CHF MEASUREMENT FOR DOWNWARD FACING SUS 304 AND CARBON STEEL PLATES UNDER ATMOSPHERIC AND POOL BOILING CONDITIONS

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ABSTRACT

There have been many studies and correlations about CHF value for the upward pool boiling condition. Size of heaters, surface materials, surface morphologies, thickness and many other influencing effects on CHF were considered and investigated. In addition to upward heating surface case, downward-facing heating surface also has been studied though accumulated data are limited compared with upward cases up to now. CHF for the downward heated surface has been measured and related models have been developed for the practical applications, especially for IVR-ERVC and core catcher strategies in nuclear power plants. Heater materials were dominantly stainless steel, carbon steel and copper. In this study, two different surfaces were prepared (stainless steel 304 & SA 508) for 2 scales of width and length, respectively (length: 100 mm & 200 mm, width: 40mm & 50mm). CHF of test sections were measured under atmospheric and pool boiling condition, and inclination angles were changed from horizontally downward-facing angle to vertical angle in 15 degree unit. Horizontally downward-facing angle is assigned to be 0 degree in this study, and angle increases as inclination angles of test sections gradually changes to vertical location. According to the experimental results, as the inclination angle increases, CHF tends to increase, which corresponds with trends have already been reported by many previous studies. However, rate of change and values of CHF value with inclination angles were different from the results acquired from Yang et al. [1] which used almost the same shape of test sections. CHF value acquired in this experiment was smaller than results from Yang et al. [1]. Besides, SA 508 surfaces were not oxidized, but they showed enhanced CHF results compared with bare stainless steel surfaces.

KEYWORDS
CHF, downward-facing surface, SUS 304, SA 508

1. INTRODUCTION

During severe accidents, when coolant is not supplied properly and core melts down, two of mitigation strategies being considered in nuclear power plant are IVR-ERVC strategy and core catcher. With the former strategy, molten core materials can be kept inside the reactor vessel if CHF is not reached. Core catcher instrument is located below the reactor vessel spreading the molten core materials using sacrifacial materials. Through these representative strategies, Molten Core-Concrete Interaction (MCCI) is prevented and thus overpressurization induced by the non-condensable gas generated in MCCI interaction is prohibited, and containment penetration is prevented. On this viewpoint, the coolability limit is one of important factors to guarantee the integrity of the mitigation systems. CHF varies

* Footnote, if necessary, in Times New Roman font and font size 10

depending on some factors such as angular position (inclination angle), system condition, heater material and working fluid. Based on the previous observations, experimental test matrix was prepared.
The purpose of this study is to evaluate the scale and surface material effects on CHF for downward-facing surfaces. For the purpose, two scales of width and length were prepared for 7 inclination angles from horizontal downward case (0 deg.) to vertical condition (90 deg.) by 15 degree unit. Also, to account for the surface material effect in real application, SA 508 surfaces were prepared for comparison.

1.1. Backgrounds

Theofanous et al. [2] and Theofanous and Syri [3] got CHF results targeted for AP 600 reactor and the Loviisa plant types with series of ULPU experiments. For the purpose, a large scale two-dimensional test sections were prepared, and the conditions for each configurations were different. Based on their results, the correlation was developed where inclination angle information was included.
Cheung et al. [4] and Yang et al. [5] carried out CHF experiments for downward-facing hemisphere with Subscale Boundary Layer Boiling (SBLB) facility. Through the hemispheric shape, 3-d depiction was possible. According to their observation, the characteristic dimensions of vapor bubbles were 30 to 40 mm with elongated shapes as inclination angle approaches to 0 degree. They showed subcooling effect on bubble size, thus on CHF, and their results were compared with full-scale experiment: ULPU experiments.
Rouge [6] and Rouge et al. [7] conducted CHF experiments using SULTAN facility under atmospheric and pressurized (5 bar) conditions for rectangular channel with two inclination angles (10 deg. and 90 deg.). For the purpose, they performed various conditions of experiments, and CHF correlation was developed based on their results.
In the studies by Kim and Suh [8] and Kim et al. [9], they carried out pool boiling CHF experiments with Gap Apparatus Mitigating Melt Attack 1-dimensional (GAMMA 1D) considering gap size effect under inclination angle from 0 to 90 degree. Used test section was 1-dimensional rectangular channel, and copper surface was utilized. The size of the gap was relatively small considering the thermal boundary layer development and slug size in the severe accident mitigation strategies.
Jeong et al. [10] performed CHF experiments targeting for the IVR-ERVC strategy in the APR 1400 reactor using a 2-dimensional test section. In their study, CHF was measured at the top of the lower head (vertical position) where heat flux is most high in real situation. For lower parts, various thickness of heaters were used to depict the stepwise heat flux distribution which simulates the actual heat load during the activation of the IVR-ERVC strategy. Various conditions were considered in their measurements, and a CHF correlation was developed based on the mass flux, inlet subcooling and exit quality information.
El-genk and Guo [11] measured CHF and minimum film boiling heat flux data using circular copper surfaces under atmospheric condition. Inclination angle was changed from 0 to 90 degree to describe the downward-facing surface. Based on the correlation developed by Kutateladze, correlations for the CHF and minimum film boiling heat flux were developed multiplying an inclination angle-dependent constant to the original form.
Yang et al. [1] performed CHF experiments for downward-facing and upward-facing stainless steel plate under atmospheric and pool boiling conditions changing the inclination angles. Dimensional effect of heater was investigated with different widths and lengths. According to their study, there was a transition angle below which CHF decreases abruptly.

2. EXPERIMENTAL SETUP

2.1. Experimental apparatus

The test pool consists of pressurized vessel, pre-heater, condenser, air cylinder and test section as shown in Fig. 1. The pressurized vessel is designed to allow pressurized experiments more than 10 bar, and one more layer of stainless steel vessel is located outside the pressure vessel for two reasons: Insulation space during experiments and water road to cool down the system in short time for the pressurized experiments. Two view windows are installed to observe the bubble or slug motion on the heater surface. The pre-heater keeps the pool system saturated before and during the experiments, and a rectifier with a maximum capacity of 45 kW (15 V, 3000 A) was used to operate the pre-heater system. Two K-type thermocouples measures operating temperatures at the elevation of the test sections. The condenser transformed the generated steam into liquid state maintaining the pressure condition. Air cylinder is located beside the pressure vessel to lift-up or –down the vessel lid.

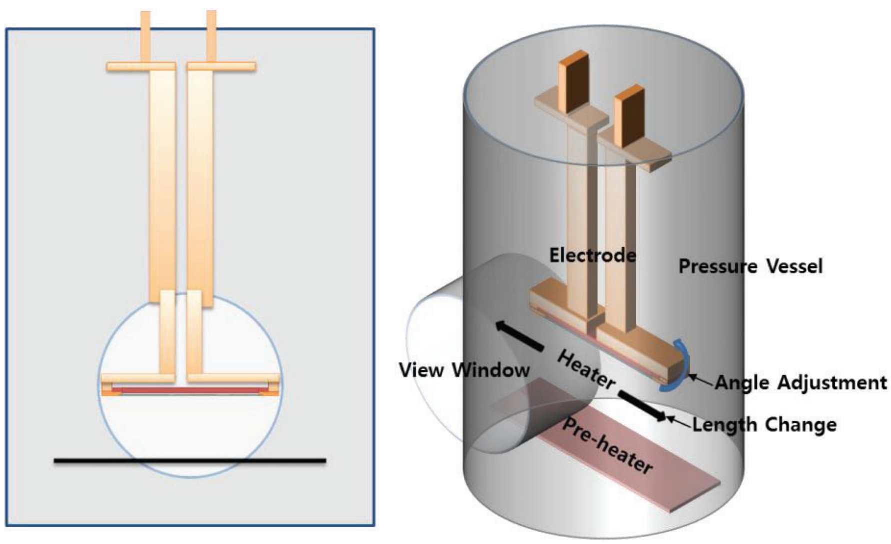

Figure 1. Schematic of test vessel.

2.2. Test sections

In order to investigate the scaling effect on downward-facing flat plate, two kinds of widths and lengths were prepared, respectively. The widths 40 and 50 mm were selected based upon the observation of characteristic bubble size in SBLB facility. In addition, to account for the length effect on CHF, two scales of length, 100 and 200 mm, were prepared. Thickness of the test sections were fixed to 1.2 mm. Furthermore, for the applicability, SA 508 surface was also used for comparison. All the test section surfaces were polished with # 400 grit sandpaper, and the upward-facing surface was insulated with silicone rubber and ceramic located above it. Copper electrodes connecting the copper electrode coming from the lid & test sections were prepared and changed for each inclination angle and dimensions. Heat flux was made by DC heating method using DC rectifier with a maximum capacity of 100 kW (25 V, 4000 A). The overall schematic is depicted in Fig. 2.

Table I. Dimensional conditions in this study

Test Sections	Width	Length	Thickness	Angle [deg]
SUS 304	40 & 50 mm	100 & 200 mm	1.2 mm	0, 15, 30, 45, 60, 75, 90
SA 508				

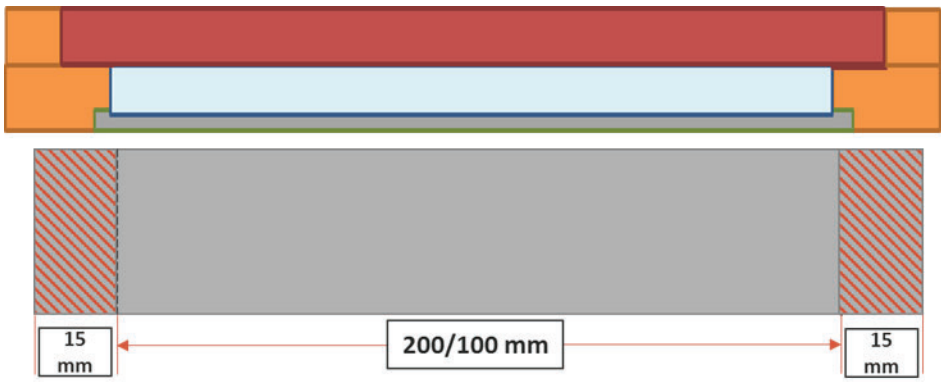

Figure 2. Schematic of test section.

2.3. Experimental methodology

Experimental conditions were adjusted and controlled using the Data Acquisition System (DAS) composed of an Agilent 34,980 A data acquisition/control unit and a personal computer where the experimental information were measured and saved as data. System temperature was measured with two K-type thermocouples located at the heater elevation, and the system pressure was measured and adjusted using the analogue pressure gauge. The current data was measured directly from the DC rectifier, and the voltage was measured by a power meter. Test sections were cleaned by ethyl alcohol before being attached to the copper electrodes. Heat flux was gradually increased, and it was kept constant during the high-speed camera recording. The resistance of the test section sharply increased after the CHF point. CHF values were calculated by dividing the amount of power supplied by the heat transfer area. For the DC heating method, CHF can be calculated by Joule's equation.

3. EXPERIMENTAL RESULTS

In this section, CHF of SUS 304 and SA 508 were compared, and analysis for each dimensional conditions was carried out.

3.1. Analysis of SUS 304 results for various dimensions

As shown in the Fig. 3, there was a width effect beyond some range of inclination angles. Width effect has largely emerged near 45 to 75 degree both for 100 and 200 mm length conditions. However, there was no width effect down to horizontal-downward cases. In order to analyze the trends, high-speed camera was utilized with 1000 fps speed at vertical condition. According to the captured images (Fig. 4), independent bubbles generated at the bottom side slides in relatively slow way and coalesced at the upper part for 50 mm-wide test sections. In comparison, for narrow test sections (40 mm-wide), a large coalesced slug was formed at the low part right above the location where independent bubbles are formed. The large coalesced slug induces merging of independent bubbles generated at the bottom, and they move along the heated surface in a fast way compared with the movements of independent bubbles in wider test sections (50 mm-wide). According to the figures captured by 1000 fps high-speed camera at 60 degree (Fig. 5), independent bubbles for wider test sections merged into each other as trend shown in narrow condition. Due to the same trend between two widths for smaller orientation, width effect diminished as angle decreased.

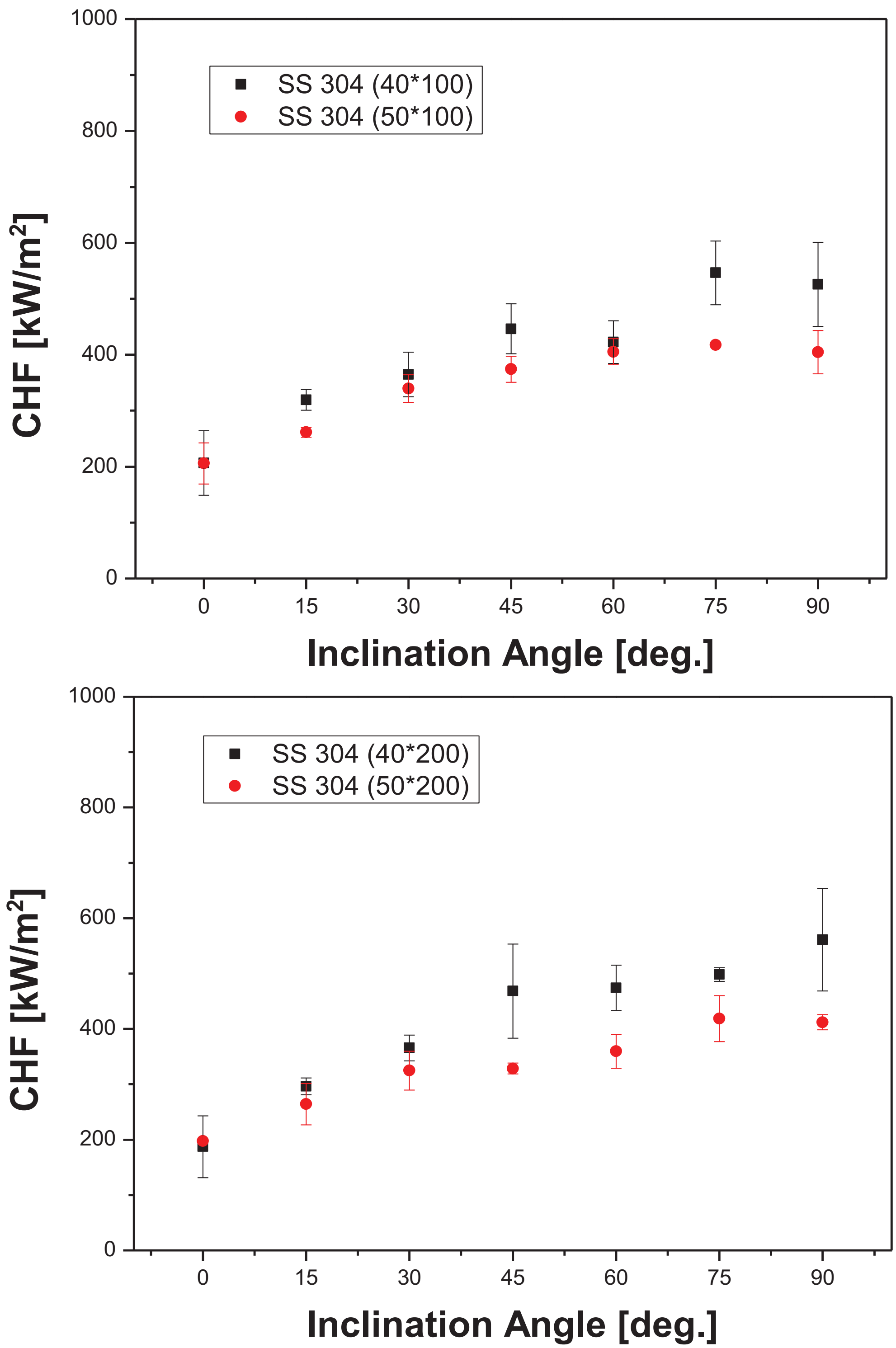

Figure 3. Width effect for 100 & 200 mm lengths.

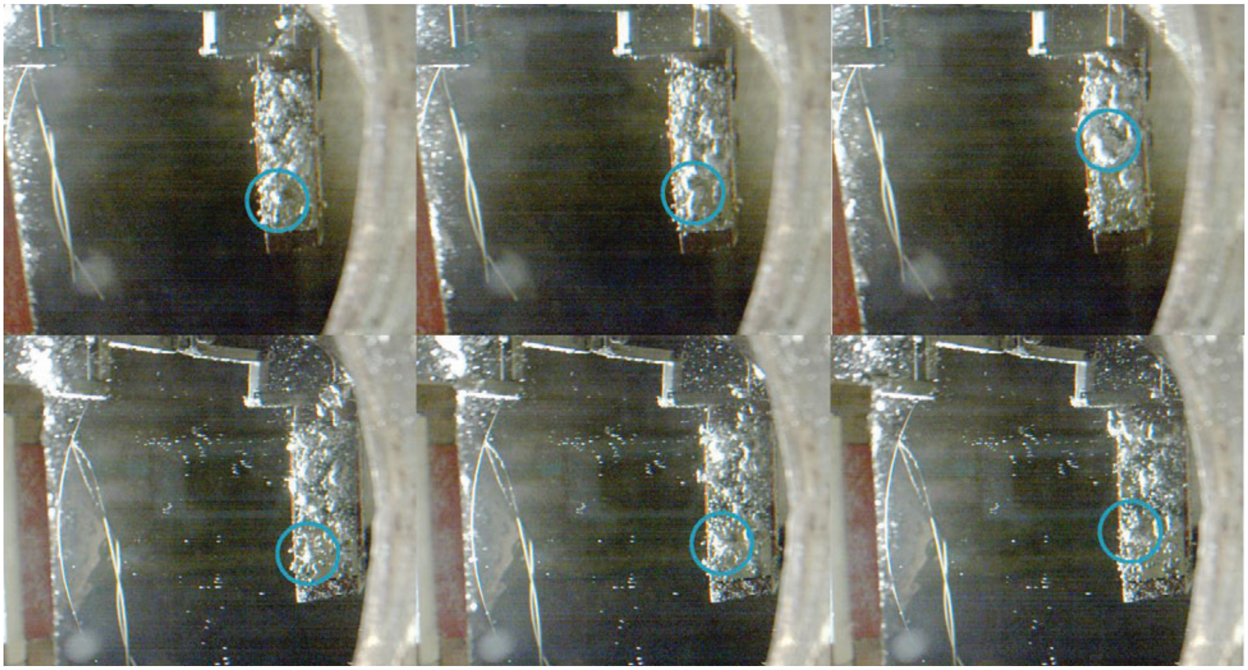

Figure 4. High-speed camera image for vertical condition Up: 40 mm, Down: 50 mm).

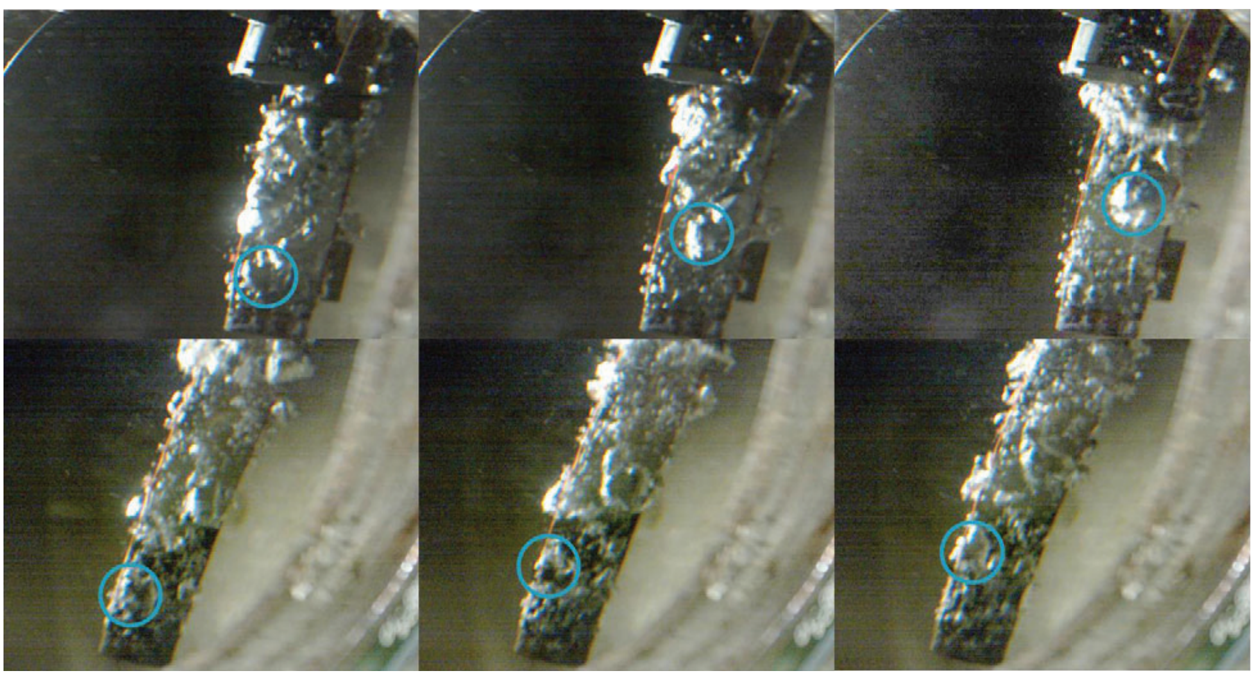

Figure 5. High-speed camera image for 60 degree (50 mm-wide).

According to the Fig. 6, there was almost no length effect for whole range of angles. The sizes of slugs sliding along the heated surface are smaller than the short test sections (100 mm-length), which could explain the absence of length effect (Fig. 7).

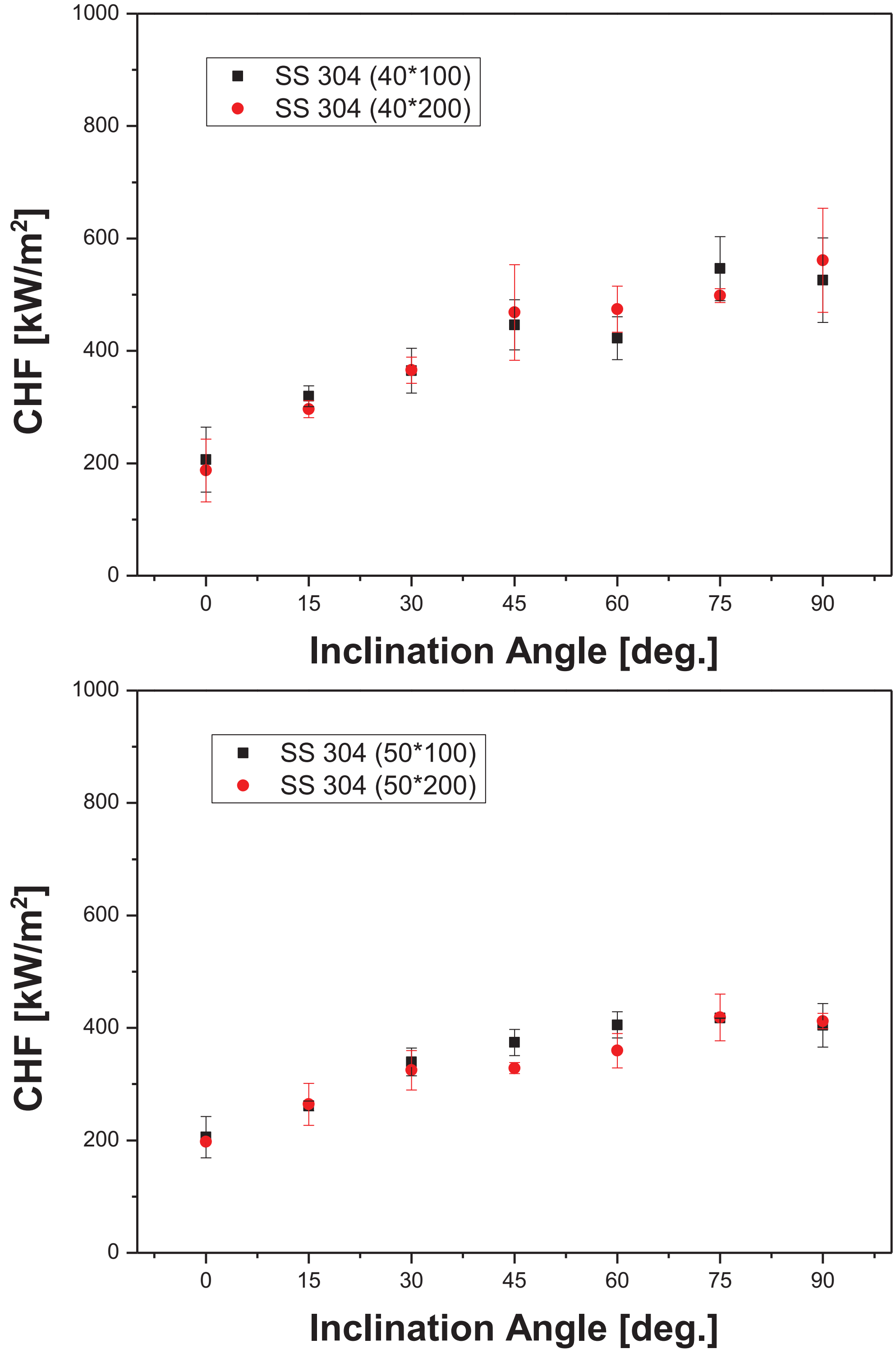

Figure 6. Length effect for 40 & 50 mm widths.

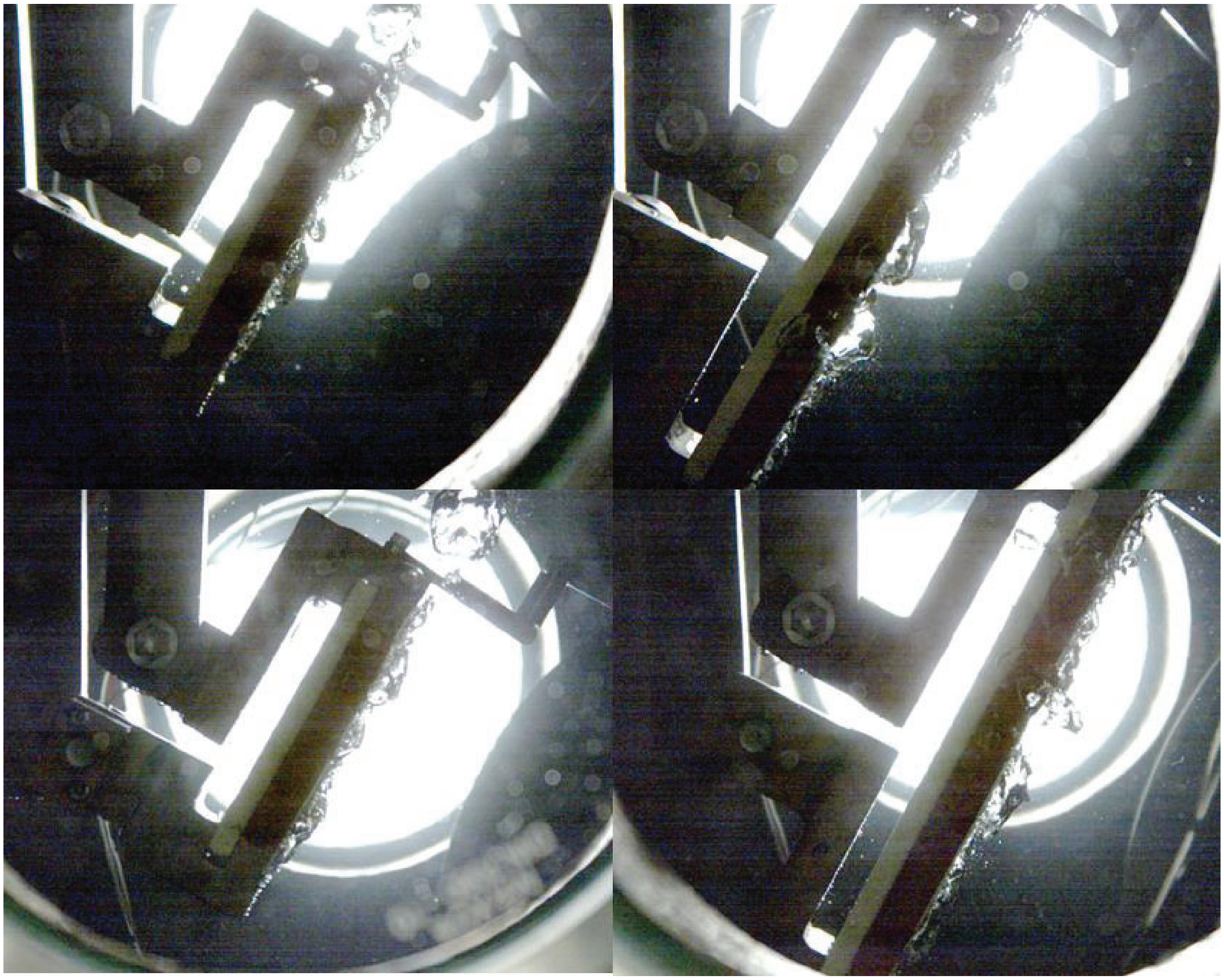

Figure 7. Size of coalesced slugs at 60º.

3.2. CHF between SUS 304 & SA 508

According to the experimental results, CHF of SA 508 was higher than that of the SUS 304 for 40 mm-wide case at high inclination angles. However, the enhancement was reduced as inclination angle approached to horizontally downward position where speed of the coalesced bubbles decrease. In comparison, reduced enhancement for 50 mm-wide case was observed. Even after the experiments, surface of the SA 508 test sections did not undergo oxidation. In addition, burn-out spread out in rather faster way for SA 508 compared with SUS 304 material when CHF is triggered.

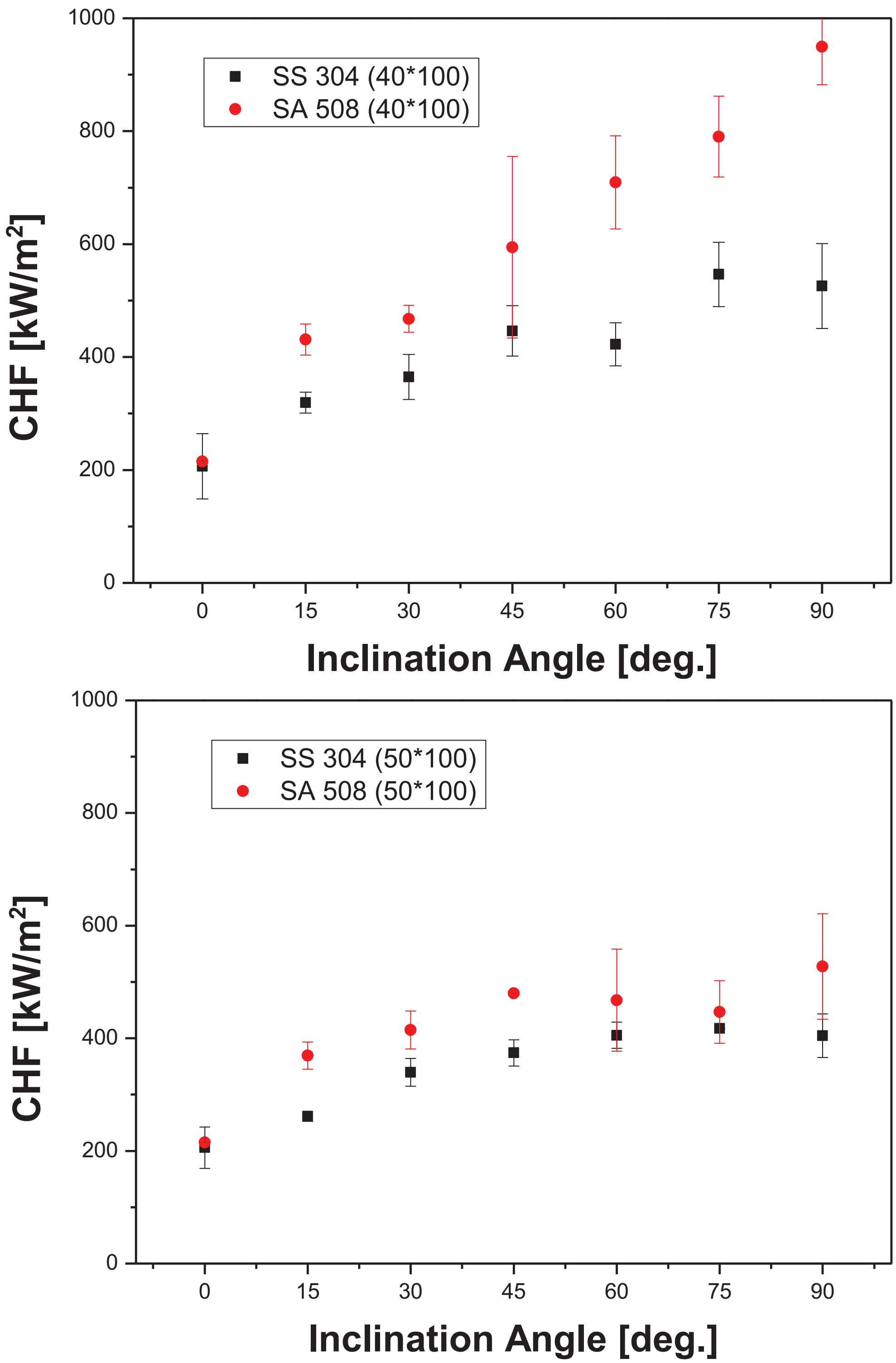

Figure 8. CHF between SUS 304 & SA 508.

In most of the preceding studies using SA 508 surfaces, SA 508 surface showed enhanced CHF results compared with stainless steel surfaces, which was explained mainly with wettability effect. Based on the previous explanations, contact angle was measured for two surfaces using 5 μL of DI water droplet. The surface affinity with DI water was rather higher for SUS 304 surface. Therefore, other factors other than wettability effect should be considered since there was almost no oxidation occurred on SA 508 surfaces in this study. The surface was clean even after the experiments.

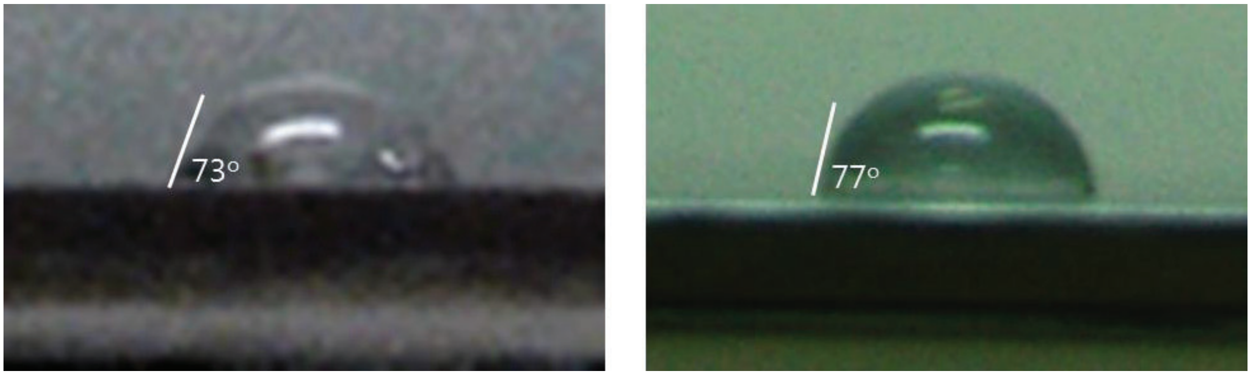

Figure 9. Contact angel measurements of two surfaces before experiments (Left: SUS 304, Right: SA 508).

4. CONCLUSIONS

According to the experimental results, there was no length effect between 100 & 200 mm-length conditions. Width effect was noticed at high angles, but the deviation gradually disappeared as inclination angle approaches to horizontally downward condition. The results could be explained by images captured with high-speed camera.
For 40 mm-wide test sections, SA 508 showed enhanced CHF results at high angles, but the difference decreases as angle decreases. In comparison, for wider test section (50 mm-wide), where bubble escape velocity is relatively low, CHF enhancement was reduced for whole range of angles.
Considering the mechanism of CHF, heat dissipation through the heater material is also one of important factors which strongly has effect on CHF according to preceding studies [12-13]. One of parameters which can describe this effect is diffusivity of a heater material. The value of SA 508 is much higher than that for SUS 304, which suggests that SA 508 contains more margin for CHF occurrence.
According to the results and observations, material property, effect of the bubble sizes (from inclination angle) and the escape velocity is related to the CHF enhancement.

ACKNOWLEDGMENTS

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