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Experimental study of the effect of the reduced graphene oxide films on nucleate boiling performances of inclined surfaces

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1. Introduction

Nucleate boiling heat transfer is an efficient method for removing high heat loads generated by a molten reactor core under severe accident conditions. With the upgrade and development of advanced power reactors, however, enhancing the nucleate boiling rate and its upper limit, Critical Heat Flux (CHF), becomes the key to the success of external cooling of reactor vessel undergoing core disruption accidents. For the enhancing the CHF, surface coating techniques are available. Yang et al. performed small scale boiling experiments for the vessel lower head, which was coated by aluminum/copper micro particles. [1] Recently, graphene has received much attention for applications in thermal engineering due to its large thermal conductivity. Ahn et al. used a silicon dioxide substrate, which was coated graphene films, as a heating surface during pool boiling experiments. The graphene films inhibited the formation of hot spots, increasing the CHF. [2] For applying novel material 'Graphene' in nuclear industry, here we investigated the effects of graphene film coatings on boiling performances. The experimental pool boiling facility, copying the geometry of lower head of reactor, was designed for verifying orientation effects

2. Methods and Results

2.1 Coating reduced graphene oxide films

Graphene colloid was prepared with chemical method as called Improved Hummer's Method.[3] Chemical oxidation of graphite and ultrasonication process made graphene oxide, and the graphene oxide was reduced using hydrazine. The graphene film was obtained via filtration, which was carried out using a vacuum. The converted reduced graphene oxide (RGO) colloid was diluted in de-ionized water (DI water). The solution was poured into the glass funnel, which was located on the top of filter holder. Cellulose paper filter with 450-nm-diameter-pores was used to filter the RGO flakes. During filtration, only RGO flakes were remained and DI water flowed through the cellulose paper, resulting in well-stacked RGO film. After filtration process, the RGO film were dried in an instant. For coating the RGO film on the silicon substrate as heating element, however, extra moisture helps contact better between RGO film and substrate. So we spread DI water on the substrate, putting RGO film and pressed in the middle of two rubbers. The specimen was placed in an oven at 63℃ for 1hour. After baking, the cellulose paper was peeled off from the substrate, leaving the RGO film on the silicon-substrate-heater. The thickness of RGO films were characterized using surface profiler, and set to be 50, 75, 100, and 200nm.

2.2 Experimental pool boiling facility

Figure 1 shows a schematic diagram of the experimental pool-boiling facility. The pool boiling facility consisted of main pool, heater mount, orientation controller, power supply and data logger. Main pool chamber was a rectangular bath formed of 10-mm-thick aluminum plate with a 30-liters capacity. The test sample consisted of a silicon substrate and a polyetheretherketone (PEEK) test sample frame. The silicon substrate was fixed on the PEEK test sample frame by using of epoxy. The combination of the test sample and heater mount prevented an inflow of water. The cavity, formed between test sample and heater mount, was vacuumized, providing adiabatic condition on backside of the heating elements. Specially, orientation controller, placed on the top of main pool, enables to incline heating elements.

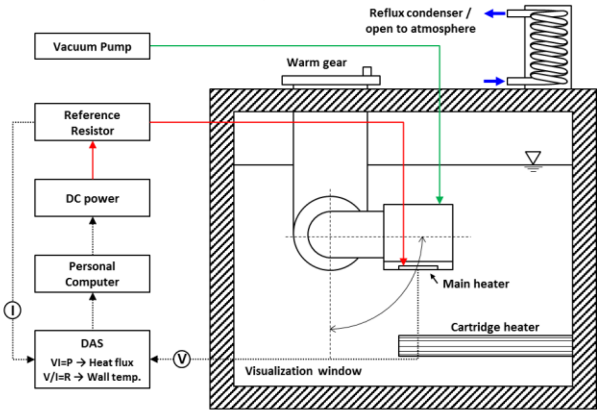

Fig. 1. Experimental apparatus.

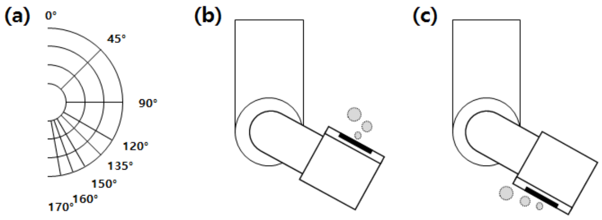

Fig. 2. (a) Experimental case introduction, (b) upward-facing boiling, (c) downward-facing boiling.

For a convenience, the orientation module, consisted of orientation controller and heater mount, could be separated from the main pool. A reflux condenser was installed at the top of the main pool chamber to prevent evaporation of the working fluid.

2.3 Pool boiling experiments

To make saturated condition, the main pool was filled with 30 liters of DI water, covered by Teflon cover and preheated for 3 hours, using 1.2kW of immersion heater. Keeping saturated condition, the orientation module was mounted, replacing Teflon cover and the heater mount was vacuumized. Heat flux was electrically applied to the Platinum resistance, which was patterned beneath of silicon substrate by MEMS fabrication. Power line penetrated heater mount and was held on the Platinum resistance by soldering. When the CHF was reached, the temperature of the heating element increased rapidly, causing it to broken and the experiment was closed.

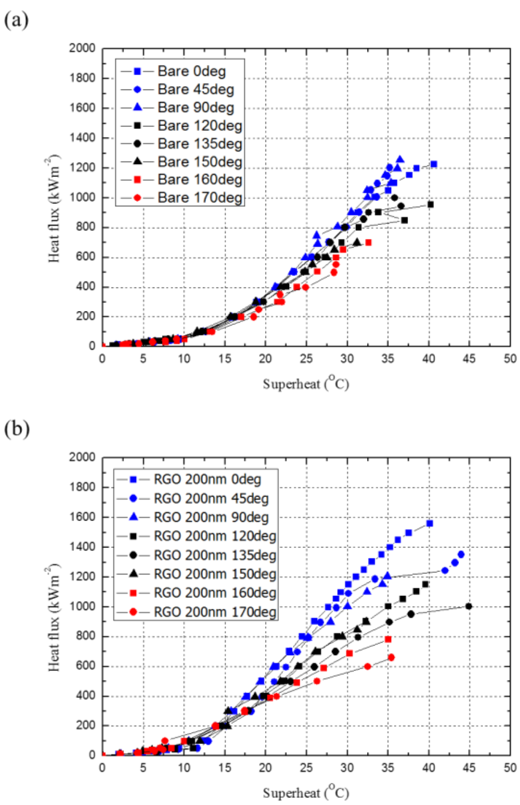

Fig. 3. Boiling curves (a) Bare (b) 200nm of RGO film

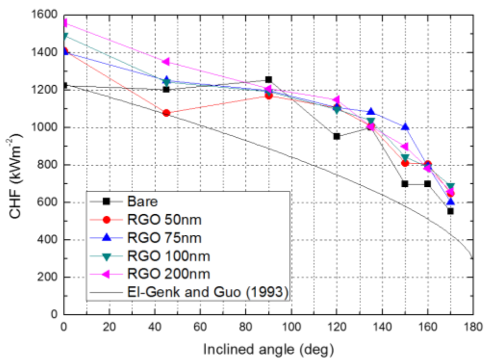

Fig. 4. Comparison of CHF value for varied inclined angles and coating thickness.

Changing the surface of heaters, the experiments were repeated at different inclined angles: upward-facing boiling (0, 45, 90 degree) and downward-facing boiling (120, 135, 150, 160, 170 degree) (Figure 2).

2.4 Comparison of boiling performance

In this study, we investigated the effects of coating of RGO films on the boiling performances. In every case, coated RGO films were not peeled out from the silicon substrate despite they experienced boiling environments. Comparing Figure 3 (a) and (b), we found that the CHF value was enhanced at upward facing region (0-45 degree), by 27-12% as coating RGO films. For the downward facing region, the general CHF behavior observed. The large bubbles escape through the upper edge of PEEK test sample frame, sliding the heater surfaces. Drag force, which acts along the interface of bubbles, makes delay hovering times. Bubbles were coalesced and covered the entire heater surface, resulting in relatively lower CHF.

As shown in Figure 4, we verified the effects of thickness of RGO films according to inclined angles of heater surface. The CHF model of Guo & El-Genk [4] are lower than the present data. The equation is expressed as follow:

$$q_{CHF} = C_{CHF,f}\left(\theta\right)\rho_g h_{fg}\left[\frac{\sigma\left(\rho_f-\rho_g\right)g}{\rho_g^2}\right]^{1/4} \quad (1)$$

$$C_{CHF,water}(\theta) = 0.034 + 0.0037(180-\theta)^{0.656} \quad (2)$$

The CHF values at 0 degree were enhanced when the thickness of coated RGO films were increased (1224.6 to 1559.0 kWm^{-2}), following the result of Ahn et al [2]. However, the effects were decreased when heater faced bottom of the pool as if the amount of enhancement is converged.

3. Conclusions

The effects of graphene films coating on varied inclined heater surfaces were investigated. The CHF values were increased at every case, but the increased amounts were decreased for downward heater surfaces. At the downward-facing region, however, coating the RGO films would change the CHF mechanisms and boiling heat transfer performances. Generally, RGO films, made by colloidal fabrication, has defects on each flakes. With the post-treatment of RGO films, the thermal conductivity could be changed. As a follow research, it will be conducted.

4. Acknowledgements

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q_{CHF} : critical heat flux

θ : inclined angle

ρ_g and ρ_f : density of vapor and water

h_{fg} : latent heat

σ : surface tension

$C_{CHF,f}$: pool boiling CHF orientation coefficient use by El-Genk and Guo [4]

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