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ScienceDirect
Applied Thermal Engineering 27 (2007) 994–1000
APPLIED THERMAL ENGINEERING
www.elsevier.com/locate/apthermeng

Effects of different multiple PCMs on the performance of a latent thermal energy storage system

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Received 19 July 2005; accepted 3 August 2006
Available online 13 October 2006

Abstract

The present study presents a theoretical model for the performance of a shell and tube latent thermal energy storage (LTES) unit using multiple phase change materials (PCMs). The model is based on the enthalpy method. Numerical simulations are carried out to investigate the effects of different multiple PCMs on the melted fraction, stored thermal energy and fluid outlet temperature of the LTES unit. Numerical results indicate that PCMs' fractions and melting temperatures play an important role in the performance of the LTES unit. As a result, appropriate choosing of multiple PCMs is very significant for the performance improvement of the LTES unit.

Keywords: Multiple phase change materials; Latent thermal energy storage; Numerical simulation; Enthalpy method

1. Introduction

Due to the advantage of the large heat storage capacity and isothermal behavior during the charging and discharging processes, latent thermal energy storage (LTES) systems have been widely used in solar energy utilization, industrial waste heat recovery and electrical power load shifting application in recent years [1–4]. However, the phase change material (PCM) used in LTES systems usually has low thermal conductivity, which is a major drawback for practical application. Therefore, efficient LTES systems are required for its development. During the past decade, the use of multiple PCMs in LTES systems was proposed by several authors [5–11] to increase the charging and discharging rates of the units.

Farid and Kanzawa [5,6] numerically and experimentally studied the performance of a LTES unit consisting of a number of vertical cylindrical capsules filled with PCMs, with air flowing across them for heat exchange. The numerical simulation showed a significant improvement in the heat transfer rate during the charging and discharging processes when phase change materials with different melting temperatures were used. And experimental results showed that there was no improvement in the heat transfer rate during the sensible heat storage period, while a maximum increase of 15% was observed during the latent heat period. Gong and Mujumdar [7] developed a finite element phase change heat conduction model for cyclic melting–freezing in composite phase change material slabs. Numerical experiments discovered that the charge–discharge rates could be greatly enhanced by using composite PCMs with different melting points as compared with using a single PCM in a slab. Gong and Mujumdar [8] further studied a storage unit of multiple phase change materials, which consists of a tube surrounded by an external coaxial cylinder. Numerical results indicated that the heat transfer rates could be significantly improved using multiple PCMs as compared with a single PCM. Aceves et al. [9] analyzed LTES with multiple energy storage cells and multiple PCMs by using a simplified model that allows the system performances to be evaluated in terms of a small set of parameters. The solutions to the optimization

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1359-4311/$ - see front matter
doi:10.1016/j.applthermaleng.2006.08.001

Nomenclature

c	specific heat (J/kg K)
D	diameter of the inner tube (m)
f	liquid fraction
Fo	Fourier number, $\alpha_p\tau/r_i^2$
h	sensible heat (J/m^3) or convection heat transfer coefficient (W/m^2 K)
H	total enthalpy (J/m^3)
k	thermal conductivity (W/m K)
L	length of the tube (m)
m	$\frac{\Delta\tau}{(\Delta r)^2}$
n	$\frac{\Delta\tau}{(\Delta x)^2}$
Nu	Nusselt number, hD/k_f
Pe	Peclet number, uD/α_f
Pr	Prandtl number, v_f/α_f
r	radius or radial coordinate (m)
Re	Reynolds number, uD/v_f
s	radial position of the solid–liquid interface (m)
Ste	Stefan number, $c_p(T_{in} - T_m)/\lambda$
T	temperature (K)
u	fluid velocity (m/s)
x	axial coordinate (m)

Greek symbols

α	thermal diffusivity (m^2/s)
Δr	radial space step (m)
$\Delta\tau$	time step (s)
Δx	axial space step (m)
λ	latent heat (J/kg)
ρ	density (kg/m^3)
v	viscosity (m^2/s)
τ	time (s)

Subscripts

0	initial condition
f	fluid
i	inside
in	inlet
k	the kth iteration
m	melting
o	outside
p	phase change material
n, s, w, e	the north, south, west and east control volume faces
P, N, S, W, E	the center, north, south, west and east nodes

Superscript

0	old value

problems indicated the potential advantages of using multiple PCMs in the LTES system. Wang et al. [10] developed a one-dimensional model for LTES systems using composite PCMs. The optimum linear phase change temperature (PCT) distributions were obtained by the theoretical analysis and were verified by the numerical simulation. The phase change time of composite PCMs with the optimum linear PCT distributions in LTES systems could be decreased by as much as 25–40% as compared with that of PCMs of a single PCT. Later, Wang et al. [11] experimentally studied the charging processes of a cylindrical heat storage capsule filled with multiple PCMs. Experimental results showed that, compared to the cylindrical capsule with a single PCM, the charging rate of the cylindrical capsule employing multiple PCMs was obviously enhanced.

Because of its high efficiency and relative small volume, the shell and tube heat storage unit is widely used in practical LTES systems. In this heat storage unit, the PCM fills the annular shell space around the tube, while the heat transfer fluid flows within the tube and exchanges heat with the PCM. This type of LTES systems has been studied by several authors using numerical and experimental methods [12–19].

In the present study, a model for the shell and tube LTES unit using multiple PCMs is developed and solved numerically. Numerical simulation is carried out to investigate the effects of multiple PCMs' melting temperatures and fractions on the melted fraction, stored thermal energy and fluid outlet temperature of the LTES unit. The numerical results are then compared with the LTES unit employing a single PCM to examine the enhancement of the thermal energy charging rate.

2. Mathematical formulation

The schematic of the physical model is presented in Fig. 1. The LTES unit consists of an inner tube, an outer tube and an annulus filled with PCMs having different melting temperatures. The outer tube is well insulated and the multiple PCMs are separated by thermal thin walls. A fluid flows through the inner tube and exchanges heat with PCMs. The melting temperatures of PCMs in the annulus decrease along the hot fluid flow direction for the charging process and increase along the cold fluid flow direction for the discharging process.

To simplify the analysis, the following assumptions are made:

(1) The flow of the heat transfer fluid is fully developed.
(2) The radial conduction of the heat transfer fluid is negligible.
(3) The thermal resistance of the inner tube surface is negligible.