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The study on the difference of the start-up and heat-transfer performance of the pulsating heat pipe with water–acetone mixtures

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ABSTRACT

An experimental study was conducted to investigate the start-up and heat-transfer performance of a closed-loop pulsating heat pipe with water–acetone mixtures (at mixing ratios of 13:1, 4:1, 1:1, 1:4 and 1:13) and pure water and acetone under various filing ratios (35–70%) and heat inputs (10–100 W). The closed-loop pulsating heat pipe was vertically placed and bottom-heated (i.e., heating wires were wrapped on the evaporation section) with inner and outer diameters of 2.0 and 4.0 mm, respectively. It was observed that (1) compared with pure water, the pulsating heat pipe with water–acetone mixtures of mixing ratios of 13:1, 1:1, 1:4 and 1:13 possessed improved start-up performances, which could be initiated under a heat input of 10 W and filling ratios of 35% and 45%. (2) Under low filling ratios (i.e., 35% and 45%), the pulsating heat pipe with water–acetone mixtures (i.e., at mixing ratios of 4:1, 1:1, 1:4 and 1:13) presented improved performance against the onset of dry-out conditions compared with PHPs using pure water and acetone. Under a heat input of 50 W, the thermal resistances of the PHP with water–acetone mixtures (i.e., at mixing ratios of 4:1, 1:1, 1:4 and 1:13) decreased from 33.6% to 68.9% compared with pure working fluids. The addition of a fraction of pure water into pure acetone (e.g., the 13:1 water–acetone mixture) was found to be effective against dry-out. Conversely, adding a fraction of pure acetone into pure water (e.g., the 1:13 water–acetone mixture) did not prevent the onset of dry-out. (3) For high filling ratios (i.e., 62% and 70%) for which dry-out conditions are rarely encountered, the heat-transfer performances of the pulsating heat pipe with water–acetone mixtures (at mixing ratios of 13:1, 4:1, 1:1, 1:4 and 1:13) were not as efficient as that of the pulsating heat pipe with pure fluids. In contrast with the minima of mixtures under certain heat inputs, the maximum thermal resistances of pure water and acetone decreased by 45.8% and 38.7%, respectively.

1. Introduction

A novel type of heat pipe patented by Akachi [1], the pulsating heat pipe (PHP), has been introduced as a promising solution for small spaces with high heat flux due to the excellent heat-transfer performance, rapid thermal response and compact structure [2,3]. In terms of structure, the PHP can be categorized as two types, an open or a closed-loop pulsating heat pipe. Because the working fluid can flow continuously, the latter typically possesses greater heat-transfer performance compared with that of the former. Due to the small inner diameter of the PHP, the working fluids naturally distribute to form liquid–vapor slugs when the PHP is charged with fluid after evacuation. Due to the non-uniform distribution of liquid–vapor slugs, the pressure difference between parallel pipes gradually increases as external heating or cooling sources are applied, which promotes the working fluid to flow inside the pipes. Once a PHP is initialized, the working fluids absorb heat at the hot end and flow to the cool end to release the heat. The operation and heat-transfer characteristics of the PHP are relatively complex and are determined by the type of working fluid, the filling ratio (FR), the heat input, the inclination and the number of turns [4]. With respect to the working fluid, pure fluids have been studied in several works [5,6]. However, an experimental study of the PHP with mixtures has yet to be conducted.

In a few thermodynamic studies, the influence of the fluid mixture was investigated [7–12]. Long and Zhang [7] used cryogenic heat pipes with N_2–Ar mixtures (at a mole ratio of 50:50), pure N_2 and Ar solutions. The study found that N_2–Ar mixtures broadened the range of functional temperature from 64 to 150 K. In other studies 8, a heat pipe with a 0.05 M 2-propanol (diluted in water) mixture was studied at different inclinations. Compared with pure water, the critical heat flux of the heat pipe with

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Nomenclature

K	coverage factor
I	current (A)
Q	heat input (W)
R	thermal resistance (°C W^{-1})
T	temperature (°C)
U	voltage (V)

Subscript

c	condensation section
e	evaporation section
i	index of thermocouple
sat	saturation
max	maximum
min	minimum

0.05 M 2-propanol increased by 52%. Nuntaphan et al. [9] experimentally investigated the heat-transfer performance of heat pipes with methanol–water and TEG–water mixtures. It concluded that a heat pipe with a methanol–water mixture had a better heat-transfer performance compared with a pipe with only pure water. Due to the evident contribution of the heat-transfer performance of TEG, the heat transferred in the heat pipe with TEG–water varied with the concentration of TEG. The literature 10 indicated that in contrast with pure water (0.41 cc or 1.9 cc), a heat pipe with water–alcohol mixtures (0.41 cc or 1.9 cc) presented better heat-transfer performance. Jouhara et al. [11] indicated the advantage of utilizing an ethanol–water mixture (95.63% ethanol and 4.37% distilled water by weight) in the two phase closed thermosyphon (TPCT) at a horizontal orientation. Compared with pure water, the TPCT with the ethanol mixture operated at lower temperatures with dampened temperature fluctuations at the evaporator. At a lower heat transfer rate and a vertical orientation, the thermal resistance of the TPCT was also lower than that of pure water. Wang et al. [12] experimentally investigated the influence of CuO (1.0 wt.%) nanofluids on the heat-transfer performance of an inclined miniature mesh heat pipe. It noted that the total thermal resistance of the heat pipe reduced by approximately half to when water-based nanofluids were substituted for pure water as the working fluid.

With respect to the PHP, Chu et al. [13,14] proposed an azeotropic binary working fluid in the PHP application. Shi et al. [15] observed that the thermal resistance of the PHP with a water–methanol mixture was lower than that of the PHP using pure methanol. Burban et al. [16] carried out open loop pulsating heat pipe experiments with a water–*n*-pentane mixture, using 2:3 and 1:3 mixing ratios, under an FR of 60%. It mentioned that the heat-transfer performance of the PHP with the mixture was better than that of the PHP with pure water or *n*-pentane. However, the range of the FR and ratios of mixtures studied in these studies were relatively limited. A PHP study focusing on mixtures with a wider FR range and diverse mixing ratios has not yet been performed.

Materials with low boiling points (i.e., generating bubbles at lower temperature) and high $(dP/dT)_{sat}$ values (i.e., producing stronger pressure impulses) have advantages in rapid initializations of PHPs. Working fluids with high specific and latent heats can absorb more heat at the hot end and efficiently transfer heat to the cool end. As seen in Table 1, because pure acetone has a lower boiling point and a higher $(dP/dT)_{sat}$ value, it can help activate the PHP at a relatively lower heat input. The high specific and latent heat properties of pure water provide favorable thermodynamic characteristics for absorbing and efficiently carrying energy. Therefore, it can be deduced that these two materials are thermodynamically complementary. Due to the properties of zeotropic mixtures, the water–acetone mixture exists shifting concentrations at vapor–liquid equilibrium, unlike pure fluids.

In this study, an experimental investigation of heat-transfer performances of a PHP using pure water, pure acetone and water–acetone mixtures of various mixing ratios (i.e., 13:1, 4:1, 1:1, 1:4 and 13:1) under a wide FR range (i.e., 35–70%) and varying heat inputs (i.e., 10–100 W), will be carried out. Through analyzing and comparing the temperature oscillations and thermal resistances, start-ups and heat-transfer performances at low (i.e., 35% and 45%) and high FR (i.e., 62% and 70%) for PHPs running mixtures and pure fluids will be discussed. The results obtained in this study may provide insight for improving the heat-transfer performance of pulsating heat pipes and initialize new investigations on using mixtures as working fluids.

2. Experimental apparatus and data processing

2.1. Experimental apparatus

As shown in Fig. 1, the experimental setup was composed of a PHP, the heating and cooling system, the charging and evacuating system and the data acquisition system. The PHP was axially oriented and was fabricated using pure copper with inner and outer diameters measuring 2 and 4 mm, respectively. The pipes were bent into several turns to form a closed loop structure with 10 parallel pipes, such that neighboring pipes were 20 mm apart as measured from the pipe centers. The PHP was sequentially divided into following sections according to functionality: a condensation section (applied via forced-air cooling), an adiabatic section (the transition section between the condensation and evaporation section) and an evaporation section (applied via a heat load), whose lengths were 80, 20 and 80 mm, respectively. The evaporation section was wrapped with a 0.2 mm diameter Ni–Cr heating wire. The evaporation and adiabatic sections were installed in an insulation

Table 1
Physical properties of working fluids at standard atmospheric pressure [17].

Type of working fluid	Boiling point T_S °C	Density ρ_l kg (m^3)$^{-1}$ (20 °C)	Specific heat C_{pl} kJ (kg °C)$^{-1}$ (20 °C)	Conductivity λ_l W (m °C)$^{-1}$ (20 °C)	Latent heat H_{fg} kJ kg^{-1}	$(dp/dT)_{sat} \times 10^3$ Pa °C^{-1} (20 °C)	Dynamic viscosity $\eta \times 10^6$ Pa s (20 °C)	Surface tension $\sigma \times 10^3$ N m^{-1} (20 °C)
Acetone	56.2	792	2.35	0.170	523	1.11	0.32	23.7
Water	100.0	998	4.18	0.599	2257	0.14	1.01	72.8