Experimental investigation of low-temperature latent heat thermal energy storage system using PCM and NEPCM

M R Wilson John*, Thrinadh Mamidi1, Satishkumar Subendran1, L R Ganapathy Subramanian2

1Department of Mechanical Engineering, Dr. M.G.R. Educational and Research Institute, Chennai, India
2Aerospace Engineering, School of Mechanical Engineering, SRM Institute of Science and Technology, Chennai, India

* Corresponding author: mrwjohn2011@gmail.com

Abstract. The current experimental work is used to investigate the latent heat thermal energy storage (LHTES) system for the low-temperature using phase change material (PCM) and nano-enhanced phase change material (NEPCM) during charging and discharging process. The water is used as the heat extraction liquid media during the charging and discharging process. The temperature curves of the PCM and NEPCM in the LHTES tank with various flow rates of the water are studied. The evaluation of the behavior of the LHTES system has been investigated using the charging and discharging rate, and total heat energy stored during the charging and discharging process of PCM and NEPCM and charging rate of water during discharging process. It was found that the temperature of the water rises nearly 54 °C during the discharging process of LHTES tank. The maximum charging and discharging rate of PCM and NEPCM based LHTES tank are available at the flow rate of 6 lpm. The charging and discharging rate in the LHTES tank using NEPCM is 33.33% and 23.51% more than discharging rate in the LHTES tank using PCM at the flow rate of 6 lpm due to adding copper oxide nanoparticles with PCM for enhancing the thermal conductivity of NEPCM.

Keywords. Heat transfer fluid, Latent heat, NEPCM, Nanoparticles, PCM, Thermal energy storage system

1. Introduction

Energy plays a significant role in any country's economy. In the last few decades, United States, China, and Russia are first three largest energy consumers in the globe and India hold the fourth-largest energy consumer. Nearly 20 to 50 % of energy in the form of heat becomes waste from industry. The waste heat energy can be recovered and stored effectively in the energy storage system, and energy storage is likely to pay an increasing role in the energy economy. Energy storage is a very important entity when compared with the energy producing system. Moreover, global warming will be reduced [1].

Thermal energy storage system is utilized to collect and save the heat energy temporarily in the form of hot and cold substances for future use. Thermal energy storage system is used in various
engineering fields such as waste heat recovery [2, 3], solar water heater [4], solar air heater [5, 6], electronic devices [7, 8], and refrigeration and heat pump [9-11] with broad ranges of temperature. Heat may be collected and stored by different classes of techniques such as latent heat, sensible heat, and thermochemical heat storage. The PCM-based LHTES system is most attractive compared to the other two thermal storage systems due to heat recovery with the minimum temperature drop, heat source at a constant temperature, the vapour pressure at the operating temperature [12]. Also, the LHTES system is more preferred in comparison to sensible heat storage system due to the high storage energy densities per unit mass/volume of nearly constant heat energy [13].

Jegadheeswaran et al. [14], and Agyenim et al. [15] gave a thorough review of LHTES systems using different PCMs. Cunha and Emaes [16] and Sharma et al. [17] thoroughly studied the thermal energy storage system for different applications using PCMs. Gang Li [18] reviewed the various influencing factors of the LHTES system like melting temperature and number of PCM, additives for PCMs, the mass flow rate of heat transfer fluid and entry temperature storage unit dimension, sensible heating and sub-cooling, and heat exchanger surface enhancement, etc.

Ashish Agarwal and Sarviya [19] experimentally examined the heat transfer characteristics of the shell and tube LHTES system during melting and solidification process using air. They concluded that the time required for solidification of LHTES is longer compared to time required for melting of LHTES due to low heat transfer rate between PCM and air during solidification. Pandiyarajan et al. [20] investigated the encapsulated thermal storage system with paraffin wax for a diesel engine exhaust recovery by experimentally. They found that the percentage of total heat recovered from the engine was 10% to 15% at the load of 3.6 kW. Dheeraj et al. [21] studied the shell and tube type LHTES system using Erythritol for stationary compression ignition exhaust recovery by experimentation. Dheeraj et al. concluded that 69.53% of charging efficiency and 11.33% of energy saved at the load of 4.4 kW. Hosseini et al. [22] carried out a combined experimental and numerical study of thermal performance and heat transfer qualities of paraffin RT50 constrained melting and solidification process in the shell and tube heat exchanger. A phase transition is inexpensive and is more desirable where large heat storage capacity and constant temperature behavior is required. PCMs are widely used in various applications like solar plants, air-conditioning, cold start-ups and turbocharging in automobile engines.

The use of PCM in LHTES system is confined by low thermal conductivity [23]. Nanoparticles help to overcome this disadvantage because nanoparticles enhanced the thermal conductivity of NEPCMs compared to conventional PCMs. Hosseinizadeh et al. [24] analyzed the unconstrained dissolving of NEPCM within a globular vessel using paraffin RT27 with copper nanoparticles by theoretically. They concluded that the copper nanoparticles enhanced the thermal conductivity of NEPCM compared to paraffin wax. Ranjbar et al. [25] examined the heat transfer characteristic of the LHTES system comprising NEPCM. Their results showed that the suspended nanoparticles substantially enhanced the rate of heat transfer and the rate of nanofluid heat transfer also increased with an increase in the nanoparticles volume fraction. Jesumathy et al. [26] experimentally studied the thermal properties of paraffin wax with copper oxide nanoparticles. They found that the mixing of copper oxide nanoparticles with paraffin wax improved the conduction and free convection very effectively in composites and also with paraffin wax.

The above literature review shows that the large number of research work has been done in the area of the thermal energy storage system but only a few studies have focused on the latent heat thermal energy storage system with PCM and NEPCM during either charging or discharging process. There is a need for the development of a simple and low cost latent heat storage system. The present study aims to work under the various flow rate of heat transfer fluid with the LHTES system using PCM and NEPCM during charging and discharging process.

2. Experimental setup
Schematic representation and photographic view of the experimental setup are shown in figure 1 and figure 2. The experimental setup includes an industrial water immersion heater, flow meters, check valves, and LHTES tank with PCM and NEPCM. The industrial water immersion heater is attached to the bottom of the hot water tank. The centrifugal pump is used to circulate in closed loop hot water to pass through the vertical tubes of the LHTES tank for the charging process. The second centrifugal pump helps to circulate in closed loop cold water, to flow through the spiral tube side of the LHTESS for the discharging process. The flow meters with an accuracy of ± 2% is used to measure the flow rate of hot and cold water. The K-type thermocouples (Nickel-Chromium / Nickel-Alumel) with the accuracy of ± 0.5 °C are located at entry and exit of the LHTES tank in the cold water pipelines to measure the temperatures. The LHTES tank, water tanks, and connecting pipelines are properly insulated by the glass wool fiber material to avoid heat leakage to the atmosphere.

**Figure 1.** Schematic representation of experimental setup
3. **Low temperature LHTES system**

The geometry of a copper spiral tube, LHTES tank, and CAD diagram are shown in figures 3(a), (b), and (c) respectively. The specifications of LHTES tank are given in table 1. The cross-sectional view and layout of LHTES system are shown in figure 4 and figure 5. The LHTES tank made up of mild steel cylindrical vessels of inner diameter 360 mm and height 460 mm with a wall thickness of 6 mm. 18 tubes with inner diameters of 10 mm and tube thickness of 2 mm are arranged. Initially, 19.8 kg of PCM (paraffin wax) and then 0.20 kg of copper oxide nanoparticles added with PCM were filled in the gap between the shell and tubes of the LHTES tank. Thermo physical properties of the paraffin (PCM), CuO and NEPCM are shown in table 2. The LHTES tank is evenly split into four layers along its axial direction such as L/Y=0.25, L/Y=0.5, L/Y=0.75 and L/Y=1.00. The K-type thermocouples are located at these four layers in the LHTES tank to measure the temperatures of PCM, as shown in figure 6. 30 and 20 kg of waters are circulated through the vertical pipe and spiral tube in the LHTES tank with various flow rates for charging and discharging process.

NEPCMs play a significant role in the enhancement of heat transfer performance of the PCM in an LHTES system. The paraffin wax and copper oxide nanoparticles are appropriately mixed by using a magnetic stirrer for thirty minutes at the temperature of 60 °C. Then the mixer of paraffin wax and copper oxide nanoparticles are dispersed by an ultrasonic vibrator for three hours to get stable suspension and homogeneity.
**Figure 3.** (a) Geometry of a spiral tube

**Figure 3.** (b) LHTES tank

**Figure 3.** (c) CAD diagram

**Figure 3.** LHTES tank
4. Experimental methodology

The experiments are carried out for the two different materials such as paraffin wax and paraffin wax with copper oxide nanoparticles for charging and discharging process. The LHTES tank is integrated with two water tanks such as hot and cold water tanks during the charging and discharging process for particular flow rate, respectively. The hot and cold water temperatures were continuously monitored using thermocouples.
Figure 6. Locations of thermocouples in the LHTES tank

Table 1. Specifications of LHTES tank

| Shell side parameters: | Mass (kg) |
|------------------------|-----------|
| Material               | Mild Steel| Paraffin         | 19.8 |
| Height                 | 460 mm    | Copper oxide nanoparticles | 0.20 |
| Inner radius           | 180 mm    | Paraffin and CuO nanoparticles | 20  |
| Thickness              | 6 mm      | Water in hot water tank    | 30  |
|                        |           | Water in cold water tank   | 20  |

| Tube parameters:       | Spiral tube parameters: |
|------------------------|-------------------------|
| Material               | Copper                  |
| Length                 | 460 mm                  |
| Inner radius           | 5 mm                    |
| Outer radius           | 7 mm                    |
| Thickness              | 2 mm                    |
| Tube type arrangement  | Longitudinal            |
| No. of longitudinal tubes | 18                    |

At the beginning of the experiments, charging line pump is switched on, and valves which are available in the charging line are opened, and simultaneously the discharging pump is stopped and also valves in the discharging line are closed. The hot water is permitted to pass through vertical pipes in the LHTES tank for charging process. Experimental analyses are conducted out at three different flow rates such as 2, 4 and 6 lpm with regular periods. The temperatures were observed at regular periods about the
The temperature behavior of PCM in the LHTES tank during charging process that is at L/Y = 0.25, 0.50, 0.75 and 1.0 are shown in figure 7a - 7c for constant entry temperatures of hot water at different flow rates such as 2, 4, and 6 lpm.

Figure 7c interprets the temperature behavior of PCM in the LHTES tank at the constant water temperature at 70 °C for a flow rate of 6 lpm during charging process. It is seen from the figure that the PCM temperature at all the layers increases at a faster rate. However, the rise of PCM temperature in the first layer is fast as the hot water enters at the head of the LHTES tank. Once PCM available in the first layer gets completely melted, then the PCM temperature in the second layer is reaches to the first layer temperature. The same trend is followed in the consecutive layers. The similar trend is observed in PCM temperature profiles for 2 lpm and 4 lpm at 70 °C as shown in figures 7a and 7b. It is seen from figures 7a and 7c that the phase change occurred at first to the fourth layer of PCM in the LHTES tank at 2 lpm load are 170 and 230 min; similarly, the phase change took place at first to the fourth layer of PCM in the LHTES tank at 6 lpm are 120 and 160 min. The maximum temperature of PCM in the LHTES tank reaches 70 °C, the total heat energy stored in the LHTES tank is 5,835 kJ. It is also seen from figures.7a - 7c the maximum temperature of PCM in the LHTES tank reaches 70 °C at the flow rate of 6 lpm compared to the flow rate of 4 lpm and 2 lpm. It shows that, when the flow rate is increased, melting rate also get increased. The charging rate of PCM in the LHTES tank at the flow rate of 6 lpm is 0.353 kW, and it decreases to 0.295 kW and 0.278 kW for 4 lpm and 2 lpm.

Total heat energy stored in the LHTES tank = Sensible heat energy + Latent heat energy

\[
\int_{T_1}^{T_{s}} \left( m_{PCM} \cdot C_{p,PCM} \right) \, dT + \int_{T_1}^{T_{s}} \left( m_{PCM} \cdot C_{p,PCM} \right) \, dT
\]
Sensible heat energy  
\[ Q_{\text{sensible}} = m \times C_{\text{pcm}} \times (T_2 - T_1) \quad \text{(kJ)} \quad \text{(2)} \]

Latent heat energy  
\[ Q_{\text{latent}} = m_{\text{pcm}} \times L_{\text{pcm}} \quad \text{(kJ)} \quad \text{(3)} \]

Where \( m_{\text{pcm}} \) is the mass, \( T_1, T_2 \) are the initial and final temperature, \( T_m \) is the melting temperature, \( C_{\mu, PCM} \), \( C_{\psi, PCM} \) are the specific heats of the liquid and solid phases and \( L_{pcm} \) is the latent heat of fusion of PCM.

The charging rate of PCM is the ratio of the total heat energy stored in the LHTES tank to the time duration of charging and is calculated using Eq. (4)

\[
Q_{cr} = \frac{\int_{t_1}^{t_2} m_{pcm} \times C_{\mu, PCM} \times dT + m_{pcm} \times L_{pcm} + \int_{t_1}^{t_2} m_{pcm} \times C_{\psi, PCM} \times dT}{\Delta t_c} \quad \text{(kW)}
\]

**Figure 7a.** Temperature variation of PCM during charging process in LHTES tank at 2 lpm
5.2 Temperature behavior of PCM in the LHTES tank during discharging process

The temperature behavior of PCM at four layers of the LHTES tank during discharging process that is at L/Y= 0.25, 0.50, 0.75 and 1.0 are shown in figures 7a - 7c for the cold water at different flow rates (that is 2, 4, and 6 lpm).

Figure 7c interprets the temperature behavior of PCM in the LHTES tank for the flow rate of 6 lpm during discharging process. It is seen from the figure that the PCM temperature at all the layers decreases. However, there is a fall in PCM temperature in the last layer at a faster rate due to the flow of cold water.
at the bottom side of the LHTES tank. Once PCM available in the last layer gets completely solidified, and then the PCM temperature in the third layer reaches to the last layer temperature. The same trend is followed in the consecutive layers. This similar trend is observed in PCM temperature profiles for 4 lpm and 2 lpm shown in figures.7b and 7a. It is seen from figures.7a and 7c that the phase change occurred at fourth to the first layer of PCM in the LHTES tank at 2 lpm load are 120 and 140 min; similarly, the phase change occurred at fourth to the first layer of PCM in the LHTES tank at 6 lpm are 50 and 70 min. The minimum temperature of PCM in the LHTES tank attains 54 °C. It is also observed from figures.7a - 7c the minimum temperature of PCM in the LHTES tank attains 54 °C during very short period of time at the flow rate of 6 lpm compared to the flow rate of 4 lpm and 2 lpm. It shows that, when there is an increase in flow rate, there is an increase in solidification rate also. The discharging rate of PCM in the LHTES tank at the flow rate of 6 lpm is 1.08 kW, and it get decreased to 0.748 kW and 0.608 kW for 4 lpm and 2 lpm due to an increase in temperature of cold water achieved at higher flow rates within a short span.

The discharging rate of PCM is ratio of the total heat recovered from PCM in the LHTES tank to the time duration of discharging and is calculated using Eq. (5)

\[
Q_w = \frac{\int_{t_1}^{t_2} m_{PCM} C_{PCM} dT + m_{PCM} L_{PCM} + \int_{t_1}^{t_2} m_{PCM} C_{PCM} dT}{\Delta t_d}
\]

(5)

5.3 Temperature behavior of NEPCM in the LHTES tank during charging process

The temperature behavior of NEPCM at four layers of the LHTES tank during charging process that are at L/Y= 0.25, 0.50, 0.75 and 1.0 are shown in figures.8a - 8c for constant entry temperatures of hot water at different flow rates (that is 2, 4, and 6 lpm).

Figure 8c interprets the temperature behavior of NEPCM in the LHTES tank at constant temperature (70 °C) of water with the flow rate of 6 lpm during charging process. It is seen from the figure that the NEPCM temperature at all the layers increases at a faster rate. However, the rise of NEPCM temperature in the first layer is very quick as the hot water enters at the head of the LHTES tank. Once NEPCM available in the first layer is completely melted, then the NEPCM temperature in the second layer also reaches the first layer temperature. The same trend is followed in the consecutive layers. This similar trend is observed in NEPCM temperature profiles for 2 lpm and 4 lpm at 70 °C as shown in figures 8a and 8b. It is seen from figures.8a and 8c that the phase change occurred at first to the fourth layer of NEPCM in the LHTES tank at 2 lpm load are 100 and 140 min; similarly, the phase change occurred at first to the fourth layer of NEPCM in the LHTES tank at 6 lpm are 80 and 110 min. When the temperature of NEPCM in the LHTES tank reaches its maximum of 70 °C, the total heat energy stored in the LHTES tank is 5,932 kJ. It is also seen from figures.8a - 8c the maximum temperature of NEPCM in the LHTES tank reaches 70 °C with the flow rate of 6 lpm when compared to the flow rate of 4 lpm and 2 lpm. It shows that, as the flow rate is increased, melting rate also get increased. The charging rate of NEPCM in the LHTES tank at the flow rate of 6 lpm is 0.471 kW, and it decreases to 0.429 kW and 0.353 kW for 4 lpm and 2 lpm.

From the table 3, it is observed that the charging rate in the LHTES using NEPCM is 33.33% more than charging rate in the LHTES using PCM at the flow rate of 6 lpm due to adding copper oxide nanoparticles with paraffin wax for enhancing the thermal conductivity of NEPCM.

The thermophysical characteristics and total heat energy stored in the NEPCM were determined using Eqs. (6) – (8)

NEPCM density, \( \rho_{NEPCM} \) was calculated from Eq. (6)
NEPCM specific heat, $C_{p, \text{NEPCM}}$, was calculated from Eq. (7):

$$C_{p, \text{NEPCM}} = \frac{(1 - \phi)C_{p, \text{PCM}} + \phi C_{p, \text{s}}}{\rho_{\text{NEPCM}}}$$

Total heat energy stored in the NEPCM, $Q_{\text{NEPCM}}$, was obtained by using Eq. (8):

$$Q_{\text{NEPCM}} = m_{\text{NEPCM}} C_{p, \text{NEPCM}} \Delta T_{\text{NEPCM}} + m_{\text{NEPCM}} L_{\text{NEPCM}}$$

The charging rate of NEPCM is the ratio of the total heat energy stored in the LHTES tank to the time duration of charging and is calculated using Eq. (9):

$$Q_{\text{cr, NEPCM}} = \frac{m_{\text{NEPCM}} C_{p, \text{NEPCM}} \Delta T_{\text{NEPCM}} + m_{\text{NEPCM}} L_{\text{NEPCM}}}{\Delta t_c} \text{ (kW)}$$

![Figure 8a. Temperature variation of NEPCM during charging process in LHTES tank at 2 lpm](image-url)
Figure 8b. Temperature variation of NEPCM during charging process in LHTES tank at 4 lpm

![Figure 8b](image.png)

Figure 8c. Temperature variation of NEPCM during charging process in LHTES tank at 6 lpm

Table 3. Experimental data for charging and discharging process using PCM and NEPCM in LHTES tank

| Name of the material | Flow rate of water (lpm) | Time to reach Max. Temp. (70 °C) in L/Y=0.25 of LHTES tank (min) | Time to reach Min. Temp. (Approx. 54 °C) in L/Y=0.25 of LHTES tank (min) | Charging rate (kJ) | Discharging rate (kJ) |
|---------------------|--------------------------|---------------------------------------------------------------|---------------------------------------------------------------|-------------------|----------------------|
| PCM                 | 2                        | 350                                                           | 190                                                           | 0.278             | 0.608                |
|                     | 4                        | 330                                                           | 150                                                           | 0.295             | 0.748                |
|                     | 6                        | 310                                                           | 110                                                           | 0.314             | 1.08                 |
| NEPCM               | 2                        | 280                                                           | 140                                                           | 0.353             | 0.824                |
|                     | 4                        | 230                                                           | 120                                                           | 0.429             | 1.098                |
|                     | 6                        | 210                                                           | 90                                                            | 0.471             | 1.412                |

5.4 Temperature behavior of NEPCM in the LHTES tank during discharging process

The temperature behavior of NEPCM at four layers of the LHTES tank during discharging process that is at L/Y= 0.25, 0.50, 0.75 and 1.0 are shown in figures 8a - 8c for the cold water at different flow rates (that is 2, 4, and 6 lpm).

Figure 8c interprets the temperature behavior of NEPCM in the LHTES tank for the flow rate of 6 lpm during discharging process. It is observed from the figure that the temperature of NEPCM at all the layers get decreased. However, the fall in temperature of NEPCM in the last layer at a faster rate due to the cold water enters at the bottom of the storage tank. Once NEPCM present in the last layer gets completely solidified, then the NEPCM temperature in the third layer attains the temperature of the last layer. This same trend is followed in the consecutive layers. The similar trend is observed in NEPCM temperature profiles for 4 lpm and 2 lpm shown in figures 8b and 8a. It is seen from figures 8a and 8c that the phase
change occurred at fourth to the first layer of NEPCM in the LHTES tank at 2 lpm load are 70 and 90 min; similarly, the phase change occurred at fourth to the first layer of PCM in the LHTES tank at 6 lpm are 50 and 60 min. The minimum temperature of PCM in the LHTES tank attains 54 °C. It is also observed from figures.8a - 8c the minimum temperature of PCM in the LHTES tank attains 54 °C during very short period of time at the flow rate of 6 lpm compared to the flow rate of 4 lpm and 2 lpm. It shows that, as the flow rate is increases, there is a rise in solidification rate also. The discharging rate of PCM in the LHTES tank at the flow rate of 6 lpm is 1.412 kW, and it decreases to 1.098 kW and 0.824 kW for 4 lpm and 2 lpm due to increase in cold water temperature achieved at higher flow rates within a short span. From the table 3, it is observed that the discharging rate in the LHTES using NEPCM is 23.51% more than discharging rate in the LHTES using PCM at the flow rate of 6 lpm due to adding copper oxide nanoparticles with paraffin wax for improving the thermal conductivity of NEPCM.

5.5 Temperature behavior of cold water during discharging process (PCM and NEPCM)

The temperature behavior of cold water at the entry and exit of the LHTES tank (PCM and NEPCM) are shown in figures 9 and 10 for different flow rates (that is 2, 4, and 6 lpm).

Figures 9 and 10 show the temperature variation of water at the entry and exit of the LHTES tank (PCM and NEPCM) with respect to time for different flow rates of water. It is seen from the figure that the cold water temperature for the flow rate of 6 lpm is increasing very quickly compare than the other flow rate such as 4 lpm and 2 lpm. The temperature of the water increases to a maximum of 54 °C from the ambient temperature. The time duration of heating the water decreases by increasing the flow rate of water. The rate of heat transfer is directly proportional to mass flow rate for the constant area of the spiral tube. Initially, the temperature of the water gradually increases due to the heat energy available in PCM (or NEPCM) until the thermal equilibrium is achieved between the water and PCM (or NEPCM). After thermal equilibrium between PCM (or NEPCM) and water is reached, the water pump is stopped. The water reaches a maximum temperature of 54 °C with the short duration of time during discharging process using NEPCM in the LHTES tank, due to the high discharging rate of NEPCM compared to PCM in the LHTES tank.

![Figure 9. Temperature variation of water during charging process in LHTES tank with PCM at various flow rates](image-url)
Figure 10. Temperature variation of water during charging process in LHTES tank with NEPCM at various flow rates

6. Conclusions

In the current experimental work on the charging/discharging of the PCM and NEPCM based LHTES tank is analyzed based on the outcomes, the following inferences are drawn:

1. The total heat energy stored of PCM and NEPCM based LHTES tank is 5,835 kJ and 5,932 kJ.
2. The temperature behavior of PCM and NEPCM for different flow rates of water during charging and discharging process with respect to time are studied.
3. The rate of charging of PCM in the LHTES tank is 0.314 kW at the flow rate of 6 lpm and it decreases to 0.295 kW and 0.278 kW for 4 lpm and 2 lpm, respectively.
4. The rate of charging of NEPCM in the LHTES tank is 0.471 kW at the flow rate of 6 lpm and it decreases to 0.429 kW and 0.353 kW for 4 lpm and 2 lpm, respectively.
5. The rate of discharging of PCM in the LHTES tank is 1.08 kW at the flow rate of 6 lpm and it decreases to 0.748 kW and 0.608 kW for 4 lpm and 2 lpm, respectively due to increase in cold water temperature achieved at higher flow rates within a short duration.
6. The rate of discharging of PCM in the LHTES tank is 1.412 kW at the flow rate of 6 lpm and it decreases to 1.098 kW and 0.824 kW for 4 lpm and 2 lpm, respectively due to increase in cold water temperature achieved at higher flow rates within a short span.
7. The rate of charging and discharging in the LHTES using NEPCM is 33.33% and 23.51% more than discharging rate in the LHTES using PCM at the flow rate of 6 lpm due to adding copper oxide nanoparticles with paraffin wax for enhancing the thermal conductivity of NEPCM.
8. The cold water temperature rises nearly 54°C during discharging process of LHTES tank.

7. Nomenclature

| Symbol | Description |
|--------|-------------|
| Cp     | Specific heat at constant pressure (J/kg K) |
| L      | Latent heat fusion (J/kg) |
| LHTES  | Latent heat thermal energy storage (-) |
| M      | Mass |
NEPCM Nanoparticle-enhanced phase change material (-)
PCM Phase change material (-)
Qcr Charging rate (kW)
\( t \) Charging time (s)
\( T_1, T_2 \) Temperatures of the PCM and NEPCM during the time interval \( t \) (°C)
Tm Melting temperature of paraffin (°C)

**Greek abbreviations**
\( \rho \) Density (kg/m\(^3\))
\( \phi \) Volume fraction of nanoparticle

**Subscripts**
c Charging
d Discharging
l Liquid
s Solid (nanoparticle)

8. REFERENCES

[1] António Domingues, Helder Santos, Mário Costa 2013 Analysis of vehicle exhaust waste heat recovery potential using a Rankine cycle, *Energy*. 49, 71-85

[2] Pandiyarajan V, Chinnapandian M, Raghavan V, Velraj R 2011 Second law analysis of a diesel engine waste heat recovery with a combined sensible and latent heat storage system, *Energy Policy*. 39, 6011-6020

[3] Dheeraj Kishor Johar, Dilip Sharma, Shyam Lal Soni, Pradeep K. Gupta, Rahul Goyal 2017 Experimental investigation and exergy analysis on thermal storage integrated micro-cogeneration system, *Energy Conversion and Management*. 131, 127-134.

[4] Nallusamy N, Sampth S, Velraj R 2007 Experimental investigation on a combined sensible and latent heat storage system integrated with constant/varying (solar) heat sources, *Renewable Energy*. 32, 7, 1206-1227

[5] Kabeel A E, Khalil A, Shalaby S M, Zayed M E 2016 Experimental investigation of thermal performance of flat and V-corrugated plate solar air heaters with and without PCM as thermal energy storage, Energy Conversion and Management. 113, 264-272

[6] Morrison D J, Abdel-Khalik S I 1978 Effects of phase-change energy storage on the performance of air-based and liquid-based solar heating systems, *Solar Energy*. 20, 1, 57-67

[7] Yaqin Wang, Xuenong Gao, Peng Chen, Zhaowen Huang, Tao Xu, Yutang Fang, Zhengguo Zhang 2016 Preparation and thermal performance of paraffin/Nano-SiO2nanocomposite for passive thermal protection of electronic devices, *Applied Thermal Engineering*. 96, 699-707

[8] Victor N Nemykin, Elena A Makarova, Jeffrey O Grosland, Ryan G Hadt, Alexey Y Koposov 2007 Preparation, characterization, molecular and electronic structures, TDDFT, and TDDFT/PCM study of the solvatochromism in cyanovinylferrocenes, *Inorganic Chemistry*. 46, 23, 9591-9601

[9] Cheralathan M, Velraj R, Renganarayanan S 2017 Performance analysis on industrial refrigeration system integrated with encapsulated PCM based cool thermal energy storage system, *International Journal of Energy Research*. 31, 1398-1413

[10] Michael Beck, Karsten Müller, Wolfgang Arlt 2016 Storing surplus solar energy in low temperature thermal storage for refrigeration applications, *Energy and Buildings*. 122, 192-198

[11] Jradi M, Veje C, Jørgensen B N 2017 Performance analysis of a soil-based thermal energy storage system using solar-driven air-source heat pump for Danish buildings sector, *Applied Thermal Engineering*. 114, 360-373
[12] Hosseini M J, Ranjbar A A, Sedighi K, Rahimi M 2012 A combined experimental and computation study on the melting behavior of a medium temperature phase change storage material inside shell and tube heat exchanger, International Communications in Heat and Mass Transfer, 39, 9, 1416-1424

[13] Abduljalil A. Al-Abidi, Sohif Mat, K. Sopian, M.Y.Sulaiman, Abdulrahman Th. Mohammad 2013 Internal and external fin heat transfer enhancement technique for latent heat thermal energy storage in triplex tube heat exchangers, Applied Thermal Engineering, 53, 1, 147-156

[14] Jegadheeswaran S, Pohekar S D 2009 Performance enhancement in latent heat thermal storage system: A review, Renewable and Sustainable Energy Reviews. 13, 2225-2244

[15] Francis Agyenim, Neil Hewitt, Philip Eames, Mervyn Smyth 2010 A review of materials, heat transfer and phase change problem formulation for latent heat thermal energy storage systems (LHTESS), Renewable and Sustainable Energy Reviews. 14, 2, 615-628

[16] Cunha J, Eames P 2016 Thermal energy storage for low and medium temperature applications using phase change materials – A review, Applied Energy. 177, 227-238

[17] Atul Sharma, Tyagi V V, Chen C R, Buddh V D 2009 Review on thermal energy storage with phase change materials and applications, Renewable and Sustainable Energy Reviews. 13, 2, 318-345

[18] Gang Li 2015 Energy and exergy performance assessments for latent heat thermal energy storage systems, Renewable and Sustainable Energy Reviews. 51, 926–954

[19] Ashish Agarwal, Sarviya R M 2016 An experimental investigation of shell and tube latent heat storage for solar dryer using paraffin wax as heat storage material, Engineering Science and Technology. An International Journal. 19, 619-631

[20] Pandiyarajan V, Chinya Pandian M, Malan E, Velraj R, Seeniraj R V 2011 Experimental investigation on heat recovery from diesel engine exhaust using finned shell and tube heat exchanger and thermal storage system. Applied Energy. 88, 77-87

[21] Dheeraj Kishor Johar, Dilip Sharma, Shyam Lal Soni, Pradeep K. Gupta, Rahul Goyal 2016 Experimental investigation on latent heat thermal energy storage system for stationary C.I. engine exhaust. Applied Thermal Engineering. 104, 64-73

[22] Hosseini M J, Rahimi M, Bahrampouri R 2013 Experimental and computational evolution of a shell and tube heat exchanger as a PCM thermal storage system. International communications in Heat and Mass Transfer. 50, 128-136

[23] Medrano M, Yilmaz M O, Nogues M, Martorell I, Joan Roca, Luisa F. Cabeza 2009 Experimental Evaluation of Commercial Heat Exchangers for Use as PCM Thermal Storage Systems. Applied Energy. 86, 2047-2055

[24] Hosseinzadeh S F, Rabienatj Darzi A A, Tan F L 2012 Numerical Investigations of Unconstrained Melting of Nano-enhanced Phase Change Material (NEPCM) Inside a Spherical Container. International Journal of Thermal Sciences. 51, 77-83

[25] Ali Akbar Ranjbar, Sina Kashani, Seyed Farid Hosseinzadeh, Morteza Ghanbarpour 2011 Numerical Heat Transfer Studies of a Latent Heat Storage System Containing Nano-enhanced Phase Change Material. Thermal Science. 15, 169-181

[26] Jesumathy S, Udayakumar M, Suresh S 2012 Experimental Study of Enhanced Heat Transfer by Addition of CuO Nanoparticle. Heat Mass Transfer. 48, 965-978