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Evaluation of dimension and surface process effects on the critical heat flux through the pool boiling experiments with plate-type 304 stainless steel heaters

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1. Introduction

In a nuclear power plant, critical heat flux (CHF) is one of the significant design parameters considered for a severe accident mitigation strategy as well as a nuclear reactor coolant system. Numerous researchers have steadily studied the CHF to understand the physical meanings and evaluate the CHF under several kinds of experimental conditions: wettability, roughness, orientation, and so on. Even though the CHF studies last for many decades, it is still the research that has not been completely resolved. Furthermore, while heater material and the experimental condition are similar, the CHF results are observed to have a large discrepancy for each CHF experimental study.

Kam et al. [1] evaluated the CHF through pool boiling experiments as a function of the heater width and orientation, especially in downward-facing conditions. As a similar study, Yang et al. [2] evaluated the CHF with large size of heater depending on the orientation (0^o to 180^o), and they suggested the CHF correlation based on the experimental results. When comparing the CHF results, the two studies show a relatively large discrepancy of CHF values despite the similar heater dimension. While trying to reduce the CHF discrepancy through pool boiling experiments under various experimental conditions, significant factors that have detrimental effects on the CHF have been found in this study.

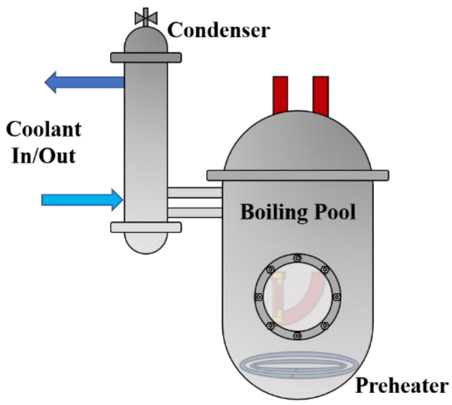
In several experimental studies, they prepared a test section considering the heater material, dimension, and surface condition. On many occasions, the heaters have been ground and polished with sandpaper for the experiments in a laboratory. However, in large size of the heater, since it is not easy to grind the heater surface using a sanding machine with sandpaper, few researchers used to prepare the ground heaters provided from a factory-worked state – having considerably small roughness and even surface. The technical process mainly used in a factory is a buffing that uses a polish. In this study, the buffing-made heaters and the sandpaper-mad heaters are used for the experiments, and the CHF results are compared to each other. In addition, according to the previous study [1], a width effect on the CHF is definitively observed, especially with the vertical-facing heaters. Thus, the vertical condition was applied for the experiments.

This study is to find the reasons for the large CHF discrepancy, which has been observed in previous studies and been just accepted as the experimental uncertainty – by conducting pool boiling experiments in a consideration of the surface process and heater dimensions. As results, the different dimension effects on the CHF trend are observed depending on the surface process. Also, the surface analyses are performed to interpret the results using surface analyzing instruments.

2. Experimental facility and procedures

2.1 Experimental apparatus and a test heater

For the pool boiling experiment, a rectifier is used to provide the direct current to the heater. In general, since the metal is relatively low electrical resistance, the high current of the rectifier is required, and the rectifier capable of 5000A is prepared for the test thereby. The stainless steel 304 is used as the heater material. The heaters are assembled on a test section consisting of copper electrodes, a bakelite, and a silicone rubber for high temperature (Fig. 1). The bakelite is for the support and assembling, and the silicone rubber is to provide the insulation at the bottom of the heater. In conclusion, the flat-type of heaters that releases the heat in one direction is prepared.



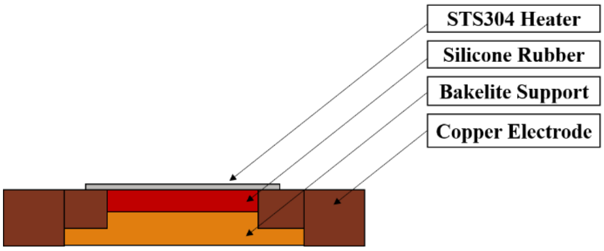


Fig. 1. Schematic figure of the configuration of an experimental facility (Above) and a test section (Below)

Besides, the large volume of a pool (~210L) is prepared to minimize water circulation effects exerted by the boiling and the pool wall. A condenser and a preheater (15kW) are also used to reduce the amount of vaporized water inside the pool and to increase the water temperature to saturation point, respectively.

To evaluate the dimension effects, heaters in a width of 10, 30, 50 mm and a length of 10, 100 mm are prepared. The heater surface is ground in two types of processing: a buffing-made heater and a sandpaper-made heater. The buffing process was conducted in a polishing factory, which uses a green chromium oxide bar to make the mirror-like surface (Fig. 3). Also, 120mesh-sandpaper was used for the relatively rough surface, which is provided by R&B company. The information of each surface morphology is dealt with in section 3.

Fig. 3. The buffing-made heater and its mirror-like surface

2.2 Experimental procedures

After the preparation of a heater and a test section, the 210L of deionized water is filled with a pool, and the preheater begins to heat the water up to saturation temperature in an atmospheric environment. Then, the direct current flows to the heater using a rectifier, and the measurement begins simultaneously with a data acquisition device (DAQ, Agilent 34980A) with 2 Hz of frequency. The voltage is continuously measured at the bottom of the heater surface during the experiments through the pre-installed copper line. The heat flux released on the heater surface is calculated following the equation (Eq. 1) with the voltage and current information. V and I are voltage and current, respectively, and the heat-released area is calculated depending on the heater dimension.

$$q''(kW/m^2) = \frac{V \times I}{Heat\ released\ area} \qquad (1)$$

While controlling the direct current, the heat flux is given at an interval of 25~50 kW/m^2 until the CHF occurs. The point of the CHF is defined at which the calculated electrical resistance rapidly rises up, caused by an increase in the temperature and specific resistance of the heater.

3. Results and discussion

3.1 The dimension effects on the CHF

The CHF experiments are conducted as a function of the heater dimension and surface process ways. For the 120mesh-sandpaper-made heater, it is observed that the CHF decreases with increasing length, while the width effects on the CHF is no longer observed with the heater in more than 30 mm of width (Fig. 4). Due to the characteristic of the test section configuration, the smaller size of heaters in 10 mm of width and length are affected easier than the larger ones by vapors generated on the sidewall. Thus, a little unstable CHF trend is observed with a relatively large deviation. Furthermore, the length effects are observed to be more dominant compared with the width effects according to the CHF results.

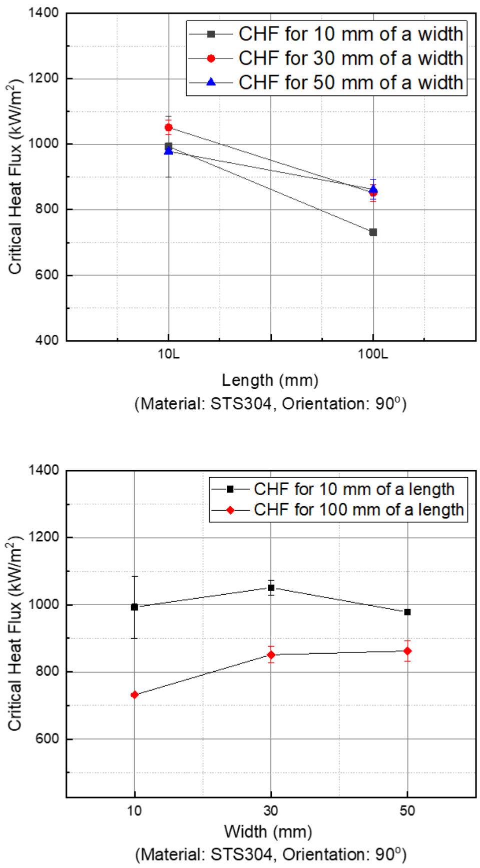


Fig. 4. The length and width effects on the CHF for the 120mesh-sandpaper-made heater

For the buffing-made heater, the CHF is observed to be reduced with an increase of the width, while the unstable trend in 10 mm width and length heaters also appears (Fig. 5). According to the CHF results for the buffing-made heater, the width effects appear more dominant than the length effects with the heaters in more than 10 mm of width. The difference of the CHF trends between the sandpaper- and buffing-made heaters should be analyzed with the observance of surface morphology. It is dealt with in the next section.

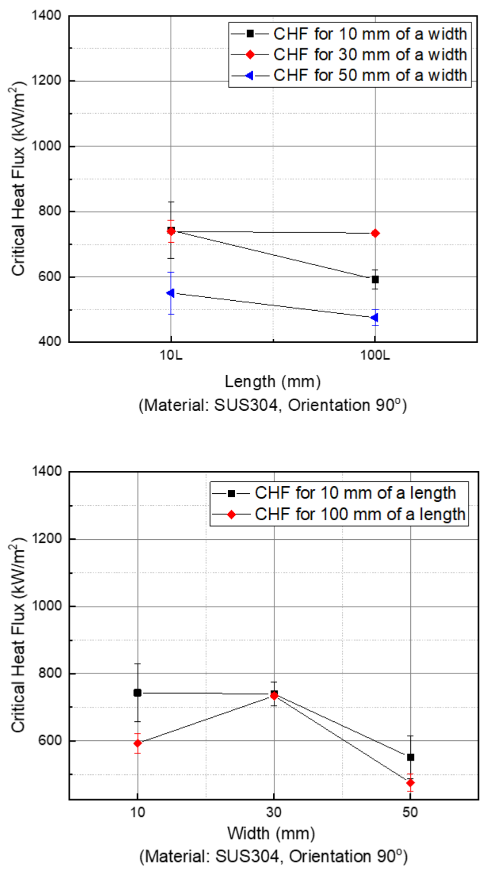


Fig. 5. The length and width effects on the CHF for the buffing-made heater

3.2 The surface process effects on the CHF

In Fig. 6, for the heater in a length of 100 mm, the CHF is compared as a function of width and the surface manufacturing process. As a result, the detrimental effects on the CHF are observed with the CHF reduction compared with the 120mesh-sandpaper-made heater. The CHF difference is getting larger with an increase in the width. The surface analyses are conducted with a Scanning Electron Microscope and Energy Dispersive X-ray Spectrometer (SEM-EDS), 3D profiler, and contact angle measurement.

Through the 3D profiler, a surface profile and roughness of each heater surface are obtained (Fig. 7). The much greater roughness is measured for the 120mesh-sandpaper-made heater surface than the buffing-made one. According to the contact angle measurement with 5ul of deionized water and the heater surface cleaned by ethanol, the contact angle is also observed to be greater for the 120mesh-sandpaper-made heater (Fig. 8). However, it is improper to conclude that the large CHF discrepancy observed in Fig. 6 is due to the difference in the contact angle and roughness. The buffing-made heater shows different CHF trends from the sandpaper-made heater, and the discrepancy is too large to be explained by the minor change of wettability. Also, the buffing-made heater should have had a higher CHF value according to the contact angle measured.

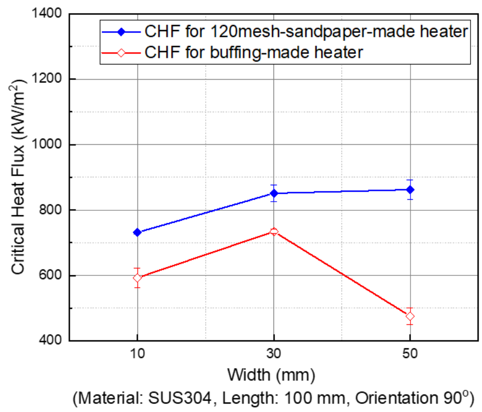


Fig. 6. The comparison of CHF values as a function of width and the surface conditions for the 100mm length heaters

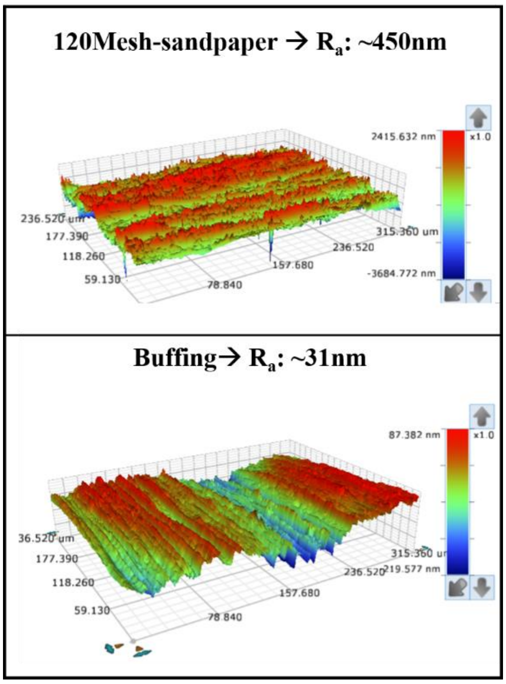


Fig. 7. The image of the 3D profile with the roughness measurement results

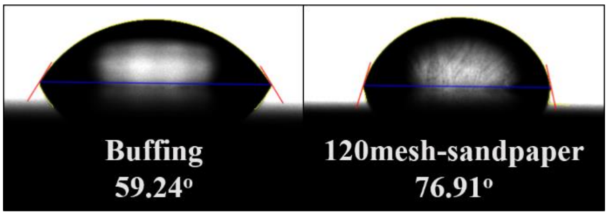


Fig. 8. The contact angle measurement depending on the surface conditions

For a more in-depth evaluation, surface morphologies are observed through the SEM-EDS. In Fig. 9, As confirmed in the 3D profile images, the buffing-made heater appears to have a much smoother morphology than the 120mesh-sandpaper-made heater. Through the EDS analysis, for being unexpected, the chromium oxide is found out inside flaws which are expected to be cavities, as shown in Fig. 10. Before the experiments, all heaters go through cleaning using ethanol. Despite the cleaning process, the chromium oxides remain, which influence a nucleation site density by blocking cavities and interrupting the nucleation – leading to detrimental effects on the CHF after all. This CHF reduction caused by blocked cavities was reported in the previous study [3] that has asserted the sparse deposition of silica nanoparticles brings the deterioration of the CHF. Thus, the chromium oxide stuck during the buffing process has a strong possibility of causing the CHF reduction.

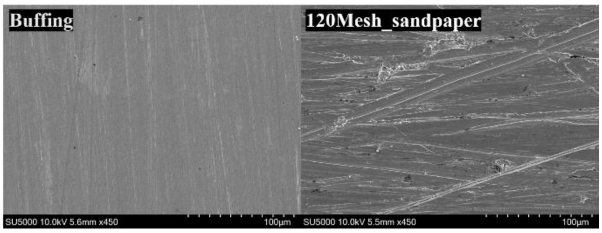


Fig. 9. The SEM image of the surface morphology made by two types of surface processes: Buffing and sandpaper

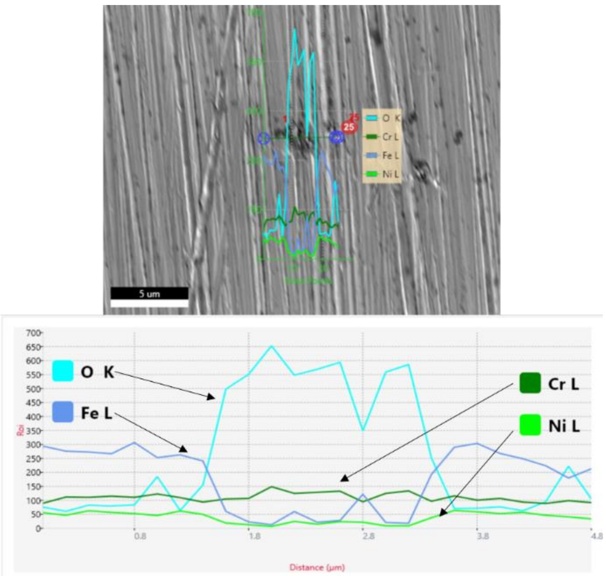


Fig. 10. The result of EDS analysis and the chromium oxide remained in micro-flaws

4. Conclusion

The pool boiling experiments are conducted in order to evaluate the CHF as a function of a heater dimension and heater surface processes. The dimension effects on the CHF are observed with two types of heaters made by sandpaper for the grinding and buffing process. The CHF results are as follows:

1. For the sandpaper-made heaters, the CHF decreases with an increase in length. The length effects are more dominant on the CHF trend compared with the width effects.
2. For the buffing-made heaters, the CHF decreases with an increase in width. The width effects are more dominant on the CHF trend compared with the length effects.
3. The much lower CHF values are observed for the buffing-made heater than the sandpaper-made one. The CHF discrepancy is getting larger with increasing the width.
4. Through the surface analyses, chromium oxides are discovered inside the flaws expected to be cavities. The detrimental effects of the buffing process on the CHF appear to be brought from the blocked cavities by chromium oxides, which affect the nucleation site density and the CHF.

ACKNOWLEDGEMENT

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