Renewable Energy 78 (2015) 438–447

Contents lists available at ScienceDirect

Renewable Energy

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

Effect of internal void placement on the heat transfer performance – Encapsulated phase change material for energy storage

Laura Solomon, Ali F. Elmozughi, Alparslan Oztekin*, Sudhakar Neti

Mechanical Engineering and Mechanics, P.C. Rossin College of Engineering and Applied Science, Lehigh University, Bethlehem, PA 18015, USA

A R T I C L E I N F O

Article history:
Received 11 August 2014
Accepted 15 January 2015
Available online

Keywords:
Encapsulated phase change materials
Thermal energy storage
Void
Concentrated solar power

A B S T R A C T

The effect of an internal air void on the heat transfer phenomenon within encapsulated phase change material (EPCM) is examined. Heat transfer simulations are conducted on a two dimensional cylindrical capsule using sodium nitrate as the high temperature phase change material (PCM). The effects of thermal expansion of the PCM and the buoyancy driven convection within the fluid media are considered in the present thermal analysis. The melting time of three different initial locations of an internal 20% air void within the EPCM capsule are compared. Latent heat is stored within an EPCM capsule, in addition to sensible heat storage. In general, the solid/liquid interface propagates radially inward during the melting process. The shape of the solid liquid interface as well as the rate at which it moves is affected by the location of the internal air void. The case of an initial void located at the center of the EPCM capsule has the highest heat transfer rate and thus fastest melting time. An EPCM capsule with a void located at the top has the longest melting time. Since the inclusion of a void space is necessary to accommodate the thermal expansion of a PCM upon melting, understanding its effect on the heat transfer within an EPCM capsule is necessary.

1. Introduction

Recently, the world has reached the realization that the Earth's resources are not infinite and that suitable replacements need to be developed. Solar energy is among several technologies that are currently being developed. The concept of harnessing the sun's power is not new; however a way to make solar energy as efficient as current fossil fuel processes needs further development. Currently there are two main ways of converting solar radiation into electrical energy; the use of photovoltaic (PV) cells or concentrating solar power (CSP) plants. PV cells generate electricity by directly converting solar radiation into electrical energy. In contrast, CSP plants generate electricity by first converting solar radiation into thermal energy, then using the thermal energy to generate electrical energy using a power generation cycle such as the Brayton or Rankine cycle. However, as with most renewable energies, solar energy is intermittent. In order to make solar energy more viable, the hours the plant can operate efficiently have to be increased. One option is to use thermal energy storage (TES). By utilizing TES at a CSP plant, the system can store excess solar energy captured during times of high solar incidence and use it for power generation during times of low solar incidence. Thus eliminating any drop in power output by the CSP plant during these transients and increasing its overall efficiency.

TES can be broken up into three major classifications based on the principle of the energy storage method; sensible heat storage, latent heat storage, and chemical storage. For example sensible heat storage is defined as the raise in temperature per unit of mass of a material. Latent heat storage on the other hand stores energy through a phase transition per amount of substance at nearly constant temperature. Lastly, thermochemical storage uses a reversible chemical reaction to release or absorb heat, however uncertainties in physicochemical and thermodynamic properties limit the understanding and use of chemical storage [1,2]. Utilization of the latent heat of a material can decrease the volume of media needed over that required by the sensible heat alone. The present work focuses in particular on latent heat energy storage using phase change materials (PCMs) that undergo a solid liquid transition due to the minimal volume change experienced by the PCM.

Research into PCMs for applications at temperatures below 120 °C is vast [3–8]. While these low temperature PCMs have

* Corresponding author. Tel.: +1 (610)7584343; fax: +1 (610)7586224.
E-mail address: alo2@lehigh.edu (A. Oztekin).

http://dx.doi.org/10.1016/j.renene.2015.01.035

Nomenclature

g	gravitational acceleration, [m/s^2]
h	convective heat transfer coefficient, [W/m^2 K]
H	total enthalpy, [J/kg]
H_s	sensible enthalpy, [J/kg]
H_{sref}	reference enthalpy, [J/kg]
k	thermal conductivity, [W/m K]
L	latent heat of fusion, [kJ/kg]
$\dot{m}$	mass flow rate, [kg/s]
Nu	Nusselt number, [−]
Nu_φ	local Nusselt number, [−]
Pr	Prandtl number, [−]
P	pressure, [N/m^2]
r	radius, [m]
Re	Reynolds number, [−]
S	source term in momentum equations, [−]
t	time, [s]
T_m	melting temperature, [K]
T_o	initial temperature, [K]
T_{ref}	reference temperature, [K]
u	velocity component, [m/s]
x	x coordinate, [m]
y	y coordinate, [m]
c	specific heat, J/kg K]

Greek symbols

α	volume fraction, [−]
β	thermal expansion coefficient, [1/K]
γ	liquid fraction, [−]
ε	a small computational constant, [−]
μ	dynamic viscosity, [Pa-s]
ν	kinematic viscosity, [m^2/s]
ρ	density, [kg/m^3]
ρ_l	density of liquid phase PCM, [kg/m^3]
ρ_m	density of molten PCM near the melting point, [kg/m^3]
φ	angular coordinate, [rad]

Subscripts

f	heat transfer fluid
i	component
j	component
s	capsule surface
lower	below melting point
upper	above melting point

Abbreviations

CSP	concentrating solar
EPCMs	encapsulated phase change materials
HTF	heat transfer fluid
PCMs	phase change materials
TES	thermal energy storage

numerous commercial uses there is a need for PCMs with melting points above 300 °C for use in TES at CSP plants [9]. However, the use of PCMs for TES has its own unique challenges to overcome. The most common type of PCM used is inorganic salts, which have a low thermal conductivity in the solid phase. This has a limiting effect on the heat transfer rate during the solidification process. Research into ways to increase the thermal conductivity of PCMs is an active area, which includes adding a high conductive material, employing multiple PCMs, and extending the heat transfer surface by fins or capsules [10]. Of particular interest here are encapsulated phase change materials (EPCMs). Encapsulating the PCM increases the heat transfer surface which results in a decrease of the total heat transfer time, thus improving the heat transfer performance of PCMs [11,12].

Nevertheless, encapsulation of PCMs raises additional problems, one of which is dealing with the increase in internal pressure caused by the expansion of the PCM upon melting. A stress analysis for various EPCM shapes has been conducted by Blaney et al. [13] and concluded that it is essential to leave sufficient void space in the EPCM to minimize the pressure increase inside and to maintain structural integrity of the capsule. While it is known that a void is necessary within an EPCM capsule no studies have been done to determine its effect on the heat transfer with the capsule.

There have, however, been numerous studies into numerical modeling of heat transfer using PCMs by applying different techniques. Typically, a phase change problem is characterized by the propagation of the solid/liquid interface, which is captured by one of two methods; a front tracking method [14] or the enthalpy–porosity method [15]. The enthalpy–porosity method uses an implicit technique for conduction controlled phase change that was developed by Voller [15]. Brent and Voller [16] discussed a fixed-grid solution of the coupled momentum and energy equations without resorting to variable transformations and by using a two-dimensional dynamic model. Using a novel semi-implicit moving mesh discretization at each time step, Mackenzie and Robertson [17] solved the nonlinear enthalpy equation. Khodadadi and Zhang [18] studied the effects of buoyancy-driven convection on the constrained melting of PCMs within spherical containers. They concluded that the effects of Prandtl number, with consideration of a fixed Rayleigh number, as well as the buoyancy-driven convection accelerates the melting process when compared to a melting from pure diffusion models. Ismail et al. [19] investigated the effect of surface temperature, diameter, and material had on the solidification process of spherical shells. Tan et al. [20] numerically studied the effect of buoyancy-driven convection on the constrained melting of Paraffin wax n-octadecane inside a glass sphere based on an iterative, finite-volume method to solve the enthalpy–porosity equations. By incorporating the enthalpy–porosity method into FLUENT, Pinelli and Piva [21] studied the TES into a cylindrical PCM (n-octadecane) capsule using a uniform heat transfer coefficient along the outer surface of the capsule. Zhao et al. [14] reported on the heat transfer analysis of EPCMs for thermal energy storage at high temperature using both front tracking and enthalpy–porosity methods. Assis et al. [22] incorporated convection in the liquid phase, volumetric expansion due to melting of the PCM, and consideration of a 15% void faction, into their numerical analysis and employed FLUENT to produce a parametric investigation on the low temperature RT27 PCM in spherical shells comparing their work with experimental results of the same PCM. Their model attempts to solve the complete transient conservation equations simultaneously for solid PCM, liquid PCM, and air, while allowing for the PCM to expand, convection to occur in the fluid media, and solid phase motion in the liquid.

More recently Archibold et al. [23] extended the low temperature results of Assis et al. [22] to higher temperatures by using sodium nitrate as the PCM with a constant wall temperature boundary condition. Their results were in accordance with Assis et al. Further high temperature investigations are needed for