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Effects of hydrophilic surface on heat transfer performance and oscillating motion for an oscillating heat pipe

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ABSTRACT

In this paper, a series of experiments were performed to investigate the effects of superhydrophilic and hydrophilic surfaces on the heat transfer performance and slug motion for oscillating heat pipes (OHPs). Deionized water was used as the working fluid. The surfaces of the OHPs were copper, superhydrophilic, hydrophilic and hydrophobic surfaces with contact angles of 73.4°, 0°, 12.9° and 141.5°, respectively. The heat transfer performance in six-turn OHPs was higher than in four-turn OHPs. Experimental results showed that the surface wettability remarkably influenced the slug motion and thermal performance of OHPs. The liquid slug movements became stronger both in superhydrophilic and hydrophilic OHPs as opposed to the copper OHP, while the global heat transfer performance of the superhydrophilic and hydrophilic OHPs increased in the six-turn OHP. For six-turn OHPs, the maximum displacement of the liquid slug in the hydrophilic OHPs and superhydrophilic OHPs increased by 5–60% and 25–60%, respectively, in comparison with that of copper OHPs. The heat transfer performance of superhydrophilic OHPs and hydrophilic OHPs increased by 5–15% and 15–25%, respectively, in comparison with that of copper OHPs. The hydrophilic surface improved the heat transport capability of OHPs, and the maximum displacement and velocity of the liquid slug increased. The startup temperature of the four-turn and six-turn OHPs varied from 45 to 55 °C and 35 to 45 °C, respectively. The startup temperature of the four-turn and six-turn superhydrophilic OHPs varied from 40 to 55 °C and from 35 to 50 °C, respectively. The startup temperature of the four-turn and six-turn hydrophilic OHPs varied from 40 to 50 °C and from 30 to 40 °C, respectively. The hydrophilic OHP also showed a better startup performance than the copper OHP. At heat input of 150 W, the thermal resistance for the four-turn hydrophobic OHPs was about two times greater than that of copper OHPs. The global heat transfer performance of the superhydrophilic OHP for the four-turn OHP was lower than that of the four-turn OHPs with hydrophilic and pure copper OHPs.

1. Introduction

The OHP is a promising technology for dissipating high grade heat and has a wide variety of applications. The considerable interest in such a heat pipe is due to its simple structure and high heat transfer performance. Therefore, extensive experimental investigations and theoretical analyses have been carried out to study the influence factors of OHPs. Qu and Ma [1] found that using a rougher surface could improve the startup performance of OHPs. Tong et al. [2], Khandekar et al. [3], Lin et al. [4] and Ma et al. [5] studied the operating mechanism and slug oscillating motions of OHPs through the images recorded by a high-speed camera. It was found that more bubbles emerged and grew up in the sharp corner, and the growth rate of bubbles increased with heat input. The liquid slug displacement, velocity, and frequency all increased with heat input. Also, Fumoto et al. [6] found that the self-rewetting fluid improved heat transfer characteristics in the evaporation section. Qu et al. [7] found that the thin liquid heat transfer area in the OHP's wetting surface was higher than that of a partial wetting surface, and the heat transfer coefficient decreased for the non-wetting surface compared with the wetting surface. Dobson and Swanepoel [8] found that a significant portion of the inside surface of OHP was covered by a thin layer of liquid. Song and Xu [9] found that OHPs with four, six, and nine turns may not work at the exact horizontal position. However, the three OHPs could operate at slight inclination angles. The heat transfer performance of OHPs increased with an increase in the number of turns, and the heat performance was generally better in the vertical heating mode. Xian et al. [10] studied the effect of working fluid on the heat transfer characteristics of oscillating heat pipe (OHP). It was found that the OHP with water as a working fluid showed a better

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performance and more stable heat transfer characteristics than the OHP with ethanol as a working fluid. Khandekar et al. [11] investigated the influence of filling ratio and heat mode on heat transfer performance of OHP. The slug pulsating action was observed in the filling ratio range of 25–65% depending on the working fluid. The OHP with small number of turns could not operate in a horizontal mode. Thompson et al. [12–15] studied the effect of operating mode, heat conditions, working fluid and high-gravity on the thermal performance of the three-dimensional flat-plate oscillating heat pipe (3D FP-OHP). It was found that the OHP operating in its bottom heating mode provided better heat transfer performance than when operating in its side heating mode. The reduction in heating area decreased the thermal performance and using water as the working fluid provided the lowest thermal resistance. The 3D FP-OHP could operate in any orientation with respect to gravity. Charoensawan and Terdtoon [16] found that the thermal performance of an OHP improved by increasing the evaporator temperature decreasing the evaporator/effective length and increasing the turn number. Ji et al. [17] found that the oscillating motion in an OHP with a superhydrophobic surface could be generated, and the OHP could function well which is very different from the conventional wicked heat pipe; however, the thermal resistance of the OHP with the superhydrophobic surface was larger than that with the hydrophilic inner surface. Lin et al. [18] investigated the effective range of OHPs with four turns and found that the inner diameter should be higher than 0.8 mm with the working fluid of water in a vertical heating mode. Chien et al. [19] investigated the thermal performance of OHP with a non-uniform channel and found that closed looped oscillating heat pipe (CLOHP) with a non-uniform channel was functional to all inclinations when the filling ratio was above 50%.

Zhang and Faghri [20–22] developed a mathematical model to predict the slug motion in the OHPs. Shafii et al.[23] established a thermal model for the behavior of liquid and vapor plugs of OHPs, and the results showed that the heat transfer in OHPs mainly depended on sensible heat. The approach in reference [22] was extended by Arabnejad et al. [24] to consider the rate of convection and boiling heat transfer in a U-shaped OHP. Ma et al. [25,26] developed a mathematical model for the fluid motion and temperature drop in an OHP. The numerical results indicated that oscillating motions occurring in OHPs significantly enhance heat transfer in OHPs. In the model of Cheng and Ma [27], vapor bubbles played a role similar to linear springs, and sensible heat played a key role in transferring heat from the evaporator to condenser.

Cubaud et al. [28] investigated the effect of hydrophilic and hydrophobic surface on two-phase flow patterns and found that the slug flow consisted of long elongated bubbles lubricated by a liquid film between the gas and the hydrophilic walls. Bico and Quéré [29] described the fall of viscous slugs in vertical capillary tubes. Slugs were found to fall slower in dry tubes than in prewetted ones. Rapolu and Son [30] investigated the role of surface wettability in two-phase flow characteristics. They determined that the influence of capillary resistance on pressure drop of hydrophilic channel flow was relatively small due to the effect of liquid film formed between the bubble and channel wall. Qu et al. [31] determined that the heat transfer performance of micro heat pipe associated with the superhydrophilic evaporation section could be improved.

In the present paper, the effect of a superhydrophilic and hydrophilic surface on the slug motion and thermal performance of two OHPs were investigated experimentally. These two OHPs have configurations of four turns and six turns, respectively. Deionized water was used as the working fluid. Four wetting conditions at contact angles of 0°, 12.9°, 73.4° and 141.5° were studied to determine the wetting condition effect on fluid flow and heat transfer performance in OHPs.

2. Experimental setup

The experimental system as shown in Fig. 1 consists of a four-turn or six-turn flat-plate closed-loop OHP, heating and cooling systems, and a data acquisition system. The operational orientation represents a vertical bottom heating mode. The channels (2×2 mm^2) were machined into a copper substrate ($130 \times 80 \times 10$ mm^3) as shown in Fig. 2(a) and (b). Fig. 3 shows the construction of the OHP. The plate copper channels were covered by a transparent polycarbonate plate (PC plate), and was fastened by bolts for visual observation and recording. The OHP was sealed by the silicone pad, as shown in Fig. 2(a). The silicone lines were filled in the channels (1.5×1 mm^2) between the channels of OHP, and there was no liquid leakage between channels in the experiments. A vacuum pump connected to the OHP was used to achieve the vacuum requirement, and the working fluid filling ratio was controlled with a syringe. Before the experiment, A McLeod vacuum gauge (PM-2, China) was connected to the OHP to measure the inner pressure of the sealed OHP after vacuum. The experimental system was maintained pressure variation of 5–10 Pa for 12 hours. Deionized water was used as the working fluid and the filling ratio was about 30%, 50% and 75%, respectively. The filling ratio can be verified by measuring the length of the whole liquid slugs. As shown in Fig. 3(b), the total channel length of the six-turn OHP was 1257.2 mm and the total liquid slugs' length was 684.5 mm. The filling ratio was 54.4%. The OHP's total length was 106 mm, consisting of a 28 mm long evaporation section, a 42 mm long adiabatic section and a 36 mm long condensation section. The heating system was an electrical heater, and the heat input was adjusted by using a direct-current source supply (SMPS 5000, China). The maximum uncertainty of the heat input was ±1.39% and the heat loss was negligible. The condensation section was cooled by water at a constant inlet temperature of 15 °C and a flow rate of 60 L/h. The flow rate of the cooling water from the low temperature and constant temperature bath (DFY-10/25, China) was controlled by the rotor flow meter (LZB-6, China). The heating block and cooling block were attached to the surface of the OHP with bolts. Thermal conductive silicon grease (HZ-KS101, China, >0.21 W/m^2 K) was used to reduce thermal contact resistance between the blocks and the OHP.

Six thermocouple holes with 1.5 mm diameter were drilled into the copper plate on each side of the OHP and these 12 T-thermocouples were located just under the channels with a distance of 2.0 mm

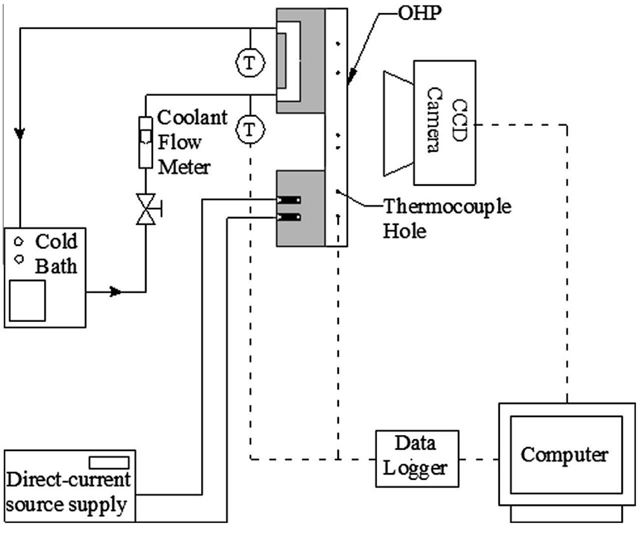

Fig. 1. Schematic of the experimental setup.