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Numerical study on the effects of fins and nanoparticles in a shell and tube phase change thermal energy storage unit

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HIGHLIGHTS

- Simultaneously studied effects of fins and nanoparticles on melting of PCM.
- Fin angle and nanoparticle concentration significantly affected PCM melting time.
- Melting time varies with creation of hot spot regions and vorticities in melted PCM.
- Adding Al_2O_3 nanoparticles decreased the overall heat transfer rate.
- Fin angle of 35° leads to the shortest charging time among studied cases.

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ABSTRACT

Energy storage is critically important for intermittent renewable sources such as solar or wind. This paper presents a numerical study on a shell and tube thermal energy storage unit using a common organic phase change material (PCM) – paraffin wax. To overcome the problem of slow charging due to low thermal conductivity of paraffin wax, this research applies a multiscale heat transfer enhancement technique, with circular plate fins on outer surface of the heat transfer fluid (HTF) tube and highly conductive nanoparticles (Al_2O_3) dispersed in the PCM on the shell side. The novelty of this research is that by simultaneous application of two enhancement methods, we are able to analyze the interactions between the two, which was not possible in previous studies on separate technique. A computational fluid dynamics (CFD) model is developed to simulate melting of the PCM with the following parameters: nanoparticle concentration ϕ from 0 to 4 vol%; fin angle α from −45° to 45°, and pitch p from 45 to 65 mm. The obtained numerical data was analyzed with a traditional method and a statistical response surface method (RSM). The latter represents another novelty of this research. The RSM analysis shows that fin angle and nanoparticle concentration are two significant parameters in affecting the PCM melting, but pitch of the fins does not show noticeable effect. Numerical results demonstrate that adding nanoparticles in the PCM does not accelerate the charging process; on the contrary it leads to longer charging time and lower overall heat transfer rate due to reduction of natural convection in the melted PCM. A strong interaction is also found between these two significant parameters, for example the charging time considerably increases when nanoparticles are added at $\alpha = -45°$, but this effect is less pronounced when $\alpha = 45°$. Positive fin angles are found to be favorable for PCM melting due to enhanced natural convection with strong local vorticities formed below the fins. A moderate fin angle of 35° leads to the shortest charging time among all studied cases. These new findings can be valuable in design of PCM units for renewable energy storage, waste heat recovery, or thermal management in engineering systems.

1. Introduction

Many renewable energy sources such as solar or wind are intermittent in nature therefore require efficient storage to bridges demand and supply. For example, thermal energy storage units are common for solar thermal and waste heat recovery systems. There are two different types of thermal energy storage systems – sensible heat systems such as hot water tanks, and latent heat thermal energy storage (LHTES) systems where phase change materials (PCMs) are used. Organic PCMs such as paraffin wax have high latent heat of fusion, allowing design of compact thermal energy storage units with large capability [1–3]. But these PCMs usually have low thermal conductivity, resulting in low

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Nomenclature

A_{Mushy}	Mushy zone constant [kg/m^3s]
$\ddot{B}$	regression coefficient
C_p	specific heat [J/kg·K]
d_{np}	nanoparticle diameter [nm]
g	gravity Acceleration [m/s^2]
h	specific enthalpy [J/kg]
h_{ref}	enthalpy at reference temperature [J/kg]
k	thermal conductivity [W/m·K]
l	length [m]
L	specific latent heat [J/kg]
LF	liquid fraction
p	pitch [mm]
P	pressure [Pa]
S	momentum source term [Pa/m]
t	time [s]
T	temperature [K]
T_m	melting temperature [K]
T_{in}	inlet temperature [K]
T_{ref}	reference temperature [K]
u	velocity vector [m/s]
W	heat flux (w/m^2)

Greek letters

α	fin angle [°]
β	coefficient of thermal expansion [1/K]
γ	local liquid fraction
ρ	density [kg/ m^3]
μ	dynamic viscosity [kg/m·s]
ϕ	volume concentration [vol.%]

heat transfer rate and long charging time [3]. Numerous techniques, including adding fins, ribs, applying surface waviness or porous media, have been employed in order to enhance heat transfer rate of PCMs [4–7]. Another method of increasing thermal conductivity of PCM is by dispersion of highly conductive nanoparticles in it. The resulted mixture is often referred to as nano-enhanced phase change material (NePCM) [8–15]. Some previous studies [10,11] showed significant increase of thermal conductivity of paraffin when different nanoparticles such as aluminum oxide (Al_2O_3) or multi wall carbon nanotubes (MWCNTs) are added. But other studies [12,13] reported insignificant or no thermal conductivity improvement with the same PCM and nanoparticles.

Despite of these disagreements, researchers have put great efforts in studying NePCM as a potential way to increase heat transfer rate in LHTES. Arici et al. [8] simulated melting of paraffin wax and aluminum oxide nanoparticles in a rectangular enclosure. They found that the highest heat transfer enhancement is attained when the enclosure is heated from the bottom with low nanoparticle concentration of ϕ_{NePCM} = 1 vol%. Dhaidan et al. [9] studied melting of *n*-octadecane with copper oxide nanoparticles (ϕ_{NePCM} = 0, 1, 2, 3 wt%) in an insulated horizontal cylindrical annulus. The researchers concluded that adding nanoparticles enhanced the effective thermal conductivity of the PCM and improved the melting characteristics such as increasing the melting rate and expediting the charging time. However other studies also showed negative effects of dispersed nanoparticles on melting of PCMs in LHTES. Many researchers reported unchanged or longer charging time when nanoparticles are added in PCMs [13–15]. It was found that the increased viscosity [13] and reduction of natural convection [14,15] in the melted PCMs lead to insignificant improvement or even decrease of the overall heat transfer rate in the LHTES units, even with confirmed increase of thermal conductivity of the NePCMs [13]. In other words, weakened natural convection overweighed enhanced heat conduction and slowed the melting down. These issues seem common for many different NePCMs, such as carbon nanotubes in 1-dodeconal [14], aluminum oxide and copper oxide in paraffin [13,15]. With nanoparticles, the reduction of natural convection was clear even in studies that showed improvement in the overall heat transfer and fast charging [16–18].

With these issues, researchers turned their interests to the traditional method of heat transfer enhancement with fins with or without nanoparticles in PCMs. Effectiveness of fins in LHTES units have been demonstrated by many researchers, such as Yang et al. [19], and Tay et al. [20]. They also analyzed effects of fin parameters, i.e., numbers, height and thickness, on local natural convection and charging time. Lohrasbi et al. [21] compared charging performance of a LHTES unit with Y-shaped fins on outer surface of HTF tube and the same unit without fins but with different volume fractions (0.025 and 0.05) of nanoparticles in the PCM. It was found that solidification rate in LHTES unit with Y-shaped fins is roughly 5.9 times higher than that in the finless LHTES unit with nanoparticles. In a similar study, Sheikholeslami et al. [22] investigated snowflake shaped fins in LHTES units and reported 4.5–7.8 times faster solidification rate. Although these authors didn't mention any other basis in their comparison, they did report that the change of maximum energy capacity is negligible when fins or nanoparticles are added. Recently Mahdi et al. [23] conducted more systematic comparisons by considering triplex-tube LHTES units in three categories, i.e., nanoparticles alone, fins alone and fins – nanoparticles combination. They set the total volume fraction of nanoparticles and fins to 0.02 and demonstrated that the highest heat transfer rate (leading to 59.2% charging time) was achieved when the fin volume fraction is 0.02 (no nanoparticles). These results indicate that finned LHTES might be a better solution than nanoparticle dispersion in terms of overall heat transfer rate and charging/discharging time.

However these studies missed one important aspect in the comparison of LHTES enhancement with fins or nanoparticles – the interactive effects between these two parameters. For example, will adding nanoparticles change the overall heat transfer rate the same way with and without fins? Or how the fins improve heat transfer in LHTES systems with or without nanoparticles? Many studies on heat transfer enhancement for LHTES indicted potentially important interactions between different parameters. For example, Mahdi et al. [24] demonstrated the dependency of nanoparticle enhancement on the porosity of a porous foam triplex-tube LHTES heat exchanger. In studies on charging performance of a mobilized thermal energy storage (M-TES) unit, Guo et al. [25], Wang et al. [26], Wang et al. [27], and Guo et al. [28] analyzed the effects of flow rate, geometry of flow channels, fins, expanded graphite (EG) nanoparticles, ways of wall heating, direct or indirect contact, and etc. Their results indicate strong interactions between these parameters in determining the melting and solidification of PCM in the M-TES units. Darzi et al. [29] analyzed solidification and melting of PCM enhanced by radial fins and nanoparticles in cylindrical annulus. Both methods were found effective for heat transfer enhancement, but simultaneous effects of fins and nanoparticles were not studied. With potential interactions between multiple parameters in LHTES, it's desirable to simultaneously analyze the effects of fin and nanoparticle parameters, particularly to find the interactions between the two. This will be considered in the current study.

When multiple factors are involved in a study, efficient tools need to be used for analysis. The response surface method (RSM), a statistical technique for data analysis [30], seems suitable for this purpose. RSM analyzes the behaviors of different parameters (inputs) on the target