Analytical study of condensation heat transfer on titanium tube with super-hydrophobic surface

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1. Introduction

There are many nuclear or fossil power plants which occupy more than 85% among entire power plants in the world. These plants release heat through condenser into nature. The condenser is an important component for cooling the working fluid after the turbine. Its performance is related with material and size of its tubes. To have good performance or to reduce condenser size, it is important to increase condensation heat transfer coefficient on condenser tubes.

Ma *et al.* executed heat transfer experiment in dropwise condensation with non-condensable gas, and studied how the amount of air and pressure difference affect condensation heat transfer coefficient. The more non-condensable gas existed, the condensation heat transfer coefficient was decreased [1]. Shen *et al.* studied condensation heat transfer at horizontal bundle tubes. Several variables such as coolant velocity, saturated pressure, and surface conditions were studied. As a result, surface modified brass tube and stainless tube showed higher condensation heat transfer coefficient as much as 1.3 and 1.4 times comparing with their bare tubes, in 70 kPa vacuum condition respectively [2]. Rausch *et al.* studied dropwise condensation on ion-implanted titanium surface. Conclusively condensation heat transfer coefficient of ion-implanted titanium tube showed 5.5 times higher than its bare tube [3].

Many previous studies evaluated condensation heat transfer coefficient of surface modified copper tube, stainless tube, etc. But, surface modified titanium tube has not been studied enough, especially in vacuum state which to be considered to apply for real power plant. The purpose of this study is to evaluate the condensation heat transfer on titanium tube coated by SAM (Self Assembled Monolayer) in vacuum state.

2. Preliminary Analysis

2.1 Heat transfer equations for analysis

To analyze the condensation phenomenon in condenser, we should consider three heat transfer mechanisms. The first mechanism is the condensation heat transfer on outer surface of the condenser tube. Nusselt theory defined as Equation (1) is used for film condensation.

$$h_o = 0.729\left[\frac{g\rho_l(\rho_l-\rho_v)h'_{fg}k_l^3}{\mu_l(T_{sat}-T_s)D_o}\right]^{1/4} \quad (1)$$

The second thing is the conduction heat transfer through the tube.

$$q_x = kA\frac{(T_{out}-T_{in})}{L} \quad (2)$$

The last mechanism is the convection heat transfer on inner side of the tube. Equation (3) is provided by Gnielinski to compute internal convection heat transfer coefficient in smooth tube.

$$Nu_D = \frac{(f/8)(Re_D-1000)Pr}{1+12.7(f/8)^{1/2}(Pr^{2/3}-1)} \quad (3)$$

The overall heat transfer coefficient from condensation, conduction and convection could be expressed as Equation (4).

$$UA = \frac{1}{R_{convection}+R_{conduction}+R_{condensation}} \quad (4)$$

The overall heat transfer rate which from vapor to inner cooling water is obtained from Equation (5).

$$Q = UA(T_b-T_w) = \dot{m}C_{p,l}(T_{c,o}-T_{c,i}) \quad (5)$$

2.2 Analysis result

Some important variables in this study are the coolant velocity which affects to the surface temperature of condenser tube, and the saturated pressure in the condenser shell. The coolant velocities with 0.5 m/s, 1 m/s, and 1.5 m/s are considered. These values are decided to ensure enough temperature difference between inlet and outlet of coolant. The saturated pressures with 0.2 and 0.4 bar are selected considering the operating pressure in power plant.

Table Ⅰ shows the analysis data with Nusselt film theory. It is computed by MS excel computation. In addition, we assumed 3 times higher dropwise condensation heat transfer coefficient than filmwise condensation to do thermal sizing of the experimental facility conservatively. Fig. 1 shows the comparison of the overall heat transfer coefficients between the dropwise and the filmwise condensation. Even though the dropwise condensation has 3 times higher heat transfer coefficient, the overall heat transfer coefficient increases only 11~20 %. In addition each vacuum condition shows similar tendency. This is because fluid characteristics are similar at absolute pressures 0.2 bar and 0.4 bar.

Table Ⅰ: Analysis data of filmwise condensation heat transfer coefficient.

		Saturated pressure (bar)			
		0.2		0.4	
		U (W/m^{2}K)	h_{cond} (W/m^2)	U (W/m^{2}K)	h_{cond} (W/m^2)
Coolant velocity (m/s)	0.5	1,692	12,847	1,701	12,625
	1.0	2,335	11,323	2,335	11,102
	1.5	2,682	10,668	2,676	10,471

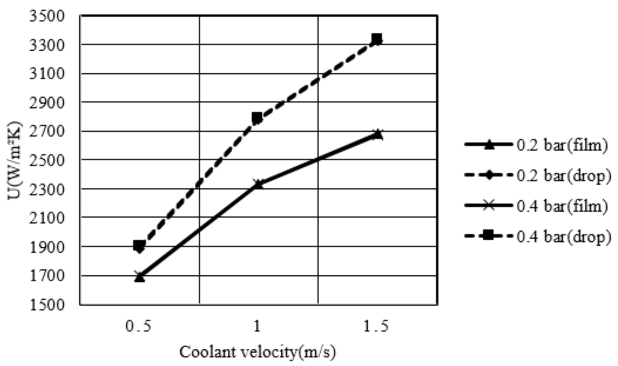

Fig 1. Overall heat transfer coefficient graph according to coolant velocity in conditions of 0.2 bar, 0.4 bar with filmwise & dropwise condensation.

3. Experiment

3.1 Surface modification of titanium tube

For this study the titanium tube with super-hydrophobic surface is prepared. The modified condenser tubes are manufactured by Pohang University of Science and Technology (POSTECH). The surface modification method to make super-hydrophobic surface is explained below.

1st step – Etching: To do passivation and to clean surface of titanium tube, the tube is etched by soaking it for 24 hours by 70% H_2SO_4 solution at room temperature [4]. It makes the surface to be hydrophilic and to have micro structure on the surface.

2nd step – Oxidation: To make nano-embossed surface and super-hydrophilic surface, soaking the tube in H_2O_2 solution for 12 hours at room temperature [4].

3rd step - SAM coating: will be executed to titanium sample. SAM coating means Self Assembled Monolayer which make its surface energy different [4]. SAM coating makes surface of titanium super-hydrophobic.

3.2 Experiment facility

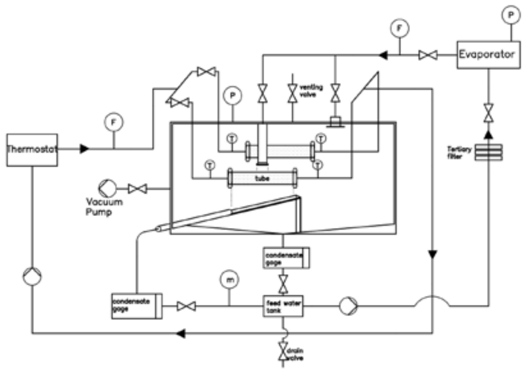

Fig. 2. Schematic diagram of experimental facility.

Fig. 2 shows schematic diagram of condensation heat trasfer experimental facility. The main components of this experiment facility are steam generator, cooler, vacuum pump and test shell. The saturated steam is produced by steam generator which can provide steam of 15 kg/hr. All temperatures of the experimental facility are measured using calibrated K type thermocouples with ±0.15K uncertainty. Cooler maintains coolant temperature with 15℃, and has 16 kW capacity. Maximum performance of vaccum pump is 6.67×10^{-7} bar. Vacuum pump sustains vacuum state inside of test shell with 0.2 bar or 0.4 bar.

The test section consists of condenser shell with thickness of 10mm stainless steel 304 to avoid from bending or destruction for vacuum state. Its bottom section has angle of 7° to flow condensate water by heat loss on condenser walls. The dimensions of the condenser shell are 1200mm of length, 500mm of height, and 500mm of width. To see the titanium tube, visualization ports are installed with size of 20 cm × 10 cm at both side of shell. Also, cooling water loop exists to cool the coolant. All lines connecting each parts are consists of 1 inch or 1/2 inch stainless tube. In addition, the parts and tubes are insulated using foam-rubber insulator in order to reduce the heat losses to the outside of facilities.

3.3 Experiment result

Experiment facility is almost prepared and its test results will be shown soon. Both bare titanium tube and super-hydrophobic titanium tube will be tested in the same condition. Every test will be executed more than twice to have validity of experimental result.

4. Conclusion

Experimental study is performed to evaluate the performance of surface modified titanium tube in vacuum state. SAM coating is used to make super-hydrophobic surface of titanium tube. Preliminary analysis were performed considering filmwise and dropwise condensations, respectively. Experiment facility is almost prepared and the test result will be shown soon.

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