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EXPERIMENTAL STUDY FOR CONDENSATION HEAT TRANSFER ENHANCEMENT BY USING ROBUST HYDROPHOBIC COATING

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1. Introduction

If there is no cooling capacity of the nuclear reactor containment building as in the accident in Fukushima nuclear power plant in Japan, the radioactive material would leak out from reactor to the outside. The Passive Containment Cooling System (PCCS) has been adopted at the present nuclear power plant and it protects the containment buildings by condensation heat transfer [1]. PCCS removes the thermal energy of the steam generated from the Design Basis Accident (DBA) such Main Steam Line Break and Loss Of Coolant Accident (LOCA) [2,3]. The Film-Wise Condensation (FWC) heat transfer, which is typically implemented in PCCS, is performed by forming a thin liquid film on the outer surface of the heat exchanger tube. When the hydrophobic coating is applied to each tube surface, the condensation phenomenon shifts to the Drop-Wise Condensation (DWC) where the condensed droplet is immediately removed [4]. It is also possible to maintain DWC by increasing the robustness of the coating under high temperature and wet steam conditions by using a hydrophobic compound having a high heat resistance. As a result, the efficiency of condensation heat transfer increases, which can lead to benefits such as the stability of the containment building and the size of the heat exchange surface area. In this study, an experimental evaluation of vertical plate condensation heat transfer efficiency is carried out by coating a high heat resistant hydrophobic compound on a metal substrate.

2. Robust hydrophobic coating material

Three hydrophobic coating films were formed by each solvent and different amounts of thermally conductive particles. For these three samples, the thermal conductivity and the thin film thickness of the coating were used to calculate the degree of condensation heat transfer enhancement compared to the bare surface.

2.1 Information of candidate sample

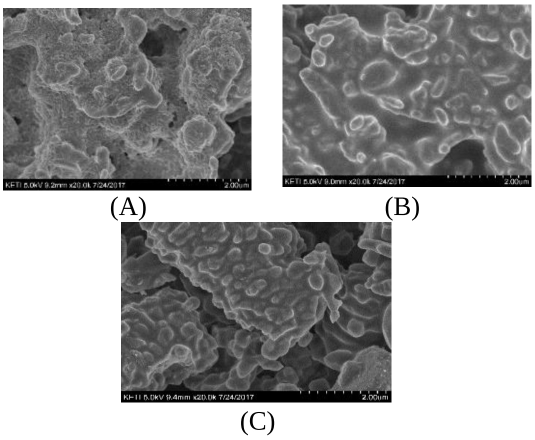
The information on the samples to be used for the condensation heat transfer experiment can be found in Table 1.

The substrate for the solution coating was made of SUS 304 metal and was made in the size of 25 mm * 25 mm * 2 (THK). In terms of the composition of the samples, there are two common materials. The first is Alumina, which is used to increase the thermal conductivity of the coating film. Basically, hydrophobic organic compounds show low thermal conductivity. Second, it is a glass-fit material, which is used to increase the contact force between the metal substrate and the Alumina particles. A coating film of each sample was formed using the G-300, PDMS, HDA material composition in addition to the common material [5].

Table 1 Sample information table

	Material Composition	Contact Angle	Thermal conductivity	Coating Thickness
A	alumina + glass frit +G-300	100.13°	1.563 [W/mK]	14.21 [μm]
B	Alumina + glass frit +PDMS-Silane +Triethoxyoctylsilane+tetraethyl orthosilicate + Triethoxy − 1H,1H,2H,2H-tridecafluoro-n-octylsilane	121.61°		
C	alumina + glass frit + HDA	121.04°		

Each sample showed different static contact angle values, among them, the contact angle of B samples was the highest. The thermal conductivity of the coating film was made the same for each sample by changing the concentration of the hydrophobic substance. Also, the same thin film thickness was obtained by the same coating solution amount and coating method. The purpose of this study is to compare the degree of condensation heat transfer efficiency according to the different types of hydrophobic coating. Figure 1 in below shows the SEM and AFM images of the coating film on the substrate.



(A) (B)

(C)

Figure 1 SEM, AFM image of each coating layer

2.2 Thickness and Thermal Conductivity Analysis of Thermal Resistance Hydrophobic Coating Thin Film

Unlike the bare surface, the thermal efficiency of the coating film was considered to improve the efficiency of condensation heat transfer. In other words, in the case of DWC heat transfer, the condensation efficiency is about 10 times that of the film condensation heat transfer, but the degree of improvement is compensated by considering the presence of the coating film for the DWC. Enhancement of heat transfer efficiency due to DWC implementation on coating surface and reduction of heat transfer efficiency according to the thermal conductivity (k_{coat}) and thickness of coating (δ_{coat}) are both significant considerations. The effective condensation heat transfer coefficient, $h_{eff} \sim f\left(\delta_{coating}, k_{coating}\right)$, can be evaluated as enhancement factor of condensation heat transfer and its expression is as follows.

$$\frac{1}{h_{eff}} = \frac{1}{h_{DWC}} + \frac{\delta_{coating}}{k_{coating}} \qquad (1)$$

In the original DWC heat transfer coefficient (h_{DWC}) value, $h_{DWC} = 51{,}104 + 2044\,T_{sat}, or\ 255{,}510\ [W/m^2\,K]$ should be used[5,6]. But, since the coating without hydrophobic thin film thickness is not applicable, the condensation heat transfer coefficient in the thinnest coating thin film is assumed to be the $h_{DWC} = 2.6 * h_{film}$ value.

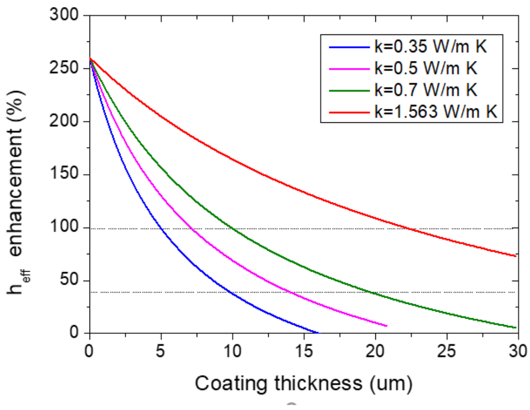


Figure 2 $\mathbf{h_{eff}}$ enhancement with $\boldsymbol{\delta_{coating}}, \boldsymbol{k_{coating}}$ changes

h_{eff} can be varied depending on the thickness and thermal conductivity of the coating film, and basically it is inversely proportional to the thickness of the film and tends to be proportional to the thermal conductivity. From the above equation, the figure 2 shows a degree of improvement of the effective condensation heat transfer coefficient. By calculating the thin film thickness and the thermal conductivity, h_{eff} value of the sample can be predicted.

3. Vertical plate condensation experiment

3.1 Experimental device apparatus

Experimental setup consists of steam supply, test part and cooling water circulation loop. The specimen of small flat structure is connected to the test part so that the adaptive shaft heat transfer phenomenon by hydrophobic coating can be observed through the visualization window. The following figure shows a schematic diagram of the experimental setup.

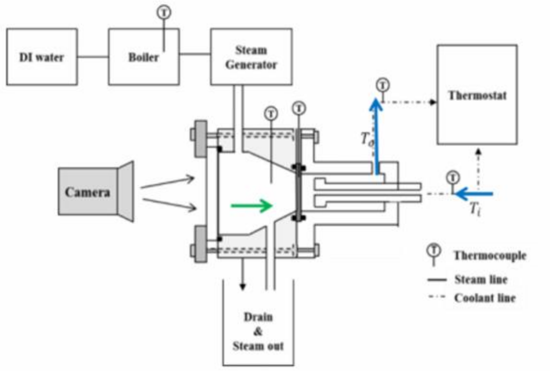


Figure 3 Vertical condensation test apparatus

3.2 Experimental procedure

The water inside the reservoir and the steam generator is boiling for 1 hour to remove the non-condensable gas and dissolved gases. Thereafter, the inside of the test section is filled with boiling water, and then the steam is pushed out to remove the non-condensed gas inside the test section. The temperature of the cooling water in the water bath is controlled to change the sub-cooling, which is the difference between the steam temperature and the wall temperature. In fixed heat transfer area (A_c), the h_{eff} data are extracted for one case while 5 minutes. Then, 4~7 cases are collected when the cooling water inlet, outlet temperature(T_{in}, T_{out}), steam temperature (T_v), wall temperature (T_{wall}) and cooling water flow rate ($\dot{m}_c$)are constant under certain sub-cooling conditions. The correlation for calculating h_{eff} is expressed as follows.

$$h_{eff} = \frac{\dot{m}_c c_p (T_{out} - T_{in})}{A_c\,(T_v - T_{wall})} \qquad (2)$$

The uncertainty of h_{eff} ($Y_{h_{eff}}$) obtained from the experimental apparatus were obtained by the following equations.

$$\sqrt{\begin{array}{l}\left[\left(\frac{1}{h_{eff}}\frac{\partial U}{\partial \dot{m}_c}Y_{\dot{m}_c}\right)\right]^2 + \left[\left(\frac{1}{h_{eff}}\frac{\partial U}{\partial \mathrm{T_v}}Y_{\mathrm{T_v}}\right)\right]^2 + \left[\left(\frac{1}{h_{eff}}\frac{\partial U}{\partial \mathrm{T_{c,in}}}Y_{\mathrm{T_{c,in}}}\right)\right]^2 \\ + \left[\left(\frac{1}{h_{eff}}\frac{\partial U}{\partial \mathrm{T_{c,out}}}Y_{\mathrm{T_{c,out}}}\right)\right]^2 + \left[\left(\frac{1}{h_{eff}}\frac{\partial U}{\partial \mathrm{A}}Y_A\right)\right]^2 + \left[\left(\frac{1}{h_{eff}}\frac{\partial U}{\partial \mathrm{c_p}}Y_{\mathrm{c_p}}\right)\right]^2\end{array}} \qquad (3)$$

4. Results and discussion

4.1 Heat transfer enhancement via DWC phenomenon

Condensation heat transfer experiment in bare sample without hydrophobic coating was performed first and the graph shows the change in condensation heat transfer coefficient according to the change in sub-cooling.

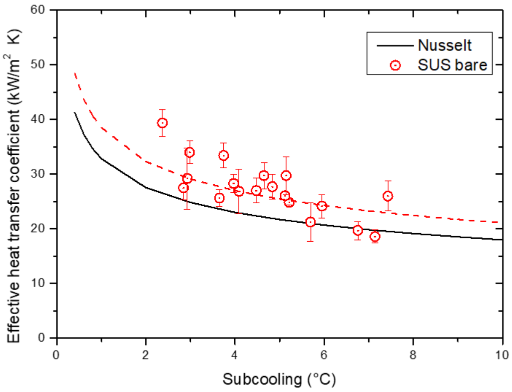


Figure 4 $\mathbf{h_{eff}}$ data at bare sample

When the experimental data is compared with the theoretical heat transfer coefficient value by Nusselt correlation [8] shown below.

$$\bar{h}_{film} = 0.943\left[\frac{g\rho_l(\rho_l-\rho_v)k_l^3 h'_{fg}}{\mu_l(T_{sat}-T_s)D}\right]^{1/4} \qquad (4)$$

The experimental data shows the same tendency with the value increased by about 17.4%. It can be concluded that the experiment using bare sample shows good reproducibility and the degree of improvement by hydrophobic coating film is compared based on this data. The graph showing the h_{eff} values of the three samples based on the bare sample data is shown below.

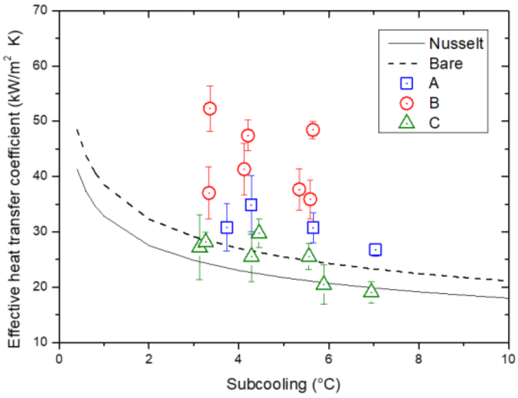
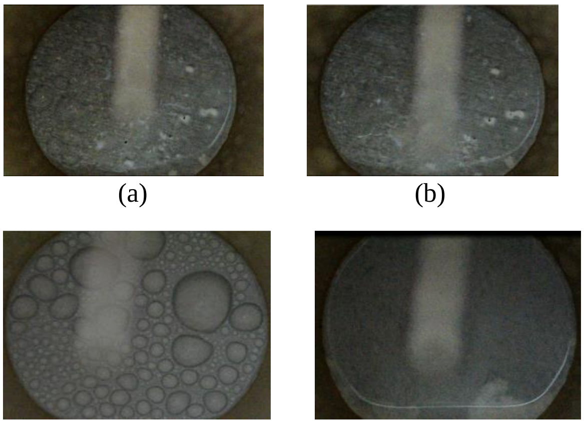


Figure 5 $\mathbf{h_{eff}}$ data at each hydrophobic coated sample

Comparing the average value of the effective condensation heat transfer coefficient obtained from each sample with the bare sample data, the sample A showed a 15% improvement and the sample B showed a 108% improvement corresponding to the top three points. On the other hand, in the sample C, a value similar to the FWC value was obtained and the improvement degree was not remarkably confirmed. DWC was observed for samples A and B, but local DWC was observed for sample A at the beginning of the experiment. After 5 to 10 minutes, FWC appeared in the overall sub-cooling range. In case of sample C, FWC was observed in all experiments and it was judged that there was no improvement in efficiency due to no condensation phenomenon transition. The visualization results of each sample are shown in fig 6.



(a) (b)

(c) (d)

Figure 6 Visualization image at 5 ℃ sub-cooling (a): Sample A at the beginning of the experiment, (b): Sample A after 5 to 10 minutes, (c): Sample B, (d): Sample C

Sample B was retested to ensure a repeatability of the data. Among the B data, the points corresponding to the following four points are data obtained by retesting, showing an average improvement of about 60%. According to the results of the first and second experiments, it is confirmed that enhancement of the effective condensation heat transfer coefficient in the sample B is 78%.

4.2 Robustness

According to literature survey for condensation heat transfer on existing hydrophobic surfaces, it was evaluated whether the hydrophobic sample maintained the efficiency improvement for a certain period of time according to the elapsed time of the experiment while changing the sub-cooling degree [9]. The graph below shows the change in the overall average improvement in the first and second experiments over time.

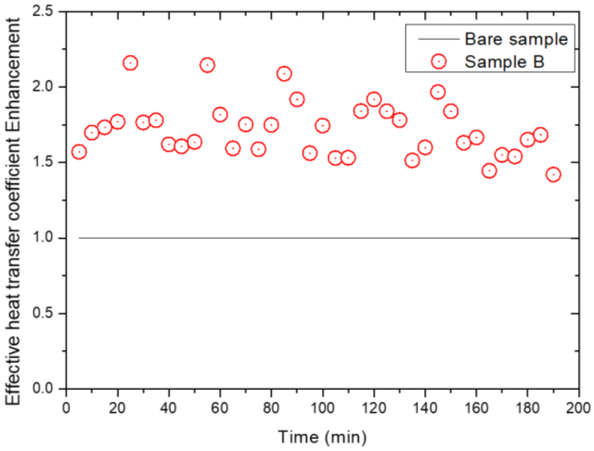


Figure 7 The changes in the effective heat transfer coefficient on the investigated surfaces

Experimental data were analyzed over a period of about 200 minutes, and it was confirmed that the improvement in condensation efficiency was constant over the entire experimental period. The efficiency improvement value is 78% mentioned above. In addition, there was no difference in the contact angle measurement after the experiment by 119.68°. As a result, it can be concluded that the integrity of the surface of the hydrophobic coating film is maintained well in a high temperature steam condensation environment for a certain period of time.

4.3 Appling to horizontal tube condensation heat transfer

In order to evaluate the enhancement of the overall condensation heat transfer coefficient outside the single tube with the same super water-repellent coating as that of the plate type condensation sample, a horizontal single tube condensation heat transfer experiment device was fabricated.

Table 2 Test condition of tube condensation facility

	KHU Tube condensation facility
Volume flow rate [LPM]	0 ~ 11.6
Coolant Temperature In/Out[℃]	88.3~90.3/89.9~91.9
Tube OD [mm]	15.88
Saturated pressure [Mpa]	0.101(1 atm,100℃)
Steam mass flow rate [kg/h]	7.65

Future studies will be conducted to analyze the improvement of the overall heat transfer coefficient by improving the effective condensation heat transfer coefficient discussed in this study.

5. Conclusion

Thin films on metal substrates were formed using different compositions of hydrophobic coating solutions. Experiments on vertical plate condensation heat transfer with bare surface samples and hydrophobic surface samples were conducted and the effective condensation heat transfer coefficient data of the hydrophobic coating films were compared. In Sample B, the effective condensation heat transfer coefficient improvement of about 78% was confirmed. In the experimental case, which showed efficiency improvement, the efficiency improvement width was constant over experiment time. It can be concluded that the hydrophobic coating has maintained its robustness without surface damage for a certain period of time in a high temperature condensation condition.

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