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Experimental investigations of charging/melting cycles of paraffin in a novel shell and tube with longitudinal fins based heat storage design solution for domestic and industrial applications

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HIGHLIGHTS

- Thermal behaviour of paraffin based novel LHS unit is experimentally investigated.
- Thermal response of LHS unit to various operating conditions are experimented.
- Impact of inlet temperature is more prominent as compared to flow rate of HTF.
- Natural convection has pronounced impact on thermal performance of LHS unit.
- Thermal storage capacity (14.36 MJ) of LHS unit is charged in as less as 3 h.

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ABSTRACT

Due to vulnerability of solar energy based technologies to weather fluctuations and variations in solar thermal irradiance, thermal energy storage (TES) systems with their high thermal storage capacity offer a sustainable solution. In this article, experimental investigations are conducted to identify thermal performance of latent heat storage (LHS) unit in connection with flat plate solar collector during charging cycles. LHS unit is comprised of novel geometrical configuration based shell-and-tube heat exchanger with longitudinal fins, paraffin as thermal storage material and water as heat transfer fluid (HTF). In order to overcome the effect of low thermal conductivity of paraffin, the effective surface area and overall thermal conductivity for heat transfer is significantly improved by employing longitudinal fins. Moreover, the vertical orientation of longitudinal fins supports natural convection, which can assure rapid charging of paraffin in LHS unit. In experimental tests, the focus is on probing the heat transfer mechanism and temperature distribution in entire novel LHS unit, the influence of inlet temperature and volume flow rate of HTF on phase transition rate and mean power. Experimental results revealed that natural convection significantly influences the phase transition rate. Therefore, enthalpy gradient is noticed between paraffin at top, central and bottom positions in LHS unit. Likewise, the phase transition rate and mean power of LHS unit is significantly increased by a fraction of 50.08% and 69.71% as the inlet temperature of HTF is increased from 52 °C to 67 °C, respectively. Similarly, it is concluded that volume flow rate of HTF has a relatively moderate influence on thermal performance; however the influence declines with an increase in inlet temperature of HTF. Due to significant enhancement in thermal performance, the novel geometrically configured LHS unit can accumulate about 14.36 MJ of thermal energy in as less as 3 hours. Furthermore, a broad range of domestic and commercial energy demands can be fulfilled by simply assembling several LHS units in parallel sequence.

1. Introduction

Energy is the backbone of a country economic development. Due to rapid increase in industrial and domestic energy demands, the dependency on fossil fuels to meet required energy demands have further increased. However, the excessive usage of fossil fuels have provoked global warming and climate change [1,2]. Therefore, in order to limit environmental pollutions and to meet energy demands, developments in technologies are essential to utilise renewable energy sources. Solar energy is considered as a crucial renewable energy source due to its

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clean, free of cost and worldwide distribution of incident solar radiations [3,4]. However, the fragmentary and inconsistent nature of solar radiations has affected the widespread applications of solar energy. To overcome the inconsistent and unpredictable nature of solar energy, TES system can provide a feasible solution. TES system can be utilised to capture thermal energy at solar peak hours and release it at solar off peak hours or night times. To shorten the energy supply and demand gap, LHS systems can be employed due to their higher thermal storage density, phase change materials (PCM) availability at wide range of temperatures, higher latent heat capacity at almost isothermal condition and lower vapour pressure [5,6].

LHS systems are employed in number of applications including solar thermal systems, energy management and peak-shaving, waste heat recovery, building heating and air conditioning, agricultural drying units and automobile [7–13]. However, the widespread practical utilisation of LHS system is still under the influence of low thermal conductivity (≈0.2–0.4 W/m·K) of PCM, which handicaps the rapid charging and discharging of thermal energy [14]. Therefore, to improve thermal performance of LHS system, efficient and responsive heat exchanging techniques are essential to be adopted. A substantial number of research articles have been published that concern developments in thermal performance of LHS system including geometrical configuration [15], using extended surfaces [16], addition of thermal conductive additives [17], form stable and encapsulation of PCM [18,19].

Thermal performance of LHS system is highly influenced by geometrical configuration of heat exchanger. Therefore, this article is focused on shell-and-tube heat exchanger based LHS systems due to the fact that it presents relatively better heat transferring performance and possesses excellent integration to number of engineering applications [20]. Wang et al. [21] conducted numerical investigations to examine thermal performance of n-octadecane in horizontal shell-and-tube heat exchanger. It was observed that with an increase in inlet temperature of HTF, the phase transition time was significantly reduced and the amount of thermal energy stored was non-linearly increased. However, with an increase in mass flow rate, the melting time was reduced whereas the amount of thermal storage was not significantly affected. Similarly, Tay et al. [22] performed experimental investigations on thermal performance of water as PCM in vertical tubes-in-tank heat exchanger. It was observed that an increase in mass flow rate from 0.01 kg/s to 0.07 kg/s reduced the phase transition duration from 215 min to 88 min. Hosseini et al. [23] conducted an experimental and numerical study to identify the influence of natural convection and inlet temperature of HTF on phase transition rate of paraffin in horizontal shell-and-tube heat exchanger. It was reported that natural convection highly influenced melting rate of paraffin in upper portion of shell. Likewise, it was noticed that the melting time was reduced by a fraction of 37% with an increase in inlet temperature from 70 °C to 80 °C. Likewise, Meng and Zhang [24] conducted an experimental and numerical investigation of melting behaviour of paraffin composite with copper form in vertical shell-and-tube heat exchanger. It was noticed that due to natural convection the temperature at top portion was higher as compared to other portions. Likewise, with an increase in inlet temperature of HTF from 75 °C to 85 °C, the melting time was reduced by a fraction of 41.67%. Moreover, an increase in flow velocities of HTF from 0.1 m/s to 0.2 m/s had only reduced the melting time by 15.1%. Furthermore, Esapour et al. [25] numerically investigated the melting behaviour of paraffin in horizontal shell-and-tube heat exchanger. It was noticed that with an increase in number of HTF tubes from 1 to 4, the melting time was reduced by 29%. Likewise, Luo et al. [26] numerically examined the effect of HTF tubes number and their orientations in horizontal shell-and-tube heat exchanger on thermal performance. It was noticed that melting time for single HTF tube was 5 times as compared to nine HTF tubes case. Likewise, centrosymmetric configuration showed better thermal performance than staggered and inline configurations.

It can be construed from previous literature that shell-and-tube heat exchanger configurations have significant influence on thermal performance of LHS system. However, the optimal advantages are still hindered by low thermal conductivity of PCM. Therefore, the most appropriate and cost effective technique to enhance thermal performance is to incorporate extended surfaces. Rathod and Banerjee [27] conducted an experimental examination of melting behaviour of stearic acid in vertical shell-and-tube heat exchanger with three longitudinal fins configuration. It was observed that with longitudinal fins, the melting time was reduced by 24.52% as compare to no fins orientation. Yuan et al. [28] examined the impact of longitudinal fins on melting rate of lauric acid in horizontal shell-and-tube heat exchanger. It was noticed that complete melting time was reduced from 328 min for no fins orientation to 180 min for two fins orientation. Likewise, the peak melting enhancement ratio for inlet temperatures of 60 °C, 70 °C and 80 °C were 1.403 to 1.362, and 1.328, respectively. Li and Wu [29] conducted numerical investigations on thermal performance of $NaNO_3$ in horizontal shell-and-tube heat exchanger with and without longitudinal fins. It was noticed that average total heat flux of heat exchanger was increased by inclusion of six longitudinal fins and consequently, the melting time was reduced by 20%. Rabienataj Darzi et al. [30] numerically examined the influence of number of fins on melting time of n-eicosane in horizontal shell-and-tube heat exchanger. It was reported that as compared to no fins orientation, the melting time was reduced by 39%, 73%, 78% and 82% by incorporating 4, 10, 15 and 20 fins, respectively. However, with an increase in number of fins, the influence of natural convection on melting rate was affected. Likewise, Tao and He [31] recommended that non-uniform melting front and temperature distribution caused by natural convection could be improved by inclusion of longitudinal fins. However, the uniformity could be distorted again if excessively large fins number, height and thickness are employed. Wang et al. [32] conducted numerical analyses to identify the impact of various angles between three longitudinal fins on thermal performance of PCM in horizontal shell-and-tube heat exchanger. The selected angles between adjacent fins were 30°, 60°, 90° and 120°. It was reported that fins angle 60° and 90° displayed better heat transfer enhancement. Moreover, Liu and Groulx [33] experimentally investigated the thermal behaviour of dodecanoic acid in horizontal shell-and-tube heat exchanger with four longitudinal fins configuration. Longitudinal fins were installed in two orientations such as straight and angled. It was reported that natural convection was a dominant mode of heat transfer. Likewise, it was observed that inlet temperature of HTF has more prominent impact on thermal behaviour as compared to flow rate of HTF. Also, it was reported that angled fins showed a slightly lower melting time as compared to straight fins. However, the impact of angled fins declined with an increase in inlet temperature.

Beside longitudinal fins, the other proposed design solutions for thermal performance enhancement with extended surfaces are radial, helical, pinned and triplex fins. Tay et al. [34] conducted numerical investigations on three models of tubes-in-tank heat exchanger configurations without fins, with pins and with radial fins. It was concluded that radial fins based heat exchanger had better phase transition rate and average effectiveness as compared to without fins and with pins orientations. However, a comparative study illustrated that longitudinal fins possess better thermal storage performance. Caron-Soupart et al. [35] experimentally studied the melting behaviour, heat exchanger power and thermal storage density of three vertical shell-and-tube heat exchanger configurations. The three selected orientations were tube without fins, with longitudinal fins and with radial fins. It was observed that heat exchanger orientations with longitudinal fins and circular fins showed significantly higher melting rate as compared to no fins orientation. Likewise, heat exchanger power was augmented by a factor of 10 as compared to no fins orientation. However, thermal storage density was noticeably reduced by radial fins orientation as compared to no fins orientation. Similarly, Agyenim et al. [36] experimentally examined the thermal performance of erythritol in