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Effect of Eccentricity on Melting and Solidification Processes of Phase Change Material Inside a Shell-and-tube Latent Heat Storage Unit

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ABSTRACT

The melting and solidification of phase change material (PCM) in a horizontal eccentric shell-and-tube latent heat storage (LHS) unit were numerically studied to design a high-efficiency LHS configuration. Firstly, the melting and solidification in a concentric configuration were studied to reveal the influence of natural convection. The results show that, because of natural convection, the solid PCM above the tube has a high melting rate during the melting process and the liquid PCM under the tube has a high solidification rate during the solidification process. Then the eccentric tube configuration was used to take the best advantage of natural convection. The results show that the eccentric tube with the tube moving to the downside can efficiently enhance the PCM melting rate. The best melting performance can be obtained when the eccentricity (ε) is -0.6, where the PCM melting time reduces about 29.8% compared with the concentric tube. However, the downward movement of the tube seriously weakens the PCM solidification rate and causes total performance deterioration of the entire melting and solidification cycle. For the whole melting and solidification cycle without rotation, the minimum total time is obtained at ε= 0.1 which is only 1.3% less than the total time at ε= 0. A new LHS unit with a rotation configuration was proposed to enhance PCM melting and solidification rates simultaneously. The validation results show the optimum heat transfer performance for the whole melting and solidification cycle can be obtained when ε = -0.2, where the total melting and solidification time reduces by 11.1% compared with concentric configuration.

Keywords: melting; solidification; eccentric tube; phase change material; latent heat storage

NOMENCLATURE

c_p	specific heat, J·kg^{-1}·K^{-1}
d	eccentric distance, m
D	pipe diameter, m
f	liquid fraction
g	gravity acceleration, m·s^{-2}
h	sensible enthalpy, J·kg^{-1}
k	thermal conductivity, W·m^{-1}·K^{-1}
L	latent heat, J·kg^{-1}
$\dot{m}$	mass flow rate, kg·s^{-1}
p	pressure, Pa
t	time, s
T	temperature, K
v	velocity, m·s^{-1}
Greek symbols	
β	thermal expansion coefficient, K^{-1}
ε	eccentricity
μ	dynamic viscosity, kg·m^{-1}·s^{-1}
ρ	density, kg·m^{-3}
φ	small number
Subscripts	
f	heat transfer fluid
l	liquid
p	phase change material
s	solid

1. INTRODUCTION

Energy crisis and environmental issues have become the two critical problems, which restrict the development of the world. The utilization of renewable energy is an effective way to ease these problems. Solar energy is a promising renewable energy source for its pollution-free and inexhaustible characteristics. However, solar radiation has a drawback of discontinuity, which needs thermal energy storage (TES) to keep the working

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condition stable [1, 2]. Latent heat storage (LHS) using phase change material (PCM) as the thermal energy storage medium is getting more attention due to its high energy storage density and isothermal operating temperature [3].

However, the thermal conductivity of most candidate PCMs is low. Therefore, the development of more efficient configurations of LHS is required to enhance its performance [4]. The passive methods such as using fins [5] or encapsulated PCMs[6] to enhance the heat transfer performance will also increase the system complexity or reduce the available PCM volume. So, a better way to enhance the performance of the LHS unit with as little negative effect as possible is urgently needed. Some studies considered the effect of natural convection and proposed the eccentric configuration, which shows noticeable advantages in the melting process. Dhaidan et al. [7] found that melting can be expedited by using an eccentric shell-and-tube arrangement. Cao et al. [8] indicated that the time-average heat transfer coefficient is relatively higher in an eccentric geometry which illustrates that the heat transfer efficiency is improved. All the above research works conducted for the eccentric shell-and-tube LHS are only about the melting process. There are a few studies about the solidification process of eccentric horizontal shell-and-tube LHS units. Huang et al.[9] calculated the freezing in an eccentric annulus. The calculation process is very complex and the effect that eccentricity had on the freezing process was not discussed.

In the present work, the melting and solidification of a PCM in an eccentric shell-and-tube LHS unit are numerically investigated. The effects of eccentricity on liquid fraction, HTF outlet temperature, melting, and solidification time are comparatively discussed for both the melting and solidification processes.

2. PHYSICAL MODEL AND NUMERICAL MODEL

2.1 Physical model

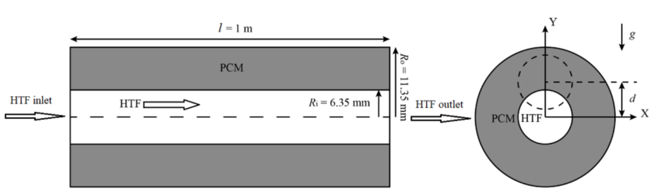

Fig. 1. Schematic view of the physical model

Figure 1 shows the schematic view of the physical model, which is a shell-and-tube configuration LHS unit with a length of 1 m. The radius of the inner tube (R_i) is 6.35 mm and the radius of the shell (R_o) is 11.35 mm. Water is used as the HTF, which flows through the inner tube, and the annulus is filled with commercial paraffin RT50 as PCM. The thermophysical properties of HTF and PCM are shown in Table 1. A dimensionless eccentricity, $\varepsilon = d/(R_o\text{-}R_i)$, is adopted, where d is the eccentric distance.

Table 1 Thermophysical properties of HTF and PCM [10, 11]

HTF		PCM	
k_f (W/m K)	0.64	T_m (K)	318 - 324
ρ_f (kg/m^3)	989.0	k_p (W/m K)	0.2
$c_{p,f}$ (J/kg K)	4180.0	ρ_p (kg/m^3)	780
$\mu_f \times 10^6$ (kg/m s)	577.0	$c_{p,p}$ (J/kg K)	2000
		L (J/kg)	168,000
		β (1/K)	0.0006

2.2 Numerical model

In this study, the enthalpy method is adopted to handle the phase change process. The governing equation is the same for the solid and liquid phases and the interface of the two phases is indicated by a mushy zone [4, 12]. The basic modeling assumptions are as follows:

(1) Boussinesq approximation is considered for density variation during phase change.
(2) PCM flow is laminar and incompressible.
(3) PCM is considered to be a Newtonian fluid in the liquid phase.
(4) Radiation heat transfer to the atmosphere is neglected as the outer surface is assumed to be perfectly insulated.

Continuity equation:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{v}) = 0 \quad (1)$$

Momentum equation:

$$\frac{\partial(\rho\vec{v})}{\partial t} + \nabla \cdot (\rho\vec{v}\vec{v}) = -\nabla p + \nabla \cdot (\mu \nabla \vec{v}) + \rho\beta(T - T_{\text{ref}})\vec{g} + \frac{(1-f)^2}{f^3+\varphi} A_m \vec{v} \quad (2)$$

where φ is a small number (0.001) to prevent division by zero. A_m is the mushy zone constant (10^5 kg·m^{-3}·s^{-1}).

Energy equation:

$$\frac{\partial(\rho h)}{\partial t} + \nabla \cdot (\rho\vec{v}h) = \nabla \cdot (k\nabla T) - \frac{\partial(\rho f L)}{\partial t} - \nabla \cdot (\rho\vec{v}fL) \quad (3)$$

where h is sensible enthalpy, L is latent heat, f is the liquid fraction:

$$f = \begin{cases} 0 & T < T_s \\ \frac{T-T_s}{T_l-T_s} & T_s \le T \le T_l \\ 1 & T > T_l \end{cases} \quad (4)$$

HTF flows in from the inlet of the tube, which imposes the mass flow rate $\dot{m}$ = 0.046 kg/s with Re_D = 1000. At the outlet of the tube, the flow is fully developed. During the melting process, the initial PCM temperature and HTF inlet temperature are set to $T_{initial,l}$ = 293.15 K and $T_{in,l}$ = 343.15 K, respectively. During the solidification process, the initial PCM temperature and HTF inlet temperature are $T_{initial,s}$ = 343.15 K and $T_{in,s}$ = 293.15 K, respectively. No-slip boundary condition is considered at all walls.

To validate the reliability of the present model, an initial run is done and compared with the experimental data of Hosseini et al. [10] under the same geometric parameters and operating conditions. The comparison of the average temperature profile in the PCM versus time between the simulation results from the present model and the numerical and experimental results of Hosseini et al. [10] is shown in Fig.2. The results predicted by the present model are in good agreement with those of Hosseini et al. [10].

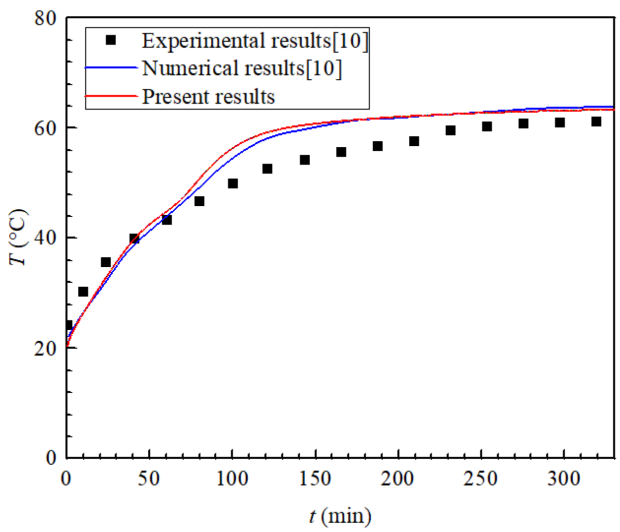

Fig. 2. Validation of numerical model with results of Hosseini et al. [10]

3. RESULTS AND DISCUSSION

3.1 Melting process

Fig.3 shows the liquid fraction contours and streamlines during the melting process for different eccentricities in the cross-section of z = 0.5 m at different times (2.5, 5, 7.5, and 10 min). For ε = 0, in the beginning, the liquid layer formed around the inner tube is very thin and the effect of natural convection can be neglected. Conduction is the main heat transfer mechanism in the liquid region. After 5 min, the liquid region becomes larger and the high-temperature liquid PCM flows upwards which accelerates the melting of the solid PCM in the upper region. In this region, natural convection becomes the main heat transfer mechanism and two distinct vortices appeared. However, in the lower region, the heat conduction remains dominant and the PCM melts much slower than in the upper region. After 10 min, most of the PCM is melted and only a small fraction of solid PCM remains unmelted at the bottom.

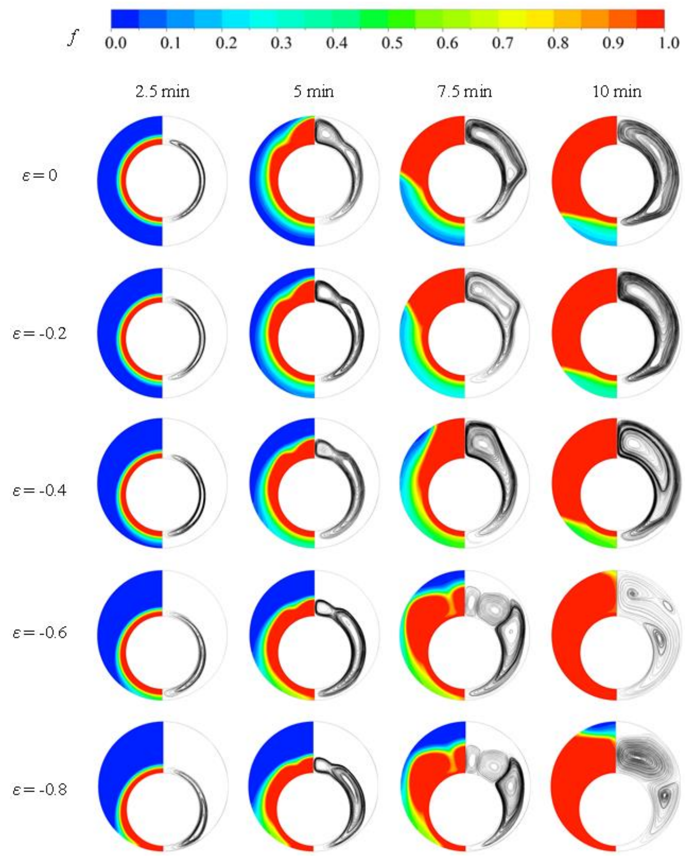

Fig. 3. Liquid fraction contours and streamlines during melting process (ε < 0, z = 0.5 m)

As can be seen, natural convection causes the nonuniform distribution of temperature and melting fraction. This weakens the total heat transfer performance compared to the uniform distributions. To maximize the effect of natural convection and enhance the heat transfer, the configuration of an eccentric inner tube is adopted. For the melting process, the inner tube moves downwards to accelerate the melting rate of PCM in the lower region. The melting process varies for different eccentricities. At 5min, the solid-liquid interface of ε = 0 first reaches the top shell wall and most PCM in the lower part is still in the solid-state; however, for ε = -0.8, the PCM in the lower part is entirely melted but most PCM in the upper part is not melted. At 10 min, the liquid phase fraction of the phase change material from ε = 0 to ε = -0.6 increases sequentially, while the liquid phase fraction of ε = -0.8 decreases instead. Too small eccentricity will reduce the performance of phase change heat storage. When ε = -0.6, the PCM melts the fastest and the melting time is 29.8% shorter than that of ε = 0.

Fig.4 shows the heat storage rate curves for different eccentricities. Before 6 min, the heat storage rate of ε = -0.8 is the lowest. As the temperature of the phase change material increases, the heat transfer temperature difference decreases, and therefore the heat storage rate decreases. However, except for ε = 0, all other eccentricities have an increase in heat storage rate within 4-8 min. This is because the natural convection gradually intensifies with the increase of the liquid phase fraction, which to some extent counteracts the effect of the decrease of the heat transfer temperature difference. This phenomenon is most obvious for ε = -0.8, whose larger upper space is more conducive to the development of natural convection.

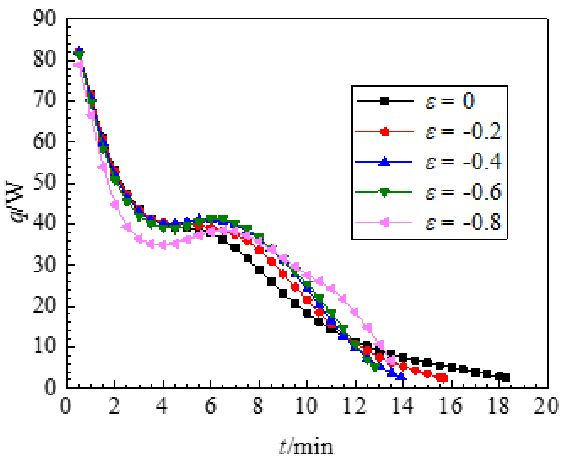

Fig. 4. Effects of eccentricity on heat storage rate during melting process

From the above analysis, it is clear that the solidification process should use positive eccentricity. Fig. 5 shows the liquid fraction contours and streamlines during the solidification process for different positive eccentricities. At 8 min, solid PCM exists in the upper region of ε = 0 and the lower region of ε = 0.2. It can be inferred that the optimal eccentricity of the solidification process is between 0 and 0.2. Compared to the melting process, there is less room for optimization of the eccentricity of the solidification process.

Based on this, we analyzed the discharging rate of the solidification process as shown in Fig. 6 with an additional eccentricity of ε = 0.1. As the eccentricity increases from 0 to 0.1, the solidification time decreases by 15.0%. In comparison, when the eccentricity of the melting process is reduced from 0 to -0.2, the melting time is reduced by 14.1%. Optimizing the eccentricity is more effective in the solidification process. There is no increasing stage as in the melting process. This is because its natural convection intensity is weaker compared to the melting process.

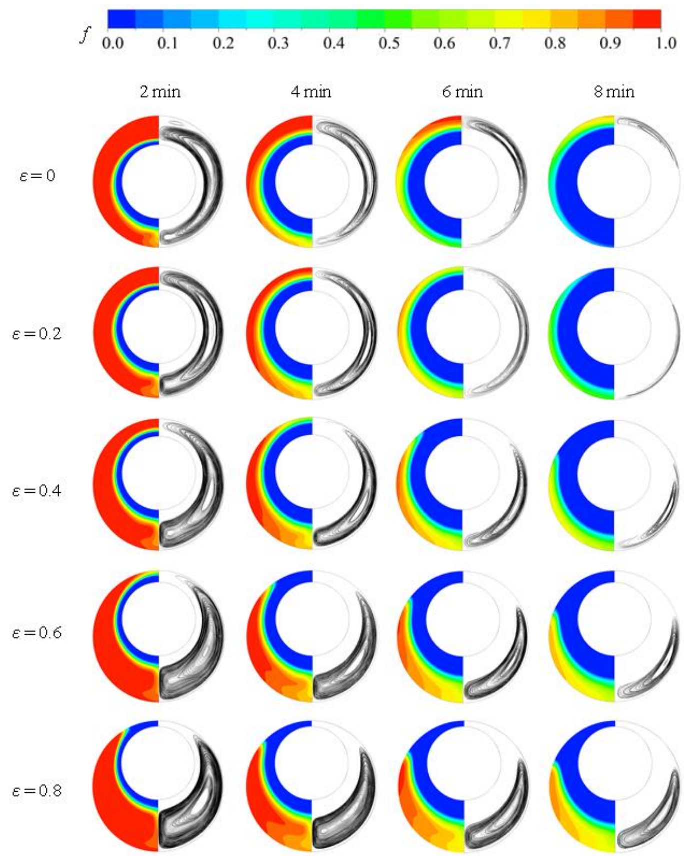

Fig. 5. Liquid fraction contours and streamlines during solidification process (ε > 0, z = 0.5 m)

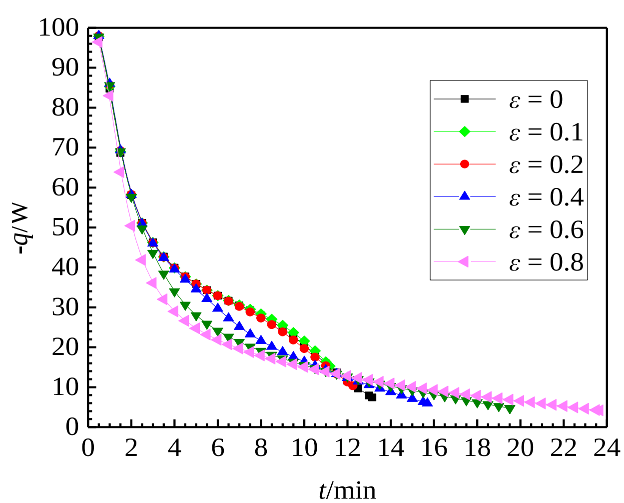

Fig. 6. Effects of eccentricity on heat storage rate during solidification process

From the previous analysis, it can be seen that the effects of eccentricity on the charging and discharging process are different. For the charging process, the tube moving to the downside is beneficial to enhance PCM melting and heat storage rates; but for the discharging process, the tube moving to the upside can enhance the heat transfer performance. To analyze the effects of eccentricity on the whole melting and solidification cycle, the effects of eccentricity on the melting time, solidification time, and the total melting and solidification time were studied. When the liquid fraction of PCM reaches f = 1, the melting process is over. Then the solidification process begins and the cold water with $T_{in, s}$ flows in to solidify the PCM which is assumed to be at the initial temperature of $T_{initial, s}$.

Fig.7 shows the effects of eccentricity on melting time, solidification time, and total time. The charging and discharging time curves of melting and solidification processes are parabolic, but the minimum points are on the different sides of the vertical axis.The total time without rotation achieves the minimum at ε = 0.1, which is only 1.3% less than that of ε = 0. Therefore, although the eccentric structure can improve both melting and solidification performance, it is not very useful for the whole melting and solidification cycle.

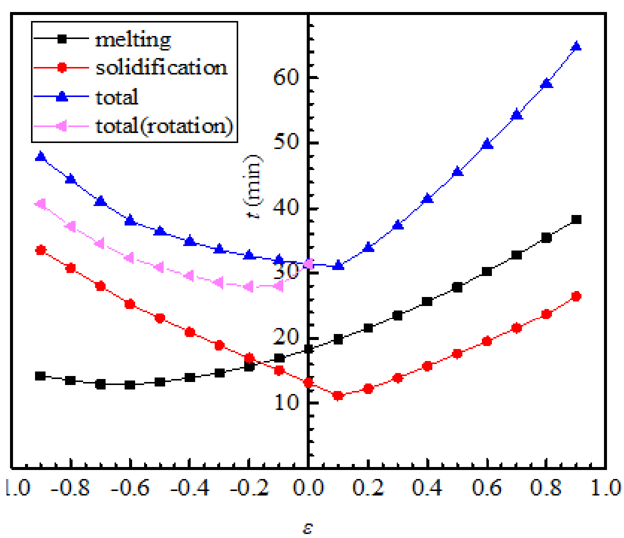

Fig. 7 Effects of eccentricity on melting, solidification and total time of the designed LHS unit

To enhance the total heat transfer performance of the LHS tube, a new configuration for the shell-and-tube LHS unit was proposed that the tube moves to the downside to enhance the charging performance; and during the discharging process, the heat storage unit rotates 180 degrees around the axis to enhance the discharging process. The total melting and solidification time with rotation decreases first and then increases with the increase of ε. When ε = -0.2, the total time is the shortest, which reduces 11.1% compared with the concentric configuration. For the melting and solidification cycle, the addition of rotation can combine the improvements of eccentric structure in both the melting and solidification process and obtain better cyclic heat storage performance.

4. CONCLUSIONS

This work investigated the melting and solidification of PCM in an eccentric shell-and-tube LHS unit. The melting and solidification in a concentric configuration are studied to reveal the influence of natural convection. Based on the results, a new configuration for the shell-and-tube LHS unit was proposed to enhance both charging and discharging performance. The following conclusions can be derived:

(1) Affected by the natural convection, the solid PCM in the upper region melts faster during the melting process and the liquid PCM in the lower region solidifies faster. In addition, the effect of natural convection on the melting process is stronger than that of the solidification process.

(2) The eccentric configuration with tube moving to the downside can efficiently enhance PCM melting rate and the best heat transfer performance can be obtained when ε = -0.6, where the total PCM melting time can be reduced by 29.8% compared with the concentric tube. However, with the tube moving to the upside, the solidification rate can be enhanced.

(3) A new configuration for shell-and-tube LHS unit with the eccentric tube was proposed to enhance the PCM melting rate and solidification rate simultaneously, and the optimum heat transfer performance for the whole cycle can be obtained when ε = -0.2, where the total melting and solidification time can be reduced by 11.1% compared with the concentric configuration.

ACKNOWLEDGEMENT

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