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Heat storage performance analysis and parameter design for encapsulated phase change materials

Qinghua Yu[a,b], Alessandro Romagnoli[c], Bushra Al-Duri[a], Danmei Xie[b], Yulong Ding[a], Yongliang Li[a,*]

[a] Birmingham Centre for Energy Storage, School of Chemical Engineering, University of Birmingham, Birmingham B15 2TT, United Kingdom
[b] School of Power and Mechanical Engineering, Wuhan University, Wuhan 430072, PR China
[c] School of Mechanical and Aerospace Engineering, Nanyang Technological University, Singapore 639798, Singapore

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ABSTRACT

This paper establishes a thermo-mechanical model considering the liquid density variation to explore the comprehensive energy storage performance of two types of small-sized encapsulated phase change materials (PCMs) as well as effects of shell thickness. The study shows that the varying ranges of internal pressure, melting temperature and latent heat are markedly diminished during melting of PCMs after taking into account the liquid density variation. The decrease of shell thickness leads to a decrease of maximum internal pressure and a larger decrease of critical cracking pressure, which will increase the risk of shell cracking. The decrease in shell thickness slows down the increase in melting temperature and the decrease in latent heat during the melting process, which consequently reduces the melting time and increases the stored latent energy. These results indicate that reducing shell thickness of encapsulated PCMs is favourable for elevating energy charging rate and energy storage capacity while it is harmful to mechanical stability. The Cu/Ni capsule has smaller critical core/shell size ratio to avoid cracking than the salts/SiC capsule, while the former offers a shorter melting period. This implies that physical properties of materials of PCM capsules should be carefully considered for improving mechanical stability and melting dynamics. This study is helpful for selection of appropriate shell thickness and materials to achieve excellent comprehensive energy storage performance of encapsulated PCMs.

1. Introduction

High-temperature thermal energy storage (HTTES) provides an effective solution to overcome the mismatch between energy supply and demand associated with concentrated solar power generation [1,2] and industrial waste heat recovery [3]. HTTES is also crucial to the round-trip efficiency enhancement of recently developed compressed air energy storage [4–6] and liquid air energy storage systems [7,8]. Latent heat storage-based solid-liquid transition of phase change materials (PCMs) has attracted increasing attention because of high energy storage densities with small temperature variations [9]. However, the applicable PCMs for HTTES, such as molten salts and metals, exhibit high chemical corrosion in the liquid phase. Therefore it is essential to encapsulate PCMs in suitable shell materials to prevent leakage of liquid PCMs. The encapsulation of PCMs can also significantly increase heat transfer surface area and establish barriers for PCMs against harmful reactions with the environment [10]. The formed spherical PCM capsules offer stable geometric and chemical structures like solid balls or particles, which are easy to handle.

The spherical PCM capsules can be used for thermal energy storage in the form of packed beds [11,12] or fluidized beds [13,14]. The diameters of the PCM capsules used in packed beds generally measure tens of millimetres [15]. This kind of large-sized capsule is fabricated by filling in a precast container (i.e. shell) with PCM [16]. There will be some void or porosity inside this kind of capsule [17]. In contrast, the diameters of the capsules used in fluidized beds generally measure a few millimetres or hundreds of micrometres [18,19]. This kind of small-sized capsule is manufactured by coating or plating PCM pellets with shell materials, which does not introduce voids inside the capsule [20,21]. In comparison with packed beds, fluidized beds offer more advantages including temperature uniformity along the bed and excellent heat transfer between the carrier fluid and the PCM. However, since small-sized capsules have no voids inside, shell cracking may occur due to volume expansion during phase transition of PCM from solid to liquid and this has to be considered in the design of PCM capsules [22]. Mathur et al. [23] developed PCM capsules tolerating

* Corresponding author.
E-mail address: y.li.1@bham.ac.uk (Y. Li).

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Nomenclature

Roman letters

a	shell thickness (m)
c_p	specific heat (J·kg^{-1}·K^{-1})
E	Young's modulus (Pa)
ES	stored energy (J)
f	fraction
g	Gibbs free energy (kJ·kg^{-1})
h	enthalpy (kJ·kg^{-1})
L	latent heat (kJ·kg^{-1})
P	pressure (Pa)
r	radius (m)
s	entropy (J·kg^{-1}·K^{-1})
t	time (s)
T	temperature (K)
u	displacement (m)
V	volume (m^3)

Greek letters

α	thermal expansion coefficient (K^{-1})
β	isothermal compressibility (Pa^{-1})
γ	heating rate (°C·min^{-1})
δ, μ	Lamé's constant
λ	thermal conductivity (W·m^{-1}·K^{-1})
ν	Poisson's ratio
ρ	density (kg·m^{-3})
σ	stress (Pa)
φ	relaxation factor

Subscripts

0	reference or initial
c	shell
e	external surface of shell
eq	equivalent
i	shell/PCM interface or PCM
l	liquid
m	melting or melting front
r, θ, φ	spherical coordinates system
s	solid
t	tensile strength

Superscripts

$*$	holistic

PCM volume expansion by incorporating sacrificial polymer as the first shell layer which decomposes below the melting point of PCM to gas leaving a void in the capsule. Obviously, the resulting void layer reduces the heat storage density and charging/discharging rate. Zhang et al. [24] examined encapsulation of copper (Cu) as PCM with a thick chromium-nickel (Cr-Ni) bilayer. The results showed that there was no leakage or crack from the outside view of the capsule after charge-discharge thermal cycles. However, the integrity of the capsule is attributed to a sufficiently thick shell, which leads to a reduction of heat storage density by 70% with respect to the pure copper. Further, the shell thickness has considerable impact on the melting dynamics of PCM, which is closely related to the energy charging rate. Therefore, it is crucial to precisely tailor the shell thickness of PCM capsules to obtain excellent comprehensive heat storage performance, including good mechanical stability (i.e. no cracking), high heat storage density and fast charging/discharging processes.

Since it is difficult to directly measure the thermal and mechanical parameters within encapsulated PCMs, especially at high temperature, numerical simulation or analysis has become a very powerful tool. Several researchers have explored the heat storage performance of encapsulated PCMs for HTTES by numerical method. Zhao et al. [25] compared the charging/discharging time for encapsulated PCMs between different heat transfer fluids using numerical simulations of heat transfer regardless of volume variation. Lopez et al. [26] established a model for a solid sphere of PCM salts encapsulated in an elastic graphite shell with a mobile internal wall and a fixed external wall to explain the behaviour of graphite/salt composites during melting. The pressure inside the shell increases linearly as melting continues, leading to a continuous increase in the melting point and continuous decrease in latent heat. Pitié et al. [27] incorporated Lamé equations into the model to describe the thermo-mechanical behaviour of a spherical PCM coated by silicon carbide (SiC) shell with a free, mobile, external wall by specifying volume friction of melted salts. The analysis indicates that the coated PCM with a low volumetric expansion resulting in a small pressure change is vital to avoid cracking. Parrado et al. [28] analysed the temperature and pressure evolutions during the melting and solidification processes of Cu-encapsulated nitrates using a decoupled model between heat transfer and mechanical deformation. However, this work did not consider the variation in density of the liquid PCM which cannot be ignored at high pressures [27]. Although the shell thickness of PCM capsules need be adjusted to make a compromise between mechanical stability and heat storage density, little work has been conducted on its effects on the comprehensive heat storage performance.

Therefore, this paper develops a new thermo-mechanical model to evaluate comprehensive heat storage performance of different types of spherical PCM capsules. This model takes into account density variations of the liquid phase PCM and pressure-dependent solid-liquid equilibria together with energy conservation and shell stress during the PCM melting process. On the basis of the model, the melting characteristics of PCM within a capsule are examined, including the evolutions of internal pressure, melting point, latent heat and stored energy as well as melting time frame. Special attention is paid to the effects of shell thickness on the melting characteristics, mechanical stability and energy storage capacity. The model is also applied to predict the minimum shell thickness to avoid cracking at specified PCM bead size and shell materials. This study provides a fundamental understanding of comprehensive energy storage performance of encapsulated PCM and significant references for tailoring shell thickness of encapsulated PCM to achieve optimum comprehensive energy storage performance.

2. Mathematical models

2.1. Geometry and main hypotheses

The geometry of a spherical capsule under melting of PCM is shown in Fig. 1, including a shell and liquid/solid PCM. The internal and external radii of the shell are referred to as r_i and r_e, respectively. The position of the melting front is labelled r_m. The radii or position of the melting front, vary during melting of the PCM.

The main hypotheses adopted to simplify the model are as follows [26,27]: (a) specific heat c_{ps} and thermal conductivity λ_s are constant for the solid phase of PCM with non-deformability; (b) specific heat c_{pl} and thermal conductivity λ_l are constant for the liquid phase of PCM; (c) convection heat transfer inside the small-sized capsule is negligible; (d) viscous energy dissipation of the liquid is also negligible; (e) the liquid within the shell has uniform pressure; (f) the shell is considered to be homogeneous, isotropic and exhibiting linear elastic behaviour