Analysis of CHF enhancement in Subcooled Flow Boiling Experiment

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1. Introduction

Critical Heat Flux (CHF) is the thermal limit of heat transfer on the heater surface, which causes a sudden decrease of the heat transfer coefficient. One of the methods for improving CHF is the deposition of a nanoparticle coating on the heater surface using nanofluids. The key factor of CHF improvement is the increase of surface wettability enhancement. Nanoparticles are deposited on the heater surface during the nucleate boiling experiment.

H. S. Ahn et al. [1] conducted an internal flow boiling CHF experiment using a micro-structured Zirlo surface. The authors concluded that the flow boiling CHF in the annular flow regime increases with mass flux because of the stability of the liquid film and the liquid replenishment. T. S. Lee et al. [2] conducted the flow boiling CHF experiments using Fe_3O_4 nanofluids. As exit quality increased from 0.07 to 0.74, CHF enhancement gradually decreased and approached zero. H. M. Park [3] conducted the flow boiling CHF experiments using additives and carbon steel and the CHF enhancement was observed due to the wettability improvement for the slug flow. The effect of the wettability improvement on the CHF can be minimized in relatively low void fraction in slug flow regime.

The purpose of our experiment is to investigate the CHF enhancement trend according to exit quality. Existing theoretical CHF model and mechanism were investigated according to the flow regime.

2. Experimental Apparatus and Procedure

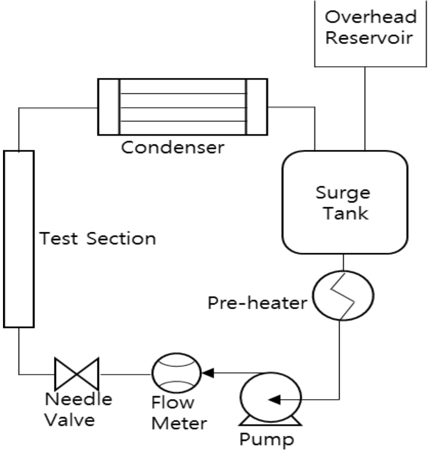

Fig. 1. Schematic of flow boiling CHF test loop

A schematic configuration of the experimental loop used in an experiment is shown in Figure 1. The experimental loop for flow boiling tests consists of a pump, flowmeter, needle valve, test section, condenser, surge tank, and preheater. The working fluid is controlled by the centrifugal pump and needle valve. The temperature of working fluid is controlled by the pre-heater and condenser.

The important characteristic on our experiment is nanoparticle deposition process in Figure 2. To make the similar nanoparticle coating on test section surface in same condition, nucleate boiling deposition was conducted in the same conditions. The reason of the process is to exclude effects of evaporation time, heat flux and mass flux on amount of nanoparticle deposition. After the deposition process, working fluid was changed to DI water. Experiment for nanoparticle coated surface was conducted in same inlet conditions with DI water case. The experimental condition is summarized in Table 1.

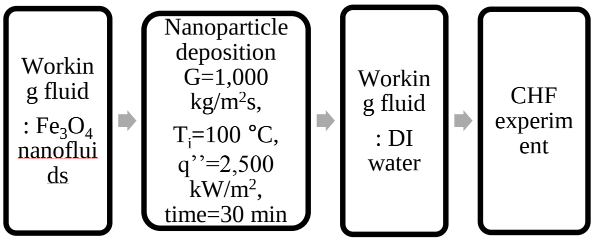

Figure 2. CHF experiment process using nanoparticle coated surface.

Table 1. Experimental condition

Test section	Bare SS316, Nanoparticle-coated SS316
Concentration	10 ppm volume
Pressure	1 bar
Mass flux (kg/m^2s)	1,000 ~ 5,000
Inlet temp. (°C)	40, 60, 80

3. Result and Discussion

The Figure 3 show the ratio of CHF enhancement according to exit quality. The overall trend is that ratio of CHF enhancement was decreased as the exit quality decreased. In low mass flux conditions (1,000~3,000 kg/m^2s), the ratio of CHF enhancement is lower under the 10 % except one result. In high mass flux conditions

(4,000~5,000 kg/m^{2}s), however, the overall ratio of CHF enhancement is higher than 20 %.

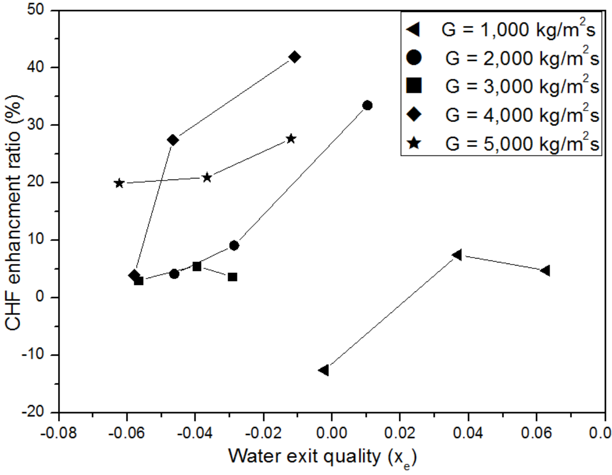

Figure 3. Ratio of CHF enhancement according to exit quality

The wettability characteristic of the surface can be identified from the contact angle. To evaluate wettability effect on the CHF enhancement, static contact angles were measured on the surface of as-received surface, DI water boiled stainless steel surface, nanoparticle coated surface (10 min, 30 min). As shown in Figure 4, the static contact angle of as-received stainless steel surface is 98° and angle of DI water boiled surface is 82°. Contact angles of nanoparticle coated surface were 43° for 10 min deposition and 25° for 30 min deposition. After the 30 min deposition process, the wettability of surface was highly enhanced compared with the bare surface.

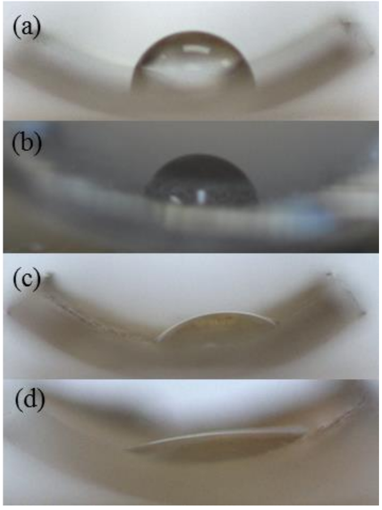

Figure 4. Image of static contact angle: (a) as-received; (b) DI water boiled; (c) Nanoparticle coated for 10 min; (d) Nanoparticle coated for 30 min.

Under subcooled flow boiling conditions, CHF mechanism can be explained by the 'Departure from Nucleate Boiling' (DNB). There are three DNB mechanism, which are 'dryout under a vapor clot', 'bubble crowding and vapor blanket', and 'evaporation of liquid file surrounding a slug flow'. The experimental data on nanoparticle-costed surface were plotted to Corre's G-x DNB map in Figure 5. [4] Additionally, the experimental data was plotted to Inasaka's G-x DNB map in Figure 6. [5] From Figure 3, 5 and 6, the data in the mechanism of (a) and (c) show the significantly low CHF enhancement trend under the 10 %. Then, the data in the mechanism of (b) show the significantly high CHF enhancement trend which is least 1,000 kW/m^2 (20 %) in mass flux of 4,000 and 5,000 kg/m^2 s.

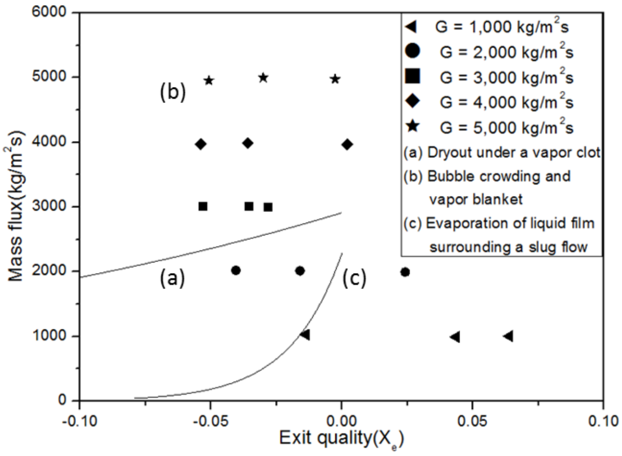

Figure 5. CHF data on Corre's flow regime

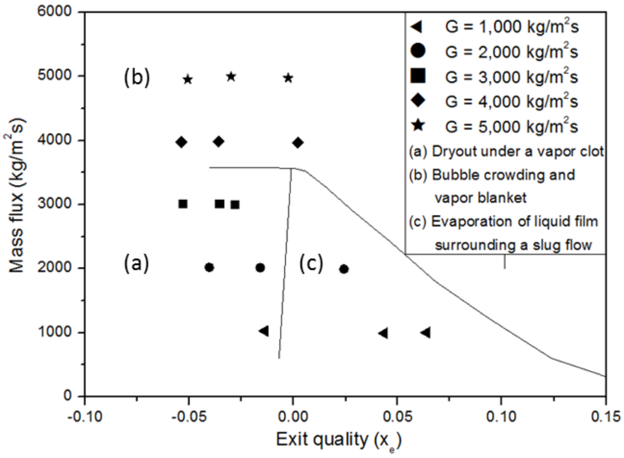

Figure 6. CHF data on Inasaka's flow regime

In our experiment, the internal bubble flow cannot be observed directly, so the analysis of bubble behavior was based on the previous visualization observation. At a given wall superheat, the nanofluids bubbles have a higher bubble departure diameter, growth time and wait time than the pure water data, while the nanofluids bubbles have a lower bubble departure frequency and nucleation site density. [6] Phan et al. [7] found that the vapor bubble departure radius on a hydrophilic surface was larger than that on a hydrophobic surface. The active nucleation site density decreased as surface wettability increase. As surface wettability improve, the possibility of filling the cavities with liquid increases and therefore active nucleation site density decreases. [8] The nucleation site density is also decreased as inlet subcooling increase. If the subcooling is high, the liquid-vapor interface may be pushed back into the cavity, thereby giving the appearance that the site has been deactivated. [9]

In our experiment, the CHF enhancement was decreased as the exit quality decreased and approached zero in the highly subcooled boiling region. This phenomenon is occurred in the low mass flux condition. The data for the mechanisms of (a), 'dryout under a vapor clot', and (c), 'evaporation of liquid film surrounding a slug flow', show low CHF enhancement under 10 % for mass fluxes of 1,000~3,000 kg/m^{2}s. This occurred because the active nucleation site density was decreased by the subcooling effect. Because the wettability could not affect CHF enhancement due to reduced nucleation sites, the CHF enhancement by nanoparticle coating was relatively small in the highly subcooled region.

The data in the mechanism of (b) 'bubble crowding and vapour blanketing' show high CHF enhancement of 1,000 kW/m^2 (20 %) in mass flux of 4,000~5,000 kg/m^2 s. This bubble coalescence approach is based on the Weisman and Pei model. [10] The CHF was assumed to occur when volume fraction in bubbly layer exceed the critical void fraction. The heat flux at DNB point was obtained in Equation (1). x_2 is calculated as the maximum void fraction (0.82) for slightly flattened elliptically shaped bubble. Only a fraction of total axial mass flux is effective velocity fluctuation in reaching the wall. With the improvement of surface wettability, the bubble departure diameter increase. The critical heat flux is a function of the mass flux into bubbly layer from liquid core and departure diameter. As the bubble departure diameter (D_p) increased due to wettability enhancement, the turbulent intensity (i_b) increased. Then, the turbulent velocity fluctuation (G') increased, and as a result, CHF was enhanced by the turbulent fluctuation.

$$\frac{q''_{DNB}}{h_{fg}G'} = (x_2 - x_1)\frac{h_f - h_{ld}}{h - h_{ld}} \qquad (1)$$

$$G' = \psi i_b G \qquad (2)$$

$$i_b = 0.462(k')^{0.6}(Re)^{-0.1}\left(\frac{D_p}{D}\right)^{0.6}[1 + \frac{a(\rho_l - \rho_g)}{\rho_g}] \qquad (3)$$

4. Conclusion

CHF experiment in DI water and nanoparticle deposited surface was investigated in mass flux of 1,000 ~ 5,000 kg/m2 s and inlet temperature of 40, 60 and 80 ℃. To make the similar nanoparticle coating on surface, nanoparticle deposition process was conducted. The experimental results show that CHF enhancement ratio decreased as exit quality decreased and approached to zero. The exceptional case is that the CHF enhancement remained about 20 % in high mass flux of 5,000 kg/m2 s. Trend of CHF enhancement was investigated using DNB mechanism and CHF model in subcooled boiling region.

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