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Numerical analysis on the thermal behavior of high temperature latent heat thermal energy storage system

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Abstract

High temperature latent heat thermal energy storage technology is a promising option for future cost reduction in parabolic trough or tower power plant. However, low thermal conductivity of phase-change material (PCM) is the major shortage of latent heat thermal energy storage. This paper proposed a new thermal energy storage system (TESS) that metal foam and fins were used to enhance the effective conductivity of PCM. Three-dimensional physical model was established for representative element extracted from TESS. Considering the natural convection in the liquid part of PCM, volume-averaged mass and momentum equations were employed with the Brinkman–Forchheimer extension to Darcy law to simulate the porous resistance. A local thermal equilibrium model was developed to obtain temperature field. The governing equations were solved with finite-volume approach and enthalpy method was employed to account for phase change. The model was firstly validated against low temperature experiments from the literature and then used to predict the charging and discharging behavior of the present TESS. The position of solid/liquid interface was explored and the effects of design parameters, including that of metal foam pore density and porosity, configuration of fin and Rayleigh number, on melting and solidifying rate and energy stored in each time step were revealed and discussed. The results indicate that metal foam and fins can effectively improve the heat transfer performance for thermal storage system and decrease charging and discharging time.
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Keywords: Phase-change; Thermal energy storage; Metal foam; Natural convection

1. Introduction

Solar energy is a prominent option to meet current and future energy shortage. However, the intermittency of solar radiation and relatively high cost of solar-generated electricity are two challenges to make this energy option competitive. To resolve the problems, thermal energy storage (TES) is an effective method that stores excessive heat from solar field and releases from dusk to late night every day, or even provides power on cloudy days. There are three types of TES, which are sensible heat thermal energy storage (SHTES), latent heat thermal energy storage (LHTES) and chemical energy storage (CES) (Gil et al., 2010; Medrano et al., 2010). Compared with SHTES and CES, LHTES has some advantages including that of high energy density, energy storing or releasing at a nearly constant temperature, stable operation and reasonable price. However, as is well known, the primary disadvantage of LHTES is the low thermal conductivity of PCM (Liu et al., 2012), which leads to large temperature differences between heat transfer surface and the solid–liquid interface of the PCM and low energy storage rate.

Reviewing the research of LHTES, lots of heat transfer enhancement techniques have been presented to promote melting or solidifying rate of PCM (Jegadheeswaran and

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Nomenclature

a	side length of triangle, m
A_{mush}	mushy zone constant
c_F	inertial coefficient
d	characteristic length, m
d_p	pore size, m
Da	Darcy number
e	relative error
E	enthalpy
f_1	liquid fraction in the pore
Fo	dimensionless time
g	gravitational acceleration, m/s^2
G	shape factor
h	fin spacing, m
H_L	latent heat of PCM, J/kg
k	thermal conductivity, W/(m K)
K	permeability, m^{-2}
P	pressure, Pa
PPI	pore number per inch
Pr	Prandtl number
q	dimensionless energy stored in each time step
q_s	heat transfer rate, W
r	radius of the vertical circular tube, m
Ra	Rayleigh number
s	additional source term in the momentum equation
Ste	Stefen number
t	time, s
T	temperature, K
u	velocity vector, m/s
u, v,	velocity in x, y and z directions, m/s
x, y, z	Cartesian coordinates, m
V	volume, m^3

Greek symbols

α	thermal diffusivity, m^2/s
β	thermal expansion coefficient, K^{-1}
γ	dimensionless fin thickness
δ	fin thickness, m
ε	porosity
η	dimensionless fin spacing
μ	dynamic viscosity, (N s)/m^2
ρ	density, kg/m^3
φ	liquid fraction
χ	tortuosity coefficient
ξ, ψ, ζ	dimensionless x, y, z coordinate
ω	pore density

Subscripts

c	cooling
eff	effective
f	fluid
fin	fin
H	heating
i	initial
m	metal foam
p	at constant pressure, or pore

Superscripts

$*$	dimensionless quantity

Pohekar, 2009; Fan and Khodadadi, 2011). Strategies to counteract the low thermal conductivity of PCM include but are not limited to (I) use of extended surfaces (Agyenim et al., 2010; Seeniraj and Lakshmi Narasimhan, 2008; Sharifi et al., 2011), (II) thermal conductivity enhancement to PCM (Karaipekli et al., 2007; Zhong et al., 2010; Cui, 2012; Li et al., 2012; Zhao and Wu, 2011), and (III) micro-encapsulation of PCM (Salunkhe and Shembekar, 2012; Lenert et al., 2013; Seyf et al., 2013).

Porous metal foam as an effective conductivity enhancement material has been studied extensively over the years. Bhattacharya et al. (2002) presented a comprehensive analytical and experimental investigation for the determination of the thermal-physical properties of high porosity metal foams. Cui (2012) set up an experiment to examine the heat charging process under two conditions: paraffin filled with and without copper foam. The results indicated that the foam material not only led to a more uniform temperature distribution within the thermal energy storage unit, but also shortened the charging time. Li et al. (2012) studied experimentally the melting phase change heat transfer in open-cell metallic foams filled with paraffin, and also the effects of foam morphology parameters. The melting heat transfer was enhanced by the high thermal conductivity foam matrix, although it suppressed the local natural convection.

Based upon the literature review, this paper proposes a new latent heat thermal energy storage device, in which sandwich structure fins and metal foams made of copper are both imbedded in PCM to enhance the heat transfer rate. The three-dimensional mathematical formulation and numerical model for representative element extracted from TESS are investigated to analyze the flow and heat transfer behavior. The effect of natural convection in the melt fraction is considered and the Brinkman–Forchheimer extension to Darcy law is used to model the porous resistance. The position of phase change interface is explored and the influences of pore density, porosity, fin spacing and thickness, tube-wall temperature on the thermal behavior are also discussed in detail.

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