Experimental Study on Heat Transfer Characteristics of Pulsating Heat Pipes with Different Working Fluids: Postprint

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Abstract

This study experimentally investigates the influence of working fluid type and filling ratio on the heat transfer characteristics of vertical pulsating heat pipes. Three liquids—deionized water, methanol, and ethanol—were employed as working fluids, with heating power varying from 5 to 80 W. The results demonstrate that the heat transfer characteristics of pulsating heat pipes are strongly dependent on the filling ratio. At a deionized water filling ratio of 50%, stable vapor plug and liquid slug flow can be established within the pulsating heat pipe, yielding optimal heat transfer performance; the minimum thermal resistance achieved is 0.47 K/W at a heating power of 80 W. At lower heating powers, both ethanol and deionized water exhibit lower thermal resistance than methanol. As heating power increases, the temperature rise in the heating section shows violent fluctuations with methanol, whereas the temperature rise remains relatively smooth with deionized water and ethanol, indicating superior heat transfer performance. The minimum thermal resistances obtained with methanol and ethanol as working fluids are 0.56 K/W and 0.48 K/W, respectively, at a heating power of 80 W.

Full Text

An Experimental Study on Thermal Performance of Pulsating Heat Pipe with Different Working Fluids

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Abstract

An experimental investigation was conducted to study the thermal performance of pulsating heat pipe (PHP) with different working fluids. Deionized water, methanol and ethanol were used in this study at varying thermal loads ranging from 5 W to 80 W. Experimental results showed that the heat transfer capability of the tested PHP was highly dependent on the filling ratios of the working fluids. At a 50% filling ratio, a stable gas-liquid slug flow can be generated and the PHP had the best performance: a minimum thermal resistance of 0.47 K/W at 80 W thermal load was obtained. At low thermal loads, the PHP with ethanol and deionized water had lower thermal resistance than with methanol. With the increase of thermal load, strong fluctuations of temperature increase at the heating section appeared when using methanol as working fluid, while the temperature was increased gently with a better heat transfer performance when using deionized water or ethanol. The obtained minimum thermal resistances for the cases using methanol and ethanol were 0.56 K/W and 0.48 K/W, respectively, at 80 W thermal load.

Keywords: Pulsating heat pipe, working fluids, thermal resistance, experimental investigation

Introduction

Pulsating heat pipe (PHP) is a novel heat transfer device proposed by Akachi in the 1990s, which has broad application prospects in solar cells, fuel cells, electronic chip cooling, and hybrid electric vehicles. PHPs offer significant advantages for high-heat-flux integrated cooling, and numerous experimental studies have been conducted by researchers. However, the operating mechanism of PHPs is extremely complex, involving multiple influencing factors. To achieve optimal operation, extensive research is still needed to fully understand their operating mechanisms and heat transfer phenomena.

Compared with conventional heat pipes, numerous studies have demonstrated that PHPs can achieve integrated cooling under high heat flux conditions. Their heat transfer characteristics depend on the dynamic features and phase change processes of the working fluid, with primary influencing factors including the working fluid, filling ratio, heating power, inclination angle, and number of turns. Generally, PHPs require sufficiently small tube diameters. Before heating, the tube is partially filled with working fluid and maintained under vacuum conditions. This configuration facilitates capillary action during heating, and due to the non-uniform distribution of gas and liquid phases in parallel tubes, pulsating flow of liquid slugs and vapor plugs forms between the heating and cooling sections. During this pulsating process, heat is transferred from the heating section to the cooling section through vaporization latent heat and sensible heat of the thermal fluid.

Zhang and Faghri proposed the fundamental working principle of PHPs and analyzed the effects of working fluid type, filling ratio, and tube inclination angle on the thermal-fluid motion and heat transfer characteristics within the device. Research has shown that thermophysical properties of working fluids—including surface tension, wettability, viscosity, and thermal conductivity—are crucial to PHP thermal performance. Several scholars have investigated the effects of different working fluids or fluid mixtures on PHP performance. Wang et al. found that water as a working fluid yielded better results than ethanol or R141b. Cui et al. used mixtures of methanol with deionized water, acetone, and ethanol as working fluids and discovered that PHP heat transfer characteristics correlated with the thermophysical properties of the working fluids. Sarangi and Rane' s experiments indicated that the startup heating power of PHPs was independent of filling ratio, while the maximum heating power was closely related to it. Tseng et al. employed deionized water, methanol, and HFE-7100 as working fluids and found that vertically oriented PHPs exhibited lower thermal resistance than horizontally oriented ones, with deionized water showing the smallest thermal resistance.

Despite extensive experimental research on PHP operating characteristics, PHP operation in practice exhibits certain complexities and randomness. Currently, the operating mechanism of PHPs is not fully understood, and comprehensive theoretical models to guide application design are lacking. To explore optimal operating conditions for PHPs, this study focuses on the operating characteristics of PHPs with different working fluids.

1. Experimental System

This experiment employed a closed-loop PHP with 8 bends, constructed from copper tubes with an inner diameter of 2 mm and wall thickness of 0.5 mm. Since bubble formation is a prerequisite for PHP operation and is closely related to surface tension and buoyancy of the working fluid, Akachi et al. noted that the tube diameter d should satisfy certain conditions.

[Figure 1: see original paper] shows the structural schematic of the PHP used in this experiment. The PHP was placed vertically, consisting of three sections: a bottom heating section (6 cm), a middle adiabatic section (4 cm), and a top condensing section (8 cm).

The overall experimental system, illustrated in [Figure 2: see original paper], comprised the PHP, heating and cooling systems, filling and vacuum system, and temperature measurement and data acquisition system. For the heating section, thermally conductive insulating silica gel was first applied to the copper tube wall, followed by wrapping with 0.1 mm nichrome wire through which direct current was passed for heating. Both the heating and adiabatic sections were insulated with foam material to block heat transfer with the environment. The condensing section was directly exposed to indoor ambient conditions and cooled by a 25 W DC fan (220V-50Hz). Thermocouples (Type K, ±0.1°C, 10 total) were placed at the heating section, adiabatic section, condensing section, and external locations, with temperatures recorded by a multi-channel data acquisition system (LR8402-21).

During experimental preparation, a vacuum pump was used to evacuate the tube to an absolute pressure of approximately 10 kPa. Subsequently, filling fluid was injected into the tube using a syringe until the desired filling ratio was reached, at which point the tube was sealed. During operation, the switch connecting the DC power supply to the nichrome wire was turned on, and heating power was increased in a stepwise manner.

The heat transfer characteristics of the PHP were primarily represented by thermal resistance, defined as:

$$R = \frac{T_e - T_c}{Q}$$

where T_e and T_c are the average temperatures of the heating and cooling sections, respectively, R is the thermal resistance of the PHP (reflecting the resistance to heat removal from the heating section), and Q is the heating power.

[Figure 3: see original paper] presents the variation of PHP thermal resistance with time after heating begins. The results indicate that the PHP reaches stable operation after 60 seconds, allowing the use of average temperatures after 60 seconds to calculate thermal resistance. Therefore, in subsequent experiments, each operating condition was maintained for 120 seconds, with data acquisition at 1 Hz for 30 minutes. Heating power was increased from 0 W to 80 W in 5 W increments every 2 minutes.

Using this experimental system, this study investigated the effects of different working fluids, filling ratios, and heating powers on PHP heat transfer characteristics. Due to system limitations, the maximum heating power was 80 W. To prevent excessive temperatures, experiments were immediately stopped when a sharp temperature surge occurred at the heating section.

The working fluids used were deionized water, methanol, and ethanol. The heat transfer characteristics of the PHP were measured at deionized water filling ratios of 20%, 35%, 50%, 65%, and 80%, as well as at 50% filling ratio for methanol and ethanol. provides the thermophysical properties of each working fluid. For reference, heat transfer characteristics were also measured at filling ratios of 0% and 100%. At 0% filling ratio, heat transfer relied solely on tube wall conduction, while at 100% filling ratio, heat transfer depended on buoyancy-driven single-phase fluid flow, both resulting in relatively high thermal resistance.

2. Results and Discussion

[Figure 4: see original paper] shows the variation of heating section temperature with time for different deionized water filling ratios. The results demonstrate that at filling ratios of 25%, 65%, and 80%, the heating section temperature increased sharply due to insufficient pulsating flow, resulting in poor heat transfer. At 25% filling ratio, dry-out occurred after 24 minutes of heating, after which temperature rose sharply. At 80% filling ratio, the temperature was significantly higher than other filling ratios after 10 minutes of heating, followed by fluctuations indicating the onset of single-phase pulsation; however, with continued heating, temperature increased sharply. At 65% filling ratio, pulsating flow lasted slightly longer than at 80%, but after 22 minutes of heating, the heating section temperature also rose sharply. In contrast, at filling ratios of 35% and 50%, the PHP could operate continuously until the end of the experiment. However, compared with the 50% filling ratio case, the 35% filling ratio case exhibited intense oscillations during the initial pulsating flow stage, which was not conducive to heat dissipation. Therefore, it can be concluded that the PHP performed optimally at a deionized water filling ratio of 50%.

[Figure 5: see original paper] presents the PHP thermal resistance at different heating powers and deionized water filling ratios. The results show that higher filling ratios resulted in larger thermal resistance, making bubble formation difficult—a prerequisite for pulsating flow—and hindering heat transfer from the heating section to the cooling section, resulting in poor performance. Lower filling ratios could improve heat transfer characteristics at higher heating powers, achieving thermal resistance similar to the 50% case (approximately 0.47 K/W). However, due to the smaller liquid quantity, the vaporization latent heat and heat carried by the liquid were insufficient, also leading to poor heat transfer characteristics. At 80 W heating power, the PHP exhibited minimum thermal resistance at a deionized water filling ratio of 50%, indicating that stable pulsating flow formed when the tube was half-filled, yielding optimal heat transfer.

To investigate the effect of working fluid on PHP heat transfer characteristics, the performance of different fluids—including methanol, ethanol, and deionized water—was compared at a 50% filling ratio. [Figure 6: see original paper] shows the variation of heating section temperature with time for each working fluid. The results reveal different temperature evolution processes among the three fluids. In the initial stage, heat transfer relied primarily on liquid conduction. Since λ_l(deionized water) $>$ λ_l(methanol) $>$ λ_l(ethanol), the heating section temperature increased slowest for deionized water, followed by methanol, and fastest for ethanol. After heating continued for a certain period, the temperature growth rate decreased sharply, which can be considered an indicator of phase change initiation or PHP startup, at which point vaporization latent heat became effective. After PHP startup, for methanol and ethanol, the heating section temperature rose sharply and then dropped sharply, with methanol even showing random fluctuations, reflecting rapid bubble generation and dissolution. For deionized water, the heating section temperature increased more slowly, indicating stable pulsating flow formation that was maintained for an extended period.

[Figure 7: see original paper] shows the variation of PHP thermal resistance with heating power for different working fluids. The results indicate different performance characteristics at various stages. At low heating powers, pulsating flow triggered by phase change had not yet occurred, resulting in relatively high thermal resistance for all three fluids, with deionized water showing the lowest resistance, followed by ethanol, and methanol the highest. As heating power increased, phase change occurred and pulsating flow formed, causing thermal resistance to decrease significantly for all three fluids, enabling rapid heat removal from the heating section. As heating power increased from 0 W to 80 W, thermal resistance decreased from 2.03 K/W to 0.47 K/W for deionized water, from 2.55 K/W to 0.48 K/W for ethanol, and from 3.30 K/W to 0.51 K/W for methanol. Methanol exhibited the largest initial thermal resistance. Therefore, at a 50% filling ratio, ethanol demonstrated better heat transfer characteristics than methanol, and deionized water performed better than ethanol.

3. Conclusions

This study experimentally investigated the heat transfer characteristics of PHPs using different working fluids and filling ratios. The evolution of heating and cooling section temperatures under different heating powers was measured, and the thermal resistance of the PHP under each condition was obtained. The following conclusions can be drawn:

(1) Regarding the effect of filling ratio on heat transfer characteristics, the results show that the PHP exhibited minimum thermal resistance at a deionized water filling ratio of 50%. Under this condition, stable gas-liquid slug flow formed within the tube, and vaporization latent heat combined with sensible heat carried by liquid flow enhanced PHP heat transfer performance.

(2) Regarding the effect of working fluid on heat transfer characteristics, the results demonstrate that at low heating powers, ethanol and deionized water yielded lower thermal resistance than methanol, with more gradual temperature increase at the heating section. As heating power increased, temperature rise at the heating section fluctuated violently when using methanol, indicating that stable gas-liquid slug flow was not formed, preventing effective heat transfer from the heating section to the cooling section. In contrast, deionized water and ethanol provided better heat transfer performance.

In summary, this study only investigated three working fluids. To obtain optimal operating parameters for PHPs and understand their operating mechanisms, further research on additional working fluids and experimental parameters is required.

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