Long-term stability of OTS coating inducing dropwise condensation heat transfer

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1. Introduction

In Nuclear Power Plants (NPPs), the pressure of containment vessel should be maintained below certain criterion about 57 psig. During a severe accident condition, however, decay heat may vaporize the released coolant and, as a result, containment pressure can increase. To maintain the containment pressure below the safety criteria, a passive containment cooling system (PCCS) have been devised and under developing [1]. The PCCS can condense the steam into the water by coolant flowing inside PCCS tube. During this progress, steam transfers their heat to coolant in a tube by condensation heat transfer. If the condensation heat transfer performance is improved, more steam can be condensed into liquid water, which, in turn, reduces the containment pressure promptly. Condensation is known to be affected by many factors and among them an important parameter is deemed as the surface wettability. Surface wettability can be affected by the surface morphology contacting with steam and correspondingly affects the overall condensation heat transfer [2]. In previous studies, several techniques have been proposed to modify the surface of materials for the purpose of enhancing condensation heat transfer. Among various techniques, it has been reported that the dropwise condensation with hydrophobic surfaces improves condensation heat transfer performance [3,4]. However, it is also known that modified surface with hydrophobic material shown a lower durability. So the durability of hydrophobic coating should be investigated to confirm its advantage. In this study, a representative hydrophobic coating material was selected as an octadecyl-trichlorosilane (OTS), which is a common hydrophobic material. To adopt the OTS surface to the PCCS, it is necessary to confirm the durability of the OTS surface applicable fot the containment condition. To fulfill the objective, a condensation heat transfer experiment was performed to confirm the durability of the OTS by considering the aging of the OTS surface.

2. Experimental method

2.1.SAM coating layer

SAM (Self-Assembled Monolayer) is a coating method to form organic molecular assemblies spontaneously on the surface. To use this method, stainless steel grade 316L (SS316L) was selected as main substrate material. To modify surface material from hydrophilic property to hydrophobic, OTS (octadecyltrichlorosilane) was selected. The OTS consists of a head group and a functional group. The OTS's functional group is the methyl group (-CH3), and this methyl group bears a hydrophobic characteristic. By forming an OTS layer on the stainless steel substrate by the SAM, the hydrophilic surface property could be modified into the hydrophobic. A detailed method is described as follows. First, the stainless steel substrate was polished by using a sandpaper, and resulting substrate was immersed into an anhydrous toluene solution made with 1mM of OTS. Next immersing was kept for two hours, because it is known that the successful SAM formation time takes about two hours. After immersing annealing was conducted under 120 ^{o}C, under atmospheric pressure condition by using a furnace.

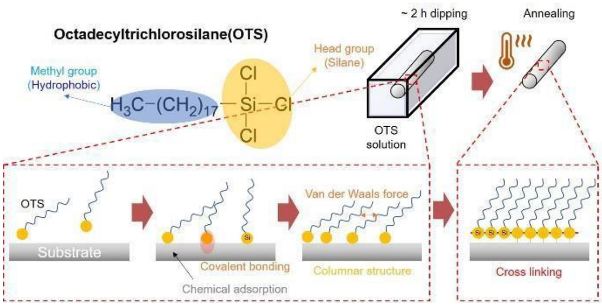

Fig.1 A schematic for fabrication of OTS monolayer coatings on the substrates.

2.2 Aging OTS coating

The PCCS was designed to be installed in containment building, whose thermal-hydraulic condition is different from room temperature. Under an normal condition, the temperature at the containment upper dome is known as about 50 ^{o}C. Considering this condition, the temperature of the furnace was set to 50 ^{o}C and test specimens were aged for 1 to 3 weeks. Depending on the aging period, contact angle was measured by using Krüss EasyDrop. It was observed that, contact angle tends to decrease with aging period. After aging 3 weeks in the furnace, contact angle decreased below 95 degrees for all measurements. It is analyzed that this contact angle difference between unaged and aged specimen may affect condensation heat transfer. So the stainless tubes were coated using the same coating method, and stainless tubes were aged maximum 3 weeks under the same conditions as mentioned above. After that, condensation heat transfer experiment was performed depending on the OTS aged tubes.

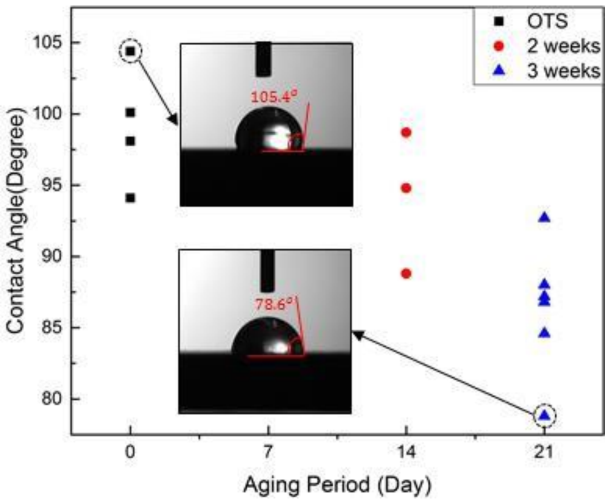

Fig.2 Contact angle dependings on the aging period in OTS coating,

3. Condensation heat transfer experiment

3.1 Experimental set up

Fig. 3 illustrates the condensation heat transfer experiment system. The test tube was located vertically in a steam chamber. The dimension of the test section is 300 mm length, 19.05 mm diameter, and 1.24 mm thickness. De-ionized water coolant was flowed upward in the test tube, which is located in the middle of the steam chamber. Coolant mass flux was maintained at approximately 415 kg/m^{2}s. 18 kW steam generator could supply saturated steam to the steam chamber through a steam/water separator at a constant pressure of 55 kPa, This saturated steam was converted into water by condensation heat transfer. After condensation, condensed water was flowed into a drain tank, which is located underneath the experiment system. The coolant temperature, tube temperature both inside and outside, and flow rate were controlled by using a proportional-integral-derivative (PID) control and coolant pump. Lastly, visualization of tube surface during the condensation heat transfer was performed by using a high-speed video system (Phantom V7.3 high speed camera).

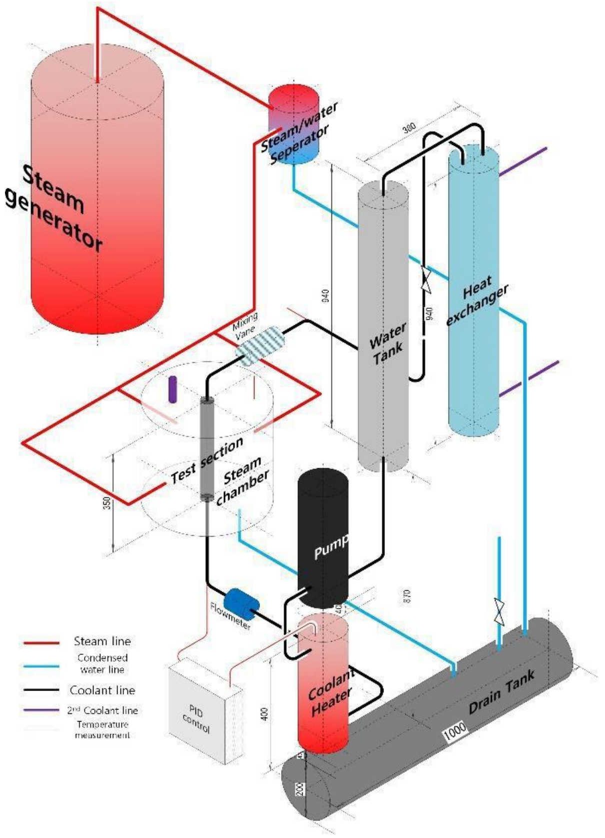

Fig.3 Schematic of condensation heat transfer experiment system.

3.2 Experimental result

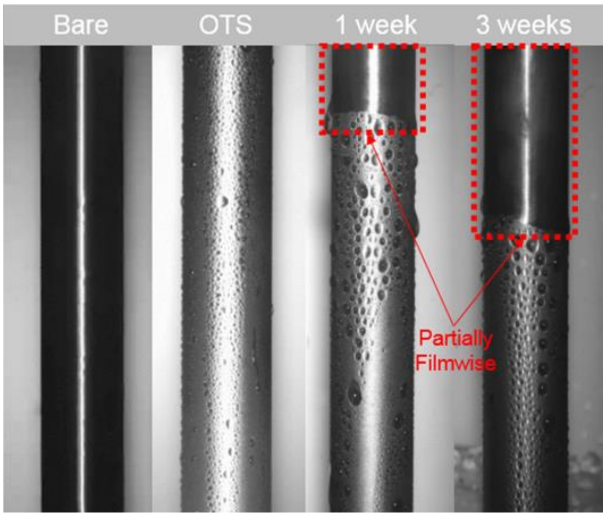

Fig.4 Visualization of the condensation on each surface.

First, it was observed that the OTS coated surface showed dropwise condensation unlike the bare surface. It is well known that the dropwise condensation exhibits the higher heat transfer performance than the filmwise condensation. After aging OTS coating, however, it was observed that filmwise condensation and dropwise condensation occur simultaneously. The filmwise region was formed from middle of the tube surface and expanded with aging time. In addition, the filmwise region was enlarged gradually from the initiated region, rather than producing multiple points at the other side. This result suggests that if the aging time is prolonged, the surface will return to the filmwise surface like the bare surface before applying OTS coating. In terms of the condensation heat transfer, the coated surface is either aged and did not show better results compared to the bare surface. This could be due to the effect of the diminished dropwise region due to the aging.

In detail, the OTS coating aged for 1 week showed slightly reduced performance compared to unaged OTS. Finally, the OTS with 3 weeks of aging showed lower than the OTS with 1 week aging.

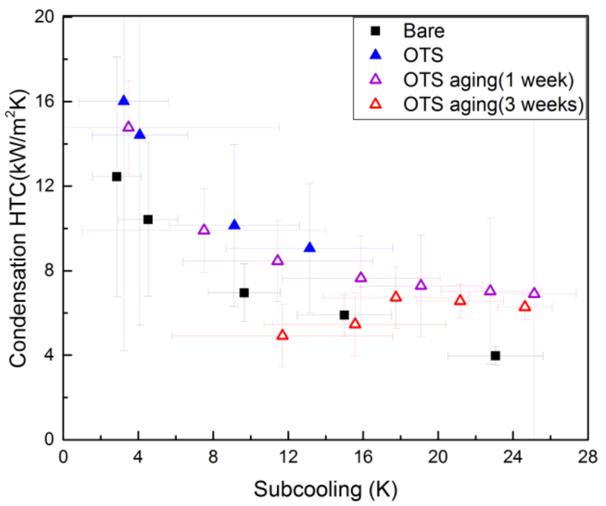

Fig.5 Condensation heat transfer of each surface with aging effect

4. Conclusion

In this study, condensation heat transfer with OTS coating was performed to confirm the durability of OTS coating and their condensation heat transfer performance after aging under certain condition. Performance of the OTS coating by SAM method was reduced from the 1 week aging. Damaged OTS coating showed filmwise condensation and dropwise condensation simultaneously, and filmwise region was expanded with aging period. As a result, the OTS coating with 3 weeks aged show decreased condensation heat transfer than 2 week aged, and its performance show decreased below bare surface before applying the OTS coating at some points. It is because the dropwise region is maintained despite the OTS coating was damaged. Based on the experimental results, the OTS coating is difficult to maintain for a long time, which is not appropriate for the current containment condition. In view of this, more research is needed before OTS be applied to PCCS. Future work should focus on the durability of OTS and the coupling effect of filmwise and dropwise condensation.

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