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Enhancement of heat transport in oscillating heat pipe with ternary fluid

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A B S T R A C T

The thermo-physical properties of working fluids play an important role in the heat transport performance of an oscillating heat pipe (OHP). In the present study, the heat transport performance of the OHP is investigated using two types of binary fluids and a type of ternary fluid as the working fluids. The working fluids include a nanofluid, self-rewetting fluid, and a mixed solution of self-rewetting fluid and a nanofluid called self-rewetting nanofluid. The tilt angle of the OHP is 90° with a charge ratio of 50%. In contrast to de-ionized water used as a base working fluid in the OHP, all working fluids can enhance the heat transport performance of the OHP. However, through an analysis of the enhancement ratios, it is found that nanofluids can only enhance the performance of an OHP within a heat load range of 30–70 W. The maximal enhancement ratio is about 11% as the heat load is 60 W. If the heat load exceeds 70 W, the heat transport performance of the OHP degrades. For a self-rewetting fluid, the maximum of enhancement ratio is only 6% as the heat load is less than 30 W, and then, as the heat load increases, the enhancement ratio decreases gradually. The OHP that uses self-rewetting nanofluids shows excellent heat transport performance over the entire heat load range. The maximal enhancement ratio is approximately 15%. Therefore, self-rewetting nanofluids are considered to be appropriate working fluids for use in the OHPs.

1. Introduction

A heat pipe is a small and highly effective two-phase heat transfer device that is typically used in electronics cooling, solar collector, power generation, spacecraft cooling, and energy recovery [1–3]. With the increase in the heat transfer load in such equipment, a conventional heat pipe using conventional working fluids, such as water, gradually reaches and even exceeds its heat flux limit. Therefore, new types of heat pipes with different working fluids are required to increase the heat transfer capacity.

An oscillating heat pipe (OHP) is a new type of heat pipe that was developed by Akachi in 1990 [4], in which heat is transported from the evaporator to the condenser via a complex pulsating action of the liquid vapor/bubble-slug system. Compared to conventional heat pipes, the oscillating heat pipe is a type of wickless heat pipe, and therefore, no countercurrent flow exists between the liquid and the vapor because both flow in the same direction [5].

In general, OHPs have a smaller diameter and are made up of capillary tubes. The thermo-physical properties of working fluids, such as surface tension, wettability, and thermal conductivity, play an important role in the heat transport performance of the OHPs [6]. In recent times, for improving the heat transport capability of the OHPs, certain binary fluids, including nanofluids and self-rewetting fluids, were used as working fluids to increase the heat flux and decrease the thermal resistance of the OHPs [7–11]. Nanofluids are suspensions of metallic or nonmetallic nanoparticles in a base fluid; they were first used by Choi in 1995 [12]. Experiment results show that nanofluids could significantly enhance the heat transport capability of the OHPs owing to high heat conductivity [13]. Self-rewetting fluids are a type of dilute aqueous solutions of alcohols with a high number of carbon atoms, first presented by Abe et al. in 2004 [14], when they studied the thermo-physical properties of dilute aqueous solutions with high carbon alcohols. Generally, the surface tension of pure working fluids decreases as temperature increases; this is known as the classic Marangoni effect. However, the surface tension of self-rewetting fluids increases with the temperature within a suitable temperature range; this is known as the inverse Marangoni effect [6,14]. This characteristic of self-rewetting fluids induces a rather strong inflow (caused by both temperature and concentration gradients) from the cold region (where liquid condensates) to the hot evaporator region [15]. Therefore, self-rewetting fluids help improve the heat transport performance of the OHPs.

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Although most research shows that nanofluids and self-wetting fluids enhance the heat transport performance of OHPs, the enhancement mechanism in the OHP is not quite clear. To understand the heat transport mechanisms of the OHP better, the heat transport performance was analyzed with different binary fluids of nanofluids and self-rewetting fluids. New ternary working fluids, referred to as self-rewetting nanofluids in this paper, are then proposed to improve the heat transport performance of OHPs with binary working fluids. Self-rewetting nanofluids are a mixed solution of self-rewetting fluids and nanofluids. The effects of ternary working fluids on the heat transport performance of OHPs have been studied in this paper.

2. Experimental apparatus and method

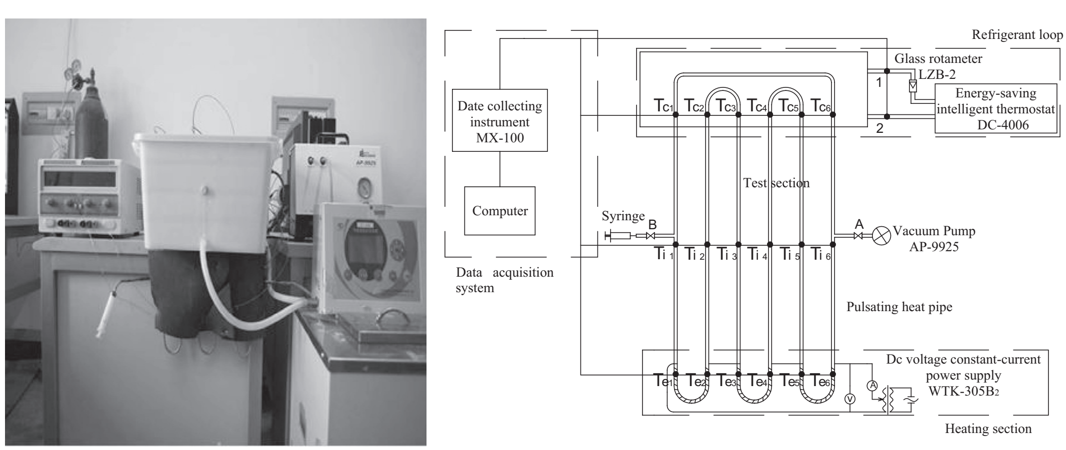
Fig. 1 shows a schematic diagram of the experimental apparatus and its photograph. The test loop consists of a test section, refrigerant loop, heating section, and data acquisition system. The test section is fabricated from a straight copper tube with inner and outer diameters of 2 and 4 mm, respectively. In the design of the OHP, the inner diameter must be small enough so that the surface tension forces are greater than the gravitational forces, and distinct vapor bubbles and liquid slugs should be able to form. The theoretical maximum interior diameter for a capillary tube occurs when the square of the Bond number is less than 4; thus, the critical diameter of the capillary tube can be expressed as

$$D_{crit} \leqslant 2\sqrt{\frac{\sigma}{g(\rho_l - \rho_v)}} \tag{1}$$

where σ is the surface tension, ρ_l is the liquid density, ρ_v is the vapor density, and g is the gravitational acceleration. The inner diameter of the copper tube in the current study is well within this constraint based on this equation. The refrigerant loop consists of a thermostatic water bath controlled by adjusting the voltage, a 20*L* cooling chamber, and a flow meter. First, the temperature of the cold water in the thermostatic water bath is adjusted to the desired level and controlled by the temperature controller in the experiment. Then, the cold water is pumped out of the thermostatic water bath, passed through the flow meter, and into the cooling chamber where the working fluid in the condenser section is cooled. Finally, the heated water is returned to the thermostatic water bath. The flow rate of the cold water is controlled by adjusting the valve; the flow rate is measured by the flow meter with an accuracy of ±0.2%. The heating section consists of a DC regulated power supply and a heater made up of Ni–Cr resistance wire. The heat load of the heater is supplied and regulated by the DC regulated power. The surface of the resistance wire is covered with an insulating tape to reduce heat loss in the experiment. The condenser section of the heat pipe is inserted into the cooling chamber with a water inlet temperature of 25 °C while the evaporator section is heated by the resistance wire powered by the DC power supply. In the experiment, the heat load was calculated by $Q = UI$, where U and I are the output voltage and current, respectively, of the DC power with an accuracy of ±0.3%. Through an analysis of the heat balance between the evaporator and the condenser, the heat loss from the evaporator and adiabatic sections of the OHP to the environment in this study was less than 4.5% of the heat load input. The data acquisition system consists of type-T copper-constantan thermocouples, a MX-100 data acquisition system, and a personal computer. The type-T thermocouples were calibrated, and the total error in the temperature measurement was less than ±0.1 °C. In the experiment, eighteen type-T thermocouples were installed to measure the temperature of the evaporator section, the adiabatic section, and the condenser section; the thermocouples were mounted on the tube wall and fixed with special glue applied to the outside surface of the tube. The temperature response at the position being measured is recorded by computer.

Before the experiment, the air in the OHP is exhausted by a vacuum pump, and the working fluids are then charged into the heat pipe by a syringe. The charge ratio used in this experiment is 50% because many studies have shown that this is ratio at which the heat transfer performance is the best [16–18]. The charge ratio is calculated for the case of de-ionized water, by calculating the difference in weight between the empty and charged pipe. For the OHP with other working fluids, the same volume solution was charged to ensure that the same charge ratio was employed. In the experiment, the OHP with a tilt angle of 90° is only tested.

In this study, a de-ionized water, two types of binary fluids, and one type of ternary fluid were used as the working fluids of the OHP. The binary fluids include nanofluid and self-rewetting fluid. Ternary fluid is a mixed solution of self-rewetting fluids and nanofluid, called self-rewetting nanofluids. The nanofluid selected was graphene oxide dispersion solution (0.5 mg/ml). The particle diameter and thickness of graphene oxide is approximately 50–200 nm and 0.8–1.2 nm, respectively; its mono-layer ratios is 99%. Fig. 2 shows a photograph of graphene oxide dispersion solution, obtained using transmission electron microscopy (TEM) and scanning electron microscopy (SEM). Graphene oxide is formed as a cluster with its particle diameters ranging from 50 to 200 nm, as visualized by TEM imaging (Fig. 2(a)). In the inset of



(a) (b)

Fig. 1. Schematic of experimental system (a) photograph, (b) test loop.