Applied Energy 138 (2015) 675–684

Contents lists available at ScienceDirect

Applied Energy

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

The effects of radiative heat transfer during the melting process of a high temperature phase change material confined in a spherical shell ☆

Antonio Ramos Archibold [a,b,e], Muhammad M. Rahman [a,b,*], D. Yogi Goswami [a,c], Elias K. Stefanakos [a,d]

[a] Clean Energy Research Center, University of South Florida, Tampa, FL, USA
[b] Department of Mechanical Engineering, University of South Florida, Tampa, FL, USA
[c] Department of Chemical & Biomedical Engineering, University of South Florida, Tampa, FL, USA
[d] Department of Electrical Engineering, University of South Florida, Tampa, FL, USA
[e] Department of Mechanical Engineering, Universidad Autónoma del Caribe, Barranquilla, Colombia

HIGHLIGHTS

- Analyzed effects of radiation heat transfer during melting in spherical shell.
- Performed analyses to ascertain the effects of optical thickness and the Planck, Grashof and Stefan numbers.
- Present correlations for melt fraction and modified Nusselt number.

ARTICLE INFO

Article history:
Received 14 May 2014
Received in revised form 15 September 2014
Accepted 28 October 2014
Available online 21 November 2014

Keywords:
Thermal energy storage module
Melting
Radiation
Phase change material

ABSTRACT

The influence of radiation heat transfer during the phase change process of a storage material has been numerically analyzed in this study. Emphasis has been placed on the thermal characterization of a single constituent storage module rather than an entire storage system, in order to precisely capture the energy exchange contributions of all the fundamental heat transfer mechanisms during the melting of a phase change material (PCM) with tailored optical properties. The equations describing the conservation of mass, momentum and energy have been solved by using the control volume discretization approach, while the radiative transfer equation (RTE) was solved by the discrete ordinate method (DOM). The enthalpy–porosity method was used to track the PCM liquid/solid interface during the process. A parametric analysis has been performed in order to ascertain the effects of the optical thickness and the Planck, Grashof and Stefan numbers on the melting rate, as well as the total and radiative heat transfer rates at the inner surface of the shell. The results show that the presence of thermal radiation enhances the melting process. Correlations for the melt fraction and modified Nusselt number are developed for application in the design process of packed bed heat exchangers for latent heat thermal energy storage.

1. Introduction

The urgent need of sustainable and clean energy sources to secure the future energy production as well as expand the existing electricity generation market has motivated the rapid growth of commercial-scale central receiver concentrating solar power (CSP) plants during recent years [1,2]. Among the major sub-components of the system namely, the heliostat field, the power conversion cycle and the receiver, the potential integration of thermal energy storage (TES) devices, during the operation of a CSP plant becomes extremely critical to dispatch power when solar irradiation is not available allowing the plant to operate in a cost-effective fashion and consequently reduce the plant levelized electricity cost. The current commercial TES option for CSP systems uses molten nitrate salts as the storage media while energy is stored via sensible heat [3,4]. In these systems, large amounts of storage material are used and, therefore, large tanks are required, thus increasing the overall cost of the system. In addition to the economic drawback, technical barriers associated with the low exergetic efficiency and material compatibility issues [5,6] are key factors to encourage the near-term development of advanced thermal energy storage concepts. Numerous research and development initiatives have been directed towards the single tank thermocline system for sensible heat storage [7–9] in an effort to reduce the cost of the TES system. However the

---

☆ This paper is included in the Special Issue of Energy Storage edited by Prof. Anthony Roskilly, Prof. Phil Taylor and Prof. Yan.

* Corresponding author at: Department of Mechanical Engineering, Wichita State University, Wichita, KS 67260, USA. Tel.: +1 316 9786343; fax: +1 316 9783236.

E-mail address: muhammad.rahman@wichita.edu (M.M. Rahman).

http://dx.doi.org/10.1016/j.apenergy.2014.10.086

Nomenclature

c_p	specific heat at constant pressure (J/kg K)
ΔT	temperature difference (°C) $(T_w - T_m)$
Fo	Fourier number $(\kappa/\rho\, c_p)(t/R_i^2)$
g	gravitational acceleration (m/s^2)
Gr_R	Grashof number $(g\beta\Delta T R_i^3\rho^2/\eta^2)$
$\hbar$	heat transfer coefficient (W/m^2 K) $(\hbar = q_t/A\Delta T)$
h	sensible enthalpy (J/kg)
L	latent heat of fusion (J/kg)
n	index of refraction
Nu	Nusselt number $(\hbar R_i/\kappa)$
P	pressure (Pa)
Pl	Planck number $\kappa(\kappa_a + \sigma_s)/4n\sigma\overline{T}^3$
Pr	Prandtl number of the fluid $(\eta c_p/k)$
q_t	total heat transfer rate at the inner shell wall (W)
R_i	inner radius of the capsule (m)
Ra	Rayleigh number (GrPr)
Ste	Stefan number $(c_p(T_w - T_m)/L)$
t	time (s)
T	temperature (°C)
$\overline{T}$	reference temperature (°C) $(T_w + T_m/2)$
υ	velocity (m/s)

Greek symbols

α	thermal diffusivity (m^2/s)
β	thermal expansion coefficient (1/K)
δ	thickness (m)
η	dynamic viscosity (kg/m s)
κ	thermal conductivity (W/m K)
κ_a	absorption coefficient (m^{-1})
λ	latent heat (J/kg)
Θ_n	dimensionless temperature at the center point, $\Theta_n = (T - T_o)/(T_w - T_o)$
ρ	density (kg/m^3)
σ	Stefan–Boltzmann constant, $\sigma = 5.67 \times 10^{-8}$ W/m^2 K^4
σ_s	scattering coefficient (m^{-1})
τ	optical thickness, $\tau = (\kappa_a + \sigma_s)R_i$
φ	dimensionless irradiation
ξ	dimensionless stream line value
ω	scattering albedo, $\omega = \sigma_s/(\kappa_a + \sigma_s)$

Subscripts

m	melting
o	initial
r	radial direction
s	solid
w	wall
θ	angular direction

primary challenge is the temperature degradation within the system, which results in lower exergetic efficiency [5]. In that context, the use of PCMs, for latent heat energy storage, seems to be one of the very promising methods because of its higher specific energy storage capacity which reduces the size and cost of the storage tank. The main drawbacks of PCMs for energy storage applications are low thermal conductivity, large volume expansion during melting [5] and chemical activity leading to corrosion. However, it is presumed that at elevated temperatures (>800 °C) radiative heat transfer becomes significant when compared to the others fundamental heat transfer modes. Consequently, the low thermal conductivity problem that penalizes the conduction energy transport during the melting and solidification processes can be overcome, particularly for transparent PCMs, by seeding the PCM with appropriate amounts of radiation absorbers. In this approach an infra-red transparent PCM with tailored absorptance for enhanced radiative transfer is encapsulated in several spherical shells with a highly emissive coating on the inner surface and use it in a packed bed heat exchanger. The objective of this study is to examine the energy exchange process during the melting of sodium chloride with enhanced radiative properties encapsulated in a spherical capsule at elevated temperatures. Among the different PCMs currently investigated as possible candidates to be used in thermal storage devices at elevated temperatures, NaCl has been selected in this investigation because of its high latent heat of fusion and relatively low cost. Also, its melting temperature (800–802 °C) matches with the typical operating range of central receiver power plants.

The problem of heat transfer by radiation in a gray medium confined between two concentric black spheres has been widely reported in the heat transfer literature. A simplified analytical method, based on a diffusion approximation, for calculating radiation heat transfer in the aforementioned system has been presented by Konakov [10]. Sparrow et al. [11] have discussed the contribution of the absorption coefficient and the size of the container on the medium temperature distribution. In the model, an absorbing-emitting, gray gas was assumed as a participating medium while uniform and equal temperatures have been imposed at the shell surfaces. A uniform internal heat generation rate per unit volume through the gas was also considered. Numerical predictions were reported and the study concluded that the gas temperature variations are greater when the absorption coefficient increases for a fixed geometry. An approximate solution of the previously described problem has been reported by Dennar and Sibulkin [12] and Chou and Tien [13] based on an extension of the Milne–Eddington approximation (moment method) originally developed for plane layers. Tong and Swathi [14] evaluated the accuracy of the spherical harmonic numerical method by solving the same problem. In their model the scattering of radiation within the medium was considered and the influence of the differential approximation technique on the wall heat fluxes was presented. Ryhming [15], Viskanta and Crosbie [16] and Jia et al. [17] extended the analysis of Sparrow et al. [11] to include a uniform but different temperature at the bounded surfaces. It should be mentioned that in the results reported by Ryhming [15] three values of inner to outer wall temperature ratios $T_1/T_2 = 2, 5$ and 25 were reported. Viskanta and Merriam [18] performed a parametric investigation on the steady state conduction and radiation heating and cooling processes of an absorbing, emitting, scattering and gray medium enclosed in the space between two black, isothermal and concentric spheres. The influences of the Planck number, optical thickness, surface emissivities, inner to outer radius ratio, internal heat generation per unit volume and inner to outer wall temperature ratios were investigated. The study highlighted the strong influence of the surface emissivities on the local radiation heat transfer flux and reported an increase of the total heat flux at the inner surface of the system when the Planck number and the optical thickness decreases and increases respectively. The transient solution of the model reported by Viskanta and Merriam [18] has been obtained by Chu and Weng [19]. In the study, the equation of radiative transfer has been numerically solved by the spherical harmonic method. The transient cooling process by radiation of a stationary spherical gas mass has been analyzed by Viskanta and Lall [20]. The energy transfer by conduction and convection was neglected and a numerical solution of the energy equation has been obtained by the method of