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Experimental study on the thermal characteristics of a microencapsulated phase-change composite plate

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The melting thermal performances of MEPCM (microencapsulated phase-change material) composite plates were investigated experimentally. The effects of MEPCM particle fraction in the plate, PCM core fraction in a single MEPCM particle, volume fraction of high thermal conductivity additives on the temperature of heated and back surfaces, the temperature difference between both surfaces, and the melting duration time were investigated based on two applications: TES (thermal energy storage) and TPS (thermal protection system). The unsteady heat transfer process for the MEPCM plate was composed of three regions: sensible heat region before melting, melting region, and sensible heat region after complete melting. The heated surface temperature, back surface temperature, and temperature difference all decreased with increased MEPCM particle fraction or PCM core fraction; however, the corresponding melting duration time was extended. For TES, high thermal conductivity additives of carbon fiber and aluminum powder were added to the MEPCM plates to enhance heat transfer. For TPS, the MEPCM plates provided a good thermal barrier compared with the conventional insulation material of silica aerogel. Moreover, the effect of the liquid-phase natural convection in the PCM core was weak and can even be neglected due to suppression by micron-sized capsulation shells.

1. Introduction

PCMs (Phase change materials) can provide large latent heat storage capacity with a small temperature difference and play extensive roles in numerous technical processes and engineering applications, i.e., applications of PCM in solar energy storage [1,2], waste heat recovery [3,4], and thermal protection [5,6], among others, whereas high volume changes during the phase-change process (nearly 20% change for the original PCM [7]) and physico-chemical interactions between PCMs and applied environment usually occur. Therefore, a MEPCM (microencapsulated phase-change material) has been developed in recent years to remedy this disadvantage and provide additional advantages [8]. The MEPCM is a composite material in which PCM (the core) is surrounded or coated with a continuous polymeric material film (the shell) to produce capsules at the micrometer or millimeter scale.

Research interest in phase-change heat transfer can be classified into the two categories of TES (thermal energy storage) and TPSs (thermal protection systems). The former focuses on large latent heat storage in which a rapid latent absorption/release rate is desirable for use of PCM as a heat sink. The latter focused on the temperature level of a back surface using PCM as a heat barrier.

Higher conductivity is beneficial for rapid latent absorption/release rate and enhancing thermal response performance for TES purposes. However, most PCMs have inherently low thermal conductivities (especially organic PCM and inorganic salt), which negatively affect energy storage. Consequently, extensive investigations have been conducted to improve the thermal response by embedding high-conductivity additives in PCM. Mettawee and Assassa [9] experimentally investigated the thermal performance of a compact PCM solar collector with aluminum powder embedded in paraffin and found that the charging time decreased by 60% for the composite compared with that of pure paraffin wax. Huang et al. [10] conducted an experimental evaluation on the thermal performance of a photovoltaic/PCM system for different internal fin arrangements in bulk PCM and found that the addition of internal fins improved the temperature control of the

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Nomenclature

α	volume fraction of MEPCM particles in MEPCM-integrated plates
β	volume fraction of PCM core in a single MEPCM particle
γ	volume fraction of conductivity additive in MEPCM-integrated plates
a	thermal diffusivity [$m^2\ s^{-1}$], $a = \lambda/\rho c$
ρ	density [$kg\ m^{-3}$]
c	specific heat capacity [$J\ kg^{-1}\ K^{-1}$]
λ	thermal conductivity [$W\ m^{-1}\ K^{-1}$]
h	latent heat [$kJ\ kg^{-1}$]
T	temperature [°C]
T_h	heated surface temperature [°C]
T_b	back surface temperature [°C]
ΔT	temperature difference between heated surface and back surface [°C], $\Delta T = T_h - T_b$
t	time [s]
U_T	test uncertainty

photovoltaic system. Li et al. [11] and Qu et al. [12] studied the phase-change heat transfer within a PCM composite infiltrated with high-thermal-conductivity metallic foam. The metal foam enhanced the melting heat transfer, which decreased the heated surface temperature and melting duration although its existence suppressed the natural convection of liquid-phase PCM. Chintakrinda et al. [13] and Sanusi et al. [14] experimentally investigated the use of paraffin PCM embedded with graphite nanobers to improve the transient thermal response and found that the time consumption for melting and solidification was both greatly reduced to approximately 60% of that without graphite nanofibers. Enhancement of thermal conductivity was also reported in the review by Fan and Khodadadi [15].

For TPS applications, PCM functions as a thermal barrier to delay or reduce heat transfer through the boundary surfaces of the system during the melting process. This process may facilitate temperature control of the protection surface, which is generally located in the back of the heated surface. Therefore, a lower conductivity will provide more effective thermal resistance for TPS. Athienitis et al. [16] studied the application of PCM in building envelope components and found that gypsum plates impregnated with PCM used in a passive solar test room might reduce the maximum daytime room temperature by nearly 4 °C. Based on a firewall structure, Ho and Chu [17] analytically studied the thermal protection characteristics of a vertical rectangular composite cell filled with solid–fluid PCM and an air layer. The results showed that heat penetration across the composite cell could be greatly retarded over an effective duration because of latent heat absorption inside the PCM layer. Furthermore, the liquid natural convection in the PCM layer degraded the thermal protection of the composite cell. Rossi and Bolli [18] studied the use of PCM to improve the thermal protection of firefighters' protective clothing and found that the thermal protection effect was more pronounced if the PCM layer was located in the inner rather than in the outer layers. Yendler et al. [19] proposed a conceptual design of integrated multiple PCM layers that use a loop heat pipe as the protection system for a planetary entry vehicle. This work showed that the TPS design is capable of using the high latent heat of PCM to absorb incoming heat and maintain the temperature of the cargo compartment of the vehicle.

In addition to the applications of PCM, investigations and applications of MEPCM have been primarily extended to three fields: MEPCM slurry for heat storage and transfer [20,21], MEPCM composite fiber for enhancing thermal comfort of textiles [22] and MEPCM-integrated plates for building energy conservation [23,24]. The MEPCM-integrated plate technology is a promising approach for PCM in practical applications (such as TES and TPS). The MEPCM particles are mixed into a curing agent and hardened into a plate form that maintains a certain structural performance to facilitate practical applications, i.e., PCM wallboard in an energy-saving building. Furthermore, certain high-thermal-conductivity additives (such as metal powder) can be added to the curing agent to enhance the thermal performance of MEPCM plate. The MEPCM-integrated plate has three geometrical parameters, namely, MEPCM particle concentration, PCM core concentration and additive concentration. Cabeza et al. [25] presented a comparative experiment between two real-size concrete cubicles, one with integrated MEPCM and the other without MEPCM. A commercial MEPCM with a melting point of 26 °C and a phase change enthalpy of 110 $kJ\ kg^{-1}$ was adapted for this work. The cubicle with MEPCM exhibited improved thermal inertia and lower inner temperatures than the one without MEPCM, thus demonstrating effective energy conservation. Liu and Awbi [26] conducted a full-cycle experimental study on the thermal performance of an environmental chamber fitted with composite plates with 60% microencapsulated paraffin loading. The PCM wall showed better heat insulation performance than the ordinary wall during the charging process and released additional heat energy during heat discharge. This characteristic could aid in reducing the energy consumption of buildings. Darkwa and Kim [27,28] comparatively investigated the thermal performance of laminated and randomly mixed MEPCM composite drywall material and found that the laminated board released approximately 27% more latent heat than the randomly distributed type at the optimum period. Thus, the authors proposed that laminated PCM could be a feasible technique for enhancing heat transfer in drywall systems.

As reviewed above, most of the previous studies have focused on the thermal characteristics of pure PCM, and the effects of the three important geometry parameters on thermal characteristics of MEPCM plates have been rarely investigated. In the current study, the transient thermal characteristics of an integrated MEPCM plate under constant heating power were experimentally investigated for TES and TPS purposes. The objective of the study was to systematically identify how the parameters of MEPCM particle concentration, PCM core concentration and additive concentration affect the transient thermal performance. In particular, two high-thermal-conductivity additives, i.e., carbon fiber and aluminum powder, were used to enhance heat transfer in the MEPCM plate for TES applications, and the MEPCM plate was compared with conventional silica aerogel to verify its feasibility as a thermal shielding material for TPS applications.

2. Experimental samples and apparatus

2.1. Test samples and their thermal properties

Ten groups of MEPCM-integrated plates with uniform dimensions of 48 mm × 48 mm × 20 mm were used as shown in Fig. 1(a), and the cross-sectional SEM picture and schematic diagram of the MEPCM plates are illustrated in Fig. 1(b) and (c), respectively. The samples were manufactured from commercial materials that included high-carbon paraffin, urea resin, epoxy resin and relevant additives. The MEPCM particles with diameters ranging from 10 μm to 20 μm were first fabricated using in situ polymerization in which the high carbon paraffin and urea resin formed the PCM core and shell material, respectively. After dilution with water, the epoxy resin was uniformly sprayed into MEPCM