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INVESTIGATION OF MELTING PROCESS OF NANO-PCM INSIDE METAL FOAM UNDER ULTRASONIC FIELD

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ABSTRACT

Phase change material (PCM) gradually becomes a promising approach to keep the temperature within a comfortable range in the application of thermal management of electronic devices nowadays. In this work, TiO_2 nanoparticles, copper foam and n-octadecane were composited by vacuum method to prepare nano-PCM(nanoparticle-phase change material) and the melting process of nano-PCM under the effects of different nanoparticle concentrations and ultrasonic powers were experimentally investigated. The results showed that the ultrasonic and nanoparticles in the melting process have positive effects on shortening the melting time of nano-PCM. As the ultrasonic power reached 100 W and the nanoparticle concentration reached 5 wt.%, the melting time of nano-PCM was reduced by 46.96%. In addition, the extra heat was found in the melting process brought by the heating effect of ultrasound. Finally, the heat source temperature increased with the increasing of ultrasonic power. Therefore, the relationship between the melting rate of nano-PCM and the heat source temperature needs to be balanced reasonably.

Keywords: nano-PCM, melting process, nanoparticle concentrations, ultrasonic power, heat source temperature

NONMENCLATURE

Abbreviations	
PCM	phase change material
nano-PCM	nanoparticle-phase change material
Symbols	
t	heating time, s
T_e	temperature, K
Greek symbols	
φ	time reduction index
σ	temperature reduction index
Subscripts	
1, 2, 3, 4, 5, 6, 7, 8	number of temperature measuring point

1. INTRODUCTION

Recently, due to the progressive device miniaturization, high chip density and compact design, electronic products produce a lot of heat during operation, disturb the normal performance of the device, and reduce the reliability and life expectancy. Therefore, the thermal management system is crucial for the safe operation of electronic equipment [1].

Phase change materials have attracted much attention in the heat dissipation of electronic devices. Because PCM absorb large amount of heat around its phase change temperature range during the phase change transition period[2]. Besides the ease of controlling the melting temperature stability, PCMs are relatively light, chemically stable and noncorrosive compared to many materials [3]. However, the thermal conductivity of most PCM is generally low, which leads to slow thermal response and low heat transfer efficiency

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[4]. Thus, improving the thermal conductivity of the PCM has received considerable attention.

On the one hand, the passive method of improving the thermal conductivity of PCM is mainly to extend the heat transfer surface of high conductivity, including adding high thermal conductivity nanoparticles into PCM to compound nano-PCM, compositing porous structure and so on. A large number of studies have shown that the thermal conductivity of PCM can be improved effectively by dispersing nanoparticles into PCM [5] [6] [7]. In addition, based on previous studies, porous materials filling with PCM can provide a stable and efficient heat transfer network, increase the heat transfer surface, and improve the equivalent thermal conductivity of PCM [8] [9]. On the other hand, the active method includes using ultrasonic field to accelerate melting process of PCM [10] [11]. But whether the active method of using ultrasonic field can further enhance the heat transfer of in the melting process of nano-PCM in porous materials or not remains to be further studied.

The objective of the present study was to investigate the melting process of PCM under the combined effect of nanoparticle, copper foam and ultrasonic field. Furthermore, the heat transfer rate from the vertical heater surface to the PCM, the solid-liquid interface shape, and the PCM temperature variations with time were measured at various ultrasonic powers in the range of 0-100 W. A comparison of melting phenomena was also made among the nanoparticle, foam copper and ultrasonic field application and the nonapplication cases.

2. EXPERIMENT

2.1 Preparation and properties of nano-PCM

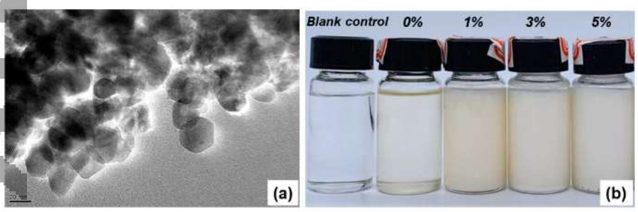

Fig 1 (a) TEM image of TiO_2 nanoparticles, (b) Nano-PCM suspension with different nanoparticle concentrations

In this experiment, the two-step approach was adopted for the preparation of nano-PCM. TiO_2 nanoparticles(30 nm, TEM image shown in Fig. 1(a)) and Span 80 were first added into the molten n-octadecane, employed as the base PCM, stirring for 30 minutes in the magnetic stirrer. Span 80 was added into n-octadecane to weaken the agglomeration and precipitation of nanoparticles, and to improve the dispersion stability of nanoparticles in the molten n-octadecane. Then, an ultrasonication probe with 600 W output power and 20 kHz frequency of power supply was applied to disperse the nanoparticles by vibration for 1 h. The nanoparticle concentrations of nano-PCM were set to 0, 1, 3 and 5wt.%, as shown in Fig. 1(b).

2.2 Experimental set-up

The experimental test apparatus consists of the thermal storage cell, electrical heaters, insulation material, water-cooling circulation system, power supply, thermocouples, the data acquisition system and ultrasonic system, as shown in Fig. 2(a). The hot wall was heated by an electrical heating film, while the cold wall was milled with channels within which temperature-control fluid was circulated from a bath. There are 3 temperature measuring ports arranged on the foam copper, and 8 T-type thermocouples assembled in the hot and cold walls at various locations along the length and depth directions to monitor the temperature (measurement error: ±0.3 °C), as shown in Fig. 2(b). The thermocouple data were processed and recorded by a data acquisition unit. The ultrasonic frequency is 28 kHz and the ultrasonic power is 50 W or 100 W.

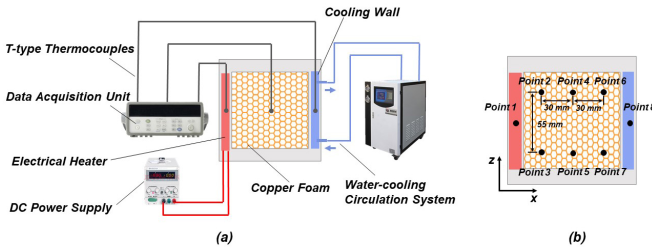

Fig 2 (a) Experimental test apparatus, (b) Coordinates of 8 T-type thermocouples

The melting experiment was started by turning on the DC power supply to raise the hot wall and setting the temperature of the cold wall to a constant temperature of 24±1 °C. The surface-averaged heat transfer rates through the isothermal hot wall is a constant value in this melting experiment.

3. RESULTS AND DISCUSSION

Fig. 3 shows the temperature change of the PCM without the effect of TiO_2 nanoparticles and ultrasonic during the whole phase change process. The temperature change of PCM can be divided into three stages: the sensible heat storage stage of solid PCM, the latent heat storage stage of solid-liquid PCM and the sensible heat storage stage of liquid PCM. In this paper, the end time of the solid-liquid phase at point 2(t_2) and point 7(t_7) is defined as the beginning time and finished time of latent heat storage, respectively. The time difference($t_{2\text{-}7}$) between point 2 and point 7 is defined as the whole latent heat storage time of solid-liquid phase. And the temperature (T_e) at point 1 at heating time t=1500s is chosen an important evaluation for the effect of heat storage temperature.

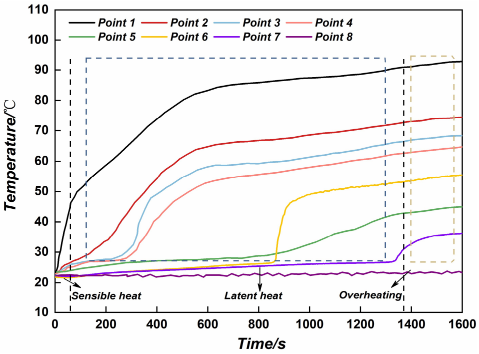

Fig 3 Temperature changes of the PCM at point 1-8 during the whole phase change process

Since the initial temperature of the experiment starts at room temperature of 23±1 °C, the sensible heat storage amount of the solid PCM is limited, which quickly changes from the solid sensible heat storage stage to the latent heat storage stage. In the early stage, heat conduction is the main way of heat transfer, and the melting of PCM mainly depends on the heat conduction between heated copper plate and foamed copper. With the melting process progressing, the temperature at point 2, 4, 6 is significantly higher than the temperature at the point 3, 5, 7. The reason is that natural convection of liquid PCM dominates the heat transfer in the middle and late melting process. The high-temperature liquid PCM flows upward to the upper area, and the low-temperature liquid PCM flows to the bottom area. Therefore, the temperature and melting rate of the PCM in the upper area is higher than the temperature and melting rate of the PCM in the bottom area. In the overheating stage, all of the PCM in the thermal storage cell have melted.

3.1 Effects on the latent heat storage time of nano-PCM

Fig. 4 shows the time reduction index (φ) of the total melting time of the latent heat of nano-PCM under the effect of ultrasonic powers and TiO_2 nanoparticle concentrations. The calculation formula of φ is as follows:

$$\varphi=\frac{t'_{2\text{-}7}-t_{2\text{-}7}}{t'_{2\text{-}7}}\times 100\% \qquad (1)$$

In Eq. (1), $t'_{2\text{-}7}$ is the total melting time of the latent heat stage of pure PCM without the effect of ultrasonic and TiO_2 nanoparticles, which is a constant value in this melting experiment (1265.5±25.6 s). $t_{2\text{-}7}$ is the total melting time of the latent heat stage of nano-PCM under the effect of ultrasonic and TiO_2 nanoparticles. φ is positively correlated with the ultrasonic powers and TiO_2 nanoparticle concentrations. The reduction index (φ=46.94%) has amaximum value in latent heat stage with 100 W ultrasonic power and 5.0 wt.% TiO_2 nanoparticle concentration.

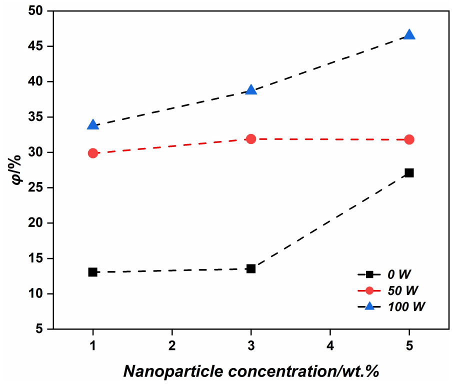

Fig 4 Reduction index(φ) of melting time of nano-PCM under the effect of ultrasonic power and TiO_2 nanoparticle

Choi et al. [10] and Oh et al. [11] have proved that ultrasonic can improve the melting rate and shorten the melting time, mainly due to the acoustic streaming effect and cavitation effect. Acoustic streaming effect makes liquid nano-PCM in a three-dimensional mixing and stirring effect mainly. Therefore, the convective heat transfer is promoted in the melting process. In addition, some tiny air bubbles occurred in the liquid nano-PCM due to the cavitation effect of ultrasonic. These bubbles would be expanded, compressed and grew up until detonated by the effect of the positive and negative pressure periodic alternate of ultrasonic. When the bubbles break, there will form the effects of micro jet, shock waves and instantaneous high temperature. These effects of ultrasonic promote the flow of the liquid nano-PCM and the heat transfer performance get enhanced.

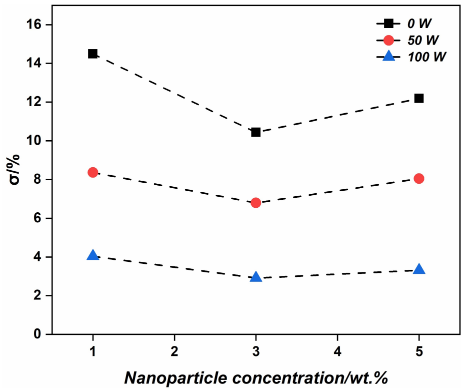

Fig 5 Temperature reduction index(σ) of T_e of nano-PCM under the effect of ultrasonic power and TiO_2 nanoparticle

3.2 Effects on the melting temperature of nano-PCM

Fig. 5 shows the temperature reduction index (σ) of T_e with and without TiO_2 nanoparticles under the ultrasonic power of 0 W, 50 W and 100 W. The calculation formula of σ is as follows:

$$\sigma=\frac{T_e'-T_e''}{T_e'}\times 100\% \quad (2)$$

In Eq. (2), T_e' is the temperature of PCM at point 1 at heating time t=1500s with ultrasonic powers of 0 W, 50 W and 100 W, which are 89.7℃, 82.4℃ and 84.5℃, respectively. T_e'' is the temperature of nano-PCM at point 1 at heating time t=1500s with ultrasonic powers of 0 W, 50 W and 100 W.

As the ultrasonic power is constant and the TiO_2 nanoparticles concentration increases, σ decreases first and then increases. σ decreases with the increasing of ultrasonic power, indicating that higher ultrasonic power leads to higher heat source temperature at t=1500s with a constant TiO_2 nanoparticles concentration. This is mainly because introducing ultrasound is an active heat transfer enhancement method, and part of the energy of ultrasonic is converted into heat energy, which makes the temperature of nano-PCM rise. In addition, the thermal effect may also be related to the ultrasonic power, the higher the ultrasonic power, the greater the heat transformed by the thermal effect. Obviously, it is not good to control the temperature of electronic devices with nano-PCM. Therefore, the relationship between the melting rate of nano-PCM and the heat source temperature needs to be balanced reasonably.

4. CONCLUSIONS

In this study, TiO_2 nanoparticles, copper foam and n-octadecane were composited by vacuum method to prepared nano-PCM. The melting process of nano-PCM was experimentally studied under the effects of different nanoparticle concentrations and ultrasonic powers. The results obtained in this study can be concluded that the ultrasonic and nanoparticles have positive effects on shortening the melting time of nano-PCM. As the ultrasonic power reached 100 W and the nanoparticle concentration reached 5 wt.%, the melting time of nano-PCM was reduced by 46.96%. The extra heat was found in the melting process brought by the heating effect of ultrasound. The heat source temperature was increased with the increasing of ultrasonic power. Therefore, the relationship between the melting rate of nano-PCM and heat source temperature need to be balanced reasonably.

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REFERENCE

[1] Anandan S, Ramalingam V. Thermal management of electronics: A review of literature. Thermal Science. 2008;12:5-26.

[2] Garimella SV. Advances in mesoscale thermal management technologies for microelectronics. Microelectronics Journal. 2006;37:1165-85.

[3] Kandasamy R, Wang X-Q, Mujumdar AS. Application of phase change materials in thermal management of electronics. Applied Thermal Engineering. 2007;27:2822-32.

[4] Fok SC, Shen W, Tan FL. Cooling of portable hand-held electronic devices using phase change materials in finned heat sinks. International Journal of Thermal Sciences. 2010;49:109-17.

[5] Fan L-W, Fang X, Wang X, Zeng Y, Xiao Y-Q, Yu Z-T, et al. Effects of various carbon nanofillers on the thermal conductivity and energy storage properties of paraffin-based nanocomposite phase change materials. Applied Energy. 2013;110:163-72.

[6] Yang L, Huang J-n, Zhou F. Thermophysical properties and applications of nano-enhanced PCMs: An update review. Energy Conversion and Management. 2020;214.

[7] Ho CJ, Gao JY. An experimental study on melting heat transfer of paraffin dispersed with Al2O3 nanoparticles in a vertical enclosure. International Journal of Heat and Mass Transfer. 2013;62:2-8.

[8] Xu Z, Li X, Zhu Z, Wang Q, Chen Y, Ma T. Experimental study on the heat transfer performance of a gallium heat sink. Energy Conversion and Management. 2020;213.

[9] Zheng H, Wang C, Liu Q, Tian Z, Fan X. Thermal performance of copper foam/paraffin composite phase change material. Energy Conversion and Management. 2018;157:372-81.

[10] Choi KJ, Hong JS. Experimental study of enhanced melting process under ultrasonic influence. Journal of Thermophysics and Heat Transfer. 1991;5:340-6.

[11] Oh YK, Park SH, Cho YIJIJoH, Transfer M. A study of the effect of ultrasonic vibrations on phase-change heat transfer. 2002;45:4631-41.