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Melting performance enhancement of phase change material by a limited amount of metal foam: Configurational optimization and economic assessment

Yang Xu[a], Ming-Jia Li[a,*], Zhang-Jing Zheng[b], Xiao-Dai Xue[c,d]

[a] Key Laboratory of Thermo-Fluid Science and Engineering of Ministry of Education, School of Energy and Power Engineering, Xi'an Jiaotong University, Xi'an, Shaanxi 710049, China
[b] School of Electrical and Power Engineering, China University of Mining and Technology, Xuzhou 221116, China
[c] State Key Laboratory of Control and Simulation of Power Systems and Generation Equipment, Department of Electrical Engineering, Tsinghua University, Beijing 100084, China
[d] New Energy (Photovoltaic) Industry Research Center, Qinghai University, Xining 810016, China

HIGHLIGHTS

- Melting performance of PCMs locally enhanced by porous media is studied.
- An economic criterion is proposed to comprehensively assess melting performance.
- A novel structure of porous inserts is built and optimized.
- A limited amount of porous inserts can offer significant melting enhancement.

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ABSTRACT

In the paper, melting performance of a latent heat thermal energy storage (LHTES) unit with phase change materials (PCMs) locally enhanced by porous media was numerically investigated. The filling ratio of the porous inserts was fixed to a low degree to reduce the material cost. The optimal configuration of the porous inserts was obtained after the discussion about the effects of porous geometry and porosity on the velocity and temperature distribution of melting process. To reveal the superiority of the optimized result, different cases were compared with the help of a new comprehensive criterion about the input-output performance. Then a generalization expression was fitted out with some dimensionless parameters for the rapid calculation of melting fraction of the optimized result in practical application. The results indicated that in the horizontal LHTES unit, the limited porous inserts should be concentrated in the bottom part without interval between the neighboring porous inserts, providing an effective enhancement in the lower part and a low degree of thermal stratification. If the mass of porous inserts is fixed, high porosity is preferred to make the thermal-conduction-dominated area sufficiently covered by the porous inserts. Compared with the non-enhancement case, the selected result in this study can remarkably save more than 80% of the melting time and enhance the melting rate by 5.1 times. More significantly, the selected result has the highest melting rate per cost of the material when the price ratio of the addition to the PCM is larger than 5 based on the results of economic assessment. Therefore, it offers an economical solution to the thermal enhancement problem of the LHTES unit in the practical application. The normalized equation of melting fraction is obtained for the parameter range of $0.187 < Ste < 0.374$, $1.325 \times 10^6 < Ra < 2.649 \times 10^6$: $f = 0.596X + 0.0438X^2 - 0.0825X^3 + 0.0130X^4$, where $X = SteFoRa^{1/8} < 2.796$.

1. Introduction

The urgency of renewable energy has arisen since the fossil energy crisis, environmental deterioration and global greenhouse effects began to endanger normal human life and the future of society. Solar energy, as an essential green energy source, is under a rapid development due to its abundance and availability. Concentrated solar power technology is a kind of utilization of solar energy with large scale and low cost, and it has been the research focus in the last several decades [1–3]. However, the intermittence and fluctuation of solar energy result in

* Corresponding author.
E-mail address: mjli1990@xjtu.edu.cn (M.-J. Li).

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Nomenclature

a	unit price($\cdot kg^{-1}$)
A_{mush}	mushy zone constant ($kg\cdot m^{-3}\cdot s$)
b	the angle between adjacent porous fins (°)
c_p	specific heat ($J\cdot kg^{-1}\cdot K^{-1}$)
C	cost of composite PCM ($)
C_i	inertia coefficient
d_f	fiber diameter (m)
d_p	pore diameter (m)
D	characteristic size (m)
f	melting fraction
Fo	Fourier number
g	acceleration of gravity ($m\cdot s^{-2}$)
H	height of porous insert (m)
K	permeability (m^2)
L	latent heat of fusion($kJ\cdot kg^{-1}$)
m	mass (kg)
N	unit price ratio of the addition to the PCM
p	TES rate (W)
p'	dimensionless TES rate
p_c	TES rate per material cost ($J\cdot s^{-1}\cdot \$^{-1}$)
p_c'	dimensionless TES rate per material cost
P	pressure (Pa)
q	TES density ($J\cdot kg^{-1}$)
q'	dimensionless TES density
Q	TES capacity (J)
r	radial coordinate (m)
R	radius (m)
Ra	Rayleigh number
s	area (m^2)
Ste	Stefan number
t	time (s)
t_m	melting time (s)
T	temperature (K)
T_m	melting point (K)
u,v	superficial velocity at x, y direction ($m\cdot s^{-1}$)
w	TES rate density ($J\cdot kg^{-1}\cdot s^{-1}$)
w'	dimensionless TES rate density
x,y	Cartesian coordinates (m)

Greek symbols

α	thermal diffusivity ($m^2\cdot s^{-1}$)
β	thermal expansion coefficient (K^{-1})
ε	porosity
λ	thermal conductivity ($W\cdot m^{-1}\cdot K^{-1}$)
μ	dynamic viscosity ($kg\cdot m^{-1}\cdot s^{-1}$)
θ	circle angle (deg)
υ	kinematic viscosity ($m^2\cdot s^{-1}$)
ρ	density ($kg\cdot m^{-3}$)

Subscripts

0	basic case without enhancement
add	additions for enhancement
e	effective value
i	inter tube
l	liquid state
o	outer tube
PCM	phase change material
ref	reference value
s	solid state
w	wall temperature

impossibility of continuous operation of the concentrated solar plants. Moreover, the temporal and spatial mismatch between the supply and the demand is a key issue that needs to be settled as well. A solution to these problems is to employ the thermal energy storage (TES). Compared with sensible heat thermal energy storage (SHTES), latent heat thermal energy storage (LHTES) is a quasi-isothermal process with large energy storage capacity, thus the LHTES is relatively easy-controlled and space-saving [4]. With the rapid advance of solar thermal power generation technologies [5,6], higher operation temperature is needed and accordingly higher temperature TES will be of more significant importance in the near future [7,8].

In the LHTES system, the surplus energy is mainly stored in the latent heat of phase change material (PCM) and released when needed, so high-performance PCMs are the essential basis of LHTES. The following items are all desired properties for an ideal PCM including proper phase change temperature, large thermal capacity per unit volume, high thermal conductivity, chemical stability, non-toxicity, non-flammability, and low cost [9]. Nevertheless, none of the existing materials can completely achieve the list of requirements. An inherent defect that most PCMs suffer from is their low thermal conductivity, lengthening the charge/discharge process and limiting the heat transfer efficiency. To improve this situation, several methods have been proposed and can be classified into three groups: (1) to expand the heat transfer surface, such as using finned unit [10,11], enhanced tubes [12], capsuled PCMs [13,14], and direct contact heat transfer [15], (2) to enlarge the temperature difference between the heat transfer fluid and the PCMs to maintain a high heat transfer capability, such as employing the cascaded PCMs with stepped phase transition points [16,17], and (3) to modify the PCMs by adding materials with high thermal conductivity, such as expanded graphite [18–20], nano-materials [21–23], and porous matrix [24,25]. Among these methods, the adoption of conductive addition is the most direct pathway. Porous materials such as metal foam and graphite foam have high thermal conductivity, large porosity, and high specific surface area. Therefore, implementing porous media into PCMs can greatly enhance the thermal conductivity of PCMs with slight influence on the TES capacity [26,27]. Yang et al. [28] experimentally studied the effects of metal foam to PCM and found that the melting time can be reduced by more than two-thirds compared to the condition of the pure paraffin sample. Abujas et al. [29] numerically compared the effects of finned pipes and conductive foams. The results indicated that foams have the best performance not only on the charge time reduction but also on the heat flux uniformity through analyzing the above-mentioned cases. Zhu et al. [30] concluded that the melting rate of paraffin embedded in aluminum foam with the high PPI can be improved because of the large interfacial area density. Foregoing studies demonstrated that the conductive foam can provide the remarkable enhancement of the melting performance because of the significant improvement of the effective thermal conductivity of PCMs.

Besides the conduction, the natural convection is also the primary heat transfer mechanism during the charging process [31]. Numerous researches have shown that the natural motion of the liquid PCMs has strong effects on the melting front shape and the melting process evolution. Liu and Groulx [32] studied from the experiment that conduction is the dominant heat transfer mode during the initial stage of the charging process in a horizontal cylindrical LHTES unit. The natural convection starts to play an important role when more liquid PCM forms around the heating surfaces. Kousha et al. [33] carried out the visualization of melting process and observed that buoyancy forces fortifies the melting of the upper half of the shell side for a horizontal case. Seddegh et al. [34] compared the thermal behaviors of a vertical and a horizontal shell-and-tube latent heat energy storage system. The