The dropwise condensation heat transfer characteristics of CNT/OTS layered surface associated with non-condensable gas effect

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1. Introduction

The dropwise condensation has been a considerable interest to many researchers due to higher heat transfer performance than filmwise condensation. Several studies have investigated the heat transfer mechanism and proposed mathematical models for dropwise condensation [1-6].

On the course of dropwise condensation heat transfer, various thermal resistances such as droplet conduction, liquid-vapor interfacial, and constriction exist. Among others, constriction resistance caused by non-uniform heat flux of the droplets can be reduced by using the substrate of high thermal conductive [7-9]. However, a selection of the substrate material is limited by its mechanical strength and integrity. So, altering the substrate material is often impractical. On the other hand, if the thin layer of highly conductive material is coated on the substrate, the constriction resistance can be reduced while keeping the original substrate body, which provides a flexible option for the enhancement of the condensation heat transfer. So, this study focused on surface modification technique by using highly conductive material to reduce the constriction resistance.

The objective of this study is to enhance the dropwise condensation heat transfer by reducing the constriction resistance by adopting a thin coating layer. Two surface coating techniques were considered. Layer-by-layer (LbL) for high thermal conductive layer consisting of the carbon nanotube (CNT) and self-assembled monolayer (SAM) to promote dropwise condensation by using the octadecyltrichlorosilane (OTS). Extensive condensation heat transfer experiment including preparation, surface characterization, and overall condensation performance evaluation was performed with LbL and OTS substrates, whose body is stainless steel grade 316 (SS 316) tube.

2. Experimental method

2.1. Preparation of CNT/OTS layered substrates

To analyze the surface effects on condensation heat transfer, different surface modifications were applied to the test specimens. The test specimen was made of SS 316 tube and were polished with 800 grits number of sandpapers before modification. After polishing, the bare substrates were cleaned with deionized (DI) water, acetone, ethanol, and DI water, sequentially [10]. Then the surface coatings were applied to the prepared test specimens.

The Multi-walled CNTs were functionalized with carboxylic groups (-COOH) resulting in the negatively charged surface. On the other hand, for the positively charged surface, polyethyleneimine (PEI) was used and finally the LbL assembly with the CNT was fabricated. The fabrication process of the LbL assembled PEI/CNT was presented in Fig. 1. First, the substrate was immersed in the PEI solution for 10 minutes and rinsed in DI water shortly. In sequence, the specimen was dipped into the MWCNT solution for 10 minutes and again rinsed with DI water. Conducting this process formed a bilayer of LbL-PEI/CNTs. In this study, a substrate of the LbL coating was deposited with 10 bilayers and resulting surface is called "CNT" hereafter.

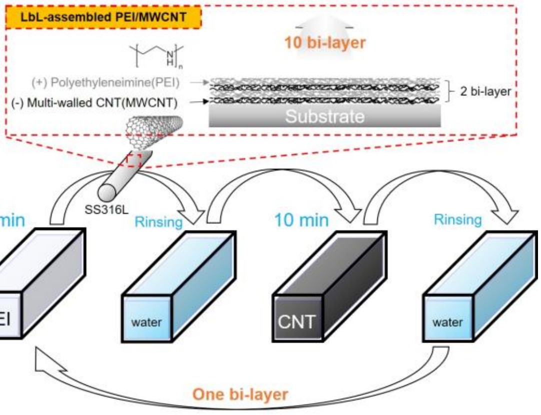

Fig. 1. A schematic illustrating fabrication of LbL-assembled PEI/MWCNT coatings on the substrates

In this study, the OTS having a methyl group (-CH3) as the terminal group was used for the solution material. The methyl group on SAM facilitates the surface to retain hydrophobic functionality. The SAM coating by using the OTS was performed by immersing the specimens into an anhydrous toluene solution of 1 mM OTS. Duration of the immersion was set to 2 hours because the effect of immersion time on the SAM formation was saturated after 2 hours in the previous study [11]. Sequentially, annealing was performed at 120 °C to crosslink silicon molecules of the OTS with each other. The SAM deposition did not change surface morphology because the OTS molecular size is about 2~3 nm [12]. Unchanged surface morphology retains the nano-porous structure of the LbL assembled PEI/CNT surface. Fig. 2 shows a schematic of the SAM deposition of the OTS.

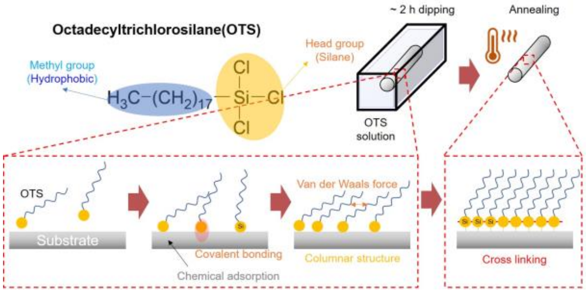

Fig. 2. A schematic for fabrication of OTS monolayer coatings on the substrates

2.2. Surface characterizations

The contact angle is a representative factor quantifying the surface wettability. It was measured by the Kruss EasyDrop contact angle measurement system. Fig. 3 shows the static contact angles of the bare, CNT, and CNT+OTS surfaces. The contact angle of the untreated bare substrate was measured approximately 74°. The CNT surface exhibited more hydrophilic characteristic showing a lower contact angle approximately 20°. This result could be due to the presence of nano-porous structure in the CNT surface, which caused capillary wicking to imbibe the water. On the other hand, the CNT+OTS surface showed a higher contact angle than the bare surface. This is because the functionality of the methyl group of OTS turned the surface into the hydrophobic property.

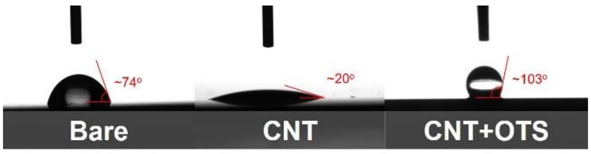

Fig. 3. Static contact angle of the bare, CNT, and CNT+OTS surfaces

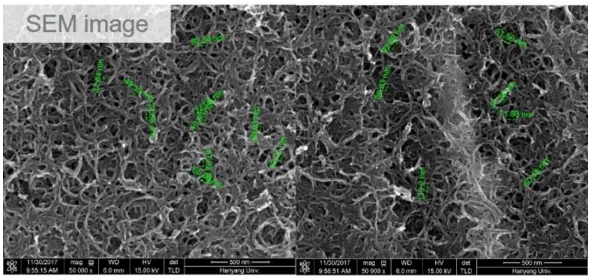

Fig. 4. SEM images of CNT layers

To confirm the nano-porous structure of CNT surface, the surface was examined by the scanning electron microscopy (SEM). Fig. 4 shows a 50,000x magnified SEM images on the CNT coated surfaces and the pore size measured. The CNT surface shows that many multi-walled CNT fibers formed the nano-porous structures on the surface. Quantifying surface parameters related to porous media is difficult due to the nano scale of factors. However, the pore size can be quantified reasonably by using distance measurement in SEM images. Because of intrinsic randomness of the LbL deposition, the pore size has a broad range from 30 to 120 nm.

2.3. Experimental setup

A schematic of the condensation heat transfer experimental system is illustrated in Fig. 5. The test section consisted of a single vertical tube made of SS316, whose length and diameter were 1,180 mm and 19.05 mm, respectively. Inside the vertical tube, the coolant flowed upward, and the saturated steam was condensed on the external surface of the vertical tube. The saturated steam was supplied from a steam generator to the test section after passing through a steam/water separator. When the steam was condensed, the condensed water entered into the heat exchanger and recirculated to the steam generator. DI water was used as a coolant at atmospheric pressure. The coolant temperature and flow rate were controlled by proportional-integral-derivative system and coolant pump, respectively. The wall subcooling is calculated by log mean temperature difference method.

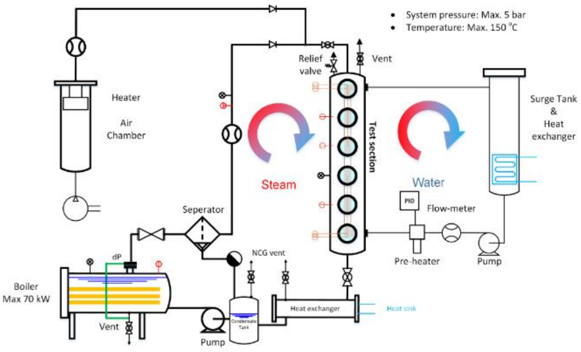

Fig. 5. A schematic of condensation heat transfer experimental system

3. Results and Discussion

3.1. Surface effects on the condensation heat transfer

Fig. 6 shows the condensation heat transfer coefficient of the bare and modified surfaces. The bare and CNT+OTS surfaces showed the higher condensation heat transfer coefficient than the CNT surface. The result could be attributed to the filmwise condensation with the CNT whereas the others showed dropwise condensation. In addition, the CNT+OTS exhibited the higher condensation heat transfer coefficient than the bare surface. This is because the CNT layer reduces the constriction resistance.

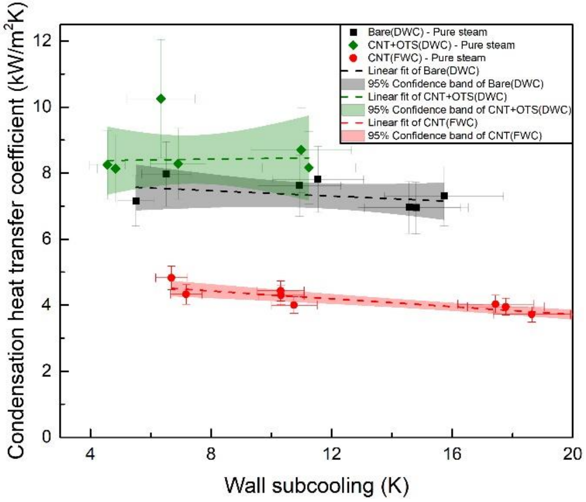

Fig. 6. The condensation heat transfer coefficient of bare and modified surfaces on pure steam condition.

The constriction resistance is related to the thermal conductivity of the substrate [7]. The bare surface has about 16 W/mK of thermal conductivity but the MWCNT porous network has about 244 W/mK [13].

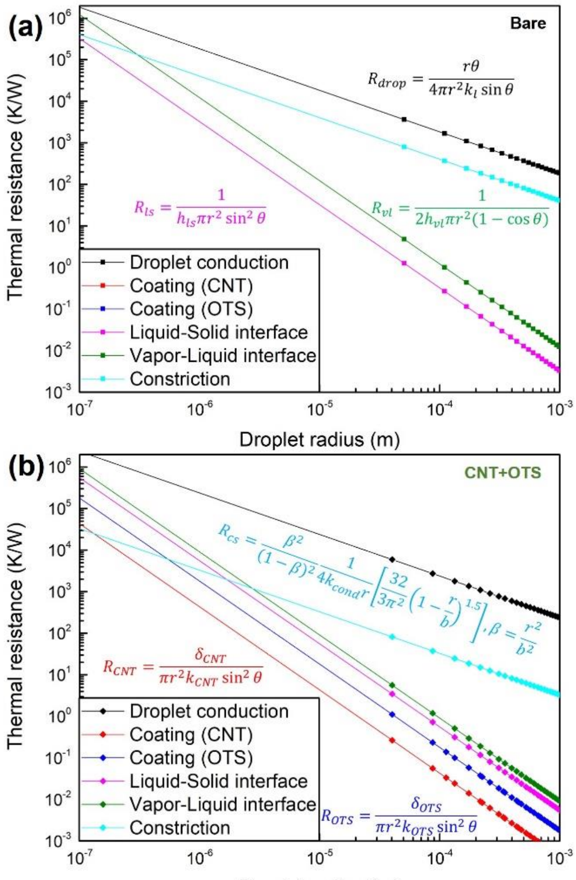

Fig. 7. Thermal resistance of bare and CNT+OTS surfaces on the dropwise condensation [3,5,7]

In the Fig. 7, the coating resistance of the CNT and OTS layers in the CNT+OTS exists, which can cause the higher thermal resistance than the bare surface. However, the coating resistance is much lower than the constriction resistance in a large droplet radius region, so the overall thermal resistance of CNT+OTS is lower than the bare.

3.2. Non-condensable gas effects on the condensation heat transfer

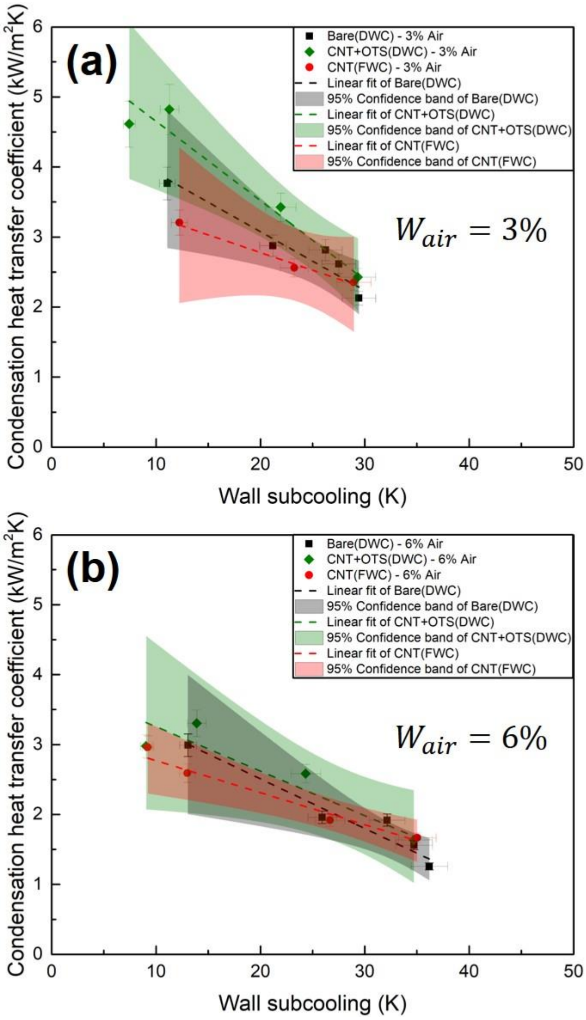

Fig. 8. The condensation heat transfer coefficient surfaces on the steam-air mixture condition (3, 6%).

Non-condensable gas can deteriorate the condensation heat transfer considerably, so it was investigated in this study. Fig. 8 shows the non-condensable gas effect on the condensation heat transfer coefficient by considering 3% and 6% of the air mass fraction. As shown in Fig. 8(a), in the 3% air mass fraction case, the heat transfer coefficient difference between each surface was reduced. On the other hand, as shown in Fig. 8(b), in the 6% air mass fraction case, the confidence band where overlaps between each surface was broadened than the 3% case. It was observed that the more the air fraction, the difference was gradually diminished. The similar tendency could be seen in 9% and 15% in Fig. 9.

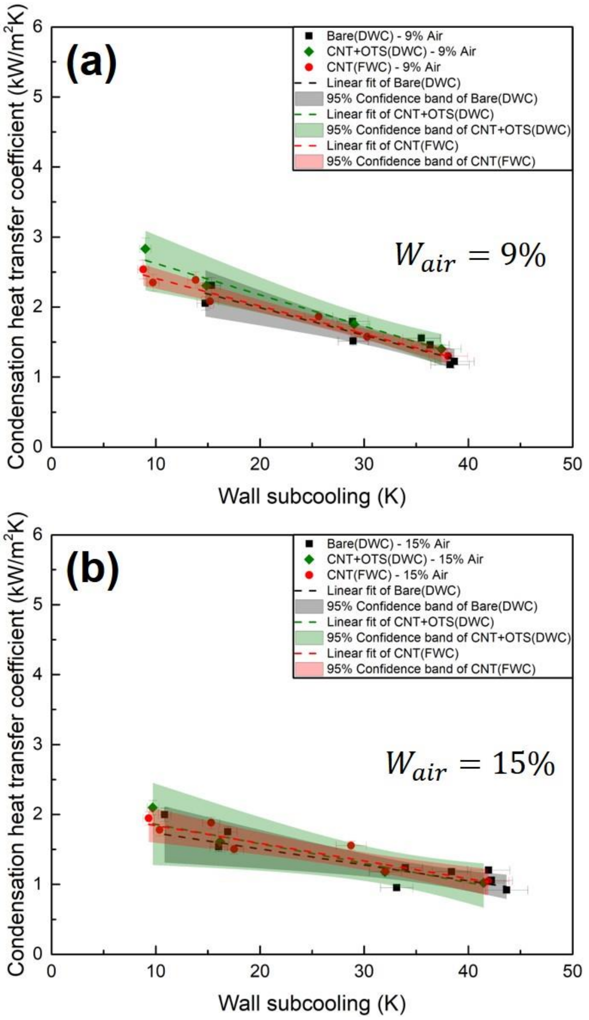

Fig. 9. The condensation heat transfer coefficient surfaces on the steam-air mixture condition (9, 15%).

4. Conclusion

In this work, the condensation heat transfer experiment on the CNT/OTS double layered coating was performed to reduce the constriction resistance on the dropwise condensation. The CNT+OTS surface had extra coating resistance but lowered constriction resistance, which resulted in the higher condensation heat transfer coefficient. However, this effect was degraded when including a non-condensable gas in the steam. It is believed that CNT/OTS layered coating can enhance the dropwise condensation heat transfer performance, but the effect of non-condensable gas may impair the net gain of such benefit.

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