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A Study on Condensation Heat Transfer at the Exterior Surface of S.A.M. Coated Titanium Tube Using in Steam Condensers

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1. Introduction

Most of power plants contain steam condensers. Like all power plants, a key contributor to the efficiency of steam cycle is the condensers. If the steam condenser’s performance is poor, it is one of the largest causes of lost efficiency. Therefore, efficiency of condensation heat transfer should be improved through many studies of condensation.

Condensation occurs when the temperature of a steam is reduced below its saturation temperature. There exist two forms of condensation on cooling surface: dropwise, and film condensations. Usually, dropwise condensation has a better heat transfer performance than film condensation, but it has limit of short period. Therefore, to maintain the duration of dropwise condensation, various researchers have tried to modify the surface by many coating processes.

Ma et al.[1] 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 exist, the condensation heat transfer coefficient is decreased. Shen et al.[2] 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.

Most of power plants use sea water as coolant, so the surface of metal tubes could be corroded by the coolant. Although, Titanium is a suitable material for tube of steam condensers, it is hard to apply surface modification to Titanium because of its stability. For this reason, there are comparatively few researches about titanium tube. Therefore, we studied on condensation heat transfer of surface modified titanium tube.

2. Experimental Setup

2.1 Surface Modification

For this experiment, we have prepared the surface modified titanium tubes. Those were manufactured by S.A.M. (Self-Assembled Monolayer) coating process. This coating process is shown in Figure 1. First of all, surface passivation will be removed by strong sulfuric acid. This process is called as etching. After etching, intrinsic surface property will be disappeared. The next process is called as oxidation, which makes the surface exposed to air. After oxidation, hydrophilic surface will be formed. Finally, the surface has to be coated by monolayer solution made by heptadecafluoro-1, 1, 2, 2-tetrahydrodecyl trichlorosilane, then the process will be completed.

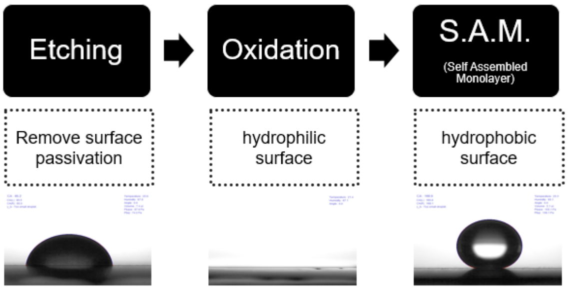


Fig. 1. Overall process of surface modification of titanium tube

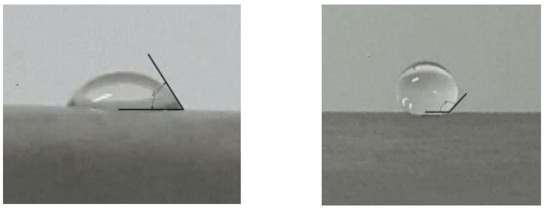
2.2 Specification of Tubes

Figure 2 shows bare and S.A.M. coated titanium tubes which were used in this experiment. As for the bare titanium tube, the thermal conductivity is 21 W/m·K, the length of the tube is 500 mm, the outer diameter is 25.4 mm, and the thickness is 0.508 mm.

Figure 3 shows contact angles of each titanium tube type. A bigger contact angle shows that the surface much more closely following a hydrophobic surface.

(a) Bare tube (b) S.A.M. coated tube

Fig. 2. Titanium tube



(a) Bare tube (57º) (b) S.A.M. coated tube(138º)

Fig. 3. Contact angle on tube surface

2.3 Experimental Procedure

Figure 4 shows the schematic diagram of experimental facility. The experimental facility is shown in Figure 5. Main components are a test shell, a steam generator, a cooler, a vacuum pump, and sensors. All sensors are listed shown in Table I. We measure the temperatures of inlet/outlet coolant, bulk. Each of flowmeters measure the data of steam flow rates and coolant flow rates. We also use a pressure transmitter to measure the absolute pressure inside the test shell.

It was important to remove non-condensable gases for our experiment. First, operate vacuum pump to remove almost of the non-condensable gases existing in the test shell. After the absolute pressure of steam in test shell reaches about 4 kPa, turn off the vacuum pump and check a leakage. Second, inject the pure steam into the test shell until the test shell reaches a high temperature, above 122 ºC, because the non-condensable gases are could be remaining in test shell. Third, turn off the steam generator and open the venting valve to decrease the temperature under 109 ºC. Repeat second and third steps at least four times. Finally, inject the coolant to condensate the remaining steam inside the test shell.

When the test shell's pressure reached to a constant pressure, regulate the valve of steam generator to maintain that pressure. We measured the coolant temperatures at both ends of the pipe. Using these data, we calculated the heat transfer rates as below:

$$Q_{Cw} = \dot{m}_{cw} C_{p,c} \Delta T_c \qquad (1)$$

Overall heat transfer coefficients was obtained by Equation (2):

$$Q_o = UA(T_{sat} - T_{cw}) = \dot{m}_{cw} C_{p,c} \Delta T_c \qquad (2)$$

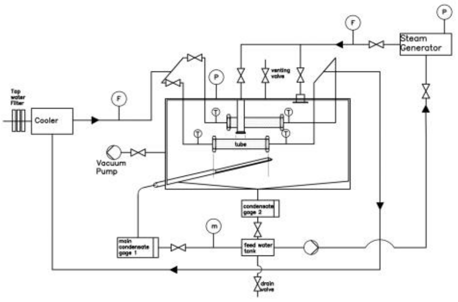


Fig. 4. Schematic diagram of the experimental facility

Fig. 5. Configuration of the experimental facility

In this study, we compared the overall heat transfer coefficients of the bare and S.A.M. coated tube to evaluate the condensation heat transfer performances.

Table I: A list of sensors

		Unit	Range	Accuracy	reference
Flowmeter	Orifice	1	0.2~20 [kg/hour]	±1 %	Steam
	Turbine	1	10~110 [LPM]	±1 %	Water
Thermocouple		5	0~100 [℃]	±0.15 °C	Calibrated by RTD
Pressure Transmitter		1	1 [bar]	±0.25 %	Absolute

3. Results and Discussion

3.1 Condensation Phenomena

Condensation phenomena are shown in Figure 6. On bare tube surface, film condensation was observed as shown in Figure 6-(a). Dropwise condensation was observed on the S.A.M. coated tube surface as shown in Figure 6-(b). However, water droplets do not fall frequently as we expected, even though the dropwise condensation happened on hydrophobic surface of S.A.M. coated tube.

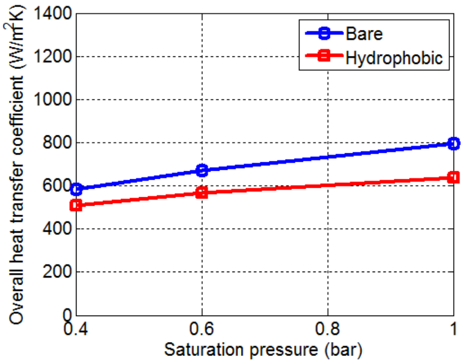
(a) Film condensation on bare tube

(b) Dropwise condensation on S.A.M. coated tube

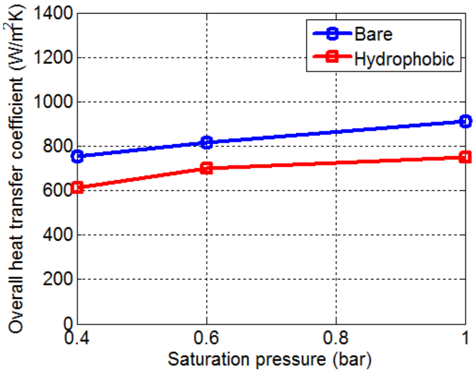
Fig. 6. Condensation phenomena on titanium tubes

3.2 Condensation Heat Transfer Performances

We obtained and compared the data of overall heat transfer coefficients for bare and S.A.M. coated tubes. Figures 7 shows the overall heat transfer coefficients in 0.5 m/s and 1.0 m/s of coolant flow rate, respectively. As saturation pressure in test shell increases, the overall heat transfer coefficient increases. Besides, as a coolant flow rate increases, the overall heat transfer coefficients also increase.



(a)0.5 m/s of coolant flow rate



(b)1 m/s of coolant flow rate

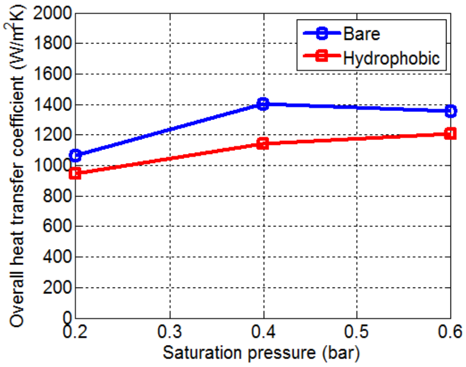
Fig. 7. Overall heat transfer coefficients

In Figure 8, we removed more air, one of non-condensable gases, from the test shell so that absolute pressure was less than 1 kPa. For reference, the absolute pressure in Figure 7 was 5 kPa. This means less non-condensable gases are remained in the test shell in Figure 8. The overall heat transfer coefficients increased more than two times in range of 0.4-0.6 bar in Figure 8, compared with the overall heat transfer coefficients in Figure 7, due to the effect of non-condensable gases. Contrary to expectations, the overall heat transfer coefficients were not increased as the coolant flow rate increased at 0.4-0.6 bar, and they were decreased at 0.2 bar. Therefore, 1 m/s of coolant flow rate was suggested for our system to get the best heat transfer rate.

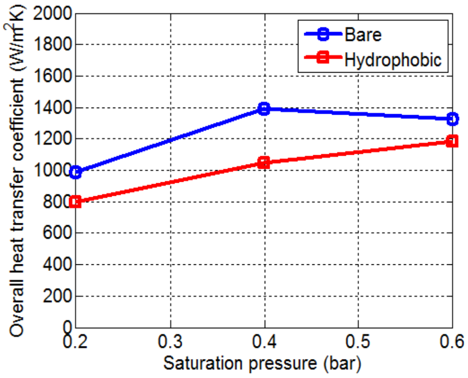
In both cases, S.A.M. coated titanium tubes had poor performances than bare titanium tubes. The main reason that we could expect was a characteristic of hydrophobic surface. As we discussed above, droplets were not detached from the surface frequently. The droplets reduced heat transfer area, and also increased thermal resistance. These results could be also checked by Jo et al.[3]. They said that Nano-structure could catch droplet at surface depending on scale of Nano-structure.

4. Conclusions

We had researched an experimental study related to condensation heat transfer on surface modified titanium tube.



(a)1 m/s of coolant flow rate



(b)1.5 m/s of coolant flow rate

Fig. 8. Overall heat transfer coefficients

Our experimental facility was designed to show how two kinds of tube's heat transfer performances are different in a same condition. We changed the range of saturation pressure and coolant flow rate to observe tube's performance change. When saturation pressure and coolant flow rate increase, overall heat transfer coefficients were increased. When residue of non-condensable gases was decreased, the overall heat transfer coefficients were increased. S.A.M. coated tube's overall heat transfer coefficients were lower than those of bare tube, because the droplets didn't have a tendency of frequently falling down.

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