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Research Paper

Low-temperature macro-encapsulated phase change material based thermal energy storage system without air void space design

J. Chiew[a], C.S. Chin[b,*], W.D. Toh[a], Z. Gao[a], J. Jia[a]

[a] School of Engineering, Clean Energy Research Centre, Temasek Polytechnic, 21 Tampines Avenue 1, 529757 Singapore, Singapore
[b] Faculty of Science, Agriculture, and Engineering, Newcastle University in Singapore, Singapore 599493, Singapore

HIGHLIGHTS

- Eliminate air void and give good heat transfer between PCM and housing by dampeners.
- Results show air void in macro-encapsulation affects heat transfer performance.
- Thermal cyclic tests show stable performance up to 50 cycles for real applications.

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ABSTRACT

A robust macro-encapsulation design of a low-temperature phase change material based thermal energy storage unit is presented. The developed macro-encapsulation container eliminates the need for the 20% air void space catered for the volumetric expansion of the phase change material during melting in conventional designs. A study was conducted to validate the effectiveness of the design on thermal conductivity with volumetric expansion on a 2-dimensional axis symmetrical model. The results from the numerical and experimental approaches came to a good agreement that heat transfer has improved. The thermal robustness of the proposed design was successfully demonstrated after multiple thermal cycles on the design.

1. Introduction

Phase change material-based thermal energy storage (PCM-TES) systems have been proven to be useful in applications such as concentrated solar plants and waste heat recovery systems [1]. However, phase change materials suffer from drawbacks such as low thermal conductivity and high volumetric expansion [2,3]. There are currently numerous ways to improve the PCM thermal conductivity, such as the addition of fins, encapsulation, metal matrixes, the addition of graphite and impregnation with expanded graphite, etc. [4–7], each method having its own merits in its field of use. However, the issue of volumetric expansion in encapsulated PCM has not been resolved [8]; instead, it has been a practice to leave a 20% void space within the encapsulation to allow for PCM expansion to occur.

Encapsulation of PCM refers to the encasing or enclosing the PCM in a shell or coating. There are different sizes and levels of encapsulation, namely on the macro, micro and nano levels. The primary purpose of encapsulation is to isolate the PCM from the surroundings, and the size of encapsulation would largely depend on its usage and application [9].

Macro PCM-TES systems usually consist of a PCM macro-encapsulated within a thermally conductive enclosure, with or without a thermal enhancing components such as a metal lattice structure [10] or additional fins [11] to improve the overall thermal conductivity of the system. However, these methods impose a trade-off between thermal conductivity and heat storage density [12]. The containing vessel is often considered as a pressure vessel and takes on multiple stresses [13], depending on the filling method. The PCM will typically fill up about 80% of the enclosure's volume [14,15] while a 20% void space remains to accommodate the thermal expansion of the PCM during its phase transition from solid state to liquid state [16]. A method used to work around this problem is to encapsulate the PCM while in its expanded liquid form. However, this method causes a vacuum to form during solidification that forms a negative pressure.

Conventionally, the void space is essential for the current design of the PCM-TES system [17–22], but the space of air creates a layer of insulation that adversely affects the heat transfer of the system. In theory, the rate of heat transfer will be hindered by the reduction in contact surface area and the blanket of air acting as insulation.

Considerable works have been carried out on the melting of phase change material within spherical encapsulation via experimental,

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* Corresponding author.
E-mail address: cheng.chin@newcastle.ac.uk (C.S. Chin).

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Nomenclature

C_P	specific heat capacity (J/kg K)
$\boldsymbol{F}$	volume force field (N/m^3)
H_f	heat storage capacity (J/kg)
k	thermal conductivity (W/m K)
p	pressure (Pa)
q	heat power (W)
t	time (s)
T	temperature (K)
$\boldsymbol{u}$	velocity field (m/s)
Q	heat source (W/m^3)

Greek symbols

α	phase volume fraction
Δ	difference
θ	phase mass fraction
μ	dynamic viscosity (kg/m s)
ρ	density (kg/m^3)

numerical and analytical methods or a combination of these methods [23–29]. Maruoka et al. [30], Ma et al. [31] and Nomura et al. [32] conducted studies on coated or plated PCM capsules, of a few millimeters in diameter, which is a technique that does not introduce a void space within the capsule. From those studies, it was reported that these PCM pellets improved the temperature uniformity and heat transfer. However, these capsules were highly susceptible to cracking due to expansion of the PCM and the absence of void space. This technique is heavily reliant of a robust mechanical-thermal analysis and parameter design [33].

However, spherical encapsulation is hardly used in macro-encapsulation systems. Instead, cylindrical containment formats are used [2,12]. Gui et al. [34] studied the influence of void ratio on the thermal performance of the phase change material within a heat pipe receiver. The void ratio showed a significant temperature gradient between the PCM and the canister wall. On the other hand, Soloman et al. [35] researched on the effects of heat transfer performance based on the location of the void placement in a spherical encasement. The study concluded that the void located at the top had the longest melting time. Due to gravitational effects, the air naturally settles to the top after melting regardless of its starting position. Niyas and Muthukumar [36] introduced a novel heat transfer enhancement technique in an encapsulated latent heat storage system. The technique featured a tube-in-tube system with a small inner tube which reduced the thickness of the PCM and increased heat transfer. This method increased the heat transfer surface area by ensuring a larger contact patch. Alam et al. [2] devised an innovative method of encapsulating the PCM with a void inside the shell that catered for PCM volume expansion. However, the method is suited for PCM with a 393–623 K melting temperature range. Fukahori et al. [12] proposed a new macro-encapsulation technique that suppresses thermal stress from volume expansion of the PCM. However, the method is specifically for high-temperature metallic PCM and also left a void as a buffer for volumetric expansion. Hence, the paper presents a robust macro-encapsulation design for a low-temperature phase change material based thermal energy storage unit that eliminates the need for an air void space catered for volumetric expansion of the PCM in conventional encapsulation.

In summary, the contributions of this paper are as follows. The macro-encapsulated PCM-TES thermal model and its design demonstrates the effective heat transfer between container and PCM and phase ratio of PCM during melting. The thermal durability of the macro-encapsulated PCM-TES was performed using a series of thermal cyclic test. The systematic approach of the testing and validation process was conducted using finite element analysis with an experimental setup of the physical PCM-TES unit under the similar simulation conditions. The simulation and experimental results demonstrated a good agreement that the void space has an adverse and undesirable effect on the overall heat transfer in a phase change material based system. As a result, the developed method of macro-encapsulation catered for volumetric expansion improves the heat transfer performance and robustness against multiple thermal cycles.

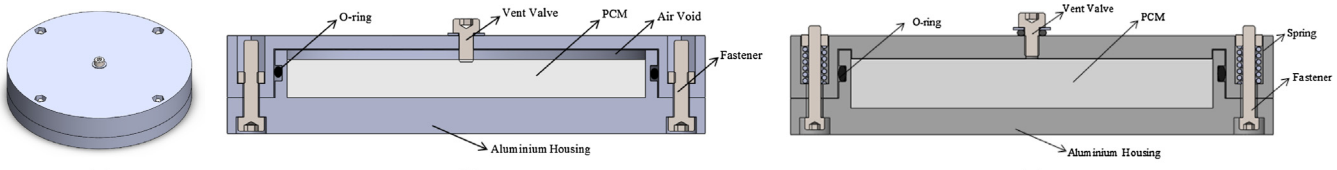
2. System and description

There are a few major concerns when designing a macro-encapsulation container for PCM, namely, accommodating for volumetric expansion of PCM during phase change and air during heating, the reactivity of PCM with container material and effective sealing of the container. The conventional methods rely on the container material strength to cope with the built up pressure by the expansion of air and providing a void space for the expansion of the PCM.

The proposed PCM-TES unit consist of a two circular aluminum bodies which encapsulates the phase change material (PCM) and the air void space. The two bodies have a dimension of ∅100 × H20.5 mm as seen in Fig. 1a. The unit houses a commercially available PCM, RT35HC by RUBITHERM® Technologies GmbH, which has a melting point of 308 K over a temperature range of 3 K. The thermophysical properties of RT35HC are shown in Table 1. The organic PCM is chemically compatible with most metals. Therefore, an aluminum casing has been selected due to its high thermal conductivity that would aid in the heat transfer and reduce overall testing time. The system also has a vent valve to prevent over-pressuring during the encapsulation process, after all, the system is considered as a pressure vessel.

Fig. 1b and c shows the sectional view of the PCM-TES, with and without the air void space respectively. The two models are similar to one another, except for the void space. The PCM-TES was designed and fabricated out of 6061 aluminum and assembled for testing. Fig. 1c is the proposed design that eliminates the need for the air void space with the addition of dampeners that provides sufficient force to hold the two bodies together while allowing the top cover to move with the expansion of the PCM during phase change.

The PCM-TES comprises of a storage space for the PCM that is securely encapsulated and fastened by corresponding socket bolt and nut. For comparison, one enclosure is 100% filled; while the other is 80% filled with PCM which leaves a 20% air gap for thermal expansion of the PCM.



(a) (b) (c)

Fig. 1. Isometric (a) and sectional view of PCM-TES with (b) and without (c) air-void.