Experimental investigation of the charging and discharging of latent heat in phase change material (PCM) based aluminium tube heat exchanger

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Abstract:
Nowadays, given the increasing importance of energy sources, the possibility of energy storage in the heat exchangers through the Phase Change Materials (PCM) and releasing it when needed has been extremely essential. This study seeks to develop a model as that of the domestic water heating system in which the phase change material is used for storing that heat energy as latent heat and it can be discharged during cooling. The behaviour of a PCM material is studied and the performance is tried to improve by using aluminium as the inner tubes instead of copper. In this experimental study, the thermal characteristics of PCM is studied by passing hot fluid and cold fluid through the tubes. Further the heat-storing capacity and the temperature distribution of wax along the tube was studied at different fluid temperatures. Also, the type of flow created by the fluid for different temperatures and the corresponding behaviour of the PCM during that particular temperature is also studied. A commercial grade Paraffin wax as PCM material with specific heat capacity of 2 kJ/kg-K is used and arrived at effectiveness around 0.48 for 40-50 °C and 0.59 for 50-60 °C. Logarithmic average of the temperature difference between 40°C-50 °C hot cycle is 10.654°C and during the cold cycle it is: 2.495°C, In the same way for 50°C-60 °C, during Hot cycle 11.56 °C and for cold cycle 3.77°C. Finally, it is observed that based on the experimental study on the charging and discharging of latent heat storage, due to the low thermal conductivity of Phase change material, the rate of heat transfer during discharging is very low and the time required for discharging of latent heat storage is longer compared to the time required for charging of latent heat storage due to low heat transfer rate between PCM and hot Temperature fluid (Water).

Keywords: Phase Change Material (PCM), latent heat, Charging and Discharging, melting, tube heat exchanger

1. Introduction

While melting process of PCMs, effects of PCMs on the heat exchange in Shell-and-tube heat exchanger is more extreme than in the single tube. The heat transfer is mainly composed of convection and heat
conduction in which nearly 70% of the PCM is melted because of natural convection process [1]. In latent heat storage system, Paraffin wax is a widely used as energy storage. The wax has suitable temperature range of 50-60 and a comparably latent heat of 206 KJ/Kg and does not undergo any subcooling condition [2]. Increasing the Stefan number and fins’ height reduces the melting time. For the heat exchanger, of PCM material is subjected to forced convection which has results showing that its parameters mainly affecting the charging of PCMs. Melting of PCM started at uppermost section because of buoyancy effect. Charging can be increased by reducing the HTF temperature Based on experimental results and Discharging can be maximised by low heat transfer rate [8].

Challenges faced in ventilation system is solved by PCM material which is used as solar heat collector, when the solar heat radiation is generated from ventilated window it heats and the energy gets stored at PCM. During night time the absorbed heat is discharged and thereby increase the temperature to save energy and provide thermal comfortableness during winter [9]. For a heat exchanger Velocity of water, number of coolant pipes, diameter of the pipe are important factors which is analysis using CFD. All types of simulations are conducted on different values to obtain best design [10]. Due to the demand for air conditioner large amount of electrical energy is consumed due to varies significantly during the day and night. To solve this phase change materials are tested to store the wasted heat in near future [11]. Analysis of energy storage in RT70 and MgCl2·6H2O is performed in which MgCl2·6H2O is not upto the mark due to phase separation whereas RT70 could be preferred due to it’s good performance in charging power [12]. Used a Tube heat exchanger made of copper and consists of a stainless-steel storage tank that has a copper HX installed inside of it (fin-and-tube type). PCM RT82 filled at an external arrangement where temperature readings are taken at 10 different points PT100 sensor and Coriolis flow meter is generally used to indicate the mass flow rate. When temperature increase more than 86°C it disobey the calculations due to change in dynamic viscosity of PCM [13]. fin type heat exchanger is explained along with the results obtained by varying the mass flux of the fluid and the load given to diesel engine. This provides a clear overview of the advantage of waste heat recovery from flue gases and their usage in file cleaning operation [14]. This paper serves as a reference for the usage of paraffin wax as PCM material. This experiment shows that the surface temperature of the tube is constant. This results act as a preliminary model [15]. overall heat exchange coefficient (UA) values are estimated. Procedure is to evaluating the UA value from the exchange energy divided by the logarithmic mean temperature difference, using the maximum temperature of the storage when a discharging process is analysed, T_max(t) and for Q_mean is we follow the mean exchanged power (Q_mean) using an exchanged energy basis [16]. Increasing T_h has a noticeable effect on melting time and influenced both simple and finned- tubes almost at same temperature. When enhanced tubes are used average temperature increases at a faster rate and flow rate of liquid influences the solidification time [17].

Some experiments were conducted at both real-time solar conditions and controlled experimental conditions which assessed the performances. During both charging/discharging the heat exchanger showed large temperature difference. Parameter like time vs temperature and time vs power output is obtained [18]. Estimation of calculations and graphs of obtained value of melting and freezing of full cycle heat transfer flux is plotted. Behaviour of a PCM plate is arrived with solidification processes at temperature profile of 50°C to 58°C [19]. In cylindrical shell container a nanoparticle liquid is analysed at the midway section. Temperature vs time character is observed, finally it was found that by maximizing the volume fraction of nanoparticle to Φ = 0.05, lower the total melting time by 14.6% [20]. Various application of PCM is discussed like solar power plant, heat pumps and energy efficiency.
in HVAC system are studied [21]. It’s our new taught process of making a household and domestic purpose heat exchanger with aluminium and mild steel with a commercial PCM material.

2. Materials & Methodology

Shell material is made of Mild steel and the tube is made of out of aluminium material. The properties of mild steel and aluminium are given in Table 1 and 2 respectively.

Table 1. Mild steel properties

| Properties          | Values          |
|---------------------|-----------------|
| Thermal conductivity| 54 W/m·°C       |
| Specific heat capacity| 0.465 J/g·°C  |
| Melting point       | 2570°C          |
| Tensile strength    | 500 MPa         |
| Yield strength      | 280 MPa         |

Table 2. Aluminium properties

| Properties          | Values          |
|---------------------|-----------------|
| Thermal conductivity| 200 W/m·K       |
| Specific heat capacity| 0.9 J/g·°C   |
| Melting point       | 616-654 °C      |
| Modulus of elasticity| 68.9 GPa    |
| Tensile strength    | 241 MPa         |
| yield strength      | 214 MPa         |

Type K Thermocouple (Nickel-Chromium / Nickel-Alumel): Here the type K thermocouple is used, since it is a common type of thermocouple. Maximum continuous temperature is around 1,100°C. The thermocouple used, is attached to the heat exchanger by direct screwing. The connection head which is splash proof, contains the connection terminal through which the electricals connections are made. There are two variants of measuring inserts. One variant is replaceable, spring loaded miniature measuring insert while other is a non-replaceable screwed in design which is permanent.

Figure 1. Type K thermocouple
The temperature of the item can be indicated by using a temperature monitor. The displays are of three types. An analogue dial, analogue range or digital readout. A bimetallic strip and a thermocouple is usually used to measure the temperature. The bending of the bimetallic strip increases with temperature. Together they act as electronic pump. The mechanical action of the pump moves the fluid. It converts electrical energy into hydraulic energy. Natural rope is used as insulating material to reduce the loss of temperature from the shell. The cotton and jute fibres are best for resisting the temperature. Paraffin C 18 is the phase change material (PCM) and water is the shell and tube fluids.

![Paraffin Wax](image)

**Figure 2. Paraffin wax**

| Properties            | Values       |
|-----------------------|--------------|
| Melting point         | 28 °C        |
| Heat storage capacity | 160 KJ/Kg    |
| Specific heat capacity| 2 KJ/Kg-K    |
| Heat conductivity     | 0.2 W/m-K    |
| Flash point           | >200         |
| Volume expansion      | 12.5%        |
| Maximum operating temperature | 80 °C |

**Table 3. Fluid properties**

The shell and tube heat exchanger are constructed and 5 temperature sensors are fit on the heat exchanger. The temperature reading of the sensors are noted at 3 points. At top, bottom and centre to note the temperature of the paraffin wax and another two sensors to note the inlet and outlet temperature of water. The data is collected and calculations are performed by LMTD method. The experiment is carried out for two ranges of temperatures and the amount of heat absorbed by paraffin wax due to convection is found.

![Heat Exchanger Schematic Diagram](image)

**Figure 3. Heat Exchanger Schematic Diagram**

The setup is constructed first the shell is filled with wax and then the tube with the tube plates is place inside the shell. The water temperature is raised to 62 degree and then the hot fluid (water) is sent inside
the tube after the water temperature is noted for every five minutes. After 12 reading the hot water is stopped and then the cold water is passed inside the tubes and then the same procedure is repeated for the cold fluid (water). The temperature reading of the sensors are noted at 3 points in the shell at top, bottom, centre to note the temperature of the paraffin wax and another two sensors to note temperature of inlet and outlet temperature of water form this temperature we can understand the amount of heat absorbed by the paraffin wax due to convection.

3. Experimental Calculation and Results

3.1 Area and Volume Calculation of Shell And 2-Tube Type Heat Exchanger

Volume of the tube = \( \pi r^2 l \)

Total volume of 6 tubes = \( n \times \) volume tubes

Total volume of Shell = (Total volume of the Shell free annular space – Total volume of the tube free annular space in shell)

| S.No | Shell (mm\(^3\)) | Tubes of 6 (mm\(^3\)) |
|------|------------------|------------------------|
| Volume free annular space | 103672556 | 765527.5899 |
| Volume of PCM | 1226167.8528 | 9665930.2272 |

3.2 Thermal Calculation

The relations for performing the thermal calculations are given here.

Heat dissipation, \( Q = m c_p \Delta T \)

Mass, \( m = \rho v \)

Reynolds number, \( Re = \rho V D / \mu \)

| Temperature(°C) | Dynamic Viscosity (Ns/m\(^2\)) | Reynolds Number (Re) | Nusselt Number (Nu) |
|-----------------|---------------------------------|----------------------|---------------------|
| 20              | 1.002 * 10\(^{-3}\)            | 12951.097            | 148.0426            |
| 30              | 5.41 * 10\(^{-3}\)             | 16261.90             | 56.839              |
| 40              | 4.34 * 10\(^{-3}\)             | 19872.89             | 59.1612             |
| 50              | 3.68 * 10\(^{-3}\)             | 23723.94             | 60.966              |
| 60              | 3.020 * 10\(^{-3}\)            | 27788.0              | 63.207              |

3.3 Effectiveness

The heat transfer can be estimated from the relation, \( Q = mc_p \Delta T \)
Table 6. Heat dissipation at hot and cold with effectiveness

| Temperature (°C) | Q_h (W)  | Q_c (W)  | Q_{avg} (W) | Q_{max} (W) | Effectiveness % |
|------------------|-----------|-----------|-------------|-------------|-----------------|
| 50-60            | 516.534   | 451.967   | 484.2505    | 1007.74     | 0.48            |
| 40-50            | 451.967   | 387.4     | 419.68      | 700.549     | 0.59            |

3.4 Thermal calculation

Figure 4. Temperature range 50 to 60 of hot cycle

Figure 5. Temperature range 50 to 60 of cold cycle
Figure 6. Temperature range 40 to 50 of hot cycle

Figure 7. Temperature range 40 to 50 of cold cycle
4. Conclusion

The following conclusions are drawn from the results of the experimental study. During charging, the Phase change material melts at the uppermost section and moves downwards due to natural convection. On the other hand, heat transfer during discharging is mainly governed by conduction. Comparatively, discharging duration of latent heat storage is longer compared to charging duration of latent heat storage due to low heat transfer rate between PCM and hot Temperature fluid (Water). This is due to the low thermal conductivity of the Phase change material. Discharging rates are minimally impacted by Natural convection. Heat transfer is weaker at bottom position.

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