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

Qinghua Yu\textsuperscript{a,b}, Alessandro Romagnoli\textsuperscript{c}, Bushra Al-Duri\textsuperscript{b}, Danmei Xie\textsuperscript{b}, Yulong Ding\textsuperscript{a}, Yongliang Li\textsuperscript{a,*}

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

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\textbf{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 materials to achieve excellent comprehensive energy storage performance of encapsulated PCMs.

\textbf{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 \cite{1,2} and industrial waste heat recovery \cite{3}. HTTES is also crucial to the round-trip efficiency enhancement of recently developed compressed air energy storage \cite{4–6} and liquid air energy storage systems \cite{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 \cite{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 \cite{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 \cite{11,12} or fluidized beds \cite{13,14}. The diameters of the PCM capsules used in packed beds generally measure tens of millimetres \cite{15}. This kind of large-sized capsule is fabricated by filling in a precast container (i.e. shell) with PCM \cite{16}. There will be some void or porosity inside this kind of capsule \cite{17}. In contrast, the diameters of the capsules used in fluidized beds generally measure a few millimetres or hundreds of micrometres \cite{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 \cite{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 \cite{22}. Mathur et al. \cite{23} developed PCM capsules tolerating...
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 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 \( c_p \) and thermal conductivity \( \lambda_s \) are constant for the solid phase of PCM with non-deformability; (b) specific heat \( c_p \) and thermal conductivity \( \lambda_s \) 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 which cannot be ignored at high pressures [27].
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