ISSN: 0974-5823 Vol. 7 No. 2 February, 2022

International Journal of Mechanical Engineering

Heat Transfer Enhancement of Sell and Tube Latent Heat Thermal Energy Storage Using Porous Metal Foam

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***Abstract* -** Latent heat thermal energy storage (LHTES) systems is essential to store the solar energy during sunshine and use it during the absences of solar radiation. The utilization use of such storages are however limited due to the low thermal conductivity of storage material. Significant thermal enhancement of phase change materials (PCMs) behavior can be achieved by addition of porous metal foam. For this purpose, an experimental analysis is conducted on a vertical LHTES with PCM using water as a heat transfer fluid (HTF). The thermal characteristics of storage unit is evaluated for LHTES with and without foam configurations during the course of charging process. Experimental results showed that the total charging time get decreases up to 82% with employing of copper foam material with shell and tube LHTES. The thermal LHTES performance has a superior phase change rates in foamed LHTES configuration over the non-foamed configuration.

Keywords **-** Copper foam, Latent Heat Thermal Energy Storage (LHTES), Melting time, PCM.

INTRODUCTION

The thermal energy research has recently shifted toward developing efficient thermal equipment's and appliances which enable to utilize alternative sources of energy. For example, utilization of solar based thermal systems needs efficient thermal storage to enable storing the surplus sun energy collected during the day time and retrieve the store energy during the absence of solar energy.

In the recent decades, the attention has increased toward utilizing solar energy in different engineering applications. However, to effectively store the energy during absence of sun radiation, a thermal energy storage is required for sustainable implementation of solar energy.

Latent heat thermal energy storage systems, enable to store larger amounts of thermal energy compare to sensible heat thermal storage (SHTS) units. However, the practical use of LHTS is limited due to the undesirable property of thermal conductivity of PCM. A detail review of thermal energy storages with phase change materials has been given by [1-7], several enhancements on LHTES have been proposed to effectively use for large scale utilizations. Different methods of enhancement were applied by adding fins surfaces [8-15], dispersing conductive nanoparticles in PCM [16-18], multiple families of PCMs [19-21], PCM micro-encapsulation [22-23] and application of highly porous PCM-filled conductive material [24-27].

The heat transfer enhancement proposed in the present study is achieved by adding porous copper foam material on the inside heat exchanger tube of LHTES. The thermal behavior of PCM LHTS is analyzed with and without foam in terms of evolution of transient temperature distribution during the course of melting process.

EXPERIMENTAL SETUP AND PROCEDURE

1. Experimental Setup

For the present work, the schematic diagram of the experiment setup which used in the experimentation is shown in Fig. 1. The experimental setup is mainly composed of PCM shell and tube storage module, thermal bath, thermocouples, flow meter, data acquisition system. The PCM storage is provided with water HTF loop coming from the thermal bath. Thus, the experimental setup enables to conduct the melting process by injection the water from bottom of heat exchanger. This setup can be used to predict the LHTES thermal performance of during charging process. The experimental work is carried out for both pure PCM tube (non- foamed LHTEF) and thermal storage with foam (foamed LHTES). The thermal behavior of LHTES is assessed in terms of the temperature distribution of PCM, time for charging. The inlet temperature and mass flow rate of HTF were maintained at a 70ºC and 0.083 kg/sec respectively.

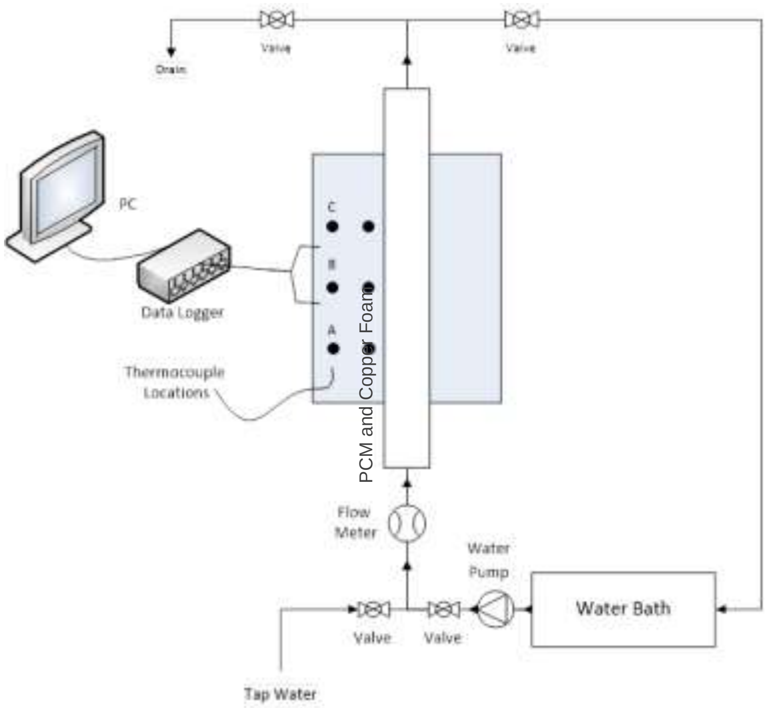

FIG. 1

SCHEMATIC DIAGRAM OF EXPERIMENTAL SET-UP FOR PREDICTION HEAT TRANSFER CHARACTERISTICS OF LHTES DURING MELTING CYCLE

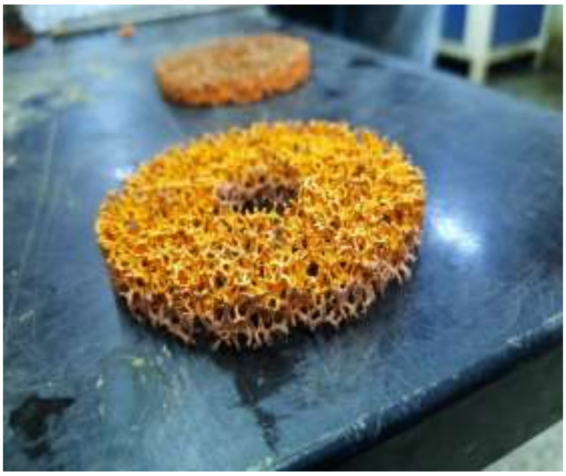

FIG. 2

RING SHAPED COPPER FOAM

2. Specifications of LHTES

The heat storage of shell and tube type consists of two concentric cylinders. The internal tube is made of copper with inner diameter of **19.1** mm and thickness of **0.1** mm. There was a shell made of Plexiglass with length **45 cm, 7** cm internal diameter and **0.5** cm thickness. The shell was selected for low thermal conductivity and high transparency and placed around the heat exchanger tube. Two flanges made from Plexiglass with **2** cm thick were used to fix the tube to shell. To avoid the expansion of PCM, a 1 cm hole was drilled in the upper flange to pass the thermocouples wires and to maintain the test section at atmosphere pressure. The annular region between the exchanger and shell is filled with selected PCM. To minimize the thermal loss, a 2 cm thick layer of glass wool insulator was placed on the outer surface of LHTES shell. The test section characteristics is given in Table 1.

To measure the temperature evolution in the PCM, six thermocouples (NTC -type) with an average uncertainty of ±0.15°C and temperature range of 0-200°C were fixed in the shell tube region. The thermocouples were installed along the axial direction of shell tube LHTS and denoted by A (10.25 mm), B (20.5 mm), and C (30.75 mm), see Fig. 1. Each axial location contained pair of thermocouples and were located at a radial position of **8** mm and **16** mm from inner tube to the outer shell. Two thermocouples were also placed at the inlet and outlet of inside HTF pipe to record the readings of inlet and outlet temperature of

HTF. Data acquisition system and a personal computer was used to record the values from sensors. The experimental data were received every 10 sec during the melting process.

A second set of copper foamed thermal storage (foamed LHTES) is made to know the heat transfer enhancement induced by adding copper foam. To prepare a composite of copper and PCM, foam is cutting as ring-shaped, each ring is 5.0 mm thick, 68 mm in outer diameter and 19.5 mm in inner diameter (see Fig. 2). There are 41 copper foam rings piled up around a HTF tube. The space of 2 cm without foam on both sides of the HTF heat exchanger tube are necessary to let some void above and below the copper foam in order to place thermocouples and to weld flanges. The HTF copper tube is 20 mm in outer diameter and 2 mm thick. The two test section were then filled by 750 kg of PCM.

3. Selection of PCM and Copper Foam

In the present study, the consideration of PCM is based on the low cost LHTS system for low temperature thermal applications. *Paraffin wax was used as the pure PCM and water as a HTF.* Differential Scanning Calorimetry (DSC), thermal conductivity analysis for PCM were done to measure the thermal properties of PCM. The thermal properties of PCM and HTF were presented in Table 2.

The thermal conductivity of the composite of copper foam-PCM is higher than that of other metal foam-PCM composites like aluminum foam or nickel foam because of the copper has a high thermal conductivity among the metal materials. For these reasons, the copper foam was used in the performance enhancement of LHTES for the present study. The porosity of the copper foam was 0.9 and the pore density is 10 PPI (pores per inch). The thermophysical properties of the copper foam listed in Table 3.

TABLE 1

SPECIFICATIONS OF SHELL AND HTF TUBE

	HTF tube	**Shell tube**
Material	Copper	Plexiglass
Density, kg/m^3	8960	
Specific heat (cp), J/g. °C	0.39	
Thermal Conductivity (W/m.°K)	386	0.19
Length, m	0.54	0.54
Inner diameter, mm		70
Outer diameter, mm	20	

TABLE 2

THERMO-PHYSICAL PROPERTIES OF PCM SAMPLE AND WATER

Property	**Value**
Paraffin wax (PCM)	
Melting temperature range (°C)	48.3-62
Heat of fusion(J/kg)	114540
Specific heat (J/kg.°C)	2000
Thermal Conductivity (W/m.°C)	0.14
Density (kg/m^3)	820
Viscosity (Pa.s)	0.033
Thermal expansion (1/K)	6×10^{-4}
Water (HTF)	
Specific heat (J/kg.°C)	4180
Density (kg/m^3)	996

TABLE 3

PROPERTIES OF COPPER FOAM

Porosity, %	90
Pore density, PPI	10
Dimension, cm	50*50

4. Experimental Procedure

The vertical position is considered for LHTES test section during the experimentation. The water was heated with two heaters of 3.3 kW electric heater and circulated using a using a circulation pump from the water storage tank (300 L) to the test section. A flowmeter with an accuracy of ±4% measures flow rate of HTF inside the storage unit. Initially, few tests were conducted to check the PCM leakage in the storage system. Melting testing of PCM was carried out when PCM comes in solid state. The initial operating conditions of melting was specified when all sensors embedded in the annular space contains the PCM records the same temperature values where thermocouples readings is logged in every 10 sec.. In the charging cycle, hot HTF from the thermal bath at a required temperature is pumped and the necessary piping and valves for regulating water flow.

The experiments is first conducted for shell and tube LHTES without adding of copper foam (non-foamed LHTS sample). To achieve a performance comparison, a copper foam added with PCM (foamed LHTS sample) was also measured to study the thermal behavior inside LHTS with foam.

RESULTS AND DISCUSSIONS

The shell and tube LHTES thermal characteristics during charging process with and without porous metal foam is evaluated in terms of the temperature evolution of PCM and completed phase change time. The PCM transient temperature evolution at various axial direction inside heat exchanger with and without copper foam are shown in Figures 3 and 4. The transient variation of PCM is presented for 70^{o}C and 3 l/min of HTF and flow rate respectively. The average temperature of PCM was measured by taking the average reading of thermocouples at different positions.

The general overview of the temperature evolution of the PCM in Fig. 3 is that three separated regions exist in LHTS during charging process: solid region, mushy region and liquid region. The conduction phenomenon of heat transfer is responsible for the heat transfer inside the solid PCM. Solid PCM receives the heat from the liquid region by convection. The convective flow of melt inside the molten region is responsible for heat transfer. The convective flow of melt is developed due to density gradients in the molten region as a result of the temperature differences. As a result, the convective flow of melt enhanced the heat transfer within the melted PCM region.

At the beginning, the heat conduction of solid phase PCM plays a dominant role in heat transfer. As more solid PCM melts, the natural convection dominates the heat transfer process gradually. The molten PCM absorbs energy from heating tube and flows upward, so the temperature of upper part is higher than the lower portion. The rapid increase in temperature of PCM in the upper portion is due to the development of a thin layer of molten PCM around the HTF wall. As the time advanced, the melting begins from the top of the test section and proceeds downward until the process is completed.

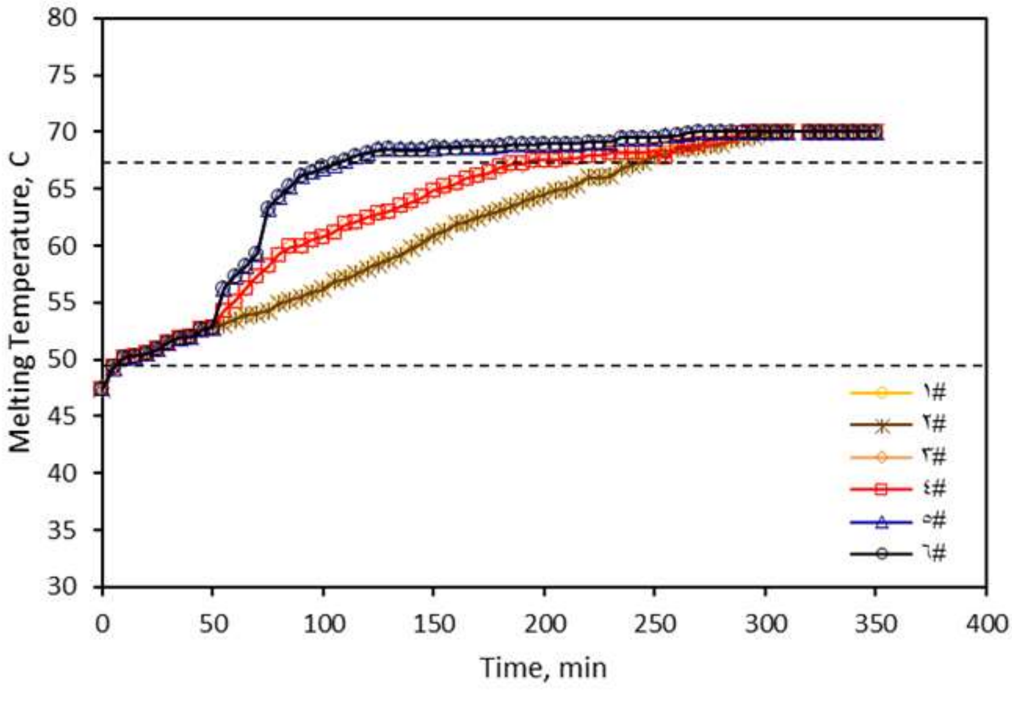

FIG. 3

MELTING TEMPERATURE VARIATIONS FOR THERMAL STORAGE WITHOUT COPPER FOAM

(VERTICAL, T_{HTF} = 70^{o}C AND M = 0.0.83 KG/SEC)

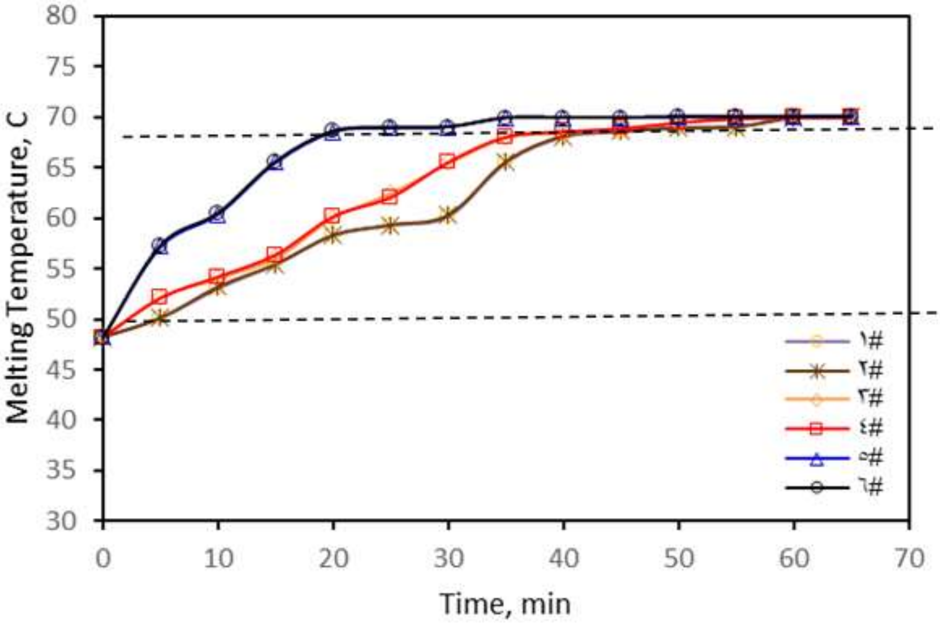

FIG. 4

MELTING TEMPERATURE VARIATIONS FOR THERMAL STORAGE WITHOUT COPPER FOAM (VERTICAL, T_{HTF} = 70^{o}C AND M = 0.0.83 KG/SEC)

The result of the temperature variations for LHTES test section with addition copper foam is presented in Fig. 4. The operational conditions for foamed LHTES were T_{HTF} = 70ºC and $\dot{m}$=0.0.83 kg/sec of HTF. As can be seen that the temperature history of the detected points has a similar trend to those discussed above are observed. The temperature of upper points is higher than that of the lower points in the vertical direction. However, the temperature difference for the composite is much less than that for pure PCM.

The transient evolution of average PCM temperature for LHTES with and without addition copper foam material is shown in Fig. 5. The foamed tube configuration enables to enhance the convection currents during the charging process.

As expected, the large heat transfer induced by the employing of copper foam leads to increase the melting rate of PCM. Thus, the PCM melting time is shorten from 360 min to 65 min is clearly observed due to addition of copper foam. The comparative assessment suggests that copper foam implemented in a shell-and-tube heat exchanger reduces the total melting time 82% as compared with LHTES without copper foam. The general overview of Fig. 5 is that the temperature profile of LHTES with an embedded foamed copper heat exchanger show large heat transfer rate and hence shorten the completed melting cycle.

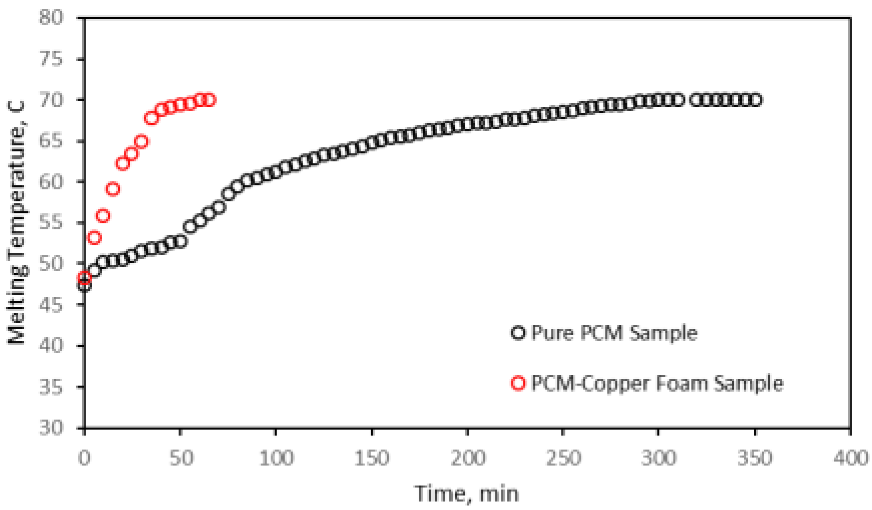

FIG. 5

TEMPORAL VARIATION OF PCM AVERAGE TEMPERATURE DURING CHARGING OF LHTS (VERTICAL, T_{HTF} = 70^{o}C AND M = 0.0.83 KG/SEC)

CONCLUSIONS

The major conclusions have been derived from experimental investigation as the following:

1. It can be seen that the heat transport rate is increased significantly with addition of copper foam as compare to LHTES without foam. The large heat transfer area provided by porous copper foam material clearly has a major impact on the progression of melting rates.

2. Evolution of PCM temperature in different axial and radial locations inside the region of heat exchange between PCM and HTF helps to determine the heat transfer behavior and melted regions in the thermal storage unit.

3. The heat exchange between PCM and HTF during melting cycle is dominated by the convection currents which drives the circulation of molten PCM due to density variation.

4. A rapid completed melting at the top part in heat exchanger test section can be distinguished for LHTES with and without copper foam. This is can be attributed to the dominated effect of natural convection.

5. The completely melting time is shortening from 360 min to 65 min because of provision of copper foam. Thus, the percentage decrease in melting time reaches to 82% due to employing of copper foam. The employing of high thermal conductivity material with PCM transfers large amount of heat into the internal part easily and thus significantly shorten the melting process.

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