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Wettability of Heated Surfaces under Pool Boiling using Surfactant Solutions and Nano-fluids

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1. Introduction

The wettability of the heated surface under pool boiling of surfactant solutions and nano-fluids has been investigated. Tri-sodium phosphate (TSP, Na3PO4) solutions (0.01, 0.05, .0.08, .0.1 w%) and Aluminum oxide (Al2O3) nano-fluids (NF) (0.5, 1, 2, 4 w%) were prepared for experiments. Stainless steel (SUS 304) strips (30×30×3 mm) were heated and quenched in the prepared solutions. Before complete quenching, when the surface temperature was 150±10 °C (nucleate boiling region), the strip was taken out and excessive liquid on the surface was removed. Contact angles of pure water and the solutions on the quenched surface and fresh surface were measured.

Contact angles of pure water on the quenched surfaces (5~25°) were much smaller than those on the fresh surface (65~70°). The solutions (TSP, NF) on the quenched surface shows the smallest contact angle (5~15°).

Through the visual observation of quenched surfaces, deposition of TSP and nano-particle was observed. Surface deposited TSP and nano-particle could affect surface energy of the strips and enhance hydrophilicity of the surfaces. Several implications of the experimental results on the pool boiling CHF model and CHF enhancement using TSP and NF were discussed.

2. Methods and Results

Test specimen made of SS304 (30×30×3 mm) and mirror-like polished was heated by alcohol lamp up to 400 ^{o}C and quenched in pure water, TSP solutions and nano-fluids. Before complete quenching, when the surface temperature was 150±10 °C (nucleate boiling region), the strip was taken out and excessive liquid on the surface was removed. Temperature was measured by Type-K thermocouple (outer diameter 0.5 mm). For understanding effect of quenching temperature, specimens were also taken out at various temperatures.

Tri-sodium phosphate (TSP, Na_3PO_4) surfactant was added to the pure water. TSP is an additive to a spray system or sump water of nuclear power plant for maintaining high pH level during accidents. Experiment was performed with six different concentrations: 0.01, 0.05, 0.1, 0.3, 0.5, 0.8 % solutions. Prepared TSP solution was filled in the test pool and the heated test specimen was quenched in the pool.

Alumina nano-fluids were prepared by dispersing alumina nano-particles into pure water. In order to make uniform nano-fluids, the solutions were pre-processed in an ultrasonic bath for about 1 hour just before the each test. Due to the ultrasonic energy, the solution temperatures increase from 25 °C to about 35 ^{o}C. After cooling the test pool, tests were made at 25 °C. Four nano-fluids were prepared and used in quenching tests: 0.5, 1.0, 2.0, 4.0 % solutions.

Solution quenched specimens were made by quenching specimens in the TSP and nano solutions. Water quenched specimens were made by quenching specimens in pure water. After quenching tests, the contact angle of liquid (pure water, TSP solutions and nano-fluids) on the quenched surfaces were measured. Contact angles were measured by sessile drop tests using the contact angle measurement instrument KRÜSS DSA10. Range of contact angle measurements was 1 to 180° and resolution was 0.1°. Temperature of droplet is 20 ^{o}C in all experiments. Sessile drop test is the standard method for quick and accurate wetting test. The deposited drop lies on the surface and forms a contact angle that depends on the properties of the three phases: drop liquid, solid and surrounding phase. The probe fluids used were pure water and nano-fluids with drop volumes of 15 μL. Solid surfaces were; 1) un-heated fresh surface, 2) water quenched surface, 3) TSP quenched surfaces and 4) nano-fluid quenched surfaces. Solid surface were also examined by video microscope EG Tech EGVMS35.

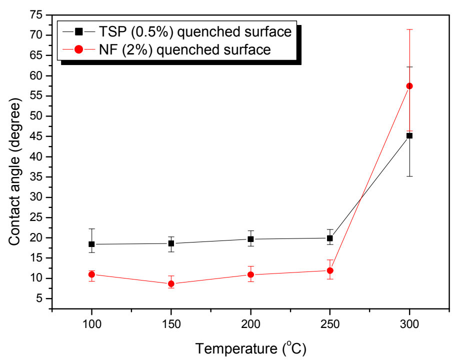

Figure 1. Contact angle and take-out temperature

Contact angles of water on the TSP solution quenched and nano-fluid quenched surfaces showed significant drop compared to those on the water quenched surface (Figure 1). It can be interpreted that the hydrophilicity of the quenched surface was highly enhanced. The one and only difference between water quenched surface and solution quenched surfaces is the existence of deposited TSP or nano-particles as observed in the post-quenching observations. Other factors, take-out temperature, liquid temperature, parameters of sessile drop test and the physical property of base material (SS304) remained the same. Therefore, the enhancement of wettability is an effect of the deposited TSP and nano-particles.

As mentioned above, take-out temperature affected the deposition of TSP and nano-particles. In Figure, the effect of take-out temperature is depicted. At the high take-out temperature (~300 ^oC), there was no considerably deposited material on the surface due to the Leidenfrost phenomenon and thus contact angle approaches that of water quenched surface.

By measuring the contact angles, the wettability change by TSP and nano-particle deposition was quantified. As the concentration of TSP solutions and nano-fluids increased, the corresponding contact angle of water on the quenched surfaces decreased. For the nano-fluid quenched surfaces, contact angle decreased monotonically. However, in the TSP solution quenched tests, there was sudden decrease of contact angle between 0.01 and 0.05%. From 0.05 to 0.8%, there was monotonic decrease as observed in the nano-fluid quenched case. 0.01% of TSP might be too low to see the considerable effect of TSP addition to water. However, the contact angle of water on 0.01% TSP solution quenched surface was 24.5^o and it was considerably lower that that on the water quenched surface (69.4^o).

In addition to the water drop test on the quenched surfaces, nano-fluid drop test to measure the contact angle of nano-fluid on the nano-fluid quenched surface was performed. During the process of nano-fluid pool boiling, the heated surface has deposited nano-particles on it and nano-fluid interacts with the surface. This configuration is very similar to the combination of nano-fluid drop on the nano-fluid quenched surface. There was further decrease in the contact angle compared to the water drop tests. This implies that the surface wettability is not only affected by the surface condition but also by fluid property.

From the results above, the surface deposited TSP and nano-particles considerably promote the wettability of the surface. Although there were differences in a degree of enhancement, previous pool boiling experiments showed enhanced CHF with TSP solutions and nano-fluids. The underneath mechanism of the CHF enhancement, there might be a role of deposited TSP and nano-particles which considerably enhance the wettability of the surface.

3. Conclusion

In this study, wettability of heater surfaces in pool boiling of TSP solutions and nano-fluids was investigated by quenching experiments. Through the visual observation of quenched surfaces, deposition of TSP and nano-particle was observed. Through the measurement of contact angle of liquid on the quenched surfaces, it is concluded that the surface deposited TSP and nano-particles enhanced wettability of the surface. Several implications of the experimental results on the pool boiling CHF model and CHF enhancement using TSP and NF were discussed: There is need of experiments and theoretical modeling which can accommodate hydrodynamic instability and surface wettability in a comprehensive manner.

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