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Experimental study on thermal performance of a pulsating heat pipe with surfactant aqueous solution

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ABSTRACT

In this work, the thermal performance of pulsating heat pipe (PHP) using surfactant aqueous solution as working fluid was experimentally investigated. The cetyl trimethyl ammonium bromide (CTAB) was applied for preparation of surfactant solution in the concentration range of 0.025–0.25 wt%. It is found that the adding of CTAB can significantly reduce the surface tension and improve the wettability, thus enhance heat transfer between the tube wall and working fluid due to the increase in the liquid film area. The thermal performance of CTAB solution PHP depends greatly on the input power, filling ratio and surfactant concentration. Experimental results indicate that the heat transfer enhancement of PHP with CTAB solution is apparent at higher input power when the concentration is very high. Comparing to the water PHP, the thermal resistance of 0.25 wt% CTAB solution is decreased by 48.5% at the input power of 100 W when filling ratio is kept as 50%.

1. Introduction

As a high-efficiency heat transfer device, pulsating heat pipe (PHP) has been considered as one of the most effective methods for heat dissipation under high heat flux due to its simple structure, low cost and excellent heat transfer capability [1]. The typical PHP is serpentine-arranged and interconnected capillary tubes or micro channels. In a PHP, the working fluid is intervally distributed by a train of liquid plugs and vapor bubbles, which functions via thermally excited pulsating motion. The pulsating motion significantly increases the heat transport capability. Hence, the heat is transferred by two ways in the PHP, the latent heat transfer as the other heat pipes, and the sensible heat by liquid slugs sweeping the wall. The research indicated that the physical properties of the working fluid, such as the thermal conductivity, surface tension, latent heat, specific heat, viscosity etc., have great influence on the heat transfer performance of PHP [1–3]. As a result, the selection of an excellent functional fluid as the working fluid plays an important role in improving the thermal performance of PHP.

Recently, application of functional fluids into PHP has become one of the most attractive topics in PHP research, such as nanofluids [4–6], self-rewetting fluids [7], surfactant solution [3,8], phase change material [9] and zeotropic mixtures [10]. Among the numerous functional fluids to improve the heat transfer performance of PHP, the surfactant solution is selected to investigate in this work. Patel et al. [3] reported the surfactant solutions with lower surface tension reduce capillary resistance which decreases the evaporator temperature of PHP, and therefore the thermal performance of surfactant solutions are observed better compared to water PHP. Wang et al. [8] investigated on influence of sodium stearate surfactant on the heat transfer performance of PHP. The experimental results indicated that the heat transfer performance of PHP was greatly influenced by the surfactant solution, and the influence was dependent on the charge ratio and the concentrations of the solutions.The surfactants are a kind of special material, which can greatly reduce the surface tension of the base fluid by a small amount [11,12]. When the vapor bubbles pulsate in a PHP, there is advancing contact angle θ_{adv} in the head of the vapor and the receding contact angle θ_{rec} in the end of the vapor. The different of θ_{adv} and θ_{rec} leads to the capillary resistance can be written as [13]:

$$F_c = \sum_{i=1}^{n} F_{ic} = n \cdot A \cdot \Delta P_{ic} = n \cdot \pi d \sigma_l (\cos\theta_{rec} - \cos\theta_{adv}) \tag{1}$$

where σ_l is the surface tension of liquid and n is the number of liquid slugs. It can be seen that the capillary resistance is in proportion to the surface tension. As a result, the surfactant solutions with lower surface tension would have a lower capillary resistance in the PHP, and thus improve the heat transfer in the PHP. Moreover,

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Nomenclature

A	cross-sectional area (m^2)
d	diameter (m)
F	force (N)
I	current (A)
K	curvature
n	number of liquid slugs
P	pressure (Pa)
Q	input power (W)
R	thermal resistance ($K \cdot W^{-1}$)
r	radius (m)
T	temperature (K)
U	electric voltage (V)

Greek symbols

ρ	density ($Kg \cdot m^{-3}$)
θ	contact angle (rad)
σ	surface tension ($n \cdot m^{-1}$)
δ	thickness of liquid film (m)

Subscripts

c	condensation section
e	evaporation section
l	liquid
v	vapor
w	tube wall
ph	vapor-liquid interface

the boiling heat transfer can be enhanced by addition of small amounts of surfactants. Zhang and Manglik [14] indicated the surfactant additive significantly alters the nucleate boiling in water and enhances the heat transfer for reducing surface tension. Meléndez and Reyes [15] added cationic surfactants into the 16% ethanol aqueous mixture, which produced an increment of the wettability of the mixture and pool boiling heat transfer by bubble's size reduction. Wang et al. [16] reported a new pool boiling phenomenon of bubble explosion in cetyltrimethyl ammonium chloride/ sodium salicylate surfactant solutions. It was observed strong jet-flow behaviors and bubble explosion strengthened the local disturbance, which leads to the boiling heat transfer enhancement. Based on the better boiling heat transfer of surfactant solution in the evaporation section, the thermal performance of PHP would be improved.

According to the literature review, adding surfactants to the working fluid could reduce capillary resistance and enhance boiling heat transfer in the PHP, which may reduce the total heat resistance and increase the heat removal capacity. In this study, the influences of surfactant aqueous solution on the surface tension and contact angle are experimentally investigated. Based on the experimental results, the profile of vapor-liquid interface in the PHP is predicted. Furthermore, an experimental investigation is conducted to explore the thermal performance of a vertical closed PHP working with deionized water and different concentration surfactant solutions at various input powers and filling ratios.

2. Experimental facility and uncertainty

In this work, cetyl trimethyl ammonium bromide (CTAB) as surfactant was added into deionized water to form surfactant aqueous solution. The purity of CTAB was higher than 99.9%. The CTAB solutions were prepared and tested by five different weight concentrations of 0.025 wt%, 0.075 wt%, 0.125 wt%, 0.175 wt%, 0.25 wt%. To better understand the mechanism of surfactant solution on the thermal performance of PHP, interfacial properties of solution such as surface tension and contact angle should be measured. Surface tension measurement was made by the Wilhelmy plate method using A801 surface tension meter of USA KINO Industry. The measurement accuracy is 0.04 mN/m measurement resolution is 0.001 mN/mand the measurement range is 0–999.9 mN/m. The liquid-solid contact angle was measured by the sessile drop method, and the experimental set up was developed in the laboratory. The experimental setup for contact angle measurement consists of a horizontal platform for the testing surface, a calibrated micropipette for depositing the sessile drop, LED illumination for ensuring sharp images, and a high-speed digital camera (Phantom V211-8G-C) coupled to an image digitalization system. The equilibrium contact angle was measured from the digitalized image of sessile drops using Phantom Camera Control software. The surface tension and contact angle measurements are conducted under indoor condition, the temperature is 20–22 °C and the relative humidity is about 55%.

Fig. 1 illustrates the schematic diagram of the PHP experimental facility. The apparatus consists of a PHP, a cooling bath, a power supply, measurement and data acquisition device. A copper tube with external diameter of 4 mm and inner diameter of 2 mm was used to make the PHP, and it was bent into five turns. The PHP consists of evaporation section, adiabatic section and condensation section, and the length of each section is 100 mm. The condensation section was directly attached to a cooling block which was cooled by a constant-temperature cold bath. The nickel chrome electric wire was wound around the copper tube of evaporation section which was wrapped in thermal insulation adhesive plaster. A DC power supply was connected to the electric wire to apply the DC electric current. The whole test section including the PHP, cooling block, and heater were well insulated by glass wool. The OMEGA K-type thermocouples with accuracy ±0.1 °C were installed at different positions of PHP to measure the wall temperature at different heat loads as shown in Fig. 1. Before conducting the each experiment, the system should be reached at the temperature of the cooling media, which is constant at 20 ± 0.5 °C.

Data from all tests are deducted using the following equations. The thermal resistance of PHP can be calculated as follows:

$$R = (T_e - T_c)/Q \tag{2}$$

where the evaporation temperature T_e and the condensation temperature T_c are based on the average temperature of five thermocouples placed on the evaporation and condensation sections as shown in Fig. 1, which can be gotten as follows:

$$T_e = (T_1 + T_2 + T_3 + T_4 + T_5)/5 \tag{3}$$

$$T_c = (T_{11} + T_{12} + T_{13} + T_{14} + T_{15})/5 \tag{4}$$

Q is the input power, it can be calculated by:

$$Q = U \cdot I \tag{5}$$

where U and I are the electric voltage and current of heating system, respectively.

The uncertainties of the measurement parameters are analyzed by the error propagation method. The relative uncertainty of the thermal resistance is calculated as follows:

$$\frac{\delta R}{R} = \sqrt{\left(\frac{\delta T_e}{T_e - T_c}\right)^2 + \left(\frac{\delta T_c}{T_e - T_c}\right)^2 + \left(\frac{\delta Q}{Q}\right)^2} \tag{6}$$