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Evaluation and optimization of melting performance for a latent heat thermal energy storage unit partially filled with porous media

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HIGHLIGHTS

- Melting performance of phase change materials with porous media is studied.
- A new criterion is proposed to comprehensively assess the melting performance.
- The filling location and height ratio of porous insert are optimized.
- Effects of porous parameters on the melting performance are analyzed.

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ABSTRACT

In this paper, melting performance of phase change materials (PCMs) in a horizontal concentric–tube thermal energy storage (TES) unit was numerically investigated with consideration of natural convection. Porous media were employed to enhance the thermal response of PCMs. Performances of different porous configurations were compared to optimize the location of porous insert, and the optimal filling ratio of porous insert was determined based on a new criterion proposed in this study, which is called TES rate density. This new criterion was proved to be effective to comprehensively evaluate the melting performance, including melting time, TES capacity, and total mass of materials. Furthermore, the effects of pore size and porous materials were discussed. The results showed that partially locating the porous media in the lower part has the best enhancement on melting performance of PCM and the optimal filling height ratio of porous media is 0.7. In this case, the TES rate density can be significantly increased by more than 6 times compared with the none-porous case. More importantly, compared with the full-porous case, 3% better comprehensive performance with about 28% less porous material can be achieved. Porous insert with high thermal conductivity, large pore size, and high porosity is recommended to enhance the melting performance of PCMs. From the point of view of practical utilization of the porous material, silicon carbide is recommended due to its relatively high conductivity, chemical inertness and low cost.

1. Introduction

Energy crisis and environmental issue have become the two critical problems which restrict the development of the current world. Utilization of sustainable energy is an essential pathway to ease the energy and environmental problems. Especially, solar energy is believed as one of the most promising alternative sources of fossil energy due to its abundance, usability, and eternalness. In the solar thermal system, thermal energy storage (TES) plays a crucial part in addressing the intermittent and unstable issue of solar energy and relieving the mismatch between supply and demand [1,2]. Recently, with the rapid development of solar thermal power generation technologies [3,4], higher operation temperature is needed and accordingly high temperature TES becomes more and more important [5].

As an advanced TES method, latent heat thermal energy storage (LHTES) has raised plenty of attractions because of nearly constant working temperature and large TES density. The performance of LHTES has been investigated by many researchers [6–14]. It has been found that the inlet temperature and the mass flow rate of heat transfer fluid (HTF), the properties of phase change materials (PCMs), and the form of heat exchangers all have effects on the thermal performance of LHTES, while the most important basis of LHTES is the high–performance PCM.

However, no matter high temperature or low temperature PCMs, most of them suffer from their inherent defects of low thermal conductivity, resulting in limited efficiency and impossibility

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Nomenclature

A_{mush}	mushy zone constant(kg m^{-3} s)
c_p	specific heat(J kg^{-1} K^{-1})
C_{i}	inertia coefficient
d_{f}	fiber diameter (m)
d_{p}	pore diameter (m)
g	acceleration of gravity (m s^{-2})
H	height of porous insert (m)
K	permeability (m^2)
L	latent heat of fusion(kJ kg^{-1})
m	mass (kg)
P	pressure (Pa)
p	TES rate (J s^{-1})
p'	dimensionless TES rate
Q	TES capacity (J)
q	TES density (J kg^{-1})
q'	dimensionless TES density
R	radius (m)
r	radial coordinate (m)
s	area (m^2)
T	temperature (K)
T_{m}	melting point (K)
t	time (s)
t_{m}	melting time (s)
u,v	superficial velocity at x, y direction (m s^{-1})
w	TES rate density (J kg^{-1} s^{-1})
w'	dimensionless TES rate density
x,y	Cartesian coordinates (m)

Greek symbols

β	melting fraction
ε	porosity
γ	thermal expansion coefficient (K^{-1})
φ_H	filling height ratio
λ	thermal conductivity (W m^{-1} K^{-1})
μ	dynamic viscosity (kg m^{-1} s^{-1})
θ	circle angle (deg)
ρ	density (kg m^{-3})

Subscripts

e	effective value
i	inter tube
o	outer tube
PCM	phase change material
por	porous media
ref	reference value

of large–scale utilization of LHTES [15]. Therefore, it is imperative to enhance the thermal performance of PCMs. A direct method is adding some materials of high thermal conductivity, such as expanded graphite [16–18], silicon carbide ceramics [19], nanomaterial [20–22], and metal matrix [23–25], to enhance the effective thermal conductivity of PCMs. Among the additions, metal foam is found as an excellent heat transfer enhancer. It has high thermal conductivity, large porosity, and high specific surface area. Thus, introducing porous media into PCMs can greatly enhance the thermal conductivity of PCMs with slight influence on the TES capacity. Chen et al. [26] prepared SEBS/paraffin/HDPE composite PCM and then embedded the PCM into copper foam, and found that the thermal conductivity was greatly enhanced from 0.272 W/m K to 2.142 W/m K. Zhang et al. [27] learned from their experimental and numerical study that paraffin/copper foam composite showed a better heat transfer performance compared to the pure paraffin because of the high thermal conductivity of copper foam. The temperature distribution of paraffin/copper foam composite was more uniform than that of pure paraffin. Meng et al. [28] experimentally investigated the charging and discharging performances of pure paraffin impregnated with copper foam. A series of experiments were carried out to study the effects of different inlet temperatures and inlet flow velocities. Atal et al. [29] experimentally studied the effect of porosity of aluminum foams on a LHTES device. It was found that the metal foam with smaller porosity could further shorten the melting–freezing cycle because of higher overall thermal conductivity. Zhao et al. [30] chose graphite foam to enhance the performance of a high-temperature LHTES system. The simulation results showed that graphite foam could significantly improve the heat transfer performance and the exergy efficiency in the LHTES system. Due to the effects of graphite foam, the number of required HTF pipes can be remarkably reduced. Mesalhy et al. [31] numerically investigated the effects of porosity and thermal conductivity of porous materials. It was found that reducing the porosity of the matrix could increase the melting rate but damp the convection motion. Nithyanandam et al. [32] conducted computational analysis of the metal foam enhanced LHTES system with heat pipes. It was found that higher pore density introduced negative effects on the augmentation in heat transfer rate of the charging process due to restriction in the formation of convection currents. Zhang et al. [33] experimentally and numerically investigated the heat transfer characteristics of LHTES unit, and found that natural convection was very dominant during heat storage in the case of pure molten–salt, and it became weak when metal foam was added. Tao et al. [34] employed lattice Boltzmann method to investigate the effects of pore density and porosity of metal foams on melting rate, heat storage capacity, and heat storage density. The conclusions showed that decreasing the porosity could improve heat storage rate but decrease the heat storage density. Foregoing studies have found that porous insert brings about significant enhancement on thermal performance of PCM, but at the same time, damps the natural motion of liquid PCM and reduces the heat storage density. To reduce this adverse effect, porous insert with large thermal conductivity and high porosity seems to be the best choice.

Actually, making the best of natural convection is not only beneficial to accelerate the melting process, but also a cost–effective way to save the quantity of enhancer for PCM. Yazici et al. [35] experimentally studied the effect of eccentricity on melting performance of PCM in a horizontal tube–in–shell LHTES unit. The results showed that enlarging the natural convection–dominated area could considerably increase the melting rate of PCM. Wang et al. [36] numerically investigated the melting process of PCM in a sleeve–tube unit and compared the impact of fin geometry. It was found that the most effective angle between neighboring fins was 60°–90° when natural convection was considered. Tao et al. [37] studied the effects of natural convection on LHTES performance and found that local enhanced fin tubes could further improve the melting performance and make the melting boundary uniform. However, to the best of our knowledge, few studies have been carried out to further optimize the distribution of porous enhancer in a LHTES unit by making the most of natural convection.

In this paper, the emphasis was placed on evaluation and optimization of melting performance for a concentric–tube LHTES unit with high–temperature PCM enhanced by partially filled porous media. The filling position of porous media was optimized by full consideration of the effects of natural convection. A new evaluation