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Performance optimization of two-stage latent heat storage unit based on entransy theory

Y.B. Tao *, Y.L. He, Y.K. Liu, W.Q. Tao

Key Laboratory of Thermo-Fluid Science and Engineering, Ministry of Education, School of Energy and Power Engineering, Xi'an Jiaotong University, Xi'an, Shaanxi 710049, China

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ABSTRACT

In order to enhance the performance of the latent heat storage (LHS) process and provide the criterion for the selection and match of the multistage PCMs, the effects of PCMs melting temperatures on the heat storage rate, entransy dissipation rate and heat storage quality were numerically analyzed based on the entransy theory. For the single stage LHS unit, although decreasing the PCM melting temperature can augment the heat storage rate, the lower melting temperature causes larger entransy dissipation and reduces the heat storage quality. The larger heat storage rate results in the larger entransy dissipation rate, which is accordant with the entransy dissipation extremum theory. For the two-stage LHS unit with reasonably matching the PCMs melting temperature, the heat storage rate can be augmented and the entransy dissipation rate can be reduced. Then the optimization for the match of the two-stage PCMs melting temperatures was performed based on the entransy theory. The results show that there is an optimal match of the two-stage PCMs melting temperatures to achieve the maximum heat transfer rate or the minimum entransy dissipation rate. And the formulas for the optimum two-stage PCMs temperatures were presented, which can provide the criterions for the selection and match of the PCMs.

1. Introduction

With the developments of renewable energy utilization and industry waste heat recovery technologies, thermal energy storage (TES) technology becomes more and more important to solve the intermittent problems of renewable energy and the industry waste heat. Among the thermal energy storage technologies, latent heat storage (LHS) has been considered as one of the preferred TES patterns, because of the high energy storage density and constant phase change temperature.

A lot of researches on the performance of LHS system have been performed. Sharma et al. [1] numerically 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 [2] investigated the performance of paraffin melting and solidification in a shell-and-tube LHS unit. Akgun et al. [3] analyzed the LHS system performance of the shell-and-tube type with three kinds of paraffin as PCMs. Guo and Zhang [4] numerically studied the effects of geometry parameters and boundary conditions on the performance of a high temperature LHS system. Wu et al. [5] performed the simulations of a packed bed cool thermal energy storage system with *n*-tetradecane as phase change material. Adine and Qarnia [6] numerically studied a LHS unit consisting of a shell-and-tube filled with P116 and *n*-octadecane. Tao and He [7] performed the numerical study on the PCM 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. [8] 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.

However, because the thermal conductivities for most PCMs are very low, the performance enhancement for the LHS unit is urgent to be carried out. Generally speaking, there are three enhancement methods: (1) enhance the PCM side performance, for example using high thermal conductivity composite PCMs [9–11], (2) enhance the heat transfer fluid (HTF) side performance, for example using enhancement heat transfer surface [12,13], (3) enhance the uniformity of the heat transfer process, such as using multistage PCMs [14–16]. The third enhancement method can not only enhance the heat transfer performance but also improve the heat storage quality. However, the total performance for the multistage LHS system greatly depends on the selection and match of multiple PCMs. So, the optimization for the multistage PCMs system must be performed to obtain the maximum performance.

* Corresponding author. Tel.: +86 29 82664349; fax: +86 29 82665445.
E-mail address: yubingtao@mail.xjtu.edu.cn (Y.B. Tao).

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Nomenclature

A	heat transfer area, πdL, m^2
c, c_1, c_2	intermediate variable, $e^{hA/\dot{m}c_p}$
c_p	specific heat, $J\ kg^{-1}\ K^{-1}$
d	diameter of the inner tube, m
f	liquid fraction
G	entransy, JK
h	heat transfer coefficient, $W\ m^{-2}\ K^{-1}$
k	thermal conductivity, $W\ m^{-1}\ K^{-1}$
L	length of the PCM unit, m
$\dot{m}$	mass flow rate of HTF, $kg\ s^{-1}$
Pr	Prandtl number
Q	thermal 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, $m\ s^{-1}$
x	axial coordinate, m

Greek symbols

μ	dynamic viscosity, Pa s
ρ	density, $kg\ m^{-3}$
υ	kinetic viscosity, $m^2\ s^{-1}$
ΔH	specific enthalpy, $kJ\ kg^{-1}$
ϕ	heat transfer rate, W/entransy dissipation rate, W °C
Π	the given entransy dissipation
Θ	the given heat transfer rate

Superscripts

$*$	last time layer value

Subscripts

1	the first stage
2	the second stage
f	heat transfer fluid
i	initial state
in	inlet boundary
l	liquid
p	phase change material
s	solid

In order to characterize the heat transfer ability of an arbitrary object, Guo et al. [17] introduced the concept of entransy and use the entransy dissipation to measure the heat transfer ability loss during the irreversible heat transfer process. And the entransy dissipation extremum theory was presented as the optimization criterion for a heat transfer process, which is expressed as that the heat transfer performance is optimal when the entransy dissipation achieves the extremum [18]. Subsequently, the entransy dissipation extremum theory has been successfully used in the optimization of heat conduction process [19–21], single-phase convection heat transfer process [22–24], radiation heat transfer process [25,26] and so on. Recently, the entransy theory is extended to the optimization of phase change heat transfer process. Xia et al. [27] performed the optimization of liquid–solid phase change processes with the entransy dissipation minimization as the optimization objective. Chen et al. [28,29] used the entransy theory to analysis and optimization of evaporative cooling system. However, there are few reports about the entransy theory used to optimize the performance of the LHS problem.

In present paper, the entransy theory is used to analyze and optimize the LHS process. First of all, the applicability of entransy theory for the LHS process was validated based on the performance analysis of the single and two-stage LHS units. Then, the optimization for the match of the two-stage PCMs phase change temperatures was performed based on the entransy theory and the formulas for the optimum phase change temperatures were derived, which can provide criterion for the selection and match of the multiple PCMs.

2. Physical model and governing equations

2.1. Physical model

The physical model for the 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 LHS unit (L) is 1.0 m, the radius for the inner tube (R_i) is 12.5 mm, the radius for shell side (R_o) is 25.0 mm. The thickness of tube wall is neglected. The outer surface of the shell side is treated as an adiabatic boundary. The HTF is the mixture of He/Xe with molecular mass 39.394 kg/kmol. The mixture of molten salts is taken as PCMs. The thermophysical properties for the HTF and PCMs are shown in Table 1 [30,31]. For the single-stage LHS case, the whole PCM region is full of PCM1; and for the two-stage LHS case, the two-stage PCMs are set as volume ratio of 1:1, which means the first half of the LHS tube is full of PCM1 and the second half is full of PCM2. 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.

2.2. Governing equations

In order to simplify the physical and mathematical model, the axial heat conduction and viscous dissipation in the HTF is negligible and the HTF flow is treated as one dimensional fluid flow. The thermophysical properties for the HTF and PCMs are constants as shown in Table 1. The effect of natural convection of PCM during melting is neglected to simplify the model and reduce the computation time, because the gap in the shell side is very limited. 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 adopted to deal with the moving boundary problem in solid–liquid phase change process. The corresponding governing equations are shown as follows.

For the HTF

$$\frac{\partial T_f}{\partial t} = -\frac{\dot{m}_f}{\rho_f \pi R_i^2}\frac{\partial T_f}{\partial x} - \frac{2h}{(\rho c_p)_f R_i}(T_f - T^*) \tag{1}$$

where T_f is the HTF temperature at present time layer and T^* is the PCM temperature at $r = R_i$ and the last time layer. h is the convection heat transfer coefficient of the HTF. $h = \frac{k}{d}0.022Pr^{0.6}Re^{0.8}$.

For the PCM

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

where T is the PCM temperature at present time layer, f is the PCM melting fraction, ΔH is the unit mass PCM melting enthalpy.