Enhanced critical heat flux in the downward facing pool boiling using layer-by-layer assembled carbon nanotube

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1. Introduction

Nucleate boiling is an effective heat transfer mechanism applicable for the thermal system. However, it could be limited by the critical heat flux (CHF), which is the upper bound in the nucleate boiling regime. So that the CHF performance is considered as a key parameter in evaluating the safety margin of the system. Regarding the orientation of the heat flow, the CHF is influenced by the heater orientation angle, whose effect tends to decrease the CHF from upward to downward facing surface [1]. In the boiling heat transfer, heater surface orientations are generally divided into three regions: upward, near-vertical, and downward facing [2]. Because each region is associated with a unique CHF trigger mechanism, it should be investigated as an individual study. Especially external corium cooling system such as core catcher consists of downward facing heating channel [3].

Using a porous coating on the substrate, CHF enhancement was investigated by researchers to increase safety margin of the system [4-6]. However, it is difficult to coat large area surface with prevalent coating technique. Fortunately, layer by layer (LbL) technique can facilitate the application of the large area coating applicable for a large scale industry. Recently, using polyethylenimine (PEI) / multi-walled carbon nanotubes (MWCNT) coating on upward facing metal surface, CHF was enhanced as verified by Seo et al. [5]. However, this CHF enhancement may differ in the downward facing heater.

Therefore, it is necessary to confirm that LbL assembled carbon nanotube coating can enhance CHF in downward facing heater. This study investigated the effect of PEI/MWCNT coating using the LbL assembly technique on downward facing pool boiling CHF in saturated conditions.

2. Experimental method

2.1. Fabrication of PEI/MWCNT layer

Layer-by-Layer (LbL) is a coating method to fabricate micro/nano structured film on surfaces of various substrates. LbL is based on electrostatic forces between materials which are charged with different “polarity”. Because of electrostatic forces, the charged materials can form layers that are adhesive and uniform along the substrate surface. MWCNT is known as excellent thermal property and chemical-mechanical stability. Also, its fiber-like shape is suitable for forming porous structure.

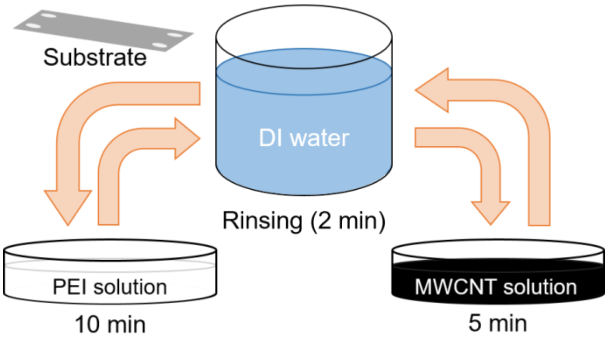

Fig. 1. Scheme for fabrication of LbL-assembled PEI/ MWCNT coatings on stainless steel (SS304) substrates.

The fabrication process of the LbL assembled PEI/ MWCNT coatings is presented in Fig. 1. Substrate is immersed for 10 minutes in the PEI solution and 5 minutes in the MWCNT solution. First, substrate was immersed in the positive solution (PEI), and washed particles are not deposited. In sequence, deep in the MWCNT solution, it deposited one bi-layer of LbL-PEI/MWCNTs on SS304. In this study, a substrate of the LbL coating was deposited with 10 bi-layers.

2.2. Pool boiling experimental set up

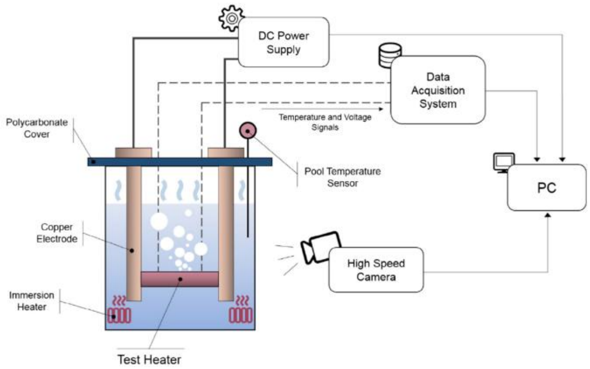

Fig. 2. Scheme of the pool boiling experimental apparatus.

The pool boiling experimental system for downward facing surfaces is illustrated in Fig. 2. The system included a water chamber, copper electrodes, a data acquisition system, and a high-speed camera. Inside of the chamber was filled with saturated deionized (DI) water at atmospheric pressure. Visualization of boiling test was conducted using a high-speed video system (Phantom V7.3 high speed camera).

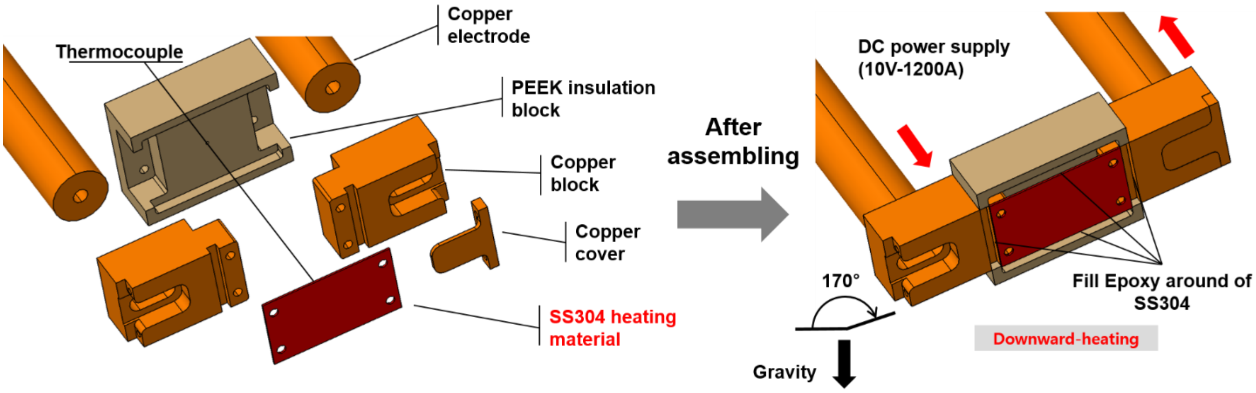

Fig. 3. Schematics of test section: detailed components of the test assembly.

A schematic of the test section is presented in detail in Fig. 3. The heater surface was inclined downward by 10° from the horizontal plane. Heating material is stainless steel grade 304 (SS304) and 70 mm in length, 40 mm in width, and 1 mm in thickness. Test specimen was heated using 12 kW DC power supply (10V-1200A). To measure the surface temperature of the heater and to detect the occurrence of the CHF, K-type thermocouple (TC) was attached directly to the back side of the test specimen. PEEK block insulated and created the cast for epoxy in liquid form. In addition, an insulation material epoxy filled a lower part and sides of the test specimen. To reduce interference of the bubbles in the upper part of the heating surface, copper cover was assembled with the copper block. The heat flux was calculated by Joule's equation as shown in Eq. (1)

$$q" = \frac{Power}{A_{heated}} = \frac{\Delta VI}{WL} \quad (1)$$

ΔV is voltage dropping across the test specimen, I is current, W is the width and L is the length of the heat transfer area. Uncertainty for heat flux was calculated as shown in Eq. (2)

$$\left(\frac{U_{q"}}{q"}\right)^2 = \left(\frac{U_V}{V}\right)^2 + \left(\frac{U_I}{I}\right)^2 + \left(\frac{U_W}{W}\right)^2 + \left(\frac{U_L}{L}\right)^2 \quad (2)$$

The uncertainties of the voltage, current, width, and heated length were less than 0.5 %, 0.5 %, 0.6 %, and 0.6 %, respectively. Thus, the measurement uncertainty for heat flux was calculated to be 3.3 %.

3. Result and discussion

3.1. Surface characterization of PEI/MWCNT and SS304

Porosity is a major factor for enhanced phase change heat transfer. The fiber-like shape of the MWCNT can be intertwined and it forms porous media using LbL assembly technique. The porous structure constructed by LbL can be found from scanning electron microscope (SEM) image of recent Seo et al.'s study [5]. Entangled PEI/MWCNT particles form some micro-pores between each other and it builds microporous structure on the surface, which can affect bubble dynamics during boiling.

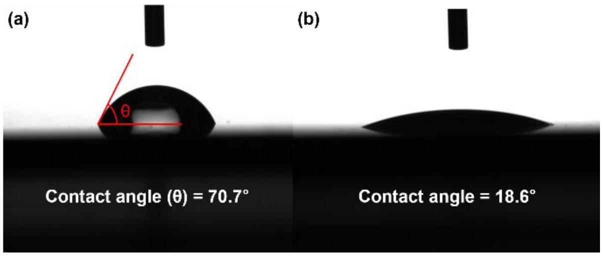

Fig. 4. Variation of the static contact angle of the SS304 surface with and without CNT coating (a) Bare surface (b) LbL assembled PEI/MWCNT coated surface.

The enhanced surface wettability was obtained by porous structure, which leads to decreased contact angle (Fig. 4). Not alone the wettability, remarkable changes in surface characteristics such as roughness and morphology was observed with PEI/MWCNT layer. As well the LbL assembled PEI/MWCNT coated surfaces increased roughness factors [5]. These multiple factors can change surface characteristics, which significantly affect the bubble dynamics and CHF.

3.2. Bubble visualization in boiling experiment

Before describing the CHF result, it is necessary to consider the difference between PEI/MWCNT coating using LbL assembled surface and bare surface. CNT layers form porous microstructure, which is related to the number of micro-scale cavity and nucleation sites affecting bubble behavior during boiling [5]. Fig. 5 shows the high-speed image of the boiling experiment: the bare SS304 and LbL assembled PEI/MWCNTs coatings on SS304. The substrate with LbL-assembled coatings created more isolated bubbles than the bare SS304 because of the nano-porous surface. The increased nucleation site brings about this result as presented in Fig. 3. In additions, enhanced surface wettability as shown by Fig. 4 affects bubble behavior. On a wettable surface, the liquid suction by capillary wicking could affect more improved rewetting [5]. As shown in Fig. 5, the LbL coated surface still shows nucleate boiling even at 234 kW/m^2 while film boiling region was observed in bare surface at 191 kW/m^2.

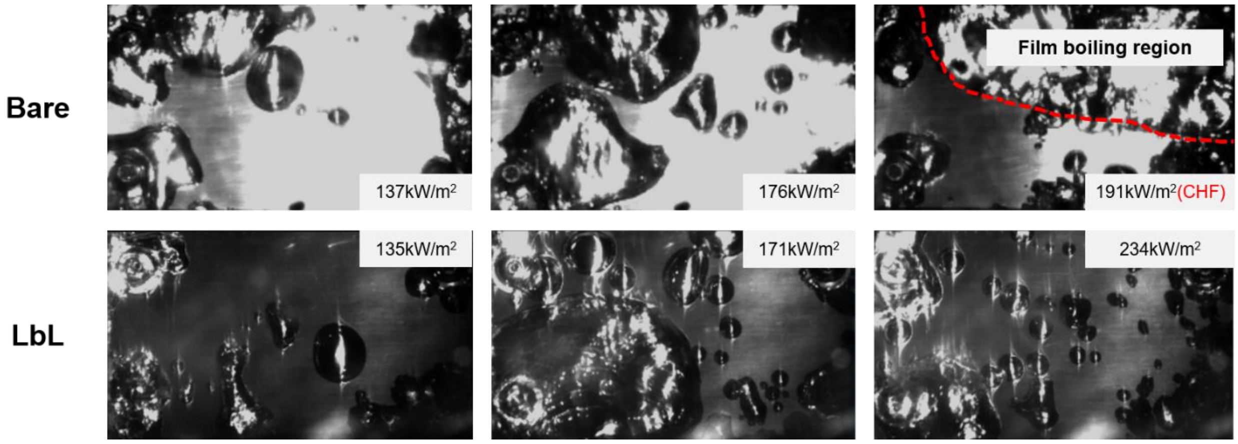

Fig. 5. Representative high-speed images of a real-time bubble generation for bare SS304 and LbL-assembled PEI/MWCNTs coatings on SS304.

3.3. CHF comparison with the LbL assembled PEI/MWCNT layer

In the boiling experiments, CHF was measured successfully on the all test specimens. In this study, CHF was determined when the surface temperature increased rapidly above 150 ºC. The CHF results of the bare and PEI/MWCNT coating surface are shown in Fig. 4. The CHF with the bare specimen was measured as approximately 178 kW/m^2, which value is lower than the CHF value obtained from other investigators on the downward facing experiments [4,6]. However, geometry and size of the heater used in the current study differ with their experiment results. The similar experiment to current study is found in Son et al.'s recent study [7]. The heating material of this study was stainless steel, whose length is 99 mm and width is 49 mm. Moreover, it was conducted in the downward facing (inclined at 170°). This similarity of the foregoing experiment could be a comparable reference for present bare CHF data. The CHF in the Son's experiment was detected at 150 kW/m^2. However, the difference with present boiling experiment is the space for bubble escape from side to side. Under the existence of the flow channel and the heating material size, CHF value of the present study is deemed satisfactory.

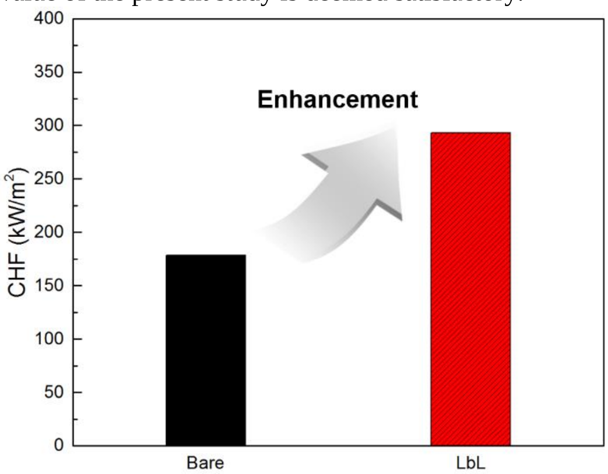

Fig. 6. Comparison of CHF values on the bare and LbL assembled PEI/MWCNT coating surface

By comparison, the CHF value of the CNT coated surface was measured as ~293 kW/m^2. Even though relatively less number of bi-layer coated the surface, the CHF enhancement was confirmed by boiling experiments. The enhancement with CNT coating is evaluated about 64 %, which is ample compared to upward facing CHF results (36 %) by Seo et al. [5] (Fig. 7).

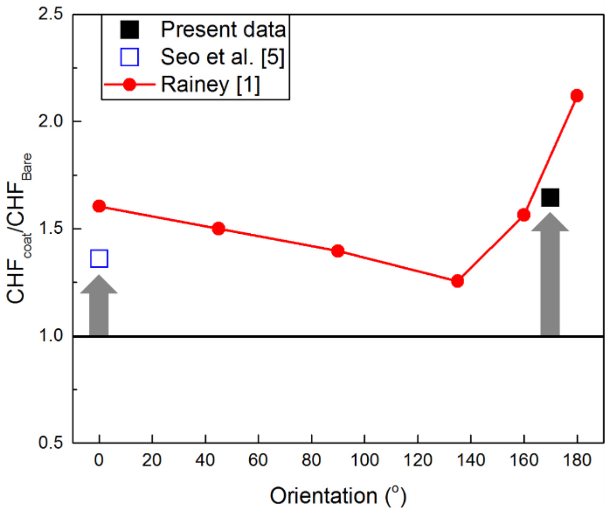

Fig. 7. The relative CHF enhancement for bare and coated heater surfaces at various inclination angles

The CHF enhancement in the current study differs with Seo et al.'s result although the same coating technique and material was adopted. This trend can be observed in the other investigator's study. In the reference data of CHF enhancement on various orientations, the downward facing condition could result in a more CHF enhancement than in the upward facing [1]. As shown Fig.7, the CHF enhancement of the Rainey data slightly decreased for an inclination angle between 0° to 135°. However, the dramatically increased CHF enhancement was observed at downward facing. Rainey did not set importance on this trend, the similar tendency was observed in experiment of Kwark et al [9]. They explained this trend using similarity of the bubble characteristics, such as merging and flattening, with respect to static pressure and heater orientation. The increased orientation (decreased pressure) causes reduced CHF due to larger bubbles and dry spots. This tendency can be observed in many studies of investigators [1,9]. As the bubbles merge, flatten, and grow, the high wettability and relatively high rewetting speed in the coating are enough to rewet even in downward facing. In short, similar results concerning increase of the proportion of wicking effect on CHF with orientation angle make the results from this study with cogency. Thus, the CHF enhancement ratio was increased significantly at the downward facing.

4. Conclusion

In this study, pool boiling experiments were conducted to investigate the effect of the LbL assembled PEI/MWCNT on downward facing CHF. The CHF data were compared with existing results obtained in the similar condition. The present results are summarized as follow.

- To confirm the surface wettability, DI water contact angle was measured on bare and LbL assembled PEI/MWCNT coated surfaces. It decreased from 70.7° to 18.6° in the bare and coated surfaces. The porous structure of the CNT layers induces enhanced surface wettability.
- The CHF enhancement of the LbL assembled PEI/MWCNT coating was measured by 64%. The CHF was measured at 178 kW/m^2 and 293 kW/m^2 in bare and coated surface. This is larger than upward facing experiment data (36%) [5]. The relatively reduced CHF than upward causes this result.

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