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An experimental investigation of thermal performance of pulsating heat pipe with alcohols and surfactant solutions

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ABSTRACT

An experimental investigation was conducted to determine the thermal performance of Pulsating Heat Pipe (PHP) with different concentrations and fill ratios (FRs) of Methanol, Ethanol and Cetyltrimethyl ammonium chloride, $C_{19}H_{42}ClN$ (CTAC) and compared with that of Deionized (DI) water. In this study, effects of thermo-physical properties of these working fluids on progression of temperature at different regions of the PHP and thermal resistance at varying thermal loads ranging from 15 W to 80 W were investigated. The closed-loop pulsating heat pipe was bottom heated and kept at vertical position for the entire period of study. 35%, 50% and 65% FRs of DI water were used and it was observed that the thermal resistance was lowest when the PHP was filled with 50% FR. The lowest thermal resistance achieved with DI water was 0.34 K/W at higher heat load. Methanol and Ethanol have lower specific heat capacity and performed almost no better than DI water. Larger $(dP/dT)_{sat}$ values of Methanol and Ethanol produced greater fluctuations in the flow and rapid movement of the fluid was induced within the pipe because of their relatively lower surface tension and viscosity. But these properties were not dominating factors for the thermal performance at higher heat loads. Lower specific heat capacity and latent heat of vaporization of these alcohols dominated the thermal resistance. When 50 ppm, 100 ppm, 1000 ppm and 2000 ppm of CTAC surfactant solutions were used, the experimental results showed that the heat transfer capability of the PHP is highly dependent on FR. It was observed that surface tension and viscosity are dominating factor in the performance of the PHP, when CTAC surfactant solution is used, and their degree of dominance varies with FR and heat loads. Lower surface tension of CTAC solution was advantageous for lower FR and heat load. Lower viscosity offered greater advantage at higher FR and heat load. The lowest thermal resistance achieved with surfactant solution was 0.30 K/W for 35% and 50% FR with 2000 ppm CTAC solution at higher heat load which are lower than that of DI water.

1. Introduction

Invented in 1990s by Akachi [1], pulsating heat pipe (PHP) is a passive heat transfer device that has potential application in many fields like solar cell, fuel cell, space and electronic cooling, and hybrid vehicle [2–5]. Many experimental researches have been conducted in the past, and PHP has been showing promising results in tackling the need of efficient heat dissipation from compact spaces. Yet further researches are needed to fully understand the complex chaotic flow dynamics and heat transfer phenomenon of PHP to achieve optimal operation parameters. Many studies have indicated that, unlike conventional heat pipes, PHPs have potential to handle much larger thermal loads while meeting demanding weight and size constraints. The thermo-fluid dynamics and phase change behavior are mostly dependent on the type of the working fluid, the filling ratio (FR), the heat input, the inclination and the number of turns [6–9].

Generally, PHPs have smaller diameter and working fluid is partially filled inside the pipe and sealed under vacuum, before any thermal load is applied. This promotes capillary action of working fluid upon supply of heat from evaporator region. The supplied heat is then transported to the condenser region via pulsating flow of liquid-vapor within the closed channel of the pipe. The heat available at the evaporator is transferred to the condenser, through the combination of vaporization and sensible heat flow via bubble/slug/annular flow [10]. This flow is induced mainly by the presence of pressure variation existing between the parallel pipes due to non-uniform distribution of liquid-vapor phases.

Zhang and Faghri [11] presented the working principle of PHP and effects of parameters like working fluid, FRs, inclination angle etc. on the fluid dynamics and the heat transfer. The thermo-

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physical properties of working fluids, such as surface tension, wettability, viscosity and thermal conductivity play an important role in the heat transfer performance of PHPs [8]. The effect of pure and mixture of different types of working fluids have been studied by many researchers. Wang et al. [12] showed that water as working fluid is better than ethanol and R141b. Experimental study by Cui et al. [13] also suggested that thermal performance of PHPs is related to thermo-physical properties of working fluids. The working fluids used in their experiment were methanol mixed with deionized water, acetone and ethanol. Experimental work done by Sarangi and Rane [14] revealed that the start-up heating power is unrelated to the filling ratios and that the maximum heating power is related to the filling ratios. The experimental results of Tseng et al. [15] showed that the thermal resistance in a vertical arrangement was lower than that in a horizontal arrangement. They used distilled water, methanol and HFE-7100 in the closed loop PHP with inner diameter 2.4 mm. The results concluded that the vertical arrangement of the PHP produced lowest thermal resistance. Moreover, the thermal resistance of the PHP with distilled water was the lowest when the heating power increased.

Currently, research works are still oriented in finding the better working fluid and understanding the heat transfer phenomenon. Yet, comprehensive understanding of effects of thermo-physical properties of various working fluids in enhancement of thermal performance of PHP is not realized. In recent studies, nano-fluids have been widely used as the working fluid in PHP so as to establish it as the substitute for the conventional fluids. Many experiments displayed evidences of better heat rejection capacity with nanoparticles compared to conventional working fluids [16–20]. Higher effective thermal conductivity and strong oscillating motion of nano-fluids are ascertained to increase the thermal performance [21]. These conclusions are also in line with the results of Park et al. [22] which claim the improvement of PHP's performance with nano-fluids is attributed to the generation of bubbles and bubbles' movement in the PHP. However the use of nano-fluids in the PHP is relatively expensive due to the cost of nano-particles and its complex preparation methods.

On the other hand, many studies have been carried out and many more are under going to enhance the boiling phenomenon of liquids. Since boiling is inevitable process of PHP, results of such investigations will be very obliging to be integrated in the boosting of its performance. Addition of surfactants on the base fluid results in decrease of surface tension. The rate of nucleate boiling heat transfer of water is considerably increased even if small amount of surfactants is added. Wu et al. [23] in their work showed how the bubble growth dynamics of aqueous surfactant solutions of sodium lauryl sulfate is bound to enhance the boiling mechanism due to the lessening surface tension. Another experimental study of Hetsroni et al. [24] showed that the different bubble behaviors of surfactant solutions at saturated boiling conditions are the reason for better heat transfer phenomenon. Wang et al. [25] experimentally studied the effects of addition of surfactants solutions on boiling mechanism. This study concludes that in pool boiling, the enhancement of heat transfer is mainly due to the bubble explosion. Surface tension being one of the factors that influences the performance of PHP, its effect was experimentally tested by Wang et al. [26]. They tested 10 parts per million (ppm), 20 ppm and 40 ppm of sodium stearate and found that the thermal performance is highly dependent on the charge ratio and heat fluxes. A paper presented by Kumar et al. [27] deals with the visualization of effects of Sodium dodecyl sulfate (SDS) as the surfactant solution in PHP. It claims that the lower surface tension of the surfactant solution bring about higher thermal performance, comparable with nano-fluids and other binary mixtures.

Literature review on use of surfactant solutions as working fluids in PHP suggests that there is still no clear and wide-ranging idea and data on the effects of thermo-physical properties on the heat transfer phenomenon. The objective of this study is to conduct an experimental study to find out the dominating thermo-physical properties of surfactant solution in the thermal performance of the PHP. In this experiment, the effects of surface tension, viscosity and concentrations of surfactants over the various fill ratios (FRs) and heat load were investigated. Different concentrations (50 ppm, 100 ppm, 1000 ppm and 2000 ppm) of Cetyltrimethyl ammonium chloride (CTAC) surfactant solution were used as working fluids to investigate the influence on the thermal resistance of the PHP and compared against the experimental values obtained with Deionized (DI) water, Methanol and Ethanol.

2. Experimental set up

The PHP designed for the experiment was a closed type and had 8 number of turns with copper tube of 2 mm inside diameter and 0.5 mm thickness. Since the production and the dissipation of bubble are affected by the surface tension and buoyancy force, the inside diameter of the capillary tube was made such that it satisfies the criterion:

$$d \leqslant d_{cr} = 2\left[\sigma/g(\rho_f - \rho_g)\right]^{0.5}, \tag{1}$$

as suggested by Akachi et al. [1]. The whole 2 mm inside diameter copper pipe was divided into three regions viz. evaporator, adiabatic section and condenser and was of length 6 cm, 4 cm and 8 cm respectively as shown in Fig. 1.

The entire experimental setup was composed of a PHP, heating and cooling system, charging and evacuation system, temperature sensors and data acquisition system. The evaporator region was winded with 0.1 cm thick NI-Cr wire in number of turns to supply DC power (by adjustable DC power supply, ZHAOXIN- RPS-3002D, voltage error ±0.01 V, current error ±0.001 A) as a source of heat. The windings were coated with silicone sealant (Kafuter K-5202, coefficient of thermal conductivity: 0.8 W m/K) afterwards. The evaporator and adiabatic region were fully isolated to the surroundings with foam insulation (Expanded Polyethylene Foam with aluminum foil cover, thermal resistance 0.0359 W/mK).

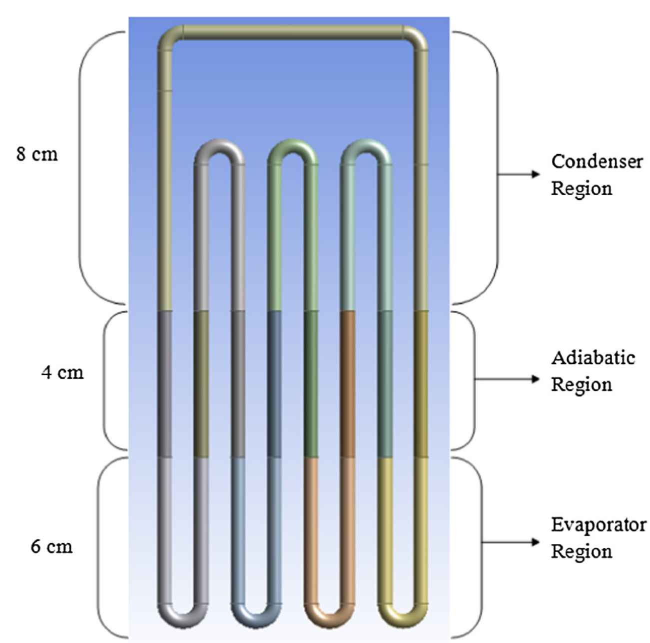

Fig. 1. Dimensions of the PHP used in this experiment.