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Parametric investigations to enhance thermal performance of paraffin through a novel geometrical configuration of shell and tube latent thermal storage system

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This paper presents a two-dimensional finite element computational model which investigates thermal behaviour of a novel geometrical configuration of shell and tube based latent heat storage (LHS) system. Commercial grade paraffin is used as a phase change material (PCM) with water is employed as a heat transfer fluid (HTF). In this numerical analysis, the parametric investigations are conducted to identify the enhancement in melting rate and thermal storage capacity. The parametric investigations are comprised of number and orientation of tube passes in the shell, longitudinal fins length and thickness, materials for shell, tube and fins, and inlet temperature of HTF. Numerical analysis revealed that the melting rate is significantly enhanced by increasing the number of tube passes from 9 to 21. In 21 passes configuration, conduction heat transfer is the dominant and effective mode of heat transfer. The length of fins has profound impact on melting rate as compared to fins thickness. Also, the reduction in thermal storage capacity due to an increase in fins length is minimal to that of increase in fins thickness. The influence of several materials for shell, tube and fins are examined. Due to higher thermal conductivity, the melting rate for copper and aluminium is significantly higher than steel AISI 4340, cast iron, tin and nickel. Similarly, the thermal storage capacity and melting rate of LHS system is increased by a fraction of 18.06% and 68.8% as the inlet temperature of HTF is increased from 323.15 K to 343.15 K, respectively. This study presents an insight into how to augment the thermal behaviour of paraffin based LHS system and ultimately, these findings inform novel design solutions for wide-ranging practical utilisation in both domestic and commercial heat storage applications.

1. Introduction

For a long era, the world energy requirements are served and assisted by fossil fuels. However, due to the number of downsides of using fossil fuels such as limited and depleting resources, inconsistent prices and emission of harmful gases have encouraged scientists and engineers to progress in technologies to take advantages of renewable energy. In order to respond to the unpredictable and fluctuating nature of renewable energy sources, latent heat storage (LHS) system provides a viable option. LHS utilises PCM to store surplus thermal energy within solar systems or heat recovery systems and retrieves it when needed, in order to minimise the gap between energy demand and supply [1,2].

However, due to low thermal conductivity of PCM, rapid energy storage and discharge has been a major obstacle. Therefore, LHS system requires a sensitive and responsive thermal energy storing and discharging technique. A significant body literature is available that deals with the enhancement of LHS system such as geometric orientations of LHS system [3,4], utilising extended surfaces [5,6], encapsulation of PCM [7–11], employing form stable PCM [12–17] and inclusion of high thermal conductivity additives to PCM [18–20].

To develop efficient and productive LHS systems, thermal behaviour of several configurations and orientations have been examined. PCMs are normally employed in rectangular, spherical, cylindrical and shell and tubes containers. Kamkari and Shokouhmand [21] conducted an experimental study to identify the effect of number of fins on heat transfer and melting rate of PCM in rectangular container. It was deducted that melting time for one fin and 3 fins were reduced by 18% and 37% as compared to without fins enclosure. However, an increase in number of fins resulted in

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Nomenclature

C_p	specific heat at constant pressure (kJ/kg K)
$\mathbf{F}$	volume force (Pa/m)
f	fraction of PCM in solid and liquid phase
f_s	fraction of PCM in solid phase
f_l	fraction of PCM in liquid phase
$\mathbf{g}$	gravitational acceleration (m/s^2)
H	specific enthalpy (MJ)
k	thermal conductivity (W/m K)
L	latent heat of fusion (kJ/kg)
T	temperature of PCM (K)
T_s	temperature of solid region of PCM (K)
T_l	temperature of liquid region of PCM (K)
T_{pc}	phase change temperature (K)
p	pressure (Pa)
q	heat source term (W/m^3)
S	momentum source term
$\mathbf{u}$	velocity (m/s)
α	small constant value
β	coefficient of thermal expansion (1/K)
κ	morphology constant of mushy zone
ρ	density (kg/m^3)
μ	dynamic viscosity (kg/m s)

Subscripts

s	solid phase of PCM
l	liquid phase of PCM

Acronyms

HTF	heat transfer fluid
LHS	latent heat storage
PCM	phase change material

reduced natural convection and thus the overall heat transfer rate was compromised. Kalbasi and Salimpour [22] numerically studied the impact of length and number of longitudinal fins on thermal performance of PCM in rectangular enclosure. It was reported that higher number of longitudinal fins with shorter length showed augmented natural convection as compared to few fins with longer length. It was recommended that an optimum value for fins length and number should be identified to optimise the system. On the contrary, Ren and Chan [23] reported that an increase in longitudinal fins length enhanced the melting rate of PCM and therefore small number of lengthy fins exhibited effective thermal performance as compared to large number of shorter fins.

Li and Wu [24] numerically investigated the influence of six longitudinal fins on melting rate of $NaNO_3$ in horizontal concentric tube. It was observed that extended fins can reduce the melting and solidification time by at least 14% compared to concentric tubes without fins. Darzi et al. [25] simulated the effect of number fins on melting and solidification rate of N-eicosane in horizontal concentric tube. It was noticed that melting time for 4, 10, 15 and 20 fins were reduced by 39%, 73%, 78% and 82% as compared to no fins case, respectively. Likewise, the solidification time was decreased by 28%, 62%, 75% and 85% as compared to no fins case, respectively. However, as an increase in fins number restrained natural convection, thus increase in fins presented more prominent influence on solidification than melting rate. Yuan et al. [26] simulated the impact of fins angle on melting rate of lauric acid in horizontal concentric tube. It was reported that fins angle plays a significant role in influencing melting rate. The different angles for installation of two fins were 0°, 30°, 45° and 90°. The melting rate for fins angle 0° was comparatively higher. Moreover, in case of fins angle 0°, an increase in inlet temperature of HTF from 60 °C to 80 °C reduced melting time by 59.24%.

Caron-Soupart et al. [27] conducted an experimental examination to identify the effect of vertical concentric tube orientations on melting rate, heat exchange power and storage density. Selected concentric tube orientations were consisted of a single HTF tube without fins, with longitudinal fins and with circular fins. It was noticed that the melting rate for tube with longitudinal fins and circular fins was significantly higher than that of the tube without fins. Likewise, the heat exchange power was increased by a factor of 10 for the fins orientations than without fins. However, due to provision of higher PCM volume, the tube without fins orientation exhibited higher thermal storage density. Likewise, Agyenim et al. [28] conducted an experimental investigation to identify the thermal response of erythritol as a PCM in three orientations of horizontal concentric tube. The three orientations were concentric tube with no fins, with circular fins and with longitudinal fins. It was noticed that after 8 h of charging, only longitudinal fins orientation was able to melt the entire PCM. Also, cumulative thermal energy storage for longitudinal fins was comparatively higher. During solidification process, longitudinal fins showed better thermal performance with reduced subcooling.

Rathod and Banerjee [29] experimentally evaluated the effect of three longitudinal fins on melting and solidification rate of stearic acid in shell and tube container. It was noticed that melting and solidification time was reduced by 24.52% and 43.6% as compared to without fins case, respectively. Luo et al. [30] numerically studied the impact of number of HTF tubes and their orientations in shell and tube container on thermal performance. It was observed that the required melting time for single HTF tube was 2.5 and 5 times than four and nine HTF tubes, respectively. Similarly, the thermal performance of centrosymmetric orientation is better than staggered and inline orientation. Esapour et al. [31] also examined the influence of number of HTF tubes in shell and tube container. It was noticed that by increasing the number of HTF tubes from 1 to 4, the melting time can be reduced by 29%. Therefore, it is evident that the number of HTF tubes has a good influence on thermal behaviour of LHS system.

Vyshak and Jilani [32] conducted a numerical study to compare the impact of rectangular, cylindrical, and shell and tube container orientations on melting rate of PCM. It was observed that for the same volume and heat transfer surface area, the melting rate for shell and tube configuration was comparatively higher.

Tao et al. [33] numerically investigated the influence of HTF tube geometry on melting time. The tested configurations involved smooth, dimpled, cone-finned and helical-finned tubes. It was reported that the melting time for dimple, cone-finned and helical-finned tube was reduced by 19.9%, 26.9% and 30.7% comparing to smooth tube, respectively. Likewise, Li et al. [34] reported that heat transfer rate can be significantly enhanced by employing internally ribbed tubes instead of smooth tubes. Furthermore, the influence of the numbers, geometrical configurations and orientations of fins on thermal behaviour of LHS system is discussed in [35–40].

The mass flow rate of HTF has a minimal influence on thermal behaviour as compared to inlet temperature of HTF and geometrical configuration of LHS system. Seddegh et al. [41] numerically examined the influence of vertical and horizontal orientation of