VISUALIZATION EXPERIMENT ON THE EVAPORATION CHARACTERISTICS IN NANOPARTICLE-LADEN MESH-WICKED HEAT PIPES

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ABSTRACT

Visualization experiments are conducted on horizontal heat pipes to investigate the effects of Al_2O_3 or Cu nanoparticles laden in mesh-wick evaporator. The nanoparticle-laden evaporator appears quiescent with no sign of boiling. With 0.01g Cu nanoparticles sintered in the evaporator, the maximum heat load $Q_{\max}$ and the minimum evaporator resistance $R_{e,\min}$ are only slightly improved. With 0.01g or 0.04g sedimented Al_2O_3 nanoparticles, $R_{e,\min}$ reduces by 20%. $Q_{\max}$ increases by 20% with a larger amount of Al_2O_3 nanoparticles. $R_{e,\min}$ improvement may be attributed to additional heat paths with numerous micro menisci for thin-film evaporation. $Q_{\max}$ increases with enhanced capillarity by nanoparticle agglomerates.

Keywords: Heat pipe, mesh wick, nanofluids, nanoparticles, evaporator resistance

1. INTRODUCTION

Nanofluids have received tremendous attention because they have considerably enlarged thermal conductivities (Kebllinski, *et al.*, 2002). They have been adopted as the working fluid of mesh-wicked heat pipes (Tsai *et al.*, 2004; Do *et al.*, 2010; Liu and Zhu, 2011; Putra *et al.*, 2012), grooved heat pipes (Kang *et al.*, 2006; Liu and Lu, 2009; Yang *et al.*, 2008), sintered-powder heat pipes (Kang *et al.*, 2009). A number of recent review papers have been available (Liu and Li, 2012; Kumaresan and Venkatachalapathy, 2012; Sureshkumar *et al.*, 2013). All these studies reported significant performance enhancement. However, the mechanism for such improvements has not been well understood. While it has been attributed to the enlarged conductivity in some studies (Kang *et al.*, 2006; Liu and Lu, 2009; Yang *et al.*, 2008; Kang *et al.*, 2009), a different view suggested that the thin porous layer formed by sedimented nanoparticles, which increases the surface wettability and capillarity in the evaporator wick, may play a primary role (Do *et al.*, 2010). Unlike pulsating heat pipes in which strong oscillating motions keep the nanoparticles suspended during operation (Ma *et al.*, 2006; Lin *et al.*, 2008), the nanoparticles in regular heat pipes tend to sediment into a thin porous layer. Especially for mesh-wicked and sintered-powder heat pipes, it is expected that the sedimented nanoparticles would agglomerate and become trapped and immobile in the wicks. On the other hand, nanoparticles have been found to improve the pool boiling performance over a grooved surface (Liu *et al.*, 2007) and a flat surface (Kwark *et al.*, 2010) under certain conditions. Direct visualization of the evaporation characteristics in the nanoparticle-laden evaporator of operating heat pipes can be helpful in identifying the mechanism for performance enhancement. In the present study, we will apply our technique of visualization experiment on operating heat pipes (Liou *et al.*, 2010; Wong *et al.*, 2010; Wong *et al.*, 2012) to nanoparticles-laden evaporators.

2. EXPERIMENTAL METHODS

The experimental methods follow our recent works (Liou *et al.*, 2010; Wong *et al.*, 2010; Wong *et al.*, 2012). A detailed description of the heat pipe structure and experimental procedure is available in Ref. (Liou *et al.*, 2010). Here is given a brief description. Fig. 1 shows the overall test setup. The 22 mm $\times$ 11 mm heated surface of the heat pipe is connected to the uniform-temperature top surface (20 mm $\times$ 10 mm) of a heating post via a layer of thermal grease. The 22 mm width of the heated area is near the 25 mm width of the wick, making the thermal distribution of the heat pipe approximately one-dimensional. A cut-off trench, leaving a plate thickness of 1 mm, is made around the heated area and across the plate width (cf. Fig. 2) to reduce lateral conduction through the base plate. The heating post is carefully insulated except at its top end. The bottom of the other end of the heat pipe is cooled by a cold plate with running water at 20 °C. Except for these heated and cooled regions, the heat pipe is well insulated during operation. To prevent condensation on the visualization window, the insulation material over the window is removed shortly for recording only. A CCD camera equipped with a microscopic lens (Optem, Zoom 125) shoots vertically downward through the observation window. High magnification of the evaporation zone can be obtained. Illumination is provided by high-intensity LED lights.

Figure 2 shows the flat-plate heat pipe designed for visualization and thermal resistance measurement, along with the positions of seven implanted thermocouples. These thermocouples, K-type 1 mm-diameter stainless-steel sheathed probe (Omega, Inc.), are denoted by T1 to T7, respectively. Thermocouple signals are recorded by a data logger (Fluke, Hydra Series II) with a resolution of 0.1 $\square$. T1 and T2 are used to calculate the total heat load Q_t through the copper heating post. T3 measures in the middle of the copper plate at the center of the heated area. Suspended about 1 mm above the center of the evaporator, T4

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measures the vapor temperature leaving the evaporator. T5–T6 are managed to evaluate the lateral conduction through the copper plate (Liou *et al.*, 2010), Q_{cond} , as will be discussed later. T7 measures the copper plate temperature in the cooled area.

Fig. 1 Overall experimental setup.

Fig. 2 The flat-plate heat pipe along with thermocouple positions.

The 100 + 200 mesh wick, with an upper 100 mesh and a lower 200 mesh woven screen, is sintered on a 4 mm thick C1020 oxygenless copper base plate under a fixed pressure in a 800 °C hydrogen/nitrogen atmosphere for 2 h. To accommodate the wick, a region of 117 × 25 mm² on the upper surface of the base plate is cut lower by a depth of 1 mm. This is done to prevent the possibility that a small amount of the working liquid may cycle back via the narrow path between the o-ring and the copper plate, rather than through the wick. Before sintering, the screens and the copper plate are carefully cleaned. The heat pipe has a top glass window for observation. The internal space of the heat pipe is 120 × 30 × 7 mm³. With the contact surfaces between different pieces sealed with o-rings, the whole structure, including the wicked copper base plate, the top glass window, and the stainless-steel frames, is tightened with bolts. It is noted that excess charge is needed in the present experiments to compensate for the liquid accumulation at the corners, gaps and walls in the heat pipe. A fixed amount of 0.8 cm³ (the saturate charge is 0.5 cm³) of degassed de-ionized water or nanofluid is filled into the heat pipe right after it is evacuated down to a pressure of 1 × 10⁻² Torr. The heat load is increased stepwise from a low heat load, and data are taken under a thermally stable condition for each heat load.

Usually, the capillarity of the sintered copper wick degrades in air with time due to surface oxidation. In this work, the copper surface wettability is quantified by the contact angle of a sessile water drop on a smooth surface. The contact angle is measured on another plate, which has been taken out of the sintering oven simultaneously with the wicked copper plate, when the heat pipe is evacuated to 1 Torr. For all the tests, the static contact angles of water on a smooth copper surface are controlled at 10°–12°.

The evaporator resistance R_e is determined as

$$R_e = (T_3 - T_4)/Q, \quad (1)$$

where $Q = Q_t - Q_{\text{cond}}$. The net heat flux $q = Q/A_e$, with the heated area $A_e = 2.42 \text{ cm}^2$. In this study, the ratios of Q_{cond}/Q_t prior to the occurrence of local dryout are about 1.1–3%, smaller for a smaller evaporator resistance. The uncertainty in the measurements of Q is 7%. This is determined by comparing the output of the DC power supply and the estimated value based on the temperature difference (T1 - T2). The uncertainty in R_e values is also 7%, since the uncertainties primarily arose from those of Q , according to the definition of R_e in Eq. (1).

Two kinds of nanoparticles, Al₂O₃ and Cu, are laden in the evaporator wick. The Al₂O₃ nanoparticles are a commercial product with a monodisperse size of about 50 nm. The Cu nanoparticles, smaller than 100 nm, have been chemically made from Cu(NO₃)₂ in our lab. The two kinds of nanoparticles are laden into the evaporator in different manners. The Al₂O₃ nanoparticles are well blended in de-ionized water using an ultrasonic blender to form a nanofluid without surfactant. The nanofluid is then filled into the evacuated heat pipe. The Cu nanoparticles are weakly sintered within the wick in a 575 °C hydrogen/nitrogen atmosphere for 0.5 h before water filling. The mass of Cu nanoparticles sintered in the wick is 0.01 g. Fig. 3 shows an SEM image of Cu nanoparticles on a flat copper plate under the same sintering condition. The Cu nanoparticles can be seen to partially bonded into numerous large porous agglomerates. Fig. 4 shows a magnified image of a dried 100+200 mesh wick with Al₂O₃ nanoparticles dried after the filling. The Al₂O₃ nanoparticles distribute non-uniformly with large agglomerates due to inter-particle adhesion. With a fluid charge of 0.8 cm³, the fraction of the Cu nanoparticles is 1.25wt% (or 0.14vol%). However, because all Cu nanoparticles are located in the evaporator, such concentration values are not to be directly compared with the concentrations of nanofluids for which the nanoparticles may be distributed over the heat pipe. The amount of Al₂O₃ nanoparticles charged into the heat pipe is 0.01 g or 0.04 g. The fraction of the Al₂O₃ nanoparticles are 1.25wt% (or 0.31vol%) and 5wt% (or 1.25vol%), respectively. During liquid filling, the heat pipe is vertically placed with the evaporator at the bottom. Thus, the Al₂O₃ nanoparticles may be distributed over the heat pipe but somewhat denser at the evaporator.

Fig. 3 Cu nanoparticles sintered on a copper plate.

3. RESULTS AND DISCUSSION

Experiments were conducted for four different test cases with the 100+200 mesh wick and a fixed liquid charge of $v = 0.8 \text{ cm}^3$: (1) pure water without nanoparticles, (2) water with 0.01 g Cu nanoparticles sintered in the evaporator, (2) water with 0.01 g Al₂O₃ nanoparticles, and (4) water with 0.04 g Al₂O₃ nanoparticles. Visualization was made for the evaporation process and the evaporator resistances were measured versus heat load until local dryout occurred in the evaporator.

Fig. 4 Al_2O_3 nanoparticles in a dry 100+200 mesh wick.

3.1 Visualization Results

For all these cases, the evaporator appears quiescent during operation with no sign of nucleate boiling. The water layer in the evaporator becomes thinner with the increase of heat load. In response to the thinning water layer, the evaporator resistance gradually decreases to a minimum value, $R_{e,\min}$, before it rises as a result of local dryout in the evaporator. Representatively, Fig. 5 compares the images near the center of the evaporator at $Q = 0$ W and 79.3 W for a test charged with pure water. At $Q = 0$ W, the wick is mostly immersed in the liquid, with exposed peaks of the upper screen. At $Q = 79.3$ W, when $R_{e,\min}$ occurs, most of the upper 100 mesh screen has been exposed but the lower 200 mesh screen is still immersed. Under heat load, the thickness of the liquid layer in the evaporator decreases toward the evaporator end of the heat pipe because the supply of the condensed liquid is gradually consumed in the evaporator. At the condition with $R_{e,\min}$, the liquid layer in the wick near the end-edge of the evaporator usually is hardly visible, as illustrated in Fig. 6 for the case with 0.01 g Al_2O_3 nanoparticles at $Q = 84.3$ W. The above characteristics are similar to our previous results for sintered multi-layer copper mesh wicks (Liou *et al.*, 2010) and sintered irregular-powder wicks (Wong *et al.*, 2010) using water as the working fluid. It is noted that nucleate boiling was not observed with a superheat as large as 13.7 K in our previous work (Wong *et al.*, 2010). The present tests indicate that the nanoparticles laden in the evaporator fail to help activate nucleate boiling when the working fluid is water.

Fig. 5 Wetted 100+200 mesh evaporator with pure water, (a) at $Q = 0$ W; (b) at $Q = 79.3$ W with $R_{e,\min}$.

Figure 7 presents the images at $Q_{\max}$, when $R_{e,\min}$ occurs, near the evaporator center for three different cases. In Fig. 7a and 7b, the lower screen is immersed in water. In Fig. 7c for the case with 0.04 g Al_2O_3 nanoparticles, the mesh wires of the lower 200 mesh screen are buried

in the nanoparticle layer. The liquid seems absorbed in the thick porous nanoparticle layer, which will be shown to result in a larger $Q_{\max}$.

Fig. 6 Nearly dried wick at the evaporator end-edge when $R_{e,\min}$ occurs for the case with 0.01g Al_2O_3 nanoparticles, $Q = 84.3$ W.

Fig. 7 Evaporator images at $R_{e,\min}$, (a) water with 0.01g sintered Cu nanoparticles, $Q_{\max} = 81.0$ W; (b) water with 0.01g Al_2O_3 nanoparticles, $Q_{\max} = 84.3$ W; (c) water with 0.04g Al_2O_3 nanoparticles, $Q_{\max} = 93.9$ W.

3.2 Evaporator Performance

Figure 8 compares the evaporator resistances R_e versus heat load Q for the four cases. As mentioned earlier, the present experimental technique has a drawback that a small amount of working liquid would be trapped on the inner corners, gaps, and wall of the chamber. According to our experience through tests without nanoparticles, this drawback, along with finite heat load increment, introduces disperse in $Q_{\max}$ of roughly $\pm 8\%$, whereas $R_{e,\min}$ is hardly influenced (Liou, *et al.*, 2010; Wong *et al.*, 2010; Wong *et al.*, 2012). Similar to the characteristics observed in these tests, the evaporator resistances in the present cases reduce with increasing heat load until local dryout occurs. For the case with 0.01 g sintered Cu nanoparticles, although there is a slight increase in $Q_{\max}$, it is limited when the uncertainty associated with the present experimental technique is considered. Slight reduction in $R_{e,\min}$ is shown. Since $R_{e,\min}$ occurs when the liquid layer in the evaporator wick is thinner, the nanoparticles near the evaporator end where the liquid layer is thinnest can be exposed. In this situation, smaller $R_{e,\min}$ may be attributed to the increased thermal paths provided by the nanoparticles. On the numerous additional micro- and nano-scale menisci, thin-film evaporation occurs. Since the copper nanoparticles are sintered on the base plate, the thermal resistances through these new paths should be pretty low. As a result, a lower overall evaporator resistance $R_{e,\min}$ is reached. For the case with 0.01 g Al_2O_3 nanoparticles, the $R_{e,\min}$ is reduced by 20%, even more than the case with 0.01 g sintered Cu nanoparticles. The reason may be explained as follows. Both sintered Cu nanoparticles and sedimented Al_2O_3 nanoparticles can provide additional thermal paths for thin-film evaporation. Between the copper surfaces and the Al_2O_3 nanoparticles there exists contact resistance which introduces higher thermal resistance. However, the volume fraction of Al_2O_3 nanoparticles (0.31 vol%) is larger than that of Cu

nanoparticles (0.14 vol%) due to the lower density of Al_2O_3 . Besides, the sintered Cu nanoparticles are largely sintered together, as shown in Fig. 3. Therefore, a much larger number of micro- and nano-scale menisci can be offered by the Al_2O_3 nanoparticles. With much more area available for thin-film evaporation, the $R_{e,\min}$ for the case with 0.01 g Al_2O_3 nanoparticles appears lower than the sintered Cu-nanoparticle case. With 0.04 g Al_2O_3 nanoparticles, the $R_{e,\min}$ is about the same as that with 0.01 g Al_2O_3 nanoparticles. Comparing Figs. 7b and 7c, we can see that the upper mesh layer is covered with nanoparticles for the 0.04 g case. It is likely that the particle densities near the bottom are similar in the two cases. The $R_{e,\min}$ s are therefore similar. As to the $Q_{\max}$ of these two cases, the increase is 6% and 20%, respectively, in comparison with the case without nanoparticles. In spite of the $\pm 8\%$ uncertainty in the present experiments, the increasing trend in $Q_{\max}$ with increased amount of Al_2O_3 nanoparticles reliably indicates the stronger effect at a larger nanoparticle loading. The reasons for improved $Q_{\max}$ may be related to the enhanced capillarity offered by the nanoparticle agglomerates (Do *et al.*, 2010).

Fig. 8 Evaporator resistances R_e versus heat load Q for various working fluids, $\nu = 0.8 \text{ cm}^3$.

4. CONCLUSIONS

Visualization experiments have been conducted to investigate the evaporation characteristics in the nanoparticle-laden mesh-wick evaporator of heat pipe with water as the working fluid. In one case, an amount of 0.01 g Cu nanoparticles is sintered in the evaporator; in two other cases, 0.8 g nanofluid respectively containing 0.01 g (0.31 vol%) or 0.04 g (1.25 vol%) Al_2O_3 nanoparticles is filled into the heat pipe. The tests are conducted as the Al_2O_3 nanoparticles have sedimented. The following conclusions are reached:

1. The evaporation process of nanoparticle-laden mesh wicks is similar to that of mesh wicks without nanoparticles. With increasing heat load, the liquid layer gradually recedes and the evaporator resistance decreases to a minimum value before a rise in response to the occurrence of local dryout in the evaporator. In all the test cases, the evaporator appears quiescent with no nucleate boiling observed.
2. The minimum evaporator resistances are slightly improved in the case with 0.01 g sintered Cu nanoparticles. Stronger improvements are obtained in the minimum evaporator resistance with 0.01 g or 0.04 g sedimented Al_2O_3 nanoparticles. In the latter case, the minimum evaporator resistance is reduced by about 20%. This may be because the nanoparticles provide additional heat paths with a large number of micro- and nano-scale menisci for thin-film evaporation.
3. The maximum heat load is slightly increased in the case with 0.01 g sintered Cu nanoparticles. The increases are more significant in the cases with 0.01 g or 0.04 g Al_2O_3 nanoparticles. In the latter case the increase reaches about

20%. This may result from the enhanced capillarity offered by the nanoparticle agglomerates in the evaporator.

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NOMENCLATURE

A_e	heated area (cm^2)
q	heat flux (W/cm^2)
Q	heat flow (W)
R_e	evaporator resistance (K/W)
ν	liquid charge (cm^3)
T	thermocouple

Subscripts

cond	lateral conduction
e	evaporator
max	maximum
min	minimum
t	total

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