Energy 79 (2015) 337–350

Contents lists available at ScienceDirect

Energy

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

Numerical and experimental study of heat transfer characteristics of a shell-tube latent heat storage system: Part I – Charging process

X. Xiao, P. Zhang*

Institute of Refrigeration and Cryogenics, MOE Key Laboratory for Power Machinery and Engineering, Shanghai Jiao Tong University, Shanghai 200240, China

A R T I C L E I N F O

Article history:
Received 26 June 2014
Received in revised form
6 October 2014
Accepted 7 November 2014
Available online 8 December 2014

Keywords:
Latent thermal energy storage
Composite phase change materials
Heat transfer characteristics

A B S T R A C T

This paper is the first portion of a two-part study of the heat transfer characteristics of a shell-tube latent thermal energy storage (LTES) system. A three-dimensional computational fluid dynamics model based on enthalpy method was developed to investigate the charging characteristics of the LTES system. Pure paraffin and paraffin/expanded graphite (EG) composite PCMs containing 7 wt. % and 10 wt. % EG were used as the phase change materials (PCMs), and water filled in a cylindrical tank was used as the heat transfer fluid (HTF). A variety of numerical investigations were carried out with different inlet temperatures and flow rates of the HTF for heat storage. The temperatures at various locations in the LTES system were experimentally measured and compared with the numerical results. It is shown that the model can accurately predict the thermal behaviors of the LTES system during heat storage. Large temperature difference between the HTF and the initial state of PCM would accelerate the charging process, which could also be significantly improved with the higher flow rate. The performance of the LTES system was affected prominently by the types of PCMs, HTF temperatures and flow rates.

1. Introduction

Nowadays, energy consumption related to human activity is increasing gradually and significantly. The thermal energy storage as a promising method to improve energy efficiency can bridge the gap between energy supply and demand, and can improve the performance of energy system. Latent thermal energy storage (LTES) technology is significant to the efficient thermal energy storage and saving, due to large heat storage capacity in the form of latent heat and small temperature variation during heat storage/retrieval processes [1]. Phase change materials (PCMs) with solid–liquid transformation have been proved to be economically attractive for application in LTES system. Researchers endeavored to study the thermo-physical properties of pure PCM and composite PCM, and explored the mechanism of heat and mass transfer of the PCMs during heat storage/retrieval processes [2,3]. It is shown that one of the major impediments of using PCM in LTES system is its low thermal conductivity, which leads to the low heat storage/retrieval rates of LTES system. It is obvious that the heat storage/retrieval rates should be improved to increase the energy efficiency of LTES system.

Pure paraffin with desirable thermo-physical properties is one of the most preferred PCMs for heat storage in the temperature range of 10~90 °C. However, its poor thermal conductivity generally below 0.4 W/(m K) restricted the utilization [4]. Expanded graphite (EG) can be used to enhance the heat transfer and was shown as the heat transfer promoter [5–7]. Sari and Karaipekli [5] studied the paraffin/EG composites, and pointed out that the composite PCM with the mass fraction of 10% EG showed stable property, high thermal conductivity and satisfying latent heat storage capacity. Fang et al. [6] studied the synthesis and characterization of stearic acid (SA)/EG composites. It was found that SA was retained easily in the pores of the EG by the capillary and surface tension forces, resulting in good thermal stability. The thermal diffusivities of the composites were improved apparently, e.g., the composite with 17 wt. % EG is 10 times larger than that of pure SA. Zhong et al. [7] prepared the paraffin/compressed EG composites using compressed EG with different densities, and investigated the thermal performance of the composites. The results indicated that the thermal conductivities of the composites could be about 28–180

* Corresponding author. Tel.: +86 21 34205505; fax: +86 21 34206814.
E-mail address: zhangp@sjtu.edu.cn (P. Zhang).

http://dx.doi.org/10.1016/j.energy.2014.11.020
0360-5442/

Nomenclature

A	cross-sectional area, m^2
a	thermal diffusivity, m^2/s
C	constant in Eq. (16)
c_p	specific heat capacity, J/(kg K)
d_e	equivalent hydraulic diameter, m
E	energy, kJ/kg
g	gravity acceleration, m/s^2
H	position of thermocouple, mm
h	specific enthalpy, kJ/kg
L	latent heat, kJ/kg
Le	liquid level, mm
l	height of PCM tube, mm
m	mass, kg
n	constant in Eq. (16)
P	pressure, Pa
$\overline{P}$	mean power, kW
P_c	wetted perimeter, mm
Ra	Rayleigh number
Re	Reynolds number
t	time, s
T	temperature, °C
ΔT	temperature difference, °C
T_m	phase change temperature, °C
u	velocity in x-direction, m/s
$\dot{V}$	volume flow rate, L/h
$\vec{V}$	velocity vector
v	velocity in y-direction, m/s
w	velocity in z-direction, m/s
x	x coordinate
y	y coordinate
z	z coordinate

Greek symbols

β	thermal expansivity, 1/K
γ	liquid fraction
η	efficiency
λ	thermal conductivity, W/(m K)
$\lambda_{p,eq}$	equivalent thermal conductivity of the PCM in liquid state, W/(m K)
$\lambda_{p,l}$	thermal conductivity of the PCM in liquid state, W/(m K)
μ	dynamic viscosity, kg/(m s)
ν	kinetic viscosity, m^2/s
ρ	density, kg/m^3

Subscripts

0	initial
c	charging
eq	equivalent
f	fluid
HTF	heat transfer fluid
in	inlet
l	liquid
out	outlet
p	phase change material
pr	provide
SS	stainless steel
s	solid
sen	sensible
w	wall

times larger than that of pure paraffin, and the linear relationships existed between the thermal conductivity and bulk density of the compressed EG matrix.

A great many studies have been performed to reveal the influences of the structural and operational parameters on the performance of LTES systems, and predicted the overall heat transfer characteristics of various LTES systems [8–18]. The LTES unit with shell-tube type is a highly attractive option in thermal energy storage applications and can be implemented easily [8–12]. Ezan et al. [11] experimentally and numerically investigated the charging and discharging characteristics of water in a shell-tube type LTES system. The effects of natural convection, flow rate and inlet temperature of HTF (heat transfer fluid), and shell diameter and thermal conductivity of the tube material on the charging/discharging performances were investigated extensively. Trp et al. [12] numerically and experimentally analyzed the effects of various operational conditions and geometric parameters on heat transfer in a water-paraffin shell-tube LTES unit. The numerical model considered the phase change heat transfer coupled with forced convection of the heat transfer fluid (HTF) as a conjugated problem. Joulin et al. [13] experimentally and numerically studied PCM27 conditioned in a parallel envelope used in passive solar walls. Both one-dimensional numerical calculation with Fortran code and two-dimensional one with Fluent were carried out, and slight difference was found between the numerical prediction and experimental observation during melting. Felix Regin et al. [14] numerically analyzed the thermal behaviors of a solar water system where pure paraffin was used as the PCM, and the influences of inlet temperature and flow rate of the HTF on the thermal performance of the system were studied extensively. Bony and Citherlet [15] developed a numerical model using TRNSYS to obtain heat transfer characteristics of paraffin plunged in a water storage tank. The equivalent thermal conductivity approach which considered both heat conduction and natural convection of PCMs was implemented in the enthalpy model. Zukowski [16] presented a mathematic model to analyze the heat and mass transfer in a ventilation duct encapsulated with paraffin wax. The effective heat capacity method which approximated the specific heat of PCM as a function of the temperature was adopted to describe the heat storage/retrieval processes. Tay et al. [17] developed a computational fluid dynamics (CFD) model for a LTES system, where water used as the PCM was filled in a cylindrical tank, and ionic solution used as the HTF was flowed through four tubes inside the tank. The model could accurately predict the thermal behavior of the LTES system during the discharging process, while slight difference were found between the numerical prediction and experimental result during the charging process due to ignoring the effect of natural convection. Cabeza et al. [18] constructed an experimental solar pilot plant for domestic hot-water supply with inclusion of the granular sodium acetate/graphite composite PCM. It was reported that the inclusion of the composite PCM module in water tank provided longer period of hot-water supply. Furthermore, some researchers studied the thermal behavior of LTES system with the modified mathematical model [19–23]. Adine and Quarnia [19] developed a mathematical model to predict the thermal behavior of a LTES unit using two types of PCMs. The impacts of the key parameters including the inlet temperature, mass flow rate of the HTF and the mass fraction of PCMs on the thermal performances were examined accordingly. Wang et al. [20] eliminated the inconsistency of the enthalpy model by employing the proposed pressure-decoupled solid velocity