Applied Energy 220 (2018) 447–454

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Eccentricity optimization of a horizontal shell-and-tube latent-heat thermal energy storage unit based on melting and melting-solidifying performance

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HIGHLIGHTS

- A fixed-grid numerical method with porous model is proposed for PCM problem.
- Optimal eccentricity for reducing melting/melting-solidifying time is gained.
- Effects of natural convection on optimal eccentricity are discussed.
- The relationship between Rayleigh number and optimal eccentricity is studied.

ARTICLE INFO

Keywords:
Phase change material (PCM)
Thermal energy storage
Heat transfer enhancement
Eccentricity
Computational fluid dynamics (CFD)
Optimization

ABSTRACT

As for a horizontal single-pass shell-and-tube latent-heat thermal energy storage unit (LTESU), the eccentricity between inner and outer tube is designed to improve the melting and melting-solidifying performances. A fixed-grid numerical method with enthalpy-double-porosities model is proposed to accurately predict the melting or solidifying characteristics of LTESUs with different eccentricities. Some optimal eccentricities are obtained to decrease the total melting or melting-solidifying time. The effects of Rayleigh number on the optimal eccentricities are also discussed. The results show that, when melting process is just concerned, vertically moving down the inner tube from the center of outer tube can obviously decrease the total melting time. However, a greater eccentricity does not always bring a better melting performance. That is to say, there exists an optimal eccentricity for the shortest melting time. It is found that the optimal eccentricity for melting process is linearly dependent on the Rayleigh number. As for a complete heat storage process including charging and discharging process, the eccentric arrangement of inner tube has benefit for decreasing the total melting-solidifying time only when the Rayleigh number ratio of solidifying process to melting process is larger than 2.0. The optimal value of eccentricity for the melting-solidifying process increases sharply with the increase of Rayleigh number ratio when the value of Rayleigh number ratio varies from 2.0 to 3.0, but the growth of optimal eccentricity slows down when Rayleigh number ratio is greater than 3.0.

1. Introduction

The improvement of energy efficiency is a perennial research direction for the utilization of fossil and renewable energy [1,2]. Thermal energy storage (TES) has a wide use both in the fossil and renewable energy systems [3]. As a promising technology to improve the energy efficiency, TES can not only decrease the energy consumption, but also correct the mismatch between the supply and demand of energy [4]. There are three main categories of TES [5]: sensible, latent and thermochemical. The heat-storage density of latent heat TES is multiple times higher than that of sensible heat TES, and latent heat TES is more stable than thermochemical TES [6]. Therefore, latent heat TES has gained a great deal of attention in recent years [7].

In a system of latent heat TES, the structure of container used for storing phase change material (PCM) has significant effects on melting and solidifying performances. Generally there are three typical PCM containers of different geometric structures, viz. rectangular, cylindrical and annular. Considerable efforts have been devoted to studying the effects of container's structure on the melting and solidifying performances. Vyshak and Jilani [8] numerically investigated the melting performances of these three typical PCM containers. They found that, for the same mass of PCM and surface area of heat transfer, annular

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https://doi.org/10.1016/j.apenergy.2018.03.126
Received 19 August 2017; Received in revised form 10 March 2018; Accepted 27 March 2018
0306-2619/

Nomenclature

A_{mush}	mushy zone constant ($kg\,m^{-3}\,s$)
A_c	cross sectional area (m^2)
c_p	specific heat ($J\,kg^{-1}\,K^{-1}$)
D	diameter (m)
D_e	hydraulic diameter (m)
Ec	eccentricity
f	melting fraction
Fo	Fourier number
g	acceleration of gravity ($m\,s^{-2}$)
H	height (m)
K	permeability (m^2)
l	center-to-center distance (m)
L	latent heat of fusion ($kJ\,kg^{-1}$)
p	pressure (Pa)
P	wetted perimeter (m)
q	heat transfer rate per unit area ($W\,m^{-2}$)
Ra	Rayleigh number
t	time (s)
T	temperature (K)
u, v	x and r velocity components ($m\,s^{-1}$)
U	velocity magnitude ($m\,s^{-1}$)
W	width (m)
x, y	Cartesian coordinates (m)

Greek symbols

α	thermal diffusivity ($m^2\,s^{-1}$)
β	thermal expansion coefficient (K^{-1})
δ	small constant number
λ	thermal conductivity ($W\,m^{-1}\,K^{-1}$)
μ	kinetic viscosity ($kg\,m^{-1}\,s^{-1}$)
ρ	density ($kg\,m^{-3}$)
ϕ	porosity

subscripts

eff	effective
i	inner tube
m	melting
max	maximum
o	outer tube
opt	optimal
PCM	phase change material
ref	reference
s	solidifying
su	insulation
tot	total

container has the least melting time. Prieto et al. [9] compared the melting and solidifying performances between a vertically arranged rectangular container and a horizontally arranged one based on numerical method. They found that, the melting performance of PCM in horizontal container is better than in vertical container, and the solidifying performance of PCM in horizontal container is the same as in vertical container. Therefore, latent-heat thermal energy storage unit (LTESU) should be arranged horizontally rather than vertically. Therefore, in view of its outstanding performance, the horizontal shell-and-tube LTESU has now become one of the most popular LTESUs [10–12].

However, the heat transfer performance of horizontal shell-and-tube LTESU still can be improved due to the low thermal conductivity of PCM [13]. Normally in the horizontal shell-and-tube LTESU, PCM is packaged in the enclosed annular space. Therefore, three methods of heat transfer enhancement can be applied to horizontal shell-and-tube LTESU [14]: (1) enhance the thermal conductivity of PCM, such as through adding some nanoparticles into the PCM [15]; (2) extend the heat-transfer surface, like through inserting fins or porous medium into the PCM [16–19]; (3) improve the structures of LTESU, such as some novel irregular structures [20]. The third method is more reasonable and much cheaper than the other two methods, because the third method neither reduces the heat storage capacity of LTESU nor consumes some expensive materials with high thermal conductivity.

With regard to the improvement of structure of LTESU, the simplest way for a horizontal shell-and-tube LTESU is to adjust the relative position between inner tubes and shell. Mahmoud et al. [21] numerically studied the melting performances of a horizontal shell-and-tube LTESU with only one tube in it. The effect of eccentricity on the melting behavior was studied. Five arrangements of inner tube named center one, top one, bottom one, left one, left-bottom one were considered. The results showed that the bottom one, vertically moving the inner tube from the shell center to the shell bottom, has the best melting performance. This is because that the natural convection plays a very important role during the melting process. Due to this, the PCM in the top has faster melting rate than in the bottom. Therefore, shifting some PCM from the bottom to the top, which can be realized through moving the inner tube down, can reduce the total melting time. Through experimental and numerical methods, Dutta et al. [22] also investigated the effect of eccentricity on the melting behavior of a horizontal shell-and-tube LTESU. They also found that vertically moving the inner tube down brings the highest heat flux. Dhaidan et al. [23] investigated the melting performance of NePCM inside a horizontal shell-and-tube LTESU. NePCM is a kind of nano-composite PCMs. They found lowering the tube can save 18.7% of the total melting time in comparison with the concentric case. Eslamnezhad et al. [17] numerically studied the melting characteristic of PCM inside a horizontal triplex-tube LTESU. They found that a combined heat transfer enhancement technique by using fin and lowering inner tube can lead to the best heat transfer performance among the selected cases. Darzi et al. [24] built a two-dimensional model to investigate the melting characteristic of the cross-section of a horizontal single-pass shell-and-tube LTESU. The melting performance of concentric case was compared with two eccentric cases. The eccentric cases were realized by moving the inner tube from the shell center to the shell bottom along the vertical direction. The research results showed that the greater the eccentricity is, the shorter time the melting process needs. Pahamli et al. [25] established a three-dimensional model to study the melting characteristic of a horizontal single-pass shell-and-tube LTESU with eccentric arrangement of inner tube. The inner tube moved from the shell center to the shell bottom vertically, and three different distances between the center of inner tube and outer tube were selected. The results showed that the case with largest eccentricity has shortest melting time. Yazıcı et al. [26] experimentally studied the melting performance of a horizontal single-pass shell-and-tube LTESU with the inner tube being moved from the shell center to the shell bottom along the gravitational direction. Three different positions of inner tube were selected, and the lowest one was found to get the shortest melting time. As for the solidifying process, Zhang and Faghri [27] investigated the the solidifying rate in an eccentric horizontal annulus based on numerical method and an analytical solution. The research results showed that eccentricity decreases the solidifying rate. This is because that the heat conduction plays a dominant role in the solidifying process. Yazici et al. [28] experimentally studied the effect of eccentricity on the solidifying performance of a horizontal single-pass shell-and-tube LTESU. It was found that vertically moving the inner tube center up or down from the shell center will