Effect of Superhydrophobic and Superhydrophilic Surfaces on Pulsating Heat Pipe Performance: Postprint

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Abstract

This experimental study investigates the performance of fully superhydrophobic pulsating heat pipes and composite-surface pulsating heat pipes featuring a superhydrophilic evaporator section and superhydrophobic condenser and adiabatic sections. Superhydrophobic surfaces exhibit low free energy, small contact angle hysteresis, and facile droplet mobility. Experimental findings reveal that, in contrast to the concave vapor-liquid interface observed in copper pulsating heat pipes, superhydrophobic surfaces exhibit a convex vapor-liquid interface. The vapor-liquid interface length in composite-surface pulsating heat pipes is significantly greater than that in fully superhydrophobic pulsating heat pipes. Compared with copper pulsating heat pipes, the amplitude of liquid slug pulsation increases in composite pulsating heat pipes, whereas fully superhydrophobic pulsating heat pipes exhibit partial dry-out in the evaporator section and a significant reduction in liquid slug pulsation amplitude.

Full Text

Experimental Investigation of the Effects of Superhydrophobic and Superhydrophilic Surfaces on Pulsating Heat Pipe Performance

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Abstract

This study experimentally investigates the performance of pulsating heat pipes (PHPs) with entirely superhydrophobic surfaces and hybrid surfaces where the evaporation section is superhydrophilic while the condensation and adiabatic sections are superhydrophobic. Superhydrophobic surfaces exhibit low surface free energy and small contact angle hysteresis, facilitating droplet mobility. Experimental observations reveal that, unlike the concave vapor-liquid interface in copper PHPs, superhydrophobic surfaces produce a convex vapor-liquid interface. The vapor-liquid interface length in hybrid-surface PHPs is significantly greater than that in uniformly superhydrophobic PHPs. Compared with copper PHPs, hybrid PHPs exhibit increased oscillation amplitudes of liquid slugs, whereas uniformly superhydrophobic PHPs experience partial dryout in the evaporation section, leading to substantially reduced oscillation amplitudes.

Keywords: pulsating heat pipe; superhydrophobic surface; superhydrophilic surface; oscillating motion

1. Introduction

Pulsating heat pipes lack the traditional wick structure of conventional heat pipes and consist of capillary tubes or multiple U-shaped channels that incorporate evaporation and condensation processes. The pressure differential induced by temperature gradients between the evaporation and condensation sections drives the oscillatory motion of liquid slugs. Heat transfer in PHPs occurs primarily through sensible heat transfer from liquid slug pulsation, making them a promising solution for high heat flux dissipation applications.

Research on the influence of surface wettability on PHP performance remains limited. Ji et al. [?] found that superhydrophilic PHPs demonstrate superior heat transfer performance compared to copper PHPs. Unlike conventional wick-structured heat pipes, superhydrophobic PHPs can operate but exhibit significantly increased thermal resistance compared to hydrophilic PHPs [?]. Hao et al. [?] conducted visualization studies showing that superhydrophilic PHPs produce more vigorous liquid slug oscillations than copper PHPs, with a liquid film deposited on the wall surface at the tail of the liquid slug during oscillation, thereby enhancing heat transfer performance. Fumoto et al. [?] investigated PHPs using self-rewetting fluids and found that the enhanced evaporation section heat transfer improved overall PHP performance and reduced thermal resistance.

Superhydrophobic surfaces exhibit small contact angle hysteresis, enabling facile droplet motion. Rothstein [?] demonstrated that superhydrophobic surfaces can reduce flow drag in both laminar and turbulent flow regimes. Studies on laminar flow pressure drop in microchannels revealed that superhydrophobic microchannels achieve up to 40% reduction in pressure drop [?]. Aljallis et al. [?] measured wall friction in high Reynolds number boundary layer flows, showing that superhydrophobic surfaces significantly reduce drag. Khandekar et al. [?] concluded that PHPs should employ surfaces with small hysteresis angles to minimize capillary resistance during liquid slug motion. Qu et al. [?]

found that contact angle hysteresis adversely affects liquid slug motion and can be mitigated by modifying capillary materials, working fluids, and filling ratios. Liu et al. [**?**] observed that superhydrophilic surfaces facilitate bubble nucleation and increase bubble generation.

Surface wettability substantially influences fluid flow, evaporation, and condensation. Chen et al. [**?**] found that nanowire-structured superhydrophilic surfaces increased the heat transfer coefficient and critical heat flux by 100% in pool boiling experiments. Phan et al. [**?**] experimentally demonstrated that among surfaces with contact angles below 30°, superhydrophilic surfaces with contact angles near 0° yielded the highest nucleate boiling heat transfer coefficients.

Current research on surface wettability effects in PHPs has focused exclusively on single-wettability surfaces. This study investigates partially superhydrophobic and superhydrophilic PHP surfaces, examining the evolution of the local three-phase contact line of liquid slugs and analyzing the operating mechanisms of superhydrophobic and hybrid superhydrophobic-superhydrophilic PHPs through observations of liquid slug oscillation patterns and heat transfer performance.

2. Experimental Setup

2.1 Apparatus

The experimental apparatus consists of a copper plate PHP, heating system, cooling water circulation system, data acquisition system, and high-speed camera, as shown in Figure 1 [Figure 1: see original paper]. Square channels with a cross-section of 2\$×2*mm*^{2}\$ were machined into a copper plate (130\$×80×10*mm*^{3}\$). Figure 2 [Figure 2: see original paper] shows a photograph of the plate-type PHP. The copper plate was sealed with a transparent polycarbonate (PC) cover plate using bolts, with a silicone gasket providing sealing. The heating power was controlled by a DC power supply and measured using the volt-ampere method. The output power was calculated from the cooling water inlet/outlet temperatures and flow rate.

The PHP contained four bends with total heat transfer length of 106 mm, comprising evaporation, adiabatic, and condensation sections measuring 28 mm, 42 mm, and 36 mm, respectively. Six thermocouple holes (1.5 mm diameter) were drilled on each side of the PHP, with temperature measurement points located 2 mm from the channel wall. Two additional thermocouples measured cooling water inlet and outlet temperatures. Each section (evaporation, adiabatic, and condensation) contained four temperature measurement points.

High-speed photography captured liquid slug oscillation images at 100 fps with a resolution of 1024\$×1024*pixels*, *coveringa*40×40*mm*^{2}\$ field of view (0.04 mm/pixel resolution). The measurement error for oscillation amplitude during image processing was \$±\$0.04 mm.

2.2 Surface Preparation

Copper PHP surfaces were cleaned with dilute sulfuric acid and detergent to remove oxides and oil, yielding a contact angle of 73.4°. Superhydrophilic surfaces were prepared by etching copper plates for 30 minutes at 70°C in a solution of 2.5 mol/L potassium hydroxide (KOH) and 0.065 mol/L potassium persulfate ($K_2S_2O_8$), forming a CuO coating. After rinsing with deionized water, the plates were heated at 180°C for 30 minutes. Droplets spread rapidly on the superhydrophilic surface with a contact angle of approximately 0°.

Superhydrophobic surfaces were fabricated using a potassium persulfate oxidation chemical etching method to create micro/nano hierarchical structures on copper plates, followed by octadecylthiol self-assembly [**?**]. The superhydrophilic CuO-coated surfaces were immersed in 0.0025 mol/L octadecylthiol solution for 30 minutes at 70°C, rinsed with ethanol, and dried, resulting in a contact angle of 155.5°.

Static contact angle images and scanning electron microscopy images of the three surfaces are shown in Figure 3 [Figure 3: see original paper] and Figure 4 [Figure 4: see original paper]. Both superhydrophilic and superhydrophobic surfaces formed micron-scale CuO cluster structures.

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3. Experimental Results and Discussion

3.1 Flow Patterns and Interface Characteristics

Figure 5 [Figure 5: see original paper] shows the flow patterns in the evaporation section during PHP operation at 60 W heating power. In copper and hybrid-surface PHPs, small bubbles formed in the evaporation section, expanded rapidly, and pushed adjacent liquid slugs toward the condensation section. Under gravity, liquid slugs returned to the evaporation section, compressing vapor plugs. This cyclic expansion and compression of vapor plugs drove liquid slug oscillation. In contrast, superhydrophobic PHPs exhibited no vapor plug expansion during startup; instead, the evaporation section experienced partial dryout with nucleate boiling of the liquid.

Figure 7 [Figure 7: see original paper] illustrates that copper PHPs exhibit concave vapor-liquid interfaces, whereas hybrid and uniformly superhydrophobic PHPs show convex interfaces. The maximum vapor-liquid interface lengths were 16.76 mm, 25.91 mm, and 16.38 mm for copper, hybrid, and superhydrophobic PHPs, respectively. The hybrid-surface PHP exhibited significantly longer vapor-liquid interfaces than the uniformly superhydrophobic PHP.

3.2 Liquid Slug Oscillation Characteristics

Figure 6 [Figure 6: see original paper] shows the temporal variation of liquid slug position and vapor-liquid interface length at 90 W heating power, with corresponding visualization images in Figure 7 [Figure 7: see original paper]. The average oscillation amplitudes were 5.86 mm, 8.35 mm, and 3.24 mm for copper, hybrid, and superhydrophobic PHPs, respectively, with maximum amplitudes of 12.97 mm, 18.12 mm, and 7.34 mm. Similar trends were observed at other heating powers. At 105 W, the average amplitudes were 7.03 mm, 7.21 mm, and 7.22 mm, with maximum amplitudes of 15.75 mm, 17.08 mm, and 14.33 mm.

3.3 Heat Transfer Performance

The hybrid PHP with a superhydrophilic evaporation section and superhydrophobic adiabatic/condensation sections demonstrated superior heat transfer performance compared to conventional copper PHPs. This improvement is attributed to two factors: (1) the superhydrophobic sections exhibited a hysteresis angle of only 2°, reducing flow resistance and facilitating liquid slug motion [**?**, **?**]; and (2) the superhydrophilic evaporation section enhanced thin-film evaporation. On superhydrophilic surfaces, a liquid film exists between the vapor phase and wall, significantly increasing film evaporation heat transfer coefficients [**?**].

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4. Conclusions

This study investigated the vapor-liquid interface shape and liquid slug oscillation behavior in three PHPs with different surface wettabilities under steady-state operation:

1. During startup, uniformly superhydrophobic PHPs exhibited no vapor plug expansion/compression in the evaporation section. Instead, nucleate boiling occurred with incomplete wetting, leading to dry spots. Copper surfaces produced concave vapor-liquid interfaces, while superhydrophobic surfaces yielded convex interfaces.
2. Hybrid-surface PHPs demonstrated larger liquid slug oscillation amplitudes than copper PHPs. In contrast, uniformly superhydrophobic PHPs showed significantly reduced amplitudes due to dry spots in the evaporation section.

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