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Numerical study on performance enhancement of shell-and-tube latent heat storage unit☆

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ABSTRACT

A compound enhancement method was proposed to improve the latent heat storage (LHS) performance of a shell-and-tube LHS unit, which is consisted of internal enhanced tube (ET) and multiple phase change material (PCM). Numerical validations on the presented method were performed based on comparisons of four different LHS cases: case 1 (basic case); case 2 (simple enhancement case); case 3 and 4 (compound enhancement cases). The results show that the simple enhancement case can only enhance PCM melting rate at the first half of the LHS tube; the compound enhancement case can obtain the synergy enhancement effect for the whole LHS tube. Compared with case 2, the PCM melting time is reduced by 37.3% and 17.4%, the total charging time is reduced by 25.6% and 16.9% for case 3 and case 4 respectively. For case 3, although the PCM melting time and charging time are the shortest, the total thermal energy storage (TES) capacity is reduced by 26.9% due to the lower PCM melting enthalpy. For case 4, not only the melting time and charging time can be obviously reduced, but also the total TES capacity is augmented by 6.6%.

1. Introduction

Solar energy has been widely used in solar water heating, solar buildings, and solar thermal power generation systems. Due to the discontinuity of solar radiation, thermal energy storage (TES) unit is a key component to keep the solar thermal utilization systems' stable operation with high efficiency. Latent heat storage (LHS) is considered as one of the preferred TES patterns, because of the high energy storage density and constant phase change temperature.

In recent years, a lot of researches on the performance of LHS system have been performed. Fang and Chen [1] examined the effects of different multiple PCMs on the melted fraction, stored thermal energy and fluid outlet temperature of the shell-and-tube LHS unit. Akgun et al. [2] analyzed the latent thermal energy storage system of the shell-and-tube type with three kinds of paraffin as PCMs. Guo and Zhang [3] numerically studied the effects of geometry parameters and boundary conditions on the performance of a high temperature LHS system. Adine and Qarnia [4] studied a LHS unit consisting of a shell-and-tube filled with P116 and n-octadecane. Tao et al. [5–7] detailedly examined the effects of geometric and operating parameters and boundary conditions on PCM LHS performance. Hosseini et al. [8] studied the heat transfer characteristics of PCM during the melting and solidification processes in a shell-and-tube heat exchanger. Kibria et al. [9] numerically and experimentally investigated the phase change process in a shell-and-tube thermal energy storage system to reveal the effects of geometric and operating parameters. Recently, Tao [10] numerically investigated the effects of liquid PCM natural convection on LHS performance in shell-and-tube LHS unit. A local finned tube was designed and the effects of fin geometric parameters were examined.

However, because the thermal conductivity for most PCMs is very low, the performance enhancement for the LHS unit is urgent to be carried out. Composite phase change material (CPCM) is a commonly used method. Several kinds of CPCM have been proposed, such as adding high conductivity nanomaterial additives into PCM [11–13], filling PCM into metal foams [14–16] and expanded graphite [17–19]. Another enhancement method usually adopted is microencapsulated PCM [20,21].

Almost all of the above studies were focused on the enhancement of the PCM side. Tao et al. [22] numerically investigated the performance of a LHS unit with three kinds of internal enhanced heat transfer tubes. The results show that the internal enhanced tubes can effectively improve LHS performance with gas as HTF. However, in the previous study, a single PCM is adopted, which leads to the same phase change temperature at the front and rear sections of the LHS tube. Then with the internal enhanced tubes, the heat transfer coefficient of HTF is improved and the heat transfer rate in the front section of the LHS tube is improved. More heat is transfered to PCM in the front section, which inevitably causes the HTF temperature to decrease and the heat transfer rate to slow down at the rear section. So, the enhancement

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Nomenclature

c_p	specific heat, $Jkg^{-1}K^{-1}$
d	diameter of the inner tube, m
f	liquid fraction
h	heat transfer coefficient, $Wm^{-2}K^{-1}$
k	thermal conductivity, $Wm^{-1}K^{-1}$
L	length of the PCM unit, m
$\dot{m}$	mass flow rate, kgs^{-1}
Pr	Prandtl number
Q	thermal storage capacity, J
Q_l	latent heat storage capacity, J
Q_t	total heat storage capacity, J
r	radial coordinate, m
R_i	the radius of the inner tube, m
R_o	the radius of the shell side, m
Re	Reynolds number
T	temperature, K
T_m	melting point temperature of PCM
t	time, s
t_m	melting time of PCM, s
u	heat transfer fluid velocity, ms^{-1}
x	axial coordinate, m
Greek symbols	
μ	dynamic viscosity, Pas
ρ	density, kgm^{-3}
υ	kinetic viscosity, m^2s^{-1}
ΔH	specific enthalpy, $kJkg^{-1}$
ϕ	heat transfer rate, W
Superscripts	
*	last time layer value
Subscripts	
f	heat transfer fluid
i	initial state
in	inlet boundary
l	liquid
out	outlet boundary
p	phase change material
s	solid

effect for the rear section is poor, which weakens the total enhancement effect of the LHS unit.

In order to further enhance the LHS performance of shell-and-tube LHS unit, a compound enhancement method was proposed in the present paper. The multiple phase change materials with different melting temperature were introduced based on the adopting of enhanced tubes to achieve the synergy enhancement of the whole LHS unit. Then numerical validations on the compound enhancement method were performed based on comprehensive comparison of PCM melting time, melting fraction, TES rate, and TES capacity for four different cases.

2. Physical model and governing equations

2.1. Physical model

The physical model is shown in Fig. 1, which is a shell-and-tube configuration. The HTF flows in the inner tube and the shell side is full of PCM. The length (L) is 1.0 m, the radius for the inner tube (R_i) is 12.5 mm, and the radius for shell side (R_o) is 25.0 mm. The thickness of the LHS tube is neglected. The outer surface of the shell side is treated as an adiabatic boundary. The mixture of He/Xe with mol. mass 39.39 g/mol is used as HTF. Three kinds of mixed salts are chosen as PCMs, named PCM1 (80.5wt.%LiF–19.5wt.%CaF_2), PCM2 (51wt.%K_2CO_3–49wt.%Na_2CO_3) and PCM3 (67wt.%LiF–33wt.%MgF_2). Thermophysical properties for HTF and PCMs are shown in Table 1 [23,24].

In order to enhance the LHS performance, a compound enhancement method was proposed, which is consisted of internal enhanced tube (ET) and multiple phase change materials. And four different cases were designed to compare and validate the performance of the presented compound enhancement method. Case 1 is a basic case with smooth tube (ST) and single PCM (PCM1). Case 2 is a simple enhanced case with internal helically-finned enhanced tube (ET) and single PCM (PCM1). The detailed descriptions for the enhanced tube can be found in Ref. [25]. Case 3 and case 4 are the compound enhancement methods with multiple PCMs and ET. The multiple PCMs for case 3 and case 4 are designed as different PCM combinations (PCM1 and PCM2 with volume ratio of 1:1 for case 3, PCM1 and PCM3 with volume ratio of 1:1 for case 4) to further investigate the effect of PCM thermophysical properties on performance. The HTF inlet velocity is 15.0 m/s and the inlet temperature is 1090.0 K. The initial temperatures for PCM and HTF are 823.0 K.

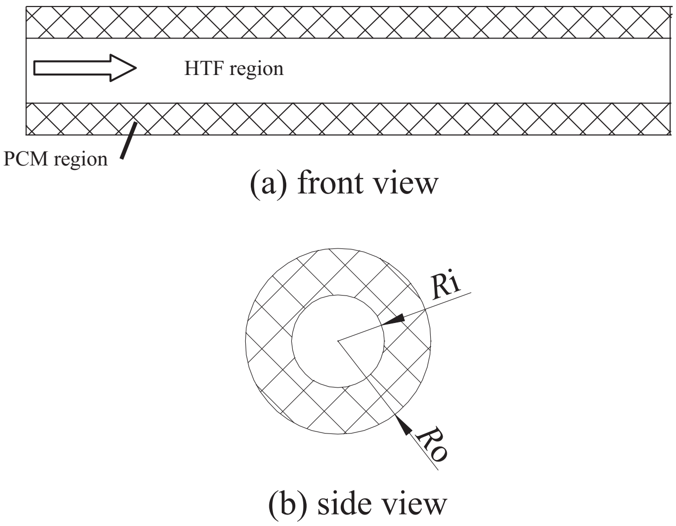

Fig. 1. Schematic of the LHS tube.