Effect of Surface Wettability and Spreading on Nanofluids Boiling Heat Transfer

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***Abstract*– Surface wettability is one of the mechanisms responsible for the enhancement of pool boiling heat transfer. This work investigates the effect of surface wettability and spreading on nanofluids pool boiling heat transfer. Water, ethylene glycol, water-ethylene-glycol base fluids and nanofluids containing TiO_2 in different concentrations were studied on polished stainless steel substrate in an environmental chamber at 20, 25, 50, 70 and 80^{0}C respectively.**

***Keywords*– Contact Angle, Pool Boiling and Surface Wettability**

I. INTRODUCTION

Cooling challenges is one of the top technical problems facing high-tech industries such as microelectronics, nuclear power plants, and automobiles. Until the evolution of nanofluids technology, conventional methods to increase heat flux rates included extended surfaces such as fins and micro-channels and increasing flow rates or pumping power, etc.

However, current design solutions already push available technology to its limits. New technologies and new advanced fluids with potential to improve flow and thermal characteristics are of critical importance. Studies of thermal conductivity of suspensions as enhanced heat transfer fluids have been confined to mm-sized particles but the major challenge has been the rapid settling of these particles in fluids. Nanofluids are promising to meet these challenges.

Pool boiling is a type of boiling where the fluid is stationary at the beginning with respect to the heating surface. Example of pool boiling can be imagined traditionally when using a gas cooker to boil water in a kettle. The degree to which water makes and retains contact with the surface of the kettle affects the rate of boiling and heat transfer. In the field of engineering, a more suitable illustration is seen in liquid cooled high-end computers.

The ability of a liquid to make and retain contact easily with a heater surface is paramount in improving efficiency of heat transfer system. Understanding the surface wettability of cooling fluids and method of enhancement at little or no cost is of great importance in engineering and technology.

Coolants with high wettability would spread quickly on the heating surface depending on its surface chemistry and the chemical composition of the liquid. A hydrophobic surface tends to avoid or minimize contact with liquids while a hydrophilic surface promotes contact, causing the liquid to spread easily.

II. EXPERIMENT METHODOLOGY

All nanofluids used were produced by evaporation and inert-gas condensation processing, and then dispersed in base fluid by mechanical agitation.Water, ethylene and water-ethylene-glycol WEG, were used as base fluids. Spherical morphology nanoparticles of titanium dioxide were used. Particle size was determined by Malvern Nanosizer at 20^{0}C. Distilled water was used throughout the experiment.

Fig. 1: Malvern nanosizer for particle size measurement and bimolecular characterization

A) Contact Angle Measurement

Sessile drop fitting method was used because it can be applied to Young-Laplace equation for quick calculation of interfacial tension since the needle diameter and density of the drop are known. For static contact angles greater than 30^0, interfacial tension was calculated separately to get reliable results.

Time-dependent static contact angle was measured other than advancing or receding contact angle. Time-dependent static contact angle enables understanding of settling effects of nanoparticles and alteration of liquid composition which was achieved by adding ethylene glycol to water.

The Interfacial tension and time-dependent static contact angle were measured using a goniometer (KRUSS GmbH). Time-dependent static contact angle was created by dispensing the liquid/nanofluid unto a solid substrate (i.e., polished steel). A screw driven syringe pump suspended on the DSA was used to infuse liquid onto the surface through a 1.83 mm ID microneedle. A series of digital still photographs were captured by the Nikon D50 camera with a sigma macro lens. Contact angles were then measured from the digital images using the sessile drop fitting method. Measurements were carried out in an environmental chamber at 20, 25, 50, 70 and 80^{0}C respectively.

The solid surface studied is polished stainless steel.

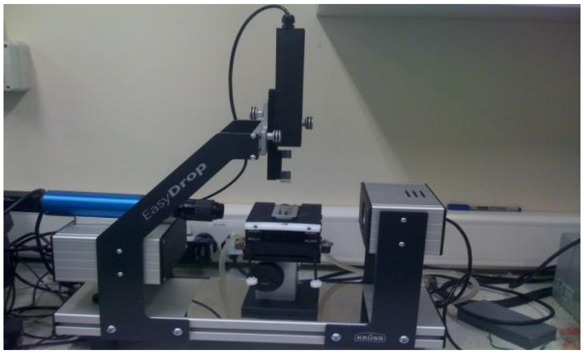

Fig. 2(a): A photograph of Kruss goniometer for contact angle measurement

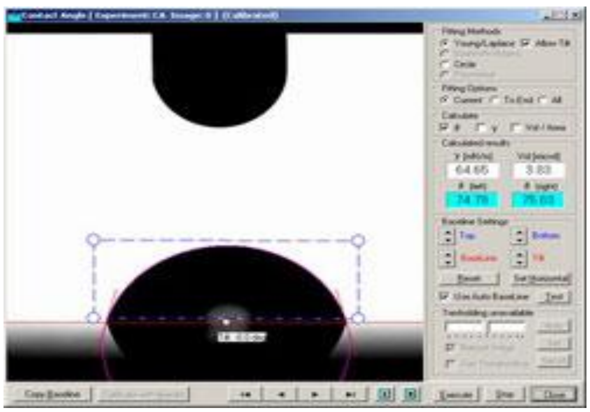

Fig.2(b): Screen capture of nanofluid drop on polished steel

III. RESULTS AND DISCUSSIONS

A) Temperature Dependence of Static Contact Angle

Contact angle is equal to the inverse of surface wettability and is a measure of the effectiveness of heat transfer, the higher the contact angle the less wettable a cooling fluid is. Temperature dependence of the static contact angle was investigated by measuring the contact angle at different temperatures. The result was analysed graphically for each sample tested.

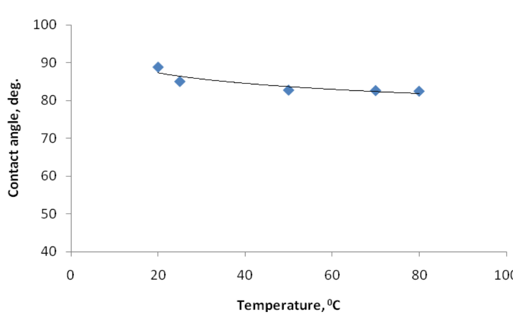

Fig. 3: Contact angle of pure water measured on polished steel substrate

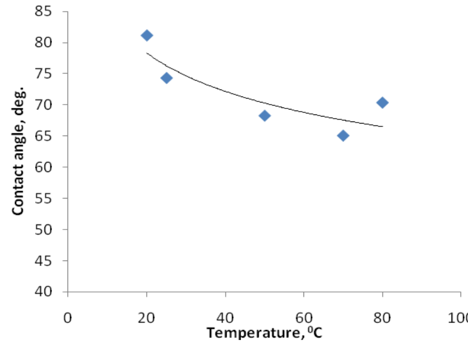

Fig. 4: Contact angle of pure EG measured on polished steel substrate

From the test result of pure base fluids on polished steel, ethylene glycol proved more wettable than pure water, evident in reduction of static contact angle which validates its use as a medium for convective heat transfer, for example in liquid cooled super computers.

B) Effect of Ethylene Glycol on the Surface Wettability of Water

The effect of ethylene glycol on the wetting properties of water was investigated by measuring the time-dependent static contact angle of pure water, ethylene glycol and water-ethylene-glycol base fluids on polished steel template at 20^{0}C for 180 seconds.

Table 1: Experiment test conditions for pure water, EG and WEG

Sample	pH	Contact angle average, ^{0}C
Pure water	7	88
EG	7	71
25%vol. WEG	7	85

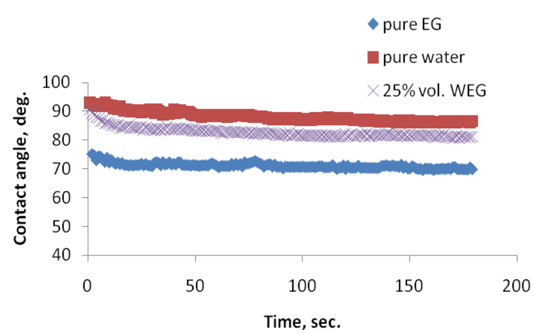

Fig. 5: Measured values of contact angles as a function of time for pure water, ethylene glycol and mixed water-ethylene glycol base fluids

To understand the dramatic enhancement of wettability of water by mixing water with EG, Young's equation $\cos\theta = (\Upsilon_{SV} - \Upsilon_{SL}) / \Upsilon_{LV}$ was considered, which relates the static contact angle to the adhesion tension $\Upsilon_{SV} - \Upsilon_{SL}$ and the surface tension Υ_{LV} [Young, T., 1805]. At a given value of adhesion tension $\Upsilon_{SV} - \Upsilon_{SL}$, surface tension of water at 20^{0}C

≈73mN/m compared to ethylene glycol 47.3mN/m. Young's equation predicts higher contact angle for water, which is in reasonable agreement with this result. Contact angle of pure water was calculated to be 88^{0}C, EG 71^{0}C and 25% WEG 85^{0}C respectively. Depending on the concentration of ethylene glycol by volume, the wettability of water is enhanced.

Next, we added nanoparticles to water, EG and WEG to investigate the mechanism responsible for improved heat transfer properties of nanofluids compared with base fluids.

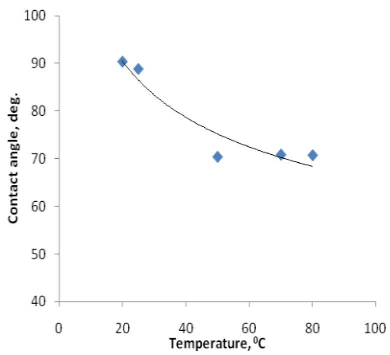

Fig. 6: Contact angle of 0.01%wt spherical TiO_2-water pH11 after boiling measured on polished steel substrate

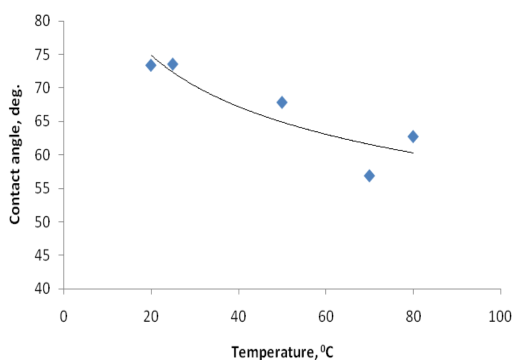

Fig. 7: Contact angle of 0.01%wt spherical TiO_2-WEG pH 11 before boiling measured on polished steel substrate

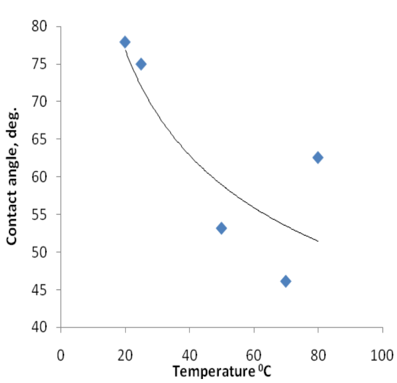

Fig. 8: Contact angle of 0.1%wt spherical TiO_2-WEG pH 11 before boiling measured on polished steel substrate

C) Physical Mechanism Responsible for Surface Wettability Change

Addition of ethylene glycol reduces the surface tension of water and the interfacial tension between water-EG nanofluid and the heater surface which is the solid substrate, causing surface wettability and spreading enhancement.

Also, as the temperature of the heating surface increases to 80^{0}C, dry out on the heated surface is reduced, and the critical heat flux condition is delayed [Hahne and Grigull, 1977]. Critical heat flux is the degradation of heat transfer and the departure from nucleate boiling.

D) Surface Wettability Change due to Boiling

Surface wettability change due to boiling was investigated using different concentrations of nanofluids before and after boiling. The time-dependent static contact angle was measured for each sample on polished steel template at 20^{0}C.

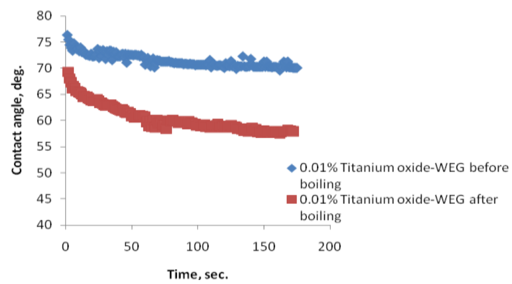

Fig. 9: Contact angle variation with time for 0.01%wt spherical TiO_2-WEG pH 11 before and after boiling

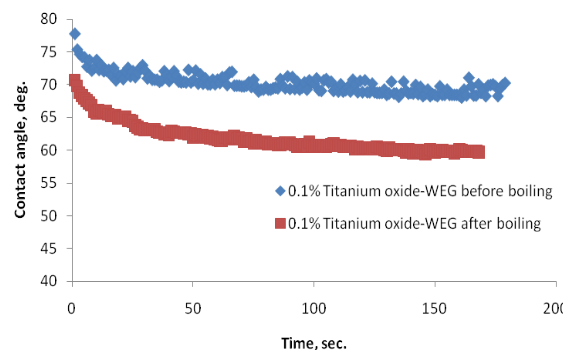

Fig. 10: Contact angle variation with time for 0.1%wt spherical TiO_2-WEG pH 11 before and after boiling

Nanofluids appeared to be more wettable after boiling. The contact angle reduction is attributed to changes in surface energy and surface morphology during boiling (J. Kim, 2006).

IV. CONCLUSION AND RECOMMENDATION

Our result shows that the surface wettability is one of the factors responsible for the enhancement of nanofluid boiling heat transfer. Ethylene glycol was found to improve the wettability of water based nanofluids by reducing the surface tension of water.

We restricted our study to pool boiling heat transfer applications by measuring only the static contact angle of nanofluids, we have not studied advancing contact angle for understanding flow based cooling applications. Also, we noted that increase in particle concentration further enhanced nanofluid surface wettability but particle aggregation required for enhancement of heat transfer properties of nanofluids conversely increases fluid viscosity which will require higher pumping power in flow based cooling applications, rendering the benefit of the technology questionable. Further research in this direction is recommended to gain optimum particle concentration at which viscosity effect will be kept at bay.

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