Applied Energy 225 (2018) 585–599

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Thermal and economic analysis of charging and discharging characteristics of composite phase change materials for cold storage

Xiaohu Yang[a,b,c], Qingsong Bai[a], Qunli Zhang[d], Wenju Hu[d], Liwen Jin[a,*], Jinyue Yan[b,c]

[a] Institute of the Building Environment & Sustainability Technology, School of Human Settlements and Civil Engineering, Xi'an Jiaotong University, Xi'an 10049, China
[b] Department of Chemical Engineering and Technology/Energy Processes, Royal Institute of Technology (KTH), 100 44 Stockholm, Sweden
[c] School of Sustainable Development of Society and Technology, Mälardalen University (MDH), 721 23 Västerås, Sweden
[d] Beijing Municipal Key Lab of Heating, Gas Supply, Ventilating and Air Conditioning Engineering, Beijing University of Civil Engineering and Architecture, Xicheng District, Beijing 100044, China

HIGHLIGHTS

- Solidification in open-cell metal foam is experimentally and numerically investigated.
- Porosity rather than pore density dominates solidification process.
- Natural convection affects greatly solidification front shape and temperature field.
- Using composite PCM is profitable with a short payback period.

ARTICLE INFO

Keywords:
Open-cell foam
Cold storage
Volume-average method
Experimental measurement
Techno-economic assessment

ABSTRACT

This study conducted both experimental and numerical investigations on the solidification behavior in a metal foam composite phase change material (PCM) for cold storage. Volume-average-method was adopted with the help of Forchheimer-Darcy equation to model the fluid flow through porous media. Experimental measurements were performed to validate the analytical model and the numerical method, with good agreement achieved. Local thermal equilibrium and non-equilibrium states were justified numerically and experimentally. Effect of pore morphological parameters (porosity and pore density) upon the solidification features of composite PCM were investigated. For the appliance of composite PCM to cold storage, techno-economic characteristics was also assessed. Results demonstrated that the full solidification time for metal foams with a porosity of 0.93 and 0.97 can be saved 87.5% and 76.7% respectively compared with pure water. It indicated that porosity of metal foam played a dominant role in heat transfer enhancement; while pore density seemed to have little influence on phase change behavior according to the results. Local natural convection in the unsolidified phase caused a remarkable promotion of the interface evolution, and the full solidification time with natural convection considered can be saved by 14.3% compared with pure conduction for the case with the same porosity of 0.97. The economic analyses indicated that using composite PCM was profitable with a short payback period less than 2 years.

1. Introduction

The energy consumption of fossil fuels all around the world accounts for as high as 87.9% in 2006, while the proportion of China is up to 93.8%. Recent studies have reported that the demand for oil would increase about 30% from 2007 to 2035 and coal and natural gas consumption would increase 50% [1]. According to research reports of 70 countries, the demand for energy has increased dramatically in recent years as many developing countries, including China, Brazil, India and South Africa have accelerated the urbanization process and improved the living standards. This makes the energy consumption increased significantly and directly intensified the scarcity of energy [2–4]. Compared with 1970, the energy consumption of China is predicted to be more than 15 times by 2050, while Brazil and India will reach to 11 and 12 times, in respective [1]. The rapid consumption of energy has caused many adverse effects on the environment, such as global warming, energy shortages, environmental pollution, etc. [5–7]. Amongst the various demands for Heating, Ventilation and Air

---

* Corresponding author.
E-mail address: lwjin@xjtu.edu.cn (L. Jin).

https://doi.org/10.1016/j.apenergy.2018.05.063
Received 28 December 2017; Received in revised form 24 April 2018; Accepted 15 May 2018

Nomenclature

Abbreviations

HVAC	heating, ventilation and air conditioning
ES	energy storage
TES	thermal energy storage
PPI	pore per inch
PU	polyurethane
MF	metal foam
VAM	volume-averaged method
FVM	finite volume method
TDMA	Tri Diagonal Matrix Algorithm
FCAC	fan coil air conditioning
PCM	phase change material
RPP	replication of polymeric path
COP	coefficient of performance

Symbols

A	area of side and top wall of container (m^{2})
A_m	numerical coefficient for damping velocity
C	capital investment ($)
C_0	profit earned by pure water as the energy storage medium ($)
C_E	inertia coefficient (m^{-1})
C_m	manufacturing costs ($)
C_w	welding costs ($)
c_d	drag coefficient
c_p	specific heat (J·kg^{-1}·K^{-1})
$c_{p,f}$	specific heat of fluid phase (J·kg^{-1}·K^{-1})
c_e	electricity price for commercial building cooling (kWh·$$^{-1}$)
C_{ut}	specific material cost for metal foam ($·m^{-3})
d	average ligament diameter (m)
d_p	pore diameter (m)
e	thickness ratio of node to solid ligament
f_s	solidification fraction
G	shape function for metallic ligaments
g	gravity acceleration (m s^{-2})
Gr	Grashof number
h_{sf}	interstitial heat transfer coefficient (W·m^{-2}·K^{-1})
K	permeability
k	thermal conductivity (W·m^{-1}·K^{-1})
$k_{e,f}$	effective thermal conductivity of metal foam saturated by fluid phase (W·m^{-1}·K^{-1})
$k_{e,s}$	effective thermal conductivity of metal foam saturated by solid phase (W·m^{-1}·K^{-1})
k_f	thermal conductivity in fluid phase (W·m^{-1}·K^{-1})
k_p	thermal conductivity of the container (W·m^{-1}·K^{-1})
L	latent heat of PCM (J·kg^{-1})
N	payback time (year)
n	operating hours (hr)
Nu	Nusselt number
$\overline{Nu}$	integral mean Nusselt number
P	pressure (Pa)
p_f	pressure in fluid phase (Pa)
Pr	Prandtl number
Q_t	total stored energy (kJ)
Q_{loss}	heat loss through side walls (W)
q_{w}	boundary wall heat flux (W·m^{-2})
Re	Reynolds number
RR	response time (K·s^{-1})
$S(t)$	solidified layer thickness (m)
T	temperature (K)
t	time (s)
$\vec{U}$	velocity vector (m·s^{-1})
u	component velocity in x axis (m·s^{-1})
V	void volume for a ES unit (m^{3})
v	component velocity in y axis (m·s^{-1})
V_c	fully charged volume for a ES unit (m^{3})
w	component velocity in z axis (m·s^{-1})
$\bar{\phi}$	integral mean quantity
$\overline{RR}$	integral-mean temperature response rate
$\langle\,\rangle$	extrinsic average of a quantity over a control volume
$\lvert\,\rvert$	magnitude of a vector

Greek symbols

α	cross-sectional area ratio of node to solid ligament
α_{sf}	specific area (m^{-1})
β	thermal expansion coefficient (K^{-1})
δ	numerical constant
ε	porosity
ρ	density (kg·m^{-3})
ρ_f	density in fluid phase (kg·m^{-3})
μ	dynamic viscosity (N·s·m^{-2})
μ_f	dynamic viscosity (N·s·m^{-2})
Π_r	30-year profit ($)
σ	liquid fraction in the porous medium
χ	flow tortuosity
ω	pore density

Subscripts

adh	adhesive
amb	ambient environment
c	copper foam
con	contact state
e	effective parameter
f	phase change material
full	full solidification rate
i	initial state
lig	metallic ligament
m	solidification point
s	solid phase
td	thermal dispersion
w	wall

Conditioning (HVAC) system is now playing an increasingly significant role in the total energy consumption in these days, due to the increasing demand for thermal comfort. The energy consumption in buildings accounts for 50% of the total consumption in America [5]. On one hand, the energy demand is significantly increasing; on the other hand, there exists severe mismatch of the energy supply and demand during the daytime and nighttime.

Energy (thermal or cold) storage technology provides an effective way to balance mismatch of energy supply and demand during day and night. The air conditioning system incorporated with ice storage technology can make full use of the cheap electricity at night to reduce operating costs, favoring playing a vital role in balancing the load of the power grid during the daytime [8]. A commercialized air-conditioning system with cold storage technology (water/glycol mixtures is utilized as the cold storage medium) is successfully applied in Xi'an Xianyang International Airport, which is demonstrated to improve the overall