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Numerical study on melt fraction during melting of phase change material inside a sphere

Wei Li [a,b,c,*], Sui-Guang Li [a], Shikai Guan [a], Yunhao Wang [a], Xu Zhang [d], Xueling Liu [b]

[a] School of Energy and Safety Engineering, Tianjin Chengjian University, Tianjin 300384, PR China
[b] Key Laboratory of Efficient Utilization of Low and Medium Grade Energy (Tianjin University), Ministry of Education, Tianjin 300072, PR China
[c] State Key Laboratory of Building Safety and Built Environment, Beijing 100013, PR China
[d] Tianjin Key Laboratory of Advanced Mechatronics Equipment Technology, Tianjin Polytechnic University, Tianjin 300387, China

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ABSTRACT

This paper presents a numerical study on the constrained melting of phase change material (PCM) inside a sphere to investigate the effect of various factors on the melt fraction. A mathematical model of melting processes of the PCM inside a sphere is developed. And experiments are conducted to verify the numerical method. On the basis of the model, the effects of the sphere radius, the bath temperature, the PCM thermal conduction coefficient and the spherical shell material on the melt fraction of PCM inside a sphere are discussed. The results show that the PCM inside a sphere melts fast as the sphere radius is small, the bath temperature increases, and the PCM thermal conductivity is high. And the metal shell with high thermal conductivity should be adopted preferentially. The present study provides theoretical guidance for the design and operation of the phase change heat storage unit with sphere containers.

Introduction

With the rapid development of economy, energy consumption has increased dramatically, resulting in the deterioration of energy supply and environment. Phase change heat storage is an effective way to improve energy utilization and energy conservation [1]. Many scholars have reported the researches on the types, thermal physical properties, heat transfer enhancement and applications of phase change material (PCM) [2–6]. PCM are generally placed in containers to be better used. There are several shapes of PCM packaging, such as plate, cylindrical, spherical, etc. [7–9]. In these shapes, the spherical containers is used most widely because it has the advantages of low volume to heat transfer surface area ratio and the ease of packing in the storage device [10,16].

S.A. Fomin et al. [11] explored numerically and analytically the close-contact melting within a spherical capsule by utilizing the boundary fixing method. Keumnam Cho et al. [12] experimentally investigated the thermal characteristics of paraffin in a spherical capsule during freezing and melting processes. J.M. Khodadadi et al. [13] studied the effects of

* *Corresponding author*. School of Energy and Safety Engineering, Tianjin Chengjian University, Tianjin 300384, PR China.
E-mail address: anplw@126.com (W. Li).
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Nomenclature

Abbreviation

PCM	Phase Change Material

Symbols

C	specific heat (J/kg °C)
g	gravity acceleration(m/s^2)
H	total enthalpy (J/kg)
h	sensible enthalpy (J/kg)
L	latent heat (J/kg)
R	inside radius of the sphere (m)
P	pressure (Pa)
r	radius (m), coordinate in r direction
T	temperature (°C)
T_{liquid}, T_{solid}	melting temperature, solidification temperature
t	time (s)
u	velocity (m/s)

Greek letters

λ	thermal conductivity (W/m·°C)
β	thermal expansion coefficient (K^{-1})
δ	spherical shell thickness (m)
ν	dynamic viscosity (m^2/s)
ρ	density (kg/m^3)
φ	liquid fraction of PCM

Subscripts

pct	phase change average temperature
ini	initial
s, m	spherical shell, PCM
ref	reference temperature
r, θ	coordinate in r, θ direction 1

buoyancy-driven convection on constrained melting of PCMs within spherical containers.

Ian W. Eames et al. [14] conducted an experimental study on the characterization of the freezing and melting processes for water contained in spherical elements, which were often founded in the beds of thermal (ice) storage systems used building air conditioning systems. Hisham Ettouney et al. [15] performed experiments using spherical capsules filled with paraffin wax and metal beads to evaluate heat transfer enhancement in phase change energy storage units.

Tan et al. [16] investigated the solidification process of an n-hexadecane inside a spherical enclosure for different constant surface temperature and initial PCM superheats. Assis et al. [9] explored numerically and experimentally the melting process of PCM in spherical geometry for different spherical radius and wall-temperature. Tan [17] experimentally investigated the constrained and unconstrained melting processes of PCM inside a sphere. S. Kalaiselvam et al. [18] developed models for solidification and melting of PCM in a sphere with conduction, natural convection and heat generation. Tan et al. [19] analyzed the role of buoyancy-driven convection during constrained melting of PCM inside a spherical capsule by experimental and computational methods.

Amin et al. [20] investigated the applicability of the effectiveness–NTU method for characterizing a PCM thermal energy storage system, and they proved that the effectiveness–NTU method is applicable for PCM encapsulated in spheres in a tank. Reda I. ElGhnam et al. [21] studied the heat transfer during freezing (charging) and melting (discharging) of water inside a spherical capsule.

Tan et al. [22] conducted an experimentally research on the melting process of n-octadecane inside a sphere under constant heat flux boundary condition, and they founded the melting is primarily dependent on temperature level and contact plane surface area. Tan et al. [23] investigated unconstrained melting of nano-enhanced PCMs (NEPCM) inside a spherical container using RT27 and copper particles as base material and nano-particle, respectively. The simulation results show that the nanoparticles cause an increase in thermal conductivity of NEPCM compared to conventional PCM, and the enhancement in thermal conductivity with a decrease in latent heat results in higher melting rate of NEPCM.

Lei Yang et al. [24] researched a packed bed heat storage system using spherical capsules filled with three kinds of PCM, and founded that this new type heat storage packed bed has higher energy and exergy transfer efficiencies than the traditional packed bed, and the average energy and exergy collection efficiency of its solar collector are higher too. N.A.M. Amin et al. [25] conducted an experimental research on the heat transfer through a single sphere subject to varying temperature differences, and developed a computational fluid dynamics model which ignored buoyancy of the PCM in the sphere. And a suitable relationship for the effective thermal conductivity was developed as a function of the Rayleigh number. Muhammad M. Rahman et al. [26] analyzed a two dimensional axisymmetric model of the heat transfer and fluid flow during the melting process inside a spherical capsule.

It can be seen from above that there are a lot of studies on the phase change and heat transfer of PCM inside a sphere, but few works involving the melting rate improvement of PCM inside a sphere from the view of heat storage unit performance enhancement. The object of the present study is to guide the design and operation of heat storage unit by analyzing the effect of various factors on the melt fraction. This paper presents a numerical study on the constrained melting of PCM inside a sphere, and conducts experiments to verify the numerical method. The effects of the sphere radius, the PCM thermal conduction coefficient, the spherical shell material and the external (bath) temperature on the melt fraction of PCM inside a sphere are discussed.

Physical and mathematical models

The schematic diagram of the physical model is shown in Fig. 1. The radius and shell thickness of the sphere are R and δ, respectively.

Governing equations

In order to simplify the problem, the following assumptions are made in this study: