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A study on the upward and downward facing pool boiling heat transfer characteristics of graphene-modified surface

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1. Introduction

Since the accident in Fukushima in 2011, a much of researchers had an effort to prevent or migrate severe accident tragedy in worldwide. One of the strategy, in-vessel retention external reactor vessel cooling system (IVR-ERVCS), was examined for applying to design feature of APR1400. As severe accident breaks out, cooling water from IRWST is supplied to cavity which surrounds reactor vessel. For eliminating decay heat from reactor vessel, a large amount of coolability could be significant issues on the wall materials. Recently, graphene, carbon in two dimensions, were highlighted as a good heat transfer materials, according to its high thermal conductivity. Especially, Ahn et al. evaluated a pool boiling performances of graphene-treated silicon dioxide substrate heater. Lateral conduction and water absorption into the structure helped graphene films to inhibit the formation of hot spots, which means increasing of critical heat flux (CHF) and boiling heat transfer coefficient (BHTC) performances [1]. In this study, we report a promising increase of CHF and BHTC results with 2D graphene films. Furthermore, we tried to observe bubble behavior via high-speed visualization to investigate a relationship between bubble behavior and pool boiling performances in downward facing boiling.

2. Methods and Results

2.1 Coating reduced graphene oxide films

A process for coating graphene films was progressed as following steps: preparation of graphene colloids and coating by direct transfer method (2D graphene) and boiling method (3D graphene). Graphene colloid was prepared by chemical method as called Improved Hummers' method [2]. Chemical oxidation of graphite and ultrasonication process made graphene oxide, and the graphene oxide was reduced using hydrazine. Then, the reduced graphene oxide (RGO) colloids were filtered through cellulose membrane by vacuum filtration process. The dehydrated 2D graphene film was transferred onto the silicon plate heater by compression in convection oven of 63C. The thickness of 2D graphene film was controlled by amount of RGO colloidal suspension when vacuum filtration, and measured by profiler. The 3D graphene was prepared by boiling method. Graphene flakes in colloidal suspension arranged at the liquid-vapor interface as bubble nucleated. The graphene flakes were self-assembled along the bubble interface with hydrogen bonding. For enough coating, heat flux was 1100kW/m2 and maintained for 10 min.

2.2 Experimental pool boiling apparatus

Figure 1 shows schematic diagram of experimental apparatus of pool boiling. The pool boiling apparatus consisted of container vessel, heater mount, orientation controller, power supply, and data logger. The container vessel was designed to charge 27L of DI water at atmospheric saturated condition. Polycarbonate visualization window was placed in front of container vessel, which enables to observe bubble behavior with high-speed camera. The main heater mount had 2 different functions to control orientation of main heater and prevent water leakage. A warm gear, placed on the cover, could rotate 90deg and the mount could be installed with the warm gear both with upward or downward facing. The main heater was double-polished silicon dioxide wafer and cut into 25×20 with 500μm of thickness. Platinum film was deposited on the bottom of the main heater as a function of both resistance heater and RTD sensor and connected DC power supply. The main heater was fixed on PEEK(polyeheretherketone) jig with epoxy sealing. Then, the PEEK jig was installed on the top of the heater mount with mechanical combination.

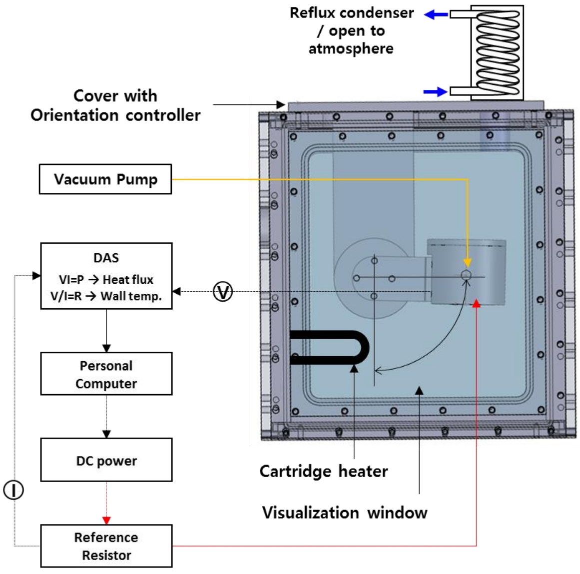


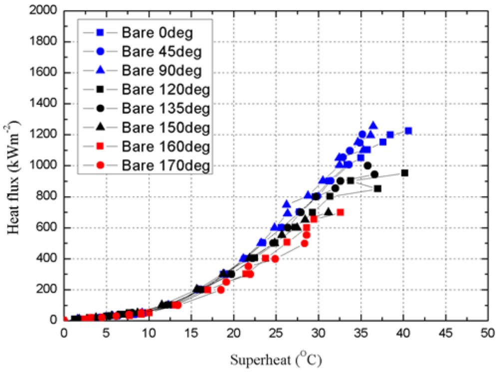
Fig. 1. Experimental apparatus

The inside of cylindrical mount was decompressed with vacuum suction to avoid seal-breaking by increase of inside pressure caused by temperature rise during boiling experiments.

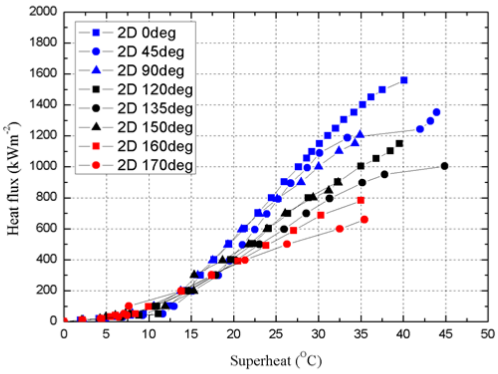
2.3 Results of pool boiling experiments.

The boiling experiments were performed according to orientation of heater surface. The orientation angle was changed from upward to downward facing, i.e. 0, 45, 90, 120, 150, 160, 170 deg. Every experimental cases was visualized with high speed camera. Figure 2 shows pool boiling curve as varied orientation angle on bare surface of double polished silicon wafer surface, 2D graphene film, and 3D graphene surface.

(a) Bare



(b) 2D graphene



(c) 3D graphene

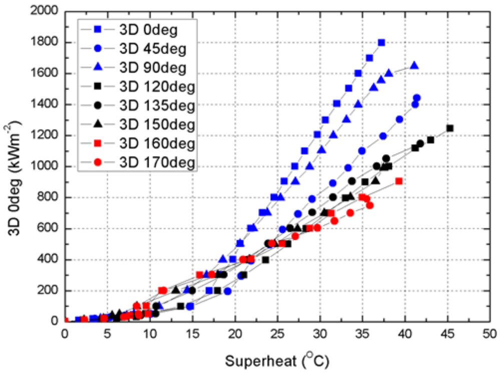


Fig. 2. Boiling curve (a) Bare surface, (b) 2D graphene film, and (c) 3D graphene.

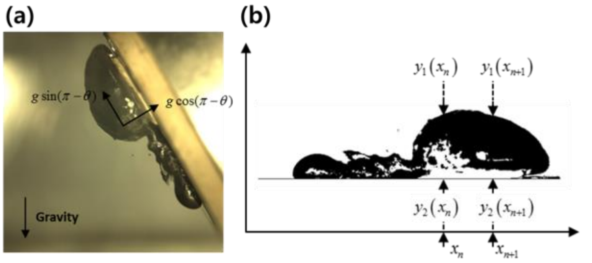


Fig. 3. Vapor region image processing (a) raw image of high speed visualization and (b) extracted bubble region profile and coordinates.

As shown in Figure 2, the slope of boiling curves, the BHTC, was getting decrease as orientation angle increase on every surfaces. At the higher heat flux, BHTCs were decreased significantly on every surface. However, graphene film had good BHTC at low heat flux. The BHTC enhancement ratios of the 2D- and 3D-graphene-coated surface were 111% and by 60%, respectively, compared with the bare surfaces. The higher BHTC of graphene film seems have high relationship between the early onset of nucleate boiling (ONB). 2D Graphene film has heat dissipation characteristics and nano-sized cavities, activating more nucleate site density [1]. Moreover, 3D graphene has micro-sized cavities which enable to absorb ambient water into the structure. We expected the increased nucleate site density, a dominant parameter affecting BHTC, contributed to increase BHTC. On the other hand, the slug bubble which formed upon the downward faced heater was affected by buoyancy forces against the surface. According to the high speed visualization, the translation speed of slug was slower, covering the almost range of heater surface. Then the slug stayed longer and prevent the liquid supply into very upside of the heater surface, called hydrodynamic choking.

The results of CHF showed a similar aspect with the results of BHTC. The absolute CHF value on the graphene coated surface decreased as the orientation angle was increased. However, the CHF was dramatically increased by 40% on 2D- and by 20-25% on 3D- graphene, compared with the bare silicon surface. This means, the CHF phenomenon was governed more by the hydrodynamics of slug behavior than by the surface characteristics. Here, we tried to observe the bubble behavior through high speed visualization on the bare surface. Figure 3 shows how we extracted the bubble region profile from original image. Using the profile, the observed instant bubble behavior could be summarized as follow:

i) the velocity of bubble had good linear relationship with gravity and orientation angle, inducing the concept of ‘Taylor bubble’

ii) the frequency of the slug was affected dominantly by orientation angle.

iii) the diameter of the slug increased with wall superheat and orientation angle.

iv) finally, the amount of evaporation heat flux was predicted and had good linearity.

3. Conclusions

The effect of graphene film coating on the pool boiling performances of upward and downward facing heater surface were examined. 2D- and 3D- graphene film showed good enhancement results on the CHF (by 111% and 60%) and BHTC (by 40% and 20-25%) performances. Bubble behavior change was significant factor on the CHF and BHTC performances in downward facing boiling. The amount of evaporation heat flux was calculated from the velocity, bubble diameter, frequency, orientation angle and superheat that the post-products of the high-speed visualization.

4. Acknowledgements

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