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Experimental study of condensation heat transfer on a horizontal tube with non-condensable gas

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1. Introduction

As the energy issues became more serious, it is important to reduce the energy loss by devising a method to increase condensation heat transfer performance of a condenser. The purpose of our study is to solve this problem. We focused on the relationship between a mass fraction of non-condensable gas(NCG) in a condenser and the condensation heat transfer performance of filmwise condensation(FWC) and dropwise condensation(DWC).

Kroger and Rohsenow [1] performed the condensation experiment in the presence of NCG, such as argon and helium. This experiment confirmed the effect of NCG on condensation phenomena. The result showed that the effect of molecular diffusion is more dominant on condensation performance than that of thermal diffusion. Tang et al. [2] established a model which is for study of FWC on horizontal tube in the presence of NCG. Based on the model, the numerical solution for condensation heat transfer coefficient (HTC) was solved using finite elements method. As a result, the mean total HTC decreases obviously even though NCG mass fraction in the bulk mixture was low. For inducing and analyzing DWC phenomena, the studies for super-hydrophobic surface has been performed. Miljkovic et al. [3] observed surface and droplet states when the condensation heat transfer occurred. The droplet jumping, dropwise and flooded state were observed, and the heat transfer rate of each state has improved about 5 times, 3.3 times and 2 times compared with FWC. Ma et al. [4] conducted a condensation heat transfer experiment on S.A.M. coated surfaces which have nanostructure surface and microstructure surface in the presence of NCG. The condensation heat transfer rate of DWC decreased as NCG increased, like FWC cases. In addition, when NCG mole fraction is less than about 20%, the heat transfer rate on the microstructure surface is higher than that on the nanostructure surface. On the contrary, when NCG mole fraction is more than about 0.2, the condensation heat transfer rate on the nanostructure surface is higher than that on the microstructure surface. The researchers analyzed that the reason is because the surface structure and NCG mole fraction affected the wettability.

In this study, condensation heat transfer performance on super-hydrophobic surface is investigated and compared with ordinary of aluminum (A1) tube. The condensation performance is described by the condensation heat transfer rate and overall HTC. Finally, we evaluated the effect of NCG mass fraction on DWC and FWC respectively, and propose a method for minimizing the effect of NCG on condensation.

2. Methods and Results

2.1 Theoretical analysis

To describe condensation heat transfer performance, two physical quantities, the condensation heat transfer rate (q_c) and overall HTC (U) should be defined (1), (2). Firstly, the condensation heat transfer rate can be calculated from the mass flow rate of condensate ($\dot{m}_c$) which is measured. After that, overall HTC is derived from the condensation heat transfer rate. It is also defined by the equation which is including the heat resistances of coolant (R_w) and tubes (R_t). The heat resistance of coolant is derived from Petukhov-Popov correlation [5]. The heat resistance of heat pipe is derived by solving the differential equation related to conduction on cylinder. We can calculate the condensation HTC (h_c) from overall HTC, because the heat resistances of coolant and heat pipe are known between the overall HTC and the heat resistances. But, we did not consider the condensation HTC because of its high uncertainty and instability. The condensation heat transfer rate and overall condensation HTC indicate the condensation heat transfer performance.

$$q_c = \dot{m}_c \Delta h_{fg}^* = \dot{m}_w C_{p,w} \Delta T_w \quad (1)$$

$$U = \frac{q_c}{\Delta T_{LMTD} \cdot A_o} = \frac{1}{R_w A_o + R_t A_o + \frac{1}{h_c}} \quad (2)$$

In this study, the key variable for the condensation heat transfer performance is NCG mass fraction (N). The NCG mass fraction is calculated by dividing the mass of the air by the mass of the air and vapor mixture. The air and vapor are assumed as the ideal gas in this case (3). Therefore, we can analyze the heat transfer performance according to NCG mass fraction.

$$N = \frac{P_a \cdot m_a}{P_v \cdot m_v + P_a \cdot m_a} \quad (3)$$

2.2 Experiment methods

S.A.M. coated Al tube was used to induce DWC, and for the comparison, bare Al tube, in which FWC occurs, was also used. The length of the tubes is 440 mm, the outer diameter of that is 25 mm and the thickness of that is 2 mm. The schematic diagram of the experiment is presented with Figure 1. Steam generator is a device for producing vapor. It will be used for steam injection to chamber. Separator is a sort of filter which makes the vapor pure state. The impingement plate will be placed below the entrance of steam in the chamber, which is to cause natural convection. The Reynolds number of cooling water is 10000 and the inlet temperature of that is 15 °C during the experiment. NCG mass fraction, as shown in equation (3), consists of the pressure of air and vapor. These are set by initial vacuum condition and the amount of vapor. Therefore, in the process above, we measure inlet and outlet temperatures of coolant and the mass flow rate of condensate. In this study, since the temperature difference is too small to measure considering thermocouple's range of error, the mass flow rate of condensate is applied for the results to get more accurate condensation heat transfer performance.

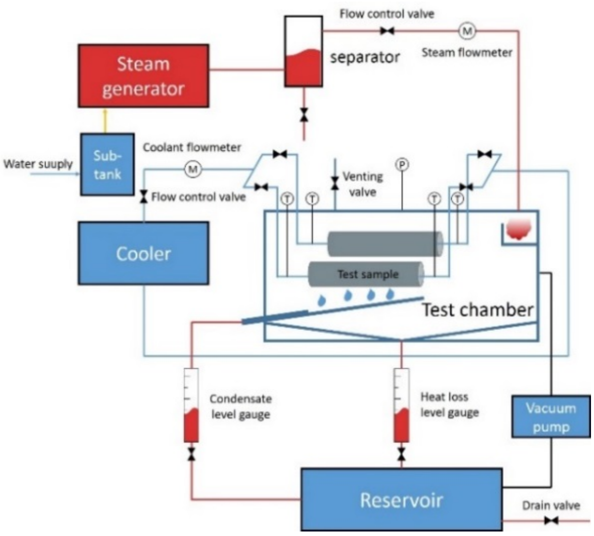

Fig. 1. Schematic diagram of experimental facility

2.3 Results

The experiment was conducted within NCG mass fraction range from 0.10 to 0.46. The results are plotted in Figure 2, which is for DWC, and Figure 3, which is for FWC. The condensation heat transfer rate and overall HTC of DWC decreased as NCG mass fraction increased. Figure 4 shows that those of FWC have same tendency as DWC, but they are 9~25 % lower than DWC. In addition, according to the results, the condensation performance enhancement by DWC induction decreases gradually in absolute numbers as NCG mass fraction increases. Especially, it is found that the range below 0.25 of NCG mass fraction has relatively sharp degradation compared to the NCG mass fraction above 0.25. This is because the heat transfer resistance by NCG diffusion layer becomes more dominant to the condensation phenomena at high NCG mass fraction.

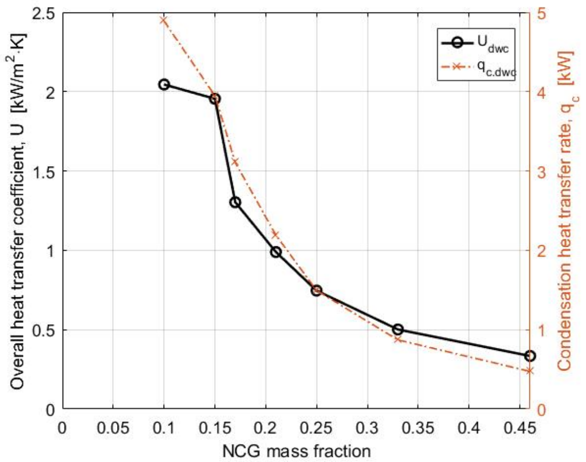

Fig. 2. DWC overall HTC and heat transfer rate versus NCG mass fraction

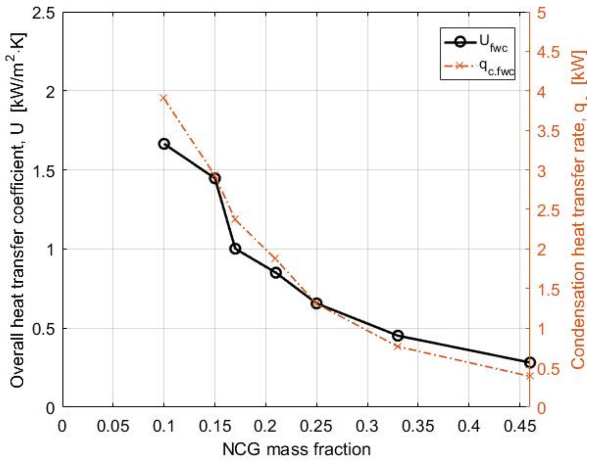

Fig. 3. FWC overall HTC and condensation heat transfer rate versus NCG mass fraction

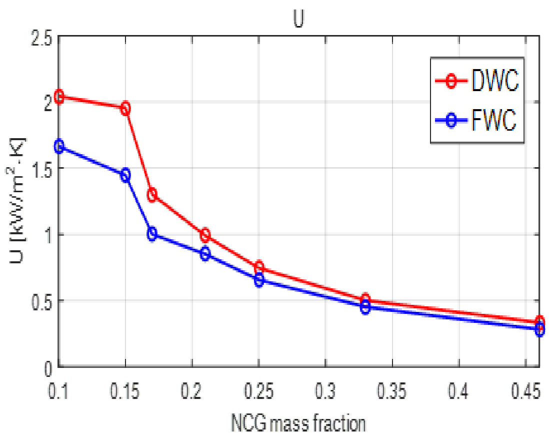

Fig. 4. Overall HTC versus NCG mass fraction of DWC and FWC mode

3. Conclusions

This study is to define the condensation heat transfer performance with Al tube which has super-hydrophobic surface and bare respectively. The condensation performance is described by the condensation heat transfer rate and overall HTC. In the experiment, NCG mass fraction is set by initial vacuum condition and the amount of injected vapor. The condensation heat transfer rate was calculated by measuring the mass flow rate of the condensate, and overall HTC was derived from the condensation heat transfer rate. As a result, as NCG mass fraction increased, the condensation performance decreased in both DWC and FWC condition, and the condensation performance of DWC is higher than that of FWC in all range. When NCG mass fraction is over 0.15, however, it is observed that the condensation performance enhancement due to DWC induction becomes very small. This result indicates next two things. First, NCG should be removed from a condenser. Second, to obtain condensation performance enhancement using S.A.M. coated surface in an actual condenser, it is recommended to operate under the condition that NCG mass fraction is less than 0.15. The further study should be done by investigating the way enables to decrease NCG mass fraction.

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