EFFECT OF WETTABILITY AND TWO-PHASE FLOW CONDITIONS ON FLOW BOILING CHF ENHANCEMENT FOR SLUG FLOW

Hae Min Park and Yong Hoon Jeong*
Nuclear and Quantum Eng., Korea Advanced Institute of Science and Technology
291 Daehak-ro, Yuseong-gu, Daejeon, Republic of Korea
hm-park@kaist.ac.kr; jeongyh@kaist.ac.kr

ABSTRACT

The critical heat flux (CHF) experiments were conducted to study the flow boiling CHF enhancement by additives and heater material for a wide range of exit qualities and void fractions and pressure conditions of 1 and 2 bar using the two-dimensional slice test section. As the methods of wettability improvement to enhance the CHF, the additives of boric acid and tri-sodium phosphate (TSP, $Na_3PO_4 \cdot 12H_2O$) and the heater material of low alloy steel (SA508) were used. As the reference case, the working fluid of deionized water and the heater material of SUS304 were used. And the CHF was observed in the bubbly-slug and slug flow through flow visualization works. For a condition of atmospheric pressure, the CHF was enhanced in the most of experimental cases under relatively high exit quality condition, and however the CHF decrease and no change of CHF were also confirmed under relatively low exit quality condition. However, the tendency related to the exit quality was not suitable when the CHF enhancement ratios for 1 bar are compared with those for 2 bar. The tendency of the CHF enhancement ratio was discussed according to the void fraction calculated from exit quality. The CHF enhancement ratio is nearly 1 in the void fraction of ~0.7 and proportional to the void fraction.

KEYWORDS
CHF enhancement, Slug flow, Wettability

1. INTRODUCTION

The critical heat flux (CHF) is a phenomenon of the sudden decrease of heat transfer coefficient between the heated surface and two-phase flow due to excessive generation of vapor. In the heat transfer system, the heat is efficiently removed by using latent heat of phase change before the CHF. However, after the CHF, the system is damaged because the temperature of the heated surface is rapidly increased by reduction of heat transfer coefficient. Therefore, the most thermal hydraulic system has a criteria of CHF for thermal failure and many researches for the CHF enhancement were carried out to secure the more thermal margin. A representative method of the CHF enhancement is the improvement of wettability between the heated surface and liquid. (Chang et al., 2006 [1])

Many researchers found the methods of the wettability improvement, such as nanofluid (Kim et al., 2008, 2009, 2010, Kim et al., 2010, Lee et al., 2013, 2014, Lee et al., 2012, 2013, Lee et al., 2012) [2-10], additives and surfactant solutions for the working fluid (Jeong et al., 2008, Lee et al., 2010, Kim et al., 2011, Park et al., 2014) [11-14] and surface coating for the characteristics of heated surface (Sarwar et al., 2007, Park et al., 2014) [15-16]. They measured the contact angle by the static sessile drop method and confirmed the improvement of wettability through the observation of reduction of contact angle. For the heated surface and working fluid which have a small contact angle (good wettability), a certain volume of the liquid on the surface can occupy wider area in comparison with the case of a large contact angle (bad wettability). Due to that, the possibility of hot spot generation in case of the good wettability can be decreased. That is the mechanism of CHF enhancement by the improved wettability.

In the flow boiling conditions, the effect of wettability on the CHF enhancement can be varied by the flow conditions. According to Lee et al. (2014) [7], the CHF enhancement rate is dependent on the exit quality condition. In an annular flow, they confirmed the CHF was highly enhanced under relatively low exit quality condition (~ 0.07) and no CHF enhancement under high exit quality condition (~0.74). In this study, the objectives are to study the CHF characteristic of additives of boric acid and tri-sodium phosphate and heater material of stainless steel and low alloy steel in the wide range of thermal-hydraulic conditions and to clarify the effect of wettability on the CHF enhancement in terms of two-phase flow conditions in a slug flow. For this purpose, Kim et al. (2012) [13] and Park et al. (2014) [14] in Korea Advanced Institute of Science and Technology (KAIST) preliminarily conducted the flow boiling CHF experiments under atmospheric pressure and the basic phenomenon and mechanism for the CHF enhancement were discussed. In this study, the additional CHF experiments were conducted under the pressurized conditions and the general tendency for the CHF enhancement by the wettability improvement was investigated in the slug flow conditions.

2. BACKGROUND

The literatures for the CHF enhancement by the wettability improvement were investigated in the flow boiling conditions. The methods of the wettability improvement and the flow regime considered in those literatures are listed in Table I.

Table I. Methods of the wettability improvement and flow conditions for the previous works

Literature	Method of wettability improvement	Flow regime
Kim et al. (2008, 2009, 2010) (MIT)	Nanofluids (alumina, zinc-oxide, diamond)	Subcooled boiling
Kim et al. (2010) (KAIST)	Nanofluid (alumina)	Annular flow
Lee et al. (2012) (UNIST)	Nanofluid (SiC)	Annular flow
Lee et al. (2013) (KAIST)	Nanofluid (magnetite)	Annular flow
Sarwar et al. (2007) (KAIST)	Microporous coating	Subcooled boiling
Jeong et al. (2008), Lee et al. (2010) (KAIST)	Boric acid, TSP	Bubbly-slug, slug flow
Kim et al. (2012), Park et al. (2014) (KAIST)	Boric acid, TSP, oxidation of steel surface	Slug flow

As the method of the wettability improvement, several water-based nanofluids were used. Kim et al. (2008, 2009, 2010) [2-4] utilized the nanofluids of alumina-water, zinc-oxide-water and diamond-water and conducted the flow boiling CHF experiments using stainless steel tube. They confirmed the wettability improvement by nanoparticle precipitation on the inner surface of tube and the CHF enhancement in the subcooled boiling condition (exit quality < 0). Due to that and high mass flux condition, the flow regime was expected to be bubbly flow. Kim et al. (2010) [5], Lee et al. (2012) [10]

and Lee et al. (2013) [6] used alumina-water, SiC-water and magnetite water nanofluids, respectively. The quantity of the CHF enhancement was different from each other and the CHF enhancement by nanoparticle deposition and wettability improvement was confirmed for all cases of nanofluid in the conditions of annular flow.

Sarwar et al. (2007) [15] and Park et al. (2014) [16] used painted and boiling-induced techniques of microporous coating, respectively, to improve the wettability. Sarwar et al. (2007) [15] conducted the flow boiling CHF experiments using the tube with alumina and TiO_2 coating and the CHF enhancement was observed for the microporous surfaces.

Jeong et al. (2008) [11] and Lee et al. (2010) [12] studied the CHF enhancement by addition of boric acid and tri-sodium phosphate (TSP, $Na_3PO_4 \cdot 12H_2O$) in the condition of flow boiling and tube geometry. Through the analysis of flow map, the flow region was expected to be the bubbly slug and slug flow. They also confirmed the wettability improvement and the CHF enhancement through the measurement of contact angle on bare, boric acid quenched and TSP quenched surfaces for deionized (DI) water, boric acid and TSP solutions. However, the reduction of CHF and no CHF enhancement were observed in relatively high mass flux conditions. Those were explained for the Kelvin-Helmholtz flow instability.

Kim et al. (2012) [13] and Park et al. (2014) [14] also confirmed the CHF enhancement by surface oxidation of carbon steel as well as addition of boric acid and TSP in the two-dimensional slice test sections and the steel oxide surface and additive solutions had a good wettability. Through the utilization of flow visualization, the bubbly-slug and slug flow were observed.

3. EXPERIMENTAL APPARATUS

To investigate the effect of wettability on the CHF enhancement in terms of two-phase flow conditions in a slug flow in the wide range of thermal-hydraulic conditions, the experimental water loop and test sections implemented by Park et al. (2013, 2014) [17,14] were used and modified. In this study, the methods of oxidation of steel surface and addition of boric acid and TSP were chosen to enhance the wettability on the heated surface.

3.1. Experimental Loop

As shown in Fig. 1, the experimental loop consists of preheater, pump, flow meter, lower plenum, test section, upper plenum, heat exchanger and surge tank. The flow conditions such as flow rate and fluid temperature were controlled by a pump and a preheater and were measured by a flow meter and a T-type thermocouple installed in the lower plenum. The flow meter (TOSHIBA, GF630/LF600) of electromagnetic type was used and an uncertainty of measurement is 0.4 % (velocity > 0.5 m/s). A measurement uncertainty of the T-type thermocouple is ± 0.5 ºC.

The flow direction of the working fluid is as follows. The controlled working fluid by a pump and a preheater according to the experimental plans was injected into the test section through the lower plenum. In the test section, the vapor was generated and the generated steam was condensed into liquid again in the heat exchanger and gathered in the surge tank. All parts of the loop were connected by type 304 stainless steel (SUS304) pipe with a diameter of 0.0254 m.

The surge tank of an open type used by Park et al. (2013, 2014) [17,14] was replaced with a closed type in order to conduct the experiments under the pressurized condition. As shown in Fig. 2, the modified surge tank has an air injection valve and a venting valve.

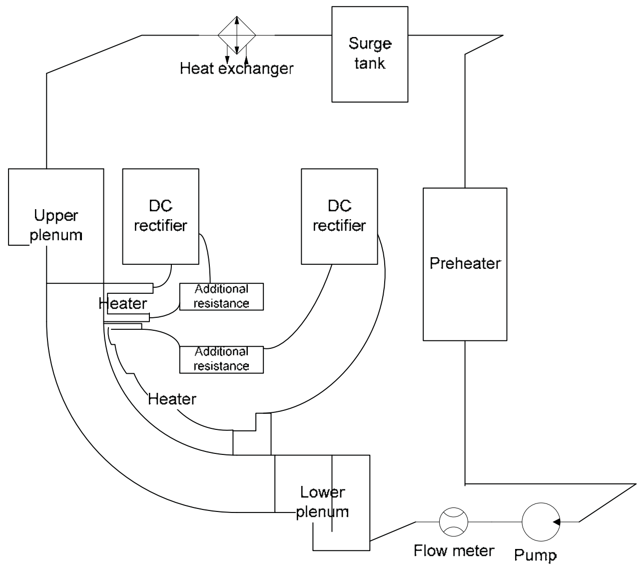

Figure 1. Schematic diagram of the experimental loop

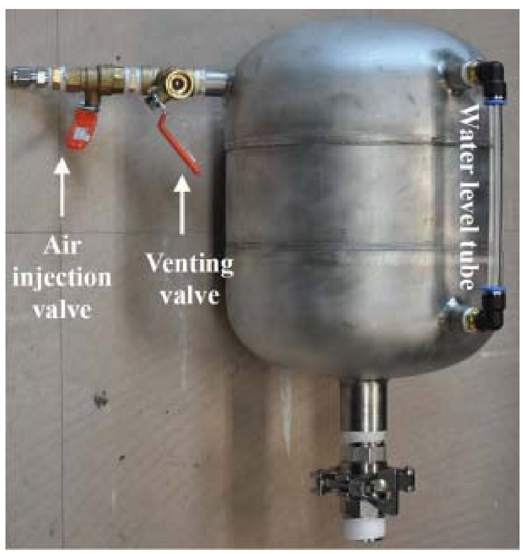

Figure 2. Pictorial view of the surge tank

3.2. Test Section

To conduct an additional series of experiments, two-dimensional slice test sections with radius of curvature of 0.5 m were used. The shape of test section was a quarter-circle, as shown in Fig. 3. In the test section the working fluid was injected from the lower plenum and discharged vertically toward the upper plenum. And, the test section had a curved and rectangular channel with the width of 0.03 m and the gap size of 0.06 m.

The heater part of the test section was divided into two heaters. One heater was the preheated region which was relatively long and controlled the void fraction of flow conditions based on a stepped heat flux distribution with respect to inclination angle, as shown in Fig. 4. Another heater was the main heater region in which the CHF was measured. This region was made of SA508 and SUS304. A surface wettability of SA508 is better than that of SUS304 and enhanced by steel oxidation during experiments. In comparison with the test section used in Park et al. (2013, 2014) [17,14], the heater and the flow channel wall were thicker except the main heater to improve the durability of test section. In the main heater region, the thin heater was also used in this study to achieve a level of the high heat flux. For the safety under pressurized conditions, the insulator block was installed behind the main heater. The heated surface was polished with #800 grit sandpaper. Using two direct current (DC) rectifiers, two heaters were directly heated and the level of heat flux was separately controlled.

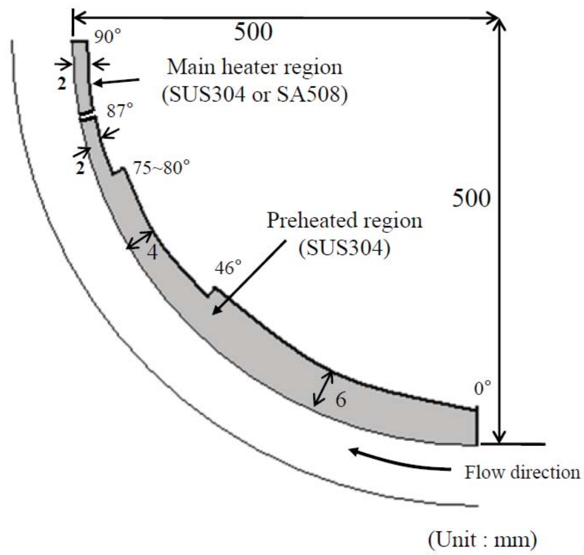

Figure 3. Geometry of the test section

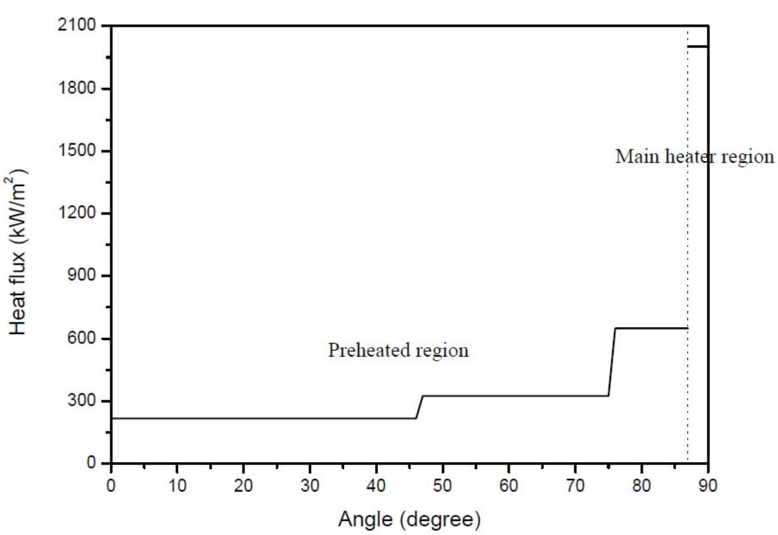

Figure 4. Heat flux distribution of the test section

3.3. Working Fluid

To improve the wettability, the working fluid of the mixture solution of boric acid and TSP was used in this study. Kim et al. (2012) [13] and Park et al. (2014) [14] demonstrated that the mixture solution of boric acid and TSP had a good wettability on SUS304 and SA508 surfaces. Especially, in the boiling condition, the wettability of SA508 surface was significantly enhanced by steel oxidation and deposition of boric acid and TSP on the surface. And, DI water was considered as the reference case.

Considering the materials of test section and the working fluids in this study, the test matrix are shown in Table II.

Table II. Test matrix in this study

Pressure	2 bar
Heater material	SUS304, SA508
Mass flux	100-300 kg/m^{2}s
Inlet subcooling	2 K
CHF point	90°
Working fluid	DI water Mixture solution of boric acid and TSP

3.4. Experimental Methodology

The detection method of CHF phenomenon was the measurement of surface temperature. For this, two K-type thermocouples were installed behind the heater. For the measurement of CHF level, a power meter (WT210) which have an uncertainty of 1.0 % was used. The heat flux level was calculated using the equation

$$q'' = \frac{P}{A_{heater}} \tag{1}$$

where q'' is the heat flux on the test section, P is the power and A_{heater} is the heater area of the test section. Based on a geometric uncertainty of the heater area of 1.0 %, the overall uncertainty for the measurement of CHF was calculated as 1.7 %, which includes a heat loss of approximately 0.3 %. All measurement data were gathered in a data acquisition system (DAS) consisting of an Agilent 34980A data acquisition/control unit and a personal computer.

The experimental procedures are described below.

1. Install the preheated region made of SUS304 and the main heater region made of SUS304 or SA508 of the test section to make the rectangular and curved channel.
2. Install thermocouple sets of K and T-type on the main heater region to detect the CHF and measure the inlet subcooling.
3. Fill the experimental loop with a scheduled working fluid consisting of boric acid and TSP.
4. Turn on all devices in the experimental loop, the DAS and two DC rectifiers.
5. Heat up the working fluid in the experimental loop and adjust the mass flux to ~300 kg/m^{2}s

6. Pressurize the experimental loop when the temperature of working fluid is nearly the saturated condition (~100 ^oC) and simultaneously heat up the working fluid.
7. Adjust the mass flux, inlet subcooling and pressure to a predetermined level.
8. Adjust the heat flux of the preheated region to a predetermined level and gradually raise heat flux level of the main heater region until CHF occurs.
9. Shut down all DC rectifiers as soon as possible after the onset of the CHF

4. RESULTS AND DISCUSSION

To investigate the effect of wettability on the CHF enhancement in terms of two-phase flow conditions in a slug flow in the wide range of thermal-hydraulic conditions, the additional series of flow boiling CHF experiments were conducted under the pressurized condition. Six points of CHF data were obtained for the inlet subcooling condition of 2 K, mass flux conditions of 100 and 300 kg/m^2s and pressure condition of 2 bar. The acquired CHF data are plotted in Fig. 5.

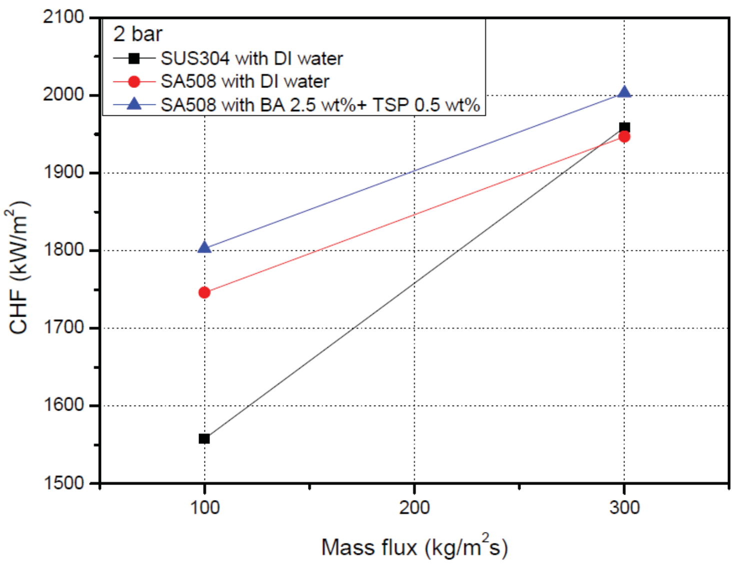

Figure 5. CHF data according to the mass flux (2 bar)

In the CHF condition at the atmospheric pressure, Park et al. (2013) [17] observed the flow using a high-speed camera (Motion HG-LE) and they confirmed that the slug flow was formed as shown in Fig. 6. Under the pressure condition of 2 bar, the slug flow was also expected to be formed in this experiments because the vapor volume and the flow velocity were not significantly changed. The mass flux conditions were maintained and there were factors of vapor expansion by increase of CHF level and reduction of vapor volume by pressurization at 2 bar.

To discuss the wettability effect in terms of flow conditions, the CHF enhancement ratios were calculated for each case and compared with each other according to exit quality for each pressure condition. To find the general tendency, all ratios of the CHF enhancement were compared each other according to void fraction for all pressure conditions.

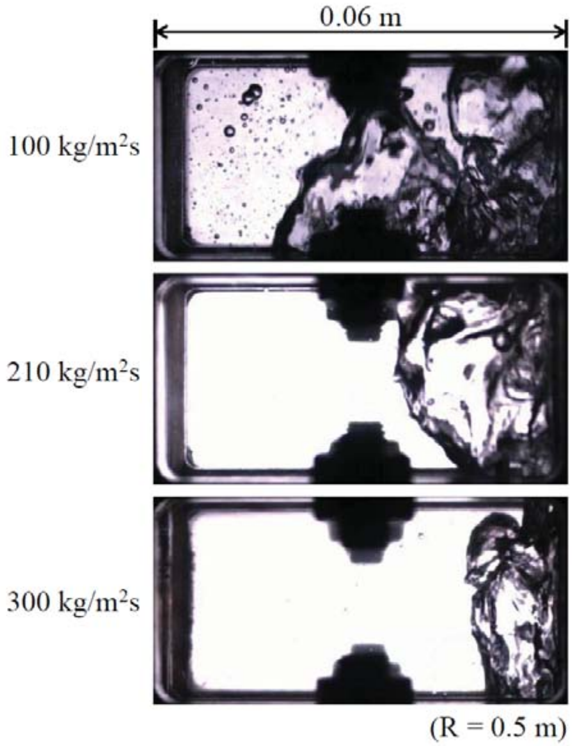

Figure 6. Flow visualization in the test section at atmospheric pressure

4.1. Analysis of the CHF Enhancement for the Exit Quality

The thermodynamic exit quality, x_e, was calculated by the following equation;

$$x_e = \frac{1}{h_{fg}}\left(\frac{1}{G\, d_{gap}}\sum_{i=1}^{4} q''_i\, L_i - \Delta h_{inlet}\right) \tag{2}$$

where G is mass flux, d_{gap} is gap size, q''_i is heat flux level in region i, L_i is heated length of region i and Δh_{inlet} is inlet subcooling. And, the CHF enhancement ratio for each experimental case was calculated as follows;

$$CHF\ enhancement\ ratio = \frac{CHF}{CHF\ \ for\ SUS304\, case\ with\ DI\ \ water} \tag{3}$$

under the same condition of scale, mass flux, inlet subcooling and pressure.

For the SA508 case with DI water and additives at 2 bar, the CHF enhancement ratios in terms of the exit quality are plotted in Fig. 7. For all cases, the CHF enhancement ratios under relatively low exit quality conditions were lower than those in the relatively high range of exit quality. In those experimental conditions and the slug flow regime, it is mainly considered that the CHF is occurred by the mechanism of evaporation of liquid film underneath a slug flow bubble, as shown in Fig 8. In this configuration, the wettability is applied between liquid, vapor and heated surface. Therefore, the effect of wettability increases as the slug grows larger and the CHF can be highly enhanced by the wettability improvement under relatively high exit quality condition.

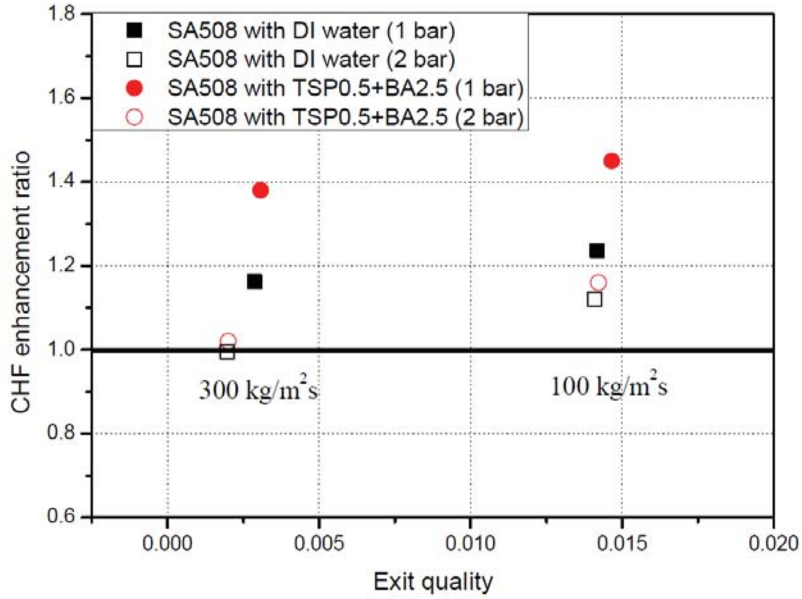

Figure 7. CHF enhancement ratio according to exit quality for SA508 case with DI water and additive

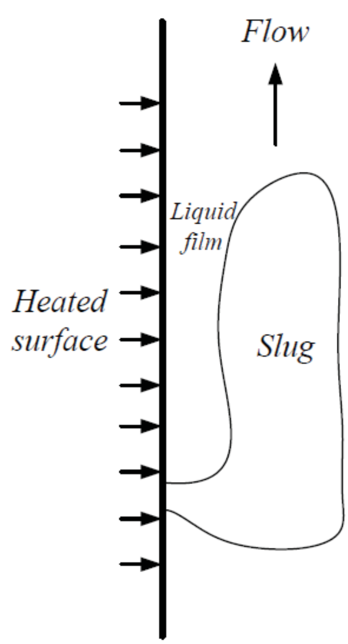

Figure 8. Schematic configuration of a liquid film and a slug

The CHF enhancement ratios for all cases including the experimental cases in Kim et al. (2012) [13] and Park et al. (2014) [14] are plotted in Fig. 9. As shown in Fig. 9, the tendency between the CHF enhancement ratio and the exit quality was confirmed for the SUS304 case with additives and SA508 case with DI water and additives at atmospheric pressure. For each condition of heater material (SUS304 and SA508) and additives, the CHF enhancement ratio increased as the exit quality increased.

However, relationships of the CHF enhancement ratio between 1 bar data and 2 bar data cannot be explained in terms of the exit quality. As shown in Fig. 7, the CHF enhancement ratio at 1 bar was higher than that at 2 bar under the same mass flux condition although there was almost no difference of the exit quality between the pressure condition of 1 bar and 2 bar.

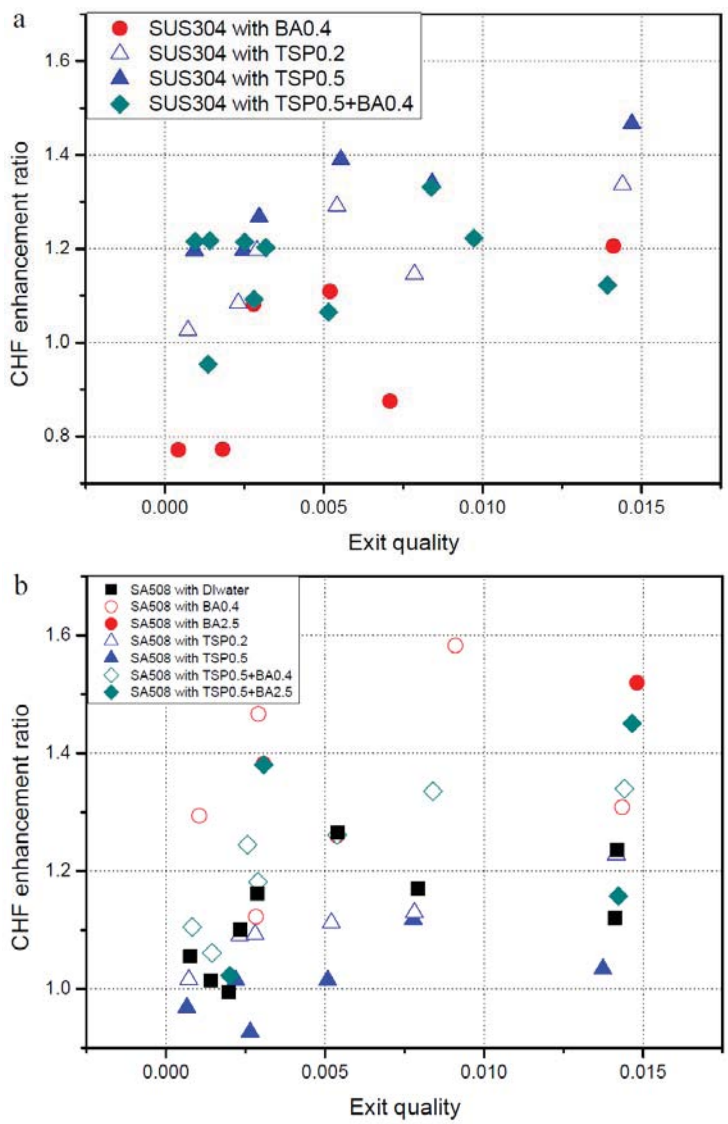

Figure 9. CHF enhancement ratio according to exit quality (1 bar) (a: SUS304 case, b: SA508 case)

4.2. Analysis of the CHF Enhancement for the Void Fraction

For the relationship between the effect of wettability and the quantity of vapor explained in previous section, the mass of vapor is not important factor and the volume of vapor should be considered. Therefore, the CHF enhancement ratio in terms of the void fraction was discussed in this section.

The void fraction was calculated using the thermodynamic exit quality because the void fraction was not measured. Assuming homogeneous flow, the void fraction is given by the following equation;

$$\alpha = \frac{1}{1 + \frac{1 - x_e}{x_e} \frac{\rho_v}{\rho_l}} \tag{4}$$

where ρ_v and ρ_l are density of vapor and liquid, respectively.

For the SA508 case with DI water and additives, the CHF enhancement ratios at 2 bar were compared with those at 1 bar, as shown in Fig. 10. As the void fraction increased from 0.6 to 0.95, the CHF enhancement ratio increased from 0. That proportional relationship between the CHF enhancement and void fraction was found under all pressure conditions considered in this study. In other words, the effect of the wettability improvement on the CHF can be minimized in relatively low void fraction.

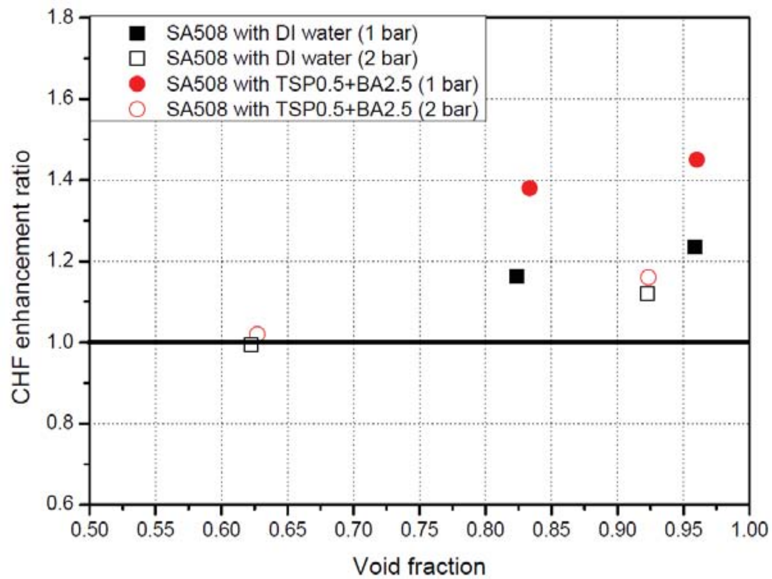

Figure 10. CHF enhancement ratio according to void fraction for SA508 case with DI water and additive

The CHF enhancement ratios according to the void fraction for all cases are plotted in Fig. 11. It was confirmed that the CHF enhancement ratio was approximately proportional to the void fraction for each case. The amount of the CHF enhancement under the same condition of void fraction depends on the degree of the wettability improvement. And it is clear that this relationship is effective in only slug flow region and the different relationship is expected to be appeared in the low void fraction condition (bubbly flow) and extremely high void fraction condition (annular flow).

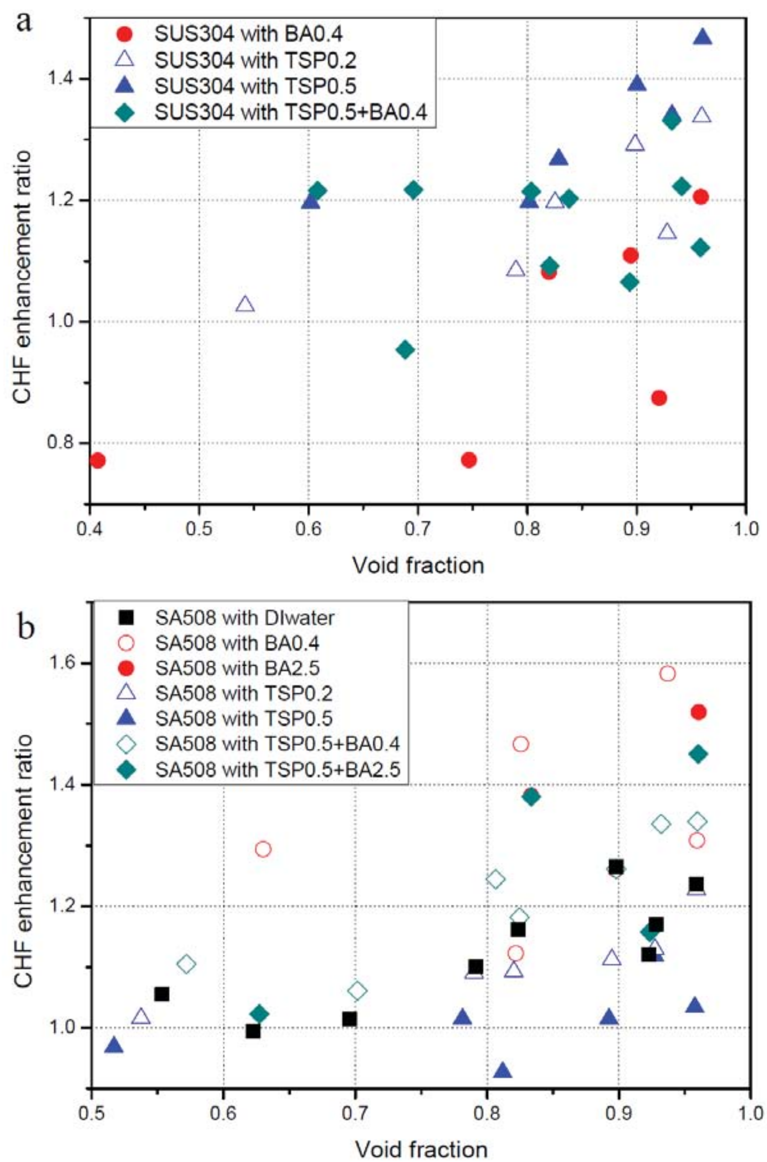

Figure 11. CHF enhancement ratio according to void fraction (a: SUS304 case, b: SA508 case)

5. CONCLUSIONS

In this study, the flow boiling CHF experiments were conducted using additives and carbon steel under the pressurized condition and the CHF enhancement by the wettability improvement for the slug flow was studied.

For the obtained CHF data from this study, Kim et al. (2012) [13] and Park et al. (2014) [14], the CHF enhancement ratios were compared with each other according to exit quality for each pressure condition to discuss the wettability effect in terms of flow conditions. The approximately proportional tendency between the CHF enhancement ratio and the exit quality was confirmed for each condition of heater material (SUS304 and SA508) and additives. The effect of wettability increases for relatively large bubble and the CHF can be highly enhanced by the wettability improvement under relatively high exit quality condition. However, relationships of the CHF enhancement ratio between 1 and 2 bar data cannot be explained in terms of the exit quality.

For the relationship between the effect of wettability and the quantity of vapor, the void fraction was also considered. The proportional relationship between the CHF enhancement and void fraction was found under all pressure conditions. The effect of the wettability improvement on the CHF can be minimized in relatively low void fraction. This relationship is effective in only slug flow region and the different relationship is expected to be appeared in the flow regime of bubbly flow (low void fraction) and annular flow (extremely high void fraction).

ACKNOWLEDGMENTS

This work was supported by the Nuclear Safety Research Center Program of the KORSAFe grant (Grant Code 1305011) funded by Nuclear Safety and Security Commission of the Korean government.

REFERENCES

1. S.H. Chang, Y.H. Jeong and B.S. Shin, "Critical Heat Flux Enhancement," *Nucl. Eng. Tech.*, **38**(8), pp. 753-762 (2006).
2. S.J. Kim, T. McKrell and J. Buongiorno, "Alumina Nanoparticles Enhance the Flow Boiling Critical Heat Flux of Water at Low Pressure," *J. Heat Transfer*, **130**(4), 044501 (2008).
3. S.J. Kim, T. McKrell, J. Buongiorno and L.W. Hu, "Experimental Study of Flow Critical Heat Flux in Alumina-Water, Zinc-Oxide-Water, and Diamond-Water Nanofluids," *J. Heat Transfer*, **131**(4), 043204 (2009).
4. S.J. Kim, T. McKrell, J. Buongiorno and L.W. Hu, "Subcooled Flow Boiling Heat Transfer of Dilute Alumina, Zinc Oxide, and Diamond Nanofluids at Atmospheric Pressure," *Nucl. Eng. Des.*, **240**, pp. 1186-1194.
5. T.I. Kim, Y.H. Jeong and S.H. Chang, "An Experiemental Study on CHF Enhancement in Flow Boiling using Al2O3 Nano-fluid," *Int. J. Heat and Mass Transfer*, **53**, pp. 1015-1022 (2010).
6. T. Lee, J.H. Lee and Y.H. Jeong, "Flow Boiling Critical Heat Flux Characteristics of Magnetic Nanofluid at Atmospheric Pressure and Low Mass Flux Conditions," *Int. J. Heat and Mass Transfer*, **56**, pp. 101-106 (2013).
7. T. Lee, D.H. Kam, J.H. Lee and Y.H. Jeong, "Effects of Two-phase Flow Conditions on Flow Boiling CHF Enhancement of Magnetite-water Nanofluids," *Int. J. Heat and Mass Transfer*, **74**, pp. 278-284 (2014).
8. J.H. Lee, T. Lee and Y.H. Jeong, "Experimental Study on the Pool Boiling CHF Enhancement using Magnetite-water Nanofluids," *Int. J. Heat and Mass Transfer*, **55**, pp. 2656-2663 (2012).
9. J.H. Lee, T. Lee and Y.H. Jeong, "The Effect of Pressure on the Critical Heat Flux in Water-based Nanofluids containing Al_2O_3 and Fe_3O_4 Nanoparticles," *Int. J. Heat and Mass Transfer*, **61**, pp. 432-438 (2013).
10. S.W. Lee, S.D. Park, S. Kang, S.M. Kim, H. Seo, D.W. Lee and I.C. Bang, "Critical Heat Flux Enhancement in Flow Boiling of Al2O3 and SiC Nanofluids under Low Pressure and Low Flow Conditions," *Nucl. Eng. Tech.*, **44**(4), pp. 429-436 (2012).
11. Y.H. Jeong, M.S. Sarwar and S.H. Chang, "Flow Boiling CHF Enhancement with Surfactant Solutions under Atmospheric Pressure," *Int. J. Heat and Mass Transfer*, **51**, pp. 1913-1919 (2008).
12. J. Lee, Y.H. Jeong and S.H. Chang, "CHF Enhancement in Flow Boiling System with TSP and Boric Acid Solutions under Atmospheric Pressure," *Nucl. Eng. Des.*, **240**, pp. 3594-3600 (2010).
13. T.I. Kim, H.M. Park and S.H. Chang, "CHF Experiments using a 2-D Curved Test Section with Additives for IVR-ERVC Strategy," *Nucl. Eng. Des.*, **243**, pp. 272-278 (2012).
14. H.M. Park, Y.H. Jeong and S. Heo, "Effect of Heater Material and Coolant Additives on CHF for a Downward Facing Curved Surface," *Nucl. Eng. Des.*, **278**, pp. 344-351 (2014).

15. M.S. Sarwar, Y.H. Jeong and S.H. Chang, "Subcooled Flow Boiling CHF Enhancement with Porous Surface Coatings," *Int. J. Heat and Mass Transfer*, **50**, pp. 3649-3657 (2007).
16. S.D. Park, S.B. Moon and I.C. Bang, "Effects of Thickness of Boiling-induced Nanoparticle Deposition on the Saturation of Critical Heat Flux Enhancement," *Int. J. Heat and Mass Transfer*, **78**, pp. 506-514 (2014).
17. H.M. Park, Y.H. Jeong and S. Heo, "The Effect of the Geometric Scale on the Critical Heat Flux for the Top of the Reactor Vessel Lower Head," *Nucl. Eng. Des.*, **256**, pp. 176-183 (2013).