energy storage density. Currently only sensible heat storage systems are used at operating CSP plants around the world. These systems either use a large volume of a solid material like concrete or a single or two-tank molten salt-based storage system. This would result in a decrease in the leveled cost of electricity at CSP plants leading to them being not only cost competitive with current fossil fuel-based plants but with other means of renewable energy as well.

1.2 Phase Change Materials

A phase change material is a substance that absorbs and releases heat energy at specific temperatures by freezing and melting. The PCM solidifies and approves a warming effect as it is still in its liquid phase and releases heat in the absorber as the external temperature decreases during this time span. The main component of a latent heat-based TES system is the phase change material (PCM) that is used.

Any material that undergoes a state change can potentially be used as a PCM for TES applications. Solid-solid, solid-liquid, liquid-gas, and solid-gas are the four common state or phase changes that may occur. During a solid phase change the crystal structure of a material changes from one lattice configuration to another. While the small volumetric changes that occur during solid phase changes make them ideal candidates for TES, the transitions are typically slow and have low transformation enthalpies relative to the other state changes. The state change that is typically studied for TES applications is that of solid-liquid phase changes due to their relatively small volume changes and moderate enthalpy changes.

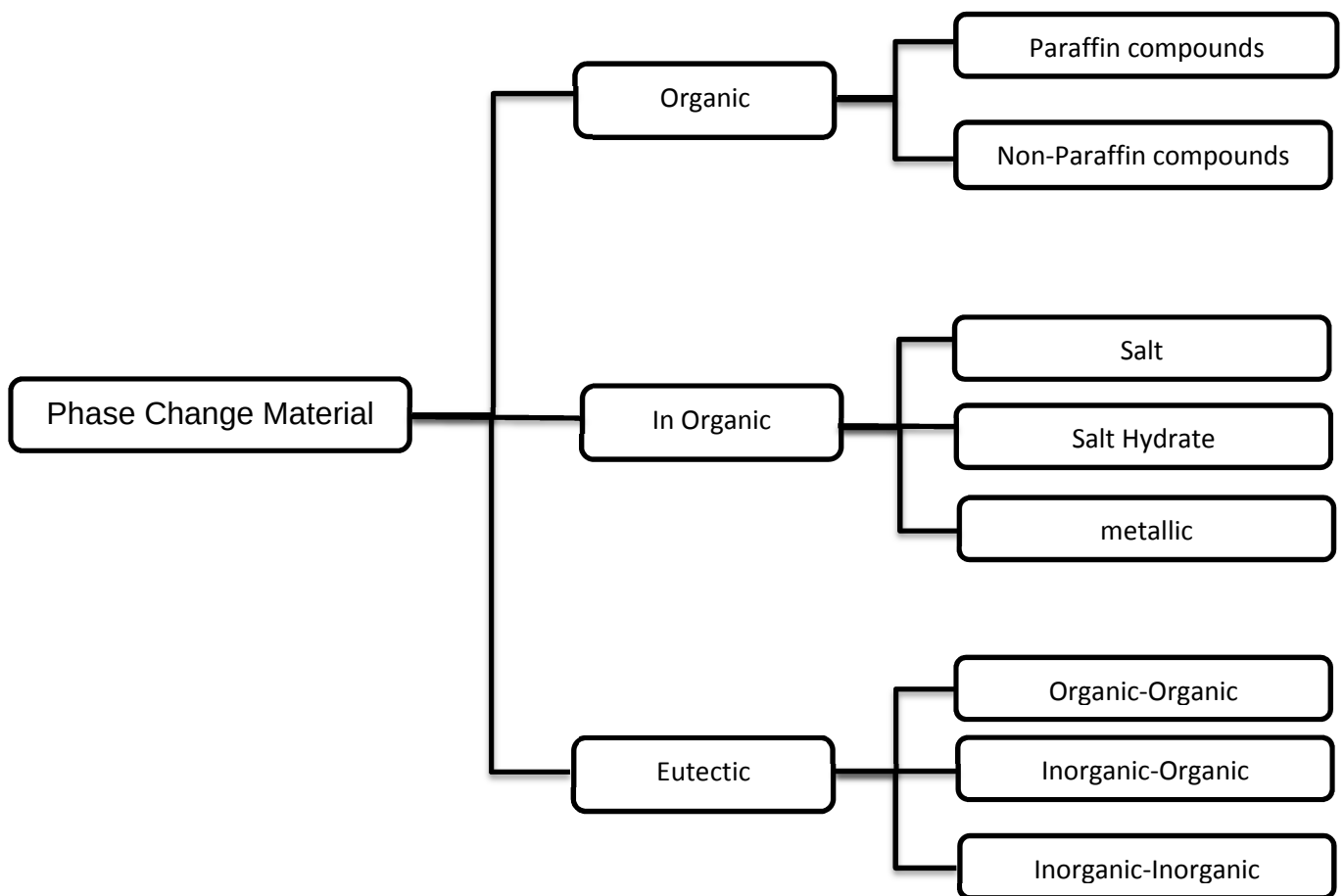


FIG 1.1 Phase change material

Although liquid-gas transitions have high transformation energies, the large volume changes that occur and the complexity of storing the gaseous medium limit their use for TES applications. The last state transformation is when a solid material directly turns into a gas, such as dry ice. Solid-gas transitions have the same drawbacks as the use of liquid-gas transitions. Therefore, the solid-liquid phase change is best suited for TES. The commonly used Phase Change materials for technical applications are: as shown in the figure 1.1 Paraffin (Organic); Salt Hydrates (In-Organic); fatty acids (Organic).

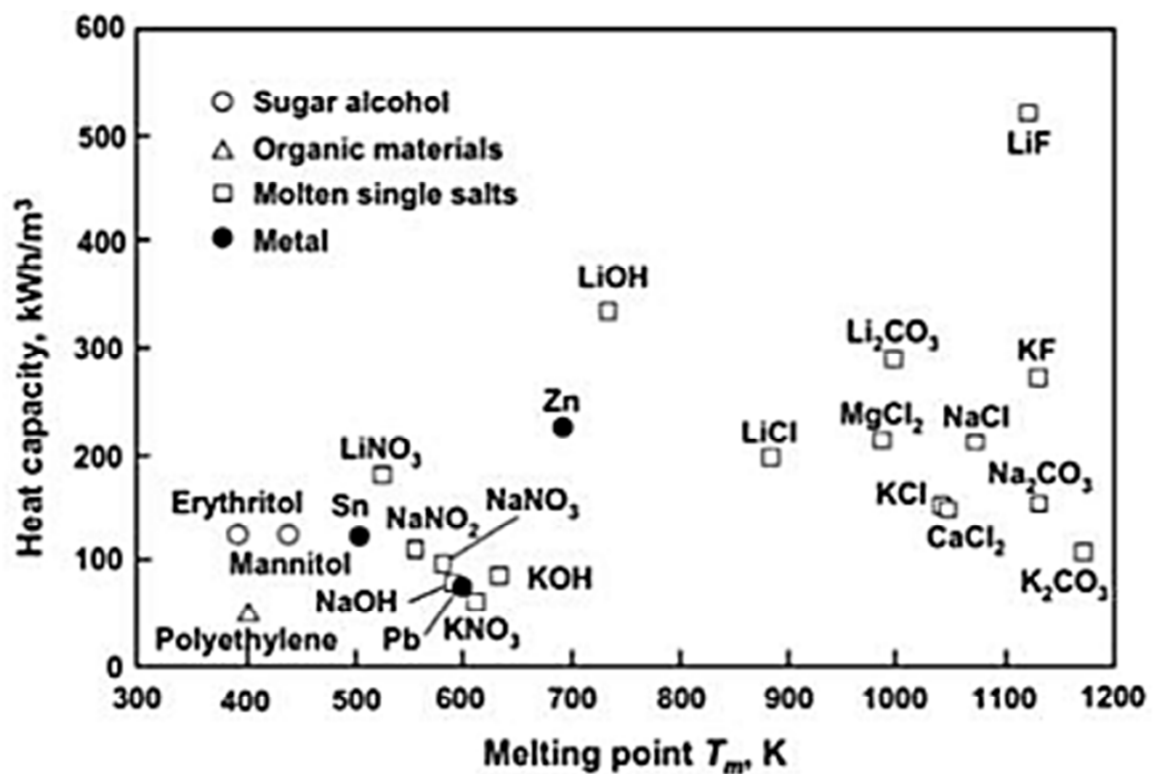


FIG 1.2 Heat capacity and melting points

While these low temperature PCMs have various applications, materials with a softening point more than 300 °C are needed for use at CSP plants.

Investigation into this high temperature territory has basically centered around the utilization of inorganic salts with probably the most remarkable materials being NaNO₃, KNO₃–NaNO₃ eutectics, and MgCl₂–NaCl eutectics. An examination of the idle warmth energy stockpiling limit of different PCMs is introduced in Figure 1.2. Notwithstanding them.

1.3 Encapsulated Phase Change Materials

Encapsulated Phase Change Materials is a substance with releases or absorbs at solve to liquid materials are usually encapsulated for installation in the end applications contain the liquid state. Fixed and well defined temperatures.

There are several classes of phase change materials. paraffin waxes are the most common PCMs for thermal management because they have high heat of fusion per unit weight, have a large melting point selection. There are six major types of phase change materials:

1. Melting
2. Freezing
3. Vaporization
4. Condensation
5. Sublimation
6. Deposition

1.4 Numerical Modeling of Phase Change Materials

Different methods have been utilized to contemplate heat move that includes a strong fluid stage change. The movement of the strong fluid interface can be followed either straightforwardly or in a roundabout way. The most famous technique is the enthalpy-porosity strategy that was created by Volar. Which by implication tracks the area of the 13 strong fluid interfaces utilizing a boundary called the fluid portion. The enthalpy porosity technique is likewise alluded to as the volume following strategy Brent and Voller. directed a fixed-framework arrangement of the coupled force and energy conditions without depending on factor changes, and by using a two dimensional powerful model they considered the impact of laminar normal convection on the softening cycle of gallium in rectangular holes. Addressed the nonlinear enthalpy condition utilizing a semi-implied moving cross section discretization at each time step. Utilized an iterative finite volume technique to contemplate the impact of lightness driven convection on the compelled softening of

PCMs inside round compartments by utilizing crude ward factors and Darcy's law to oversee convection in a permeable medium.

Their outcomes exhibited the significance of the Prandtl number on the softening cycle at a fixed Rayleigh number and that characteristic convection in the liquid PCM speeds up the liquefying interaction in contrast with unadulterated dispersion models. Portrayed the cementing of different PCMs inside barrel shaped and round shells by looking at the how changed shell materials, case widths, and surface temperatures influenced the general hardening measure. Contemplated the impact of lightness driven convection both tentatively and mathematically by considering the obliged softening of n-octadecane inside a round glass shell. Consolidated the enthalpy-porosity strategy into Ansys Familiar to research the utilization of n-octadecane in round and hollow cases that were dependent upon a uniform outside heat move coefficient. Led a parametric examination of the dissolving of a paraffin wax PCM epitomized inside 14 circular shells. Utilizing the enthalpy-porosity technique inside Familiar they had the option to display a 20% void division, volumetric extension of the PCM after softening, and convection inside the liquid media by at the same time settling the protection conditions for the air void, strong PCM, and fluid PCM. Their model incorporated a vent at the highest point of the case that ousted the air void as the PCM extended.

They approved their model utilizing exploratory outcomes and had the option to precisely catch the spread of the strong fluid interface. Likewise led a comparable to concentrate on the hardening interaction inside a similar EPCM cases. To higher temperatures by utilizing C_nH_{2n+2} as the PCM. They acquired comparable outcomes and had the option to catch the pressure of the air void by thinking about a fixed case.

The impacts of radiative warmth move inside EPCM case was concentrated by Archibold. By utilizing C_nH_{2n+2} as the PCM and their outcomes demonstrate that radiative warmth move expands the dissolving rate inside the containers. Utilized a viable stuffed bed model to contemplate the warmth move that happens in a bed of centimeter-sized round EPCM containers and the impact of warmth move liquid (HTF) stream rate, Stefan number, shell thickness, and shell material. Thought about the consequences of utilizing both a front following and enthalpy-porosity strategy for

the dissolving of C_nH_{2n+2} in both on a level plane and vertically orientated round and hollow EPCM containers and inferred that the two models can precisely catch the proliferation of the strong fluid interface for both the liquefying and cementing measures.

1.6 Flow solvers:

FLUENT takes into account the decision between thickness-based and pressure-based solvers. The solitary distinction between these solvers is the linearization interaction used to 24 tackles the discretized conditions. Nonetheless, since the entirety of the mathematical recreations directed includes a stage change measure, just pressing factor-based solvers can be utilized. These pressing factor-based solvers utilize calculations that have a place with an overall class of techniques called the projection strategy wherein the preservation of mass inside the speed field is accomplished by settling a pressing factor condition. An isolated calculation is utilized in which the overseeing conditions are tackled consecutively inside an iterative circle until the combination is acquired by means of the cycle illustrated underneath:

1. Update liquid properties
2. Address the force conditions consecutively for u , v , and w
3. Address the pressing factor revision (coherence) condition
4. Update face mass transitions, pressing factor, and speed field
5. Tackle extra scalar conditions (energy and choppiness)
6. Check for union

1.7 Enthalpy Porosity Method

To demonstrate a stage change measure, the standard energy preservation condition should be altered to incorporate the dormant energy delivered during the stage change. There are two different ways to mathematically follow the advancement of the softening front inside a computational area: either unequivocally or by implication. The most widely recognized technique is that of the enthalpy-porosity strategy created by Voller et al. [26] which by implication tracks the movement of the strong fluid interface utilizing a boundary called the fluid portion, γ . Concerning the enthalpy-porosity strategy, the computational area is separated into

a strong locale, a fluid district, and a soft zone dependent on the estimation of the fluid part inside a given cell.

1.8 Volume of Fluid Method

To contemplate the pressure of an inward void space coming about because of the volumetric extension of the PCM after dissolving, the above set of overseeing conditions for a strong fluid stage change should be stretched out to numerous stages. While FLUENT offers three multiphase models just the volume of liquid (VOF) model can be utilized related to the enthalpy-porosity-based liquefying and hardening model. The VOF model can be utilized to display spaces that comprise at least two immiscible liquids. The model tracks the volume part of every liquid present in the area and afterward addresses a solitary force and energy condition over the whole space utilizing volume-weighted properties.

1.9 Turbulence Modeling

At the point when the stream around a chamber is violent, the warmth move coefficient around the case is expanded, in this way disturbance is useful in TES frameworks; in any case, it adds an additional degree of intricacy to the mathematical reenactments. Reynolds (Re) number is utilized to decide if a stream is in the laminar or choppiness system. Re dependent on the breadth of the round and hollow EPCM cases is characterized as:

$$\mu \text{ pvD Re} = (20)$$

Where p is the thickness of the HTF, v is the shallow speed, D is the breadth of the case, and μ is the consistency of the HTF. Stream past a chamber can be considered experiencing significant change when Re is more prominent than 100. For the stream conditions seen at CSP plants, all things considered, this will be the situation and along these lines, a choppiness model should be utilized.

1.10 OBJECTIVES OF THE WORK

- To formulate a numerical model to predict the multi-phase (solid to liquid) heat transfer in a PCM encapsulated panels by considering inner void space and extruded surfaces
- To identify best PCM suitable for high temperature application ($T > 150^{\circ}\text{C}$)
- To identify best encapsulation material for the PCM
- To develop numerical model for identifying thermal behaviour of encapsulated PCM.
- To develop a pilot-scale experimental setup for the validation of numerical results
- By using somewhat void we store more energy in small space
- In 20% of void thermal expansion was done in capsule.

CHAPTER 2:

LITERATURE SURVEY

In this part, a writing review of late investigations related with nuclear power stockpiling, stockpiling materials, heat move rate upgrade procedures, microencapsulation, research center scale inert warmth pressed bed stockpiling framework with exemplified PCMs and liquefying/cementing inside a round case are examined.

2.1 Thermal Energy Storage

1. Tanvir E.Alam, January 2015, Thermal Energy Storage in a Encapsulated Phase Change Materials ,

Inference: This chapter discussed probable steps involved with the production process of the capsule. It also discussed several important parameters to ensure quality control of the product capsules.

2. Suhas Ramchandra Pawar, June 2015, Thermal Storage System and Applications.

Inferences: Developing efficient and inexpensive energy storage devices is seen as important developing new sources of energy. This literature survey we learn about different types of thermal energy storage systems.

3. Sachin N. Avghad, Ashok J. Keche, Abhijit Kousal ; June 2016, thermal energy storage.

Inferences: The primary applications of latent heat TES devices stored from the automobile engine during this operation and to provide the stored energy to warm up the engines in the cold weather and at a start. Latent heat thermal energy storage system stores 5-14 times more heat than sensible heat thermal energy storage material.

4. Ioan Sarbu and Calian Sebarchievici, January 2018, a comprehensive review of thermal energy storage.

Inference: Numerous mechanical and Nano-level enhancement have been achieved to increase the heat transfer rate, which is promising. Micro encapsulation increases the heat transfer surfaces area and also a solution for phase segregation in salt hydrates.

5. B. Akhmetov, A. G. Georgiev, A. Kaltayev A. A. Dzhomartov, R. Popov M. S. Tungatarova; 2016; Thermal Energy Storage Systems.

Inference: Ates system are highly dependent on the geological structure of the subsurfaces layer. In this thermal energy storage techenoliges, especially large-scale thermal storages such as aquihire and borehole thermal storage tank and pit thermal energy storages.

2.2 Encapsulation of Phase Change Materials

1. Weihuan Zhao, 2013, Characterization of Encapsulated Phase Change Materials for Thermal Energy Storage.

Inference: The present work includes immersion calorimeter experiments and heat transfer simulations for EPCM capsules for thermal energy storage system. The aim has to been to study single EPCM for their usage in TES systems.

2. Alptug Yataganbaba, Bengi Ozkahraman, Irfan Kurtbs, 2015, Encapsulation of phase changing materials using bibiliometric analysis

Inference: The findings obtained from bibiliometric analysis provide insights for future research. Based on raw data from scopus database, the publication characteristics such as quantity and quality were analysed by using the bibiliometric analyse techniques over the past few years.

3. Carolina cardenas-Ramfrez, Franklin Jaramillo, Maryory Gomez, 2020, Encapsulation stabilization of phase change materials.

Inference: Encapsulation and shape stabilisation of organic PCM were studied using bibiliometric analysis. A systematic review was performed for the materials and methods used in CS-PCM and SS-PCM. Opportunities to investigate in leakage, heat exchange, thermal conductivity and thermal cycling.

4. Hassan Nazir, Maraih Batool, Francisco J, 2019,

Inference: The strategy adopt in improving the thermal energy storage characteristics of the phase change materials through encapsulation as well as nanomaterials additives, are discussed in detail. Specifically, the future research trends in encapsulation and nanomaterials are also highlighted.

5. Hussein Akeiber, Mazlan A wahid, Hasanen M hussen, 2014, phase change materials models in building applications.

Inference: The properties of the PCM are as shown in the below table 2.1.

Table-2.1 Properties of PCM

	Melting times (Minutes)	Melting times per unit mass of PCM (Minutes/kg)
No gravity effect of solid PCM; No natural convection in molten PCM; No void space in capsule	114.8	12.1
Gravity effect of solid PCM	79.4	8.4
Buoyancy –driven convention in molten PCM + Gravity effect of solid PCM	76.1	8.0
20% void space in capsule + Gravity effect of solid PCM	65.6	8.6

2.3 Numerical comparison between single PCM and multi-stage PCM

1. K.E.Elfeiky, N. Ahmed and Qiuwang Wang *, April 2018, Numerical comparison between single PCM and multi-stage PCM based high temperature thermal energy storage for CSP tower plants.

Inference: They have developed a transient concentric depression (C-D) model to investigation on the thermal performance of the single PCM and three stage PCMs of a molten salts packed-bed TES system containing capsule filled with high temperature PCM with different thermo-physical properties.

2. Taha Aldoss, Muhammad M. Rahman, march 2014, Comparison between the single-PCM and multi PCM thermal energy storage design.

Inference: They have been increases thermal performance of cascade Latent Heat Thermal Storage System (LHTES) increases with number of PCMs. The complexity and operating cost of the system grows. That they have been conclude using more than three PCMs is not recommended from a practical and economical point of view.

3. Abdel Hassan Sweidan, Yousef Heider and Bernd Markert, 2020, modeling of PCM-based enhanced latent heat storage system using a phase-field-porous media approach.

Inference: Numerical study of latent heat storage system, based on phase change material (PCMs) with various heat transfer enhancement techniques. They have been concluded on Additionally, the energy charging rate depends on the arrangement type of the multiple PCMs.

4. Lakshmi Narasimhan N, June 2019, Assessment of latent heat thermal storage systems operating with multiple phase change materials.

Inference: As compared to sensible heat storage devices, systems that use phase change materials (PCMs) have many advantages. However, due to poor heat transfer, poor thermal conductivity of PCMs, and other factors, they have a poor thermal efficiency. Methods such as replacing single PCMs with multiple PCMs, adding fins, creating micro/macro/nano-encapsulated composite PCMs, and dispersing high conductivity particles into PCMs have all been proposed and investigated. Various authors have used it in the past to boost the efficiency of LHTS systems.

5. K. E. Elfeky, N.Ahmed, S.M.A Naqvi, Qiuwang Wang, 22-25 August 2018, Numerical Investigation of the melting temperature effect on the performance of thermocline thermal storage tank for csp.

Inference: Low cost and high efficient thermal energy storage (TES) technologies are vital for large scale applications of concentrated solar power (CSP) system. With TES, CSP systems can not only generic stable and dispatchable electricity.

2.4 Encapsulation of PCMs in Latent Heat Thermal Energy Storage

1. Laura Solomon, May 2016, Numerical & Experimental Evaluation of Encapsulated Phase Change Materials for Use in Thermal Energy Storage Applications.

Inference: A numerical heat transfer analysis of encapsulated phase change material (EPCM) capsules was conducted by employing the enthalpy-porosity and

VOF methods simultaneously to capture the complex multi-phase heat transfer that occurs within the capsules. They increased melting rate resulting from convection in the molten PCM further reshapes the solid-liquid interface. In contrast, the solidification process is conduction-dominated and limited by the thermal conductivity of the chosen PCM resulting in considerably longer solidification times.

2. Ioan Sarbu, Alexandru Dorca, 24 July 2018, Review on heat transfer analysis in thermal energy storage using latent heat storage systems and phase change materials.

Inference: one of the obstacles that preventing the development of pcm technologies is the lack of international technical standards for testing pcms. This has led to research groups using their own method for characterization of energy storage materials. The elaboration of the current status and research related to the experimenting and testing procedure is very important.

3. Tiago Silva, Romeu Vicente, Maria Fernanda Silva Rodrigues, January 2016, Phase change materials in glazing and shading solutions.

Inference: The large energy consumption of the building sector is mainly resourcing to active systems for cooling and heating of indoor spaces. According this, the external envelopes of offices and commercial buildings are systematically composed by large glazed areas that lead to high energy losses in the winter and large solar gains in summer. The incorporation of phase change materials into building elements is a growing trend for improving the thermal energy storage capacity in the latent form and the thermal inertia.

4. G.Murali, May 2015, Latent Heat Thermal Energy Storage Systems.

Inference: It is important that the thermal energy storage systems have the necessary characteristics to improve the performance of the storage. Usage of Phase Change Materials (PCM) for energy storage provides a great benefit but, their low thermal conductivity becomes a major drawback. This can be compensated with

the use of phase change material in an appropriate design for successful functioning of the system.

5. Guangjian Peng, Guijing Dou, Yahao Hu, Yiheng Sun, and Zhitong Chen, December 2019, phase change material (pcm) microcapsules for thermal energy storage.

Inference: The physical, thermal, chemical, and mechanical properties of PCM microcapsules are significantly affected by the raw materials and synthesis processes during microencapsulation. Since these properties are of great importance to applications of PCM microcapsules, there is an increasing demand for accurate quantification and characterization of the physical, thermal, chemical, and mechanical properties.

2.5 Heat Storage Tanks

1. Appasaheb Raul, Mohit Jain, Swapnil Gaikwad, Sandip K. Saha†, Modeling and Experimental Study of Latent Heat Thermal Energy Storage with Encapsulated PCMs for Solar Thermal Applications.

Inference: To make the solar thermal power plants a viable solution for continuous power generation. In this work, a mathematical model of encapsulated phase change materials (PCMs) based latent heat thermal energy storage (LHTES) is developed considering simplified non-equilibrium two energy equations coupled with enthalpy technique to analyse the transient variation in heat transfer fluid (HTF) temperature at the outlet of LHTES and PCM temperature. Experiments on a spherical capsule reveal melting and solidification behavior of PCM from the measured temperature field.

2. Tianrun Yang, Wen Liu, Gert Jan Kramer, Qie sun, April 2021, Seasonal thermal energy storage.

Inference: STES is a key technology for replacing fossil-based heat supply with renewable heat sources, such as solar thermal energy, geothermal energy, or waste

heat generated from industries. This paper presents a comprehensive techno-economic literature review of STES technologies and projects. Within the class of SHS technologies, TTES and PTES are mature and mass-market technologies and have an advantage in terms of storage temperature and efficiency because of their good insulation; however, their space requirement and potential of leakage are substantial, and thus, limits their application.

3. Ali Mohammed Hayder, Azwan Sapit, Qahtan A Abed, November 2017, Solar thermal storage techniques.

Inference: The literature concerning the usefulness of using the most important two core components in solar heat Consequently, thermal energy storage is considered a perfect option to solve this problem. A thermal energy storage unit works to enhance the conservation of energy and hence, improve the performance of the solar heating system.

4. Haydar Boyali, Muiz Adekunle Agabaje, Ali bulasmak, melike Hatice Guney, June 2020, Literature survey on the storage and usage of solar heat in ground source heat pump systems.

Inference: One of the fastest growing sources of renewable energy and a viable alternative to fossil fuel is solar energy. Solar energy is also a proven sustainable and reliable energy source. Solar energy is used for heating in various application ranging from small scale domestic space heating to large scale desalination and for electric power generation in solar thermal plants. However, the effective use of solar energy sometimes necessitates the use of other energy sources along with it.

5. Mr.Kamlesh chhajer, Prof.N C Ghuge, December 2015, Study and investigation of solar water heating system using phase change material (PCM).

Inference: — In order to utilize the solar energy from the sun at all times energy should be stored and used when needed. Phase change material is a viable for storing thermal energy in solar water heating system and has the advantages of its isothermal behaviour during the charging and discharging processes and high

energy storage density. They store 5 to 15 times more amount of heat per unit volume than sensible storage materials. As shown in figure 2.1.

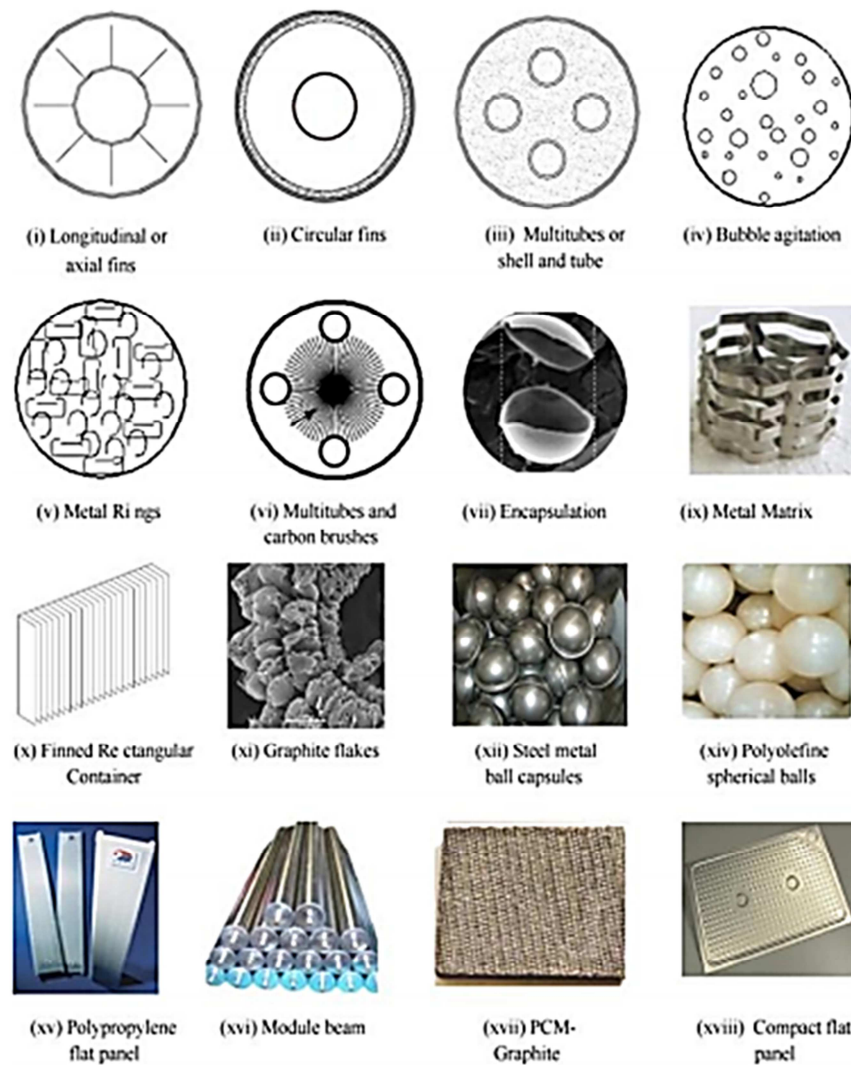


Figure 2-3: Various methods employed by the researchers to enhance the heat transfer rate [37] (permission is in Appendix C)

Fig-2.1 Enhance the heat transfer rate

To amplify the move region in the TES blades or expanded surfaces are utilized. On the off chance that the conductivity of the PCM is lower than HTF, the balance will be set in the PCM side or the other way around.

CHAPTER 3

AIM AND SCOPE

Numerical heat transfer Analysis of Encapsulated Phase Change Materials for Use in High Temperature Thermal Energy Storage Applications.

3.1 Aim

Many heat transfer analyses in phase change material (PCM) based thermal energy storage (TES) system has been conducted to analyse the PCM behaviour at elevated temperature. In general, the analysis was conducted without considering void inside the PCM encapsulated shell. The main objective of the work is to analyse the multi-phase heat transfers in encapsulated PCM under controlled environmental system. The analysis will be carried out by employing the enthalpy-porosity method to capture the complex multi-phase heat transfer that occurs within the capsules.

3.2 Scope

In this investigation, liquid soluble base metal nitrate-based salts and their eutectics are chosen as the PCM. The test is to manufacture typified PCMs that can withstand the profoundly destructive climate and the volumetric extension of the PCMs on liquefying. The current work is worried about the security of the embodiment material and thermophysical properties of the PCM when warm cycling in different conditions like air, warm oil, and liquid salt.

As is clear from the writing review, the vast majority of the LHTES examines have either been completed for low-temperature typified PCMs (300°C) embodied in the huge metallic round and hollow holders. There are a couple of reports on the mathematical investigation of high-temperature LHTES dependent on the full scale or microencapsulated circular PCMs cases notwithstanding, there is no report on the test exhibit of the stuffed bed LHTES framework that contains high temperature typified round PCM cases ($m.p > 300^{\circ}\text{C}$). Accordingly, this examination centers around developing a pressed bed LHTES framework with manufactured circular cases, and furthermore, on assessing the warm presentation of the framework by estimating the temperature profile for various stream rates.

The absence of reports on liquefying and hardening of various estimated round cases loaded up with high-temperature PCM marks the requirement for the

investigation toward this path. In this examination, diverse measured total cases will be tried to notice the temperature profile and their charging releasing time. As graphene has a lower thickness than C_nH_{2n+2} PCM and has higher warm conductivity, different wt% of graphene are utilized as the scattering molecule to improve the warmth move rate and contrasted and unadulterated C_nH_{2n+2} cases.

CHAPTER 4

EXPERIMENTAL PROCEDURE AND METHODS

4.1 EXPERIMENTAL PROCEDURE

The cycle comprises consistent charging and releasing of the LHTES loaded up with embodied PCMs for the investigation of its warm presentation. At first, the LHTES and the HTF are at the encompassing temperature. The temperature of HTF is raised to the necessary temperature utilizing electric warmers and the HTF is flowed at first through the detour line. When the temperature of HTF spans to the necessary level, the detour valve is shut and the HTF is permitted to course through the LHTES. During tests, the HTF temperature is controlled utilizing a cooler and electric warmer to keep up at a specific level. The ideal stream rate in the arrangement is acquired by an outward canned engine siphon joined with a variable recurrence drive. The volume stream rate is estimated by Emerson make F-arrangement Coriolis mass stream meter. A differential pressing factor transmitter of Yokogawa make is utilized for the estimation of pressing factor drop in the framework. One complete cycle comprises three modes, (I) beginning mode, (ii) charging mode, and (iii) releasing mode. In the beginning mode, the HTF gulf temperature is warmed to the set temperature. From that point onward, the charging of the LHTES has proceeded for ~1000 s, trailed by releasing of LHTES for ~1500 s. During releasing period, the warmth exchanger is utilized to cool the gulf HTF temperature to the ideal level. The temperature and mass stream rate is estimated at a time interval of 1 s. Combined energy put away and separated from the PCM by the HTF is determined for various working boundaries.

4.2 Process of phase changing material

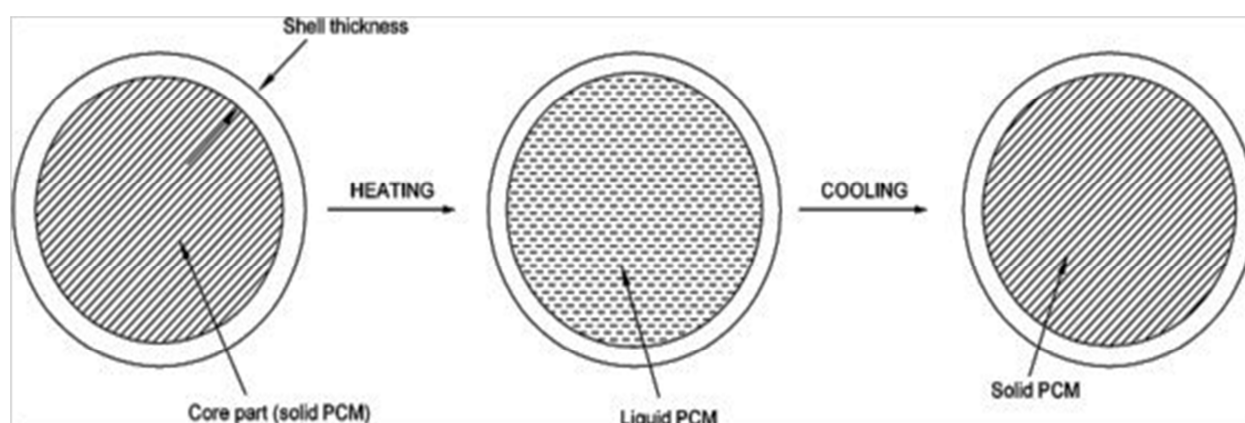


Fig 4.1 Process of phase changing material

As shown in Figure 4.1, a phase change material (PCM) is a substance that releases/absorbs enough energy at phase transition to provide useful heat/cooling. From the

fundamental states of matter, the transformation will take place. It changes to solid to liquid and liquid to solid and to the other.

4.3 Encapsulate ball:

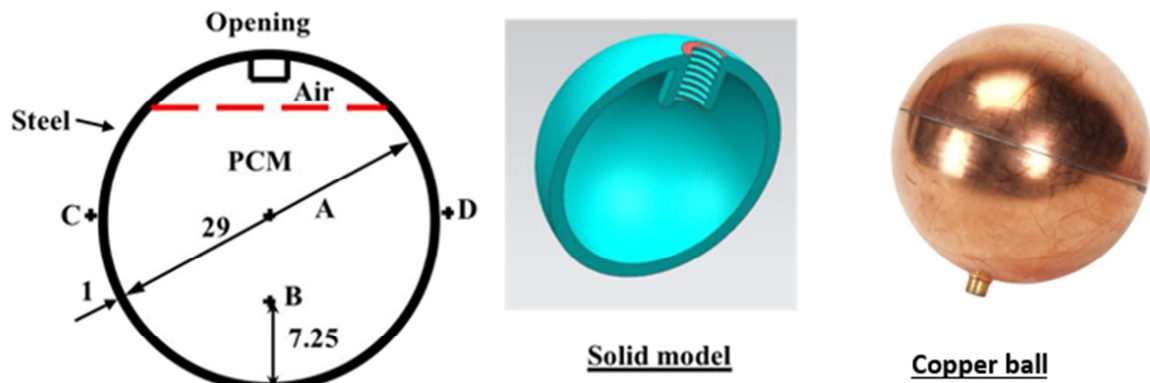


Fig 4.2 Encapsulate ball

This encapsulate ball is made up of copper ball and filled with paraffin wax. And this ball was fixed in the container and ball will be heat in the container. And this encapsulated ball is filled 80% of paraffin wax and 20% of void. And in that 20% of space will be filled with the air as shown in the figure 4.2 in that place thermal expansion is taken place.

4.4 Numerical modeling

A two-dimensional topsy-turvy actual space is picked as the mathematical area, as demonstrated in the figure, for foreseeing the fleeting varieties in temperature of PCM and HTF during charging and releasing cycles. The LHTES considered in the mathematical reenactments is the same as the lab scale test arrangement.

In the numerical model, epitomized PCMs are considered as permeable construction through which HTF streams. Changed energy conditions for the permeable medium are considered for the investigation of stuffed bed LHTES. While coursing through the LHTES, HTF trades energy with filler material, for example, embodied PCMs, in the permeable medium. The suspicions made in the improvement of the mathematical model are

- (i) The flow of HTF is laminar, Newtonian, and incompressible.
- (ii) The thermo physical properties of HTF and PCM are taken as consistent over a scope of temperature.
- (iii) Isothermal stage change and
- (iv) Unimportant volume change of PCM during stage change.

Liquefy convection in fluid PCM as shown in the figure 4.3 and along the pivotal course in the permeable PCM structure are thought of, anyway spiral warm conduction in HTF and PCM, and radiation heat move are disregarded.

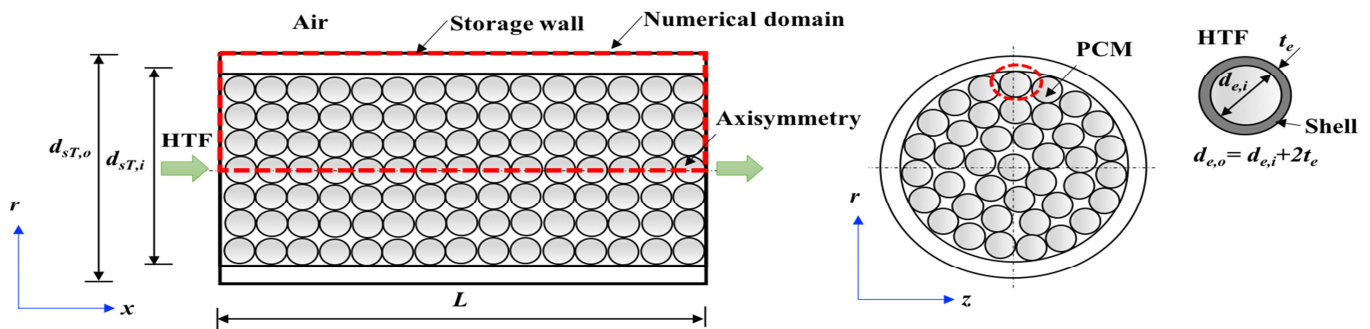


Fig 4.3 Heat transfer fluid

4.5 Repeatability of experiments

To ensure that the experimental results are repeatable, each experiment is repeated at least three times with the same inlet operating conditions. The time-dependent difference of inlet and outlet HTF temperatures in a sample case with an inlet HTF temperature of 185°C at the time of charging.

Figure 4.4 displays a schematic diagram of a latent heat thermal energy storage device with encapsulated PCMs. A cylindrical packed bed LHTES, heat transfer fluid (HTF) reservoir, canned motor pump for HTF circulation, twenty-two electric heaters with capacities of 500 W each, heat exchanger, and 3-way valve make up the experimental system. A commercial grade organic material is chosen as the phase change material (PCM). The LHTES, which is designed using steady state heat transfer analysis considering latent heat capacity of 200 Wh, has a dimension of 170 (diameter) x 360 (height) mm.

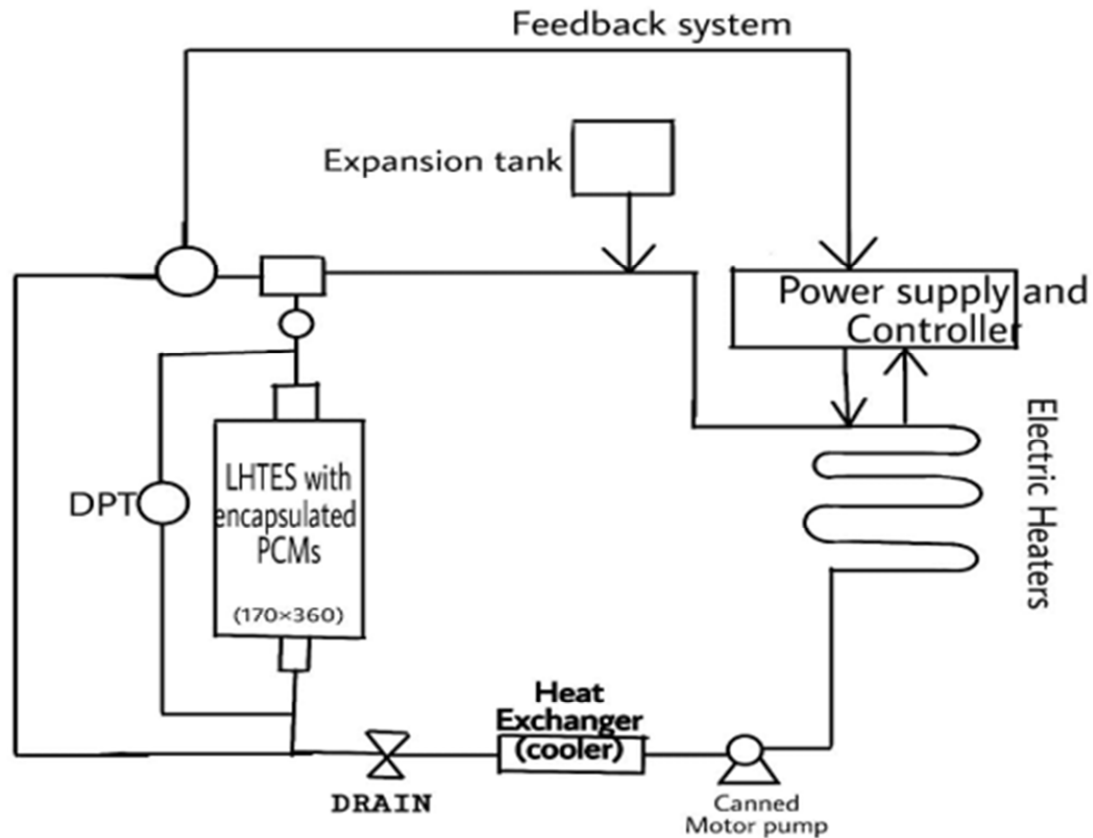


Fig 4.4 Repeatability of experiments

Each capsule has an inner diameter of 29 mm with thickness of 1 mm and total 209 numbers of capsules are randomly packed in the cylindrical storage, resulting in porosity of 0.6. The storage with encapsulated PCMs is placed vertically, which serves as the HTF, is pumped from the top of the LHTES through an inlet diameter of 20.87 mm during charging and discharging periods, as shown in the figure 4.4. The storage system's outlet diameter is the same as the inlet diameter. Stainless steel (SS316) is used as the material of PCM capsules and storage container. Each capsule has an opening to fill the liquid PCM and the capsule is filled 95% of the total volume using liquid PCM to accommodate vapour pressure as shown in figure 4.2. After the PCM has solidified, a stud is used to close the capsule's opening, which is then sealed with high-temperature RTV silicone sealant. Leakage test is performed on all capsules under multiple thermal cycles in an electrical furnace at different temperature above the melting point of PCM, before keeping in the storage container.

4.6 Uncertainty analysis

The uncertainty analysis is performed to predict the overall uncertainty in the measured Parameters. The uncertainty of the K-type and T-type thermocouples. This results the uncertainty of the temperature measuring system, neglecting the uncertainty of the data acquisition unit (NI systems). The uncertainty of the Emerson makes F-series Coriolis mass flow meter and the differential pressure transmitter of Yokogawa make is $\pm 0.2\%$ of total mass flow rate and $\pm 0.1\%$ of the measured pressure, respectively. Hence, the total uncertainty is calculated.

4.7 Mathematical modeling

(a) Energy equation for HTF

(b) Energy equation for PCM

(c) Energy equation for storage wall

The outside walls of the storage structure are in contact with ambient air, and the inside walls are in contact with heat transfer fluid.

4.7.1 Energy equation for HTF

Two-temperature non-equilibrium model is adopted to analyses heat transfer in porous region, where separate set of energy equations are written for HTF and encapsulated PCMs. Thermal non-equilibrium between HTF and PCM in the packed bed is modeled using h_{conv} , F as,

$$\phi \rho F c_p \frac{\partial T_F}{\partial t} + \partial (\rho F c_p T_F u) \partial x = \partial^2 (\phi k F \nabla T_F) \partial x^2 + h_{conv} F (T_S - T_F)$$

In equation, u is taken as the interstitial velocity (U) at the inlet, where $U = \dot{m} / \rho F A S T$, $i\phi$ and the velocity in r direction is considered as zero.

4.7.2 Energy equation for PCM

$$(1 - \phi) \rho S c_p \frac{\partial T_S}{\partial t} = \partial^2 [(1 - \phi) k S \nabla T_S] \partial x^2 + h_{conv} F (T_F - T_S) + S_2$$

where, the source term is defined as $S_2 = - (1 - \phi) \rho S \frac{d\Delta E}{dt}$. The source term S_2 takes the latent heat content (ΔE) into account during phase change of the PCM. The enthalpy content in PCM is dependent on temperature whose value varies in a

range of $[0, L_{lat}]$. For an isothermal phase change, for P th control volume after n th iteration latent heat content is given as, $[\Delta EP]_{n+1} = [\Delta EP]_n + \Delta p \Delta p_0 c_p S \lambda ([TPCM]_n - T_m) [\Delta EP]_n = 0$ If $[\Delta EP]_{n+1} < 0$ (7)

$[\Delta EP]_n = L_{lat}$ If $[\Delta EP]_{n+1} > L_{lat}$

Parameters Δp , Δp_0 are obtained by discretizing equation (5). The liquid fraction fl of PCM at any instant can be calculated as $fl = \Delta E / L_{lat}$.

The energy equations are solved using an acceptable set of initial and boundary conditions.

4.8 Design of storage tank:

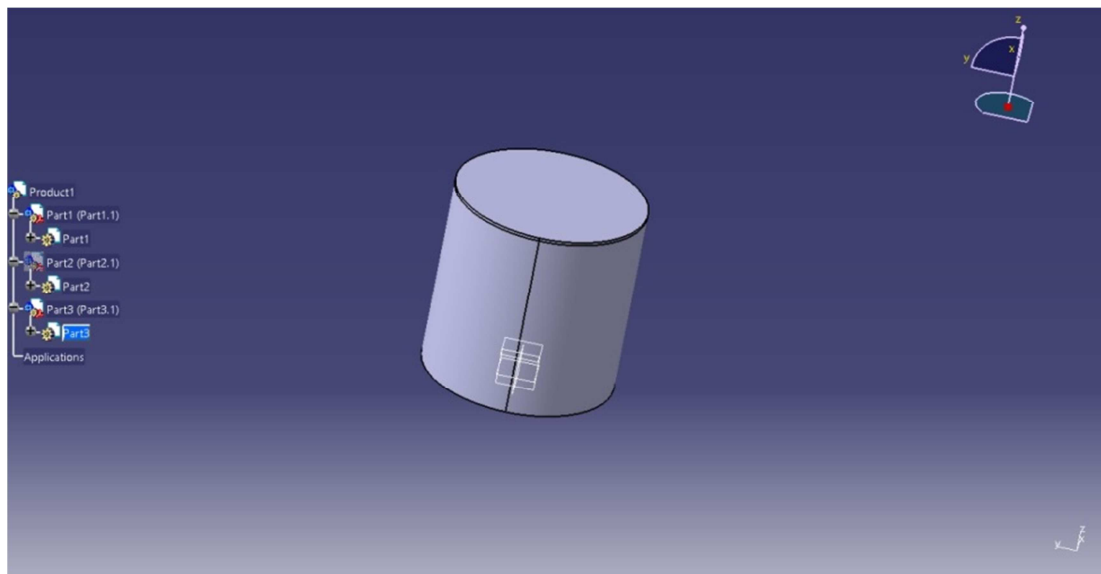


Fig 4.5 Inside the tank Encapsulate balls

The above figure 4.5 shows that outlet of an container where we are going to do the experimental procedure.

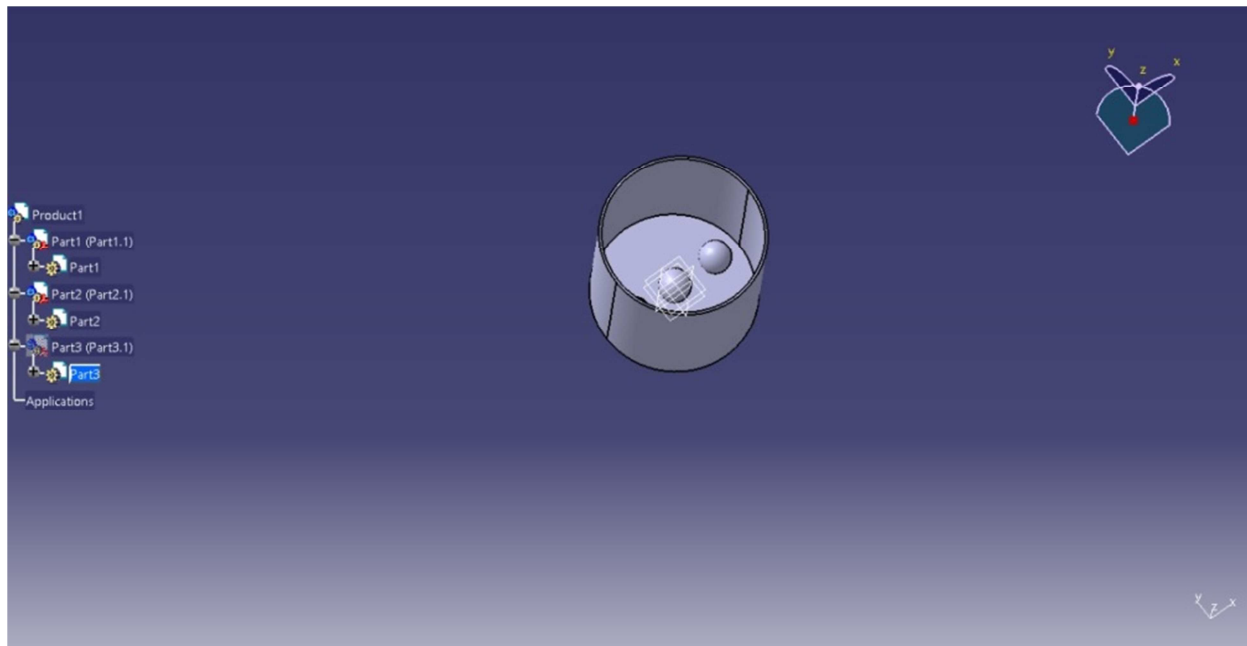


Fig 4.6 Inside the tank Encapsulate balls

The figure 4.6 shows that the inlet diagram of a container with three pcm balls carries same material. And totally covered with therminol 55 oil in the container.

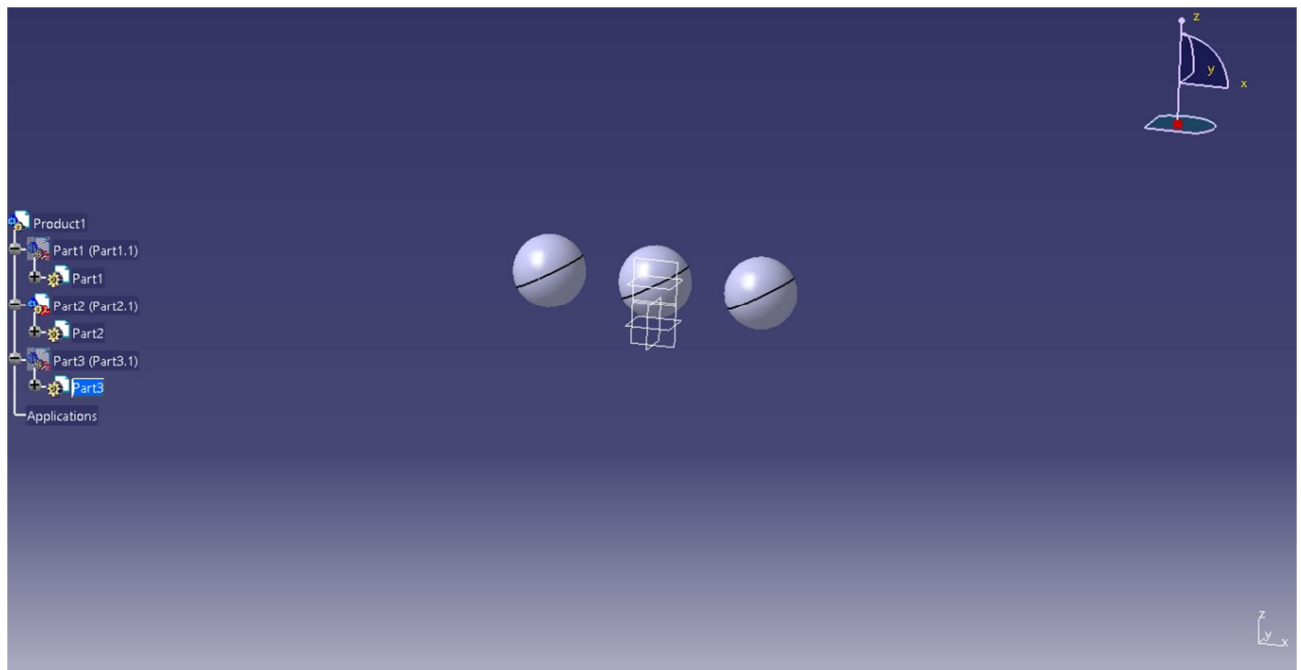


Fig 4.7 Encapsulate balls

The figure 4.7 denotes that encapsule ball which are made up of cooper material. And inside these copper balls are filled with paraffin wax which are keeping in the container.

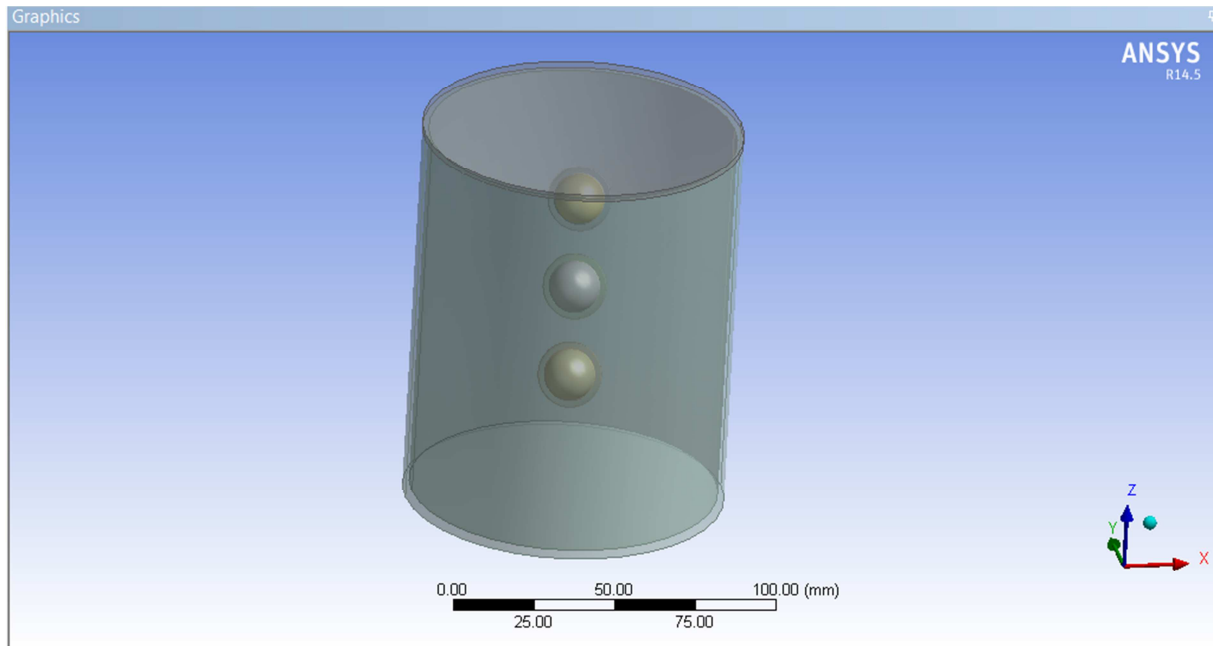


Fig 4.8 Design of encapsulate material

The above figure 4.8 shows that the design of an experimental procedure. Mild steel material as used as a container and balls are placed like this and in the container therminol 55 oil will be filled. The heating and cooling process will be taken places in this container.

4.9 MATERIALS USED

- (i) Paraffin wax
- (ii) Therminol 55
- (iii) Copper capsule
- (iv) Mild steel storage tank
- (v) Thermometer

4.9.1 Paraffin wax:

Paraffin wax is a smooth, solid wax that is white or colorless. Saturated hydrocarbons are used to make it. It's commonly used on the hands in skin-softening salon and spa treatments. Since it's colorless, tasteless, and odorless, it's often used in skin-softening salon and spa treatments on the palms, cuticles, and feet. It may also be used to relieve pain in sore muscles and joints. The benefits of paraffin wax are numerous. There are many other applications as well. It's also used as lubricant,

electrical insulation, and in the production of candles and crayons.



Fig 4.9 Paraffin wax material

Heating and cooling curves for paraffin wax in the range of 20-40°C

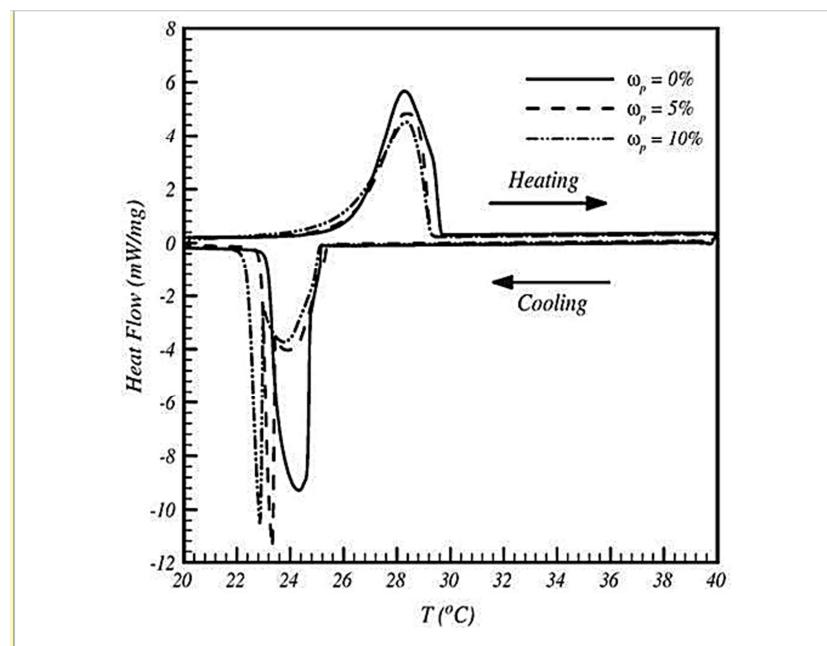


Fig 4.10 Heating and cooling curves for paraffin wax

Thermal conductivity of paraffin wax and composite versus temperature.

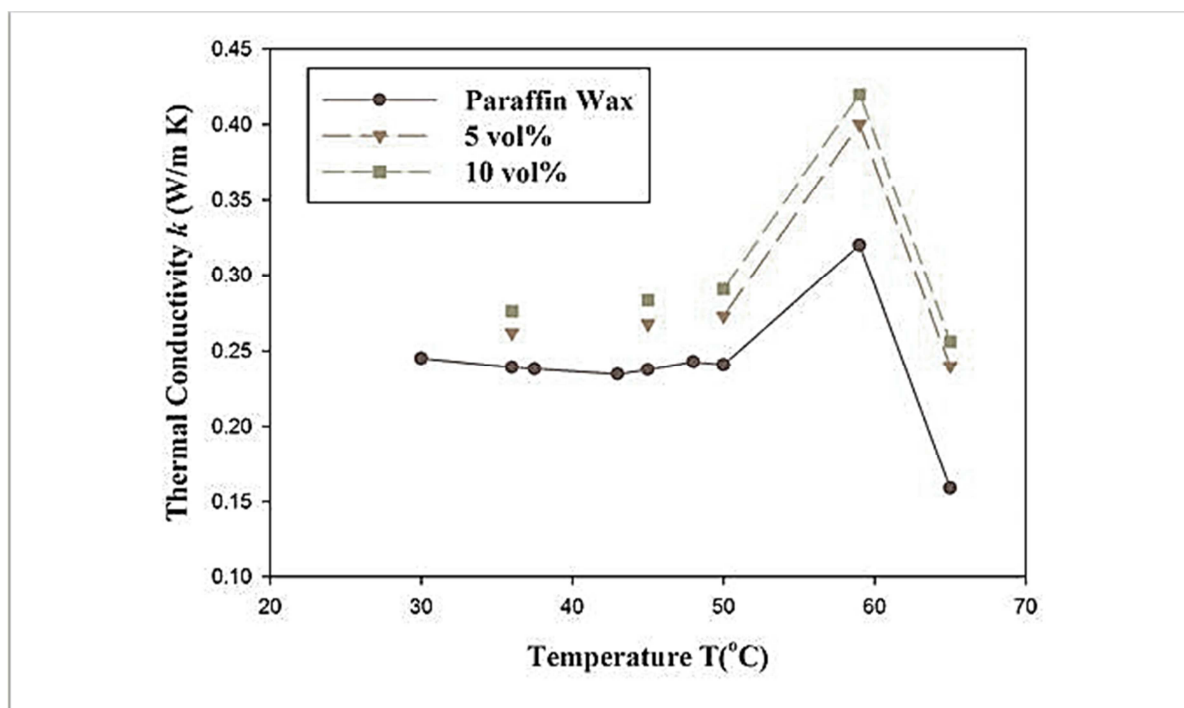


Fig 4.11 Thermal conductivity of paraffin wax and composite versus temperature.

DSC thermograms of 10 wt% copper oxide nanoparticle enhanced paraffin

Thermal conductivity of paraffin wax and composite versus temperature

Table-4.1

Temperature (°C)	Thermal Conductivity (W/mK)		
	Paraffin wax	$\phi=5$ vol%	$\Phi=10$ vol%
30	0.2450		
36	0.2390	0.2620	0.2760
37.5	0.2380		
43	0.2344		
45	0.2375	0.2677	0.2834
48	0.2427		
50	0.2406	0.2729	0.2906
59	0.3200	0.4000	0.4200
65	0.1590	0.2400	0.2560

4.9.2 Therminol 55 Heat Transfer Fluid

Therminol 55 is an engineered heat move liquid utilized in moderate-temperature applications. Therminol 55 liquid is intended for use in non-compressed/low-pressure, backhanded warming frameworks. It conveys productive, trustworthy, uniform interaction heat with no requirement for high pressing factors.

Long Life—you will get long periods of dependable, savvy execution, in any event, while working your framework persistently at 300°C (570°F). This implies you don't need to over determine your liquid.

Excellent protection from fouling—Because Therminol 55 is an engineered liquid, it opposes the impacts of oxidation multiple times better compared to mineral oils, which means less oxidation and solids development. For frameworks without nitrogen embedding's, the presentation benefits are critical.

Excellent Low-Temperature Pump capacity—Therminol 55 is still siphon capable at – 28°C (– 18°F), contrasted for certain mineral oils that won't siphon at temperatures beneath – 7°C (20°F). With Therminol 55, your warmth move liquid framework can fire up rapidly and without any problem.

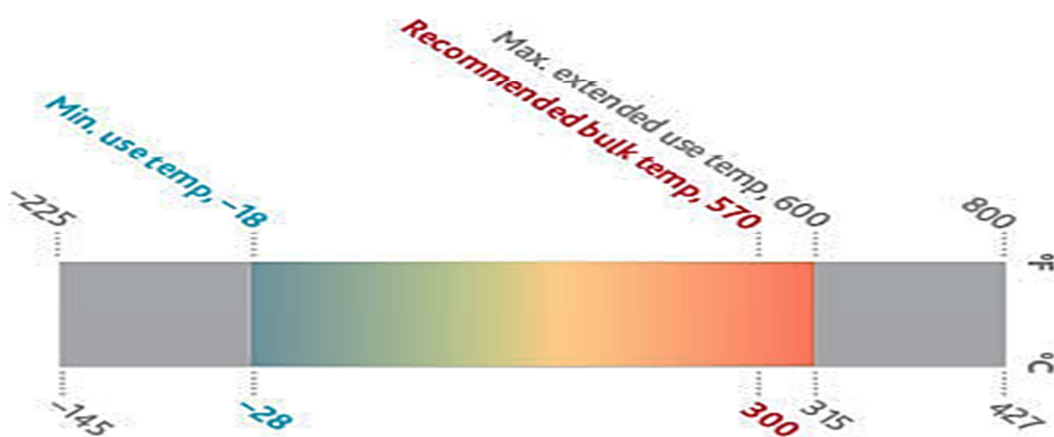


Fig-4.12 Eastman Therminol 55 heat transfer fluid

Eastman Therminol® 55 heat transfer fluid is a one-of-a-kind synthetic fluid that provides long-term heat transfer reliability and consistency at high bulk temperatures of 290°C (550°F).

Therminol 55 fluid is intended for use in indirect heating systems that are not pressurized or have low pressure. It provides reliable, consistent, and uniform process heat without the use of high pressures. Therminol 55's high boiling point helps to reduce the instability and fluid leakage issues that come with other fluids.

Despite its high flash point, Therminol 55 is not rated as a fire-resistant heat transfer fluid. As a result, using protective devices to reduce the risk of fire might be necessary, and consumers of Therminol 55 should consult with their protection and risk management departments.

CHAPTER - 5

RESULTS AND DISCUSSION

5.1 Internal Heat Transfer Results

At the point when the hot EPCM tests are lowered inside the calorimeter they start to move their put away energy to the silicone oil and the PCM starts to quickly set. The PCM starts to harden at the edge and lower part of the container. Since the hardening cycle is conduction-ruled, the strong fluid interface gradually spreads radially inwards and the consistently expanding strong layer lamentingly affects the warm move inside the container. As the PCM cools it contracts anyway the set PCM adheres to the container surface at the extended stature; along these lines, as the air void grows it frames a "round and hollow" (as shown in the figure 5.1)- formed in the focal point of the case. The upward expansion in the strong found in Figure 5.2 is a result of the manner in which the thickness of the PCM is displayed and it straightens throughout the span of the reproduction.

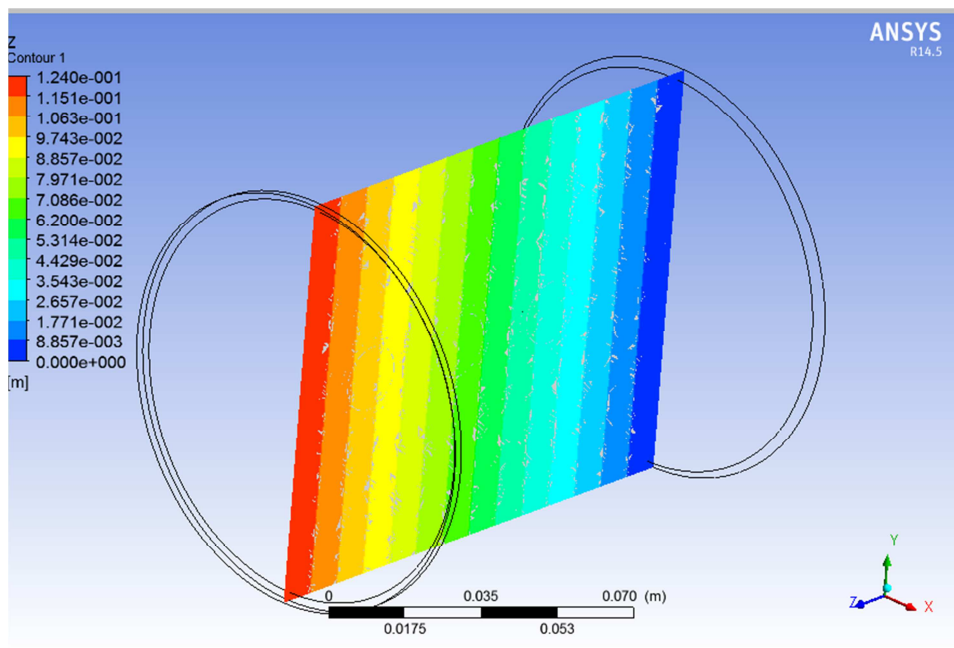


Fig 5.1 Internal Heat Transfer Results

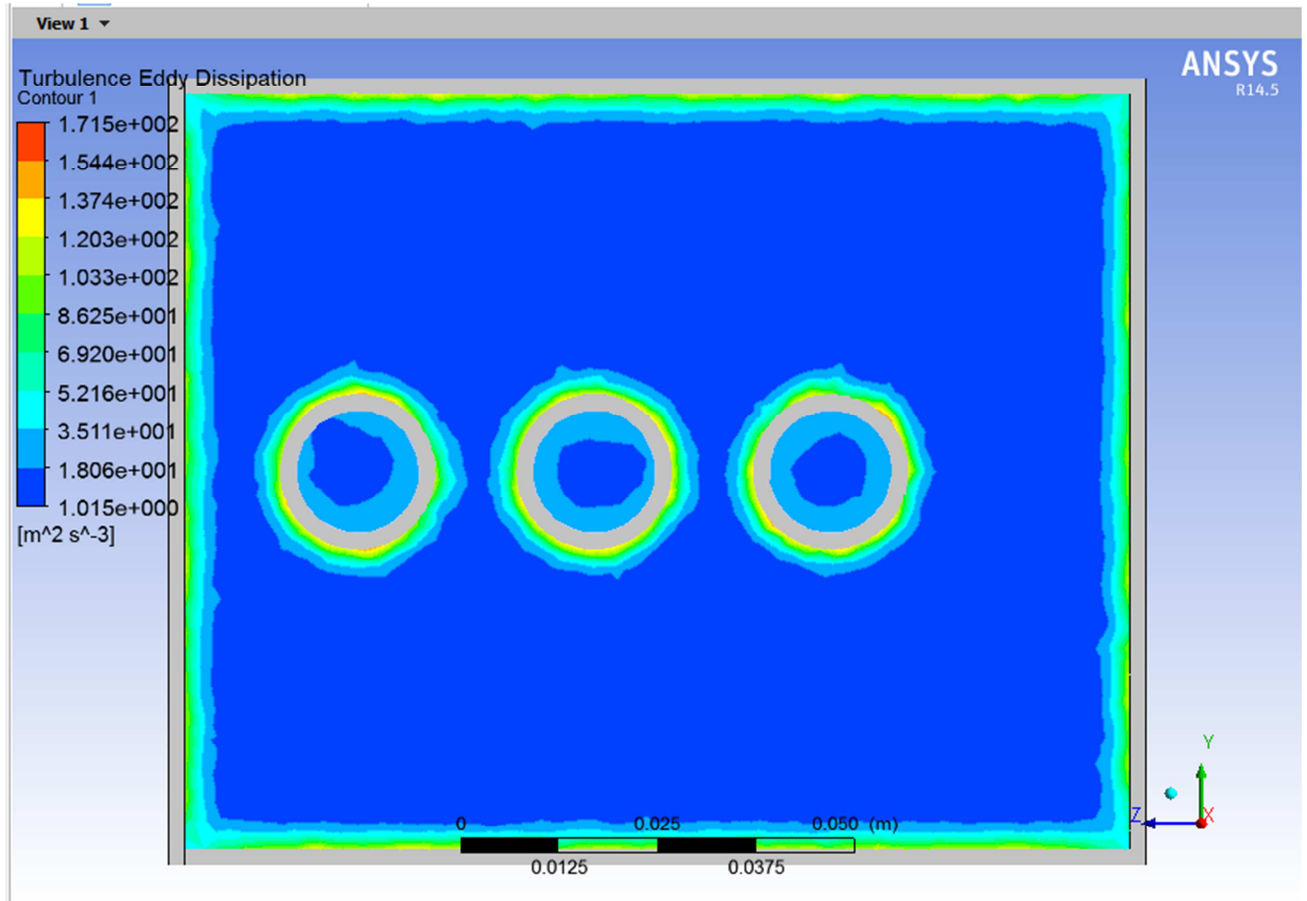


Fig 5.2 Internal Heat Transfer Results with capsules

5.2 External Heat Transfer Results

The temperature of the device rapidly increases after the EPCM sample is submerged in the calorimeter before eventually reaching equilibrium. A wide thermal gradient forms in the therminol oil immediately above the EPCM sample after the EPCM capsule is submerged in the system, as shown in Figure. As a result of the convection in the oil, a large vortex develops over the sample. As the air is heated, two small vortices form in the air gap at the top of the device, as well as a vortex around the EPCM capsule's outside. The below figures shows that 5.3, 5.4, 5.5 the heat transfer more than room temperature and slowly changes its states of solid to liquid.

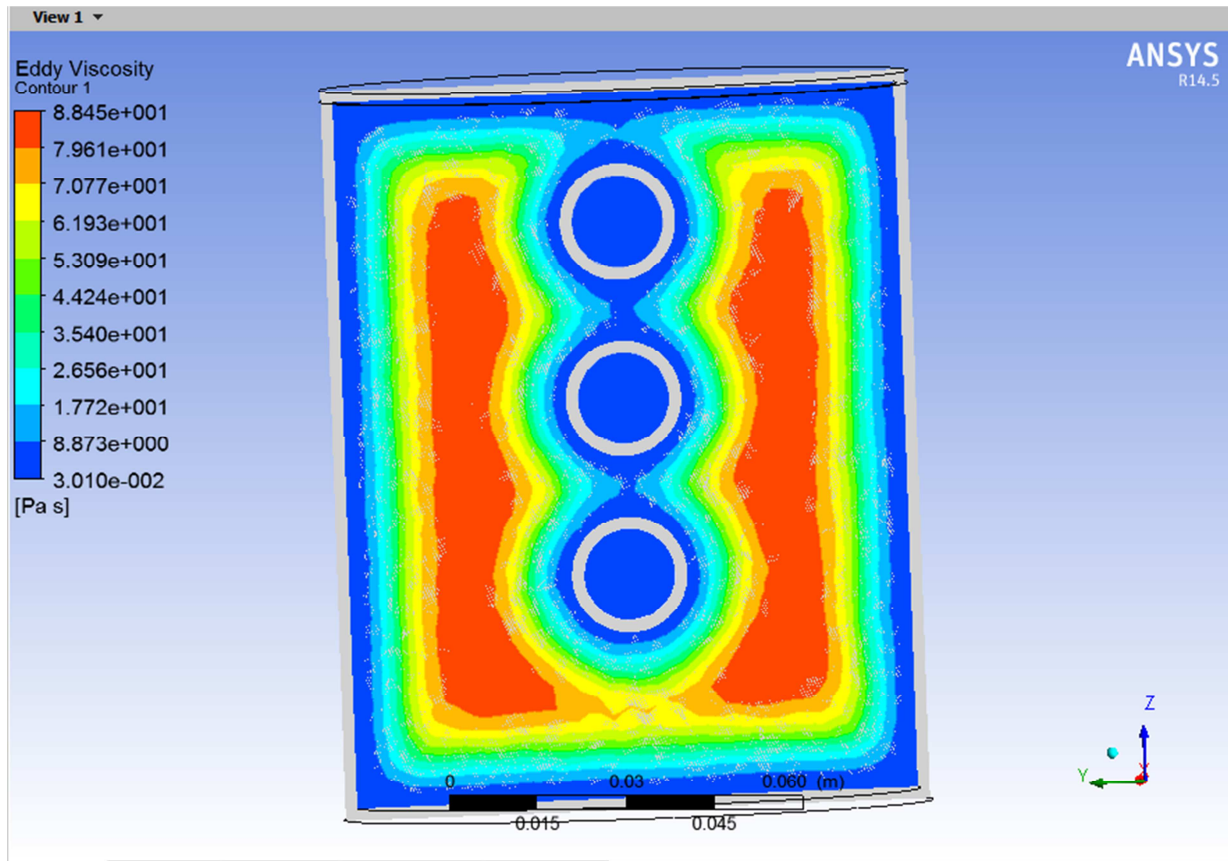


Fig 5.3 External Heat Transfer Results

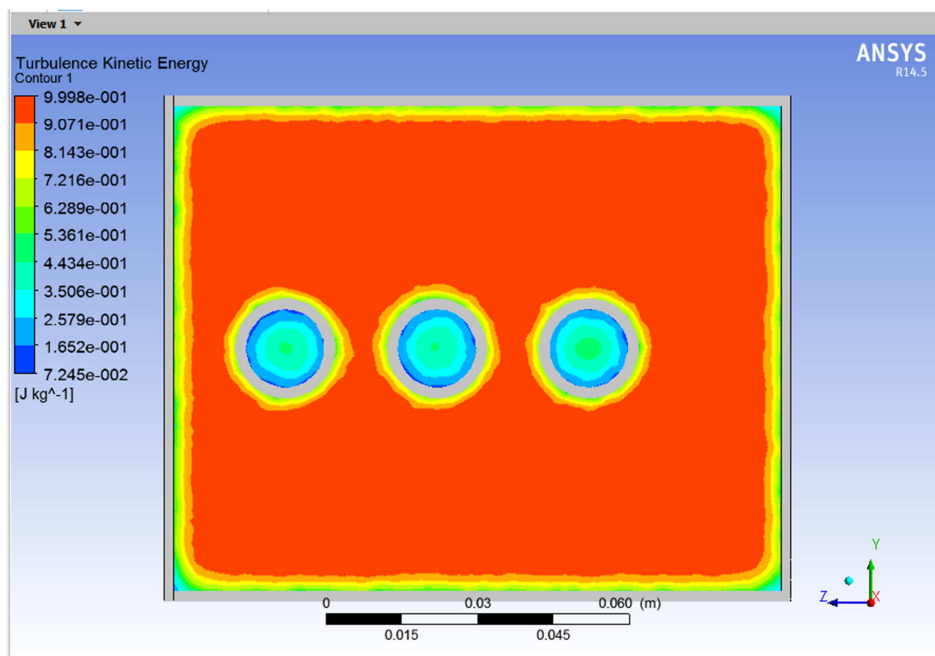


Fig 5.4 External Heat Transfer Results

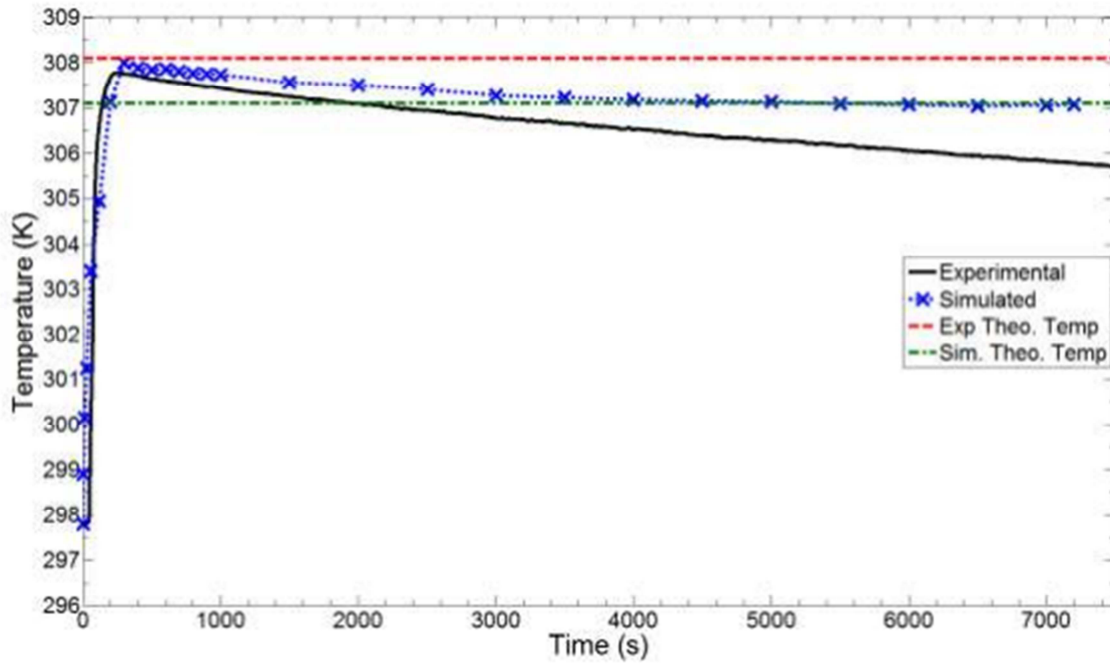


Fig 5.5 Experimental temperature

Experimental temperature, predicted volume averaged temperature, and theoretical equilibrium temperature for aluminum sample 3 cycle 3

5.3 SPHERICAL EPCM CAPSULES

5.3.1 Mesh Independence

The use of the enthalpy-porosity and VOF methods to capture the complex heat transfer inside EPCM capsules, as defined in Chapter I, has been previously validated in the literature [34-36] using experimental results. A 25.4 mm capsule with a constant surface temperature of 773 K and an initial capsule temperature of 523 K was tested for mesh independence and time phase independence. Refinement of the mesh. The meshes with 2290, 4276, and 8736 uniformly distributed nodes were evaluated using three meshes with decreasing nominal cell size. The results are shown in Figure 5.6, with blue representing the solid area and red representing the molten PCM. The remaining solid has the same overall shape in all three cases; the only difference is the refinement of the mushy region.

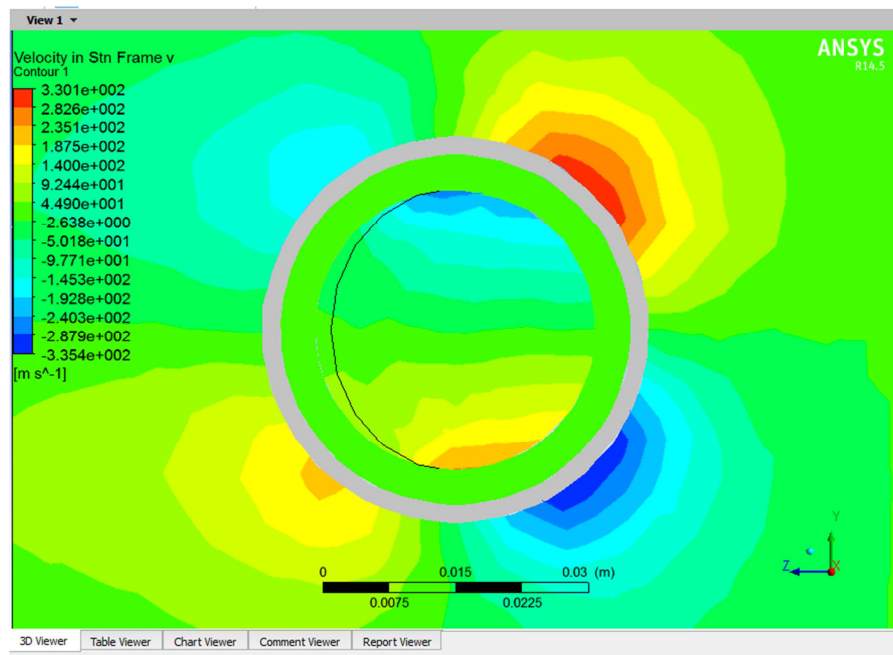


Fig 5.6 Mesh Independence

5.3.2 Melting of Spherical EPCM Capsules

Because of evenness about the Y-pivot, the warmth moves in the XY and YZ planes are indistinguishable and hence, just the outcomes for the XY plane are appeared. Notwithstanding, the presence of the void at the highest point of the case eliminates the balance about the X-hub that would result from a consistently warmed case. The isotherms, speed greatness, fluid portion, and explicit warmth limit 5 sec into the dissolving cycle are appeared in Figure 5.7. The particular warmth limit is utilized to portray the advancement of both the solid liquid interface and the void-PCM interface as a consistent worth was utilized for both the strong and fluid NaNO₃ stages just as for the air. Here and all through blue indicates a strong district and red a fluid area. The strong fluid and void-PCM interface are appeared in Figure where blue is the hardened steel shell, green is the air void, orange is strong CnH_{2n+2}, and red is liquid CnH_{2n+2}. As the PCM dissolves it extends and gradually packs the void as it presently involves roughly 13% of the container's volume.

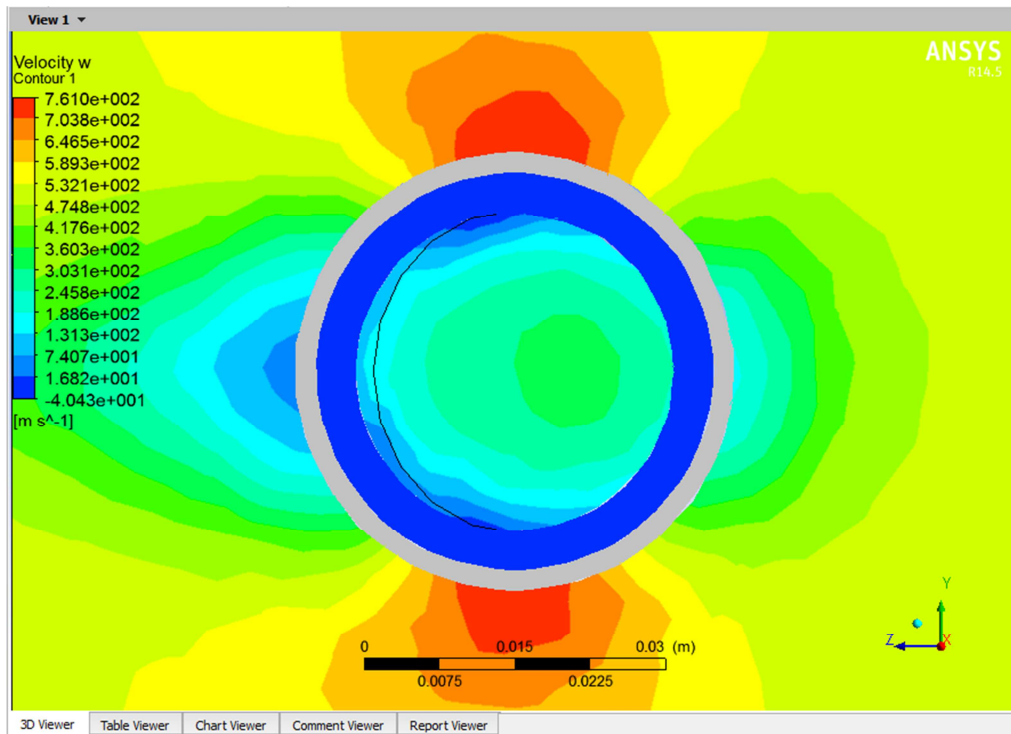


Fig-5.7 Melting of Spherical EPCM Capsules

5.3.3 Solidification of Spherical EPCM Capsules

The capsule was allowed to cool to a uniform temperature of 750 K after the melting process was completed before the solidification process was started by raising the surface temperature to 523 K. After the surface temperature is switched, the temperature within the molten PCM decreases rapidly resulting in a linear temperature distribution in the XY plane and a nominal temperature of 650 K in the ZX plane, Figure 5.8. During this initial period, a recirculating vortex forms along the capsule edge but it is much weaker than that seen during the melting phase, Figure. The PCM starts to solidify at the bottom of the capsule and eventually works its way up the sides. As the PCM solidifies, the heat transfer rate decreases asymptotically, resulting in an increase in total solidification time.

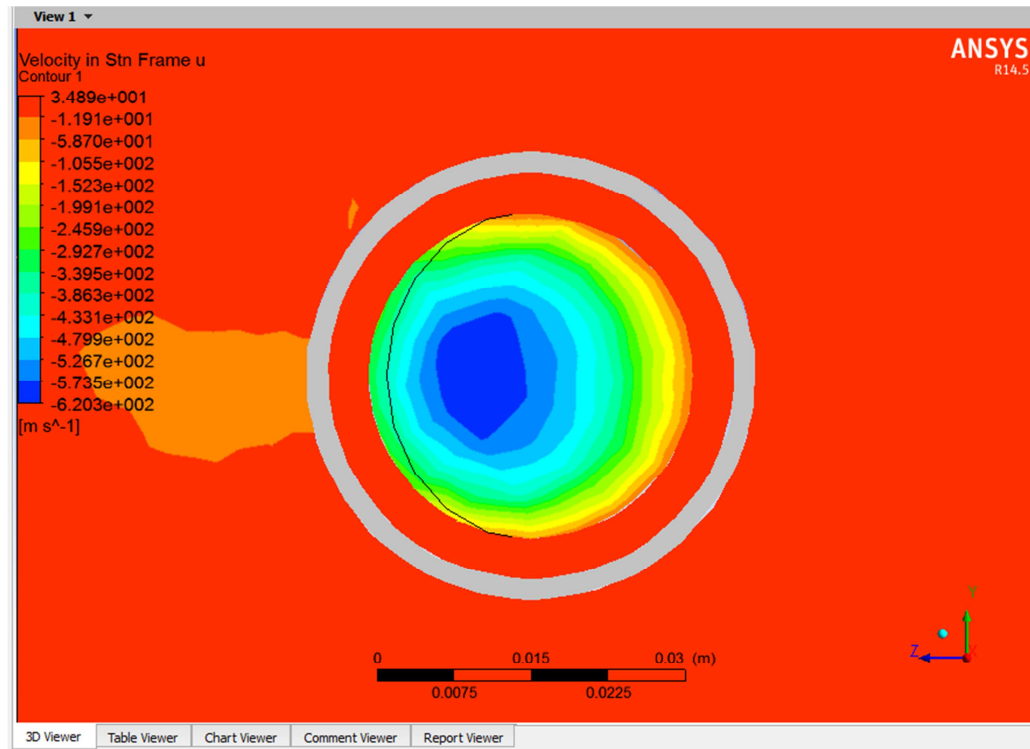


Fig-5.8 Solidification of Spherical EPCM Capsules

Figure 5.8 demonstrates how the air void has decreased the amount of heat transmitted from the shell to the PCM, allowing the PCM to solidify from the bottom up. During the melting process, it was clear. Since the heat transfer rate in the ZX plane is higher than in the XY plane, the solidification time is shorter. The air gap has completely grown back to its original size after total solidification. The average time for solidification is 300 seconds. For both melting and solidification, the evolution of the solid-liquid and air-PCM interfaces is shown in Figure.

5.4 EFFECT OF INITIAL VOID LOCATION

As shown in the Figure is the schematic of the EPCM cylinder in a cross flow arrangement considering the 20% void space at the top of the capsule. The local Nussle number around the capsule varies in the angular direction as described in Figure. Based on the volume expansion of C_nH_{2n+2} due to phase change, 20% of the capsule is kept as a void. The void space is occupied by the air. The buoyancy-driven convection in the molten PCM is neglected for these simulations. Figure 5.9. The EPCM capsule geometry with void space is depicted in this diagram.

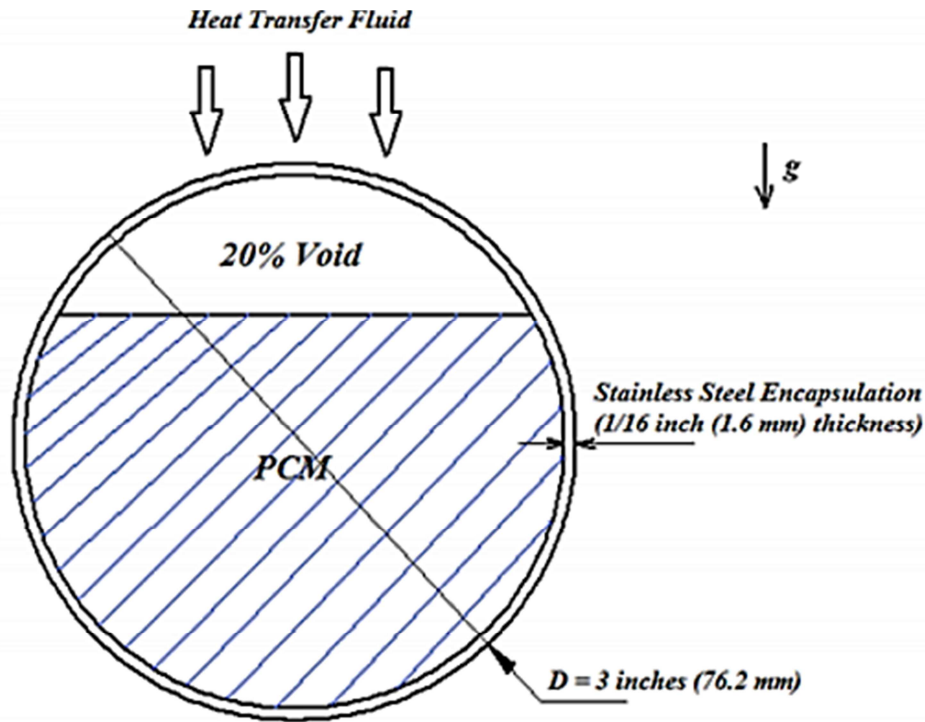


Fig 5.9 The Effect of Void

5.4.1 Initial Random Void

Compression of a powder PCM into a pellet offers control over the void fraction by varying the force applied. This results in an initial uniform distribution of air throughout the entire PCM. The given HTF arrangement results in the heat transfer coefficient being highest at the top of the capsule, thus the PCM begins melting along the capsule shell in the upper portion of the capsule. The isotherms, liquid fraction, volume fraction, and velocity magnitude at 90 sec into the melting process are presented in Figure. The results have also been non-dimensionalized using the product. Because of the uniform thermal conductivity of the PCM, the isotherms inside the capsule are initially concentric. The air and C_nH_{2n+2} have continued to separate as the PCM melts leading to the formation of a distinct air void at the top of the capsule. Two recirculating vortices have formed within the molten PCM, one along the capsule edge where the 74 molten PCM is heated and rises and the other along the remaining solid PCM where the molten PCM cools and sinks. The results shows that as below figures 5.10,5.11 of an initial random void shows.

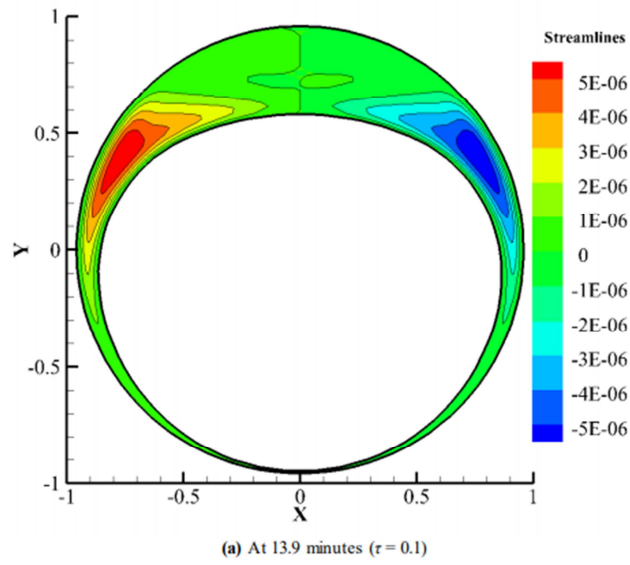


Fig 5.10 Initial Random Void

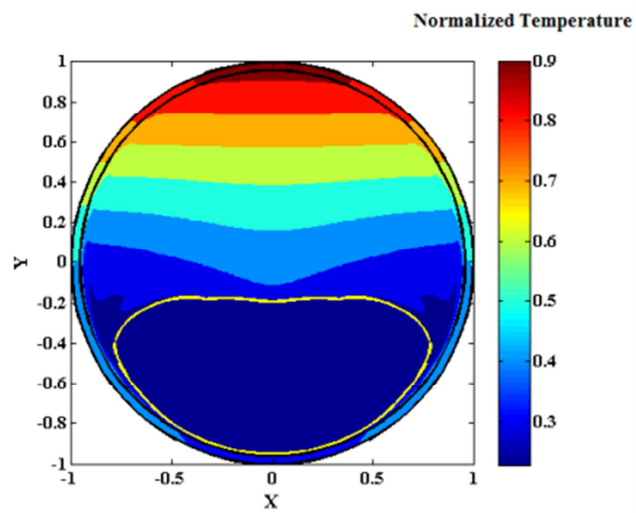


Fig 5.11 Initial Random Void

5.4.2 Initial Central Void

In the event that a strong PCM is utilized to fill the case shell, the middle can be penetrated out to leave adequate void space inside the case; along these lines, an underlying focal void area was thought of as shown in the figures 5.12. PCM is in direct contact with the container shell it has the most elevated warmth move rate toward the beginning of softening. Besides, the uniform warm conductivity in the PCM brings about concentric roundabout isotherms per the answer for the precarious dissemination condition for unadulterated diffusional heat move. Similar as on account of an irregular void dispersion, the PCM creatures to dissolve along the upper bit of the case shell. As the air is totally encased inside the strong PCM, it can't diffuse until the PCM liquefies along the air-PCM interface, anyway recycling vortices can be seen inside the air void. As time advances, convection in the liquid PCM has expanded the warmth move rate in the upper segment of the case, making the strong fluid interface smooth.

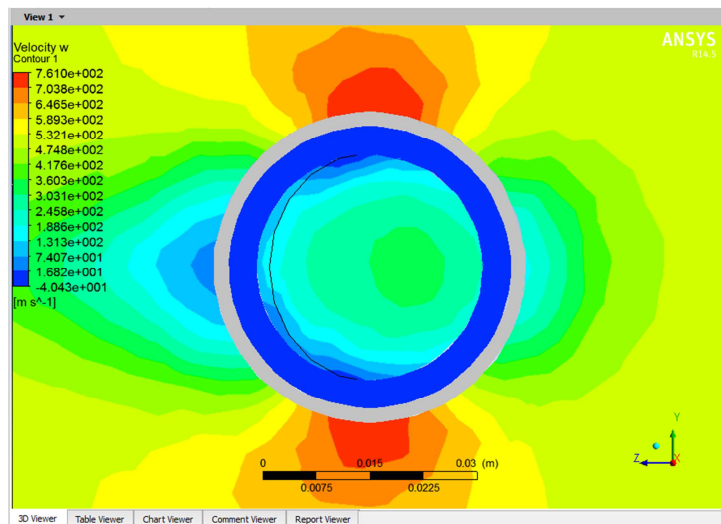


Fig 5.12 Initial Central Void

5.4.3 Initial Upper Void

Because of gravitational impacts, almost certainly, the air would diffuse to the highest point of the EPCM case and for an evenly orientated barrel shaped case would bring about the upper void circulation. This underlying void area could be fabricated by filling the EPCM cases with the ideal mass of liquid PCM and afterward cooling the cases on a level plane or by machining a strong PCM into the ideal

shape as in the figure 5.13, 5.14. The impact of the void space at the highest point of the case is promptly seen as the isotherms inside the container are not, at this point round however are "barrel shaped"- molded. The air goes about as a protector lessening the warmth move rate in the upper portion of the case and as the containers are warmed from the top it impedes the underlying warming of the case, hence it takes more time for the PCM to start softening. When dissolving at last beginnings, it starts along the container shell at the air-PCM interface. As the PCM dissolves it grows and packs the air void. Notwithstanding convection inside the air, two recycling vortices have framed along the container edge and strong PCM. These vortices increment the warmth move along the air-CnH₂n+2 interface expanding the dissolving rate regardless of the poor conductive warmth move from the air to the PCM.

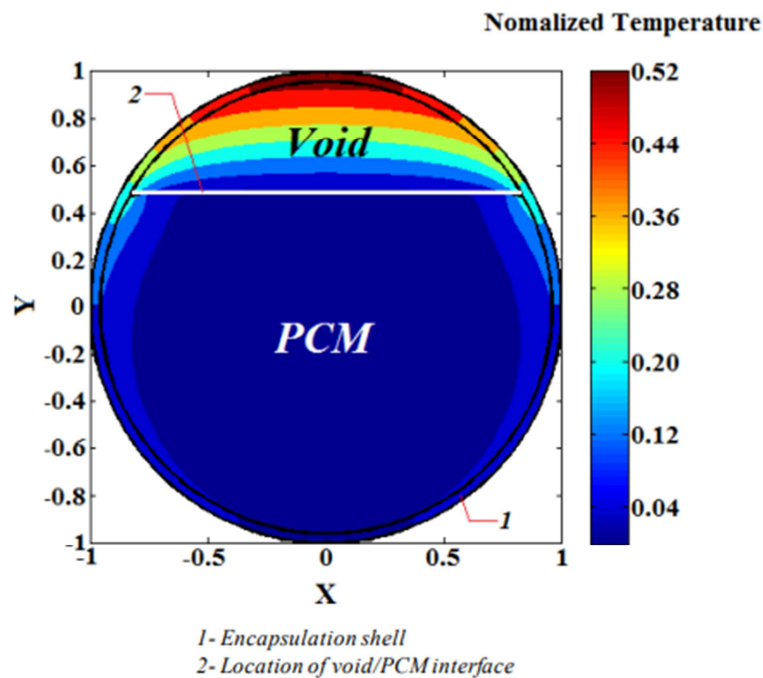


Fig 5.13 Initial Upper Void

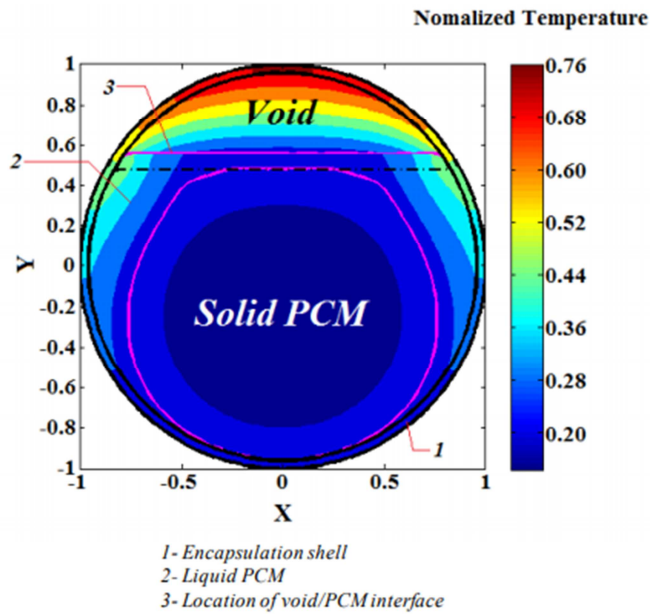


Fig 5.14 Initial Upper Void

5.5 USE OF METALLIC OXIDES AS PCMS FOR TES

Although encapsulating a PCM has many benefits, it also has its own set of challenges. It is important to ensure that the encapsulation shell and PCM are thermally compatible so that chemical and metallurgical reactions do not occur during the EPCM capsule's thermal cycling. Furthermore, the shell must endure the thermal stresses that it is subjected to. Enable for the PCM's thermal expansion as it melts for a better experience. The down table 5.1 denotes that testing of a capsules in solid and liquid state. And below graphs figure 5.15 shows heat flow and volumetric expansion.

Testing of C_nH_{2n+2} (paraffin wax) Capsules

Table-5.1

Properties	Solid phase	Liquid phase
Melting point	56(°C)	56(°C)
Latent heat	142.7(KJ/KG)	142.7(KJ/kg)
Thermal conductivity(K)	0.4(W/m °C)	0.2(W/m °C)
Density (ρ)	670(kg/m ³)	640(kg/m ³)
Specific heat (c_p)	2.4(KJ/Kg °C)	1.6(KJ/kg °C)

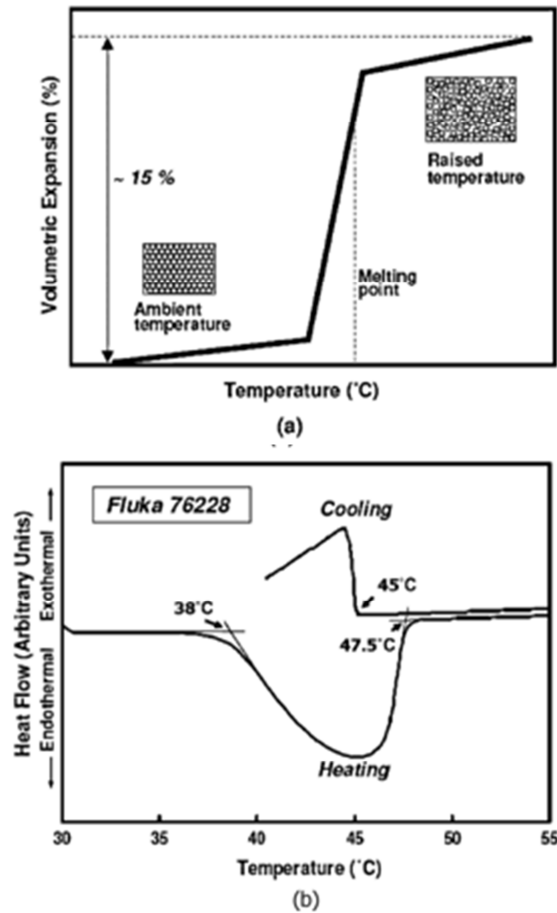


Fig 5.15 USE OF METALLIC OXIDES AS PCMS

5.6 SEM Results

EDS was used to analyse fifteen positions from four areas of sample 1 (top, center, edge, and dip). Each element's atomic percentage in the region where the beam was centered was recorded. The results revealed that the samples contained only oxygen and sodium, suggesting that contamination from another material was not present. It's worth noting that the EDS can't detect hydrogen or boron. As a result, the SEM findings of sample 1 do not rule out the possibility of material hydration as shown in figure 5.12. The table 5.2 tells about the composition of paraffin wax.

Table 5.2 SEM Results

Particulars	Spectrum 1			Spectrum 2		
	C	O	Total	C	O	Total
App. Concentration	12.99	0.13	--	10.53	0.00	--
Intensity corn.	0.2877	0.0667	--	0.3058	0.0635	--
Weight (%)	45.14	1.95	47.09	34.42	0.00	34.42
Weight (%), sigma	0.96	0.68	--	0.83	0.00	--
Atomic (%)	96.86	3.14	--	100.00	0.00	--

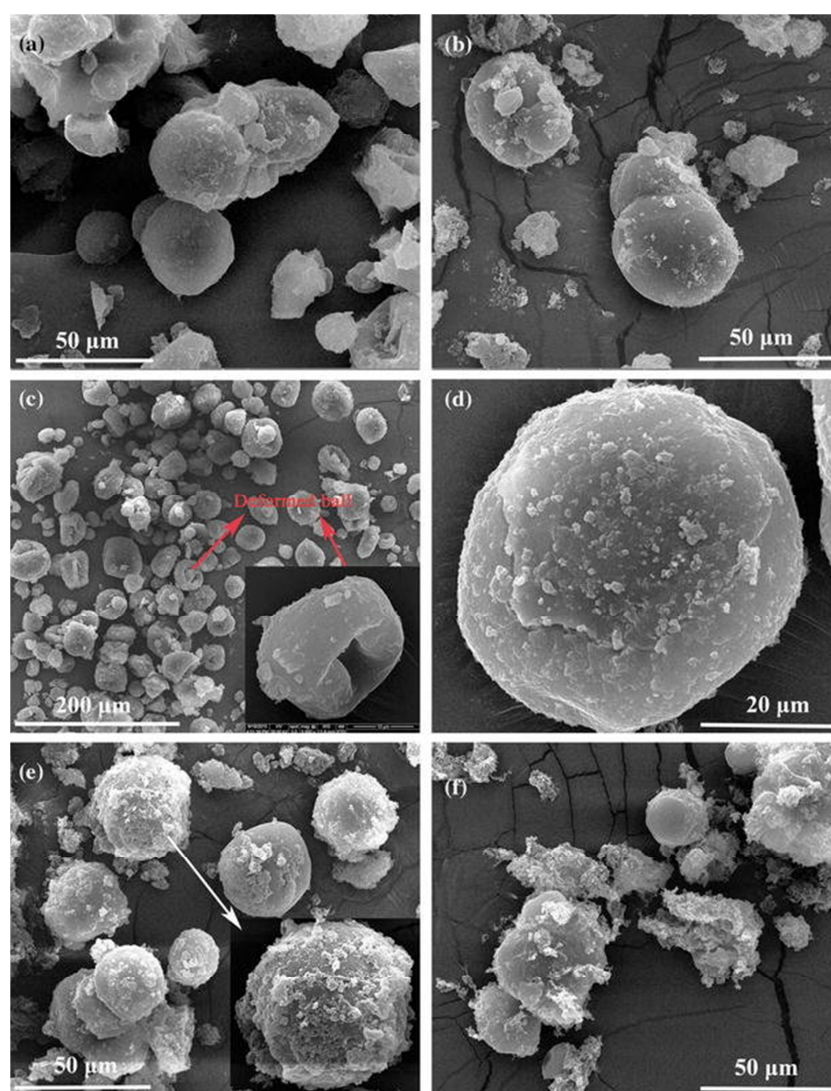


Fig 5.16 SEM Results

5.7 DSC Results

While the SEM results provided insight into the initial makeup of the material and lent credence to the formation of two distinct regions within the material, further evaluation is required. By performing DSC on the different regions of the sample, their thermal properties can be verified with those reported in literature. Additionally, based on the melting temperature reported, the initial composition of the material can be determined. One sample from each section of sample.

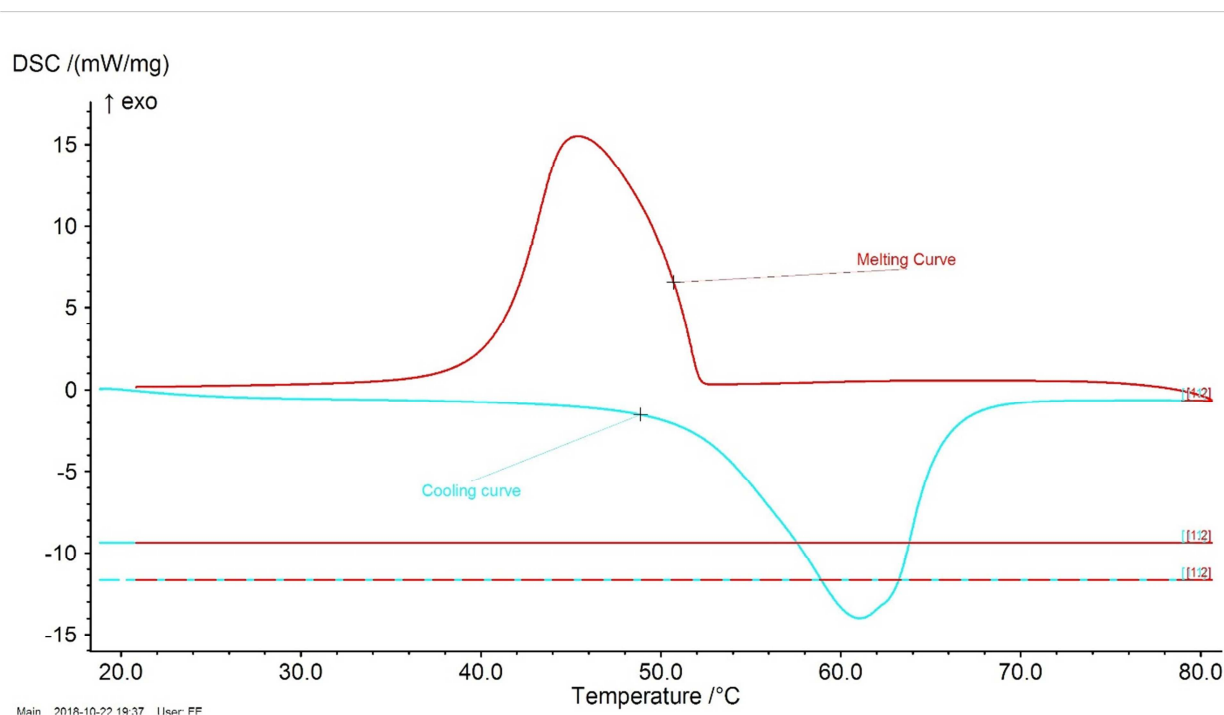


Fig 5.17 DSC Results (Temperature)

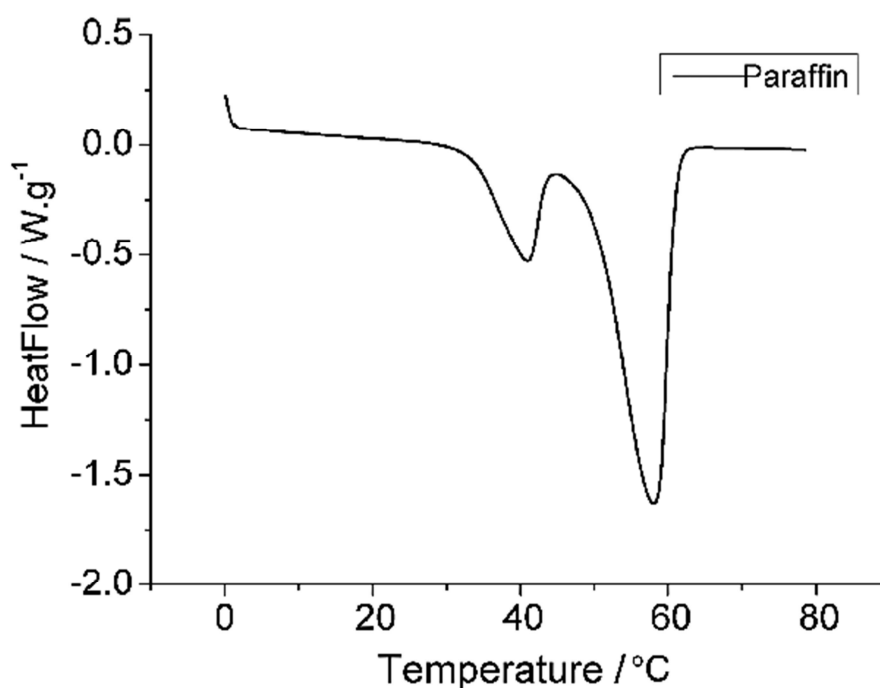


Fig 5.18 DSC Results (Heat flow)

Table-5.3

Cycling numbers	Melting temperature (c)	Melting latent heat (J/g)	Freezing temperature (c)	Freezing latent heat (J/g)
0	53.2	31.0	46.4	32.6
200	53.2	30.6	44.9	31.5
400	53.3	30.0	45.2	31.5
600	53.3	30.3	45.1	30.6
800	53.4	30.6	45.5	30.7
1000	53.5	30.5	45.4	30.7

The DSC curves for the two locations for sample 1 presented in Figure are extremely similar. The peaks at 102 °C, 256 °C, and 300 °C correspond to the dehydration of C_nH_{2n+2} as the samples are highly hygroscopic and were exposed to the atmosphere post-sectioning prior to the DSC runs.

CHAPTER 6

SUMMARY AND CONCLUSIONS

6.1 SUMMARY

The present work includes immersion calorimeter experiments and heat transfer simulations for EPCM capsules for thermal energy storage system. The aim has been to study single EPCM for their usage in TES systems.

In the thermal analysis of packed bed LHTES filled with encapsulated PCMs is performed experimentally and numerically.

Experiments are conducted on a single spherical capsule and a lab-scale setup to investigate melting and solidification processes of PCM inside the capsule and thermal performance of the storage.

Thermal energy stored and extracted from the LHTES is calculated for different performance parameters, inlet HTF temperature during charging and discharging processes and HTF flow rate.

A mathematical model is developed with simplified non-equilibrium two energy equations coupled with enthalpy technique to analyses the effect of capsule diameter and porosity on the LHTES.

The melting of PCM inside the capsule initiates at the heated surface and melted PCM rises above inside the capsule.

Highlights:

1. Thermal behaviors of single and multi PCM thermocline storage are presented.
2. Temperature response and phase change process within capsules are revealed.
3. Energy analysis of thermocline latent heat thermal storage systems is presented.
4. Multi-stage PCM is a promising solution to store thermal energy for CSP plants
5. The objective of this work is to study the effect of various pertinent parameters
6. On the heat transfer within the encapsulation.

Keywords:

Spherical capsule; phase change material; melting temperature; Concentrating solar power.

6.2 Conclusions:

Heat transfer simulations were conducted for EPCM capsules. Various heat transfers and material combination for EPCM were compared; the heat transfer processes inside the capsule to help design EPCM based thermoclines. The conclusions from the heat transfer analysis are summarized as follows:

1. Larger sizes of capsules would have longer heat transfer times.
2. The heat transfer process is significantly improved by using liquid as HTF instead of a gas because of higher density and heat capacity of liquids.
3. Larger temperature differences between HTF and EPCM would increase the energy storage/retrieval rate in the capsule during phase change process.
4. During energy storage and melting of the PCM, the effect gravity and the higher density of solid PCM in the EPCM capsule would shorten energy storage times.
5. Buoyancy-driven convection in molten PCM could impact the liquid/solid interface movement in PCM, the temperature profiles in the EPCM capsule, and shorten the energy storage times. However, for the conditions considered here, the average Rayleigh number is relatively small and thus the convection effects are likely to be not significant.
6. Using liquid as HTF could slightly enhance the natural convection in molten PCM compared to when air is used as HTF.
7. There must be sufficient void space inside the EPCM capsule for volumetric expansion of PCM due to phase change and temperature increases. The void space could act as an insulator and could slightly slow down the heat transfer rate inside the capsule (comparing the melting times per unit mass of PCM between considering the void space in the capsule case and no void space case).

8. The melting of PCM inside the capsule initiates at the heated surface and melted PCM rises above inside the capsule. The melting of the PCM in upper part is faster than the lower part and is mainly dominated by convection. When PCM solidifies inside a capsule, the PCM layer nearby inner wall solidifies faster than the center layer of PCM and conduction is the dominant mode of heat transfer.

9. The variation in PCM temperature in the radial direction in the lab-scale LHTES is found negligible compared to that axially, which justifies the assumption of negligible heat conduction radially in LHTES in the numerical domain.

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