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Experimental study of condensation heat transfer on the aluminum tubes with S.A.M coating method

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1. Introduction

Condensation heat transfer is the core heat transfer phenomenon of the condenser that condenses remaining steam after the turbine in the power plant. The more energy efficiency is important due to energy shortage, the more condenser efficiency is important. We can increase the size of the condenser or the number of tubes to improve the condenser efficiency, but these two ways are economically infeasible. On the contrary, it is simple and economical to apply surface modification method making hydrophobic characteristic in order to induce dropwise condensation instead of film condensation on condenser tubes. There are several hydrophobic surface modification methods such as S.A.M coating and Teflon coating. S.A.M stands for Self Assembled Monolayer, which is a method of forming nano-sized particles on the surface to create the hydrophobic surface.

Das et al.[1] conducted condensation heat transfer experiments in 10 kPa high-degree vacuum condition using copper and copper-nikel alloy tubes applied 1 ~ 1.5 nano size organic S.A.M coating in 2000. Vemuri et al. [2] carried out an experiment study for long-term testing of copper tubes applied n-octadecyl mercaptan S.A.M coating. They reported that condensation heat coefficient increased about 3 times after 100 hours, and about 1.8 times after 2600 hours. Chen et al.[3] studied super-hydrophobic S.A.M coated copper surface using octadecanethiol solution in 2009. They reported that dropwise condensation had 1.7 ~ 2.1 times higher condensation heat transfer coefficient than filmwise condensation. On the other hand, in 2010, Lan et al.[4] reported that the condensation heat transfer performance of S.A.M coated plate decreased. For this study, they used copper and copper-nikel alloy plates applied n-octadecyl mercaptan S.A.M coating.

In this study, we conduct condensation heat transfer test of horizontal aluminum tube which is applied heptadecafluoro-1,1,2,2-tetrahydrodecyl trichlosilane solution S.A.M coating. Length of test section is 440 mm, and diameter is 25 mm. Major test variables are the saturated pressure of steam and the flowrate of coolant. We will carry out the comparative evaluation of the S.A.M coated aluminum tube with the bare aluminum tube in terms of overall heat transfer coefficients.

2. Experiment

2.1 Test samples and Surface modification

Specifications of aluminum tubes are 25 mm outer diameter, 2 mm thickness, and 440 mm Length.

For surface modification, aluminum tubes were washed in 1 mole of NaOH solution for 1 minute at room temperature before acid etching. Cleaned aluminum tubes were than etched in 1 mole of HCl solution for 5 minutes at 70 ℃. During the etching process, micro structure of 1 to 10 μm is formed on the surface. The etched aluminum tubes were dipped in deionized (DI) water for 5 minutes at over 90 ℃ for oxidation. Flake-like aluminum hydroxide nano structure of 5 to 10 nm is formed on the microstructure during the oxidation treatment. To obtain super-hydrophobic characteristic on the surface, S.A.M coating method was used. The aluminum tubes were dipped in a mixture of n-hexane and heptadecafluoro-1,1,2,2,-tetrahydrodecyl trichlosilane (HDFS), volumetric ratio of 1000:1, for 10 minnutes. HDFS S.A.M coating dramatically lowers the surface energy, preserving the micro-nano surface structure.

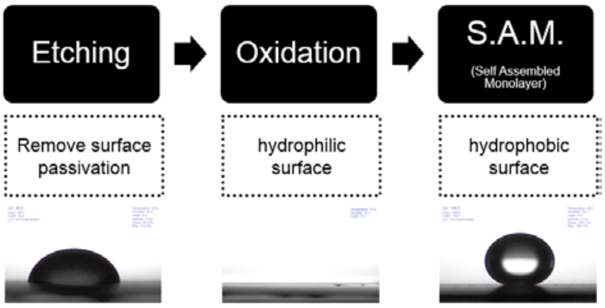

Fig. 1. Diagram of the S.A.M coating process.

2.2 Experimental facility

Fig. 2 represents a schematic diagram of the condensation heat transfer experimental facility. Main components are shown in Fig. 3 which are (a) the test shell, (b) the cooler, and (c) the steam generator. Saturated pressure of the test shell is controlled by a vacuum pump.

K-type thermocouples, a pressure transducer, a turbine flowmeter and a differential pressure steam flowmeter are used as sensors. K-type thermocouples are calibrated to ±0.1 ℃ accuracy, and the pressure transducer has ±0.25 % measurement error in the range of absolute pressure 0 to 2.1 bar. The turbine flowmeter has an error of ±1 % in the range of 10 to 110 LPM, and the steam flowmeter has an error of ±1 % in the range of 4 to 20 kg/hr.

Overall heat transfer coefficient can be obtained by 2 methods. First method is using temperature difference between thermocouples (1) and (2) in Fig. 2. Second method is measuring condensed water flowrate at condensate gauge indicated as (3) in Fig. 2. The test shell can test two tubes at the same time to allow the same experimental conditions for comparison. Each tube part is named as section #1 and #2. When two tubes of the same shape and material were connected, it was verified that the temperature differences and the condensate flowrate in section #1 and #2 were same. But, there were some deviations between the calculated heat transfer rate from the temperature difference and that from the condensate flowrate. The method measuring condensed flowrate is more reliable because the method using temperature difference has larger uncertainty due to small temperature difference. Therefore, experimental results were derived through the second method measuring the condensate flowrate. In addition, we compared overall heat transfer coefficients of section #1 and #2 instead of condensation heat transfer coefficients. We checked that the condensation heat transfer coefficients calculated from Nusselt’s theory had high deviations according to small condensate flowrate fluctuations. Finally, it can be evaluated that condensation performances of S.A.M coated tubes compared to bare tubes.

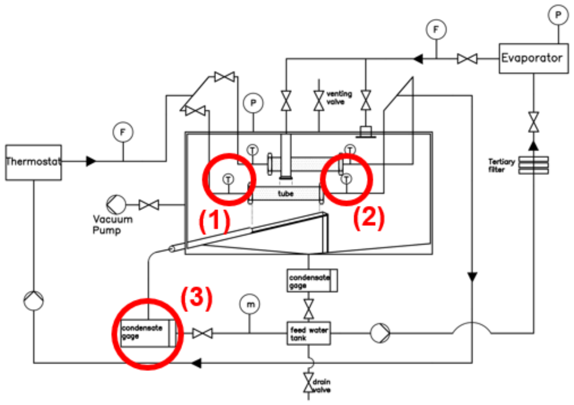

Fig. 2. Schematic diagram of experimental facility.

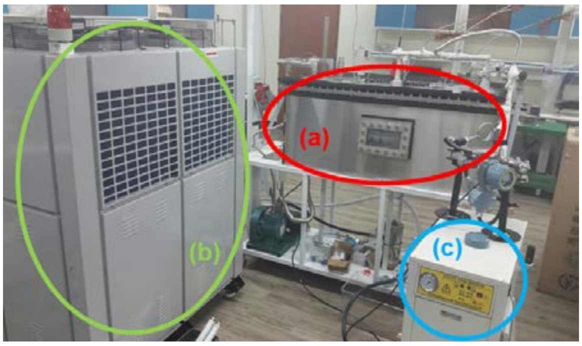

Fig. 3. Photograph of experimental facility ((a): test shell, (b): cooler, (c): steam generator).

2.3 Test methods

All experiments were carried out after evacuating the air until the pressure of the test shell reached 0.04 bar. Table I shows the test matrix of this experimental study. Major test variables are the saturated steam pressure and the coolant flowrate, which are 0.2, 0.4, 0.6 bar and Reynolds number 10000, 20000, respectively.

For the condensation experiments of a sample, it were conducted in the order of 0.2, 0.4, 0.6 bar with Reynolds number 10000. And then, the experiments were conducted in the order of 0.6, 0.4, 0.2 bar with Reynolds number 20000. As the order of experiments, we named them as test #1, #2, #3, #4, #5, and #6. The bare and S.A.M coated aluminum tubes were connected in section #1 and #2, respectively. Overall heat transfer coefficients were obtained according to experimental procedure. In addition, the S.A.M coated aluminum tube was dried during 144 hours after first experiment, and then repeatability experiments were conducted in the same test order.

Table I. Test matrix of experiments.

	Saturation pressure (bar)		
	0.2	0.4	0.6
Re 10000	test #1	test #2	test #3
Re 20000	test #6	test #5	test #4

3. Results and Discussion

3.1 Experimental results

Table II represents overall heat transfer coefficients according to test numbers and tube types. Fig. 4 and Fig. 5 show the graphs for the comparison of overall heat transfer coefficients between bare and S.A.M coated tubes.

Condensation performance of the S.A.M coated tube was improved 4 to 35 % than the bare tube in test #2, #3 and #4 in the first experiment. On the other hand, we could observe performance degradation in test #1 and #5, especially it was observed 55 % rapid decline in test #5.

It was improved until 19 to 34 % in test #1, #2, #3 and #4 in repeatability experiments. Similarly, it was observed 52 % rapid performance decline in test #5.

Table II. Overall heat transfer coefficient of each tubes according to test number.

Test number	Bare tubes [W/m^{2}K]	S.A.M tubes (first) [W/m^{2}K]	S.A.M tubes (repeatability) [W/m^{2}K]
1	744	588	886
2	1426	1926	1919
3	1705	1771	2108
4	2318	2664	2971
5	1854	830	882

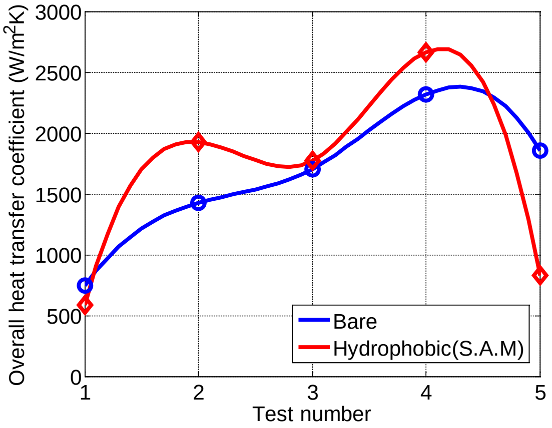

Fig. 4. Overall heat transfer coefficient according to test number in the first experiment.

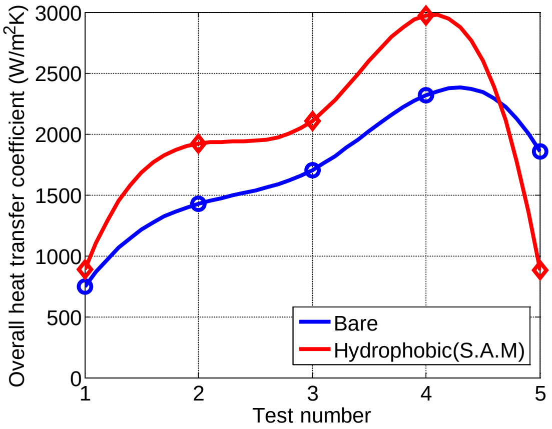

Fig. 5. Overall heat transfer coefficient according to test number in repeatability experiments.

3.2 Discussions

Test # 6 of the S.A.M coated tube test did not need to be carried out, because it was difficult to derive overall heat transfer coefficient due to sudden reduction in condensation performance after test #5. Therefore, we consider there are some physical factors which are the causes of serious performance degradation between test #4 and #5. Fig. 6 shows dropwise condensation phenomenon before test #5. Fig. 7 shows the condensation phenomenon of S.A.M coated tube after test # 5, and Fig. 8 shows filmwise condensation of the bare tube. When the S.A.M coated tube loses its hydrophobic characteristic in test #5, it shows similar shape with film condensation on the bare tube. However, this newly generated adhesion condensation is a little different from filmwise condensation of the bare tube. In Fig. 8, the condensate film on the bare tube shows flowing shape along the longitudinal direction of it, but the adhesive condensate film on the S.A.M coated tube just shows the phenomenon of falling from top to bottom. In such a phenomenon, it can be explained why the performance of the S.A.M coated tube in test #5 is lower than that of bare tube.

Furthermore, we analyzed what conditions make losing the hydrophobic characteristic of the S.A.M coated surface between test #4 and #5. Test #4 is different from #5 in saturation pressure, and test #2 is different from #5 in coolant flowrate. From the standpoint of the tube, the saturation pressure is related to the droplet temperature attached on the outer wall of the tube, and the coolant flowrate is related to the surface temperature. It is thought that the surface temperature and the droplet temperature are useful for explaining the degradation performance of dropwise condensation, so additional studies are necessary for this point of view in the future.

Fig. 6. Dropwise condensation phenomenon of the S.A.M coated tube before test #5.

Fig. 7. Adhesion condensation phenomenon of the S.A.M coated tube after test #5.

Fig. 8. Filmwise condensation phenomenon of the bare tube.

4. Conclusions

This study was performed to compare condensation performance of bare aluminum tubes and S.A.M coated tubes. The S.A.M coating was made to have hydrophobic properties through three steps of etching, oxidation, and HDFS solution coating. Experiments were conducted on horizontal tubes according to saturated pressure and coolant flowrate. The S.A.M coated tube was verified repeatability once, and the results was analyzed by overall heat transfer coefficient in order of test number. Performance improvement of the S.A.M coated tube was confirmed in test #2, #3, and #4. On the other hand, it was observed performance degradation in test #5. We explained that the cause is adhesion condensation. Finally, we proposed surface temperature and droplet temperature as a variable to explain performance degradation in dropwise condensation.

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