Experimental Study of Dropwise Condensation Heat Transfer with Visualization of Droplet Distribution

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1. Introduction

Currently, nuclear industry has great interest in passive safety system after Fukushima accident. To maintain containment integrity, passive containment cooling system (PCCS) is one of the candidate as a corresponding safety system. However, heat exchanger type of PCCS that is used in concrete type containment has the challenge to minimize the heat exchanger size. Moreover, several experiments reported that the upper part of heat exchanger shows dropwise condensation phase. Therefore, dropwise condensation, which has much higher condensation heat transfer coefficient (HTC) than filmwise condensation, need to be studied to design optimized heat exchanger.

Many papers were reported for the condensation with non-condensable gas. For filmwise condensation experiment, Kuhn et al. (1997), Park&No (1999) and Lee&Kim (2008) studied the steam condensation for the steam pressure (1~5bar) suitable to PCCS. On the other hands, Griffith&Lee (1967)[1] and Hannemann&Mikic (1976)[2] conducted dropwise condensation experiment. Le Fevre&Rose (1966) [3], Mikic (1969) [4], Tanaka (1975) [5] and Tsuruta&Tanaka (1990) [6] studied about the model of dropwise condensation.

2. Experimental Method

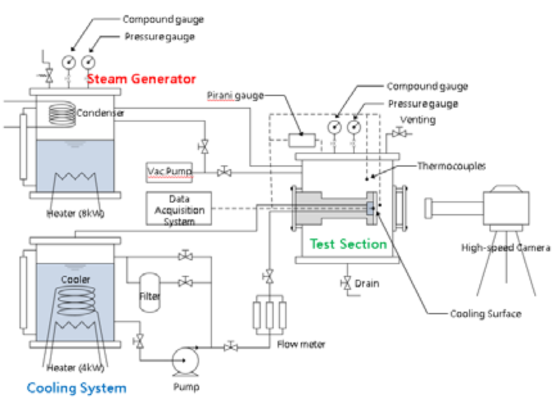


Fig. 1. Experimental apparatus

Structure of experimental apparatus of this study is shown in figure 1. Experimental apparatus is consist of steam generator, cooling system and test section. Pressure was measured at the steam generator and test section part and temperature was measured at outlet of steam generator, inlet/middle of test tank and in front of test section. To measure condensation heat transfer coefficient (HTC) of cooling surface, the temperatures at four different depth from the condensing surface (1, 2, 3 and 4 mm) were measured. Temperature of cooling surface can be predicted by the extrapolation of these four temperature measurements.

Overall experiment condition is shown in Table 1. Condensation experiment on vertically oriented flat SUS316 surface was conducted for 1 bar pressure and stagnated steam flow. Air was used as non-condensable gas and subcooled temperature range 1 K to 30 K was controlled by the flow rate of coolant. To visualize the cooling surface, film of cooling surface was recorded by high-speed camera with three magnification with two different frame rate. Then, recorded surface photo was processed by MATLAB R2014b to quantify the size, number and covered ratio of individual droplets.

Table. 1. Experimental condition

Parameter	Condition
Cooling surface	Polished SUS316 (vertical, flat)
Steam flow	Stagnated (<2 cm/sec)
Pressure	1 bar
Noncondensable	Air (0~40%)
Subcooled temperature	1 ~ 30 K
Magnifications	x2.28, x16.0, x36.8
Frame rates	60, 250 fps

3. Results and Discussions

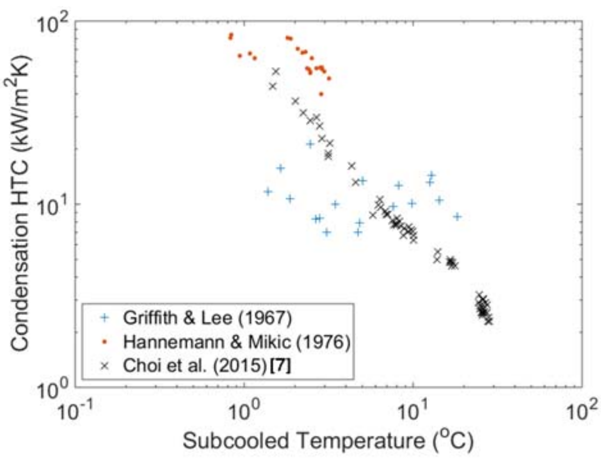


Fig. 2. Dropwise condensation on stainless steel surface (vertical, flat)

The condensation HTC of dropwise phase on stainless surface is shown in figure 2. All experiment results shown in figure 2 were conducted for 1 bar pressure, pure steam and vertical flat stainless steel surface, but only the range of subcooled temperature and steam flow rate were different. The experimental results were well overlapped with the results from Griffith&Lee (1967)[1] and Hannemann,&Mikic (1976)[2].

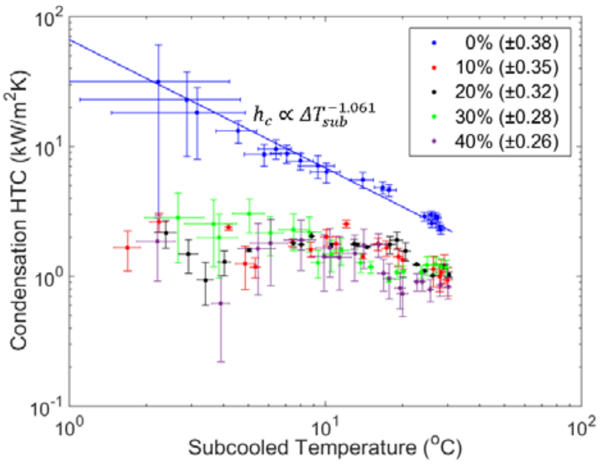


Fig. 3. Subcooled temperature versus condensation HTC

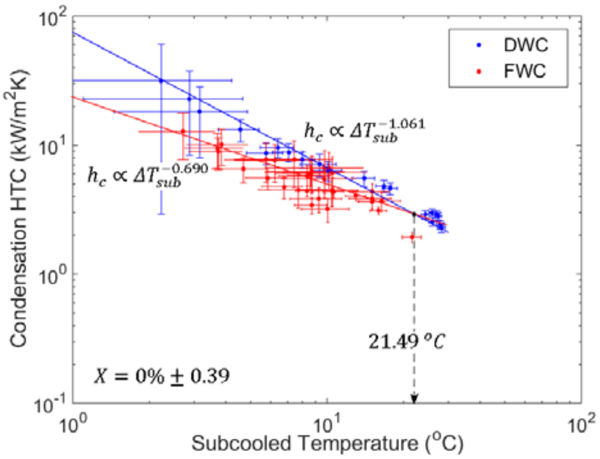
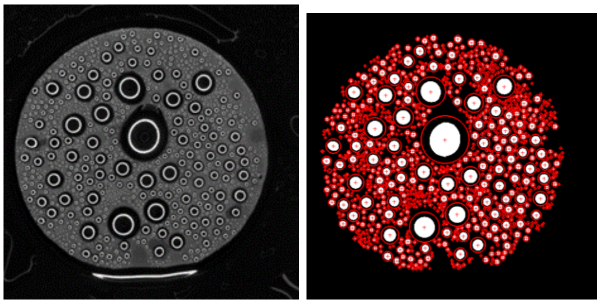


Fig. 4. Comparison of condensation HTC between DWC and FWC phase at pure steam condition

Figure 3 also showed HTC of dropwise condensation for non-condensable gas concentration range from 0% to 40%. For pure steam, condensation HTC shows clear trend expressed by the function of subcooled tempeature powered by constant. For the case in presence of non-condensable gas, condensation HTC is decrease with incresing subcooled temperature at the range of 10 K to 30 K. On the other hands, the condensation HTC seems to increase with increasing subcooled temperature for subcooled temperature lower than 10K. However, it is not clear due to high uncertainty of the result. Figure 4 shows the difference of dropwise condensation and filmwise condensation on condensation HTC. Dropwise condensation showed higher condensation HTC than filmwise condensation only for the condensation with subcooled temperature higher than around 20 K.

As we easily notice from the previous condensation models, condensate thickness and covered area are great factor of HTC. To develop dropwise condensation model, condensing surface was processed to visualize the the size, number and covered ratio of individual droplets. The results is shown in figure 5.



(a) (b)

Fig. 5. (a)Visualization of condensing surface, (b) Image processed result

With the process images, droplet behavior of all experimental conditions were quantified into size, number and coordinate of droplet center for 60 seconds. Droplet radius larger than 0.05 mm was countable by the image processing and the largest droplet radius which can stick to condensing surface was 1.2 mm. In figure 6, three experimental result was shown with the droplet distribution models of other researchers. Data 1, 2 and 3 was obtained under pure steam condensation experiment and measured under the subcooled temperature of 6.0 K, 8.5 K and 10.1 K, respectively. The time-average droplet distribution was same regardless of subcooled temperature. At last, the drop covered fraction, which is shown in figure 8, was estimated.

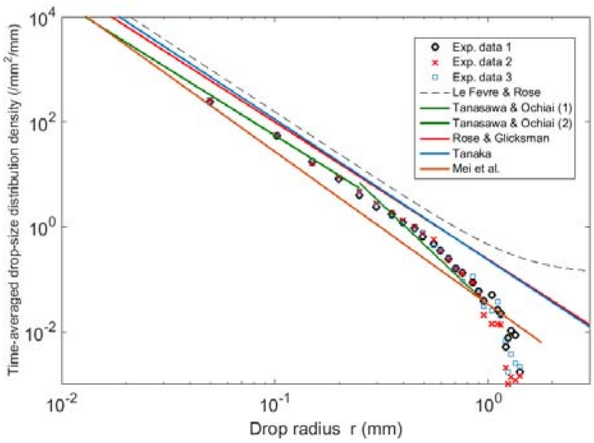


Fig. 6. Time-averaged drop-size distribution density

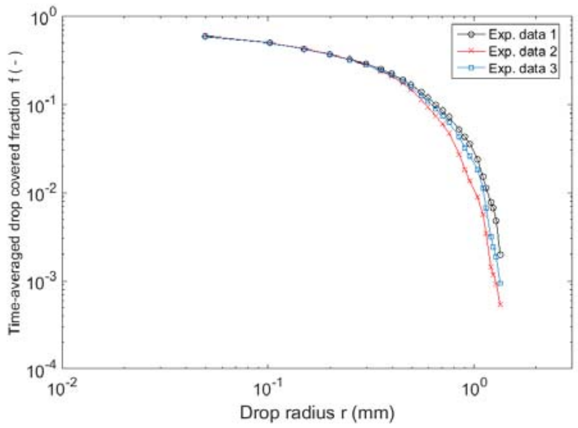


Fig. 7. Time-averaged faction of the area covered by drops with larger than radius

4. Conclusion

In this study, followings were known.

(a) Dropwise condensation on SUS316 surface enhances condensation heat transfer maximum 3.5 times depend on subcooled temperature and the enhancement is negligible around over 20 K of subcooled temperature

(b) Conventional droplet distribution model over-estimate the number of large droplet over around 1.0 mm

(c) Time-averaged drop-size distribution density and drop covered fraction was constant regardless of subcooled temperature and around 30 % of condensing surface is always not covered by inactive droplets.

5. Acknowledgement

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