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Effect of natural convection on melting performance of eccentric horizontal shell and tube latent heat storage unit

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ABSTRACT

In order to improve melting rate of latent heat storage system, the effect of natural convection during melting process in eccentric horizontal shell and tube storage unit is investigated in this study. The melting performance in different eccentricity (e) and boundary temperature (T_w) is obtained through experiment research and numerical simulation. During the experiment study, the temperature variations at different positions are measured. Then, the temperature and fluid field, movement of the phase interface are analyzed by numerical simulation. With the increase of eccentric distance, the natural convection dominated area increases, so the melting rate is improved. The eccentric geometry with $e = 30$ mm and $T_w = 80$ °C results in a 57% decrease in the total melting time. The special attention is paid on the evolution of natural convection and the heat transfer mechanism during the melting process, so the parameter of time-average heat transfer coefficient ($\bar{h}$) is proposed. $\bar{h}$ is relatively higher in an eccentric geometry which illustrate the heat transfer efficiency is improved. The variation of $\bar{h}$ also reflects transformation of the heat transfer characteristic in concentric unit and eccentric unit.

1. Introduction

Latent heat storage technology realizes heat storage/release through melting and solidification process. Consequently, it has many advantages such as high energy storage density, simple and stable system, and a near-isothermal process during the phase change period. The latent heat storage technology has attracted increasing attention and applications in building energy efficiency, waste heat recovery, and solar thermal electric power in recent years. Phase change materials (PCMs), phase change container, and phase change heat transfer devices are the key components of a Latent heat storage system (Kamkari & Shokouhmand, 2014), and to improve the system performance, a series of research works have been carried on the development of new composite PCMs (Yu & Joshi, 2002), thermal conductivity enhancement of PCMs (Nada, 2007), PCM microencapsulation (Nada, 2007; Rao et al., 2006), container heat transfer enhancement (Allouche et al., 2015), and system structure optimization.

The shell and tube storage container, either horizontal or vertical, are very common, in which the PCM is kept in the annular space while the heat transfer fluid (HTF) flows through the inner tube. Compared with rectangular and cylinder, cylindrical shell containers take the least time for equal amounts of energy storage under the same volume and heat transfer area (Tari & Mehrtash, 2013). The researches mainly focus on the influence factors of melting/solidification rate and the enhancement method.

Operating and geometric parameters greatly affect the phase change rate (Hsu, Huang, & Liu, 2016; Shatikian, Ziskind, & Letan, 2005). Akgun et al. (Hsu et al., 2016) conducted a series of experiments to investigate the effect of increasing the inlet temperature and mass flow rate of heat transfer fluid on both the charging and discharging processes. They found out that an increase in the inlet temperature of the HTF decreases the melting time, and for lower energy consumptions, lower values of the HTF mass flow rate are recommended. The phase change heat transfer process of fatty acid, including myristic and stearic acid, was experimentally studied by Sari and Kaygusuz (Faraji & El Qarnia, 2010; Saha & Dutta, 2010; Sari & Kaygusuz, 2001). They found that the inlet temperature and mass flow rate are more significant in the solidification process. Adine and Qarnia (Ye, 2016) studied the effect of multiple PCMs with different melting temperatures in horizontal shell and tube heat exchanger. They used a two-PCM system and a single PCM system during the charging process and compared the thermal performance of the latent heat storage units. Their results showed that when the mass flow rate increased, the two-PCM system was efficient only for the lowest HTF inlet temperature. Therefore, multiple PCMs units are more efficient for low values of the mass flow rate and inlet temperature. Seddegh et al. (Seddegh et al., 2017) investigated the

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Nomenclature

e	Eccentric distance (m)
r	Radius (m)
L	Latent heat(J/g)
f	Liquid fraction
T	Temperature (K)
T_s	Temperature of solid region of PCM (K)
T_l	Temperature of liquid region of PCM (K)
T_m	Phase change temperature (K)
T_w	Inner wall temperature (K)
c_p	Specific heat capacity at constant pressure (J/kg·K)
p	Pressure(Pa)
$\vec{V}$	Velocity(m/s)
t	Time(s)
g	Gravitational acceleration (m/s^2)
$\vec{S}$	Momentum source term
H	Enthalpy(J/kg)
ΔH	Sensible enthalpy(J/kg)
h	Heat transfer coefficient (w·m^{-2}·K)
D	Equivalent diameter (m)
Nu	Nusselt number
Fo	Fourier number, fo $= \alpha t/D^2$
Ste	Stefan number for constant cylinder surface temperature, Ste $= \frac{c_p(T_w - T_m)}{L}$
Ra	Rayleigh number, Ra $= \frac{g\beta D^3(T_w - T_m)}{\alpha\nu}$

Greek symbols

β	Expansion coefficient(1/K)
μ	Dynamic viscosity(Pa·s)
ν	Kinematics viscosity(m^2/s)
α	Thermal diffusivity(m^2/s)
λ	Thermal conductivity (W/m·K)
σ	Small constant value
ε	Eccentric ratio
ρ	Density (kg/m^3)

Subscripts

s	Solid phase of PCM
l	Liquid phase of PCM
i	Inner annulus
o	Outer annulus

physics of heat transfer mechanism in vertical cylindrical shell and tube LHTES, temporal variation of the experimental temperature and a combined conduction/convection model was applied to investigate the melted PCM's convective circulation The results shown that during the charging process liquid PCM ascended to the upper part of the system and the melting front moved downward, during the discharging process, the solidification front moved along both radial and axial directions. Bathelt and Viskanta (Bathelt & Viskanta, 1980) experimentally studied the thermal characteristics of *n*-paraffins in a horizontal cylindrical shell. Experiments were performed for both uniform heat flux and constant surface temperature of the inner tube. They concluded that at the upper half of the cylinder, the melting process more rapidly progresses than that at its lower half.

However, because of the low thermal conductivity of PCMs, a melting process is encountered with a low rate of progression. Accordingly, numerous studies have been conducted to improve the melting rate. Extended surfaces have been considered as an efficient means of increasing the heat transfer rate in PCMs (Liu, Sun, & Ma, 2005a; Liu, Sun, & Ma, 2005b; Yuan et al., 2016). The melting and solidification of a PCM in three different horizontal annulus configurations were numerically investigated by Darzi et al. (Rabienataj Darzi, Jourabian, & Farhadi, 2016). The results indicated that natural convection plays important roles in the melting process in which the melting rate at the bottom section of the annulus is lower than that at the top section. The pure conduction model was compared with combined conduction and natural convection by Joybari et al. (Mastani Joybari, Haghighat, & Seddegh, 2017) to identify the dominant heat transfer mechanism. It was found that the former could be applied to the initially fully melted PCMs with small error, but for the initially solidified PCMs neglecting the natural convection would result in unacceptably large error. Inserting fins led to significant enhancement of the melting and solidification rate, but it was more efficient during the solidification process because of the suppression of the natural convection effect during the melting process (Dhaidan & Khodadadi, 2017). Hosseini et al. also studied the melting and solidification processes of a PCM in a shell and tube heat exchanger for varying fin heights and Stefan numbers (Ste). Their results showed that increasing the Ste number reduces the melting time. Therefore, for a specific wall temperature, an optimum value for the fin number exists (Cao et al., 2018; Hosseini, Rahimi, & Bahrampoury, 2015).

Due to the consequences of buoyancy during melting process, for a horizontal shell and tube container, when the inner cylinder tube moves

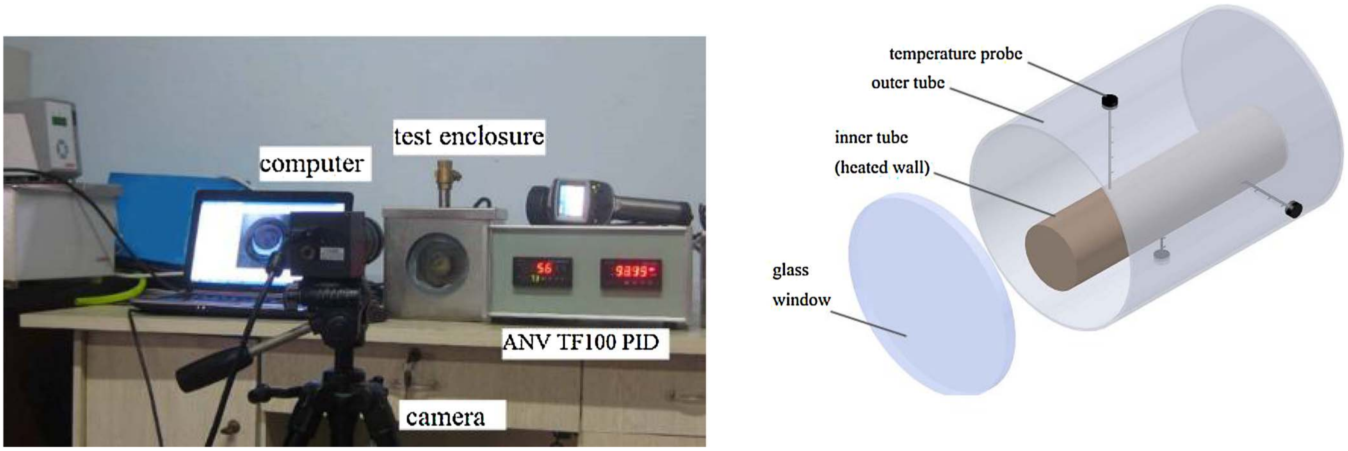

Fig. 1. Experiment test system.