Applied Thermal Engineering xxx (2014) 1–8

Contents lists available at ScienceDirect

Applied Thermal Engineering

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

Effects of parameters on performance of high temperature molten salt latent heat storage unit

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A R T I C L E I N F O

Article history:
Received 23 September 2013
Accepted 19 January 2014
Available online xxx

Keywords:
Molten salt
Latent heat storage
Variable conditions
Performance analysis

A B S T R A C T

In order to investigate the performance of high temperature molten salt latent heat storage (LHS) unit under variable conditions, the effects of heat transfer fluid (HTF) inlet temperature, velocity and tube geometric parameters on melting time, melting fraction, heat storage rate and solid–liquid interface were numerically investigated. The results show that within the studied parameters, the HTF inlet temperature has the largest effect on LHS rate. With the HTF inlet temperature increasing from 1070 K to 1110 K, the melting time reduces 53.0%. However, the larger inlet temperature will result in more non-uniform melting rate and solid–liquid interface distribution. The second important influential factor is the HTF inlet velocity. When inlet velocity increases from 10 m/s to 20 m/s, the melting time reduces 45.4%. And the effect of velocity on the solid–liquid interface distribution is uniform. LHS tube diameter has the lowest effect on performance. With outer tube radius increasing from 24.0 mm to 28.0 mm, the melting time only augments 16.3% and the solid–liquid interface distribution becomes more uniform. In a general conclusion, when the heat load of the heat source is larger, a larger HTF mass flow rate is suitable to maintain a moderate HTF temperature. And then for the LHS unit, a larger tube diameter is recommendable.

1. Introduction

In recent years, with the deteriorations of energy crisis and environmental pollution, a lot of researches on solar thermal utilizations have been carried out, such as solar water desalination systems [1,2], solar building systems [3,4] and solar energy generation systems [5,6]. Due to the instability of solar energy with different weathers, times and seasons, thermal energy storage (TES) unit, especially latent heat storage (LHS) unit has become a necessary component in the solar thermal utilization systems to ensure the system continuous and stable operation with high efficiency. Now, a lot of studies on the LHS performance have been carried out.

In numerical studies, Gong and Mujumadar [7] numerically analyzed the cyclic heat transfer of molten salt phase change material in a shell-and-tube latent heat energy storage exchanger with finite-element method. Sharma et al. [8] studied the effects of PCMs physical properties, heat exchanger materials and patterns on the performance of a LHS system with fatty acids as PCMs. Trp et al. [9] presented a mathematical model for the conjugated problem of transient forced convection and solid–liquid phase change heat transfer based on enthalpy method. Fang and Chen [10] investigated the effects of different multiple PCMs on the melted fraction, stored thermal energy and fluid outlet temperature of the shell-and-tube latent thermal energy storage unit. Guo and Zhang [11] numerically studied the effects of geometry parameters and boundary conditions on the performance of a new type high temperature latent heat thermal energy storage system. Adine and Qarnia [12] numerically studied a latent heat storage unit consisting of a shell-and-tube filled with P116 and n-octadecane. Tao and He [13] performed the numerical study on the LHS performance under non-steady-state inlet boundary and the effect of the unsteady inlet temperature and mass flow rate on the performance were examined. Then Tao et al. [14] numerically investigated the performance enhancement of high temperature molten salt LHS unit with three kinds of enhanced heat transfer tubes. Koizumi and Jin [15] proposed a new compact slab type container for latent heat thermal energy storage system and numerical investigations were performed by the enthalpy-porosity approach. Al-Abidi et al. [16] numerically investigated the PCM melting process in a triplex tube heat exchanger with internal and external fins. Mosaffa et al.

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http://dx.doi.org/10.1016/j.applthermaleng.2014.01.038

Nomenclature

Symbols

Pr	Prandtl number
Q	thermal storage capacity, kJ kg^{-1}
r	radial coordinate, m
R_i	inner radius of the tube, m
R_o	inner radius of the shell side, m
T	temperature, K
t	time, s
x	axial coordinate, m

Greek symbols

ρ	density, kg m^{-3}
μ	dynamic viscosity, Pa s
θ	relative temperature ($T - T_m$), K
ΔH	enthalpy, kJ kg^{-1}
Φ	heat flux, W

Superscripts

*	last time layer value

Subscript

f	heat transfer fluid
i	initial state
in	inlet boundary
M	melting point
out	outlet boundary
p	phase change material

[17] performed a numerical investigation of the performance enhancement of a free cooling system using a latent heat thermal storage unit employing multiple PCMs. The energy storage effectiveness and coefficient of performance were studied and compared. Tao et al. [18] performed numerical studies on coupling phase change heat transfer performance of solar dish collector and found the non-uniform heat flux on the tube surface would result in seriously non-uniform temperature distribution in PCM. In experimental studies, Trp [19] experimentally analyzed the transient heat transfer characteristics during phase change material melting and solidification. Akgun et al. [20,21] analyzed the latent thermal energy storage system of the shell-and-tube type with three kinds of paraffin as PCMs. A novel tube-in-shell storage geometry was introduced and the effects of the Reynolds number and Stefan number on the melting and solidification behaviors were examined. Long [22] investigated heat transfer performance of a triplex concentric tube thermal energy storage unit. Nomura et al. [23] experimentally investigated the heat storage performance of a direct-contact latent heat exchanger using the phase-change material (PCM) erythritol and the operating mechanism was proposed to explain the results. Languri [24] proposed a newly designed TES system with octadecane as PCM and its effectiveness was investigated.

The foregoing literature review shows that a lot of studies have been performed on the LHS performance. But most of them were focused on the low temperature LHS applications and constant working conditions. For the optimization design and practical application of the LHS system, the performance characteristics under different operating conditions and structural parameters is urgent to reveal. In present paper, in order to investigate the performance of high temperature molten salt LHS unit under variable conditions, the physical and mathematical model was established for the shell-and-tube LHS unit with high temperature molten salt as PCM. The simulation code for the LHS process was self-developed based on enthalpy method and the effects of the HTF inlet temperature, velocity and tube diameter on the LHS performance were numerically investigated.

2. Model description

2.1. Physical model

The physical model for LHS unit 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 for the computation domain (L) is 1.5 m, the radius for the inner tube (R_i) is 12.5 mm, the radius for the shell side (R_o) is 25.0 mm. The thickness of tube wall is neglected. The HTF is the mixture of He/Xe with molecular mass 39.394 kg/kmol. The PCM is a mixture of molten salt consisted of 80.5% LiF and 19.5% CaF_2. The thermophysical properties for HTF and PCM are shown in Table 1 [7]. The initial temperature for the PCM is set to 823 K. The HTF inlet temperature is 1090 K and the inlet velocity is 15 m/s in the rated operating condition.

In order to simplify the physical and mathematical model, the following assumptions are adopted.

(1) The axial heat conduction and viscous dissipation in the HTF are neglected. HTF is treated as one dimensional fluid flow along the tube axial direction.
(2) The thermophysical properties for the HTF and PCM are constant as shown in Table 1.
(3) The effect of liquid PCM natural convection is neglected.
(4) The outer surface of the shell side is treated as an adiabatic boundary.

2.2. Governing equations

Based on the above assumptions, the LHS process in the shell-and-tube unit can be treated as an axisymmetric model. The enthalpy method is used to deal with the moving boundary problem in PCM melting process. The governing equations for the HTF region and PCM region are shown as follows [12].

For the HTF region

$$\frac{\partial \theta_f}{\partial t} = -A\frac{\partial \theta_f}{\partial x} - B\left(\theta_f - \theta^*\right) \tag{1}$$

where, $\theta_f = T_f - T_M$; θ^* is the temperature for PCM at $r = R_i$ and the last time layer. $A = \dot{m}_f/\rho_f \pi R_i^2$, $B = 2h/(\rho c_p)_f R_i$, $h = k/d0.022Pr^{0.6}Re^{0.8}$.

For the PCM region

$$(\rho c_p)_p \frac{\partial \theta}{\partial t} = \frac{\partial}{\partial x}\left(k_p\frac{\partial \theta}{\partial x}\right) + \frac{1}{r}\frac{\partial}{\partial r}\left(rk_p\frac{\partial \theta}{\partial r}\right) - \rho_p \Delta H\frac{\partial f}{\partial t} \tag{2}$$

where, $\theta = T - T_M$, f is the PCM melting fraction. The melting fraction is determined as

$$\begin{cases} f = 0, & \theta < 0 \\ 0 < f < 1, & \theta = 0 \\ f = 1, & \theta > 0 \end{cases}$$

Please cite this article in press as: Y.-B. Tao, et al., Effects of parameters on performance of high temperature molten salt latent heat storage unit, Applied Thermal Engineering (2014), http://dx.doi.org/10.1016/j.applthermaleng.2014.01.038