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REAL-TIME VISUAL AND QUANTITATIVE INVESTIGATION ON MELTING CHARACTERISTICS IN LATENT HEAT THERMAL ENERGY STORAGE SYSTEM INFUSED WITH PARTIAL FINS

Varun Joshi*, Akhil KV, Manish K. Rathod
Mechanical Engineering Department, Sardar Vallabhbhai National Institute of Technology, Surat-395007, India
here.varunjoshi@gmail.com

ABSTRACT

A present experimental study demonstrates the visual characteristics of the liquid-solid interface during the melting process in the Latent Heat Thermal Energy Storage System (LHTES) system. The instantaneous morphology of liquid-solid interface and temperature are directly obtained at the different locations in the enclosure when heated at an isothermal temperature condition. The visualization of the phase front and temperature field shows the significance of fins to alleviate the melting phenomenon by the formation of thermal plumes above the top surface of the fins. The role of natural convective transport as a governing mechanism for the phase change process in the partial assisted enclosure is also discussed.

Keywords: Latent heat thermal energy storage system, partial fins, liquid-solid interface morphology

1. INTRODUCTION

A latent heat thermal energy storage (LHTES) system using liquid-solid phase change has witnessed wide applications in thermal energy storage (TES) and thermal management systems (TMS). These can be attributed to the large storage density within a small volume, broad latent heat of fusion and a wide range of melting temperature of phase change materials (PCMs). However, the explicit disadvantage of these PCMs is weak thermal conductivity. This constrained thermal conductivity restrains rapid response to thermal absorption and dissipation and thus, limits widespread utilization of LHTES. Many researchers proposed various methods for thermal conduction enhancement of PCM [1]. The association of extended surfaces/fins to improve thermal transport is in the research trend [2]. The fins embedded in LHTES systems are longitudinal, annular, plate and pin fins. The literary reports often focus on specific variables as essential parameters in the fin design and acknowledge substantial dependence of fins on overall LHTES. Thus, shape, size, volume, specific geometry and allocation of fins are highly dependent on the thermal behavior of PCM. Lacroix and Benmadda [3] presented the effect of fin number and size of fins in a rectangular vertical cavity filled with n-octadecane as PCM. The study advised to increase in the length of fins over increasing the number of fins. The longer fins were found to be more prominent in thermal penetration over shorter fins. Gharenaghi and Sezai [4] carried out a thermal and a geometrical parametric study for establishing the thermal performance of a finned rectangular cavity filled with PCM. An observable reduction in time was found when the fin spacing decreased for melting of vertical and horizontal modules. In addition, the larger temperature difference across walls, higher heat transfer enhancement was obtained by inserting fin arrays. It is also mentioned that the decrease in PCM module thickness should be preferred over decreasing inter fins distance. Rathod and Banerjee [5] experimentally investigated the influence of inlet temperatures and mass flow rates of a heat transfer fluid on the thermal performance of shell and tube type LHTES system associated with longitudinal fins. It was shown that the inlet temperature of heat transfer fluid has a substantial effect over the mass flow rates. In addition, the solidification time was found to be reduced by 43.6% with the installation of fins.

It can be stated that numerous researchers have studied the thermal performance of these fins in different configurations of LHTES experimentally and numerically. It is concluded that the addition of these fins can significantly enhance thermal transport in PCM. However, it is observed that very few studies can be identified which discusses thermal transport in a rectangular enclosure subjected to partial fins during melting process experimentally. The real-life movement of the liquid-solid interface and temperature history are found to be very rarely established.

Thereby, the objective of the present study is to present a real-life visualization of liquid-solid interface and temperature evolution during the melting process. The morphology of the liquid-solid interface is captured at different time events and simultaneously, the temperature evolution at various selected points are recorded to estimate the overall thermal performance of LHTES. The visualization process assists to understand the fundamentals of natural convective as governing thermal transport phenomenon during the melting process.

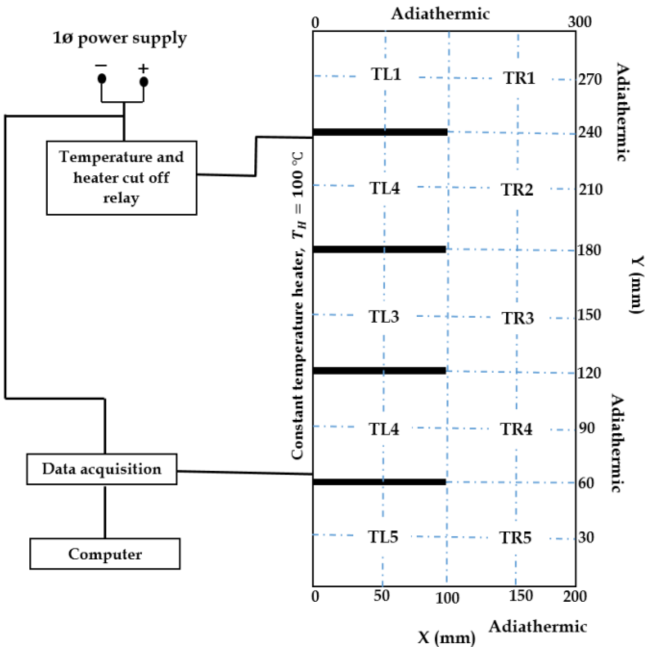

Figure 1: Experimental setup schematic for a LHTES system associated with fins

Table 1: Thermo-physical properties of stearic acid and brass fins

Properties	Stearic acid	Brass fins
Density (kg/m^3)	960	847
Specific heat (J/kg.K)	2860	380
Thermal conductivity (W/m.K)	0.3 (solid) 0.172 (liquid)	115
Latent heat (kJ/kg)	165.0	-
Melting temperature (°C)	56.7-57.7	-
Dynamic viscosity (kg/m.s)	0.00342	-
Coefficient of thermal expansion (1/K)	0.0003085	-

2. SYSTEM DESCRIPTION AND EXPERIMENTATION

A schematic layout of the developed LHTES system, which consists of a rectangular enclosure with four equal size fins made of brass, is shown in Figure 1. The enclosure size is 200 (length) × 100 (width) × 300 (height) mm3. The fin size is 100 (length) × 3 (height) mm2. The fins are mounted on the thermal energy source wall at the left side of the enclosure. The fins were installed, ensuring no thermal contact resistance between contact surface and fin base. The left wall is exposed to a constant temperature of 100 °C using an immersing rod type heater while others are well-insulated using cerawool. For transient monitoring of temperature distribution, 10 numbers of thermocouples are arranged in a vertical midplane of the enclosure. The thermocouples are positioned in a staggered way in five rows and two columns (Figure 1). The experiments are performed at the initial solid phase of PCM maintained at 30 °C and continued during the complete melting process. The enclosure with fins is filled with Stearic acid with thermo-physical properties as shown in Table 1.

2. RESULTS AND DISCUSSION

The evolution of liquid-solid interface and temperature evolution at selected points during the melting process are presented in Figures 2 and 3 respectively. At the beginning of the melting process, the solid PCM absorbs heat from the high-temperature source wall and supply it to an adjacent layer of solid PCM with low temperature. As PCM reaches its melting temperature, a thin layer of liquid PCM can be visible around the periphery of fins and between solid PCM and high-temperature source wall. This can be clearly visible in the liquid-solid interface after 30 min in Figure 2. Afterward, the high-temperature liquid PCM reaches to top portion due to the influence of buoyancy-induced natural convective transport. The liquid-solid interface can be observed to be more curvilinear at top of the enclosure as compared to the bottom of the enclosure. As shown in Figure 2 after 60 min, the more volume of accumulated liquid PCM at top portion can be noticed which decreases towards fins intermediate spacing and bottom of the enclosure. Simultaneously, the significant melting of PCM at the top surfaces of fins can be observed due to the formation of thermal plumes caused by vortices on the top surface. While the melting process at the bottom surface of fins can be attributed to the boundary layer formed between the tip of the fins and the bottom of the thermal energy source wall. With the progress of the melting process, the buoyancy-driven liquid PCM from top surfaces of fins reaches to the bottom portion of successive fins. Due to the large temperature difference between liquid PCM and high-temperature source wall, the liquid PCM experiences drag at the base of fins. The liquid PCM moves towards the tips of fins after 150 min. The liquid PCM transfers heat at fins tips to neighboring solid PCM and erodes solid PCM. This movement of liquid PCM to flow the upper portion of the enclosure though fins tips resemble channeling flow after 60 min. When the solid PCM within the space between the fins melts completely, the phase interface propagates with uniformity at the top enclosure portion. A large slope of phase interface can be observed after 180 min. This is due to accumulation PCM at the top portion of the enclosure which expresses a strong presence of buoyancy-induced convective transport. The movement of the phase interface resembles melting of PCM without the presence of fins. Although, the slop of curvature in phase interface contours reduces towards the bottom of the enclosure, which ensures the presence of conduction dominant thermal transport (after 270 min). The melting time required by proposed configuration during the complete melting process can be seen to be 540 min.

The temporal variation of temperature recorded by thermocouples depicts detailed thermal characteristics of thermal transport perceived in PCM during the melting process. The temperature measured by thermocouples, TR located between fins and TL located away from fins in the enclosure is presented in Figures 3(a) and (b) respectively. The thermal energy source wall is maintained at 100 oC. It can be observed that the rise in temperature of PCM for all thermocouples between the fins is almost identical when the temperature of PCM is below the melting temperature (55.7-56.7 ^{o}C). This indicates that the conductive thermal transport is prevalent through solid PCM. When the temperature of solid PCM reaches to melting temperature limits of PCM, the steep increase in temperature can be observed in both left and right sides of thermocouples (Figures 3(a) and (b)). This steep increase in temperature can be attributed to flow transport of liquid PCM near the tip of thermocouples from solid PCM to liquid-solid interface (including semi liquid-solid phase / mushy region). It can be seen from Figure 3(a) that the value of steep rise in temperature decreases from a top thermocouple (TL1) to remaining lower positioned thermocouples in the same column. In other terms, the transition time of a steep rise in temperature reduces from top to bottom positioned thermocouples. This delay in transition time from top to bottom thermocouples can be credited

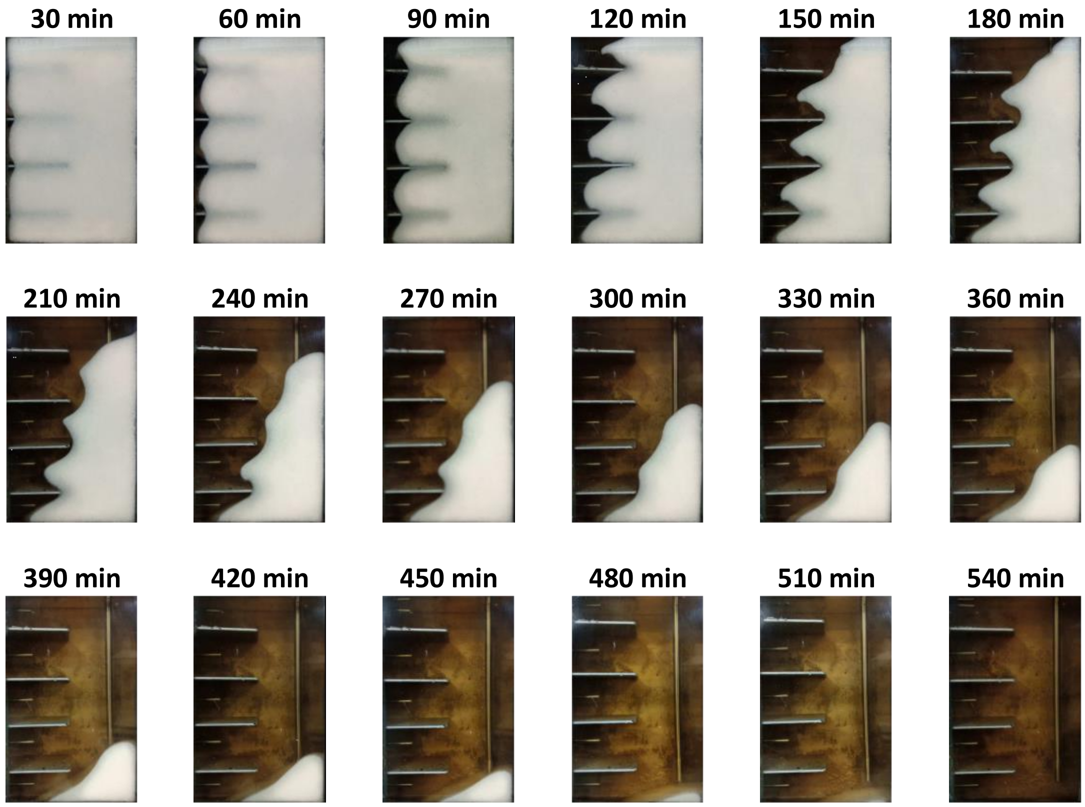

Figure 2: Temporal evolution of liquid-solid interface during melting process

broad mushy region as it flows downwards along the liquid-solid interface. This is also due to lower temperature of bulk liquid PCM at the bottom portion of the enclosure (high-temperature PCM flows to top portion due to buoyancy). Similar observations can be made for thermocouples on the right side of the enclosure (Figure 3(b)). Further, it can be seen that the liquid perceives thermal stratification (thermal layers of high temperature to low-temperature liquid PCM) with the progression of time. The liquid PCM near to a thermal energy source wall achieves thermal stratification at the middle stage while the liquid PCM at the interior of enclosure achieves it after a middle stage of the melting process.

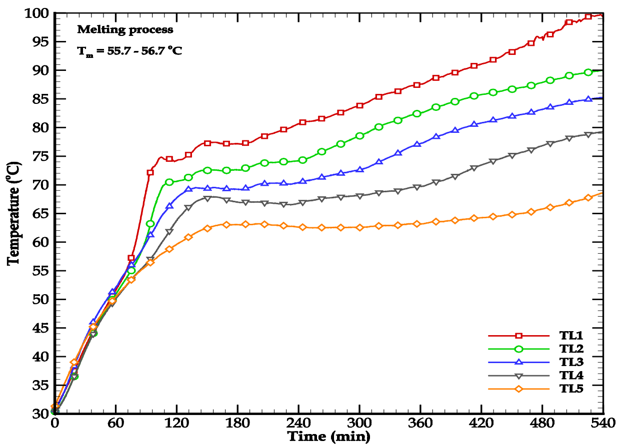

Figure 3 (a): Thermocouple points between fins

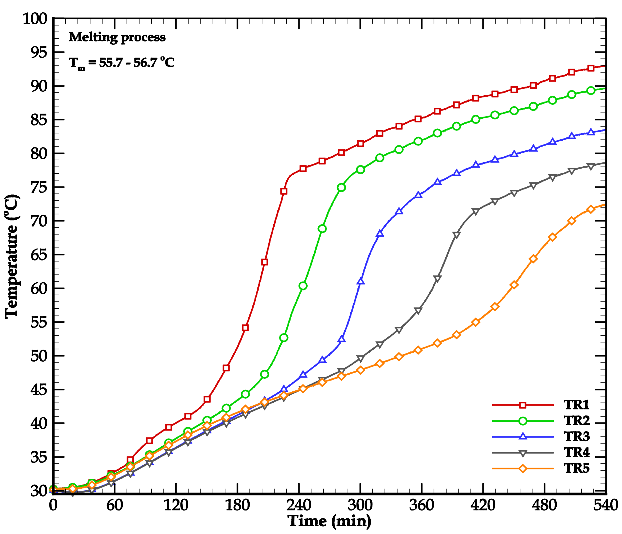

Figure 3 (b): Thermocouple points away from fins

Figure 3: Temporal variation of temperature recorded by various thermocouple during the melting process

4. CONCLUSION

An experimental study is carried out to visualize the liquid-solid interface propagation and estimate the thermal transport perceived in the partial fins assisted LHTES system. The real-life liquid-solid interface is traced at different time events while the temperature evolution at various selected points is measured to establish the overall thermal performance of the LHTES system. It is shown that the liquid-solid interface visualization and associated temperature measurement describe the qualitative and quantitative details on the natural convective transport and evidence of its influence on the morphology and propagation of the liquid-solid interface.

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