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Experimental study on augmentation of nucleate boiling heat transfer on nano-porous surfaces

Youngjae Park[a], Hyungdae Kim[a*]
[a]*Department of Nuclear Engineering, Kyung Hee University, Yongin, Gyeonggi, Republic of Korea*
[*]*Corresponding author: hdkims@khu.ac.kr*

1. Introduction

Nucleate boiling broadly occurs in thermal-hydraulic and safety systems of nuclear power plant (NPP). Heat transfer performance of nucleate boiling is closely related to efficiency and safety of NPPs. Hence, there have been numerous researches to effectively enhance nucleate boiling heat transfer performance.

A number of recent studies have reported significant enhancements in nucleate boiling heat transfer coefficient (NBHTC) and critical heat flux (CHF) by fabricating nano/microscale structures on a boiling surface. Wei et al. [1] showed that both NBHTC and CHF can be significantly enhanced with micro-pin-finned structures. They explained enhancement of NBHTC and CHF that occurred by increase in effective heat transfer area due to micro-pin-finned structures. Ahn et al. [2] reported 100% enhancement in CHF on a boiling surface with nano/micro hybrid structures. They analyzed CHF enhancement that was caused by improvement of surface wettability on Nano/micro hybrid structures.

In this study, an ordered nano-porous surface was prepared using anodized aluminum oxide (AAO) technique and nucleate boiling heat transfer performance was examined in a pool with FC-72. Furthermore, the pool boiling result on the nano-porous surface was interpreted based on heterogeneous bubble nucleation theory from a cavity.

2. Experiment

2.1 Preparation of nano-porous boiling surface

Anodized aluminum oxide (AAO) technique has been extensively applied to industry as it can easily fabricate ordered nano-structure on a large area at low cost. AAO nano-structured samples were prepared for this study. At first, a smooth plate is fabricated by electro-polishing process. Then in order to fabricate nano-sized initial pores, anodization of the electro-polished sample is carried out by applying 40 V to the sample in oxalic acid (0.3 M, 15℃). The anodized sample has the initial pore diameter of 30 nm. The pore can be widened by widening process. Figure 1 is a FE-SEM picture of the prepared AAO surface. Pore diameter and depth are 85 nm and 500nm, respectively.

2.2 Experimental apparatus for boiling heat transfer

Figure 2 shows a schematic diagram of the experimental apparatus. A double jacketed isothermal bath is used as a chamber for boiling test. FC-72 refrigerant is used as a working fluid for boiling test. Isothermal condition of FC-72 in the chamber is maintained by controlling temperature of water circulating between the inner and outer walls of the double jacketed bath. The main heater used in this experiment is a Misumi ceramic plate heater and is powered by a DC power supply (Agilent N8760A). Temperature in the working fluid and test sample are measured with T-type thermocouples and a data acquisition system (Agilent 34972A).

3. Results and Analysis

3.1 Nucleate boiling heat transfer results

Figure 3 shows heat flux and NBHTCs of the bare and AAO nano-structured surfaces in FC-72. The AAO surface exhibits higher NBHTC than the bare one: 70% at 30 kW/m^2 and 50% at 70 kW/m^2. After the middle of heat flux at 120 kW/m^2, NBHTC of AAO surface is still larger than bare surface. However, NBHTC of AAO surface shows decreasing trend. More study and discussion are needed to determine this result.

3.2 Data interpretation

According to Clausius-Clapeyron and Young-Laplace equations [3], a cavity can be activated when its mouth radius is larger than r_{min} as

$$r_{\min} > r^* = \frac{2\sigma T_{sat}(P_l)\upsilon_{l\upsilon}}{h_{l\upsilon}[T_l - T_{sat}(P_l)]} \quad (1)$$

The minimum cavity radius calculated by equation (1) for FC-72 is shown in Fig. 4. The minimum cavity radius to activate boiling bubbles was approximately 600 nm – 200 nm at 10℃-30℃ liquid superheat. The individual nano-pore of 85 nm does not exist in the range of the prediction. However, it is found from Fig. 1 that too much widened cavities were interconnected each other, creating a larger non-circular cavity. It is supposed that the resulting non-circular pores with larger effective cavity radius can play a role in more effectively activating boiling bubbles. Effective cavity radius r_c^* was defined by Wang and Dhir. [4]. Eq. (2) gives effective cavity radius.

$$2r_c^* = D_c^* = \sqrt{\frac{4A_c}{\pi}} \qquad (2)$$

As a result, NBHTC was enhanced by an increase in nucleation site density due to the network-type nano-porous structures.

4. Conclusions

Nucleate pool boiling experiments of FC-72 were performed on nano-structured surfaces, fabricated using the well-established aluminum anodic oxidation technique at atmospheric pressure and saturation condition.

Nano-porous surfaces enhanced NBHTC by 50-70% at various heat flux conditions due to large non-circular cavities with large effective radiuses. According to heterogeneous bubble nucleation theory, a cavity can be activated when its effective radius satisfies the minimum cavity radius criteria.

Further parametric studies are needed to fully understand effect of nano-sized pores on nucleate boiling heat transfer. We plan to test and analyze different sizes of nano-pores on boiling heat transfer.

Acknowledgements

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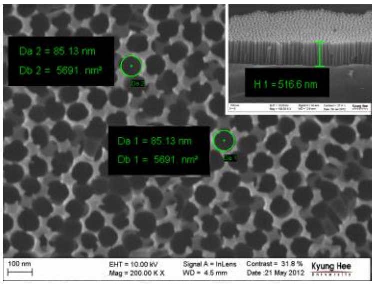

Fig. 1 FE-SEM photo of a prepared nano-structured surface

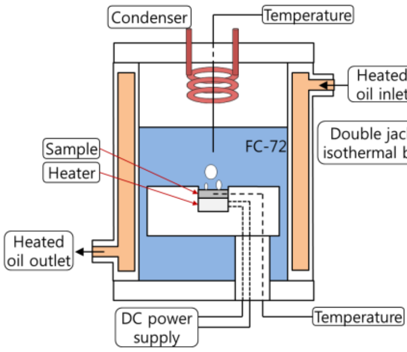

Fig. 2 Schematic diagram of experimental apparatus

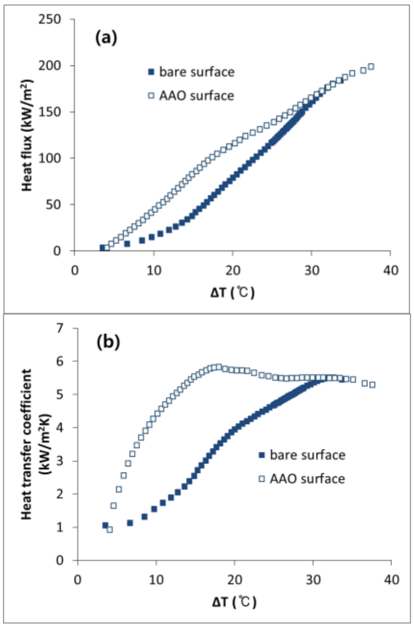

Fig. 3 Comparison of (a) boiling curve and (b) heat transfer coefficient of FC-72 on the bare and nano-structured surfaces.

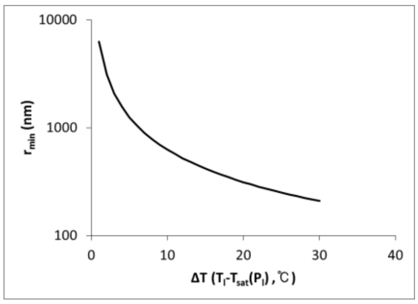

Fig. 4 Minimum active cavity radius vs. liquid superheating