The effect of the dispersion of nanoparticles on the melting of phase change material inside a shell-and-tube storage unit using pulsating heat transfer fluid flow

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Abstract

The aim of this work is to investigate the effect of a laminar pulsating heat transfer fluid (HTF) flow on the melting of nanoparticle-enhanced phase change material (NEPCM) inside a shell-and-tube latent heat storage unit (LHSU). The shell space is filled with n-octadecane as a base phase change material (PCM) dispersed with copper nanoparticles. A heat transfer fluid (HTF: water) flows in the inner tube and transfers heat to NEPCM. A mathematical model based on the energy conservation equations has been developed and validated by experimental, numerical and theoretical results. Numerical simulations were conducted to investigate the effect of the volumetric fraction of nanoparticles on the thermal behavior and performance of the storage unit.

Keywords: *Latent heat storage unit (LHSU); Pulsating flow; Nanoparticles; Phase change material (PCM); Nanoparticle-enhanced phase change material (NEPCM); heat transfer fluid (HTF).*

1. Introduction

Due to the benefits owned by latent heat storage units (LHSUs) such as high energy storage density and nearly isothermal behavior during melting and solidification processes, phase change materials (PCMs) have been widely used in several practical applications. These applications include solar water heating, building envelop, electronic cooling and air conditioning. However, the most of PCMs have low thermal conductivities, which limit the heat transfer rate. To overcome this drawback, several approaches have been suggested in the literature including the dispersion of nanoparticles in pure PCMs, use of multiple PCMs, integration of metal matrix in PCMs and porous matrix.

In order to evaluate the thermal energy storage performance in a shell-and-tube LHSU, a number of numerical, experimental and theoretical studies have been performed. Wang, Zhang, Wang and He [1] investigated the thermal performance of a shell-and-tube LHSU during charging and discharging processes. The effect of the HTF inlet temperature and mass flow rate on heat charging and discharging performance are numerically evaluated. The results show that the increase in the inlet temperature and mass flow rate of HTF decreases the charging and discharging time. Khodadadi and Hosseinizadeh [2] compared the thermal behavior in a horizontal and vertical shell-and-tube thermal energy storage system using a combined conduction and convection heat transfer model. The results show that for the horizontal orientation, the convective heat transfer strongly affects the melting of PCM in the upper part, while it is less significant in the lower half part. However, the thermal behavior was found the same for both horizontal and vertical shell-and-tube storage system during the solidification process. Dhaidan [3] proposed a new kind of shell-and-tube latent heat storage unit, which can be integrated with conventional air conditioner to improve the coefficient of performance (COP). The effects of the conductive fin height, mass flow rate and inlet temperature of HTF on the thermal performance of the storage system have been numerically evaluated. The results show that the fin height and HTF mass flow rate need to be optimized in order to achieve best storage performance of the shell-and-tube storage system. Parry, Eames and Agyenim [4] developed a numerical simulation model to investigate the melting and solidification processes of a fixed mass of PCM filled in a shell-and-tube thermal energy storage system. Their simulation results are in good agreement with the measurement temperature and the difference between both one dimensional and two dimensional models was evaluated within 8.5%. Ait Adine and El Qarnia [5] numerically investigated the impact of HTF mass flow rate and inlet temperature on the thermal behavior and performance of a shell-and-tube thermal storage unit using two kinds of PCMs. The simulation results show that the high thermal storage efficiency is achieved for the storage unit using two PCMs for low mass flow rate and inlet temperature of HTF. Elbahjaoui and El Qarnia [6] investigated the thermal performance of a shell-and-tube LHSU heated by a pulsed HTF flow during melting process. The effects of the pulsation frequency, pulsation amplitude, Reynolds number and Stefan number on the thermal characteristics of the storage unit were numerically evaluated. The results show that the pulsating parameters of HTF flow affect the melting time of PCM and the shorter melting time is obtained for a low pulsating frequency (less than 0.052) and high pulsating amplitude. Elbahjaoui et al. [7, 8] studied the melting of PCM (Paraffin wax P116) dispersed with alumina nanoparticles in a rectangular LHSU heated by laminar HTF flow. The storage unit is made of a number of vertically arranged slabs of nanoparticle-enhanced phase change material (NEPCM) separated by a laminar flow of HTF (water). They investigated the effects of the volumetric fraction of nanoparticles, aspect ratio of PCM slabs, Reynolds number and Rayleigh number on the storage performance and flow characteristics of the storage unit. They also developed a correlation including all the investigated parameters to estimate the time required for the complete melting of the storage unit.

The thermal energy can be stored in shell-and-tube LHSU using pulsating HTF flow instead of a classical stationary flow. This kind of flow can be generated by reciprocating pumps or by steady flow pumps integrating some mechanical pulsating device. In this paper, the study of the use of both pulsating HTF flow and NEPCM instead of a stationary flow and a base PCM on the thermal performance of a shell-and-tube LHSU is proposed. The numerical simulations were conducted to investigate the effect of the volumetric fraction of nanoparticles under pulsating HTF flow on the thermal behavior and performance of the storage unit.

2. Mathematical Formulation

Fig. 1 shows the system under investigation which consists of a shell-and-tube latent heat storage unit (LHSU) of 1 m length. The radiuses of the inner and outer tubes are 0.635 cm and 1.83 cm, respectively. Water acting as a heat transfer fluid (HTF) circulates in laminar pulsating flow inside the inner tube.

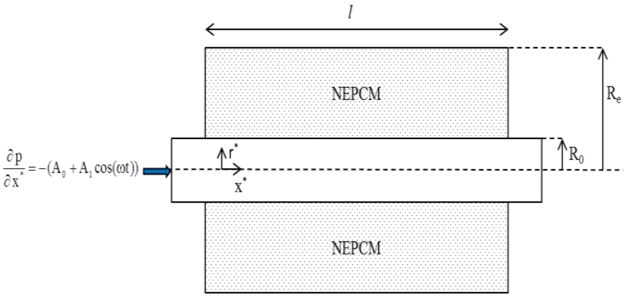

Figure 1 : Schematic of the shell-and-tube LHSU

The dimensionless form of the governing equations is described as follows:

For NEPCM

$$\frac{\partial \theta_{nm}}{\partial \tau} = \frac{\partial}{\partial x}\left(\frac{\bar{\alpha}_{nm}}{\bar{\alpha}_f \, Pr_f} \frac{\partial \theta_{nm}}{\partial x}\right) + \frac{1}{r}\frac{\partial}{\partial r}\left(r \frac{\bar{\alpha}_{nm}}{\bar{\alpha}_f \, Pr_f} \frac{\partial \theta_{nm}}{\partial r}\right) - \frac{1}{Ste} \frac{1-\phi}{1+\phi(\bar{\rho}_n \bar{c}_{p,n} - 1)} \frac{\partial f}{\partial \tau} \quad (1)$$

For NEPCM

$$\frac{\partial u}{\partial \tau} = (8 + \beta \cos(\Omega \tau)) + \frac{1}{r}\frac{\partial}{\partial r}\left(r \frac{\partial u}{\partial r}\right) \quad (2)$$

$$\frac{\partial \theta_f}{\partial \tau} + \frac{R_{ey}}{2} \frac{\partial (u \theta_f)}{\partial x} = \frac{1}{r}\frac{\partial}{\partial r}\left(\frac{1}{Pr_f} r \frac{\partial \theta_f}{\partial r}\right) + \frac{\partial}{\partial x}\left(\frac{1}{Pr_f} \frac{\partial \theta_f}{\partial x}\right) \quad (3)$$

Considering the system linearity, the momentum equation for HTF flow in the inner tube (Eq.2) can be analytically resolved. The velocity solution is expressed as follows:

$$u(r,\tau) = 2(1-r^2) + \mathrm{Real}\left(\frac{i\beta}{\Omega}\left(\frac{J_0(\sqrt{-i\Omega}\, r)}{J_0(\sqrt{-i\Omega})} - 1\right) e^{i\Omega\tau}\right) \quad (4)$$

where J_0 is the zero order Bessel function of the first kind, β and Ω are the dimensionless amplitude and frequency of the pressure gradient oscillations.

The initial and boundary conditions are written as follows:

$$\tau = 0: \quad \theta_{nm} = \theta_f = 0 \quad (5)$$

$$x = 0: \quad \theta_f = 1, \; \frac{\partial \theta_{nm}}{\partial x} = 0 \quad (6)$$

$$x = l / R_0: \quad \frac{\partial \theta_f}{\partial x} = \frac{\partial \theta_{nm}}{\partial x} = 0 \quad (7)$$

$$r = 0: \quad \frac{\partial \theta_f}{\partial r} = 0 \quad (8)$$

$$r = 1: \quad \bar{k}_f \frac{\partial \theta_f}{\partial r} = \bar{k}_{nm} \frac{\partial \theta_{nm}}{\partial r} \quad (9)$$

$$r = R_e / R_0 = \bar{R}_e: \quad \frac{\partial \theta_{nm}}{\partial r} = 0 \quad (10)$$

The control parameters of the present storage system are: ϕ, Ω, β, R_{ey}, Ste, $\bar{R}_e$, $\bar{l}$, Pr_f, $\bar{\rho}_n$, $\bar{c}_{p,n}$, $\bar{k}_n$, $\bar{k}_f$ and $\bar{\alpha}_f$.

3. Results and Discussions

The effect of the nanoparticles' volumetric fraction on the instantaneous solid-liquid interface location is shown in Fig. 2. At the initial time, the HTF begins to flow inside the inner tube and transfers heat to the solid NEPCM which starts to melt. At this stage, the solid-liquid interface appears close to the heat exchange wall ($r = 1$) and it is more profound at the HTF inlet area ($x = 0$). As time elapses, the solid-liquid interface for the various volumetric fractions of nanoparticles penetrates more into the NEPCM interior toward the outside wall ($r = \bar{R}_e$).It should be noted that at the same moment, the solid-liquid interface is more penetrated in NEPCM for a high volumetric fraction of nanoparticles, which implies the larger melting rate of NEPCM.

The effect of the volumetric fraction of nanoparticles on the time-wise variation of the melting fraction is illustrated in Fig. 3. The melting fraction gradually increases over time to reach the value 1 when the

NEPCM becomes completely melted. It should be noted that the larger slope of melting fraction curves is produced for high volumetric fraction of nanoparticles, which presents the higher NEPCM melting rate.
The effect of the volumetric fraction of nanoparticles on the time-wise variation of the sensible, latent and total heat stored in NEPCM is shown in Fig. 4. The time-wise variation of the sensible, latent and total heat undergoes three distinct behaviors. At the early stage, the latent and total heat curves are comparable, which means that heat is mainly stored by latent form in NEPCM. This behavior is due to the fact that the NEPCM is initially solid, and its temperature is equal to the melting point. As melting progresses, the latent and total heat curves gradually rise over time, while the sensible heat curve undergoes a very small increase. It should be noted that during this second stage, the slope of the total heat curves is slightly higher than that of latent heat curves. It is also interesting to note that the large amount of sensible, latent and total heat is stored in NEPCM for high volumetric fraction of nanoparticles. Toward the melting end, a major portion of NEPCM is melted, and the slope of latent heat curves decreases.

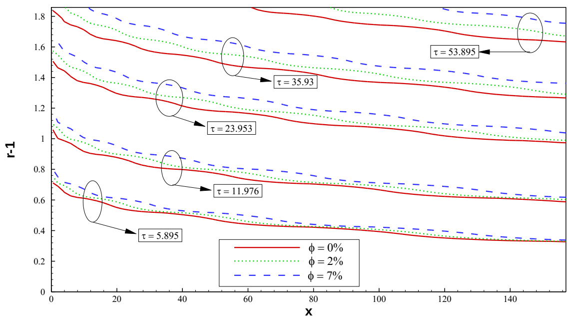

Figure 2: Effect of the volumetric fraction of nanoparticles on the instantaneous solid-liquid interface

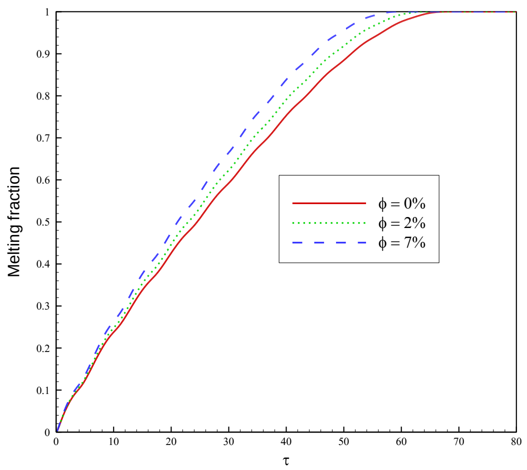

Figure 3: Effect of the volumetric fraction of nanoparticles on the temporal variation of the melting fraction

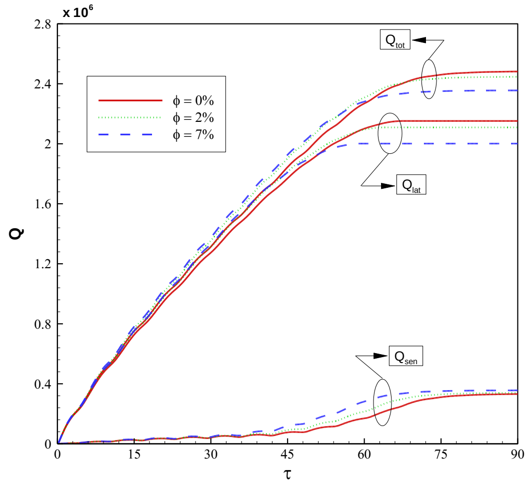

Figure 4: Effect of the nanoparticles' volumetric fraction on the temporal variation of the sensible, latent and total heat stored in NEPCM

4. Conclusion

This work presented a numerical investigation of the melting of nanoparticle-enhanced phase change material inside a shell-and-tube LHSU heated by a laminar pulsating HTF flow. The effect of the volumetric fraction of nanoparticles on the thermal behavior and storage performance was numerically examined.

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