Experimental Study on Phase Change Heat Transfer Characteristics of Paraffin-Filled Metal Foam (Postprint)

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Abstract

This paper presents an experimental study on the phase change heat transfer characteristics of paraffin filled with copper metal foam. By testing the temperature response curves at the heating surface and within the specimen, the influence of metal foam filling and natural convection on the unsteady phase change heat transfer process of paraffin was analyzed. The research results demonstrate that under top heating configuration, heat transfer within the paraffin is dominated by pure conduction, while under bottom heating, natural convection in the liquid paraffin accelerates phase interface migration, improves internal temperature uniformity, and enables temperature control of the heating surface in the phase-change convection region. Metal foam filling enhances thermal conduction within the paraffin but suppresses natural convection in the liquid paraffin; the former mitigates temperature rise at the specimen heating surface and expedites phase interface movement, whereas the latter causes the paraffin' s phase change region to be divided into a phase-change conduction region and a phase-change convection region during bottom heating. The thermal conductivity enhancement capability of metal foam plays a dominant role in the specimen' s heat transfer.

Full Text

Experimental Study on Phase Change Heat Transfer Characteristics of Paraffin Saturated Metal Foam

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Abstract

In this study, the thermal performance of paraffin saturated open-cell metal foam was experimentally investigated by tracking the heated surface and internal temperatures. The effects of metal foam and natural convection on heat transfer in paraffin were discussed. The results showed that heat conduction played a dominant role for the case of top heating. For the case of bottom heating, natural convection in liquid paraffin led to quicker phase change interface movement and more uniform internal temperature. Meanwhile, the temperature of the heated surface was controlled in a small range in the phase change-convection zone. The inclusion of metal foam greatly improved the thermal conductivity of paraffin but suppressed the liquid natural convection. The former resulted in slower temperature rising of the heated surface and quicker phase change interface movement. The latter led to the phase change zone being divided into the phase change-conduction zone and phase change-convection zone for bottom heating. The enhanced heat conduction due to the fill of metal foam played a dominant role in the heat transfer of paraffin.

Keywords: paraffin; metal foam; phase change zone; natural convection

Introduction

With the progressive miniaturization of electronic devices and continuous increase in operating power, thermal management has become one of the major bottlenecks constraining their development. Solid-liquid phase change materials can absorb large amounts of latent heat during melting while maintaining temperature within a narrow range, making them highly valuable for thermal management applications in electronic devices [1-4]. Since electronic devices typically cannot operate at high temperatures, low-temperature organic phase change materials are commonly used for temperature control, offering advantages of high latent heat and stable chemical properties. However, conventional organic phase change materials generally suffer from low thermal conductivity, typically ranging from 0.1 to 0.3 $\mathrm{W \cdot m^{1} \cdot K^{1}}$, which results in slow latent heat absorption/release rates and severely limits their energy conversion efficiency. To address this issue, numerous heat transfer enhancement methods have been developed in recent years to improve the thermal conductivity of phase change materials, such as adding metal fins, graphite or metal porous structures, and high thermal conductivity powders [5].

Huang et al. [6] experimentally investigated the thermal control performance of aluminum fins added to paraffin as a heat sink for solar panels, demonstrating that increasing fin quantity enhanced heat conduction within the paraffin and improved temperature control of the heat sink system, thereby enhancing the battery charging efficiency of solar panels. Lafdi et al. [7, 8] embedded aluminum foam into paraffin to enhance its thermal conductivity, experimentally and numerically studying the effects of foam characteristics and heat sink geometry on cooling performance. Mesalhy et al. [9] investigated the heat transfer characteristics of phase change materials filled in carbon foam, finding that the heated surface temperature was lower for foams with high thermal conductivity and high porosity, as heat could be more effectively transferred away from the heated surface under such conditions. Zhang et al. [10, 11] conducted experimental and numerical studies on heat transfer in phase change microcapsule plates with added high thermal conductivity carbon fibers, showing that carbon fiber addition significantly enhanced heat transfer within the composite plate, accelerated phase interface movement, and improved overall temperature uniformity.

Focusing on the low thermal conductivity limitation of phase change materials, this paper presents an experimental study on the unsteady heat transfer characteristics of paraffin saturated copper foam, analyzing the effects of metal foam filling, heating direction, and heating power on the phase change heat transfer process of paraffin.

1.1 Experimental Apparatus

Commercial paraffin was selected as the phase change material in this experiment, and its latent heat properties were measured using a Differential Scanning Calorimeter (DSC, TA-Q20). The test results for the paraffin are shown in [Figure 1: see original paper], revealing a phase change latent heat of 141.2 J/g, a phase change temperature range of 42.46°C to 59.62°C, and a phase change peak temperature of 49.22°C. Other physical properties provided by the manufacturer are listed in . The metal foam used was copper foam with dimensions of 100 mm × 100 mm × 80 mm, a porosity of 0.98 (the fraction of pore volume to total volume), and a pore density of 10 PPI (pores per inch).

[Figure 2: see original paper] presents a schematic diagram of the experimental setup, which primarily consists of three components: the test section, heating section, and data acquisition section. The schematic of the test section is shown in Figure 3: see original paper. Molten paraffin was injected into the copper metal foam, and after solidification, this composite structure (metal foam + paraffin) was placed in an acrylic square cavity. A 6 mm thick aluminum plate was placed at the bottom of the cavity as the heated surface, with an electric heating film attached above the aluminum plate to provide the heat source, while polyurethane board (thermal conductivity of 0.02 W · m^{1} · K^{1}) was used for insulation beneath the aluminum plate.

In this experiment, the heat flux of the electric heating film was set to 5000 W/m^{2} using a linear power supply. A total of 12 T-type thermocouples were employed to measure temperature variations in the specimen, with five thermocouples measuring the heated surface temperature in the arrangement shown in Figure 3: see original paper. During data processing, the heated surface temperature was taken as the average of these five points. The remaining seven thermocouples measured internal temperatures of the specimen. To facilitate internal temperature measurement, a through-hole with a diameter of 3 mm was drilled at the center of the specimen, and thermocouples were placed at 10 mm intervals starting from the heated surface, totaling seven measurement points as shown in Figure 3: see original paper. Thermocouple data were recorded every 5 minutes during the experiment using a Keithley 2700 data acquisition system. Experimental measurement errors primarily included thermocouple measurement error (0.1°C), linear power supply error (1.22%), and electric heating film power error (5%).

1.2 Experimental Conditions

To analyze the effect of metal foam on the paraffin melting process, experiments were conducted comparing pure paraffin cases with metal foam-filled paraffin cases. Additionally, to investigate the influence of natural convection after paraffin melting, both bottom heating and top heating configurations were considered, with the top heating configuration achieved by inverting the test section shown in Figure 3: see original paper. The four experimental conditions are summarized in . The initial temperature and ambient temperature were both 25°C for all cases, and each case was heated until the paraffin was completely melted. To prevent the heated surface temperature from exceeding the temperature limit of the electric heating film, the experimental duration for the pure paraffin top heating case (C1) was limited to 60 minutes.

2.1 Phase Interface Movement Characteristics

In this experiment, two methods were employed to record the phase interface movement during paraffin melting. The first method determined the phase interface location when the temperature measured by a particular thermocouple reached the phase change peak temperature of 49.22°C. The second method used a digital camera to capture visualization images of the phase interface during melting, with a scale employed to obtain the actual interface position. [Figure 4: see original paper] shows the phase interface variation over time for cases C2 and C3 obtained using both methods, demonstrating good agreement between the two approaches and validating the temperature measurement method for tracking the phase interface.

Figure 5: see original paper presents the phase interface variation curves for all cases based on thermocouple measurements. The results indicate that the phase interface moved slowest for the pure paraffin top heating case (C1), due to weak natural convection heat transfer after paraffin melting in the top heating configuration. In contrast, the phase interface moved significantly faster for the pure paraffin bottom heating case (C2), demonstrating that natural convection in liquid paraffin substantially enhanced internal heat transfer and accelerated phase interface movement. Similarly, the phase interface moved faster for the metal foam-filled paraffin bottom heating case (C4) compared to the foam-filled paraffin top heating case (C3). The visualization images in Figure 5: see original paper and (d) also reflect that the phase interface moved faster in case C4 than

in case C3, with the interface in case C4 being less planar than in case C3 due to the disturbance of natural convection in liquid paraffin caused by metal foam filling. Comparing top heating cases C1 and C3 or bottom heating cases C2 and C4 in Figure 5: see original paper reveals that metal foam filling significantly increased the phase interface movement speed compared to pure paraffin cases, as the foam enhanced thermal conduction within the paraffin. Overall, the phase interface movement speeds from slowest to fastest were: C1, C3, C2, and C4.

Furthermore, Figure 5: see original paper shows that the phase change initiation time was 10 minutes for both pure paraffin cases C1 and C2, while it was delayed to 20 minutes for the metal foam-filled cases C3 and C4. This resulted in the phase interface position for case C2 being significantly higher than that for case C4 during the early phase change period ($t < 70$ min), as shown in Figure 5: see original paper and (d), despite the slower interface movement speed of case C2 compared to case C4.

2.2 Heated Surface Temperature Response Characteristics

[Figure 6: see original paper] shows the heated surface temperature variation curves over time for all cases. Beginning with the two top heating cases C1 and C3, the heated surface temperature increased nearly linearly in both configurations because natural convection in the melted paraffin was weak, making heat conduction the dominant heat transfer mechanism. As indicated in Figure 5: see original paper, the paraffin phase change initiation points were 10 minutes and 20 minutes for cases C1 and C3, respectively. Correspondingly, [Figure 6: see original paper] shows that from these phase change initiation points onward, the temperature rise rates for both cases C1 and C3 slowed due to latent heat absorption during paraffin melting. Moreover, the temperature rise rate for the metal foam-filled paraffin case C3 was significantly slower than that for the pure paraffin case C1, because metal foam filling enhanced internal heat conduction, allowing heat near the heated surface to be promptly transferred into the specimen interior. Consequently, the temperature rise was relatively slower, with the heated surface temperature of case C3 being 110°C lower than that of case C1 at the 60-minute mark.

Analyzing the pure paraffin bottom heating case C2, the heated surface temperature variation can be divided into three stages: solid region, phase change-convection region, and liquid region. In the solid region (0–10 min), heat transfer within the specimen was dominated by conduction, resulting in a temperature curve that almost completely coincided with that of the pure paraffin top heating case C1. In the phase change-convection region (10–100 min), the temperature curves for cases C2 and C1 began to diverge, with the temperature rise rate for bottom heating case C2 significantly slowing thereafter. This occurred because, for bottom heating case C2, natural convection dominated heat transfer in the liquid paraffin after melting, while latent heat absorption during paraffin melting further reduced the heated surface temperature rise rate. The combined effect resulted in a very slow temperature rise (80–90°C) for case C2 in the phase change-convection region, demonstrating obvious temperature control characteristics. After the phase change material was completely melted, case C2 entered the liquid region, where the heat transfer at the heated surface was solely by sensible heat absorption, causing the temperature rise rate to increase again.

Examining the metal foam-filled paraffin bottom heating case C4, the temperature curve coincided with the top heating case C3 in the solid region (0–20 min). In the phase change region (20–90 min), unlike the divergence observed between pure paraffin cases C2 and C1, the temperature curves for foam-filled cases C4 and C3 remained coincident during the early phase change period (20–45 min) and only began to gradually separate during the later phase change period (45–90 min). This phenomenon occurred because metal foam filling suppressed natural convection in the melted paraffin. Consequently, the phase change region for case C4 could be further subdivided into a phase change-conduction region (20–45 min) and a phase change-convection region (45–90 min). In the phase change-conduction region, heat transfer within the specimen remained conduction-dominated, while in the phase change-convection region, natural convection dominated as more liquid paraffin accumulated, with the specimen heated surface exhibiting obvious temperature control characteristics (73–77°C) during this stage. After the paraffin was completely melted, heat transfer entered the liquid region. In summary, the heated surface temperature response for metal foam-filled paraffin bottom heating case C4 could be divided into four regions: solid region, phase change-conduction region, phase change-convection region, and liquid region.

Additionally, comparing bottom heating cases C2 and C4 reveals that the temperature for foam-filled case C4 was significantly lower than that for pure paraffin case C2 at any given moment, indicating that despite metal foam filling suppressing natural convection heat transfer in liquid paraffin, the enhanced conduction through the foam skeleton remained dominant. This also resulted in a noticeably shorter temperature control duration for case C4 (45–90 min, i.e., the phase change-convection region) compared to case C2 (10–100 min).

2.3 Internal Temperature Response Characteristics

[Figure 7: see original paper] shows the internal temperature variation curves for cases C1 and C3 under top heating. Due to weak natural convection after paraffin melting in the top heating configuration, the internal temperature curves for both cases exhibited essentially linear growth. For pure paraffin case C1, the temperature difference between points near the heated surface ($y/H = 0$) was significantly larger than that between points near the back surface ($y/H = 0.75$) at any given moment. This resulted from the extremely low thermal conductivity of paraffin (see), which caused heat accumulation at the heated surface and thus a large temperature gradient, while minimal heat transfer to the back surface produced a small temperature gradient there. In contrast, Figure 7: see original paper shows that the temperature differences between internal points were essentially uniform for metal foam-filled case C3, as the high thermal conductivity of the metal foam substantially improved heat conduction within the paraffin, resulting in a more uniform internal temperature field distribution.

[Figure 8: see original paper] presents the internal temperature variation curves for cases C2 and C4 under bottom heating. Compared to the top heating cases ([Figure 7: see original paper]), the natural convection phenomenon in the liquid phase was stronger for bottom heating, leading to more uniform internal temperature distribution. Comparing Figure 8: see original paper and (b) reveals that after filling the paraffin with metal foam, the high thermal conductivity of the foam improved temperature uniformity within the paraffin, resulting in relatively smaller temperature differences between various points.

Conclusions

This study experimentally investigated the phase change heat transfer characteristics of paraffin saturated metal foam, analyzing the effects of metal foam filling and natural convection on the unsteady temperature response and phase interface movement features. The main conclusions are as follows:

(1) With top heating, heat transfer within the paraffin was dominated by pure conduction, resulting in a linear temperature increase trend. With bottom heating, natural convection in liquid paraffin caused slower heated surface temperature rise, faster phase interface movement, and better internal temperature uniformity.

(2) Metal foam filling enhanced conduction within the paraffin, delayed the phase change initiation time, reduced the heated surface temperature, accelerated phase interface movement, and improved internal temperature uniformity. Particularly for bottom heating, metal foam filling suppressed natural convection in liquid paraffin, causing the phase change zone to decompose into phase change-conduction and phase change-convection sub-zones, whereas pure paraffin cases only exhibited a phase change-convection zone. However, the conduction enhancement provided by metal foam remained dominant over its suppression of natural convection in the overall heat transfer of the specimen.

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Note: Figure translations are in progress. See original paper for figures.