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Heat transfer performance of closed loop pulsating heat pipes with methanol-based binary mixtures

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ABSTRACT

In this paper, an experimental study is presented on the thermal resistance characteristics of closed loop pulsating heat pipes (CLPHPs) with methanol-based binary mixtures. The working fluids were methanol mixed with deionized water, acetone and ethanol. The volume mixing ratios used were 2:1, 4:1 and 7:1, and the heating power ranged from 10 W to 100 W with filling ratios of 45%, 62%, 70% and 90%. The results showed that adding other working fluids to methanol could change the thermal resistance characteristics of a PHP. At a low filling ratio (45%), adding water to methanol could prevent dry-out at a high heating power; when ethanol was added to methanol, the thermal resistance of the CLPHP was between that with pure methanol and ethanol; when acetone was added, the thermal resistance of the CLPHP was slightly lower than that with pure methanol and acetone. At a high filling ratio (62%, 70%, 90%), the thermal resistance characteristics of CLPHPs with methanol based mixtures were not much different from those with pure fluids except for methanol–water mixture where the thermal resistance was greater than that with pure methanol and pure water. It can be inferred that the heat transfer performances of CLPHPs with methanol-based binary mixtures are related to the thermal-physical properties of the working fluids, vapor–liquid phase transition properties, molecular interactions and the additional resistance to mass transfer.

1. Introduction

Pulsating heat pipes (PHPs) are emerging heat transfer devices, and their heat transfer mechanism is markedly different from that of a conventional heat pipe. The unique features of PHPs, compared with conventional heat pipes, are as follows: (1) PHP has small capillary tubes/channels in a meandering arrangement, and the ends of the tube may be connected to one another in a closed loop, or pinched off and welded shut in an open loop. (2) PHP is partially filled with working fluid, which will distribute itself randomly in liquid slugs and vapor bubbles. (3) The operation of PHP is by thermally induced pressure difference, which drives liquid slugs and vapor bubbles to move in an oscillating way [1,2]. Similar to conventional heat pipes, PHPs also have an equivalent thermal conductivity exceeding that of any known metal [3]. In the field of electronic equipment cooling, PHPs have great potential. The heat transfer performance of a PHP is primarily determined by the physical properties of the working fluids, pipe material, number of turns and inner/outer diameter, etc. The physical properties include the boiling point, specific heat, latent heat of vaporization, dynamic viscosity, density, saturation pressure gradient versus temperature $(dp/dT)_{sat}$, etc. Apart from a multitude of different physical properties which affect the system, the performance is also strongly linked with the flow patterns existing inside [4].

Early studies on PHPs only focused on pure working fluids. For example, Cui et al. [5] studied the heat transfer performances of closed-loop PHPs with inner diameters of 2 mm with pure water, methanol, ethanol and acetone as working fluids and analyzed the effects of different physical properties. The authors indicated that the heat transfer performance was determined by whether the PHP starts up and how large the pulsating flow velocity is, which was determined by dynamic viscosity. Once the PHP began to pulsate, the difference in the pulsating frequency and amplitude reduced gradually with increases in heating power and flow velocity. Subsequently, under this circumstance, the influences of dynamic viscosity, liquid specific heat and latent heat of vaporization resulted in differing thermal resistances of PHPs with different working fluids. When the heating power continued to increase, the flow velocity increased, the effect of viscosity decreased, the inertia effect was enhanced and the sensible heat transfer increased. Zhang et al. [6] experimentally investigated the temperature

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Nomenclature

Q	heating power (W)
U	voltage (V)
I	current (A)
R	thermal resistance (°C/W)
T	temperature (°C)
T_i	temperature of the ith measuring point (°C)

Subscripts

c	condensation section
sat	saturation
i	index of thermocouple
e	evaporation section

fluctuation characteristics of a CLPHP with an inner diameter of 1.8 mm with water, FC72 and ethanol. The authors found that the temperature fluctuation period was primarily related to the latent heat of vaporization and that the fluctuation range was related to surface tension. The CLPHP with water exhibited better overall heat transfer performance once the heating power was higher than a minimum value. Due to the lower minimum heating power at start-up, FC-72 was suggested for use in low-heat-flux conditions. The appropriate filling ratio was approximately 70% for all three working fluids. Sarangi and Rane [7] experimentally investigated the start-up heating power, maximum heating power and optimal filling ratio of a CLPHP with an inner diameter of 1 mm and outer diameter of 2 mm, which was charged with pure water and ethanol. It was mentioned that the start-up heating power is unrelated to the filling ratios and that the maximum heating power is related to the filling ratios. Under the same working temperature, the optimal filling ratio at the maximum heating power is related to the working fluids. PHPs with water and ethanol had maximum heating powers at filling ratios of 62.5% and 50%, respectively, which were known as the optimal filling ratios. Liu et al. [8] investigated the start-up performance of a CLPHP with an inner diameter of 2.6 mm with water, ethanol and methanol. It was found that the optimal filling ratio was approximately 41% for water, 52% for ethanol and 35–41% for methanol. Shafii et al. [9] experimentally investigated the heat transfer performance of a CLPHP with an inner diameter of 1.8 mm with water and ethanol. The results indicated that the optimal filling ratio was 40% for water and 50% for ethanol and that the heat transfer performance decreased when the filling ratio was lower than 30% or higher than 70%. Yuhsing Lin et al. [10] used a high-speed video camera to study the heat transfer performance of a CLPHP at a filling ratio of 60% with methanol and ethanol under different heating powers. It was reported that the thermal resistance of methanol was lower than that with ethanol within a range of heating powers, which primarily depended on the fact that $(dp/dT)_{sat}$ of methanol was higher than that of ethanol.

According to research on heat pipes, PHPs with binary mixtures exhibit different characteristics from pure working fluids. Savinoa et al. [11] hypothesized that a proper binary fluid improved the heat transfer performance of conventional wicked heat pipes. It was indicated that heat pipes filled with a long-chain alcohol could replace heat pipes filled with pure water in conventional heat pipes. More studies on heat pipes that investigated N_2–Ar mixtures [12], 2-propanol–water mixtures [13], methanol–water and TEG–water mixtures [14], ethanol–water mixtures [15] and N_2–CF_4 [16] have been performed, and these mixtures proved to be effective in increasing the performance of heat pipes or broadening the functional temperature range.

There have only been a few studies on binary mixtures applied in PHPs. Charoensawan and Terdton [17] experimentally investigated the heat transfer performance of a CLPHP with a water–ethanol mixture. It was reported that both the water–ethanol mixture at a filling ratio of 30% with an evaporating pipe length of 150 mm and a water–ethanol mixture at a filling ratio of 30% or 50% with an evaporating pipe length of 50 mm effectively improved the heat transfer performance of the PHP. Zhu et al. [18] investigated the heat transfer and start-up performance of a CLPHP with a water–acetone mixture at various filling ratios, which ranged from 35% to 70% (mixing ratios of 13:1, 4:1, 1:1, 1:4, 1:13). It was shown that at low filling ratios (45% and 55%), water–acetone mixtures (mixing ratios of 4:1, 1:1, 1:4 and 1:13) exhibited better performance against the onset of dry-out compared with that of using pure water and acetone as the working fluids. Burban et al. [19] performed OLPHP experiments with water and an n-pentane mixture (mixing ratios of 2:3 and 1:3) at a filling ratio of 60%. It was indicated that an OLPHP with a mixture exhibited better heat transfer performance than an OLPHP filled with pure working fluids at low temperatures.

This study tested CLPHP with methanol-based binary mixtures. Methanol has a relatively low boiling point and a relatively high latent heat of vaporization and $(dp/dT)_{sat}$; thus, methanol is often applied in PHPs. Clement and Wang [20] tested a CLPHP with an inner diameter of 1.651 mm and 15 turns with acetone, methanol and deionized water. The author concluded that methanol outperformed acetone and water, where the optimal filling ratio of PHP with methanol was 45%. Han et al. [21] investigated the heat transfer performance of a CLPHP (inner diameter = 2 mm) with acetone, deionized water, ethanol and methanol. The results indicated that PHP with acetone exhibited the best heat transfer performance when the filling ratio was approximately 60–80%; the CLPHP with deionized water exhibited the best heat transfer performance when the filling ratio ranged from approximately 55% to 70%; a CLPHP with methanol had the best heat transfer performance when the filling ratio was 90% or greater. Tseng et al. [22] experimentally investigated the heat transfer performance of a CLPHP (inner diameter = 2.4 mm) with distilled water, methanol and HFE-7100. The results showed that the thermal resistance in a vertical arrangement was lower than that in a horizontal arrangement, and the PHP with HFE-7100 had the lowest thermal resistance when the heating power was low, whereas the thermal resistance of the PHP with distilled water was the lowest when the heating power increased. The references above are summarized in Table 1. Similar to most working fluids, methanol has several disadvantages in terms of physical properties compared with those of other working fluids. For example, its specific heat is lower than water and its viscosity is higher than acetone. The heat transfer performance could be improved by adding another working fluid with different physical properties to methanol. In the following, thermal resistance characteristics of PHPs with different binary mixtures are presented.

2. Experimental setup and uncertainty analysis

2.1. Experimental setup

As shown in Fig. 1, the experimental device consisted of a vertical CLPHP sample, charging and evacuating system and electric heating and air cooling equipment. The CLPHP sample was made from a red copper capillary and vertically placed. The inner/outer diameter of the CLPHP was 2.0/4.0 mm. As shown in Fig. 2, the setup consisted of an evaporation section (ES), adiabatic section