Design, Modelling and Experimental Investigation of Modular Latent Thermal Energy Storage System for Heating Applications

By

Fawad Ahmed
Reg#00000202988
Session 2017-19

Supervised by
Dr. Adeel Waqas

A Thesis Submitted to the US-Pakistan Center for Advanced Studies in Energy in partial fulfillment of the requirements for the degree of MASTER of SCIENCE in (Thermal Energy Engineering)

US-Pakistan Center for Advanced Studies in Energy (USPCAS-E)
National University of Sciences and Technology (NUST)
H-12, Islamabad 44000, Pakistan
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THESIS ACCEPTANCE CERTIFICATE

Certified that final copy of the MS/MPhil thesis written by Mr/Ms. FAWAD AHMED, (Registration No. 00000202988), of USPCAS-E School/College/Institute) has been vetted by undersigned, found complete in all respects as per NUST Statues/Regulations, is within the similarity indices limit and is accepted as partial fulfillment for the award of MS/MPhil degree. It is further certified that necessary amendments as pointed out by GEC members of the scholar have also been incorporated in the said thesis.

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CERTIFICATE

This is to certify that work in this thesis has been carried out by **Mr. _FAWAD AHMED___** and completed under my supervision in Solar Thermal laboratory, US-Pakistan Center for Advanced Studies in Energy (USPCAS-E), National University of Sciences and Technology, H-12, Islamabad, Pakistan.

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LIST OF PUBLICATIONS

1. **Fawad Ahmed,** Adeel Waqas "Experimental Investigation of Using Latent Thermal Energy Storage System Comprising of Magnesium Chloride Hexahydrate (MgCl2.6H2O) With Domestic Gas Heater" International Conference on Energy Conservation and Efficiency (ICECE), October 2019, UET Lahore.

DEDICATIONS

This work is dedicated to my loving parents, who consumed everything for our better future. Their love and support drove me through the difficult times of my life. I also dedicate this to my lovely wife who supported me during the research with her words and tasty dishes. I would also like to dedicate this to my siblings, who bucked me up during the entire research.

At the end I would like to dedicate this work to all the non-degree holding technical hands working in different walk of life e.g., the automobile mechanics, plumbers, tile fitters etc. who are master of their respective fields and making our lives lot easier.

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ABSTRACT

Pakistan is situated in the region where it experiences all kinds of weather, from exhausting heats to shivering colds. As human is sensitive to the temperature changes and requires a comfortable condition to perform efficiently. In such conditions different equipment operating on various energy sources are used to achieve thermal comfort. In Pakistan mostly gas heaters are used due to the availability of natural gas as a common household commodity. This is an in-efficient way of achieving thermal comfort as it consumes more energy than required to raise the temperature to a comfortable limit. In this work Latent Thermal Energy Storage (LTES) was designed to be integrated with domestic gas heater to utilize the excessive energy during space heating. This energy was used to charge Magnesium Chloride Hexahydrate and during the unavailability of the heating source the same energy was used for heating the room. Lab scale experimentations were carried out. Findings revealed that 60g of MCHH can store up to 30kJ of thermal energy. If the process involves natural convection, then the stored energy can be discharged to the atmosphere in 25 mins increasing the source availability time for 46% in the absence of gas. If the same system is designed for providing 1kW for 3hrs then the cost on material will be approx. PKR 63000 and the cost of encapsulation will be added to this cost which will become too costly for a domestic user. The system is not recommended at domestic level as the material behavior in not controllable during charging, therefore, some other systems are recommended with TES for efficient heating applications.

Keywords: *Thermal Energy Storage, Latent Thermal Energy Storage, Phase Change Material, Salt Hydrates, Inorganic PCMs, TES systems for heating Applications, Modular Thermal Energy Storage*

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Acronyms

TES	Thermal Energy Storage
PCM	Phase Change Material
HTF	Heat Transfer Fluid
LHTES	Latent Heat Thermal Energy Storage
MTES	Modular Thermal Energy Storage
CSP	Concentrated Solar Powerplant
IWH	Industrial Waste Heat
MCHH	Magnesium Chloride Hexahydrate

Chapter 1

Introduction

1.1 Background

Pakistan is situated in the region where it experiences all kinds of weather, from exhausting heats to shivering colds. As human is sensitive to the temperature changes and requires a comfortable condition to perform efficiently. In order to maintain the comfort conditions, various equipment is used which controls the temperature, humidity and undesirable particles to provide better indoor conditions. During the summers air-conditioning, evaporative cooling and fans are used for achieving the comfortable conditions as required. During winters gas heaters, electric heaters and radiator take the place for heating the living spaces. This is the conventional way of heating and cooling normally followed in the country. This way of achieving comfort conditions convert the high quality of energy into low quality energy and hence are not an efficient way. The main reason why these techniques are adopted is the unavailability of alternate solutions to these problems.

1.2 Climate of Islamabad

In winters the temperature of Islamabad falls under the freezing point[1], this really is an uncomfortable condition for people living in this region. As per the ASHRAE standards, the comfortable temperature is considered in the range of 21 – 24 ^{o}C[2]. To heat up the air to the requisite temperature, different kinds of appliances are used. Below are some of the basic appliances used for heating.

Fig. 1-1: Heating appliances used for heating applications

The basic drawback in some of the systems used for heating is converting the high quality of energy (electrical) into low-quality energy (heat). This kind of conversion is not desirable to achieve economical heating.

1.3 Heating appliances

To get a fair idea of working and energy consumption in various heating appliances, a brief description is given below;

1.3.1 Electric heater

There is a different kind of electric heaters according to the applications, that include the radiant heaters, convection heaters and fan heaters for space heating and resistance heaters for water heating. The basic working principal of the electric heater is to convert the electric current into heat while passing it through the resister. Electrical energy is the high-quality energy and converting it into heat being low-quality energy is not a good idea. Moreover, per unit cost of the electric unit is approx. PKR 15/unit and if 1500W heater is used for 4hrs of heating then 6 units are consumed per day and roughly PKR 2700 will be paid for the month as per the fixed rate.

1.3.2 Gas Heater

Methane (CH_4) gas is provided as a common commodity to the household which is used for cooking and heating applications. According to studies the natural gas sources are depleting with the passage of time. The reason for fast depletion may be the diversified uses of the fuel. As it ranges from cooking and heating to industrial processes and transportation. To minimize the dependence on one fuel, it is necessary to rationalize the use of the source. This can be done by analyzing the applications and minimizing the use of specific applications only. It means that the use of methane should be restricted to the applications that require high temperatures around 900-1500^{o}C[3]. Using methane gas for heating consumes extra energy than required to heat the same mass of air. To avoid this extra consumption, some other ways for heating need to be adopted like geothermal, solar space heating or hybrid heating solution using thermal energy storage techniques. By adopting these methods, consumption can be efficiently reduced.

1.3.3 Radiator

This is normally a better way of heating as compared to the other two but unfortunately it is not common amongst the masses. People are unaware of the system operation and the systems are not designed for a small house. The other main factor is the high capital cost of the system and no support from the government. The developed countries use this system as the district heating system and charge the consumers according to consumption. The same system can be designed for newly developing housing schemes. The policy makers should consider this option and make is mandatory for the builders to provide a centralize heating solution. This system can then be further optimized and economized by integrating it with solar thermal heaters and thermal energy storage.

1.4 Thermal Energy Storage

At present thermal energy storage (TES) is an active field in applied energy[4]. It encompasses energy efficiency and conservation. It effects the efficiency by shifting the load to the off-peak hours and reduce the expenditure effectively. In the case of solar energy, it conserves energy during the daytime and uses the same during the night. It also helps in reducing the intermittence behavior of renewable sources[5]. The main advantage of the thermal energy storage system is its integration with the existing system, and this alone can save a lot of cost of retrofitting. The basic working principal of the TES systems is shown below;

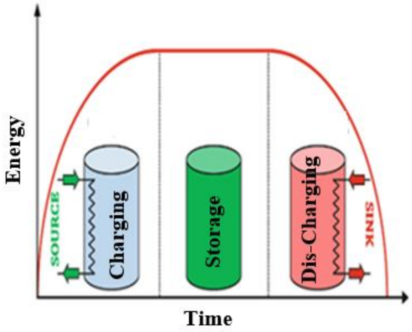

Fig. 1-2: Schematic of simple TES

The figure above shows a simple TES system. The system is charged with a source during the charging phase. The source can be solar thermal, electric or natural gas. After the system is fully charged the energy is stored in a storage tank and is sent to the load/ sink when required, which can be seen in the graph. TES systems can be further divided into many categories as per the applications or the material used for storage. The different kind of thermal storage is shown in the diagram below;

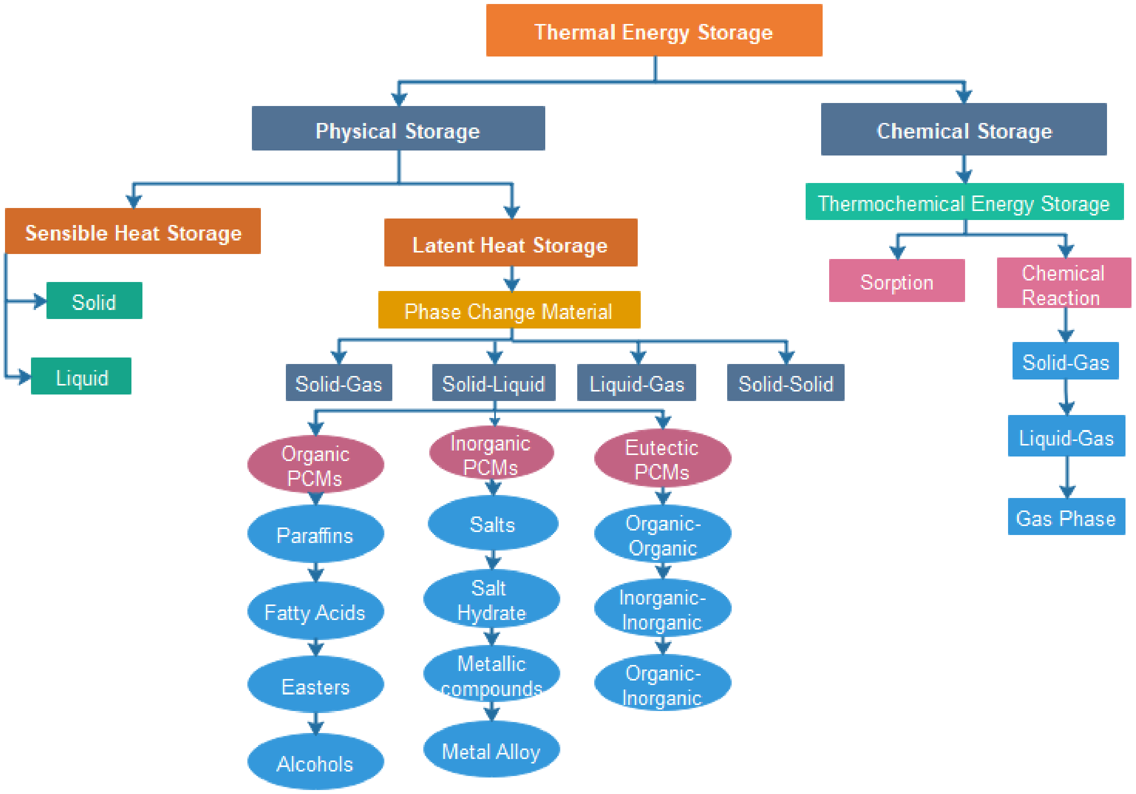

Fig. 1-3: Types of TES systems

TES systems can broadly be classified into two major categories one is known as physical storage that does not involve the chemical changes of the substance and the other is known as chemical or thermochemical storage that involve the chemical changes of the substance during each thermal cycle and hence reduces the durability of the system. Physical storage is further divided into two major categories i.e., Sensible (which does not change phase during the thermal cycle) and Latent (which changes phase during the thermal cycle, solid-liquid, liquid-gas etc.).

1.4.1 Selection of TES system

Selection of an appropriate TES system is very important and mainly depends upon certain factors that are listed in the table below;

Table 1-1: Selection criteria of TES system [4]

System Factors	Sensible	Latent	Chemical
Durability	YYY	Y	XXX
Commercial Viability	YYY	Y	XXX
Temperature	Y	YYY	XXX
Storage Density	XXX	Y	YYY
Capacity	XXX	Y	YYY
Efficiency	XXX	Y	YYY
Cost	YYY	Y	XXX
Storage Volume	70m^3 for 100 MJ	16m^3 for 500 MJ	7m^3 for 1000 MJ

YYY - Strongly Recommended
Y - Recommended
XXX - Not Recommended

In the above table, the systems are categorized upon certain factors, but it should be kept in mind that these are not the only factors there may be some other factors depending upon the applications. The above table shows that by comparing the three systems based on factors listed to the left, Latent thermal energy storage is preferred over the rest because the rest of the two contains some factors that are not recommended. After selection of the requisite type, the next step is to select the suitable material that will be required to store the energy in the system.

1.4.2 Material Selection Criteria

Material for TES is selected based on the application. Melting temperature is considered the basic criteria for initial material selection. For the selection of the Phase Change Material, various properties like thermophysical and chemical properties of the material are important to consider. These properties are relevant as inherent material characteristics but there are also some externalities that have a major effect on the selection of the material, which include the cost, commercial availability, product safety, adaptability and reliability after multiple thermal cycles. The general selection criteria for the PCM is shown below;

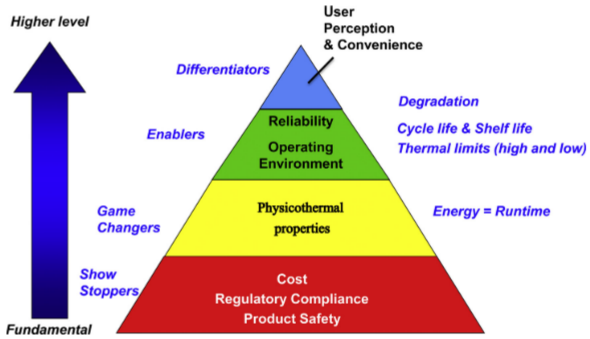

Fig. 1- 4: General selection criteria for PCM [4]

The above figure clearly depicts the selection criteria for PCM. The level of concern decreases from bottom to top which means the factors at the bottom are vital for PCM selection. Then the second most important group of parameters is the thermophysical properties of the material which include, thermal conductivity, heat capacity, latent heat of the material and the melting point according to the application. These portions cannot be overlooked during the selection criteria. After these the third main group that will tell us the durability of the system comes into play. It is also important to consider that till how many thermal cycles this system will be useful for the users. It also includes the suitability of the material according to the environment of its operation. If all these parameters are qualified by multiple materials, then the selection is based on user convenience.

1.4.3 Material encapsulation

After the selection of the material, the next step is to encapsulate that material. The encapsulation can be made in regular or irregular shapes. The factor of expansion and contraction of PCM during thermal cycles should be kept in mind during the encapsulation material selection. The encapsulation for organic and inorganic materials can be classified into physio-mechanical, chemical, physical and physio-chemical[4]. The other factor that needs to be considered is the material behavior towards the encapsulation. For inorganic materials, the possibility of corrosion exists or reaction with metals exists while for organic the tendency is reduced but still cannot be overlooked[6]. It is also worth mentioning that encapsulation should not create hinderance for heat transfer to and from the material while charging and discharging cycles. The thermal resistance of the encapsulation must be kept as minimum as possible to enhance the heat transfer between the HTF and the material.

1.5 Problem Statement

The problem highlighted in this research is the over consumption of the gas in the domestic gas heater. To efficiently resolve this issue, the use of a PCM based TES system was proposed. The system will be integrated with the domestic gas heater to absorb the additional amount of thermal energy when the heater will be in **ON** position and provide the stored heat during the unavailability of the gas. The gas load shedding is common in a crowded city. By integration of TES with a domestic gas heater the duration of a thermal source for thermal comfort will increase.

1.6 Thesis Outline

The overview of the thesis proceedings is as follows;

Chapter 2 will discuss the literature relevant to the TES systems. Different materials and systems in the literature will be discussed. The material properties specific to the Magnesium Chloride Hexahydrate will be discussed. Formulation and modeling of the systems will be analyzed, and the research gap will be highlighted based on the available literature.

Chapter 3 will describe the mathematical modeling for the specific case discussed in the thesis and the simulations results on MATLAB for the charging cycle. Some descriptions of the results of the simulation will be covered. Detailed design of the TES system will be discussed that include the drawings with dimensions and 3-D sketch of the system to be fabricated.

Chapter 4 will cover the most important part of the thesis that is the experimentations. In this chapter, the schematic of the experimental setup will be described and the instrumentations for the system to monitor the temperature variation of the material will be described in detail. The integration of the setup with a gas heater will be done and the process of data logging will be discussed in detail.

Chapter 5 will mostly be on the analysis and discussions about the data sets acquired from the experimentations. The graphs plotted among different parameters will be discussed and outcomes will be analyzed.

Chapter 6 consists of the conclusions based on the outcomes of the experimentations. Findings will be discussed based on material, system, and outcomes. In the second section, the recommendations based on the findings will be discussed.

1.7 Objectives

It is necessary of indicate the objectives of the research to keep the future activities focused for the achievement of the objectives. The objectives of the research are mentioned below;

a. Formulation of Mathematical and 3-D modelling of the TES system.
b. Design and Fabrication of portable TES system for medium range (100-130^{o}C) temperature heating.
c. Study of charging and discharging of Phase Change Material.
d. Thermal analysis of the system and the material.

1.8 Summary

In this chapter's introduction to the problem-statement is given. In the beginning, the climate conditions in the area are discussed and then the requirement for a heating system to achieve thermal comfort is discussed. After that different kinds of heating appliances used in the region were discussed and the one which is common is highlighted. Potential for using a TES system with the heating device was observed. After observing a good potential for the TES system with a heating device the idea of integration of TES with the gas heater was formulated. In this chapter, the basics of the TES system were discussed and PCM classification was discussed in brief. Then criteria for selection of an appropriate TES system were discussed. After that, the selection criteria for material that is to be used in the TES system was discussed and the importance of encapsulation was discussed. At the end of the chapter, the problem statement was described for a better understanding of the readers.

1.9 References

[1] "Climate of Islamabad - Wikipedia." [Online]. Available: https://en.wikipedia.org/wiki/Climate_of_Islamabad. [Accessed: 29-Oct-2019].

[2] ASHRAE, *2013 ASHRAE Handbook: Fundamentals*. 2013.

[3] J. Jarosinski and B. Veyssiere, *Combustion phenomena : selected mechanisms of flame formation, propagation, and extinction*. CRC Press, 2009.

[4] H. Nazir *et al.*, "Recent developments in phase change materials for energy storage applications: A review," *Int. J. Heat Mass Transf.*, vol. 129, pp. 491–523, 2019.

[5] I. Dincer and M. A. Rosen, *Thermal Energy Storage Systems and Applications*. .

[6] S. Höhlein, A. König-Haagen, and D. Brüggemann, "Macro-encapsulation of inorganic phase-change materials (PCM) in metal capsules," *Materials (Basel).*, vol. 11, no. 9, 2018.

Chapter 2

Literature Review

In this chapter, the literature that was consulted during the research will be discussed. It seems better for the readers to summarize the methodology by which the literature was searched and categorized for references. As a first step, the key words that were closely related to the thesis topic were shortlisted. Key words came out to be "*Phase Change Materials (PCM), Thermal Energy Storage (TES) Systems, Latent Heat Thermal Energy Storage (LHTES) System, Modular Thermal Energy Storage (MTES) systems, TES systems for heating applications*". The flow chart of the literature review is as under;

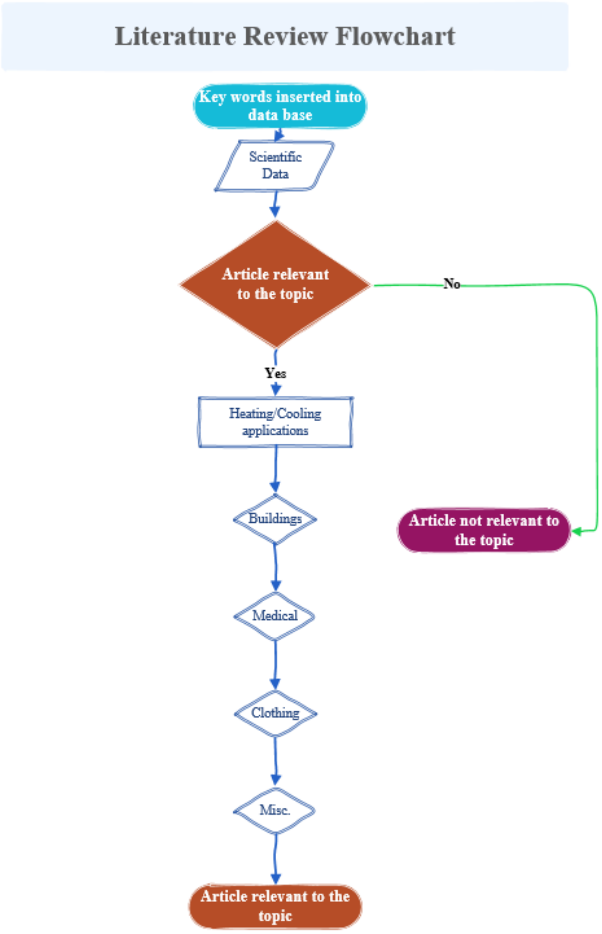

Fig. 2-1: Literature review flow chart

After gathering the papers, those were categorized by their applications. The schematic of the categorization of the literature review is shown below;

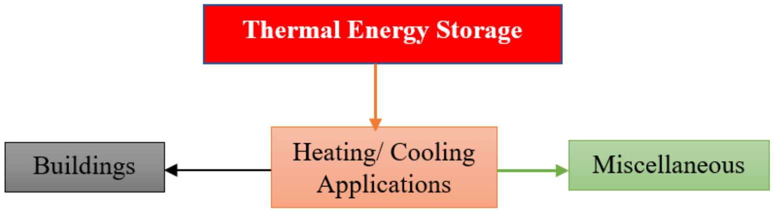

Fig. 2-2: Flow diagram of Literature Categorization

The above diagram illustrates that the papers were categorized based on their applications only. Two major categories in applications were formed i.e., the heating/ cooling applications in buildings and the other one was misc. applications of TES in all other areas and papers were separated based on their applications. The range for literature review was kept from 2012-2019 so that the newly established concepts and data should be used in the research.

2.1 Thermal Energy Storage (TES) system

Thermal Energy is not a new concept but evolved during the passage of time. The book published by Ibrahim Dincer and Marc A. Rosen [1] summarized all the concepts available by that time. The book published in 2010, encompasses the basic concepts of TES systems and then discussed the different categories and applications. It also gave a brief introduction to the modeling of the TES system and the basic thermodynamics analysis of the system. Another big contribution to the field was done by Dr. Fleischer[2] by presenting a comprehensive introduction to the applications of the solid-liquid phase change materials. He significantly highlighted the amount of energy stored by the material in the latent form. The selection criteria of the material for some applications are also covered in this publication. In short, the author of this book summarizes the PCM applications over the last 10 years. Another book published by L. Cabeza[3] provides an over view of all the storage technologies available. The book covers the fundamental in-depth study of the TES technologies and provides some comparison between them for the understanding of the reader. The book published by F. Mayinger et al. [4] explains the fundamental concepts and their application in a single book. In this kind of arrangement, the reader can appreciate the practical application of the system that is to be manufactured. The author of the book admitted that the book may not be the complete guide to the thermal energy storage but despite the fact it still adds up a major contribution in the field.

Another book published by P. Li et al [5] considers the importance, advantages and practicalities of TES systems. The book is categorized in different chapters covering all the important aspects of the TES systems. It also provides an in-depth knowledge of TES system analysis and explains the different design criterions. All these books were consulted for establishing the fundamentals of the TES systems along with the text books for Heat and mass transfer and thermodynamics. Details on the TES and modern developments in this field were learned through the review articles. The detailed review of PCM and its application were first written by Zalba et al[6]. This paper was focused on the materials, their heat transfer properties and possible applications of the materials. Initial selection for PCM material can be done by going through this paper.

Ming Liu et al[7] published a review on storage materials and thermal performance. This paper covered the current and construction technologies of CSP. The paper also reviewed the PCMs operating above the 300°C temperature that can be used in CSP and provided a summary of heat transfer enhancement techniques for these materials. In the concluding remarks, the author enlisted the different materials that can be used in CSP for energy storage purposes. P. Salunkhe et al[8] published a review on the effects of PCM encapsulation on the thermal performance of a system. The paper provided a detailed overview of the encapsulation of the PCMs and the effects of the encapsulation on the performance of the PCMs. The main parameters investigated were encapsulation size, shell thickness, shell material and encapsulation geometry. The author observed that the core-to-coating ratio plays an important role in the determination of the thermal and structural stability of the PCM. The author also observed that *an increase in core-to-coating ratio results in a weak encapsulation, whereas, the amount of PCM and hence the heat storage capacity decreases with a decreased core-to-coating ratio*. The author further observed the influence of the thermal conductivity of the shell material during the heat transfer between the HTF and PCM. The paper also reviewed the solidification and melting characteristics of the PCM and the effect of various encapsulation parameters on the phase change behavior. The author observed that *a higher conductivity of shell material, lower shell size and high temperature of the HTF results in the rapid melting of the encapsulated material*. He also observed that the conduction is dominant during solidification and natural convection is prominent during the melting process. The author observed a significant increment in the heat transfer effect when the PCM was encapsulated into microencapsulation, but the drawback of this phenomenon is, increase in viscosity and pressure drop when the concentration of the material is increased. The author concluded by suggesting *the experimental validation for the stability of the micro encapsulated PCMs before their adaption into the commercial sector*.

Aran Sole et al [9] published a review on the methods for the determination of the thermophysical properties of PCM. The paper reviewed the methods in practice for the determination of thermophysical properties and provided a certain proposal based on the previous studies for T-history commercial setup. The author concluded *that the T-history method is having advantages over the methods that are actively used for the determination of the thermophysical properties of the PCM materials like DSC and DTA because of the large sample size and optimized measuring time*. The author combined the suggestions presented by the researchers regarding the T-history method and classified them based on three groups that are experimental setup, mathematical model and result presentation. The author emphasized that for a commercial setup of the T-history method researcher should agree on a common instrumental setup, data analysis and presentation of results. M. Rathod and J. Banerjee[10] presented a review of the thermal stability of PCM. The paper is focused on the thermal stability of different groups of PCMs like organic, inorganic and eutectics. The paper aimed to provide a strong conclusion for the material selection for various applications based on the thermal cycle stability of the PCM. The author concluded the paper with some deductions based on his analysis of the literature available. The author concluded that *the life span of PCM depends on thermal stability, chemical stability and corrosion resistance of the container*. The change in latent heat and melting point can also give a rough idea of material stability. The author also recommended that the researcher must not focus only on the melting temperature and latent heat but also *consider the temperature dependent properties like density, thermal conductivity and heat capacity*. The author also highlighted that most PCMs investigated in the literature lie in the temperature range of 30 to 60^{o}C and latent heat in the range of 150-250 kJ/kg. Similarly, most eutectics studied in the temperature range of 20 to 60^{o}C and latent heat of 125 to 200 kJ/kg.

Gerard Ferrer et al[11] reviewed the methodologies used in the thermal stability characterization of PCM. The author classified the test procedures and results of different characterization techniques used for PCMs, where cycling stability was discussed in detail. Different parameters considered essential for cyclic tests are highlighted. Important issues that were considered in the review are, the type of equipment used to perform cyclic tests, the characterization techniques used for PCM before and after the thermal cycle, the number of thermal cycles and the heating rate and cycling method used. The author concluded that *there is no standard cycling method for PCM and a common standard for thermal cycling should be formulated for future work*. J. Pereira and P. Eames [12] presented a review on low and medium temperature PCM based TES. This paper reviewed the PCMs with a melting range between 0 to 250^{o}C. The authors also reviewed the heating and cooling applications of the LHTES, and the containers used for indirect latent heat storage and the heat transfer enhancement techniques used within the PCM. The aim of the paper was to analyze the PCMs domain that could be used for heating and cooling applications in order to reduce the CO_2 emissions within domestic heating and cooling appliances. The paper concluded by proposing the temperature ranges for different materials. Below 100^{o}C organic compounds and salt hydrates were found promising, eutectic mixture with urea worked better for above 100^{o}C and from 130^{o}C to 1250^{o}C eutectic mixture of inorganic salts showed the best results for energy storage.

Gargi Sanjay Khot and Khanwalkar P.M.[13] presented a review on TES using PCMs. The authors gaves an overview of the thermal energy storage systems using latent energy PCMs. The authors concluded with the remarks that *there are very few experimental studies conducted for thermal enhancement techniques with PCM*. The authors also observed that there is a need to investigate more materials in the temperature range of low and medium. The authors summarized their recommendations in the conclusion. They observed that *PCM with good thermal conductivity and latent heat of fusion performs better in storage systems*. The shell and tube type arrangements were recommended to be adopted. The authors also emphasized the use of heat transfer enhancement techniques for PCM usage and the flow arrangement should be parallel to that of heat transfer fluid. P. Pradeep Castro et al[14] presented a review on the design of PCM based TES systems. This paper covered the recent designs of thermal energy storage systems containing PCMs for effective energy storage. The author concluded that the performance improvement of TES can be obtained through proper consideration of the material having high thermal conductivity and latent heat of fusion. In addition to that other parameters like input temperature, dimensions and flow rate should also be considered. R. Bayon and E. Rojas[15] presented the feasibility of D-mannitol as PCM for TES. During this study, the feasibility of D-Mannitol as PCM for TES was ascertained by keeping it melted at 180 C in air for up to 16 Days. It was observed that more than 80% of the mass was lost in the form of water and other carbon volatile compounds which clearly depicts that D-Mannitol undergoes thermal degradation that may be due to dehydration, condensation and polymerization. *Due to degradation D-Mannitol was not recommended for a thermal energy storage system.* It is recommended to carry out long term melting experiments for ascertaining the thermal stability of the PCM. This study concluded with a recommendation not to use D-Mannitol as PCM.

S. Hohlein et al[16] presented a thermophysical characterization of different PCMs for LHTES. In this paper investigation of thermal energy storage material for mobile storage that can serve for the temperature range of 90-150^{o}C was carried out. Three materials Xylitol, Erithritol, and Magnesium chloride hexahydrate were tested. Based on the analysis, *Xylitol and Erithritol were rejected because of high supercooling and magnesium chloride hexahydrate were recommended for use in thermal energy storage for mobile heat storage systems*. During experiments, DSC was used to observe the behavior of the thermophysical properties of the material. N. Ibrahim et al[17] presented a critical review of heat transfer enhancement of PCMs for TES. The paper presented a state-of-the-art review on heat transfer enhancement techniques of latent heat thermal energy storage systems (LHTES). The authors highlighted that the heat transfer enhancement in LHTES can be done either by geometric configuration or the enhancement of thermal conductivity. As per the author's observations, the use of extended surfaces and heat pipes were commonly used for heat transfer enhancement techniques in LHTES. The authors also studied the thermal conductivity enhancement techniques like the addition of porous material, nanoparticles and low-density materials. The authors concluded *that the heat transfer of LHTES can be enhanced by increasing the surface area or the thermal conductivity of the material*. The author also recommended the combined heat transfer enhancement technique in which techniques mentioned before, are combined to get a greater impact. S. Mohamed[18] et al presented a review paper on the status and challenges of using inorganic materials for TES. The paper highlighted the pros and cons of organic and inorganic PCMs. Inorganic PCMs are having high thermal conductivity and storage density but also having the potential of corrosion and phase separation as compared to organic PCMs. The author predicted that the organic PCMs have more potential in the TES field specifically considering the medium to high temperature range. The author concluded that supercooling is one of the major problems in inorganic PCMs that can be overcome by the addition of the nucleating agents, but further work is required for determining the types and performance of the nucleating agents. The author also recommended the use of microencapsulation for catering to the problem of phase separation in salt hydrates. The author emphasized the need for stability evaluation of the storage material and highlighted the need for a standard testing procedure.

N. Tay et al[19] presented a review on transportable PCM based TES systems. The author reviewed the transportable PCMs and analyzed the heat transfer enhancement techniques reported in the literature. The author classified the transportable PCM system into three categories: *PCM slurry, direct-contact PCM system, and dynamic PCM systems*. The author also highlighted the limitations of these systems like PCM slurry has a very low energy storage capacity, direct-contact PCM systems have a challenge of pressure build up and volumetric expansion. *Based on the performance the author recommended the dynamic PCM systems because it is cost effective and reliable method.* F. Cao et al[20] presented a paper based on a concept of the TES system comprising tunable melting point PCMs. Presently material used for latent thermal energy storage is constrained by fixed melting points. The selection of the PCM for power plant application is dependent on the melting point of PCM, its type and environment temperature. In this research, the tuning of $CaCl_2.4H_2O$ was carried out according to the requirement of the melting temperature. The author observed that the lower-melting point of $CaCl_2.6H_2O$ (29^oC) can be tuned to the higher melting point of $CaCl_2.4H_2O$ (39^oC) by removing the moisture with dry air. The process can be reversed by the addition of moisture. The author also observed that the tuning process is controllable and reversable. He also claimed that 1.6% of energy can be saved per annuum in power plants by using tunable materials. Y. Lin et al[21] reviewed the thermal conductivity enhancement techniques in TES systems. The author reviewed the methods of thermal conductivity enhancement techniques like adding high thermal conductivity additives and PCM encapsulations. The author highlighted that the addition of thermal conductivity enhancement filters improves the thermal conductivity of PCM very effectively. The author focused more on two methods one was the addition of carbon - based filler material and the other was the encapsulation of the PCM. The author concluded by recommending the shell type encapsulation for PCM for the reduction in leakages and improvement in thermal conductivity. K. Reddy et al[22] published a review on LTES for improved material stability and effective load management. The author focused on the functional principle, thermophysical properties and other material characteristics of PCMs. The author also discussed the long - term thermal stability of the PCM and its interaction with the encapsulation container. He further discussed some of the tested systems and their applications in thermal load management. In the end, the author summarized the energy and exergy analysis of some thermal energy storage systems. N. Zhang et al[23] presented a review based on LHTES with solid-liquid PCMs. The author tried to provide a specific review of the solid-liquid phase change materials (PCMs) for LHTES applications. The basic drawbacks with PCMs used in LHTES are low thermal conductivity and leakage during the melting phase. The author covered thermal conductivity enhancement techniques and studied the enhancement of convection heat transfer and optimization of the structures for PCM containers. The author recommended *the microencapsulation and form stable PCMs for leakage problems in LHTES*. Y. Tao and Y. He[24] presented a review on PCM and performance enhancement methods for LHTES. The author reviewed the development of PCMs and performance enhancement methods for LHS and classified the enhancement methods into three categories like the addition of high thermal conductivity additives and porous media for thermal conductivity enhancement, the extension of heat transfer areas by fins and PCMs encapsulation and the use of cascaded LHS techniques and optimized thermodynamic process for uniform heat transfer through the material. The author concluded that *the metal foam and expanded graphite are efficient for thermal conductivity improvement in low and high temperature PCMs*. He further highlighted that the finned tubes are the simplest way to enhance heat transfer, moreover, PCM encapsulation plays an important role in the extension of the heat transfer area of the PCM.

G. Wei et al[25] reviewed the selection principles and thermophysical properties for high temperature PCMs for TES. The author reviewed the selection principles of high temperature PCMs and analyzed the selection with material selection software. The author tried to provide an overview of high temperature inorganic material selection, innovation and investigation of thermophysical properties for their development. The author concluded that *the selection principles must satisfy the important requirements of thermodynamics, kinetics, chemistry, and economics of the system*. The author recommended that the material should be selected by keeping all parameters in mind but for practical applications, some leniency should be kept if the material fulfills the major criteria like melting temperature and latent heat. The author also highlighted that no high temperature commercial system is fabricated so for. The author also highlighted the container material compatibility with the PCM material that needs to be analyzed in detail. The author further highlighted that the basic data for all materials are not available and the researchers should work on establishing the data bank for reliable primary parameters of the PCMs. The author emphasized that the unavailability of the uniform testing standards for determining the different parameters like density, latent heat, thermal conductivity resulted in different values of the same parameters in the literature. I. Sarbu[26] presented a comprehensive review of TES. The author focused on TES technology application in the utilization of solar thermal energy in building and reducing the energy demands of the building. The author concluded that *SHS storage is better in terms of availability, but it stores a limited amount of energy and acquires a large area as compared to PCMs which comparatively stores more energy with relative less area occupation*. The author recommended to formulate a policy regarding the use of PCMs and further materials investigation is emphasized.

H. Nazir et al[27] reviewed the recent developments in PCMs for energy storage applications. The author focused on the applications of PCM based on their thermophysical properties like melting temperature, storage density, thermal conductivity with a wide temperature range and considered all categories. The energy storage enhancement techniques like encapsulation and addition of nanomaterials are also discussed. The author highlighted that although the latent heat TES systems store more energy but are not durable as sensible storage systems. The author also highlighted that the recent research in this field is focused on the performance enhancement of PCMs in power plants and no other commercial application is seen. He further highlighted the application of TES in smart grid to remove the intermittency of renewable sources. The further literature review is categorized under different applications as mentioned earlier.

2.1.1 Building

U. Stritih et al[28] presented a paper on PCM based TES for heating of ventilation air. The author published the numerical as well as experimental findings. The author used LHTES for heating of ventilation air with a hot air solar energy collector. It was observed that the efficiency of solar air heaters (solar air collectors) decreases somewhat steeper with the increasing temperature difference between the ambient temperature and the fluid temperature in the collector. Solar air heater applied for heating of ventilation air operates under more favorable conditions than solar air heaters used for space heating. The author observed that the mean air temperature in the solar air heater in case of ventilation air heating operation was lower than the mean air temperature in case of a space heating operation. The author highlighted that the prediction of the behavior of PCM based systems is difficult because of their inherent nonlinear nature at moving interface where the displacement rate is controlled by latent heat absorbed or lost at the boundary. The experimental setup fabricated by the author consisted of solar air collectors, LHTES, ducts and fans. Designed for heating and cooling. Day time charging took place with the help of warm air and during night discharging of the stored energy was done. The author performed the experiments with a constant air flow rate. He also used the TRNSYS simulations to carry out annual calculations which revealed that *the highest coverage ratio of ventilation heat loss was in a transition period between season April (92%) and October (89%). Annual cost saving in comparison with district heating with TES was 91% and without TES was 93%.*

P. Devaux and M. Farid[29] presented a paper on the benefits of PCM underfloor heating with PCM based wall boards for space heating. The author analyzed the benefits of PCM when incorporated in a building envelop. The author experimented with two different kinds of PCMs, PCM with a higher melting point was used in the floor for maximum peak load shifting, and PCM with lower melting temperature was used in walls and ceilings for better thermal comfort. The experimentation was carried out at Tamaki Campus of the University of Auckland (New Zealand). The author validated the energy plus software outcome against the experimental data for a period of 10 days and observed the energy and cost savings up to 32% and 42% respectively. H. Akeiber et al[30] presented a review on PCMs that can be used in passive cooling in the buildings. The author drew attention to the greenhouse effect caused by the heating and cooling appliances used in the buildings. The author highlighted the effectiveness of passive cooling techniques using PCMs as the storage medium. The author also investigated the different PCMs available for passive cooling and studied the full-scale study and numerical modeling for experimental and theoretical analysis. In the concluding remarks, the author provided a list of potential PCMs that could be effectively used for passive cooling in the buildings. K. Du et al[31] presented a review on the applications of PCMs in cooling, heating and power generation in different temperature ranges. The author provided an up to date summery of the PCMs applications in heating, cooling and power generation in the temperature range of -20^{o}C to 200^{o}C. The author broke down the temperature range into four categories that included, *low temperature range (-20^{o}C to +5^{o}C) PCMs normally used for domestic cooling applications, medium range (+5^{o}C to +40^{o}C) PCMs used for heating and cooling applications in buildings, medium temperature range for solar based heating (+40^{o}C to +80^{o}C) used for heating, hot water, and electronics applications and the high temperature range (+80^{o}C to +200^{o}C) used for absorption cooling, waste heat recovery and electricity generation*. The author discussed the materials in terms of performance, heat transfer enhancement techniques, environmental impact and economic analysis. The author also highlighted the energy saving up to 12% and a reduction in cooling load up to 80% using PCMs in low to medium temperature range. The author concluded the paper by giving the recommendations that the experimental validation of numerical and analytical models for PCMs is costly therefore an improvement in the numerical methods should be applied to get better simulation results for PCMs related systems. He also highlighted to study the environmental impacts of the PCMs before practically using them into the systems. He further highlighted that there are two heat transfer methods used in PCMs that is heat conduction and heat convection, most of the heat transfer enhancement techniques only increase the heat conduction and not giving importance to the convection phenomenon occurring inside the material. The author also recommended investigating other materials in the temperature range of 5^{o}C to 80^{o}C as mostly paraffin is used in this range for commercial purposes. D. Zhou et al[32] presented a review on TES with PCM in building applications. The author summarized the previous works on latent thermal energy storage in building applications that covered the PCM, their encapsulation method, applications in buildings and thermal analysis. The author came up with the conclusion that *the PCMs used in the building applications must fulfil the thermal comfort criteria*. It means that the melting temperature of the material should be between 18^{o}C to 30^{o}C. The author also highlighted the crucial properties of PCMs used in building applications, that include chemical stability, fire characteristics and compatibility with the encapsulation material. The author also highlighted the necessary parameters, like the thermal inertia (time lag/ decrement factor), TETD, effective thermal capacitance, U-value, R-value that is to be considered during the selection of the material. H. Madessa[33] presented a review on the performance of buildings integrated with PCM specifically in cold climate. The author provided a review of the thermal performance of the PCMs available for building applications and analyzed the type of integration of these materials into the buildings. The author also investigated the potential for PCMs in passive cooling techniques specifically in the Nordic climate. The article revealed *the capacity of PCMs to reduce the indoor peak temperatures, loads shifting by reducing the excess temperature hours beyond the thermal comfort range, enhancement of the overall energy performance of the building*. The author concluded with a strong recommendation for using the PCMs having a melting temperature at the thermal comfort zone (26°C). He also suggested that the integration of such material will reduce energy consumptions for cooling.

Y. Cui et al[34] presented a review on PCMs integrated into building walls for energy savings. This author specifically reviewed the work related to PCMs integrated into buildings for energy conservation. The author highlighted the thermophysical properties, type, incorporation method suitable for PCM wall and specific application method. The author concluded by providing the datum line of different parameters of PCMs used in buildings, the temperature ranges from 19 to 28°C for organic and 25 to 35°C for inorganic, the latent heat remained in the range of 120 to 280 kJ/kg irrespective of the PCM, thermal conductivity for organic was close to 0.2 W/m.K and for inorganic it was observed as 0.6 W/m.K, range of density observed was 700 to 900 kg/m^3 for organic and 1300 to 1800 kg/m^3 for inorganic. Furthermore, the author highlighted the coordinates of the locations where these systems are used more often it covers from 25 to 60 degrees north and 35 to 40 south latitude and maximum use frequency is 87.5%. A. Waqas and Z. ud Din[35] presented a review on PCMs for free cooling in buildings. The author reviewed the work conducted by different researchers on PCM based free cooling. The author highlighted the major challenges being faced by the researchers in designing the PCM based free cooling system like PCM, thermophysical properties of the PCM and the geometry of encapsulations. The author further discussed the effecting parameters of charging and discharging, the effect of melting temperature and the ambient conditions on the thermal performance of free cooling. The author also highlighted the impact of free cooling on CO_2 emissions. The author concluded by recommending that the technique is quite effective for the region where the temperature variations are between 12 to 15°C. The author highlighted that the reduction in cooling load in summer was observed by adopting this technique. The author recommended establishing the commercial setup of free cooling and emphasized that the cost of the material should be reduced to bring the PCM based free cooling devices in competition with other available in the market.

2.1.2 Miscellaneous

A. Al-abidi et al[36] presented a review on TES for air conditioning systems. This paper reviewed the applications of TES systems in air conditioning and applications of PCMs in different parts of air conditioning systems like air distribution network, chiller water network, microencapsulated slurries, thermal power and heat rejection of the absorption cooling. The author concluded that the configurations used so for are shell and tube and double pipe due to their efficiency, the author emphasized that other methods should also be tested for improvements. He further added that the integration of the TES systems into air conditioning systems will reduce the unit size and improve the efficiency of the system. A. Shukla et al[37] presented a paper regarding the development of thermal energy storage materials for biomedical applications. The author claimed the development of PCMs that could be used in biomedical applications. The author observed that with the integration of PCMs the quality of biomedical applications enhanced. The author highlighted that interdisciplinary research among the fields of biomedical sciences, material sciences, and medical experts should be conducted for large benefits.

B. Xu et al[38] presented a review on the applications of PCM based TES in CSP. The author discussed the recent TES technologies applied to CSP. The author discussed the five issues faced by technology. In the first part, the author discussed the PCMs and the encapsulation technologies used in CSPs. In the second part, the author focused on the state of the research and application of latent heat storage in CSP. Then the author discussed the mathematical modeling of the phenomenon. In the fourth part, the author discussed the integration of PCM based TES into CSP. In the last portion, the author discussed the cost analysis of sensible and latent energy storage with CSPs. The author concluded that significant storage volume reduction is observed if latent technology is used in comparison with sensible technology. M. Saleem et al[39] presented a review on solar thermal water heater simulation by using the TRNSYS software. The author covered the applications of TRNSYS in solar thermal water heaters with forced circulations and thermo-syphon systems using Flat Plate Collectors and Heat pipe evacuated tube collectors. The author also presented comparative studies between the results. The author concluded that he TRNSYS system needs to be expanded to encompass all the required areas for simulation. He also concluded that evacuated tube solar collectors are better than the heat pipes collector system with free circulations. D. Thomas et al[40] presented a performance analysis of an LHTES system for solar energy applications. The author carried out the experimental energy and exergy analysis during the charging period of PCM with a heat input of 2000W and with 4 different flow rates of HTF. The author used sodium thiosulfate pentahydrate as PCM. The author analyzed the energy and exergy efficiency of the storage unit with heat flux and mass flow rate. The author observed that the exergy efficiency was low when compared to the energy efficiency of the system. The author deduced from the experiments that the latent thermal energy storage exergy is destroyed mainly because of high entropy generation during the process.

M. Liu et al[41] presented a review on CSP and new developments in high temperature TES technologies. The author provided a comprehensive review of the CSP plants both in service and under construction. The author covered almost all the aspects of the CSP like a receiver, thermal storage, power block, and heat transfer fluid. The author also reviewed the development of high temperature PCMs over the past years and discussed the material degradation and economic aspects of the systems. The author also described the current research efforts made in the sensible TES systems that consists of the development of new molten salts with low freezing temperatures and high decomposition temperatures, development of ionic liquids for HTF, utilization of nanofluid technology for improvement of the specific heat and thermal conductivity and development of low-cost sensible storage that is compatible with the molten salts. The author also highlighted the major issue of corrosion by using the salts with metal encapsulation. L. Miro et al[42] presented a review on TES for IWH recovery. The author reviewed the potential of a TES system w.r.t the industrial sector. The author studied around 50 case studies considered characteristics of heat source, the heat, the TES system and the economic, environmental and energy savings, these parameters for this paper. The author recommended *the metals manufacturing* *industry to be useful for IWH and the recovered heat can be used for heating or electricity generation*. The author concluded that the IWH is underutilized for some reason. The integration of TES systems can provide a solution for a mis match between demand and supply. He also suggested that waste heat recovery will also reduce CO_2 emissions. Experimental validation of the MTES systems is also recommended by the author. K. Pandey et al[43] presented a review on Orthopedic device having gel pads with PCMs. In this paper, the application of phase change material in the field of medical is described. The author gave the idea of combining the PCM with the gel pad to enhance the thermal energy storage for the treatment of the injured joints. The paper concluded with the remarks of using multiple PCMs for enhancement the thermal energy storage.

A. Crespo et al[44] presented a review on LTES for solar process heat applications in the medium-high temperature range. The author covered the area of TES used with solar radiation to suppress the mismatch between the load and the radiation. The paper is specific for the use of solar energy integrated with TES in industries of food, brewery, and chemicals. The author studied the medium temperature level PCM as a heat storage material for industrial applications. The author studied the PCMs with values of heat of fusion ranging from 74 to 535 kJ/kg and presented this review based on the experimental and mathematical model. The author highlighted that in the temperature range of 120-400^{o}C most experimental setups were developed for steam generation for CSP applications. The author concluded by highlighting the potential of TES in the above-mentioned industrial applications. A. Waqas et al[45] presented a review on thermal and electric management of PV panels using PCM. The author focused on the topic of thermal and electrical management of PV systems integrated with PCMs. Different aspects such as technology development, performance, PCM selection criteria, heat transfer enhancement, simulation, and current applications were discussed. The author deduced by the literature survey that a total temperature of 20^{o}C could be reduced and 5% of electrical efficiency could be increased by using PCM. The author also claimed that ~2.6kg PCM per meter square of the panel area is required to reduce the temperature by one-degree of the panel during peak hour. The author concluded that PCM with a melting temperature range of 25 to 35^{o}C is more suitable for this application. The author further recommended that the PCM selection is dependent upon the geological location and climate condition. Organic PCMs are more suitable for this application. The author recommended real time experimentation for a better understanding of the system. Y. Dong et al[46] presented a review on latent TES for solar air conditioning systems. The author reviewed the selection of PCM and the strengthening of the container for LHTES for solar air-conditioning systems. The author highlighted that *not necessarily hybrid enhancement can perform better in terms of thermal storage as compared to the single enhancement technique*. He also claimed that latent thermal storage has fewer applications in the field of solar air-conditioning because of the cost and storage time. The author concluded that at present only limited materials are studied for solar air-conditioning applications. He also highlighted that the development of a new container configuration can also affect heat transfer enhancement. The author also emphasized on the development of the relationship between the structure and geometrical factors of the container to achieve the design and selection of the PCM container. R. Gulfam et al[47] reviewed the advanced thermal systems driven by paraffin based PCMs. The author reviewed the advanced thermal systems based on paraffin waxes and categorized the systems into thermo-management, thermo-mechanical, thermo-responsive and thermo-chemical systems. The author also worked on standardizing the PCM diagram for future reference and a flow chart of thermal re-enforcements to fabricate an ideal thermal composite. The author concluded that the thermo-management systems are bet best suited for duplex thermal composites having high thermal conductivity and large pristine latent heat of fusion and comparatively with better shape-stability. The author further emphasized that only need based thermal composites should be promoted and unnecessary fillers should be avoided that reduce the latent heat of the material. The author further recommended the microporous thermal reinforcement instead of nano-porous in order to avoid the high viscosity of paraffin wax. The author also recommended that the paraffinic phase change materials should be synthesized with controlled responses for further applications in thermo-mechanical, thermo-responsive and thermo-chemical.

2.2 Inorganic Materials in TES systems

This portion of the chapter comprises of the literature related to inorganic PCMs. The material selected for experimentation was inorganic therefore this portion was created to review the specific literature for that material.

R. Pilar et al[48] presented a paper on Magnesium Chloride Hexahydrate as Heat storage material. The author analyzed the Heat capacity in the range of 298 to 400 K and a polynomial function was developed to study the behavior on 371K and corresponding thermodynamic functions such as Enthalpy, Exergy, and Entropy were analyzed. Thermal cycling testing up to 50 cycles were carried out and supercooling up to 37K was observed. The author suggested the addition of a nucleating agent for curbing the supercooling. A. Safari et al[49] presented a review on the supercooling of PCM in TES. The author covered the phenomenon of supercooling in PCMs and projected a different angle of research on supercooling, instead of suppressing supercooling the author wanted to make the supercooling region operational for specific applications. The author included the study of thermal energy storage of supercooled liquids, degree, and measurement of supercooling and the factors that affect the degree of supercooling. The paper was aimed to give an insight to the researchers of the supercooling control techniques necessary for the development of the efficient heat exchangers. The author concluded the article by emphasizing the importance of the thermodynamic properties of the materials that are to be used for the purpose. R. Raud et al[50] presented a critical review of the eutectic salt property prediction for LHTES. The author focused on the use of eutectic salts as a storage medium and the selection criteria of the material were discussed. The author highlighted *that the properties specially the melting temperature of eutectic salts can be predicted based on the properties of the single salt within 5% to 7%*. This procedure is void in the estimation of the latent heat of eutectic. The author concluded that *the density of the mixture can be easily determined by the equation mentioned in the paper while other properties like thermal conductivity, latent heat and heat capacity are difficult to determine through simple equations and require some experimentations and testing for such properties*.

Y. Milian et al[51] presented a review of the encapsulation techniques for inorganic PCM. The author reviewed the encapsulation and characterization techniques for inorganic PCMs and analyzed the influence of encapsulation on the thermophysical properties. The author reported the two methods, core-shell EPCMs and Shape- Stabilized PCMs. The author concluded that CS-PCMs and SS-PCMs obtained through different methods have provided the larger heat transfer area, decreased the subcooling and controlled the volume changes of the storage materials during the phase transition. The author highlighted *the research gap in the area of material encapsulation which can be further investigated and the room for improvement of PCMs performance lies with the maturity of this area.* Y. Lin et al[52] presented a review on thermal performances and applications of TES with inorganic PCMs. The author reviewed the researches on the inorganic PCMs in recent years and analyze their integration with the heat exchangers. The author concluded that the inorganic PCMs have a wide temperature range and their integration in the heat exchanger can highly improve energy efficiency. The author also mentioned that hydrated salts are good for thermal storage but with problems of supercooling/subcooling and phase segregation, some measures like the addition of nucleating agent and constant stirring are required for material stability over a long period. The author also recommended the use of eutectic molten salt instead of a single molten salt because of the better melting temperature range. The author highlighted that present researchers are more focused on the thermophysical properties of the material and there is no work carried out towards the PCM and encapsulation material interaction. The author emphasized that such work must also be carried out for enhancing the life of TES systems.

2.3 Research Objective

The objective of the research is to develop a modular latent thermal system that can be used for heating applications. The system will be integrated with a domestic gas heater to store excess energy wasted during the combustion when the heater is ON. As it is clear from the literature review that no such integration was reported up till now. Therefore, the novelty of the concept is proven. Different configurations can be tried that can be categorized as direct contact and indirect contact of the thermal source. In this research, a direct contact TES system based on the Inorganic PCM is analyzed. A test setup was fabricated, and the concept was analyzed experimentally. The results of the same will be discussed in the later chapters.

2.4 Summary

In this chapter, a detailed literature review was discussed. At the beginning of the chapter, the literature search methodology and the range in years for literature to be consulted was given in order to ascertain the domain of current work. Then the literature reviewed was listed according to ascending order so that the development in the area should be highlighted. The applications were broadly divided into two categories to avoid complications. The aim of the chapter was to illustrate the working and development of TES in different applications and then specifically in thermal energy storage, which is the main topic of the research. At the end of the chapter, the inorganic materials were discussed because the material selected for the experimentation was inorganic.

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Chapter 3

Modeling, Simulations, and Fabrication

This chapter will mainly cover the step by step research methodology followed during the research. The temperature range at which the system will be operating during the charging and discharging phase and the application in which the system will mainly provide its output are two basic parameters for the selection of the TES system. After a detailed literature review, the latent heat thermal energy storage (LHTES) system was selected for integration with the heater. In the selection of the TES system, all conditions mentioned earlier were considered. Based on the temperature range, the available PCMs in the literature were shortlisted. The final selection of the material was based on commercial availability and the cost factor. Considering all these parameters, Magnesium Chloride Hexahydrate ($MgCl_2.6H_2O$) was selected as an energy storage material for the TES system to be integrated with the domestic gas heater.

From now on the modeling and fabrication of the experimental setup will commence. Before proceeding further let us look at the research methodology flow diagram. That will help us in indicating future events. The flow diagram is shown below;

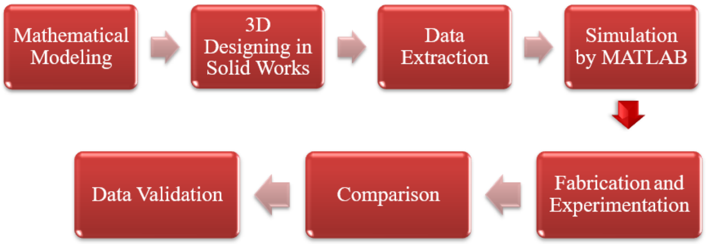

Fig. 3-1: Research Methodology flow diagram

3.1 Mathematical Modeling

In this section, the mathematical formulation of the model will be discussed. A mathematical model was developed using the enthalpy method[1]–[4] Figrue 3-2 represents the 1-D model for the charging process with specific conditions applied.

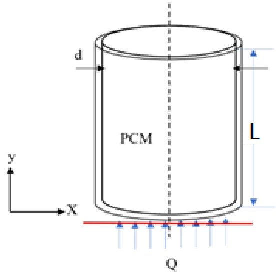

Fig. 3-2: 1-D model for charging

During charging the energy will be provided from the bottom of the cylinder and heat will gradually flow upwards, melting the entire PCM to store latent energy. Following assumptions were taken into consideration while formulating the mathematical model for charging of the system;

a. Heat flow is considered in 1-D only i.e., in the axial direction from bottom to top.
b. Internal convection of the material is not considered.
c. Thermophysical properties were assumed to be constant for the charging process.
d. Heat losses during the charging process are neglected.

Following boundary conditions were used for modeling the heat transfer equations during charging of the system;

At Y = 0 $\dot{q}_o$(X = 0) = Constant (Constant Heat Flux)

At Y = L Convection

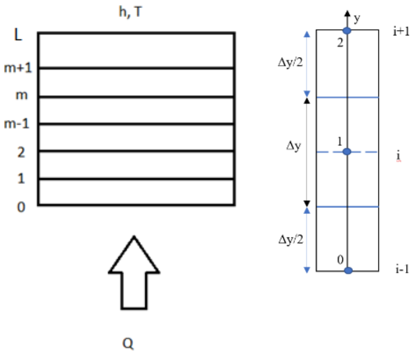

Fig. 3-3: Division of cylinder into small nodes and element description with node location

In the enthalpy method, the enthalpy represents the heat content of the material and is totally dependent upon the temperature of the substance. The method is useful for PCMs because of the involvement of the phase transition. There are normally two types of Enthalpy functions used those are called implicit and explicit. In this model, the implicit function of the enthalpy formulation is used. The entire domain was divided into nodes as shown in the figure 3-3. Before the division of the domain into several nodes, the nodes are to be calculated by the following equation.

$$\boxed{Number\ of\ nodes = N = \frac{L}{\Delta y} + 1 \qquad \textit{Eq. 1}}$$

Here 'L' represents the total length and Δy represents the small portion in which the total length is divided. The general equation of enthalpy formulation for
phase change material is given below;

$$\boxed{p\,\frac{\partial H\,(T)}{\partial t} = \nabla.\,(k\Delta T) + g(r,t) \qquad \textit{Eq. 2}}$$

For phase change material the term g(r,t) is discarded as there is no generation within the material.

3.1.1 Boundary Node (y=0)

Starting with the boundary node, we will consider the energy supplied as the boundary condition and the heat will be conducted to the next node through conduction. The enthalpy formulation for boundary node cab be derived as;

$$\dot{q}_o^i A + kA\,\frac{(T_1^i - T_o^i)}{\Delta y} = \rho C_p A\,\frac{\Delta y}{2}\,\frac{(T_o^{i+1} - T_o^i)}{\Delta t}$$

With some simplifications the final form of the equation will come out to be;

$$\boxed{H_o^{i+1} = H_o^i + \frac{2k}{\rho}\eta\left(T_1^i - T_o^i\right) + \dot{q}_o^i\,\frac{2\Delta t}{\rho\Delta y} \qquad \textit{Eq. 3}}$$

Here $\eta = \frac{\Delta t}{\Delta y^2}$, H is the enthalpy of the node, k is the thermal conductivity of the material, T is the temperature, q represents the flux and t represents the time. Superscripts on the terms represent the time and subscript represents the location of the node. Superscript (i+1) represents the next time step and (i) represents the previous time step.

3.1.2 Inner node

After the initial boundary node and the last node, all other nodes are called the inner nodes. The enthalpy formulation for the rest of the nodes is similar with the difference of the position of the node only. The difference can be observed in the subscript where the location of the node is mentioned. The heat transfer in the inner nodes takes place due to conduction. The enthalpy formulation for node 1 can be obtained by the following equation:

$$\frac{kA}{\Delta y}\left(T_o^i - T_1^i\right) + \frac{kA}{\Delta y}\left(T_2^i - T_1^i\right) = \frac{\rho C_p A \Delta y}{\Delta t}\left(T_1^{i+1} - T_1^i\right)$$

After simplification, the equation for node 1 will come out to be;

$$\boxed{H_1^{i+1} = H_1^i + \frac{k}{\rho}\eta\left(T_o^i - 2T_1^i + T_2^i\right) \ \ here\ \eta = \frac{\Delta t}{\Delta y^2} \qquad Eq.\ 4}$$

The general equation for the inner node can be written as;

$$\boxed{H_m^{i+1} = H_m^i + \frac{k}{\rho}\eta\left(T_{m-1}^i - 2T_m^i + T_{m+1}^i\right) \qquad Eq.\ 5}$$

The above equation is the general equation for the inner node where m is the number of nodes or locations for which the enthalpy formulation is required.

3.1.3 Boundary node (y=L)

The boundary at y=L consists of the last and second last node of the material. The heat from the second last node to the last node will pass through conduction and the boundary condition at the last node is natural convection. The enthalpy formulation for the last node can be obtained by the following equation.

$$\frac{kA}{\Delta y}\left(T_{n-1}^i - T_n^i\right) + hA(T_n^i - T_\infty) = \frac{\rho C_p A \Delta y}{2\Delta t}(T_n^{i+1} - T_n^i)$$

After simplification, the equation turned out to be;

$$\boxed{H_n^{i+1} = H_n^i + \frac{2k}{\rho}\eta\left(T_{n-1}^i - T_n^i\right) + \frac{2h\Delta t}{\rho \Delta y}(T_n^i - T_\infty) \qquad Eq.\ 6}$$

Combining Eqs. 3,5 and 6 will give us the enthalpies of all the nodes w.r.t time steps. We need a stability criterion for the system, by following the criteria the system will converge to its solution. Therefore, for stability following condition must be satisfied;

$$\eta = \frac{\Delta t}{\Delta y^2} < \frac{\rho C_p}{2k} \ which\ is\ equivalent\ to\ r = \frac{\alpha \Delta t}{\Delta y^2} < \frac{1}{2}$$

Temperature-Enthalpy relations are used to calculate the temperature of the PCM in different regions. Therefore, it is important to understand that only the relevant relation will give the right temperature. The relations are given below;

$$T = \begin{cases} \frac{H}{C_p} & H < C_p T_m \\ T_m & C_p T_m \leq H \leq (C_p T_m + L) \\ \frac{H-L}{C_p} & H > (C_p T_m + L) \end{cases} \qquad \text{Eq. 7}$$

Eq.7 provides the temperature of the material in all regions. In these equations H represents the enthalpy, C_p represents the heat capacity, T_m is the melting temperature and L is the latent heat of fusion of the material. It should be understood if the enthalpy of the material is less than the product of the heat capacity and the melting temperature then the temperature of the material can be calculated by the first part of the Eq.7. In the mushy region, the temperature of the material can be considered as the melting temperature and in this region, the enthalpy will be in between the maximum sensible enthalpy and the latent enthalpy. If the enthalpy is greater than the sum of latent heat of fusion and the maximum sensible enthalpy, then the temperature can be calculated by the last part of the Eq.7.

Another important parameter during the simulations of PCM is Liquid Fraction (LF). It provides information about the phase of the material in liquid or solid. If the material is completely melted, then the value of LF will be 1 and if the material is solid the value will be 0. LF is important during the transition phase. At this stage, LF can be calculated with the help of the material's enthalpy. The relations used for determination of LF are appended below;

$$L.F = \begin{cases} 0 & for \quad H \leq 0 & Solid \\ \frac{H}{L} & for \quad 0 < H < L & Meshy\ Region \\ 1 & for \quad H > L & Liquid \end{cases} \qquad \text{Eq. 8}$$

The mathematical modeling of the system is completed at this point. The equation derived above can be used to formulate the model in EES or MATLAB for simulations. It should be noted that in these equations the varying parameter is the temperature and all other values are based on the values of temperature. During experimentations, the temperature can be easily measured with the help of thermocouples and can be recorded with the help of a data logger.

3.2 3-D Model of TES system

The 3-D model of the TES system was developed on Solid Works. The setup consisted of 3 cylinders placed above a flat plate on equal distance. All the dimensions in the drawings are in inches. The dimensions of the Aluminum base plate are given below;

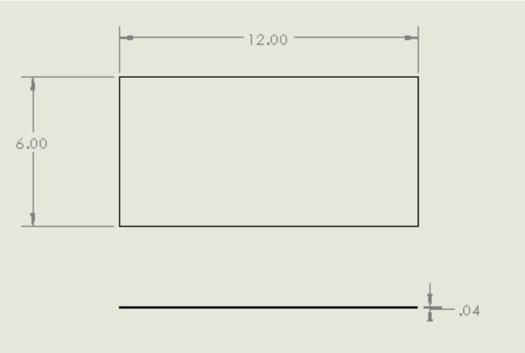

Fig. 3-4: Dimensions of the base plate

This plate will work as the base plate and cylinders will be welded upon the plate. The dimensions of the Aluminum cylinders are shown below;

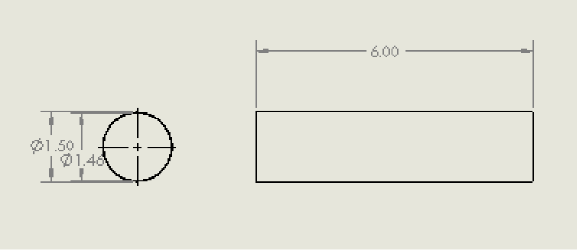

Fig. 3-5: Dimensions of Cylinder

The thickness of the cylinder and the base plate are kept the same to have a similar effect over the PCM encapsulation. The placement of the cylinders on the plate is important. It was kept in consideration that the cylinders should be equally spaced because during the discharging of the stored energy, the natural convection process is used. The spacing of the cylinders is shown below;

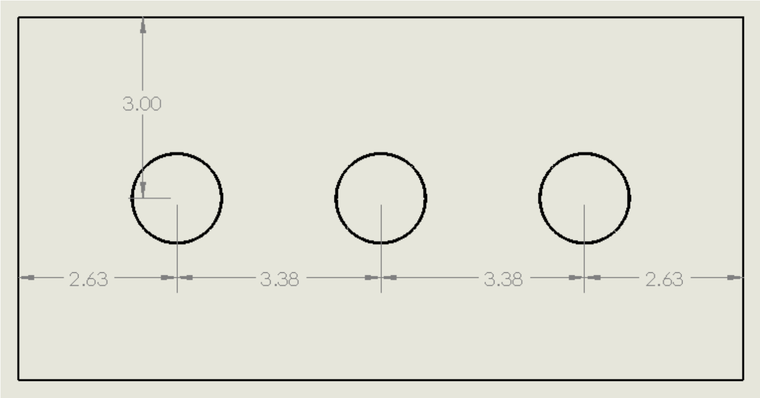

Fig. 3-6: Cylinders spacing over the base plate

The final 3-D model is shown below;

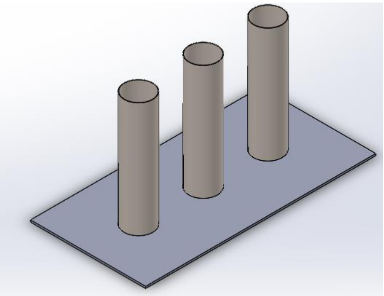

Fig. 3-7: 3-D model of the TES system

3.3 Thermophysical Properties of PCM

Thermophysical properties contain the melting temperature, the heat capacity of the material, latent heat of fusion, thermal conductivity and density of the material. Magnesium Chloride Hexahydrate ($MgCl_2.6H_2O$) (MCHH) is a well-known material in the field of energy storage and therefore well researched as compared to other materials. Thermophysical properties of the selected material are available in the literature and the same will be used during this research. The material is famous amongst the researchers and therefore is well researched. The reason for using this material as a storage medium is the low cost and commercial availability. The properties of the energy storage material after consultation with the literature[5]–[8], are given below;

Table 3-1: Thermophysical properties of MCHH

S. No.	Parameter	Symbol	Value	Unit
1.	Latent heat of PCM	λ	168.6	kJ/kg
2.	Density – Solid	ρ_s	1569	kg/m^3
3.	Thermal Conductivity – Solid	k_s	0.694	W/mC
4.	Thermal Conductivity – Liquid	k_l	0.57	W/mC
5.	Specific Heat – Solid	C_{ps}	1.720	kJ/kgC
6.	Melting Temperature	T_m	117.15	C

Properties given in the above table will be used for the calculations and simulations of the given problem.

3.4 Simulations

In order to analyze the energy storage effect and charging time of the material, a model (Appendix A) was formulated in MATLAB based on the enthalpy formulations derived earlier. After inserting all the required parameters, the simulations were executed, and the following outcomes were observed.

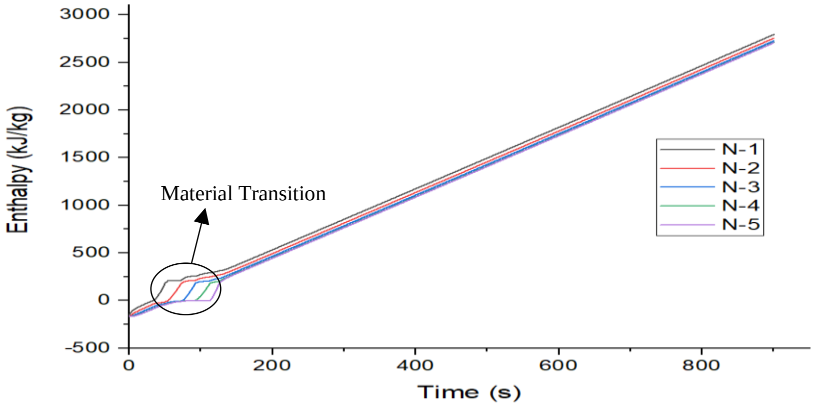

Fig. 3-8: Graph of Enthalpy and Time

The graph shown in figure 8 represents the Enthalpy obtained through simulations and the time. Calculations were carried out by dividing the material into 5 nodes represented by N (1-5). The thermophysical properties and exterior conditions were kept constant. It can be clearly seen from the graph that the material changed its phase during the initial 150s of the simulations. After that the material stored the energy in sensible form. The elaborative graph of the transition phase is shown below;

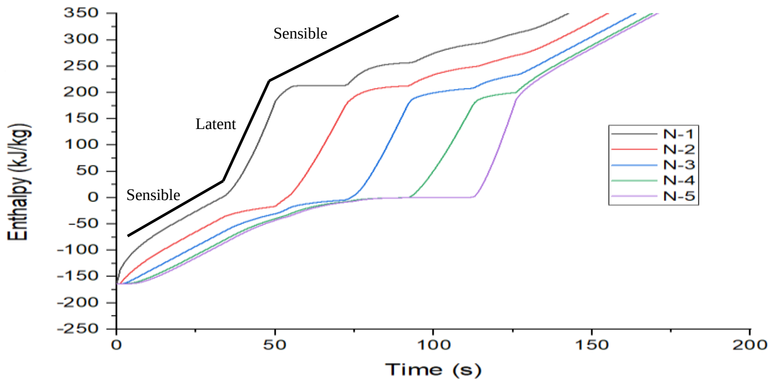

Fig. 3-9: Enthalpy in Transition Phase

The material observed the same trend according to the literature available. The initial part of the energy was stored as sensible, then the second part of the graph represents the energy storage in the latent form and in the last part of the graph the material again stored the energy into sensible form after changing its phase into liquid. As mentioned earlier that the properties in enthalpy formulation mainly depend upon the temperature of the material, therefore similar kind of behavior can be observed in the Temperature plot. The graph is shown below;

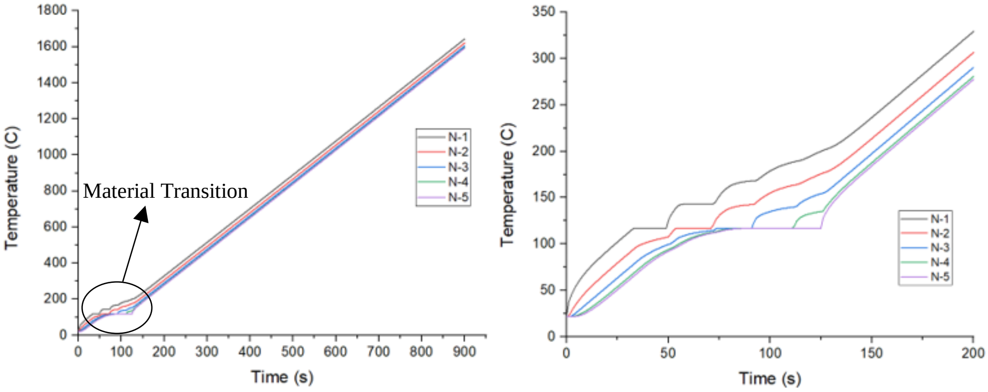

Fig. 3-10: Graph of Temperature and time

The above plots are necessary for understanding the material behavior and it also provides information regarding the material’s behavior with the passage of time against the provided conditions. In the above graphs, it could be observed that the nodes were treated as a discrete entity. The calculations were carried out simultaneously for a single node at a time until the phase transition. The energy is transferred to the next node when the previous node was fully melted. This limitation gave the shape of stairs to the graphs as it progressed through the transition phase. The problem was rectified by Voller in his work [2] and introduced a corrective term for smoothing the plots.

The main interest of the researchers in the simulation is how much energy is stored in the material and how much time is taken to store this amount of energy. The plot of Energy Stored and time is shown below;

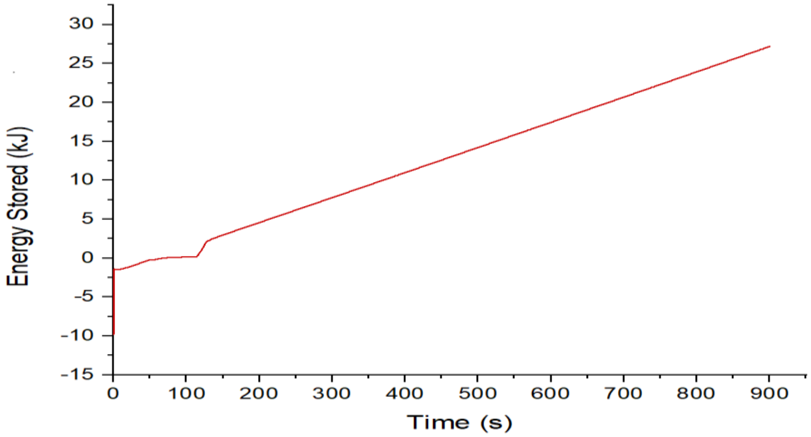

Fig. 3-11: Energy Stored Vs Time

It is evident from the graph above that initial energy was used to overcome the internal bonding of the material. The material started storing energy in sensible form till 100s. After that, a sudden notch could be seen that is a representation of the fusion energy of the material. The material stored approximately 30 kJ of energy as sensible and latent content during the charging phase.

3.5 Fabrication

After getting the result of the simulation, the proposed system was fabricated. A local market survey was carried out to obtain the desired Aluminum pipe and Base plate. The pipe was cut to the size of the cylinder and the base plate was also cut to the dimensions. Because of the ductile properties of Aluminum, normal arc welding cannot be performed for joints. Therefore, the Aluminum welding was done for joining the cylinders onto the base plate and it was made sure that the welded portion should be leak proof so that PCM should not leak out during the phase transition.

Fig. 3-12: The Assembly

The final assembly is shown in the above figure.

3.6 Summary

The chapter discussed in detail the step by step methodology. In the beginning, the mathematical modeling was discussed and enthalpy formulation for the system was developed. The later part discussed the thermophysical properties of the material and detail design discussions were carried out, also mentioning the drawings of the fabricated system and finally the 3-D model of the system was discussed. The MATLAB code based on the formulations was developed and executed and various simulations results were obtained and discussed. The energy stored by the material as per the simulations was shown to be approx. 30 kJ. At the end of the chapter, the fabrication of the system was discussed.

3.7 References

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Chapter 4

Experimentations

The experimental setup consisted of a gas heater, TES system, gas cylinder, data acquisition systems, and connecting pipes. The experimentation was divided into two parts. During the first half, thermophysical properties of the selected material i.e., MCHH were tested. It was necessary to testify the material available in the local market and observe its behavior and compare the same with the literature. The second half consisted of the lab scale testing of TES with heater. In this part, all parts were combined, and the material was filled in the TES system and the system was integrated with the gas heater for experimentations. Details of the experimentations follow.

4.1 Investigation of thermophysical properties

The PCM was purchased from the local market. The initial investigation regarding the thermophysical properties of the material was carried out by the T-History method[1]–[5]. This is a simple method in which the material is subjected to the external energy (heat, electrical) and then the behavior of the material is observed with the variation of the temperature. In this experimentation, a 10g sample of MCHH was tested. The sample was placed in a glass transparent glass tube. The glass tube must be heated from 30 to 150^{o}C, to observe the phase transition of the material. In the literature, the melting point of the material is mentioned at 117.15^{o}C, which is higher than the boiling point of water. For equal heating from all sides, the test tube containing the PCM must be put into a beaker having liquid that can bear temperature more than the melting point of the PCM.

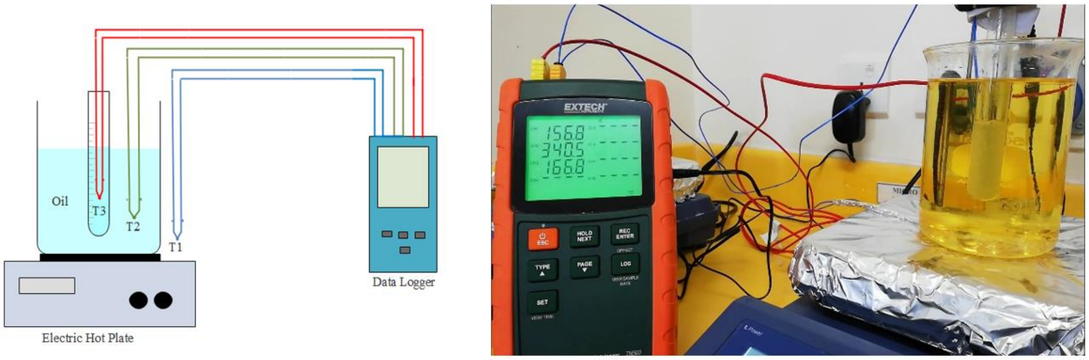

Fig. 4-1: Schematic and experimental setup for Thermophysical properties investigation

Figure 4-1 represents the schematic and actual setup that was set for investigation of the thermophysical properties of the material, specially the melting temperature. As shown in the schematic, three thermocouples were placed for logging the temperature variation during the experiment. T_1 was placed to monitor the temperature of the hot surface on which the beaker was placed. T_2 was placed in the oil (edible), this oil was used to transfer heat to the test tube from all directions and was also used to slow down the heating and cooling to observe the temperature variation and phase transition of the material. T_3 was placed inside the test tube to monitor the temperature variation in the PCM. All the temperature variations were recorded in the portable datalogger for analysis.

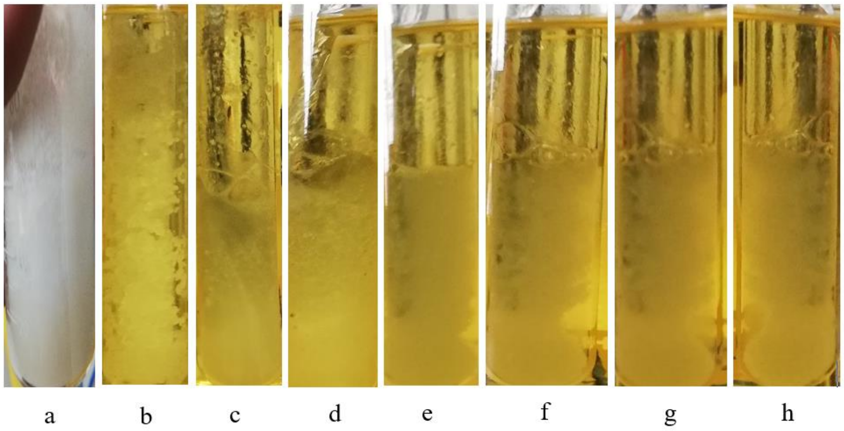

Fig. 4-2: Visual representation of different transition phases of PCM during a thermal cycle

The above figure represents the different phases during the transition of the material from solid to liquid phase in a thermal cycle. At the start of the experiment, the PCM was in a white powder form, shown in figure 2(a). As soon the heating was started, the water molecules associated with the powder got separated and the material transformed into granular shape from powder form, as shown in figure 2(b). Upon further heating, it absorbed the heat in the form of sensible energy till the time it reached its melting temperature and as soon as it reached its melting point the phase transition began, which is shown in figure 2(c, d). Upon further heating the material further absorbed the energy and starts boiling, as in figure 2(d-h) bubbles on the surface of the material can be seen.

The other phenomenon that was visually observed, was phase segregation. As it is mentioned in the literature [6]–[9] that in hydrate salts, phase segregation is a normal phenomenon. Because of repeated thermal cycles, the material undergoes various transitions in the liquid and solid phases. During solidification, the material that solidifies earlier sit in the bottom leaving the moisture above and at the end the liquid (water) above the surface of the salt can be seen clearly.

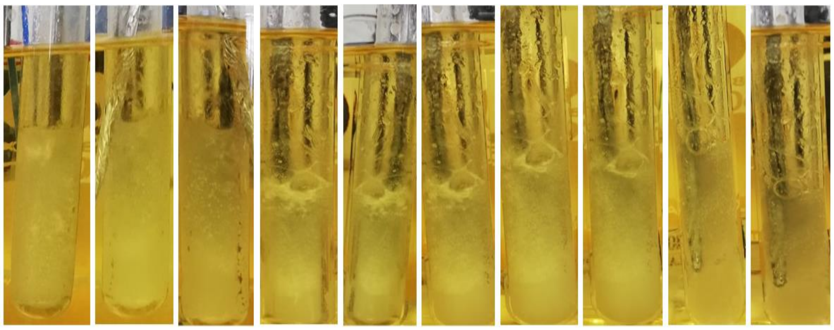

Fig. 4-3: Visual representation of Phase Segregation

The figure above contains the visual representation of the phase segregation. It is obvious that the bottom of the test tube possesses a high quantity of the salt while on the top surface the diluted solution containing a larger amount of water is present. The researchers provided the solution to avoid such abnormality by the addition of a nucleating agent or by constant stirring during the solidification process or having a micro encapsulation of the material not giving too much room to separate from each other.

The temperature range of 20 -160°C was selected because the melting temperature of the material is 117.15°C. The mentioned temperature range will cover all the phases of the material in a complete thermal cycle. A complete thermal cycle of the material is shown below;

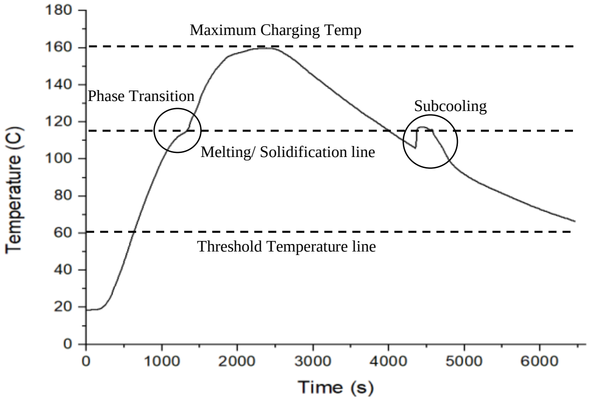

Fig. 4-4: Complete thermal cycle of PCM

The graph shows all the important factors of a thermal cycle. A 10g sample of MCHH ($MgCl_2.6H_2O$) was heated on an electric plate from 20-160°C and then let it cool till 60°C. It can be observed from the graph that the material started storing heat in sensible form from 20 - 115^{o}C and started phase change at about 116^{o}C till 118^{o}C after 22 minutes of heating, as indicated by the circle on the graph. The material was charged maximum till 160^{o}C. It attained a maximum temperature in 36 minutes. After achieving maximum temperature, the material was cooled down gradually till 60^{o}C (threshold temperature). Time taken during discharging was 72 minutes. During discharging supercooling was observed, which is indicated on the graph, the temperature dropped down till 100^{o}C before material started forming into crystal form. Following observations were made during this experiment;

a. The melting temperature of the material was observed between 116-118^{o}C.
b. Phase segregation was observed during multiple thermal cycles. Fig. 3 refers to the same.
c. A slight shift in thermal properties was observed with multiple thermal cycles because of the physical changes occurred during the previous thermal cycles. In the figure below this phenomenon can be observed.

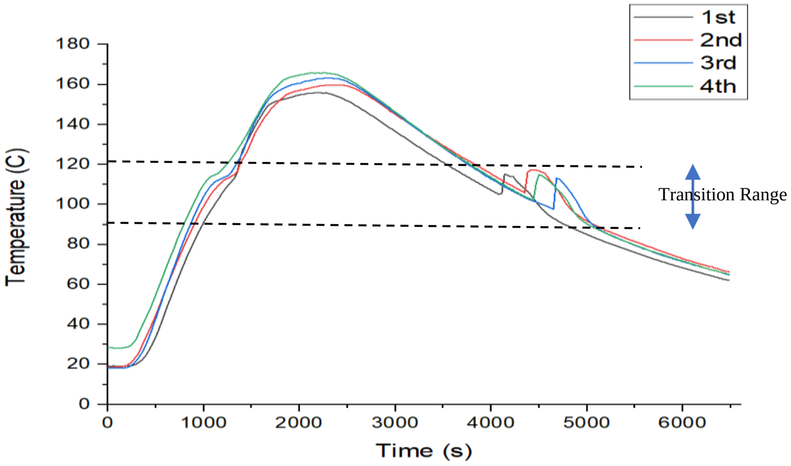

Fig. 4-5: Comparison of Multiple Thermal Cycles

d. Subcooling was observed during solidification. The temperature dropped down till 100^{o}C when crystals formation started.

With these experiments, the thermophysical properties of MCHH were confirmed practically and verified through literature for further application in this research. After confirming the properties, the next phase of the experimentations was started, in which the integration of the TES system was done with a domestic gas heater.

4.2 Integration of TES with a gas heater

After an initial investigation of the thermophysical properties of the material, the designed system was integrated with the gas heater for experimentations. The schematic of the system is shown below;

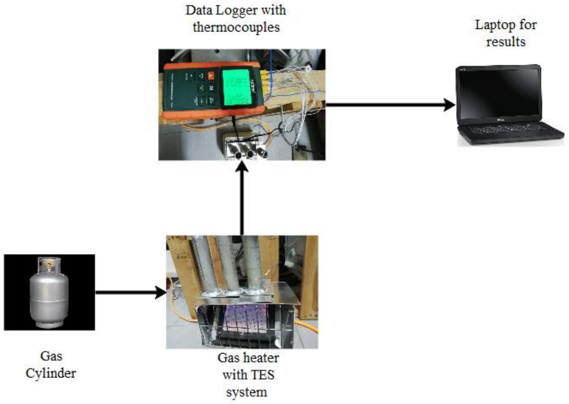

Fig. 4-6: Schematic of the Experimental Setup

The cylinder contained the propane usually available in the local market, the gas will be used in heater as combustion material, the TES system was placed above heater where it was directly in contact with the flame of the heater. Thermocouples placed in the system for temperature monitoring at different locations were connected to the portable data logger. The data logger can connect a maximum of 12 thermocouples at a time. Data logging through the data logger was carried out with a time step of 5 seconds. The data was recorded in the SD card inserted in the data logger. The data recorded was then taken out of the card in a worksheet and analysis of the same was carried out at the computer through analysis software.

The important thing in the experimentation is the instrumentation. The sensors should be placed from where the data can be recorded easily and accurately. Moreover, the sensors should monitor the critical happenings within the system. In this experiment, the cylinder is the most important component as it is containing the PCM and needed to be monitored with great precision. Therefore, a total of 8 thermocouples were placed, 4 inside of the cylinder, dipped in the material to monitor the material temperature as it was changing with the time, 4 outside of the cylinder to monitor the outer surface temperature of the cylinder. The thermocouples were placed at 1 inch from each other. Thermocouples used were of “K” type, bead-shaped with a tolerance of ± 1^{o}C. The arrangement of thermocouples is shown below;

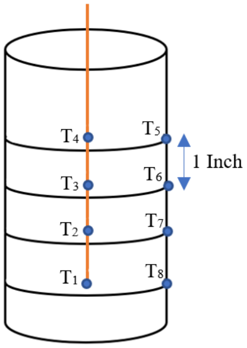

Fig. 4-7: Schematic of the thermocouples attached along the cylinder

Fig. 4-8: Thermocouples stacked for monitoring the inside temperature of the cylinder (centerline)

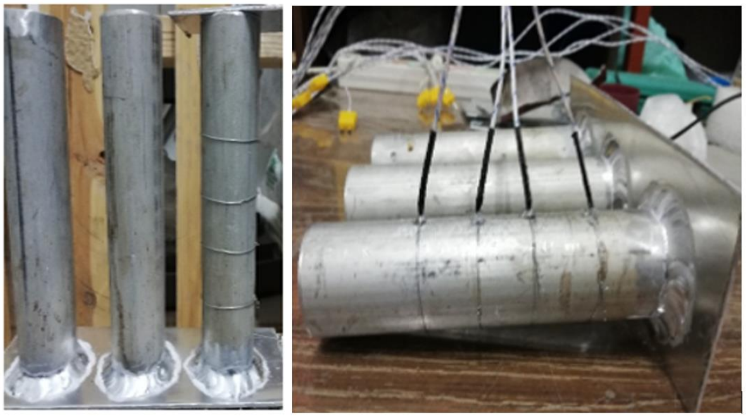

Fig. 4-9: Thermocouples placed at the outer surface of the cylinder for observing the heat transfer rate during charging and discharging phases

Figures 4-7 to 4-9 shows the placement of thermocouples along the cylinder. Few other thermocouples were placed, one on the base plate to observe the temperature that the flame is providing to the bottom of the cylinder. The other one was placed to observe the ambient temperature of the room. Both thermocouples were of “K” type, surface-shaped thermocouples. Description of thermocouples is given in table 1 below;

Table 4-1: Thermocouples descriptions with position

S No.	Description	Type	Notation
1.	Thermocouple 1 (1” above the bottom surface of the cylinder from inside)	K	T_1
2.	Thermocouple 2 (2” above the bottom surface of the cylinder from inside	K	T_2
3.	Thermocouple 3 (3” above the bottom surface of the cylinder from inside)	K	T_3
4.	Thermocouple 4 (4” above the bottom surface of the cylinder from inside)	K	T_4
5.	Thermocouple 5 (4” above the bottom surface of the cylinder from outside)	K	T_5
6.	Thermocouple 6 (3” above the bottom surface of the cylinder from outside)	K	T_6
7.	Thermocouple 7 (2” above the bottom surface of the cylinder from outside)	K	T_7
8.	Thermocouple 8 (1” above the bottom surface of the cylinder from outside)	K	T_8
9.	Thermocouple 10 (For measurement of ambient temperature)	K	T_{10}
10.	Thermocouple 12 (For measurement of surface temperature)	K	T_{12}

After the installation of the thermocouples, the system was put together for testing. A sample of 60g in wright of MCHH was put into one cylinder and the system was placed above the heater, as shown in the figure below;

Fig. 4-10: Experimentation in Progress

After placing the sample, the heater was turned **ON**. As soon the material started heating up the values of thermocouples in the data logger. These cycles were repeatedly many times to obtain data and check the consistency of the experimentations.

4.3 Summary

In this chapter, the experimentation phase of the research was discussed. In the beginning, the verification of the thermophysical properties of MCHH was carried out through the T-History method. The experimental setup was discussed in detail. The instrumentations of the cylinder for monitoring different parameters were discussed and finally, the integration of the TES system with the gas heater was carried out. 60g of MCHH was tested for energy storage and results will be discussed in the coming chapters.

4.4 References

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Chapter 5

Results and Discussions

The data stored in the SD card was divided into data sets and then analyzed for the material’s capacity to store thermal energy. MS Excel and Origin were used for data analysis. The analysis of the system was divided into two portions i.e., *charging and discharging* cycles. At present only energy content stored in the system and heat transfer rates with temperature were analyzed. The first charging cycle will be discussed.

5.1 Charging cycle

Before starting the experimentations, it will be beneficial to describe the initial conditions. Here the most relevant initial conditions are time and temperature. The initial temperature of the PCM was 20^{o}C, the surface temperature on which the cylinders were welded was 24^{o}C and the ambient temperature of the room was 17^{o}C. The thermal cycle was started with these initial conditions. After 300s the temperature of the lower thermocouple (T4) reached 100^{o}C. The material at the bottom of the cylinder reached its melting point in 465s. After the melting started at T4, the temperature of the material rose quickly. Within the next 300s, the average temperature of the material was 120^{o}C, which is higher than the melting point of the material. Melting of the rest of the material took place in the 300s. The final average temperature of the material reached to 204^{o}C after 855s. Following graph represents the temperature against the time during the charging cycle:

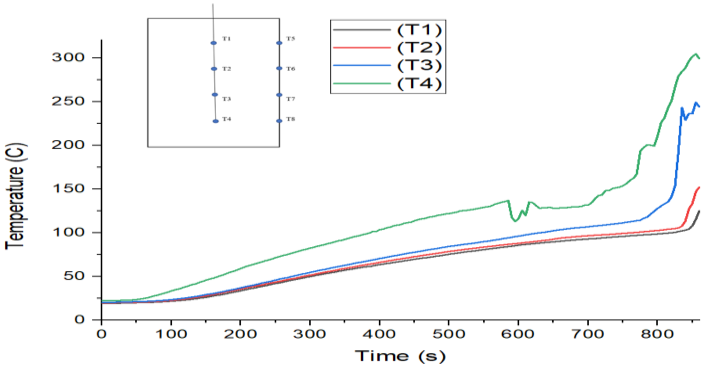

Fig. 5-1: Graphical representation of the charging phase

This data was acquired from the inner thermocouples placed inside the cylinder. The temperature of the thermocouple T_4 being the closest to the bottom started rising as the bottom of the cylinder encountered the flame. Till 550s, the material stored the energy in sensible form and the line shows the temperature rise with a constant rate. After 550s, a sudden drop in the temperature line of T_4 is observed, this is the indication of the internal movement of the material, as material at the bottom of the cylinder started melting and solid material above the melted material, because of higher density and low temperature, took place of melted material. Hence the temperature dropped suddenly. The trend continued until the whole material was melted. Because of this phenomenon, the line of thermocouple 4 (T_4) shows an irregular rise. If the rest of the thermocouples are compared with thermocouple T_4, it can be observed that other lines show a smooth trend during the temperature rise. This is because most of the material was melted in the bottom part of the cylinder which was measured by thermocouple 4 and hence maximum disturbance was observed in that part. It could also be deduced that most of the material transition took place in the bottom of the cylinder as shown by the temperature line and on the upper portion of the cylinder the material behavior was observed relatively constant. The total energy stored by the material was calculated by the following equation

$$Q \;=\; mC_{p_s}(T_m - T_i) + m\lambda \;+\; mC_{p_l}\left(T_f - T_m\right)$$

The total energy content stored in one cylinder during the charging phase of the thermal cycle was calculated to be 29.10 kJ that can cater to a total thermal load of .0081 kWh or it can provide 8.1 W of thermal energy to a load for 0.486s. This is the energy that can be stored in 60g of MCHH.

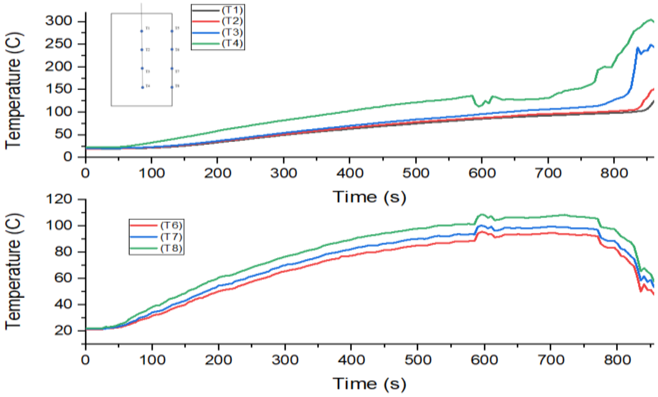

Fig. 5-2: Comparison of internal and external temperatures during the charging phase

The figure above shows the comparison of internal and external thermocouples of the cylinder. External thermocouples also show the variation in the reading during the transition period of the material in the form of a hump. These are shown because of the energy released by the moisture present in the material as it changed the phase into vapors from the liquid. The extra energy was discharged to the environment. Overall temperature rise is smooth in external thermocouples. Energy content variation with respect to time can be observed in the graph below;

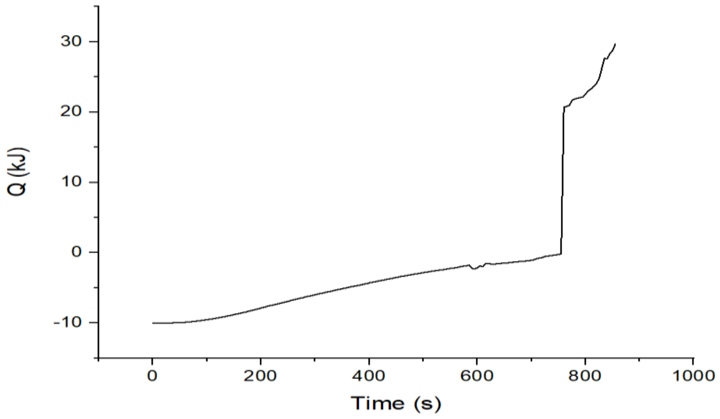

Fig. 5-3: Energy content stored with time

This graph shows that at the start of the process the energy was used to overcome the internal bonding of the material and that energy was stored in the form of sensible energy. When the material absorbed energy equivalent to its bonding energy it immediately started melting down and started storing energy in the latent form shown by the nearly vertical line of the graph. After storing the entire latent energy, material again started storing the rest of the energy in sensible form.

Fig. 5-4 shows the comparison of simulated and experimental results. In simulation, the effect of internal convection of the material was neglected due to which the material melted in initial stages and stored the rest of the energy in sensible form after 100s, while in experiment, due to internal convection the complete transition took place after 700s and then material was melted completely and then stored the rest of the energy in sensible form.

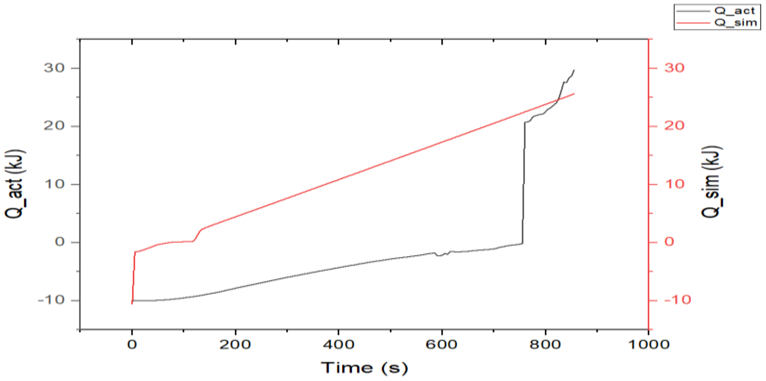

Fig. 5-4: Comparison of simulated and experimental results

At the outer surface of the cylinder, the heat transfer rates were calculated based on natural convection. Thermocouples 6,7 and 8 measured the external surface temperatures. The heat transfer rate was calculated and plotted against time; the graph is given below;

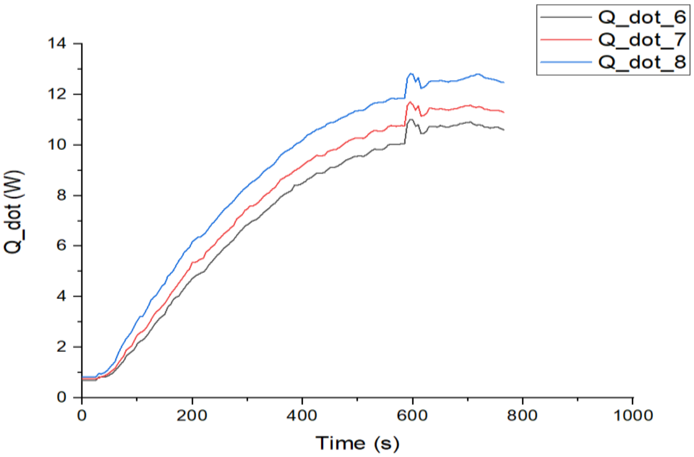

Fig. 5-5: Heat transfer rate during the charging phase

The trend of heat transfer rate is the same as the external temperature because of its dependence on temperature. The hump in the line shows that the phase transition of the material started at about 600s. Maximum heat transfer can be seen at a one-inch height from the bottom which is approximately 13W.

5.2 Discharging Cycle

During the discharging cycle, the heat was released through natural convection and in the radial direction. The outer surface of the cylinder was not insulated, so the heat transfer took place from the surface of the cylinder. The total energy that the material was able to absorb was 29.1 kJ and now the same was to be discharged.

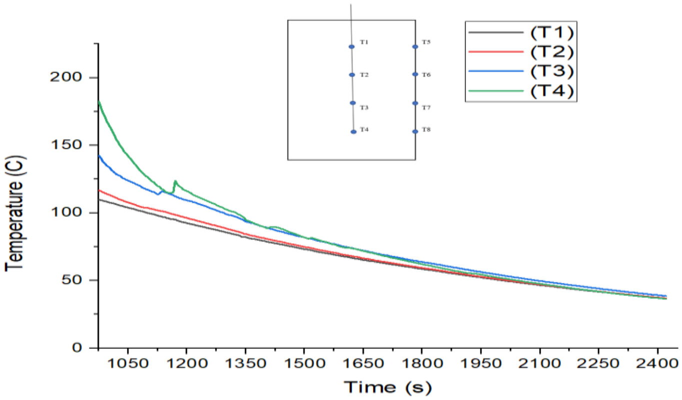

Fig. 5-6: Graphical representation of Discharging Cycle

The above graph represents the discharging cycle. These temperature lines are of inner thermocouples. The same trend can be observed while discharging that most of the transition of the material took place on the bottom side of the cylinder therefore, some disturbance in thermocouple 4 and 3 is observed. On the other hand, thermocouple 1 and 2 lines are smooth during discharging as well. The phenomenon of supercooling can also be observed clearly on thermocouple 4 line and some can also be seen on the thermocouple 3 line. All temperature lines converged at 60°C which was set as the threshold temperature because beyond this temperature the heat transfer rate will be minimum. The time taken by the material to reach this temperature by emitting all the heat stored was approximately 23 minutes. Comparison of external and internal thermocouples during discharging is shown below;

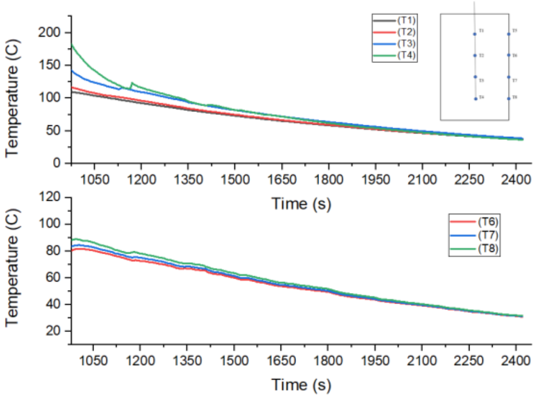

Fig. 5-7: Comparison of internal and external temperatures during the discharging phase

The same trend can be observed in the internal and external sides of the cylinder. The only difference is the difference in temperature values. The reason behind the lower temperature values is the low thermal conductivity of the material due to which the temperature inside of the cylinder is not conducted very efficiently to the surface of the cylinder.

The figure 5-8 shows that how the energy content stored was released during the discharging phase. It is evident from the graph that when the discharging phase started the energy was released in sensible form and it started releasing energy in latent form when the material reached its solidus temperature. After releasing the latent content of energy stored it again started to release sensible energy until the material becomes fully solid. The system can provide effective thermal energy till the threshold temperature of 60^{o}C after that the temperature difference becomes small for heat transfer and hence the rest of the energy cannot be utilized effectively until some heat transfer enhancement measures are taken for the same.

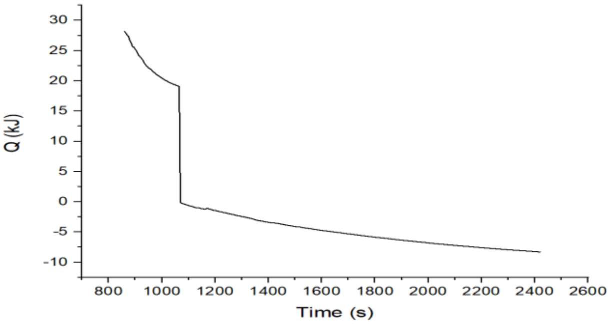

Fig. 5-8: Energy content variation with time during the discharging cycle

The heat transfer lines again observed the same trend as the surface temperature. Maximum of 10W heat transfer rate was observed during the discharging cycle that can also be seen in the graph below;

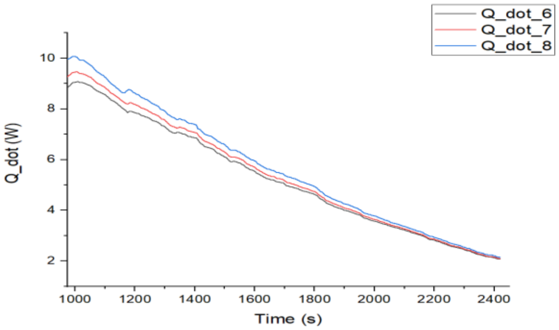

Fig. 5-9: Heat transfer during the discharging cycle

Heat transfer rate decreased from 10W to 2W in 25 minutes with a constant slope. It shows that the rate of heat transfer observed a linear trend during discharging.

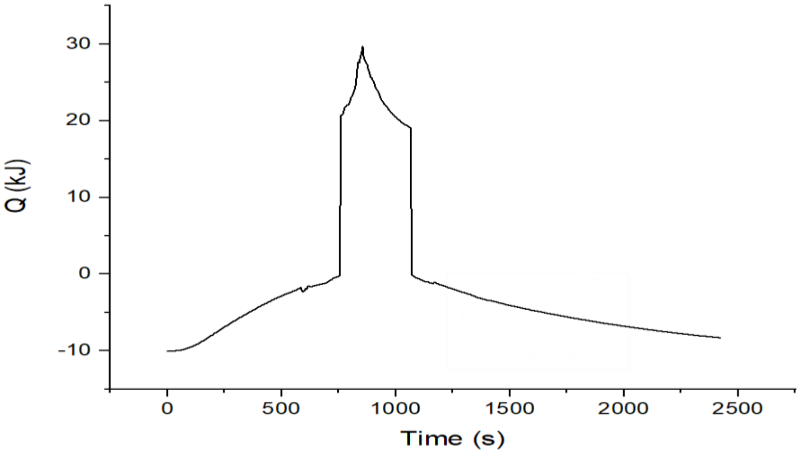

Fig. 5- 10: Energy content variation in the whole thermal cycle

The figure above shows the energy content variation in the complete thermal cycle. The peak of the graph represents the latent and post latent sensible content of the material. It can also be observed that the material has the capacity to increase the discharge time by 46%.

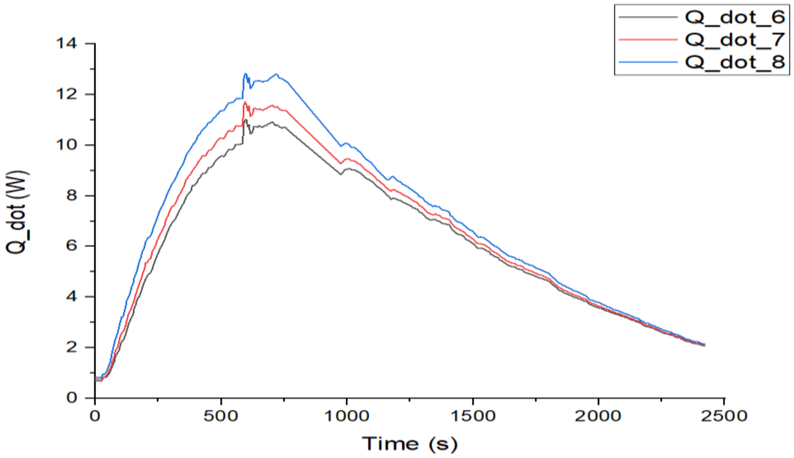

Fig. 5-11: Rate of heat transfer during the complete thermal cycle

The above figure represents the rate of heat transfer during the entire thermal cycle. The same observation can also be drawn from this graph that the material supplied heat for more time after it charged during the first phase of charging.

5.3 Summary

This chapter mainly consisted of the experimental results and detailed discussions about the results. At the start, the initial conditions of the experiment were described. Initial conditions have great importance in moving boundary problems. After describing the initial conditions, the discussion about the experiments was started. Mainly the experiments were divided into two phases i.e., *Charging* and *Dis-charging* phases. Mainly variations with temperature, energy content storage and heat transfer rates were explained with the help of graphical support. The total time taken during the charging phase to reach the MCHH to a temperature of 204^{o}C was 855s. The material stored about 30kJ of energy. During the dis-charging phase, the material was discharged until the threshold temperature of 60^{o}C and the outcome shows that the discharge time was increased by 46%.

Chapter 6

Conclusions & Recommendations

This study was based on the experimental investigation of using the Magnesium Chloride Hexahydrate based TES system with a domestic gas heater for storing the excessive energy discharged in the environment during the heating process. The concept of using a TES system with the domestic gas heater was a novel concept and was aimed to determine the effectiveness of a TES system if used with heater as an energy storage device. The experiments were also carried out to determine the heating time enhancement by the addition of the TES system.

6.1 Findings

In this part of the chapter, the findings of the experimentations will be discussed. These findings will be classified as material, the system, outcome etc.

6.1.1 Material properties

Before starting the experimentations, the material used in the TES as energy storage material was tested experimentally to ascertain the thermophysical properties of the material listed in the literature. The material used was Magnesium Chloride Hexahydrate ($MgCl_2.6H_2O$). The literature mentioned the melting temperature of 117.15^oC. The same was validated with the T-history method. 10g of the material was put into a test tube and heated in an oil bath up to 160^oC to observe the melting temperature and behavior of the material. The findings related to the material can be enlisted as follows;

a) The findings revealed that the material transformed from solid to liquid in the temperature range of 116 to 118^oC. This range can be called the melting range and the solidus range as the material solidifies in the same range.

b) The phenomenon of subcooling also called the supercooling was observed during the solidification of the material. The phenomenon of subcooling can be described as the material property of solidification after crossing its solidus temperature and once the solidification starts the temperature jumps back to its solidus temperature. The same was observed during material testing. During solidification, the material temperature dropped down from its solidus temperature of 117.15^{o}C to 105.80^{o}C, when the material starts solidification. Subcooling of about 11.35^{o}C can be observed in the graph shown below;

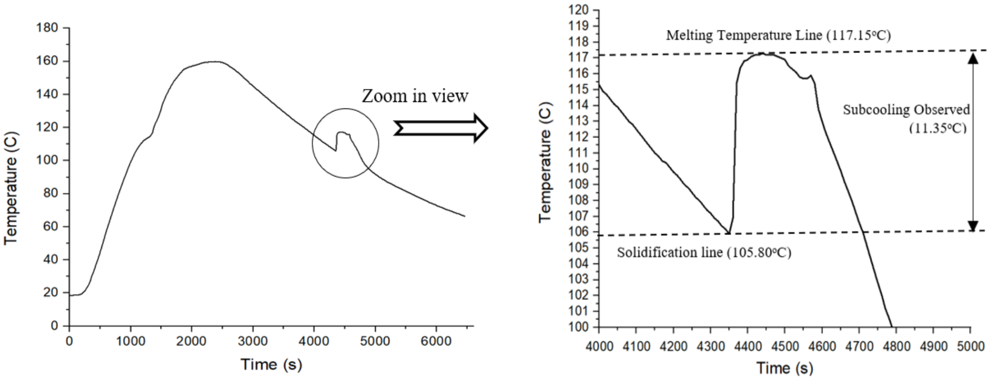

Fig. 6-1: Subcooling observed during experimentation

c) Another phenomenon observed during the thermal cycles of the material that while performing multiple thermal cycles, phase segregation of the material was observed which effects the thermophysical properties for the next thermal cycles. The same was observed when multiple thermal cycles were plotted together. The phase segregation was physically observed by capturing the photographs during melting and solidification processes, shown in the previous chapter 4.

6.1.2 The TES system

The system used for integration with the domestic gas heater was based on the Aluminum material. The material of cylinders was chosen carefully keeping in view the inorganic material that was to be used for energy storage. In literature, it is mentioned that inorganic materials are prone to cause corrosion to the encapsulation. In all the available commercially viable materials the Aluminum was put on top to be used as inorganic pcm encapsulation material. The system was shaped in the round to avoid sharp bends. During multiple thermal cycles, the expansion and contraction of the material along with the material are devastating for sharp edges as they are weak and tend to leak during multiple thermal cycles. Moreover, the top of the material was kept open for observing the material behavior and to avoid pressurizing the cylinders from the escaping moisture contained within the material.

This system was a direct contact system, means that the base of the system was directly in contact with the source and there was no HTF involved for heat transfer to and from the material. The important finding in the system instrumentation was observed that the sensors should be placed after proper testing before attaching it to the system. A faulty sensor can ruin the whole experiment. Another important aspect of the instrumentation is to place the sensors where they are most required. The critical places can be nominated by the observation required to be recorded. As in our experiments, the behavior of the material was important to be observed as most of the properties were related to material temperature. Therefore, most of the thermocouples were installed such that the material temperature at different points can be monitored and stored. The attachment of the sensors should be done with great care so that the temperature stored should not contain any false value.

It is important to consider that the sensors should only monitor the desired value and not false values. Consider if the sensor inside the cylinder is touching the cylinder wall, it will not give you the temperature of the material contained in the cylinder, rather it will give the temperature of the cylinder wall. It is therefore, important to keep in mind to set the sensors with precision.

Another critical aspect of the experimentation is the conditions in which the experimentations are carried out. Changing conditions will affect experimental outcomes. It is important that during one complete cycle the conditions should be maintained otherwise the properties on which external conditions affect will give false value. Say if the ambient temperature or other convection properties are changed it will directly affect the rate of heat transfer from the cylinder. Similarly, the changing flux can affect the charging time of the material.

6.1.3 Outcomes of the experimentations

The useful data that is recorded during the experimentations are the basic outcome of the experimentations. Based on the data, certain analysis techniques are adopted to analyze the data and quantify the outcomes in terms of efficiency or another tangible outcome. In these experiments, the outcomes were analyzed by MS Excel and Origin. The further analysis depends on the parameters that are to be determined. The aim of these experiments was to determine the material storage capacity, the heat transfer during the experiments and the charging and discharging time of the material. Relevant formulations were determined for certain outcomes discussed in chapter 2 and chapter 5. By application of these formulations, tangible outcomes were plotted with time. These graphs were discussed in detail in chapter 5. In short, the tangible outcomes can be enlisted as follows;

a) 60g of MCHH can store approx. 30kJ of thermal energy.

b) Material thermophysical properties were analyzed and validated with experiments. The melting point/ solidus temperature range was 116-118^oC. Phase segregation was physically observed during multiple thermal cycles. Subcooling of 11.35^oC was observed during discharging. Time taken to completely melt the 60g of the material was 855s (14.25mins) and the average temperature of the material raised up to 204^oC.

c) The energy stored in 60g of the material can supply thermal energy of .0081 kWh.

d) The heat transfer rate during the charging phase was 13W from the outer surface of the cylinder.

e) During the discharging phase, natural convection was used to release the stored energy to the environment. The threshold temperature was set as 60^oC.

f) Time taken to release the stored energy to reach the threshold temperature was 23mins

g) The maximum heat transfer rate observed during discharging was 10W. The material took 25mins in reducing the rate from 10W to 2W.

h) The discharge time was 46% more than the charging time. This can be utilized during the absence of the thermal source.

i) Keeping in view the complete thermal cycle it can be deduced if the system must provide 1kW of thermal load for 3hrs then the system must store 10800kJ of thermal energy. Presently 3 cylinders of the system can contain 180g of material and this can store up to 87.3kJ, which is equivalent to 24.25W. To store 20,000 kJ of thermal energy, 42 kg of the material is required which will cost about PKR 63,000. The encapsulation cost will be surplus to that.

6.2 Concluding remarks

The experiments showed the potential for using the TES system with a domestic gas heater. As the surplus energy can be stored in the PCMs as latent form. The same can be extracted afterwards. The material used in the experimentations is a good contestant for thermal energy storage and supported by the literature, but it also has some technicalities that are not simple for domestic users. The system proposed in this work did not contain any safety as it was a lab scale system but for a proper commercial system, all safeties must be incorporated if the same material will be used as storage material. MCHH is used in CSP in abundance as storage material. The observation made in these experiments showed that the material exhibits uncontrolled heating after melting which is a negative phenomenon for a small system that is to be used for domestic purposes.

The other drawback of the system is, to store thermal energy for a longer period will require more material and with an increase in material quantity, the dimensions of the cylinders must be increased. An increase in cylinder size will be a difficult task as the system is to be placed in the room and the space inside a living room is limited.

Viewing the outcomes of the experimentations, the system is not recommended for the domestic user. There are multiple reasons mentioned in the above lines. The system should be safe for use and health also. Though the potential of the storage is there.

6.3 Recommendations

It is evident from the fact that using natural gas in heaters for thermal comfort is not an efficient way of achieving thermal comfort. This can be seen by the graph shown below;

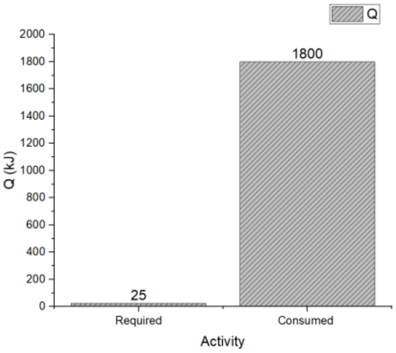

Fig. 6-2: Comparison of energy consumed for thermal comfort

In the above graph, the energy required for getting the required comfort temperature is far less than the energy consumed for the same purpose. This directly affects the energy mix of the country because gas heaters are common among people in achieving thermal comfort during winters. This phenomenon causes temporary gas shortage during the season and the gas remains unavailable for much needed processes like industrial heating and domestic cooking etc.

Moreover, combustion within the room produces certain toxic elements and destroy the indoor air quality. Indoor combustions raise the levels of particles that are standardized by the WHO for better indoor air quality. These standards were reviewed by S. Ahmed Abdul-Wahab et al[1] and are listed in the table below;

Table 6-1: Standards for different particles for Indoor Air Quality

Particle	**Value**	**Organization**	**Region**
CO	90 ppm as 15-min avg 50 ppm as 30-min avg 25 ppm as 1-hr avg 10 ppm as 8-hr avg	WHO	Worldwide*
CO_2	1000 ppm	WHO	Worldwide*
HCHO	0.081 ppm (100µg/m^3) as 30-min avg	WHO	Worldwide*
NO_2	0.1 ppm (200µg/m^3) as 1-hr avg 0.02 ppm (40µg/m^3) as 1-yr avg	WHO	Worldwide*
O_3	0.064 ppm (0.120 mg/m^3) as 8-hr avg 0.05 ppm (Max level)	WHO	Worldwide*
SO_2	0.19 ppm as 10-min avg 0.133 ppm as 1-hr avg 0.048 ppm as 24-hr avg 0.012 ppm as 1-yr avg	WHO	Worldwide*

*- If specific standards for specific regions are available then those are to be consulted.

These are some critical parameters that are to be considered for indoor air quality. The process normally used for getting thermal comfort in Pakistan is by burning the natural gas supplied as a commodity and in rural areas people use coal for getting the same output. Both methods are in-efficient and dangerous for health. Many incidents of suffocation are reported due to these methods. Some alternate methods can be used for the replacement of the normally used processes.

6.3.1 Geothermal Heating/ Cooling

This process can be used for both heating and cooling purposes. The temperature below the surface is normally stable as compared to the surface where certain external effects cause the variation in the temperature like wind, sun rays etc. Therefore, this system can perform in both kinds of weather. It should be considered that any sustainable or renewable system cannot completely replace the convectional heating or cooling system, but it can help in the reduction of the heating or cooling loads which will ultimately reduce the usage of the conventional systems and hence reduce the emissions at the same time.

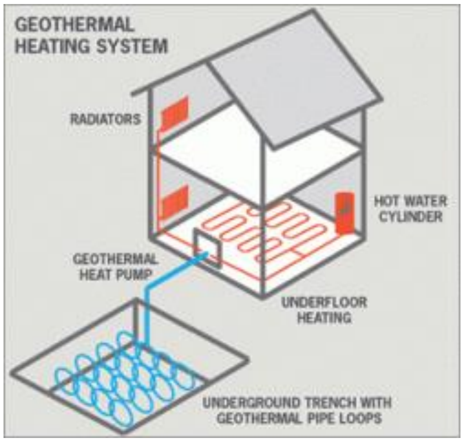

Fig. 6-3: Schematic of Geothermal heating/ cooling system [2]

These systems are best suited for extreme temperature variation regions. Regions with moderate temperature variation can use the normal heat pump systems.

6.3.2 Community based centralized heating

This system is also effective for heating applications. The concept works on the basis of a small grid. The heating source is constructed at a specified place within the community. Heating is carried out by any method e.g., conventional or non-conventional. Then the heat is supplied to the units associated with this source with the help of a heat transfer fluid, which can be any suitable fluid.

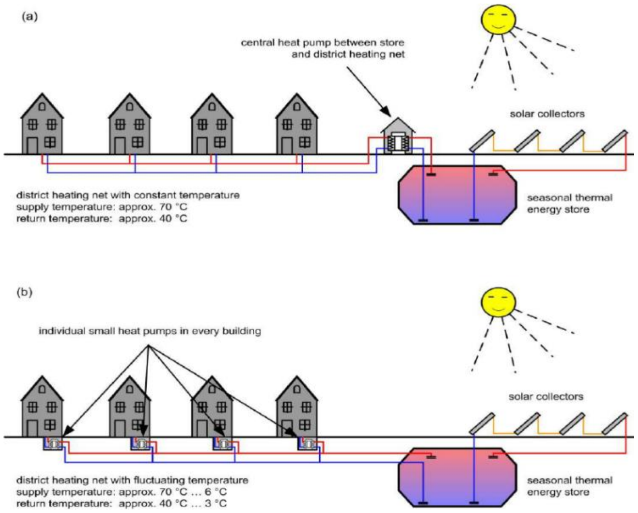

Fig. 6-4: District heating with different configurations [3]

The system shown in the above figure uses solar thermal energy for heating purposes. The stored energy is supplied to the connecting units through heat pumps and pipelines. There are two configurations of heat supply. In one configuration the single heat pump is placed right after the source and this pump supply the hot fluid to the connected unit. In other configuration, separate heat pumps are installed for each unit to supply the demand of a specific unit as required. This system gives the flexibility of changing the installed technology with an almost negligible effect on the connected units.

6.3.3 Solar thermal heating system

These systems can be called the off-grid independent systems because they are not completely connected to the external sources. The schematic of the same is shown in the figure below;

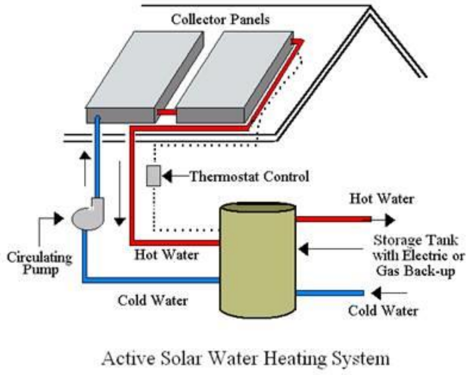

Fig. 6- 5: Schematic of Solar thermal heating system [4]

This is the simple schematic of the system using solar energy for heating the water which can be used for space heating or hot showers. Thermal collectors are installed on the rooftop and the rest of the system is installed within the house. The system works independently till the time the sun is shining on the sky.

It can be observed that all the systems mentioned in the recommendations as the replacement of the conventional heating systems used for heating can be integrated with a thermal energy storage unit to enhance their capacity and increase the utility of sustainable sources like sun etc. By adopting these systems, the load on our energy mix reduce at large. Because most of the natural gas is consumed for heating, converting high-quality energy (Gas) into low grade energy (Heat), the same energy can be used in other high temperature applications like electricity generation or industrial heating applications. It is the responsibility of policy makers to make a policy focused on the issue discussed in this chapter.

6.4 Summary

In this chapter, the conclusions of the experiments were discussed. In the beginning, the findings of the experiments divided into headings of material, system and outcomes were discussed. Outcomes were listed down for ease of understanding. In the next portion of the chapter, the recommendations of the alternative systems were discussed. Some important issues like indoor air quality and particle limitations were discussed. The table containing the limits for different parameters was discussed. The conventional system is not recommended as it contains the health issues by combustion of natural gas inside the room.

6.5 References

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Appendix A

```
clear all
clc
%% Dimensions of PCM Cylinder in Axial Direction
h = ;%Height of the cylinder (m)
d = ;%Dia of the cylinder (m)
r = d/2; % radius of the cylinder (m)
Vol_pcm= pi*r^2*h; % Volume of PCM cylinder (m3)


%% Properties of PCM
L_pc= 168.6;%Latent heat of PCM (kJ/kg)
rho_Pc_s= 1569;%Density of PCM_solid (kg/m3)
L_pc1=rho_Pc_s*L_pc;%Latent heat (kJ/m3)
k_pc_s=0.694;%Thermal conductivity of PCM solid phase(W/mK)
k_pc_l = 0.57; % Thermal conductivity of PCM liquid phase (W/mK)
C_pc_s= 1.720;%Specif heat capacity of PCM solid phase(kJ/(kg-C))
alpha_pc_s=k_pc_s/(rho_Pc_s*C_pc_s);
Tm=117.15;%Melting point temperature of PCM (C)
T_ini=22; % Initial Temperature (C)
q_0 = 600; % Constant heat flux (W/m2)
h_air = 10; % Heat Transfer Coefficient of air (kJ/kg.C)
T_amb = 15; % Ambient Temperature (C)
T_f = 600; % Flame Temperature (c)
m = .06; %mass (kg)
%m = rho_Pc_s*Vol_pcm; % mass (kg)
%% Formulation of heat transfer
dy_pcm=0.03; % Delta y (m)
y=0:dy_pcm:h;
dt=1;%time for measurment (s)
t=0:dt:(900);
n=length(t);
my_pcm=length(y);
eta=dt/dy_pcm^2;
r_1=eta*alpha_pc_s;
%% Condition
if r_1>0.5
error('value of "r_1" needs to be checked')
end
%% Calculations
H_pcm=(C_pc_s*(T_ini-Tm))*(ones(n,my_pcm));
T_pcm=(T_ini)*(ones(n,my_pcm));
LF=zeros(n,my_pcm);
Q = m*H_pcm;
%Q =(C_pc_s*T_ini)*(ones(n,my_pcm));
```

```
for i=2:1:n
   for j=2:1:my_pcm
      if j==2
      H_pcm(i,j)=H_pcm(i-1,j)+(2*k_pc_s*eta/rho_Pc_s)*(T_pcm(i-1,j+1)-T_pcm(i-
1,j))+ q_0*2*dt/(rho_Pc_s*dy_pcm);
      elseif j>2 && j<my_pcm
         H_pcm(i,j)=H_pcm(i-1,j)+(k_pc_s*eta/rho_Pc_s)*(T_pcm(i-1,j-1)-2*T_pcm(i-
1,j)+T_pcm(i-1,j+1));
      elseif j==my_pcm
          H_pcm(i,j)=H_pcm(i-1,j)+(2*k_pc_s*eta/rho_Pc_s)*(T_pcm(i-1,j-1)-T_pcm(i-
1,j))+(2*h_air*dt/rho_Pc_s*dy_pcm)*(T_pcm(i-1,j)-T_amb);
      end
      if H_pcm(i,j)<0
        T_pcm(i,j)=Tm+H_pcm(i,j)/(C_pc_s);
      elseif H_pcm(i,j)>L_pc
         T_pcm(i,j)=Tm+((H_pcm(i,j)-L_pc)/C_pc_s);
      else
          T_pcm(i,j)=Tm;
      end
      if H_pcm(i,j)<0
          LF(i,j) = 0;
      elseif H_pcm(i,j)>0 && H_pcm(i,j)< L_pc
          LF (i,j) = H_pcm(i,j)/L_pc;
      elseif H_pcm(i,j)>0
          LF (i,j) = 1;
      end
     %  if T_pcm(i,j)<Tm
     %     Q(i,j) = m*C_pc_s*(Tm-T_pcm(i,j));
     %  else
     %     Q(i,j) = m*C_pc_s*(Tm-T_pcm(i,j))+m*L_pc+m*C_pc_s*(T_f-Tm);
     % end
          Q(i,j) = m*[H_pcm(i,j)-H_pcm(i-1,j-1)];
   end

end
T_avg = mean(T_pcm,2);
H_avg = mean(H_pcm,2);
Q_avg = mean(Q,2);
```

Experimental Investigation Of Using Latent Thermal Energy Storage System Comprising Of Magnesium Chloride Hexahydrate ($MgCl_2.6H_2O$) With Domestic Gas Heater

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***Abstract*— Thermal energy storage is an active field of research that can be adopted for energy efficiency and conservation in thermal applications on conventional systems. Moreover, they are equally effective to be used with renewable resources to mitigate their intermittency in terms of availability. This paper covers the experimental investigation of the latent thermal energy storage system, in which Magnesium Chloride Hexahydrate ($MgCl_2.6H_2O$) was used as thermal energy storage material. Literature lists $MgCl_2.6H_2O$ as a strong candidate for thermal energy storage in the medium range with melting temperature of 117.5°C and latent heat of 168.6 kJ/kg. Aluminum encapsulation was used with PCM for testing with gas heater. The flame temperature of domestic gas heater ranges from 600 to 800°C, at this temperature the PCM was fully charged in less than 900s and stored about 30 kJ of thermal energy till the final temperature of the material reached to 320°C. In the discharging phase, subcooling was observed and the material released thermal energy to a threshold temperature of 60°C in 930s. This study considered the direct contact TES system. (*Abstract*)**

Keywords*— Latent Thermal Energy Storage Systems, Phase Change Materials, Salt hydrates (*key words*)

I. INTRODUCTION

Domestic gas heaters normally operate on methane gas that is provided as a common commodity to the household. During combustion, it produces maximum flame temperature of 900-1500°C[1], which is quite high. The minimum temperature that was recorded in the area during past years was 2°C and that was only for one day. The thermal energy required to heat a room to a comfortable temperature of 25°C from 2°C is 24 kJ for a unit mass of air whereas the gas heaters consume approximately1000 to 1800 kJ of thermal energy for the same cause. This clearly indicates the energy conservation opportunity is available. Thermal energy storage can be effectively used for the purpose[2], [3]. Literature is available with detailed information about the TES systems and applications[2], [4]–[6]. To develop a thermal energy storage system, at first, a temperature range is selected which should be according to the application[7]. Therefore, certain rules were chalked out in this regard [8], [9]. In this case, the latent thermal energy storage system was chosen to be used as thermal energy storage, to store the excessive heat contents and the material selected was Magnesium Chloride Hexahydrate (MCHH) ($MgCl_2.6H_2O$) because of its temperature range and other thermophysical properties as phase change material like heat capacity, thermal conductivity, latent heat and melting temperature[10]–[13]. Thermal cycle analysis of the material carried out also suggested that it can be a good choice in this case[14], [15]. The simple working and comparison of different types of TES is shown in the figure below;

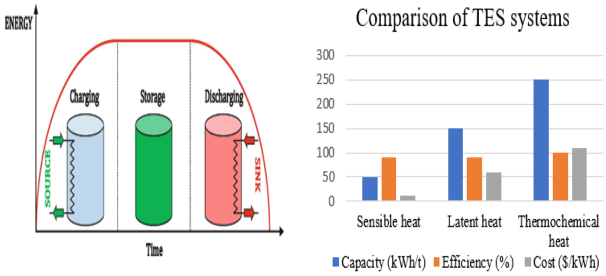

Fig. 1: TES working and comparison of different TES systems

The system can simultaneously store energy and deliver it to load. There may be a scenario when energy is not required during off-peak hours, so the TES system can be charged at that time for utilization in peak hours when demand is high. The detailed graph of Latent Thermal Energy Storage systems is given in Fig. 2. The graph shows detailed behavior of the PCM during charging and discharging phases. During heating/ charging the material starts storing energy in sensible form till it reaches the melting temperature and then latent energy comes into play after the complete phase transition, the material again starts storing energy in sensible form till the final temperature. During the discharging phase, the material first discharges the sensible energy to reach its solidus temperature but it does not start solidification right at that temperature because of subcooling and sometimes phase segregation[11], [16]–[18]. After crystal formation starts in the material it starts releasing latent energy and then sensible energy to reach the threshold temperature. Time taken during this activity is called a thermal cycle which may vary with the conditions applied to the material[14], [15], [19].

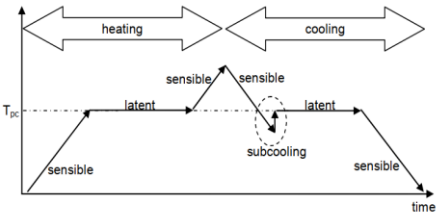

Fig. 2. Detail graphical representation of LTES[6]

II. INVESTIGATION OF THERMOPHYSICAL PROPERTIES

The initial investigation of thermophysical properties was carried out by T-History method[20]–[24]. Different phases of PCM thermal cycle are shown below;

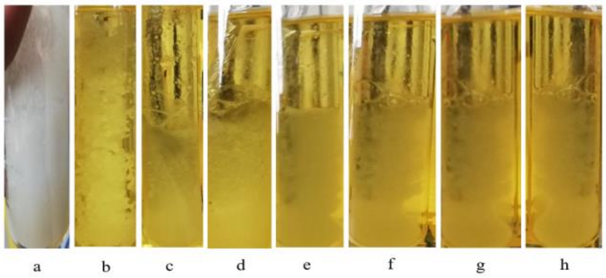

Fig. 3. Visual representation of different phases of the thermal cycle

At the start of the experiment, the material could be seen as a white powdered form when that material was subjected to heating the water molecules associated with the powder got separated and the material transformed into granular shape from the powder form and with further heating it melted down. In Fig. 8 (c, d), a hazy solution can be seen which confirmed that the material was melted and the bubbles over the surface showed that it started boiling after melting. This also shows that the temperature rose rapidly after the phase change.

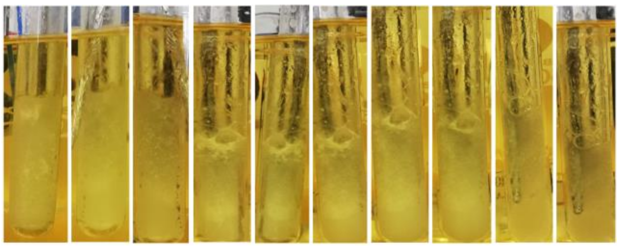

Fig. 4. Different phases of melting of the material

Fig. 9 represents the different phases of melting and solidification of the material. In the initial figure, it could be seen that the bottom of the tube contained most of the solid material. It happened during the solidification of the previous thermal cycle that solid and liquid phases segregated from each other and most of the solid settled down[13], [17], [25], [26]. This could be avoided by constant stirring or addition of some nucleating agent[27]. Complete graph of the thermal cycle is shown below in which charging and discharging is shown in a single graph.

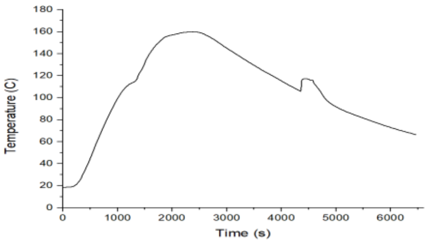

Fig. 5. Graphical representation of material thermal cycle

Fig. 10 represents the detailed thermal cycle of the material. A 10g sample of Magnesium Chloride Hexahydrate ($MgCl_2.6H_2O$) was heated on an electric plate from 20 - 160°C and then let it cooled till 60°C. It could be observed from the graph that the material started storing heat in sensible form from 20 - 115°C and started phase change at about 116°C till 118°C after 22 minutes of heating. The material was charged maximum till 160°C. It attained a maximum temperature in 36 minutes. After achieving maximum temperature, the material was cooled down gradually till 60°C. Time taken during discharging was 72 minutes. During discharging supercooling was observed, the temperature dropped down till 100°C before material started forming into crystal form. Following observations were made during this experiment;

a. Melting temperature of the material was observed between 116-118°C.
b. Phase segregation was observed during multiple thermal cycles. Fig. 9 refers to the same.
c. A slight shift in thermal properties was observed with multiple thermal cycles because of the physical changes occurred during thermal cycles

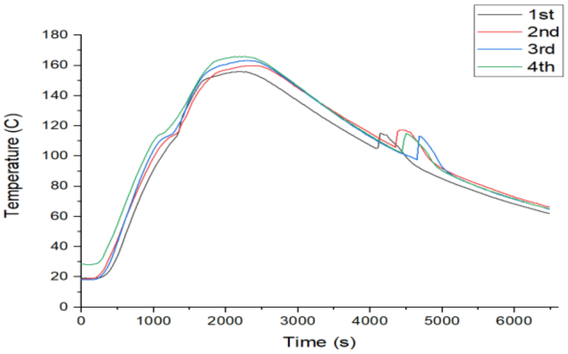

Fig. 6. Comparison of multiple thermal cycles

d. Supercooling was observed during solidification. The temperature dropped down till 100°C when crystals formation started

III. INTEGRATION OF TES WITH GAS HEATER

After an initial investigation of the thermal properties of the material, the system was designed for integration with domestic gas heater. 3-D model of the simple design made of Aluminum is shown below;

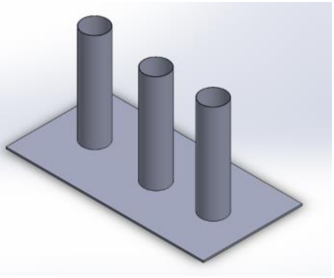

Fig. 7. 3-D model of TES system

Three aluminum cylinders of **1½** inch diameter and **6** inches of length were welded over the aluminum plate. The pictorial representation of the experimental setup is shown in fig. 13. Thermocouples were placed at 1-inch spacing both on the outside and inside. For the first experiment, 60g of PCM was filled and the first thermal cycle was initiated.

Fig. 8. Experimental Setup

Portable data logger of 12-channels was used for recording the temperature variation of the material. K-type bead and surface thermocouples were used for temperature measurement. Important parameters that were measured during the experiment are shown in the table below;

TABLE 1. Parameter recorded during the experiment

S no.	Description	Type	Notation
1.	Thermocouple 1 (1” above the bottom surface of the cylinder from inside) – Bead Type	K	T_1
2.	Thermocouple 2 (2” above the bottom surface of the cylinder from inside) – Bead Type	K	T_2
3.	Thermocouple 3 (3” above the bottom surface of the cylinder from inside) – Bead Type	K	T_3
4.	Thermocouple 4 (4” above the bottom surface of the cylinder from inside) – Bead Type	K	T_4
5.	Thermocouple 5 (4” above the bottom surface of the cylinder from outside) – Bead Type	K	T_5
6.	Thermocouple 6 (3” above the bottom surface of the cylinder from outside) – Bead Type	K	T_6
7.	Thermocouple 7 (2” above the bottom surface of the cylinder from outside) – Bead Type	K	T_7
8.	Thermocouple 8 (1” above the bottom surface of the cylinder from outside) – Bead Type	K	T_8
9.	Thermocouple 10 (For measurement of ambient temperature) – Surface Type	K	T_{10}
10.	Thermocouple 12 (For measurement of surface temperature) – Surface Type	K	T_{12}

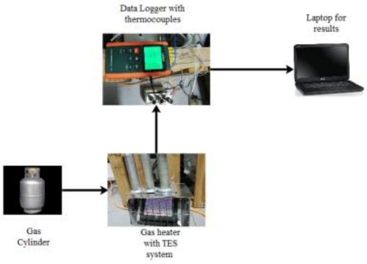

Fig. 9. Schematic of the Experimental setup

Schematic of the system is shown in the figure above. Gas for the heater was provided by a portable gas cylinder containing LPG (Liquid Petroleum Gas). Timestep of 5 seconds was selected for data logging. K-type thermocouples were used. Thermocouple used to monitor the temperature of the cylinder from inside and outside were of bead type while surface type thermocouples were used to measure the surface and ambient temperature.

IV. RESULTS AND DISCUSSIONS:

The analysis of the system can be split into two portions i.e., charging and discharging cycles. At present only energy content stored in the system and heat transfer rate were analyzed. First charging cycle will be discussed.

A. *Charging Cycle*

The initial temperature of the PCM was 20^{o}C, the surface temperature on which the cylinders were welded was 24^{o}C and the ambient temperature of the room was 17^{o}C. The thermal cycle was started with these initial conditions. After 300s the temperature of the lower thermocouple (T4) reached to 100^{o}C. The material at the bottom of the cylinder reached to its melting point in 465s. After the melting started at T4, the temperature of the material rose quickly. Within next 300s the average temperature of the material was 120^{o}C, which is higher than the melting point of the material. Melting of rest of the material took place in 300s. The final average temperature of the material reached to 204^{o}C after 855s. Following graph represents the temperature against the time during the charging cycle:

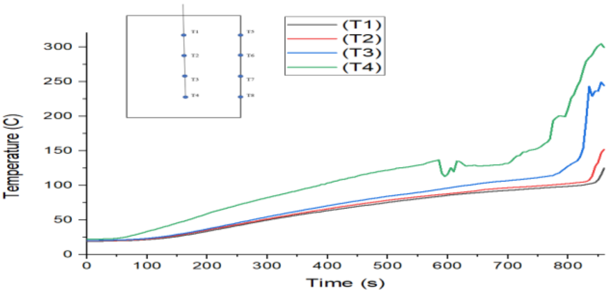

Fig. 10. Graphical representation of charging phase

This data was acquired from the inner thermocouples placed inside the cylinder. The temperature of the thermocouple T4 being the closest to the bottom started rising as the bottom of the cylinder encountered the flame. Till 550s, the material stored the energy in sensible form and the line shows that the temperature rose with a constant rate. After 550s, a sudden drop in the temperature line of T_4 is observed, this is the indication of the internal movement of the material as material at bottom of the cylinder started melting and solid material above the melted material, because of higher density and low temperature, take the place of melted material. Hence the temperature dropped suddenly, and this trend continued until the whole material was melted. Because of this phenomenon, the line of thermocouple 4 (T_4) shows the irregular rise. If the rest of the thermocouples are compared with thermocouple T_4, it is observed that other lines show the smooth trend as the temperature rise. This is since most of the material was melted in the bottom part of the cylinder which was measured by thermocouple 4 and hence maximum disturbance was observed in that part. It could also be deduced that most of the material transition took place in the bottom of the cylinder and on the upper portion of the cylinder remained in a relatively constant phase. The total energy stored by the material was calculated by the following equation

$$Q = mC_{p_s}(T_m - T_i) + m\lambda + mC_{p_l}(T_f - T_m)$$

The total energy content stored in one cylinder during charging phase of the thermal cycle was calculated to be 29.10 kJ that can cater for a total thermal load of .0081 kWh or it can provide 8.1 W of thermal load for 0.486s. This is the energy that can be stored in 60g of MCHH.

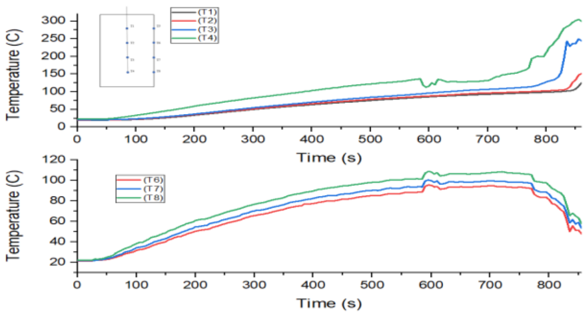

Fig. 11. Comparison of internal and external temperatures during the charging phase

The figure above shows the comparison of internal and external thermocouples of the cylinder. External thermocouples also show the variation in the reading during the transition period of the material in the form of a hump. Overall temperature rise is smooth in external thermocouples. Energy content variation with respect to time can be observed in the graph below;

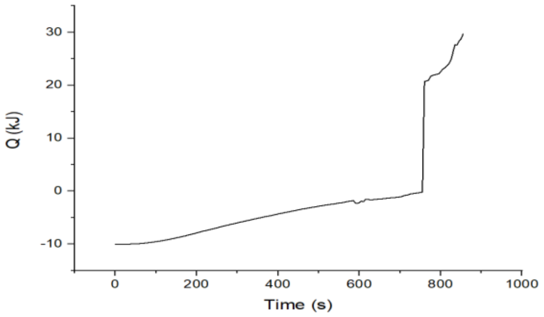

Fig. 12. Energy content stored with time

This graph shows that at the start of the process the energy was used to overcome the internal bonding of the material and that energy was stored in the form of sensible energy. When the material absorbed energy equivalent to its bonding energy it immediately started melting down and started storing energy in the latent form shown by the vertical line of the graph. After storing the entire latent energy, material again started storing the rest of the energy in sensible form.

At the outer surface of the cylinder, the heat transfer rates were calculated based on natural convection. Thermocouples 6,7 and 8 measured the external surface temperatures. The heat transfer rate was calculated and plotted against time, the graph is given below;

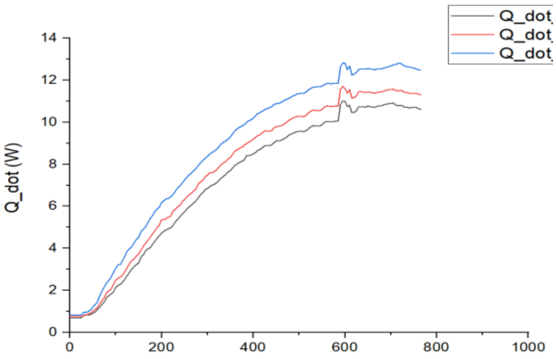

Fig. 13. Heat transfer rate during the charging phase

The trend of heat transfer rate is the same as the external temperature because of its dependence on temperature. The hump in the line shows that the phase transition of the material started at about 600s. Maximum heat transfer can be seen at a one-inch height from the bottom which is approximately 13W.

B. *Discharging Cycle:*

During the discharging cycle, the heat was released through natural convection and in the radial direction. The outer surface of the cylinder was not insulated, so the heat transfer took place from the surface of the cylinder. The total energy that the material was able to absorb was 29.1 kJ and now the same was to be discharged.

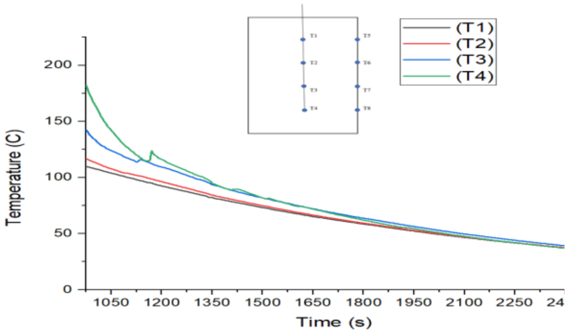

Fig. 14. Graphical representation of discharging

Above graph represents the discharging cycle. These temperature lines are of inner thermocouples. The same trend can be observed while discharging that most of the transition of the material took place on the bottom side of the cylinder therefore, some disturbance in thermocouple 4 and 3 is observed. On the other hand, thermocouple 1 and 2 lines are smooth during discharging as well. The phenomenon of supercooling can also be observed clearly on thermocouple 4 line and some can also be seen on the thermocouple 3 line. All temperature lines converged at 60°C which was set as the threshold temperature because beyond this temperature the heat transfer rate will be minimum. The time taken by the material to reach this temperature by emitting all the heat stored was approximately 23 minutes. Comparison of external and internal thermocouples during discharging is shown below;

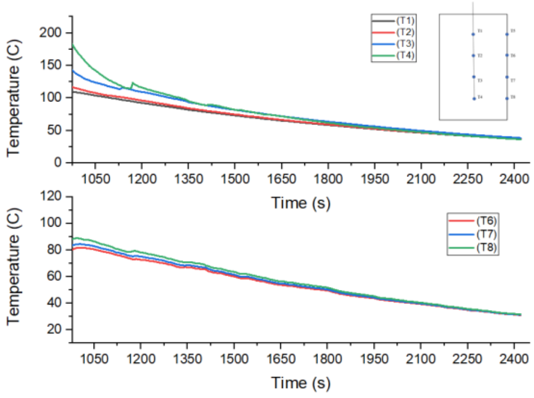

Fig. 15. Comparison of internal and external temperatures during discharging phase

The same trend can be observed in the internal and external sides of the cylinder. The only difference is the difference in temperature values. The reason behind the lower temperature values is the low thermal conductivity of the material due to which the temperature inside of the cylinder is not conducted very efficiently to the surface of the cylinder.

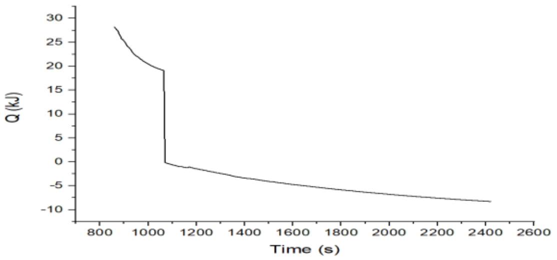

Fig. 16. Energy content variation with time during discharging

The figure above shows that how the energy content stored were released during the discharging phase. It is evident from the graph that when the discharging phase started the energy was released in sensible form and it started releasing energy in latent form when the material reached its solidus temperature. After releasing the latent content of energy stored it again started to release sensible energy until the material becomes fully solid. The system can provide effective thermal energy till the threshold temperature of 60ºC after that the temperature difference becomes small for heat transfer and hence the rest of the energy cannot be utilized effectively until some heat transfer enhancement measures are taken for the same. The heat transfer lines observed the same trend as of the surface temperature. Maximum of 10W heat transfer rate was observed during the discharging cycle that can also be seen in the graph below;

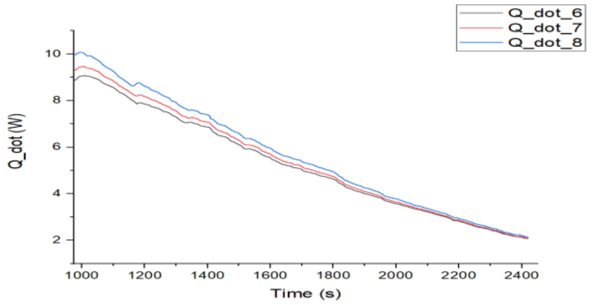

Fig. 17. Heat transfer during discharging

Heat transfer rate decreased from 10W to 2W in 25 minutes with a constant slope. It shows that the rate of heat transfer observed a linear trend during discharging.

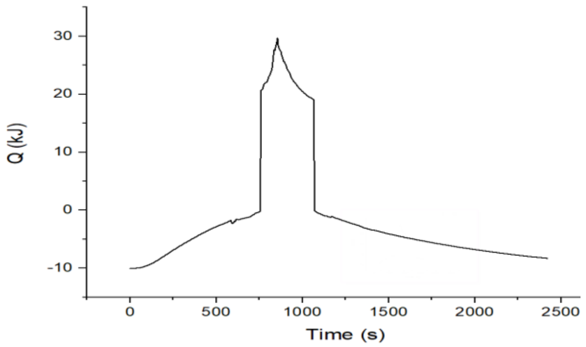

Fig. 18. Energy content variation in whole thermal cycle

The figure above shows the energy content variation in complete thermal cycle. The peak of the graph represents the latent and post latent sensible content of the material. It can also be observed that the material has the capacity to increase the discharge time by 46%.

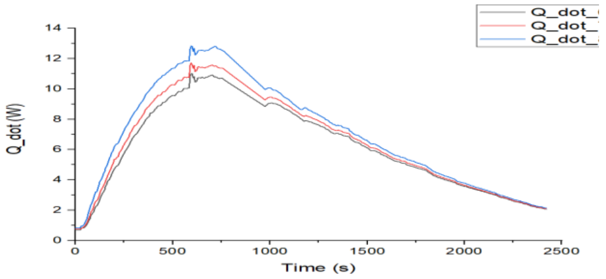

Fig. 19. Rate of heat transfer during complete thermal cycle

Figure 26 represents the rate of heat transfer during the entire thermal cycle. The same observation can also be drawn from this graph that the material supplied heat for more time after it charged during the first phase of charging.

V. CONCLUSION

In this study, a thermal energy storage system that is to be integrated directly with the domestic gas heater was analyzed with MCHH as the PCM. The analyses were based on the thermal energy content stored and the rate of heat transfer that is provided by the system. The storage capacity of 60g of the material was observed to be 29.1 kJ, that is about 8.1W. The system was designed in comparison to the system that can provide 1kW of thermal load for 3 hours, it means that the system should store more than 10800 kJ of thermal energy. At present, if the system with all cylinders is utilized, it can have the mass of 180g which can store 87.3 kJ of thermal energy that is equivalent to 24.25 W. To store about 20,000 kJ energy 42 kg of MCHH will be required that will cost approximately 63,000 PKR. This system is not cost-effective for the domestic user. Another drawback of the system will be to contain this much of PCM the size of the cylinders will get bigger and it will be difficult for the user to fit it in the room. It is concluded by this experiment that MCHH is not recommended for small systems although it is a good candidate for thermal energy storage and can be used effectively in CSP plants for storing the thermal energy.

VI. FUTURE WORK

In the future, the thermal system will be designed to provide the required thermal energy for heating and storing the excessive to be used later for better energy consumption. For this further working will be carried out on the design and material for storage. It will also be considered to have strict compliance on the indoor environmental quality standards.

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