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Improvement of dropwise condensation heat transfer using hydrophobic nano-porous surfaces

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1. Introduction

Recently interest of passive system in thermal-hydraulic safety system of nuclear power plants has been increased. Passive residual heat removal system (PRHRS) is applied to SMART and APR+ for providing the sufficient cooling capacity against accident conditions. PRHRS is a device for removing the decay heat that cools steam through condensation heat transfer in emergency tank.

Condensation is one of most important heat transfer methods in almost industry including the PRHRS. Condensation is classified, according to shape of condensate, into drop-wise condensation and film-wise condensation. Drop-wise condensation (DWC) exhibits a significantly higher heat transfer coefficient than film-wise condensation (FWC). Whether DWC or FWC occurs in a heat transfer surface is strongly affected by wettability of a surface. It is known that DWC is appears on low wettability surfaces while FWC is appears on high wettability one. In this study, nano-porous hydrophobic surfaces were prepared and tested for the improvement of dropwise condensation heat transfer performance.

2. Review of drop-wise condensation model

One of the relevant dropwise condensation modeling was performed by Kim and Kim [2]. They derived a mathematical equation of the model to predict the dropwise condensation heat transfer on a hydrophobic surface with a contact angle higher than 90°. The model is formulated with a focus on the conduction heat transfer through a single droplet and the size distribution of drops.

$$q`` = \int_{r_{min}}^{r_e} q_d(r)n(r)dr + \int_{r_e}^{r_{max}} q_d(r)N(r)dr \quad (1)$$

where $q``(r)$ is heat transfer rate of a single droplet of r. $q``(r)$ is presented by a combination of resistances on a single droplet. Resistances exist on the drop itself, the hydrophobic coating layer, the curvature of the drop and the vapor-liquid interfacial. A population balance model is divided into two for small and large drops. For small drops, a drop distribution function is determined by direct condensation but for large drops by coalescence of pre-existing drops.

3. Experimental

3.1 Design of hydrophobic nano-porous surface

Wetting state of porous nanostructured surfaces can be predicted by well-known Cassie-Baxter models. Contact angle changes according to alteration repulsive power between the surface and liquid by roughness. In the Cassie-Baxter model the apparent angle is given as $cos\theta_c = \emptyset_s(cos\theta + 1) - 1$ where $\emptyset_s$ is a fraction of the bottom contact area to total area. The fraction is given as;

$$\emptyset_s = \frac{\pi b}{a^2} \quad (2),$$

where b is a radius of pore, a is a pitch between pores

Therefore, the contact angle of and Cassie-Baxter model is determined by pore size, pitch, pore shape. In the other words, the contact angle is changed by pore volume per unit area. The more density is the larger the fraction$\emptyset_s$. The characteristic of surface is controlled by the pore density.

3.2 Fabrication of hydrophobic nano-porous surfaces

In this study anodic aluminum oxide (AAO) technique is used to fabricate various nano-pore surfaces with variations in density of pore because of having relatively simple fabrication methods compared to other nano structured surfaces. A first step of AAO fabrication is electropolishing that makes the bare aluminum plates smooth. Next step is anodizing at 15℃, 40 V and then the widening is performed at 30℃. At this point, the pore size and depth of nanosurface is controlled of nano-surface as changing duration of anodizing and widening process.

In Cassie-Baxter model pore density only affect to the wettability. Therefore the surfaces used in this study have 500 nm depths and various pore sizes matched contact angle 110° and 140° estimated by the Cassie-Baxter model.

Self-assembled monolayers (SAM) is coated on the prepared AAO surfaces for presenting hydrophobic characteristic. Before the SAM coating process, moisture of the AAO surface is removed. Then the surface is dipped in a solution of mixed HDFS (hepadeta-fluoro-1,1,2,2-tetrahydrodecyl- ichlorosilane) and hexane for 20 min and finally baked in oven for 20 min at 75℃. Table 1 shows a comparison of contact angles of nanosurfaces between the prediction with Cassie-Baxter model and the measurement results. A perfect agreement of the two confirms that the AAO nano-porous surfaces were prepared well.

Table 1. Contact angles of water droplets on different nano-surfaces (contact angle of a bare surface: 95°, pore depth : 500 nm, pore pitch : 100 nm)

b (radius)		30 nm	38 nm	48 nm
Contact angle	Cassie-Baxter model	110°	120°	140°
	Measurement	110°	120°	145°
photograph				

3.3 Experiment apparatus

The experimental apparatus is shown schematically in Fig. 1. The center of figure is condensation experiment part. The size of the sample is 25 mm by 25 mm and thickness is 2 mm. Condensation occurs in the center circle of 15-mm diameter. Saturated steam at 100℃ is supplied from the steam generator. The steam is produced filled apparatus to DI water at staring point for reducing non-condensable gas and passes through boiler for reducing temperature fluctuation in the condensation part. Water is used to cool the test surface. Coolant temperature and mass flow rate were controlled and maintained using the thermostat. Condensation is observed through the visible window using the CCD camera.

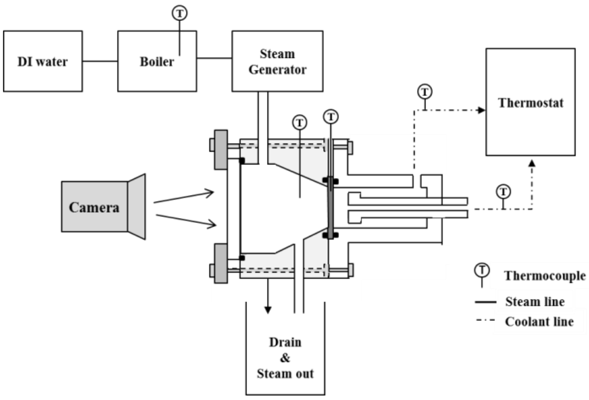

Fig. 1 Schematic diagram of the apparatus.

4. Experiment results and Discussion

4.1 Experiment results

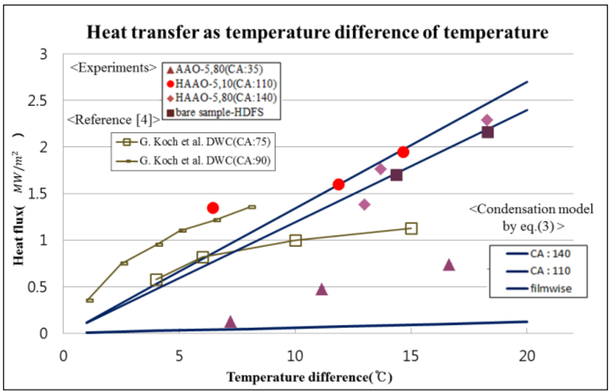

Fig. 1 Comparison of experimental results and models

The experiment results are presented in Fig. 2 and compared with the previous data in relevant reference and the prediction of the DWC of model of Kim and Kim [2]. It is well known that DWC heat transfer is much superior to FWC. In the present experimental results at 20℃ of temperature difference, it is found that the performance of the DWC heat transfer is almost three times higher than the FWC. In the reference and modeling results, the dropwise condensation heat transfer rate increases according to contact angle. But such effect of contact angle on DWC heat transfer could not be confirmed in the present experiment results. It is supposed that the experimental accuracy was not precise enough to identify the effect of contact angle, or that the hydrophobicity coating layer of the test sample was hurt during condensation of hot steam. Further investigations are needed to clearly understand the contact angle effect on drop-wise condensation heat transfer performance.

4. Conclusions

Drop-wise condensation heat transfer was experimentally investigated. Drop-wise condensation is presented on modified hydrophobic nano structured surfaces. In this study technique of anodic aluminum oxide fabrication surface is achieved and the surfaces were fabricated on various conditions. Hydrophobic surfaces are obtained from the anodic aluminum oxide surfaces and self-assembled monolayers. Using this surfaces drop-wise condensation is presented and obtains superior heat transfer rate to film-wise condensation.

Acknowledgments

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