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Boiling heat transfer enhancement by impurities deposition of tap water

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ABSTRACT

We studied the effectiveness of using tap water and deionized water as working fluids in enhancing critical heat flux levels. During boiling processes, impurities from tap water formed a thin film deposit on a substrate. This thin film layer substantially improved the wettability of the surface and reduced the contact angle of the surface from 90° to <10°. To investigate the properties of the thin film layer, we used a scanning electron microscope equipped with an X-ray energy dispersive spectrometer, and the results confirmed that the surface was composed of impurities.

1. Introduction

With the increasing efficiency for cooling of high temperature of surface, liquid-vapor heat transfer has become an attractive heat transfer technique. For example, heat pipes and vapor chambers have been widely used for cooling in the heat exchanger and electric device [1,2]. Favorable evaporation performance of heat pipes or vapor chambers considerably improves the computational efficiency of devices. To obtain a favorable boiling heat transfer performance from heat pipes and vapor chambers, many critical factors must be considered, the effects for surface including, surface characteristics [3], wettability [4,5], and capillary force of microstructures [6].

However, the working fluid could also have significant effect on boiling heat transfer. Water is the optimal working fluid for use in heat pipes or vapor chambers for cooling electronic devices, because water is inexpensive, environmentally friendly, and demonstrates a favorable figure of merit within the operating temperature range of heat pipes for cooling high power devices. Currently, deionized (DI) water is one of the working fluid used in commercial heat pipes and vapor chambers. Heat pipe and vapor chamber manufacturers are concerned that impurity deposits in tap water may considerably affect the performance of their products. However, the manufacturers generally establish a system to convert tap water into DI water. Such a system is not only expensive but also energy inefficient. Working fluid has fine particles of impurity may improve the boiling heat transfer such as tap water. In recent years, numerous researchers have conducted studies by using nanofluids as the working fluid in heat pipes and vapor chambers [7] or in pool boiling [8–13]. Most studies have observed the thermal performance of heat pipes or the critical heat flux (CHF) in pool boiling and discovered that thermal performance can be considerably enhanced by using nanofluids as the working fluid. Moreover, nanofluids can enhance the CHF in pool boiling. Various materials have been tested in nanofluids including alumina (Al_2O_3) [10], zirconia (ZrO_2) [11], silica (SiO_2) [12], and titanium dioxide (TiO_2) [13], and such materials have been reported to be associated with 10–200% CHF improvements. During nucleate boiling, a substantial amount of nanoparticles were found to be deposited on the heated surface; therefore, surface properties including the roughness, wettability, and capillary wicking performance have been measured. Because impurities deposited from tap water exhibit material properties similar to that of the nanoparticles in nanofluids, our objective was to investigate how tap water impurities deposited on a heated surface influence heat transfer and CHF in pool boiling. If material impurities deposited from working fluids are conducive to heat transfer in pool boiling, then heat pipe and vapor chamber manufacturers can consider bypassing energy-intensive processes completely by converting tap water into DI water.

To prove the preceding statement, we investigated how working fluid material impurities deposited on a heated surface influence heat transfer in nucleate boiling. Tap water and DI water were used as the working fluids to systematically investigate

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how the deposition of material impurities affects heat transfer in nucleate boiling. The experimental results provided insights into how the deposited impurities change the characteristics of heat transfer from wall superheat.

2. Pool boiling experiment

We used the setup showed in a Fig. 1 of pool boiling experiments involving different working fluids. Tap water and DI water served as the working fluids in a tank. A Cu block with a heated surface was fixed to the bottom of the pool tank, and holes 0.7 mm deep were drilled on the sides of the Cu block. A thermocouple was placed at the top, side, and bottom of each hole, and the thermocouples were attached using sink grease to reduce contact resistance; the accuracy of the T-type thermocouples was ±0.1 °C. The holes were separated by a distance of 4 mm. The condenser was fixed on the top of the tank to maintain the condensed liquid in the pool and the temperature of working fluid adjusted to the saturated temperature (100 °C) by heater. The camera was placed on the side of the tank to record the photos of growth bubbles. The heat source was placed under the Cu block. The heating source was supplied by four 200 W electric heating rods. The control heating source passed through an electricity supplier and outputs. After the surface was heated, a thermometer recorder (Yokogawa MX-100) was used to read the data measured using the thermocouples. The data were then transferred to a computer for analysis. Fourier's law was used to calculate the heat flux into the boiling liquid. An energy balance was used to calculate the heat loss, which was 16%. All thermocouples were calibrated using an OMEGA-HH41 thermistor. The accuracy of the T-type thermocouples used in the present experiments was ±0.1 °C. The maximum fabrication error of the temperature measuring positions was 0.15 mm. The overall maximum uncertainties in the heat flux and wall superheat measurements were 5.1% and 5.8% at $q = 100\ \mathrm{kW/m^2}$, and 1.1% and 1.6% at $q = 1000\ \mathrm{kW/m^2}$, respectively.

3. Elemental analysis

Investigating the deposition of impurities on the heated surface entailed conducting elemental analysis by using a scanning electron microscope equipped with an X-ray energy dispersive spectrometer (SEM-EDS; model: JSM-6510). This instrument emits a beam of electrons to excite an electron in an inner shell, ejecting it from the shell and creating an electron hole at its position. An electron from an outer, higher-energy shell then fills the hole, and the difference in energy between the higher- and lower-energy shells may be released in the form of an X-ray. This unique X-ray can be captured and measured to understand the different elements on a surface.

4. Results

Fig. 2 illustrates boiling curves of the wall superheat versus heat flux derived from the pool boiling experiment. The CHF was located at higher temperatures, at which the curves demonstrated sharp variations. These curves were plotted using three sets of experimental data of high repeatability. The first set of data, DI water-1, 2, was derived from experiments that involved using plain Cu as the heated surface, with DI water serving as working fluid; these data revealed that the CHF was approximately 1000 $\mathrm{kW/m^2}$. Zuber developed a model for predicting the CHF and this model shows that the CHF for water is 1100 $\mathrm{kW/m^2}$ [14]. Gerardi et al. [15] reported 900 $\mathrm{kW/m^2}$ of the CHF and 13° of superheat by using the ITO surface with working fluid of DI water. This study presented results similar to my experimental data. However, we determined that the CHF increased for all experiments that entailed using plain Cu as the heated surface, but with tap water serving as the working fluid. The second set of data was derived from experiments that involved using tap water-1, 2, 3 as the working fluid; these data revealed that the CHF values were 1500 $\mathrm{kW/m^2}$. The definition of exposure time is when the plain Cu surface in boiling test of the boiling curve reached CHF values. Comparing tap water and DI water as working fluids revealed that tap water was associated with a higher heat flux value. These CHF enhancement results indicate that some impurities from tap water might be deposited on the heated surface during boiling processes. Deposited materials change the characteristics, such as the geography, roughness, and wettability, of a heated surface. In this study, we denoted such a surface as an "impurity-coated surface." To confirm the effect of impurities deposited on the heated surface, we simply executed the boiling experiments again by using various impurity-coated surfaces and DI water as the working fluid.

We conducted experiments by using tap water-1, 2, 3, and impurity-coated surfaces-1, 2, 3 were produced. Subsequently, we executed additional boiling experiments by using impurity-coated surfaces-1, 2, 3, with DI water serving as the working fluid. The CHF value derived from the experiments involving the impurity-coated surfaces and DI water (Im-Coated-Sur-DI) was

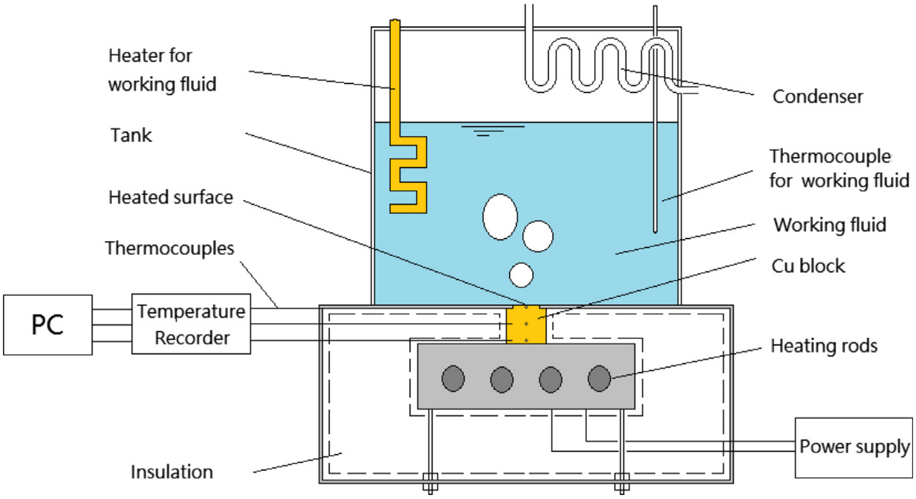

Fig. 1. Boiling experimental facility setup.