Experimental and Numerical Studies of Thermal Energy Storage using Paraffin Wax Phase Change Materials

R.R. Thirumaniraj\textsuperscript{1*}, K. Muninathan\textsuperscript{2}, V. Ashok Kumar\textsuperscript{2}, B. Jerickson Paul\textsuperscript{1}, Rahul R Rajendran\textsuperscript{3}

\textsuperscript{1} Student, St. Joseph’s College of Engineering, Anna University, Chennai, India
\textsuperscript{2} Assistant Professor, St. Joseph’s College of Engineering, Anna University, Chennai, India
\textsuperscript{3} Research Scholar, Lehigh University, Bethlehem, USA

*E-mail: thirumaniraj97@gmail.com

Abstract: The main idea of this work is to design and analyze efficient storage of thermal energy using phase change material. Solar energy is a readily available and renewable source of energy. It is also a clean energy as it does not emit carbon dioxide. However, maximum utilization of solar energy is not possible without the use of thermal energy storage (TES). This thermal storage system can form an integral part of solar heating system. In this work a TES tank is designed and fabricated. Paraffin wax is the phase change material used. It is encased in stainless steel balls. The high specific heat capacity of PCM is used to store latent heat which can be used any time. Temperature measurements are taken using T-type thermocouple along with indicator. Numerical analysis is done using the CFD software Ansys Fluent.

This work mainly focuses to find the solution for the mismatch of abundant solar energy available during daytime and non-availability of energy during night-time. This project work also forms a part of a wider study to explore the possibility of PCMs to store the energy during off-peak load and releases the same during peak load. In several countries, during the daytime the load will be at peak level which leads to high cost for production. Therefore, cost saving can be achieved if heat pumps can be operated during the off-peak periods to store heat for use during the peak periods.

Key words: TES, Phase Change Materials, paraffin wax, thermal storage

List of Symbols and Nomenclature

| Symbol | Description |
|--------|-------------|
| Q1     | Heat given by hot water |
| \( \dot{m}_h \) | Mass flow rate of hot water |
| \( \Theta_i \) | Specific heat of hot water |
| \( \Theta_o \) | Inlet temperature of hot water |
| \( \Theta_i \) | Average outlet temperature of hot water |
| Q2     | Heat gained by cold water |
| \( \dot{m}_c \) | Mass flow rate of cold water |
| \( c_{pc} \) | Specific heat of cold water |
| \( T_{co} \) | Average outlet temperature of cold water |
| \( T_{ci} \) | Inlet temperature of cold water |
| \( \eta_{storage} \) | Efficiency of Storage system |
1. Introduction

Energy storage is a major issue to be faced to allow intermittent energy supply, typically renewable sources, to match energy supply with demand. Most of Technologist are facing a problem in storing the thermal energy. It cannot be economical used if we store in batteries and so it should be stored in the appropriate form with suitable procedure. Xiang Lu et al. conducted an experiment on Nano sheets for thermal energy storage using polyurethane phase change materials in which he proposed energy storage is a major issue to be faced to allow intermittent energy supply, typically renewable sources, to match energy supply with demand is Thermal energy [1]. H. Wei et al. done a study on shell composite phase change materials for high temperature thermal energy storage, he said that it was reported that the 80% of utilization of energy is in the form thermal energy and 45% of energy is wasted. Most of Technologist is facing a problem in storing the thermal energy. It cannot be economical used if we store in batteries and so it should be stored in the appropriate form with suitable procedure. In many regions of the world, direct solar radiation is considered to be one of the most prospective sources of energy. The major disadvantages of solar energy are its intermittent supply. To overcome this drawback, it is necessary to develop energy storage devices [2]. Chuanfei Shen et al proposed that most of the experiments carried out in this issue results in 11.18%-36.17%. They used molten salts and phase change materials generally. The molten salts like Sodium sulphate dehydrate, sodium chloride, chlorides, silicates and other inorganic salts [4]. Vivek Tiwari et al. has done a SWOT analyses of high –temperature phase change materials for thermal energy storage, he says that the thermal energy storage is classified into two types. They are

- Latent heat thermal energy storage (LHTES)
- Sensible heat thermal energy storage (SHTES)

N.Nallusamy et al. has done an Experimental investigation on a combined sensible and latent heat storage system integrated with constant/varying (solar) heat sources which resulted that the Latent thermal storage materials are very effective. They store 5 to 14 times more heat per unit volume than sensible heat storage materials such as water, masonry, or rock. Phase change materials (PCMs) absorb and emit heat energy whenever supply energy is surplus and not able to meet the demand. This may be major reason to suggest PCM as an alternative to conventional storage mediums. Thermal gradients during charging and discharging are small and hence simultaneous charging and discharging is possible with appropriate selection of heat exchanger [6]. Samira Golestani Ranjbar et al. has done a study on Fabrication and Characterization of phase change material –SiO2 for Thermal energy storage in buildings they proposed that there are some basic qualities to be seen while selecting the phase change material as storage medium which includes the specific heat capacity, thermal and chemical stability, non-toxic, non-flammable and phase transition temperature should be practically and economically attained. The main aim is to store and use the thermal energy efficiently [7]. There is variety of phase change materials can be used but the PCM which is economically beneficial is paraffin. The paraffin has a phase transition temperature near to the normal temperature 20° to 30°C. Other PCM’s are having higher range of about 350°C-1500°C which is not economically beneficial to store the thermal energy.
2. Material Selection

2.1 TES Tank
For both TES tank and spherical balls Stainless steel is selected because it has more corrosion resistance and high tensile strength. It also has higher degree of reusability.

2.2 Paraffin Wax
Paraffin wax has high heat trapping capacity and it is insoluble in water also it is not affected by any chemical reagents. Its Heat of combustion is 42MJ/Kg. Hence it is used a Phase Change Material in this process.

2.3 Geometry of Balls
Paraffin wax is stored in a spherical shaped hollow ball. Spherical shape is chosen because it has more surfaces to volume ratio which permits uniform heat transfer between the bonds of paraffin wax.

2.4 Grade of Stainless Steel
High chromium ferritic grades (446) of stainless steel are used as TES tank material in this process. Austenitic grades of stainless steel have high strength at elevated temperatures.

2.5 Melting Point of Wax
The paraffin wax having melting point in the range of 40-degree Celsius to 43 degree Celsius is selected for this process.

2.6 Thermocouples
Six T-type thermocouple are used to obtain the temperature values. A channel for measuring inlet water temperature, a channel for measuring outlet water temperature and four channels for measuring the layer by layer temperature of paraffin wax are connected to get digital output.

3. Layout of Project

Fig. 1. Experimental Setup of Thermal Energy Storage
Fig. 2. Tes Tank Isometric View
4. Experimental Work

The experimental work consists of the following major components:
1. Thermal energy storage tank
2. Hot water supply tank for charging
3. Cold water supply tank for discharging
4. Pump
5. Control valves
6. Flexible hoses
7. Thermocouple for temperature measurements

4.1 Thermal Storage Tank
The thermal storage tank made of stainless steel of 400 mm height and 220 mm diameter. The PCM are filled in spherical stainless balls and arranged in six rows with the help of wire mesh. Each row contains 13 spherical balls. Hence 72 numbers of spherical balls are used to store thermal energy. The tank has also provision to admit hot water at top and the hot water leaves at bottom. The cold water is admitted at bottom and leaves at the top. Valves are provided at both entrance and exit to control the flow rate of waters.

Two thermocouple wires are embedded in the PCM materials to sense the temperature of the PCM during charging and discharging.
4.2 Hot Water Supply Tank for Charging
The hot water supply tank is located at top of thermal storage device in order to avoid pumping. An electric heater is installed in the hot water tank to heat the water and maintain the water temperature. This tank serves as a source of heat which is like solar water heating system. The main reason for using the electric heater is to simulate the process of solar heater in order to maintain constant temperature of hot water. It also incorporated with control valves and thermocouple to regulate and measure the hot water temperature.

4.3 Cold Water Supply Tank for Discharging
The cold-water supply tank is located at the bottom of thermal storage device to enable the entry of cold water at bottom of thermal storage tank. The cold water takes the heat energy stored by the PCM and leaves at top. A pump is used to circulate the cold water through the PCM storage tank.

4.4 Pump
A centrifugal pump of small discharge is used to pump the cold water from cold water tank to thermal storage tank.

4.5 Control Valves
Spherical ball type control valves of 12 mm size are used to regulate the hot and cold-water entry and exit.

4.6 Flexible Hoses
Flexible hoses are used to carry the water from hot and cold-water tank to thermal storage tank.

4.7 Thermocouple
There are 6 number of T type thermocouple used to obtain temperature values. These thermocouples are connected to a six-channel temperature indicator to get digital output.

5. Experimental Procedure
The experimental procedure consists of the following four steps

1. Charging
2. Draining the hot water
3. Discharging
4. Temperature data acquisition

5.1 Charging
The electric heater provided in the hot water tank is switched on and the temperature of hot water is observed. When the temperature reaches to a predetermined level, the control valves are opened, and the water is allowed to enter into the thermal storage tank. This hot water increases the temperature of PCM and then melts it. The charging process continues until the PCM attains a steady state.

5.2 Draining the Hot Water
The hot water available in the thermal storage tank is drained so that the storage tank is ready for discharging process.

5.3 Discharging
The cold water available in the cold-water tank is pumped into thermal storage tank. The heat energy stored in PCM is released and this heat is absorbed by the cold water and hence the cold-water temperature rises. The discharging process continues until the PCM reaches to its original temperature.
6. Temperature Data Acquisition

The temperature readings were recorded with the thermocouples connected to a temperature indicator. There are six thermocouple wires used to acquire data at the following locations during charging and discharging:
1. Hot water inlet
2. Hot water outlet
3. Cold water inlet
4. Cold water outlet
5. Top layer of PCM
6. Bottom layer of PCM

7. Efficiency Calculation of Thermal Storage System

7.1 Heat given by Hot Water

The heat given by the hot water during charging is calculated as follows:

\[ Q_1 = \dot{m}_h \cdot c_{ph} \cdot (T_{hi} - T_{ho}) \]  
\[ Q_1 = 0.307 \cdot 4186 \cdot (80 - 35) \]  
\[ Q_1 = 57829.59 \text{ J/s} \]  
\[ Q_1 = 57829.59 \text{ W} \]

7.2 Heat gained by Cold Water

The heat gained by the cold water during discharging is calculated as follows:

\[ Q_2 = \dot{m}_c \cdot c_{pc} \cdot (T_{co} - T_{ci}) \]  
\[ Q_2 = 0.307 \cdot 4186 \cdot (60 - 32) \]  
\[ Q_2 = 35982.85 \text{ W} \]

7.3 Efficiency of Storage System

\[ \eta_{storage} = \frac{(\text{Heat gained by cold water}/\text{Heat given by hot water}) \times 100}{100} \]  
\[ \eta_{storage} = \frac{Q_2}{Q_1} \times 100 \]  
\[ \eta_{storage} = \frac{35982.85}{57829.59} \times 100 \]  
\[ \eta_{storage} = 62.22 \% \]

8. Experimentation

![Thermocouple connections](image)

Fig. 7. Thermocouple connections
8.1 Experimental Readings

The Thermocouples are connected as shown in the Figure. The experiment is started by switching on the water heater and the pump. During the charging the temperature readings were noted down from the six channel temperature indicator at a regular interval of 5 minutes. The charging process is continued till the temperature of the paraffin wax reaches to about 90 °C. The readings are tabulated as shown in the table 1.

Discharging is done by allowing water at room temperature into thermal energy storage tank. Here the temperature readings are recorded for a regular interval of 3 minutes. The discharging process is continued till the temperature of the Paraffin wax reaches to room temperature. The readings are tabulated in the table 2.

| S. No | Time | T1 | T2 | T3 | T4 | T5 | T6 |
|-------|------|----|----|----|----|----|----|
| 1     | 5    | 28 | 28 | 28 | 27 | 27 | 28 |
| 2     | 10   | 29 | 29 | 29 | 28 | 28 | 29 |
| 3     | 15   | 29 | 29 | 30 | 28 | 28 | 29 |
| 4     | 20   | 29 | 30 | 31 | 29 | 29 | 30 |
| 5     | 25   | 30 | 31 | 35 | 30 | 29 | 30 |
| 6     | 30   | 30 | 33 | 32 | 33 | 29 | 32 |
| 7     | 35   | 32 | 40 | 47 | 41 | 31 | 40 |
| 8     | 40   | 46 | 50 | 56 | 51 | 37 | 44 |
| 9     | 45   | 49 | 51 | 59 | 53 | 39 | 45 |
| 10    | 50   | 52 | 57 | 66 | 54 | 43 | 50 |
| 11    | 55   | 56 | 60 | 70 | 63 | 45 | 52 |
| 12    | 60   | 59 | 64 | 71 | 66 | 47 | 55 |
| 13    | 65   | 62 | 67 | 74 | 68 | 49 | 57 |
| 14    | 70   | 65 | 69 | 76 | 71 | 52 | 61 |
| 15    | 75   | 67 | 72 | 80 | 74 | 55 | 62 |
| 16    | 80   | 71 | 76 | 82 | 78 | 60 | 75 |
| 17    | 85   | 72 | 77 | 82 | 79 | 63 | 76 |
| 18    | 90   | 76 | 80 | 87 | 82 | 68 | 81 |
| 19    | 95   | 78 | 82 | 90 | 84 | 74 | 83 |
| 20    | 100  | 81 | 85 | 93 | 87 | 78 | 86 |
| 21    | 105  | 84 | 88 | 95 | 89 | 82 | 89 |
| 22    | 110  | 88 | 91 | 98 | 92 | 88 | 92 |
| 23    | 115  | 85 | 91 | 93 | 92 | 87 | 93 |
| 24    | 120  | 83 | 91 | 88 | 91 | 87 | 93 |
| 25    | 125  | 78 | 90 | 80 | 90 | 86 | 93 |
| 26    | 130  | 77 | 90 | 77 | 89 | 85 | 92 |

| S. No | Time | T1 | T2 | T3 | T4 | T5 | T6 |
|-------|------|----|----|----|----|----|----|
| 1     | 0    | 77 | 90 | 77 | 89 | 85 | 92 |
| 2     | 3    | 36 | 81 | 90 | 89 | 69 | 91 |
| 3     | 6    | 30 | 37 | 88 | 88 | 62 | 84 |
| 4     | 9    | 30 | 33 | 77 | 78 | 51 | 77 |
| 5     | 12   | 30 | 31 | 68 | 60 | 50 | 62 |
| 6     | 15   | 30 | 31 | 40 | 39 | 47 | 59 |
| 7     | 18   | 29 | 30 | 39 | 36 | 46 | 58 |
| 8     | 21   | 29 | 30 | 37 | 33 | 43 | 57 |
| 9     | 24   | 29 | 29 | 35 | 32 | 41 | 56 |
| 10    | 27   | 29 | 29 | 33 | 31 | 40 | 56 |
| 11    | 30   | 29 | 29 | 32 | 31 | 39 | 55 |
| 12    | 33   | 29 | 29 | 31 | 31 | 38 | 54 |
| 13    | 36   | 29 | 29 | 30 | 30 | 36 | 54 |
| 14    | 39   | 29 | 29 | 30 | 30 | 36 | 53 |
| 15    | 42   | 29 | 29 | 30 | 30 | 34 | 52 |
| 16    | 45   | 29 | 29 | 30 | 30 | 34 | 51 |
| 17    | 48   | 29 | 29 | 30 | 30 | 32 | 48 |
8.2 Graphs Obtained from Charging

Fig. 8. Temperature vs Time Graph for $T_1$

Fig. 9. Temperature vs Time Graph for $T_2$

Fig. 10. Temperature vs Time Graph for $T_3$

Fig. 11. Temperature vs Time Graph for $T_4$

Fig. 12. Temperature vs Time Graph for $T_5$

Fig. 13. Temperature vs Time Graph for $T_6$

8.3 Graphs Obtained from Discharging
9. Computational Details of The Present Study

9.1 Numerical Model and Mesh Formation
The first task in the process of simulation is the creation of a computational mesh to represent the flow domain of the geometry. The model of the diffuser representing the fluid domain has been modelled using the Ansys Fluent Geometry Modeller. In this chapter, the details of the fluid domain and the mesh generated for the diffuser models will be discussed.

9.2 Model Geometry
The Tank Model is created in the Fluent Geometry Modeller. The six layers of PCM are also given in the tank. Boolean operations are given for the required parts. The different parts of geometry are joined to form a new Part. Inlet and outlet pipes were also given in the tank.
10. Results of Numerical Analysis

10.1 Charging

From the Static temperature contours during discharging (Figure 9.2.1) it can be seen that cold water entering at the bottom of the tank gains heat from the charged PCM layers and leaves the TES tank as hot water. The water is discharged in reverse manner only for the purpose of experimentation.

10.2 Discharging

From the Static temperature contours during discharging (Figure 9.2.1) it can be seen that cold water entering at the bottom of the tank gains heat from the charged PCM layers and leaves the TES tank as hot water. The water is discharged in reverse manner only for the purpose of experimentation.

Conclusion

In this project work experimentation is done on Thermal storage system using Paraffin wax as Phase Change Material and water as heat transfer fluid. This storage system helps for the simulation of continuous supply of heat energy when the source is intermittent such as solar water heating system. In this work a method to calculate the efficiency of storage system is arrived. By this project the overall
efficiency of the experimental setup amounts to 62%. The efficiency can be increased by using different PCM with higher latent heat and better insulation materials such as glass wool. CFD analysis is also done by giving the properties of paraffin wax and temperature and pressure contours are obtained during both charging and discharging.

REFERENCES

[1] N.Nallusamy, S.Sampath, R. Velraj, “Experimental investigation on a combined sensible heat and latent heat storage system integrated with constant/ varying solar heat sources. Renewable energy, April 2006.

[2] Atul Sharma, V.V. Tyagi, C.R.Chen, D.Buddhi. “ Review of thermal energy storage with phase change materials and applications”. Renewable and Sustainable energy Reviews, 2009

[3] G. Senthil Kumar, D Natarajan, L.A. Chidambaram, V. Kumeresan, Y.Ding, R.Velraj. “Role of PCM addition on stratification behavior in a thermal storage tank - An experimental study”. Energy 2016. Vol-115, Pgs-1168-1178.

[4] A. Felix Regin, S.C.Solanki, J.S.Saini ”An analysis of a packed bed latent heat thermal energy storage system using PCM capsules: Numerical Investigation”. Renewable Energy, December 2009.

[5] Velraj R., et al.(1997), heat transfer enhancement in a latent heat storage system. Solar energy Vol.65, No.3, pp.171-180.

[6] K. Muninathan, R R Thirumaniraj, and M A Suryanarayanan, “Heat Transfer Modeling and Analysis Of Annular Diffuser with and without Double Tapered Struts”, 2018 IEEE International Conference on System, Computation, Automation and Networking (ICSCA), Pondicherry, 2018, pp.1-5. doi: 10.1109/ICSCAN.2018. 8541227

[7] Arasu, A.V., Sasmito, A.P., Mujumdar, A.S. (2013). Numerical performance study of paraffin wax dispersed with alumina in a concentric pipe latent heat storage system. Thermal Science 17 (2) : 419-430. ScholarBank@NUS Repository.https://doi.org/10.2298/TSCI110417004A.

[8] K. Muninathan, R. Lakshminarayanan and Binesh S. Kumar. Design, Heat Transfer Modeling and Analysis Of Environmentally Benign Charcoal Kiln, IJEP 39 (2) : 173-177 (2019).