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Heat transfer enhancement mechanism of pool boiling with self-rewetting fluid

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ABSTRACT

Self-rewetting fluid (SRWF) is believed to be a promising and useful working liquid for the application of boiling to the development of high efficient cooling devices with micro structure. To clarify the fundamental heat transfer characteristic and heat transfer enhancement mechanism of pool boiling with SRWF, by employing dilute heptanol aqueous solution as SRWF, a series of boiling experiments have been carried out. In pool boiling tests, a boiling system using a horizontal heated wire was employed. The experimental results show that, the critical heat flux (CHF) of the SRWF increased up to 2.52 times the CHF of water, and the heat transfer enhancement mechanism was discussed. With a high speed video camera, the nucleation boiling process on the heated wire has been recorded. It is found out that, the bubble size of the SRWF is much smaller than that of pure water, and the bubbles of SRWF were hard to coalesce, which is beneficial for the application in small thermal devices. Furthermore, when the heat flux was up to a certain value, the micro-bubble emission boiling (MEB) appeared in the SRWF. It can be concluded that the Marangoni convection induced by surface tension gradient of SRWF is probably one of the key factors causing the formation of MEB.

1. Introduction

Boiling is one of the most efficient mode of heat transfer. Due to its high efficiency, boiling heat transfer has been widely used in industries and the cooling devices such as CPUs and LED chips. However, the recent rapid increase of power consumption in electronic packages including highly integrated circuits causes the major issue of the cooling. The heat flux is very concentrated, and it is difficult to cool down the temperature in time. Moreover, the cooling flow passages in the small thermal device are usually mini, and the generating bubbles by boiling of the normal working fluids are usually large in size when compared with the size of the flow passage, yielding high pressure drop or unstable flow due to the flow blockage by the vapor bubbles [1]. So the bubble size of the working fluid needs to be sufficiently small for the application of boiling to small thermal devices.

Subcooled boiling is a recommended boiling mode for efficient cooling or temperature control systems because it has high heat transfer rate [2,3]. Furthermore, at high heat flux of highly subcooled boiling, bubbles emitted from the heated surface become very small, which can fulfill the application of boiling to small thermal devices. Inada et al. [4] carried out pool boiling experiments about a heated copper cylindrical tip submerged in water at the subcooling of 30 K with the void probe method. They discovered the existence of microbubble emission boiling (MEB) phenomena, where the bubbles were generated on the heated surface at high heat flux and broken to many microbubbles after contacting with the surrounding subcooled liquid. Subsequently, Shoji and Yoshihara [3] measured the critical heat flux (CHF) of highly subcooled pool boiling of water on a thin heated wire and found that the CHF could reach 10 MW/m^2. With a high-speed camera and a microscope, they found that MEB occurred on the wire at the subcooling temperature of more than 40 K. Wang and Cheng [5] fabricated a microchannel integrated with a Pt microheater to investigate subcooled flow boiling and microbubble emission boiling (MEB) phenomenon of water. They also found that the microbubble emission boiling (MEB) phenomena occurred in a microchannel with a high inlet subcooling temperature and at a high heat flux. However, keeping high subcooled temperature in limited area is rather hard, since the bulk temperature of flowing liquid is easy to increase in small passages subjected to high heat flux due to the small thermal capacity of the flow. The

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utilization of some kind of new efficient working fluids may be one of the possible options to solve this problem.

It has been known that the CHF in pool boiling of water is often enhanced when small amounts of alcohols or ketones are added to the water. For example, only a small amount of addition of butanol to water, generating bubbles become very small even at the high temperature close to the saturation temperature of the solution. Moreover, it is possible to enhance CHF a few times higher than that of pure water. Thus the aqueous solution of butanol has a promising possibility in the use of micro or mini channel thermal systems [6]. Many researchers [7–11] carried out experiments of boiling on horizontal wires with aqueous binary mixtures. Their results showed that the CHF was enhanced 1.7–3.4 times compared to the CHF of water. Furthermore, self-rewetting fluid (SRWF) is believed to be a promising and useful working liquid for the application of boiling to the development of high efficient cooling devices with micro structure [12,13]. SRWF is non-azeotropic solutions satisfied to enjoy a particular surface tension behavior – an increase in the surface tension with increasing temperature. Due to the Marangoni effect caused by the concentration gradient and the temperature gradient, the fluid spontaneously flows to the hotter region, thus enhancing the heat transfer and preventing the dry out phenomenon of the heated surface. Abe [14] employed 1-butanol aqueous solution (6 wt%), 1-pentanol aqueous solution (2 wt%), and 2-pentanol aqueous solution (4.8 wt%) as SRWF. A significant enhancement in nucleate boiling heat transfer was noticed in self-rewetting fluids. Sakashita [15] carried out experiments on the CHF of SRWF (2-propanol/water mixtures) in pool boiling on an upward-facing heated surface under atmospheric pressure. They found out that the CHF of 2-propanol/water mixtures are enhanced 1.7 times compared with the CHF of water at a 2-propanol concentration of around 3.0–4.7 mol%. To sum up, the heat transfer enhancement effect of the self-rewetting fluid is obvious. However, the fundamental characteristics of boiling of such solution have not been fully understood, and the heat transfer enhancement mechanism of self-rewetting fluid has not been clear enough. What is more, seldom articles have examined the microbubble emission boiling (MEB) phenomenon of SRWF, and its formation mechanism is still unknown.

All above, there are a number of studies on the CHF of binary mixtures, but the mechanism of the CHF enhancement of the self-rewetting fluid (SRWF) is not clear. To clarify the fundamental heat transfer characteristic and heat transfer enhancement mechanism of pool boiling with self-rewetting fluid (SRWF), by employing dilute heptanol aqueous solution as SRWF, a series of boiling experiments have been carried out. In pool boiling tests, a boiling system using horizontal heated wires was employed. Furthermore, in order to clarify the heat transfer enhancement mechanism of pool boiling with self-rewetting fluid, the nucleate boiling processes have been recorded using a high speed CCD. The experimental results are shown as follows.

2. Experimental details

The experiments were carried out in pool boiling under atmospheric pressure. The dilute heptanol aqueous solution was heated on a horizontal platinum wire. The schematic diagram of the experimental apparatus is shown in Fig. 1. The apparatus consists of a Pyrex glass water vessel for the observation, a liquid temperature controlling unit, electronic data acquisition system, and optical observation system. The diameter and the length of the platinum wire were fixed to be 0.2 and 20 mm, respectively. Before every experiment, to ensure the deaeration, the working fluid in the vessel was heated to be boiling for at least 1 h. The heated wire and the water vessel were carefully cleaned with acetone prior to

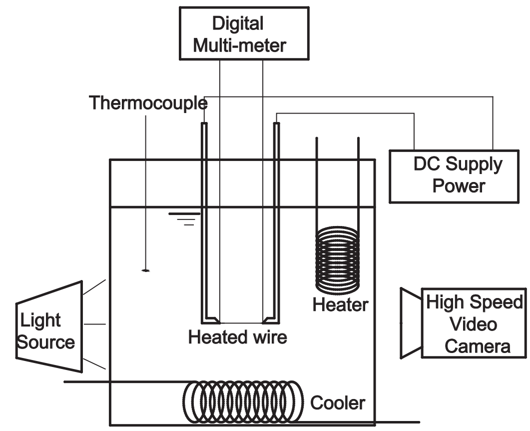

Fig. 1. The experimental apparatus.

the experiment. The test wire was heated through the electrical rods by DC power supply (MCH 1550). To avoid the perturbation of the boiling liquid and degrade the effect of the subcooling, the temperature of test liquid in the vessel was controlled and maintained to be 99 ± 0.5 °C using an auxiliary heater and cooler which is controlled by a thermostatic bath. A thermocouple was used to monitor the bulk liquid temperature within ±0.5 °C throughout each experimental run, therefore, the uncertainty in the measurement for temperature is less than 0.5 °C. The cooler inside the condenser is the coiled copper pipes in which tap water constantly flows. The upside of the vessel was open to the air and the system pressure was maintained at the atmospheric pressure. The concentration of test liquid (heptanol aqueous solutions) was realized to be a prescribed value by mixing water and heptanol with a corresponding ratio of weights. The concentration was 0.1 wt%. (0.1 wt% is the saturation concentration at 18 °C) The heat flux of the test wire was changed by controlling the applied electric power in the range from low heat flux nucleate boiling to critical heat flux, and the heat flux was stepwise increased up to CHF at which the experiment was stopped. The heat flux was increased at an increment of 5% in a previous heat flux, so the onset of boiling and the CHF were measured within an accuracy of 5%. The temperature of the wire was determined from the temperature dependence of electric resistance of the test wire, and the temperature-electric resistance characteristic of the platinum wire is given in [16]. The characteristic curve is in agreement with experimental data within a mean error of 8%.

In the experiment, an observation system was employed to capture the boiling behaviors close to the heated wire. The overall aspects of boiling and the behaviors of generating bubbles were observed using high-speed video (American Fastec Corporation, model Troubleshooter HR) whose frame rate is up to 1000 fps. The images were recorded digitally inside.

3. Results and discussion

3.1. Critical heat flux

Fig. 2 shows the dry out phenomenon of the heated wire. When the phenomenon came up, the heated wire reached the critical heat flux, and the experiment was stopped. Fig. 3 shows the boiling curve of the pure water and the SRWF. It is found from the results that the CHF of water reaches 0.85 MW/m^2, while the heptanol solutions show much better heat transfer performance. The CHFs is 2.14 MW/m^2 for the 0.1 wt% heptanol solutions. The CHF of the SRWF of 0.1 wt% heptanol solutions increased up to 2.52 times the CHF of water. The CHF value has been greatly improved, which