Heat Transfer Enhancement in a PCM Based Thermal Energy Storage System Using Water Based Nanofluids

S.Naresh#1, Dr. R. Meenakshi Reddy*2, E. Siva Reddy*3 & K. Thimma Reddy#4
#Department of mechanical engineering, G.Pulla Reddy Engineering College, Kurnool, Andhra Pradesh , India
*Associate professor Department of mechanical engineering , G.Pulla Reddy Engineering college, Kurnool , Andhra Pradesh , India
*Assistant professor Department of mechanical engineering , G.Pulla Reddy Engineering college, Kurnool , Andhra Pradesh , India

Abstract -- Thermal energy storage (TES) systems are becoming an increasing concern in modern technologies and it provides several alternatives for efficient energy use and conservation. The fundamental idea of a TES system is to support the energy management by storing thermal energy at periods when it is abundantly available and using it when required. Among different possibilities using PCMs are more fashionable for its consistency in latent heat storage. The present experimental investigation on the thermal energy storage (TES) system is developed using stearic acid as PCM by use of water based NANO FLUIDS. In the present system constant heat is used as heat source to store the thermal energy in the form of sensible heat and latent heat. In the TES system stearic acid are stored in the form of spherical capsules of 150 mm diameter.

Thermal conductivity is considered important factor for rapid cooling and heating application. Base heat transfer fluid normally having low thermal conductivity, so we goes to Nanofluid for increases the heat transfer rate. Nanofluid is nanometer sized particle such as metal, oxide, and carbide etc., dispersed into base heat transfer fluid. The performance of the system is analyzed such as energy storage capacity, energy retrieval capacity of the system by varying water flow rate, charging time, discharging time.

Keywords -- Thermal energy storage(TES), Phase change material (PCM),Heat transfer fluid (HTF), Flow rate

I. INTRODUCTION

Energy is one of the most important inputs for the economic growth of any nation. In the case of the developing countries, the energy sector assumes a decisive importance in view of the rising energy needs requiring huge investments to meet them. The continuous increase in the level of utilization of energy and the climb in fuel prices are the main driving forces behind the research toward energy storage. The thermal energy is a main topic in research for last 20 years .thermal energy can be stored as a change in the internal energy of certain materials as sensible heat, latent heat or both.

Energy Conservation and Its Importance

Energy conservation is achieved when growth of energy consumption is reduced, measured in physical terms. Energy Conservation can, therefore, be the result of several processes or developments, such as productivity increase or technological progress.

Thermal Energy Storage

The continuous increase in the level of utilization of energy and the climb in fuel prices are the main driving forces behind the research toward energy storage. Thermal energy storage (TES) in general and phase change materials (PCM) in particular, have been an area of researchers for the last two decades. Latent heat storage system has the advantages of high –energy storage density and isothermal behavior during the charging and discharging process. The utilization of TES systems reduces energy consumption and provides an alternative as fossil fuels are getting depleted.

Three types of TES systems are common in practice:

Sensible, latent, and thermo-chemical. The selection of TES is generally dependent on the storage period required, economic viability and operating conditions.

Combined sensible and latent heat storage systems
For the purpose of transfer of heat the containers of PCM are surrounded by SHS material in the combined sensible and latent heat storage system.

The following Benefits are observed from such systems:

- Compact in size,
- Superior heat capacity,
- Improved heat transfer rate,
- Isothermal charging and discharging, and
- Economical operation.

This system finds many applications in domestic, commercial and industrial sectors. It is interesting to note that the combined sensible and latent heat storage system has been successfully introduced in the air-conditioned application also.

Advantages of Thermal Energy Storage:

- Dynamic balancing between energy demand and availability.
- Conservation of primary fuels
- Reduce the equipment size and the initial cost.
- More effective and efficient utilization of equipment.
- Utilization of waste heat recovery
- Maintenance of environmental quality
- Greater flexibility in operation
- Economical energy consumption
- Thermal protection and control of electronic components
- Heating and cooling of buildings and Hot water preparation.

Steric acid properties:

PCM plays a very dominant role in the TES system. The selection of the PCM is made based on various parameters like latent heat, melting point, operating temperature range, specific volume, boiling point, availability, cost etc., After the consideration of these factors, Stearic Acid is selected as PCM for present work. The function of the PCM is to absorb the heat energy from the surface of exhaust gas flow type. After gaining the sufficient heat energy it changes its phase from solid to liquid and again converts to solid phase after releasing heat energy.

The properties are as follows:
- Molecular Formula – C18H36O2
- It is a waxy solid
- Appearance White solid Odor pungent
- Melting point is 57°C
- Boiling point is 383 °C
- Thermal conductivity 0.173W/mK

Extended surfaces (Fins):

This is used to increase the rate of heat dissipation from or to the environment by increasing the rate of convection. The total of convection, conduction, or radiation of an object decides the amount of heat it dissipates. It increases with the difference of temperature between the environment and the object, also increasing the convection coefficient of heat transfer, or increasing the surface area.

Nanofluids:

Suspended nanoparticles in various base fluids can alter the fluid flow and heat transfer characteristics of the base fluids. These suspensions of nano sized particles in the base fluids are called nanofluids. Nanofluids are suspensions of nanoparticles in a base fluid, typically water. The term nanoparticle comes from the Latin prefix ‘nano’. It prefix is used to denote the 10^-9 part of a unit. Recent development of nanotechnology brings out a new heat transfer coolant called ‘nanofluids’. These fluids exhibit larger thermal properties than conventional coolants. The much larger relative surface area of nanoparticles, compared to those of conventional particles, not only significantly improves heat transfer capabilities, but also increases the stability of the suspension.

Characteristic Features of Nanofluids:

- Increased thermal conductivity even at low concentration of nano particles.
- Strong temperature dependent thermal conductivity.
- Non linear increase in thermal conductivity with concentration of nano particles.
- Increase in boiling critical heat flux.

II. EXPERIMENTAL SETUP AND DESIGN DETAILS:

A TES system is intended and evaluated for its thermal performance observance in that the system should be able to supply hot water at an average temperature of 45°C for domestic use in general. The thermal performance of the system is investigated by water based nanofluids with fin. Both charging and discharging experiments are carried out for evaluating the performance of
the system, by integrating with constant inlet heat source.

Estimation of Nanoparticle Volume Concentration

The amount of Al2O3 nanoparticles required for preparation of nanofluids is calculated using the law of mixture formula.

\[
\% \text{ volume concentration } \phi = \frac{W_p/\rho_p}{W_f/\rho_f + W_p/\rho_p}
\]

Where,

- \( W_p \): Weight of Nano Particles, Grams
- \( \rho_p \): Density of Al2O3 Nano Particles = 3.9 gm/cm³
- \( W_f \): Weight of base fluid (water), Grams
- \( \rho_f \): Density of base fluid (water) = 995 kg/m³

Volume Concentrations of Al2O3 Nanoparticle with corresponding weight

The amount of Al2O3 nanoparticles required to prepare nanofluids of different percentage volume concentration in a 20liter of base fluid is summarized in the Table shown below.

<table>
<thead>
<tr>
<th>S.no</th>
<th>Volume concentration (%)</th>
<th>Weight of nano particle(gms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.02</td>
<td>15.6104</td>
</tr>
<tr>
<td>2</td>
<td>0.08</td>
<td>62.448</td>
</tr>
</tbody>
</table>

Test Rig:


The above fig. Shows the set-up used in the study of thermal performance of TES system using latent heat and sensible heat of the PCMs. In present system Investigations are carried out to improve the performance of the system adding of nano fluids to heat transfer fluid (water) and used it as heat transfer fluid (HTF) and also to increase heat transfer, fins are arranged to the PCM storage spherical capsule finally the storage tank is insulated to reduce the heat transfer losses like conduction, convection, radiation losses.

Experimental Procedure:

The processes in a general TES system.

Charging process

The heat is transferred to or from HTF as it flows on the spherical capsule. During charging the hot HTF is circulated through the tank by the pump employed in the circuit. The PCM inside the capsules absorbs heat and melts. The difference between the mean temperature of HTF and PCM must be sufficient to obtain a satisfactory rate of heat transfer.

During this process at various levels the HTF temperature and PCM temperatures are noted. After the tank is filled, the outlet valve is opened and adjusted such that the water level in the tank is maintained constant.

The circulation of HTF is continued at the given flow rate, till the same temperature is
attained by the PCM. The charging experiments are conducted for the HTF at 2lit/min, 4 lit/min with 0.02% and 0.08% concentrations of nano fluids. The charging experiments are repeated for the mild steel spherical capsule with fin (circular) and without fin.

**Discharging process**

The discharging process can be by continuous/batch wise process. However, it is reported in the literature that batch wise process is more effective where the requirement is intermittent.

A certain quantity of hot water (5 Lit) is withdrawn from TES tank and the tank is again filled with cold water of quantity equal to the amount of water withdrawn. This fixed quantity of 5 lit of water which is withdrawn from the TES tank to facilitate filling up of fresh cold water is termed as batch. After a time interval of 20 minutes allowing for transfer of energy from PCM, another batch of 5 lit of water is withdrawn from the TES tank. This process is continued until the average temperature of the complete amount of water withdrawn is about 45°C.

**Numerical Studies:**

A thermal energy storage system is designed and evaluated for its thermal performance. The thermal performance of the system is evaluated based on the heat energy retrieval from the system. In this the theoretical calculations are carried out for evaluating the performance of the system.

**Calculation Procedure:**

**Mass of the PCM:**

Volume of the ball = 1.6 lit

Clearance volume of the ball = 0.2lit

Total volume considered for the PCM = 1.4lit (1.6lit-0.2lit)

Mass of the PCM ($m_{pcm}$)

= Density × volume = 960 × 1.4 × 10^{-3}

$m_{pcm}$ = 1.344 kg

**Total heat of PCM stored in spherical capsule is**

\[ Q = (m_{pcm} c_p \Delta t)_{solid} + (m_{pcm} L) + (m_{pcm} c_p \Delta t)_{liquid} \]

\[ Q = 0.0387 + 0.2673 + 0.0710 \]

\[ Q_{pcm} = 0.377MJ \]

**Mass flow rate of HTF**

Mass flow rate of water = density of water × flow rate

- **Flow rate of HTF when it is 2lit/min**

  Mass flow rate ($m_{htf}$)

  \[ = 1000 \times 2 \times (10^{-3}) \div 60 \]

  \[ m_{htf} = 0.0333 kg/sec \]

- **Flow rate of HTF when it is 4lit/min**

  Mass flow rate ($m_{htf}$)

  \[ = 1000 \times 4 \times (10^{-3}) \div 60 \]

  \[ m_{htf} = 0.0666 kg/sec \]

**Calculation of amount of Heat transfer and Efficiency of TES system:**

Heat transfer and efficiency of PCM based TES system with Circular fin by using water as HTF when the flow rate is 2lit/min:

Total time duration for charging process = 140min

Mass flow rate of HTF ($m_{htf}$) = 0.0333kg/sec

Specific heat ($c_p$) = 4.187kJ/kg k

Temperature difference ($\Delta t$) = $T_{in}$-$T_{out}$

Heat input of HTF ($Q$) = $m_{htf} c_p \Delta t$

\[ Q = 0.0333 \times 4.187 \times 10^3 \times (80-79) \]

\[ Q = 139.427 J/s \]

Total heat input of HTF ($Q_{in}$) = heat input × total time duration

\[ Q_{in} = 139.427 \times 140 \times 60 \]

\[ Q_{in} = 1.171 MJ \]

Heat output of HTF ($Q_{out}$)

\[ Q_{out} = Q_{in} - Q_{pcm} \]

\[ Q_{out} = 1.171 - 0.377 \]

\[ Q_{out} = 0.794 MJ \]

Efficiency of the TES system ($\eta$)

\[ \eta = \frac{Q_{out}}{Q_{pcm}} \]

\[ \eta = \frac{1.171-0.377}{1.171} = 32.17\% \]
### Summary of Numerical results for the TES system:

<table>
<thead>
<tr>
<th>s.no</th>
<th>Nanofluid concentration (%)</th>
<th>Fin type</th>
<th>Flow rate of HTF (lit/min)</th>
<th>Charging time (mins)</th>
<th>$Q_n$ (MJ)</th>
<th>$Q_{pcm}$ (MJ)</th>
<th>$Q_{out}$ (MJ)</th>
<th>$\eta$ (%)</th>
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<tbody>
<tr>
<td>1</td>
<td>NA</td>
<td>NA</td>
<td>2</td>
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<td>0.377</td>
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<td>140</td>
<td>1.171</td>
<td>0.377</td>
<td>0.794</td>
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<td>0.377</td>
<td>0.962</td>
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<td>0.711</td>
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<td>0.377</td>
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<tr>
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<td>0.627</td>
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<td>Circular fin</td>
<td>2</td>
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<td>0.463</td>
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<td>4</td>
<td>45</td>
<td>0.755</td>
<td>0.377</td>
<td>0.378</td>
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<td>0.711</td>
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<td>60</td>
<td>1.004</td>
<td>0.377</td>
<td>0.627</td>
<td>37.46</td>
</tr>
</tbody>
</table>

### RESULTS AND DISCUSSION

The temperatures of both HTF & PCM during the process of charging are as follows.

<table>
<thead>
<tr>
<th>S.NO</th>
<th>FLOW RATE (lit/min)</th>
<th>NANO FLUID CONCENTRATION (%)</th>
<th>FIN TYPE</th>
<th>HTF INLET TEMP(°C)</th>
<th>HTF OUTLET TEMP(°C)</th>
<th>CHARGING TIME (mins)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2</td>
<td>NA</td>
<td>NA</td>
<td>80</td>
<td>79</td>
<td>170</td>
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<tr>
<td>2</td>
<td>2</td>
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<td>80</td>
<td>79</td>
<td>140</td>
</tr>
<tr>
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<td>80</td>
<td>79</td>
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<tr>
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<td>4</td>
<td>NA</td>
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<td>79</td>
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<tr>
<td>5</td>
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<td>0.02</td>
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<td>6</td>
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<td>0.02</td>
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<td>80</td>
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<tr>
<td>7</td>
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<td>0.08</td>
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<td>0.08</td>
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<td>0.08</td>
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<tr>
<td>12</td>
<td>4</td>
<td>0.08</td>
<td>CIRCULAR</td>
<td>80</td>
<td>79</td>
<td>45</td>
</tr>
</tbody>
</table>
Effect of Nanofluids

In present system experiment is carried out to improve the performance of the system adding of nanofluids to heat transfer fluid (water) and used it as heat transfer fluid (HTF). The effect of this nanofluid on heat transfer by using stearic acid as PCM and the results are shown by using the graphs.

**Water based nanofluids as HTF compared with water as HTF (2lit/min)**

![Image of graph showing temperature over time for different flow rates]

It is observed from the above graphs that the charging time decreases with the use of Nanofluids (15.6104gms) along with base fluid with a mass flow rate of 2 lit/min and 4 lit/min of Volume concentration of 0.08%, Thermal conductivity is considered important factor for rapid heating application. Base heat transfer fluid normally having low thermal conductivity, so we go to Nanofluids for increases the heat transfer rate. This causes reduction in charging time with the use of nanofluids.

**Effect of Flow rate**

The experiment is carried for different flow rates like 2lit/min and 4 lit/min the effect of this flow rates on heat transfer is enhanced by using nanofluids and the results are shown by using the graph.

**Compared with flow rates (2lit/min & 4lit/min) using 0.02% concentration of nanofluid**

![Image of graph showing temperature over time for different flow rates]

It is observed from the above graph that the charging time decreases with the increase in mass flow rate from 2 to 4lit/min. This is because as the mass flow rate is increased, the thermal energy supplied to the TES tank through HTF in a given time increases and as there always exists a temperature difference between HTF and PCM. This causes reduction in charging time with increased mass flow rates.

**Effect of Fins**

The experiment is carried out to improve the performance of the system by using circular fins for the PCM stored spherical capsules due to this the surface area will be improved and the results are shown by using the graph.

**With fins**

![Image of graph showing temperature over time for with and without fins]

It is observed from the above graph that the charging time decreases by using of extended surfaces i.e., the contact surface area is increases for the spherical capsules so it increase the rate of heat transfer from the system. It increases with the difference of temperature between the system and the object, also increasing the convection coefficient of heat transfer. This causes reduction in charging time with increased surface area.
Effect of Nanofluid concentration

The experiment is carried for different nanofluids concentrations like 0.02% and 0.08% the effect of these concentrations on heat transfer is illustrated and the results are shown by using the graph

Temperature Variation of PCM Spherical capsule by using different nanofluid concentrations (2lit/min):

![Graph showing temperature variation](image)

It is observed from the above graphs that the charging time decreases with the increase in nanofluid concentration from 0.02% to 0.08%. This is because as the nanofluid concentration is increased, the thermal conductivity of HTF will be increased due to this the energy supplied to the TES tank through HTF in a given time increases and as there always exists a temperature difference between HTF and PCM. This causes reduction in charging time with increased mass flow rates.

CONCLUSION

A TES system is developed for the supply of hot water at an average temperature of 45°C for various applications such as water heating, air heating, building applications, printing on the cotton cloths and dying the threads and cleaning of utensils etc. Experiments were conducted on the TES unit to study its performance by integrating it with constant heat source.

The variables studied include Nanofluids, mass flow rate, extended surfaces (FINS) and nanofluid concentrations of HTF, on the performance of TES.

From the experimental results it is concluded that the TES system is using HTF without nanoparticles the charging time of PCM is less when compared to the HTF with nanoparticles and by increasing the mass flow rate, the thermal energy supplied to the TES tank through HTF in a given time increases so the charging times can be reduced. By using extended surfaces the contact surface area is increases for the spherical capsules so it increases the rate of heat transfer from the system. Hence, it is concluded that by charging times can be reduced by using of extended surfaces.

SCOPE OF FUTURE WORK

- In place of PCM being used in the spherical capsules, PCM based nanoparticles may be employed.
- To increase heat transfer rate in HTF, low density nanoparticles may be employed, it may give better results than the present used nanoparticles.
- To reduce the heat transfer losses perfect insulation provided to the TES system.

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