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Heat transfer characteristics of a molten-salt thermal energy storage unit with and without heat transfer enhancement ☆

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HIGHLIGHTS

- Heat storage and retrieval tests in a LTES unit were studied.
- Molten salt and metal foam/salt composites were used as the PCMs comparatively.
- Thermal non-equilibrium model was established to describe the heat transfer characteristics.
- Time-duration with composite PCM during heat retrieval process was reduced more.
- Slight temperature difference existed between the metal skeleton and PCM.

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ABSTRACT

Eutectic molten salt can be used as the latent thermal energy storage (LTES) medium in solar energy applications. In the present study, eutectic salt (50 wt% $NaNO_3$, 50 wt% KNO_3) with a melting temperature of about 220 °C was employed as the PCM for the middle-temperature solar energy application, which can be powered by the parabolic-trough solar collector using oil as the heat transfer fluid. There are many LTES units in which the molten salt is encapsulated in the thermal energy storage tank, where the heat transfer characteristic of the LTES unit is very important for the overall performance of the entire thermal energy storage tank. We experimentally and numerically investigated the heat transfer characteristics of the molten-salt in a LTES unit with and without heat transfer enhancement. Various heating temperatures of 240 °C, 250 °C, and 260 °C and cooling temperatures of 30 °C, 70 °C, and 110 °C were employed in the study, so as to extensively reveal the heat transfer characteristics during heat storage and retrieval. It was found that natural convection was very dominant during heat storage in the case of pure molten-salt, especially when the heating temperature was higher, and it was weakened in the case of molten-salt with metal foam; while the heat retrieval process was enhanced by the presence of the metal foam. The numerical results were compared with the experimental results, showing reasonable agreement, which indicated that such numerical model could be used for the further study of the performance of the LTES system.

1. Introduction

With the depletion of fossil fuels and the gradual increase of the energy consumptions, a lot of greenhouse gases have been emitted into atmosphere, which results in energy crisis and global warming simultaneously. Such energy and environment issues promote the development and utilization of renewable energy. Human society has made efforts on steering energy sources toward renewable energy. Solar energy as one of the renewable energy resources shows potential to alleviate the energy issues. However, its intermittent and unstable characteristics are the major drawbacks, which restrict its extensive application. Energy storage is an appropriate method to overcome this time-dependent limitation. Thus thermal energy storage systems are perceived as indispensible components in solar energy applications [1–3]. Comparing with other thermal energy storage methods, latent thermal energy storage (LTES) is a hot research topic for the advantages of high density and small temperature variations during heat storage/retrieval processes.

High temperature molten salt as phase change material (PCM) has been considered effective as a thermal storage medium for solar thermal power systems, which can significantly improve the stability of the system and make solar energy utilization more

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Nomenclature

A_s	additional term in momentum equation
a_{sf}	interfacial surface area (m^{-1})
C	mushy zone constant
c_p	specific heat (kJ/(kg K))
D	diameter (m)
Da	Dacry number
d_f	fiber diameter (m)
d_k	characteristic length (m)
d_p	pore size (m)
e	constant in model of Boomsma and Poulikakos
F_I	inertial resistance (m^{-1})
g	gravitational acceleration (m/s^2)
H	height (m)
h_{sf}	interfacial heat transfer coefficient ($W/(m^2 K)$)
K	permeability (m^2)
L	latent heat (kJ/kg)
p	pressure (Pa)
Pr	Prandtl number
R	thermal resistance (K/W)
Ra	Rayleigh number
Re	Reynolds number
T	temperature (°C)
U	velocity vector (m/s)
u	velocity in x direction (m/s)
v	velocity in y direction (m/s)
w	velocity in z direction (m/s)
x,y,z	Cartesian coordinates

Greek symbols

β	thermal expansion coefficient (K^{-1})
γ	liquid fraction
ε	porosity
ζ	small constant in additional term of momentum equation
λ	thermal conductivity (W/(m K))
μ	dynamic viscosity (kg/(m s))
ρ	density (kg/m^3)
τ	time (s)
σ	parameter in model of Boomsma and Poulikakos
χ	tortuosity coefficient
ω	pore density (pore per inch, PPI)

Subscript

amb	ambient
e	effective value
f	PCM
m	melting
sf	surface
s	solid skeleton
td	thermal dispersion

practical [4–6]. For the middle temperature range of 200–300 °C in solar energy applications, nitrate mixtures with low melting point, low unit cost, high heat capacity and energy storage density have been used for decades in the concentrating solar power industry as heat transfer fluids and thermal storage media [7,8].

Solar salt with a certain mass fraction of sodium nitrate and potassium nitrate ($NaNO_3$: KNO_3 = 54:46 or 60:40) as a typical molten salt has been studied extensively [9–14]. Bauer et al. [12] reviewed the thermo-physical data of solar salt (60 wt% $NaNO_3$, 40 wt% KNO_3), and pointed out that the density, heat capacity, thermal conductivity of solar salt were temperature dependent. An overview of the various aspects of steel corrosion in molten nitrate salts was also given in their research. Iverson et al. [13] extensively investigated the thermal and mechanical properties of solar salt, including specific heat, coefficient of thermal expansion, thermal conductivity, latent heat, then the values of those parameters have been presented as a function of temperature. Normally, molten salt is with low thermal conductivity [9,10], and effectively improving its thermo-physical properties is of great interest in both academic research and applications. Impregnating PCMs into a continuous porous structure with high thermal conductivity appears to be an effective way to compensate the low thermal conductivity. Metal foam has been widely studied and used because of its good mechanical and thermo-physical properties. The attractive advantages include low bulk density due to its high open porosity which will not significantly increase the weight of the thermal storage system, high specific strength and stiffness, and especially high thermal conductivity for continuous skeleton structure. Thus composite PCMs fabricated by porous metal foams and pure PCMs have been used for LTES systems [15,16]. Several numerical studies have been performed to investigate the heat transfer characteristics of PCM in porous structure, and it was found that the hypothesis of local thermal equilibrium in porous media was not exactly valid [17]. As a result, the thermal non-equilibrium phenomenon should be considered in the numerical analysis. DeGroot and Straatman [18] proposed a model with the volume-averaged energy equations under local thermal non-equilibrium conditions, which would be useful in analyzing the heat transfer in porous media. Liu et al. [19] established a numerical model to predict the melting characteristics of PCM in porous media, and the effects of the structural parameters of porous media and the inlet conditions of HTF on the thermal performance of a LTES unit were analyzed accordingly. Mesalhy et al. [20] numerically investigated the effects of impregnating porous matrix with high thermal conductivity of various porosities with PCM on the thermal performance of a LTES system. A two-temperature energy equation model was applied to analyze the local thermal non-equilibrium due to the large difference in thermo-physical properties between the solid matrix and PCM. Furthermore, the non-Darcy, Brinkman and Forchiemer effects were also considered in the investigation. Krishnan et al. [21] numerically investigated the natural-convection-coupled melting in a cavity filled with metal foam/PCM composite in the case of step change of the boundary temperature. A two-temperature energy equation to deal with the local thermal non-equilibrium between PCM and skeletons of the porous structure was used, and the heat transfer between PCM and metal foam was modeled by empirical correlations. Lafdi et al. [22] numerically analyzed the heat transfer process and the related liquid motion of the molten PCM by using thermal non-equilibrium model. It was shown that the graphite foam infiltrated with PCM significantly increased the heat transfer rate, and the decrease of the porosity largely accelerated the melting process due to high thermal conductivity of the graphite skeleton. Yang and Garimella [23] developed a two-temperature energy equation model to investigate the melting process of PCM impregnated into metal foams, and studied the effect of volume shrinkage/expansion of the PCM on the heat transfer between the foam and PCM.

It can be seen from the above literature review that, however, very limited experimental data have been provided for the LTES system using metal foam/PCM composite, especially for metal foam/salt composite. And the heat transfer characteristics of the composite PCM in a LTES unit have not been understood, which is

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