DOI: 10.11916/j.issn.1005-9113.2019017

Role of Composite Phase Change Material on the Thermal Performance of a Latent Heat Storage System: Experimental Investigation

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Abstract: Paraffin wax is a perfect phase change material (PCM) that can be used in latent heat storage units (LHSUs). The utilization of such LHSU is restricted by the poor conductivity of PCM. In the present work, a metal foam made of aluminium with PCM was used to produce a composite PCM as a thermal conductivity technique in PCM-LHSU and water was used as heat transfer fluid (HTF). An experimental investigation was carried out to evaluate the heat transfer characteristics of LHSU using pure PCM and composite PCM. The study included time-dependent visualization of the PCM during the melting and solidification processes. Besides, a thermocouple network was placed inside the heat storage to record the temperature profile during each process. Results showed that better performance could be obtained using composite PCM-LHSU for both melting and solidification processes. The melting time of composite PCM-LHSU was about 83% faster than that of a simple PCM-LHSU, and the percentage decreasing in the solidification time was about 85% due to the provision of metal foam.

Keywords: phase change material; metal foam; latent heat; composite PCM

CLC number: TB3 **Document code: A**

1 Introduction

Nowadays, the trend of energy demands has been significantly raised, particularly in the Middle East region[1-2]. A latent heat thermal storage unit (LHSU) is considered as an alternative approach to store energy in different industrial applications. During the last two decades, several research studies have been extensively investigated on the applications of phase change materials (PCMs) that are used in thermal storage units[3-8]. Furthermore, these applications have been adopted dramatically in modern life, e.g., energy conservation unit in houses and buildings, heat recovery from the industrial waste, and cooling of electronic devices and solar energy systems[9-12].

Paraffin wax has been regarded as one of the most important materials that have high latent of melting, which can be used for energy storage applications[13-14]. Researchers are keen to improve LHSU performance, PCM properties, cooling system, and thermal conductivity for both materials and units[15-17]. It has been reported that different enhancement methods have been performed, including metal fins embedded in PCM, as well as pin fins and combinations of heating pipes with PCM[18]. Experimental efforts have been made to improve the thermal behaviour of latent heat in storage units, which involve fins geometry, nanoparticles, and metal foams[19-20].

Thermal properties of PCM-LHSU for shell and tube (heat exchanger) were investigated in Ref. [21], and the profile of the temperature-time in PCM was measured. Additionally, heat transfer fluid (HTF) temperature and rate of mass flow were examined for the processes of melting and solidification. Results showed that there is an increase in the melting time of PCM when the HTF inlet temperature and mass of flow rate are decreased. The inlet fluid temperature has a noticeably effect on the heat fraction compared with the flow rate of HTF during the PCM melting. It was concluded that the most important factor in the melting process is convection, while conduction plays an essential role in the discharging process.

Chaichan et al.[22] improved the paraffin wax

Received 2019-03-09
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thermal conductivity by using alumina (Al_2O_3) and (TiO_2) nanoparticles with different mass weight ratios, and the thermal conductivity was measured experimentally. In the study, the PCM thermal conductivity was enhanced and the rate of charging and discharging was significantly increased.

In Ref. [3], the thermal behaviour of LHSU was studied using water as a PCM and added with aluminium foam. It was found that the aluminium foam causes a noticeable enhancement to the heat transfer during the phase change process. Besides, a reasonable improvement was gained for melting (approx.100%) compared with solidification (approx.20%) due to the poor conductivity of the liquid water relating to ice.

A validated model was presented by Ref. [23] to study the heat transfer characteristic of composite PCM during the melting process. A copper foam was used to produce a composite PCM and improve the paraffin thermal characteristics. The phase change cycle and the temperature profile were obtained experimentally during melting cycle. Then, a numerical model was developed to simulate this process and the results were compared with measured temperature data. A good temperature difference was observed inside the copper foam in the experiment. Yang et al.[24] experimented the dynamic thermal behavior of the shell and tube LHSU, in which three cases were studied including pure PCM, as well as PCM/copper composite foam with and without bottom radial fins. The study considered various HTF temperatures and flow rate values, and results showed that the completed PCM melting time in the composite is 1/3 less than that for pure PCM under similar operating conditions. Moreover, among the three cases, the lowest melting time and the highest heat transfer rate were obtained in the case of composite with bottom fin. Finally, it was found that the effect of HTF is more important than the flow rate value of HTF.

PCM foam composite was studied in Ref. [2], in which the discharging of the storage system cold based design was experimentally examined followed by a numerical modelling. The role of using metal foam on the thermal characteristic of PCM was also investigated. The phase change evolution and interface behavior between PCM and metal foam were visualized. Besides, the temperature profile during the cycle of phase change was measured. The analytical model was based on the solution of Neumann, and the predicted data of the heat transfer was validated with measured data, in which a good agreement was observed. A new insight regarding the energy storage system and design was produced from the study by using composite PCM.

An intensive experimental assessment for the PCM-LHSU unit was conducted in Ref. [25], in which the copper foam was utilized to increase the heat exchanger characteristics in terms of heat transfer. Three types of heat exchanger were used, including simple tube, finned copper, and tube-carbon foam surrounded, whose horizontal and vertical configurations were studied. The temperature distribution was recorded, and both charging and discharging processes were visualized for all cases. It was found that copper foam can improve the heat transfer of the heat exchanger, because of the high heat transfer rate and the low density of the composite PCM based metal foam. Furthermore, the work revealed that the melting and solidification time of the vertical configuration is faster than that of the horizontal configuration.

More recently, Rehman et al.[26] studied the thermal behaviour of the copper foam based heat sink for both melting and solidification processes. Paraffin, RT-35 HC, RT-44 HC, and RT-54HC were used as PCM and inserted in the copper foam with the volume fraction values of 0.68 and 0.83. Results indicated that various PCMs have different behaviours at different power loads. The greatest reduction in the temperature is 25% for RT-35 at the power load of 0.8 KW/m^2, while RT-54 provides a minimum reduction of 10%. Generally, the composite PCM/copper foam has better temperature control than the plane one.

It is worth mentioning that time-dependent visualization of such process has not been fully covered in previous studies although some efforts have been made. For instance, visualization was not clearly presented in the work of Martinelli et al.[25] Moreover, it was concluded in the study of Zhang et al.[9] that more intensive investigations are needed to get a deep understanding of the characterization and enhancement of the heat transfer of PCM foam.

In the current study, an experimental investigation was conducted on a vertical shell and tube LHSU to examine the heat transfer enhancement using composite PCM. The composite PCM is composed of paraffin wax as a matrix and metal foam as an enhancement technique, which might be utilized to improve thermal storage performance. Different experiments have been performed to study the influence of HTF inlet temperature on the performance of LHSU with and without metal foam during the phase change cycle. Besides, the phase change cycle was conducted with and without foam from a quantitative point of view using a transparent shell, which helps to visualize against time during the process.

2 Experimental Setup and Procedure

The experiment for evaluating the heat transfer characteristics of LHSU was carried out using plane PCM and composite PCM as storage material (Fig.1). The experimental setup is presented in Fig.2, which is composed of shell and tube heat storage, electrically heated water tank, temperature and flow rate data loggers, and personal computer. The thermal storage unit was provided with HTF from thermal bath during melting and from a tap water source during the solidification process. Furthermore, the LHSU was placed vertically and the HTF was injected from the bottom side of the HTF tube.

The storage tank consists of two concentric cylindrical tubes (Fig.1). The external tube was a transparent shell made of acrylic, while the internal tube was made of copper. The dimension of the LHSU is listed in Table 1. As can be seen in Fig.1(b), the metal foam was placed between the shell and the tube. The metal foam is made of aluminium alloy with a density of 0.35 Kg/cm^3 and a porosity of 85%. The space between external and internal tube was filled by 1.25 Kg molten PCM. Thermal insulating of glass wool of 30 mm thickness was used to cover the shell surface to reduce the heat loss. During the experimentation, each experiment was repeated for three times to verify its repeatability, and the experiments were repeatable with about ±3%.

(a) Plane (without foam) LHSU (b) Foamed LHSU

Fig.1 Shell and tube LHSU

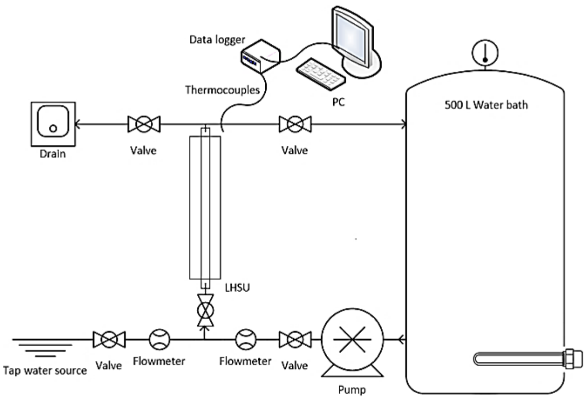

Fig.2 Flowchart of the experimental procedure

Table 1 Geometrical details of the considered double pipe LHSU (mm)

	Inner diameter	Outer diameter	Length	Materials
Inner tube	20	21	470	Copper
Outer tube	80	90	390	Acrylic
Foam	20	70	370	Aluminium

A low commercial grade of paraffin wax (P56-58) provided by Zhengzhou Allis Chemical Co., Ltd. was selected as pure PCM wax. The type of PCM was chosen based on the low temperature applications of LHSUs. The characterization of the selected PCM was needed to evaluate the cycles of the heat transfer of LHSU. Differential scanning calorimeter (DSC, LINSEIS, STA PT-1000, Germany) was used to measure the latent heat of fusion and the melting temperature of the PCM (Fig.3). The temperature range adopted in this analysis was 30-130 ℃. Further details relating to the DSC test can be found in Ref. [4].

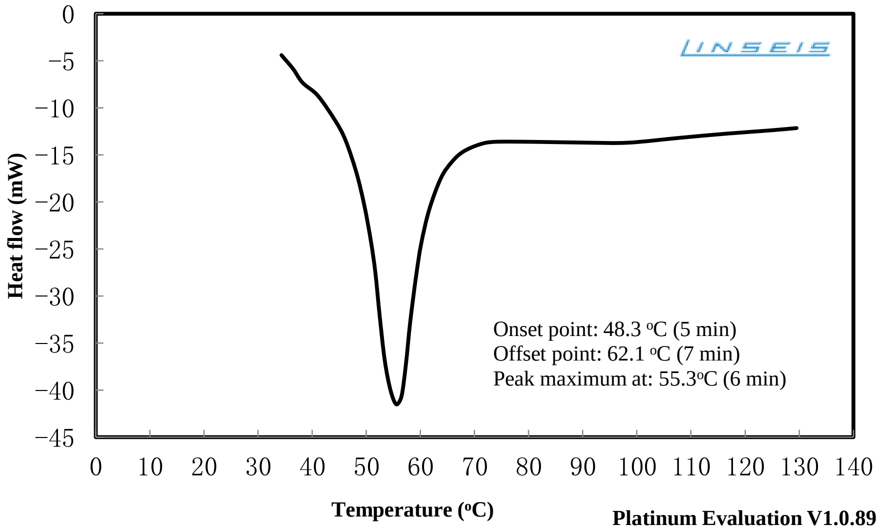

Fig.3 DSC curve for the selected paraffin wax

Four thermocouples of T-type were inserted in the PCM storage to measure the temperature variation at different phase change time, and the uncertainty of the measurement was about ±1.5 ℃. The thermocouples were set along the axial direction of the storage unit (Fig.4).

During melting experiments, the HTF was supplied from the water bath at the constant temperature of 70, 75, and 80℃ and the mass flow rate of 5 L/min. The melting process was finished when all the thermocouples readings were above the melting temperature. For the solidification experiments, cold water at a constant flow rate and a constant temperature from the tape water source was used to circulate the flow. The HTF temperature and the mass flow rate during solidification were 25 ℃ and 5 L/min respectively. It is noteworthy that the thermal performance of LHSU without metal foam was first evaluated. A camera was placed in front of the test section to capture pictures during different time of the phase change cycle of the experiments.

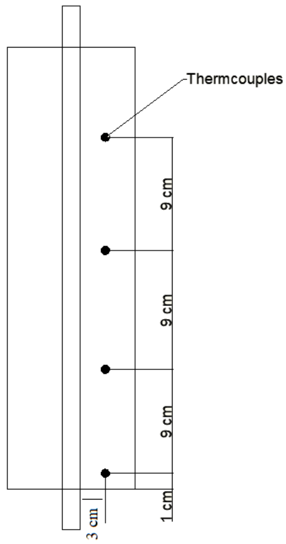

Fig.4 Thermocouples locations of the LHSU test section

3 Results and Discussion

Several experiments were conducted to study the heat transfer features and thermal behaviour of PCM-LHSU. The heat storage with and without foam was evaluated in terms of the temperature variation of PCM and HTF inlet temperature. Finally, the visualization analysis of the phase change cycle was presented during charging cycle.

3.1 Melting Process

The transient temperature profile of the PCM-LHSU without metal foam through the charging cycle at the HTF temperature of 75℃ and the mass flow rate of 5 L/min is shown in Fig.5. The measurements of temperature for the used PCM at various axial locations were performed at locations T1, T2, T3, and T4. These positions are in the LHSU test section, as presented in Fig.4. According to the results, three regions of PCM inside LHSU were determined. Region I was located between 20-48 ℃, i.e., between the start of the charging process and the completed melting process. The temperature trend of the wax at four locations inside LHSU was increased uniformly due to the sensible heat absorbed from HTF pipe. This thermal behaviour of PCM can be argued to the fact that the heat is transferred inside the solid PCM region by conduction. Region II was located between 48-63 ℃, where the PCM was in the solid-liquid phase transition state.

It is clear that there was a significant increase in the temperature values of the molten PCM, where the PCM absorbed heat from the HTF pipe by convection. The convection flow motion of the PCM was developed because of bouncy effect, which is the result of the temperature variation along the test section. Evidently, the PCM temperature at T4 increased significantly compared with those at locations T1, T2, and T3. The rapid increase of the temperature of T4 is due to the development of a layer of melted PCM near the HTF pipe during the charging period. The melted PCM started to circulate because of the convection currents. It can be noted that the completion of PCM melting of location T4 occurred at 40% of the total melting period, and the lowest temperature of PCM occurred at location T1. Similar observations were reported in Ref. [21]. Region III was located at the temperature range of 63-75℃, i.e., between the end of PCM melting and the complete charging cycle. The PCM temperature at all locations inside the LHSU had similar behavior. To examine the influence of metal foam, the melting time of LHSU with foam was also investigated.

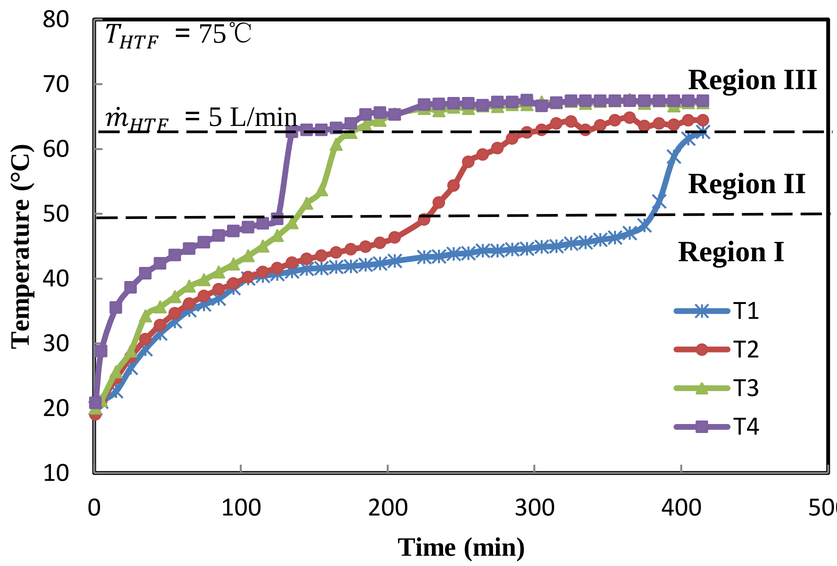

Fig.5 Temperature variation of PCM during the melting process for plane LHSU

Fig.6 shows the PCM temperature variation at four axial locations T1, T2, T3, and T4 during the charging of the foamed LHSU. The operating temperature and flow rate of HTF are 75℃ and 5 L/min, respectively.

From the results, it can be found that the PCM temperature increased significantly at all locations inside PCM compared with that of LHSU without foam. This is due to the provision of metal foam near HTF pipe which causes an improvement in the rate of heat transfer from HTF. Thus, the completed melting was reduced largely from 420 min to 70 min because of the presence of metal foam in the PCM zone. The charging time decreased up to 83% with foamed LHSU than plane LHSU.

The temperature values at the four locations (Fig.5) indicate significant differences, among which the hottest PCM was at the top of the unit (top region). It can be argued to the point that the heat is transferred by natural convection and the convection current is circulated along the storage height, i.e., between the hot top region and the cold lower region.

However, this is not the case in Fig.6 as the temperatures of the four regions were more close to each other, as the foam cause an increase in the temperature of the wax along unit height uniformly. Moreover, the natural convection current was circulated locally, i.e., inside the foam pores.

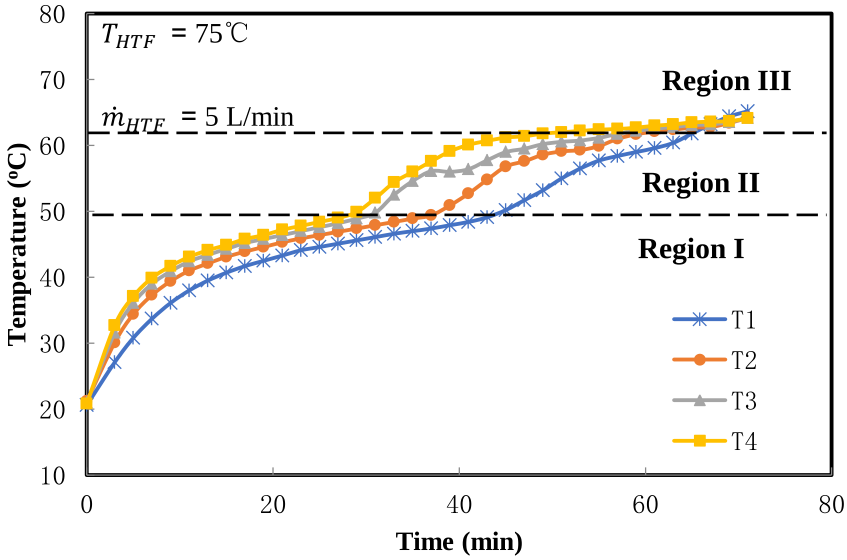

Fig.6 Temperature variation of PCM during the melting process for foamed LHSU

Fig.7 and Fig.8 show the liquid fraction image captured during the melting process in both plane and foam LHSUs at the HTF inlet temperature of 75℃. Mostly, it can be noticed that for both cases, the solid wax near the HTF pipe absorbed the heat and melted at the beginning of the charging cycle. As time advanced, the melting rate at the test section (top part) was faster due to the buoyancy effect. This behaviour has been reported by other researchers[21,27].

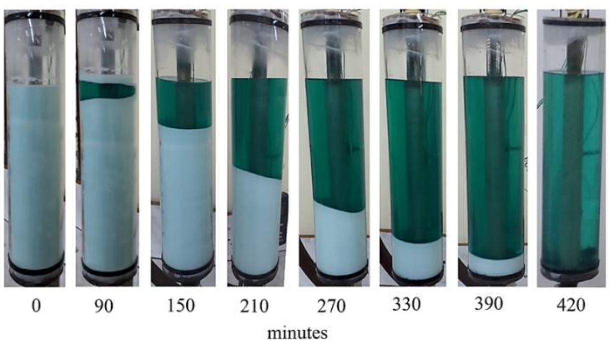

Fig.7 Visulization of melting fronts during melting cycle for plane LHSU (T_{HTF} = 75℃, $\dot{m}_{HTF}$ = 5 L/min)

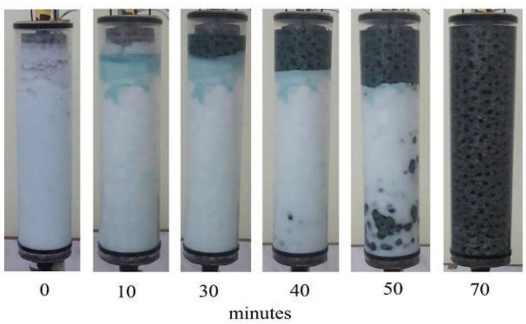

Fig.8 Visulization of melting fronts during melting cycle for foamed LHSU (T_{HTF} = 75℃, $\dot{m}_{HTF}$ = 5 L/min)

The liquid fraction images show that the melting rate of plane LHSU was more uniform than that of LHSU with foam. The convection current for the plane LHSU circulated uniformly compared with the liquid PCM due to the symmetrical zone of the annulus space inside LHSU. This is unlike the foam geometry which confines the PCM at its pores.

Fig.9 and Fig.10 demonstrate the relationship between the average PCM temperature and melting time for plane and foamed LHSUs at different HTF inlet temperatures of 70, 75, and 80℃ and mass flow rate of 5 L/min. Clearly, the average PCM temperature almost increased at the highest value of HTF inlet temperature (80℃) compared with the HTF temperatures of 75℃ and 70 ℃. The sharp rise at the average PCM temperature occurred when the HTF temperature increased. This is due to the increase of the heat transfer from HTF to PCM. It was found that the completed melting time in plane LHSU was 340, 420, and 520 min for HTF temperature values of 80, 75, and 70℃, respectively. In the foamed LHSU, the time was 58, 70, and 80 min for the HTF temperature of 80, 75, and 70℃, respectively. The melting time decreased significantly due to the increase of HTF temperature. The reason is that higher temperature of HTF could increase the potential temperature difference between the metal foam and the PCM, which can improve the heat transfer rate. The improvement percentage due to the use of metal foam with PCM was about 83% for all HTF inlet temperatures.

3.2 Solidification Process

Fig.11 shows the transient temperature profile of PCM during the solidification process of plane LHSU at the flow rate of 5 L/min and the HTF temperature of 25℃. As described in the previous section, the average PCM temperature was measured at four locations of T1, T2, T3, and T4. It can be seen that the PCM temperature reduced very fast until reached the solidification point of PCM. At the start of the solidification, due to the direct contact between the HTF tube and the liquid PCM, a high variation of tempertaure between HTF tube and liquid PCM occurred. Thus, a rapid decrease in the PCM temperature was observed. When the time advanced, a thin layer of solid PCM was developed around the pipe. The thickness of this layer increased with time and provided a thermal conduction resistance, leading to the reduction of the heat transfer rate.

Unlike the melting process, there was no significant temperature gradient of the PCM observed at various axial locations in the plane LHSU test section. This can be attributed to the fact that the heat transfer near the PCM pipe was uniform along the axial direction due to the condition. Similar observation for the temperature distribution of PCM was found in other experiments[4,14].

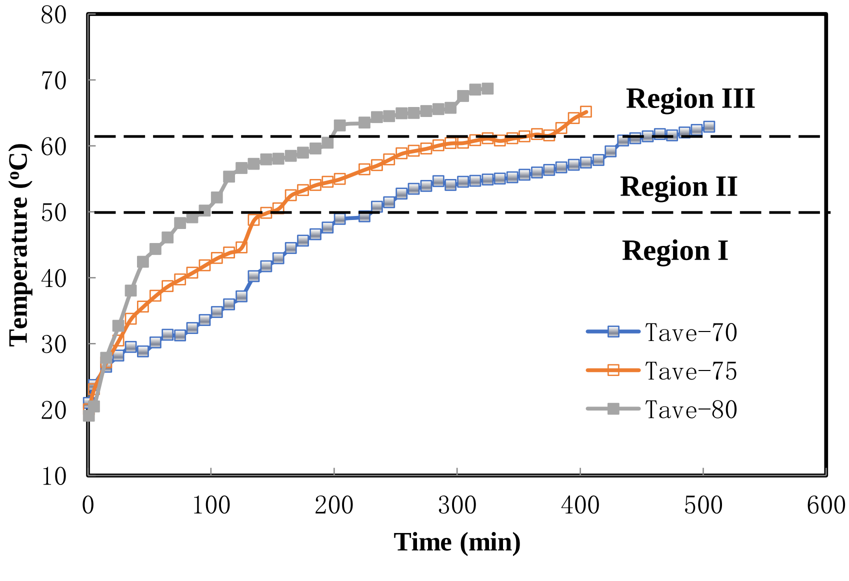

Fig.9 Average temperature of PCM for plane LHSU during melting process at different HTF temperatures

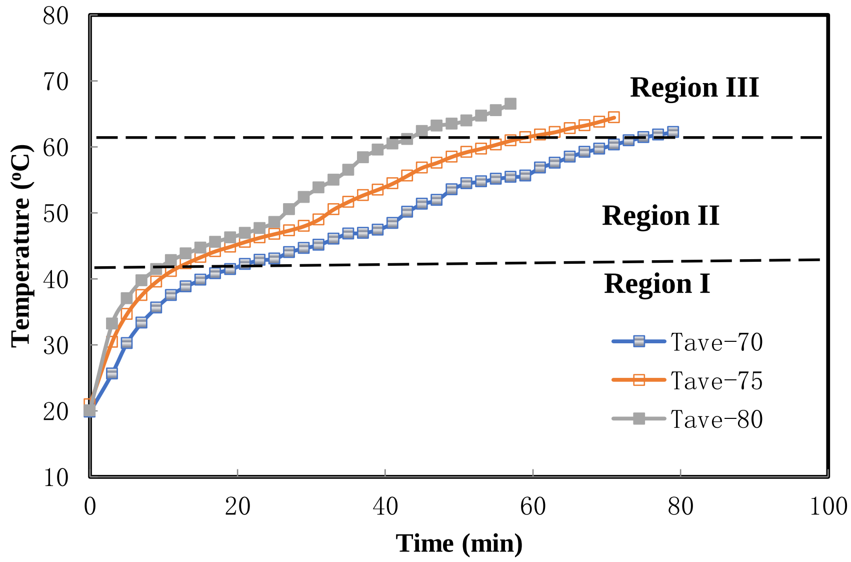

Fig.10 Average temperature of PCM for foamed LHSU during melting process at different HTF temperatures

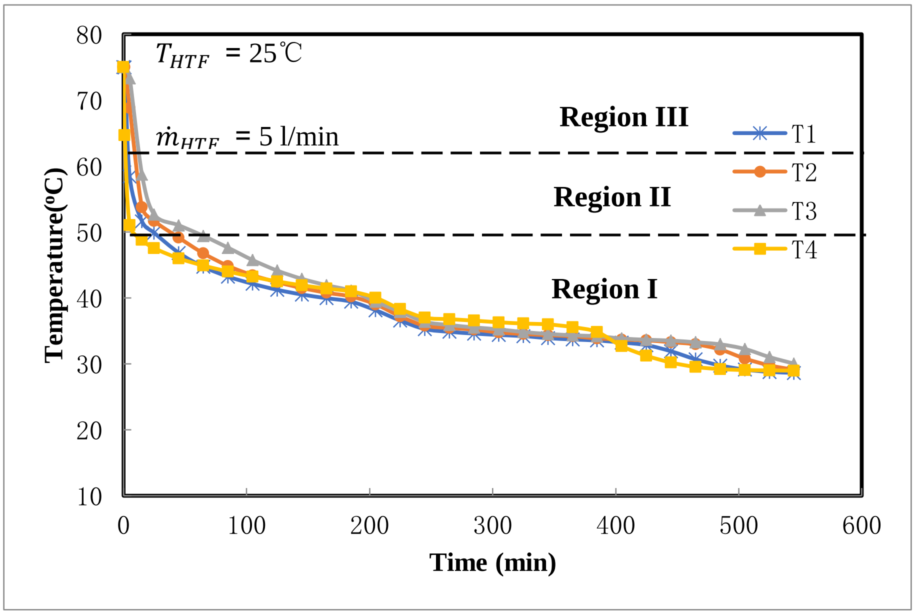

Fig.11 Temperature variation of PCM during solidification process for plane LHSU

The transient temperature profile for the solidification cycle of the foamed LHSU is shown in Fig.12. Results of the foamed LHSU were presented at the HTF inlet temperature of 25℃ and the mass flow rate of 5 L/min. The heat transfer rate was uniform along the test section of LHSU with and without foam. It can be concluded that the profile of the wax temperature near the PCM tube side was almost similar to those of the LHSU with and without foam. Furthermore, the solidification rate was increased due to the presence of foam, where better contact existed between the molten PCM and the metal foam body. The PCM temperature was reduced from 60 to 40℃ in 200 min for the plane LHSU while it reduced to 40 min through using foam LHSU. Thus, a significant reduction in the time of the solidification reached 85% by employing composite PCM.

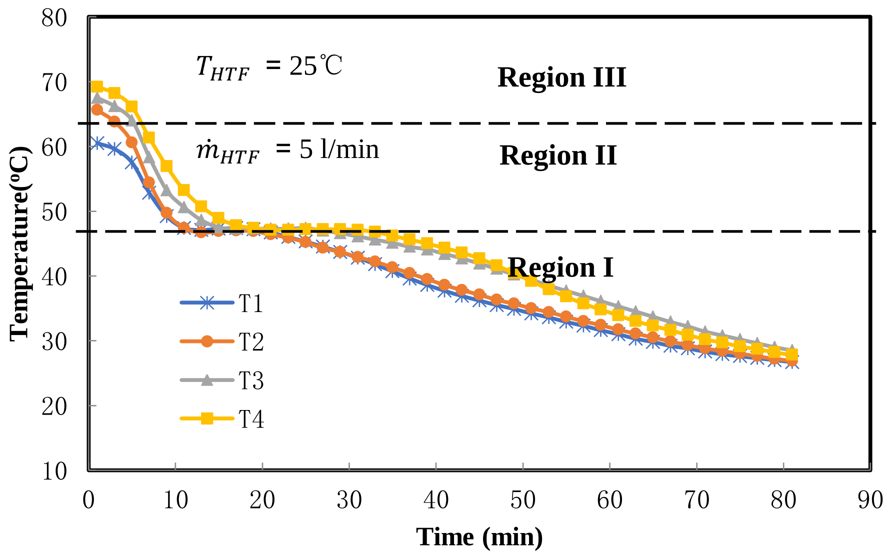

Fig.12 Temperature variation of PCM during solidification process for foamed LHSU

4 Conclusions

The experimental results in terms of phase change cycles (melting and solidification) for PCM-LHSU with and without aluminium metal foam were discussed, and the main conclusions can be drawn as follows:

1) During melting, the heat transfer was significantly influenced due to natural convection. The wax melting initially occurred at the upper portion of the LHSU due to bouncy effect and then moved downward.

2) During solidification, the heat transfer was mainly governed by conduction because of the poor conductivity of PCM, and thus the heat transfer rate was comparatively low. However, the completed solidification time of the LHSU was longer than the melting process.

3) High HTF temperature had great impact on the thermal performance of LHSU.

4) It should be noted that the required time for melting was largely decreased by employing metal foam with LHSU test section compared with the plane LHSU. However, the enhancement of the performance of the storing energy was increased with HTF temperature. The greatest percentage decrease in melting time reached to 83 % due to the use of metal foam.

5) The percentage decrease in solidification time was about 85% compared with the plane LHSU case because of metal foam.

Acknowledgments

The authors would like to thank College of Engineering, The University of Diyala for laboratory working space. The authors are thankful for technical support during measurement to BSc. Eng. Ream Samaan kahtan and Shahad Ahmed Atwan.

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