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Experimental study of condensation heat transfer in the presence of noncondensable gas on the vertical tube

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1. Introduction

The Passive Containment Cooling System (PCCS) that will be introduced in the next generation nuclear power plant removes released energy to containment through the condensation heat transfer phenomenon in the event of the loss of coolant accident(LOCA) or main steam line break(MSLB). The released steam is mixed with the air inside the containment and condensed on the tube bundle's outer surface of PCCS.

In this study, an experimental study is performed to investigate the condensation heat transfer in the presence of noncondensable gas on vertical tube. Experiments were conducted using a tube with 1000 mm in length and 40 mm in outer diameter tube. The experimental data are obtained at pressure of 2, 3, 4 bar and the air mass fraction varied from 0.1 to 0.7. The experimental results are compared to the prediction of existing correlations.

2. Experiment

2.1 Experimental apparatus

As described in Fig. 1, experimental loop consists of mainly two sections: condensation section and cooling section. The condensation section includes chamber which installed tube inside, steam generator, condensation water tank and recirculation pump. The cooling section has water storage tank and pump.

The diameter of chamber is 609 mm and the height is 1950 mm. A vertical tube with 40 mm in outer diameter, 3 mm in thickness and 1000 mm in length installed inside of the chamber. Both of them are made of SUS-304.

The steam is generated submerging heaters (30 kW × 4) in the steam generator and it goes to chamber. The steam is mixed with air in the chamber and condensed on the tube. The condensate flows to the condensate tank and it is sent to steam generator using the recirculation pump to maintain the water inventory.

Fig. 2 describes the location of thermocouples (K-type) in the tube and the chamber. To find internal gas mixtures distribution, 14 thermocouples were installed inside of the chamber. For measurement of temperature on the tube, thermocouples (K-type) are installed along the axial direction.

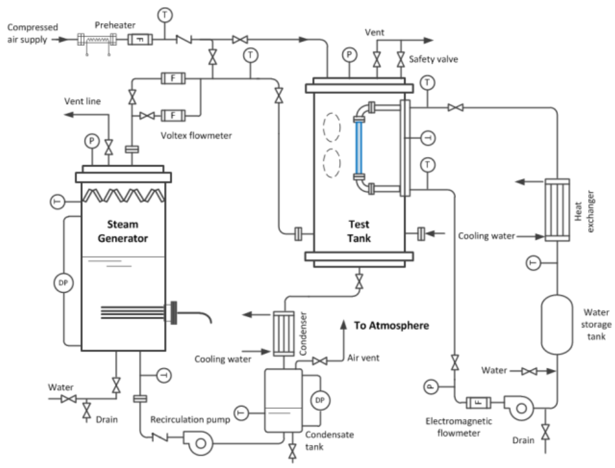

Fig. 1. Condensation experiment facility.

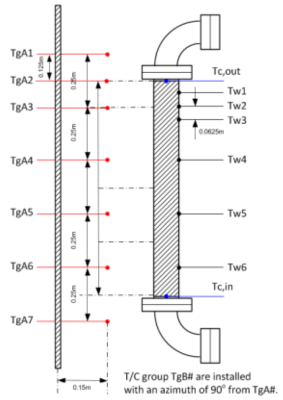

Fig. 2. Scheme of temperature measurement in the chamber.

2.2 Experimental procedure

After filling water up in the steam generator for condensation section and the water storage tank for cooling section, the heaters are turned on for pressurization and generation of steam. The chamber was ventilated for degassing when temperature and pressure of systems approach a proper level. After the degassing, noncondensable gas is injected into the chamber and the system is pressurized to prescribed condition. If the pressure reaches to the setting level, steady state should be confirmed. Then, the temperature of the gas mixtures, tube's outer wall, inlet and outlet coolant are measured to obtain the heat transfer coefficient.

Table I represents test matrix of this study. Generally, the design pressure of the containment is about 4 bar. Therefore, heat transfer coefficient is measured at 2, 3, 4 bar to reflect the transient status of the containment in this experimental study. The air mass fraction is adjusted from 0.1 to 0.7 to investigate the effect of noncondensable gas on the condensation.

Table I: Test matrix

2 bar		3 bar		4 bar	
W_a	ΔT	W_a	ΔT	W_a	ΔT
0.10	23.3	0.12	28.7	0.11	42.2
0.21	33.1	0.22	42.7	0.21	54.8
0.31	40.1	0.32	41.7	0.29	44.9
0.41	44.2	0.41	72.7	0.37	45.0
0.51	44.7	0.51	49.7	0.49	34.4
0.60	45.8	0.61	63.9	0.61	55.8
0.70	45.2	0.71	50.1	0.71	56.7

(W_a: air mass fraction, ΔT : wall subcooling)

2.3 Data reduction and Measurement uncertainties

To measure the condensation heat transfer coefficient, the heat transfer rate is measured using the inlet and outlet temperature of the coolant in the tubs as:

$$Q = \dot{m}c_p\left(T_o - T_i\right) \quad (1)$$

where, $\dot{m}$, c_P , T_o and T_i represent mass flow rate of coolant, specific heat, outlet and inlet temperature of tube, respectively. Utilizing the Newton's cooling low, Eq. (1) can be used to express the average condensation heat transfer coefficient of the condensing surface as:

$$\bar{h} = \frac{\dot{m}c_p\left(T_o - T_i\right)}{A\left(T_b - T_w\right)} \quad (2)$$

where, A , T_b , T_w represent total heat transfer area, temperature of steam and noncondensable mixtures and temperature of outer surface of tube, respectively.

To quantify the measurement uncertainties, uncertainty analysis is conducted about total heat transfer rates and the average heat transfer coefficients. The bias errors of measurement instruments are summarized in Table. II and relative error of condensation heat transfer coefficient is calculated as followed:

$$U_{\bar{h}}^2 = \left(\frac{\partial\bar{h}}{\partial\dot{m}}U_{\dot{m}} + \frac{\partial\bar{h}}{\partial\Delta T_c}U_{\Delta T_c} + \frac{\partial\bar{h}}{\partial\Delta T_w}U_{\Delta T_w}\right) \quad (2)$$

where, ΔT_c , ΔT_w represent inlet and outlet temperature difference of coolant and wall subcooling. Maximum error of the heat transfer coefficient is 35.6 % from analysis results. Most of it comes from flow measurement uncertainty. The measurement error of the wall subcooling is found to be relatively negligible.

Table II: Bias error of measurement equipment

Parameter	Measurement equipment	Bias error
Fluid Temperature	Thermocouple (K-type)	1.1 ℃
Wall Temperature	Thermocouple (K-type)	1.1 ℃
Coolant flow rate	Electrical flow meter	0.1 % of span
Steam flow rate	Vortex flow meter	1.0 % of reading
Chamber pressure	Pressure transmitter	0.075 % of span

3. Results and Discussions

3.1 Condensation heat transfer coefficient

Figs. 3 to 5 show that the condensation heat transfer coefficients measured at 2 to 4 bar. The condensation heat transfer coefficient reduces with an increase of the noncondensable mass fraction due to the noncondensable effect. The physical distribution of the steam and the noncondensable gas determines the condensation heat transfer performance. Fig. 6 shows that distribution of gas mixture in the presence of noncondensable gas on the tube. The steam is changed into liquid film due to condensate on the tube wall and the noncondensable gas is accumulated near the liquid film. This boundary layer interrupts heat transfer between the steam and the tube. Therefore, the condensation heat transfer rate is reduced by noncondensable gas.

The experimental results show that heat transfer coefficients increase with increasing pressure. It can be explained by Kang et al [1]. The Kang's results showed that increasing gas pressure induces increment of the gas density. When gas density increases, the heat transfer coefficient increases due to increase of contact efficiency between gas particles and condensing tube.

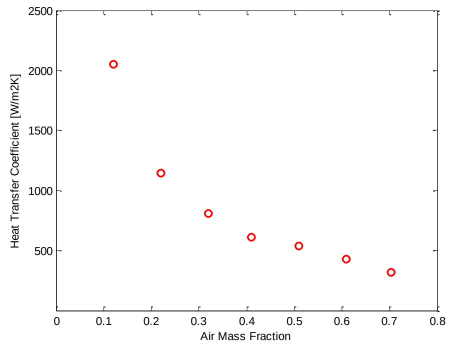

Fig. 3. Condensation heat transfer coefficient in the presence of noncondensable at 2 bar.

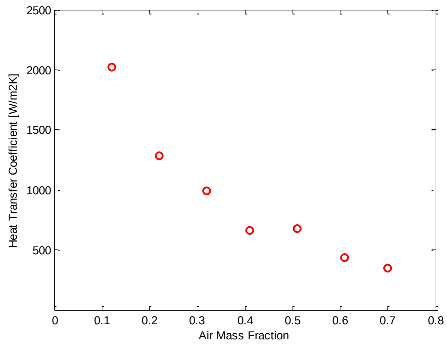

Fig. 4. Condensation heat transfer coefficient in the presence of noncondensable at 3 bar.

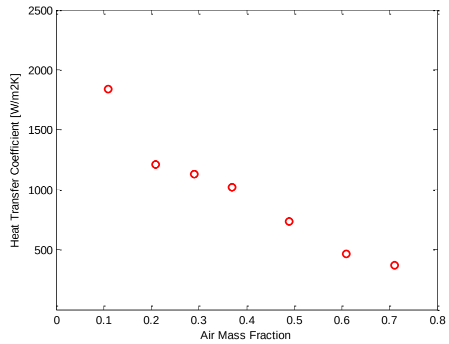

Fig. 5. Condensation heat transfer coefficient in the presence of noncondensable at 4 bar.

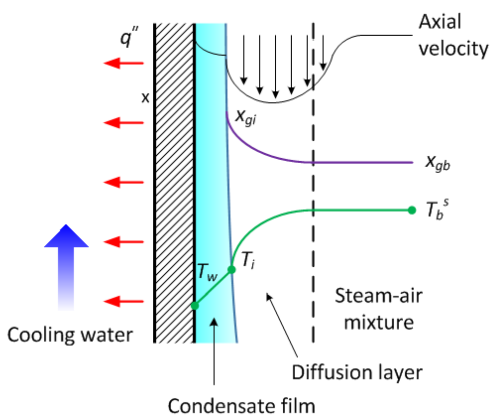

Fig. 6. Schematic diagram of distribution of gas mixture in the presence of noncondensable gas on the tube.

3.2 Comparison with existing correlations

The condensation heat transfer coefficients from the experiment are compared with existing correlations by Dehbi [2], Uchida et al. [3] and Tagami [4]. Correlations of Uchida, Tagami and Dehbi are as following:

$$\bar{h}_U = 379\left(\frac{W}{1-W}\right)^{-0.707} \tag{3}$$

$$\bar{h}_T = 11.4 + 284\left(\frac{1-W}{W}\right) \tag{4}$$

$$\bar{h}_D = \frac{L^{0.05}\left[(3.7+28.7P)-(2438+458.3P)\log W\right]}{(T_b - T_w)} \tag{5}$$

From the comparison results, experimental results have a slight difference with Uchida's and Tagami's correlations. These correlations take account of noncondensable mass fraction, only and their prediction of the condensation heat transfer coefficient is known to be conservative. Generally, these correlations estimate conservative heat transfer coefficients. The Dehbi's correlation takes account of noncondensable mass fraction, total pressure and wall subcooling. In that respect, experimental results are similar with prediction of the Dehbi's correlation. But still the Dehbi's heat transfer coefficients underestimate the experimental results. That's because Dehbi's experiment did not maintain the uniform gas mixtures state inside chamber and significant wall temperature gradient along the tube height. Also, Dehbi applied the same assumption of the dependency on the wall subcooling as Nusselt's theory [5], but it is applicable only to pure steam state.

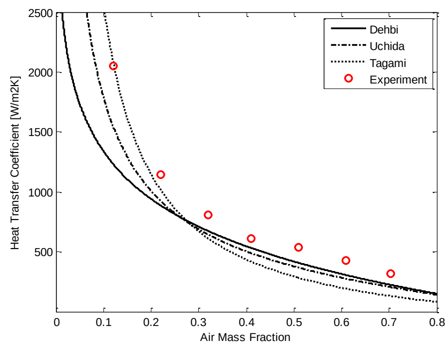

Fig. 7. Comparison result at 2 bar.

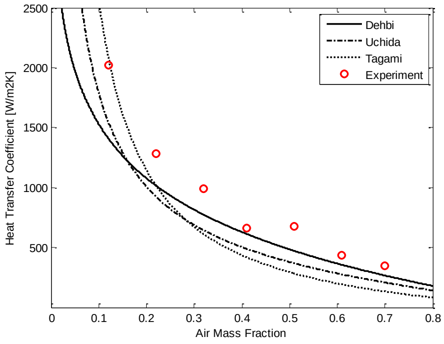

Fig. 8. Comparison result at 3 bar.

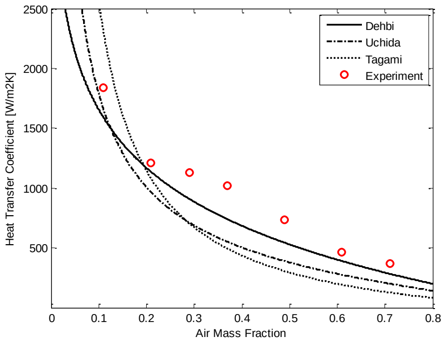

Fig. 9. Comparison result at 4 bar.

4. Conclusions

In a vertical tube with 40 mm in O.D. and 1000 mm in height, three sets of experiments to measure the condensation heat transfer coefficient are performed at 2, 3, 4 bar. Experimental results show that the condensation heat transfer coefficient reduces with an increase of the noncondensable mass fraction. The results are compared with the prediction of existing correlations by Uchida, Tagami and Dehbi. The compared result shows that these correlations underestimate the experimental results. That's because Uchida's and Tagami's correlations do not reflect all the effects of primary physical parameters and Dehbi's experiment did not maintain the uniform gas mixtures state inside chamber and has significant wall temperature gradient along the tube height.

As further works, a new correlation will be proposed based on the experimental results. In addition, the heat transfer enhancement by using a finned tube is to be experimentally investigated.

ACKNOWLEDGEMENTS

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REFERENCES

[1] Y. Kang, Y. R. Kim, M. H. Ko, G. T. Jin, J. E. Son, S. D. Kim, Immersed Heater-to-Bed Heat transfer in a Pressurized Gas-Solid Fluidized Bed, Journal of the Korean Institue of Chemical Engineers, Vol. 35, p. 282-288, 1997.

[2] A.A. Dehbi, The effects of Noncondensable Gases on Steam Condensation under Turbulent Natural Convection Conditions, Ph. D thesis, MIT, USA, 1991.

[3] H. Uchida, A. Oyama, Y. Togo, Evaluation of Post-incident Cooling Systems of Light-water Power Reactors, Proceedings of the Third International Conference on the Peaceful Uses of Atomic Energy, Geneva, August 31 – September 9, 1964.

[4] T. Tagami, Interim Report on Safety Assessment and Facilities Establishment Project for June 1965, No. 1, Japanese Atomic Energy Agency, Unpublished work, 1965.

[5] W. A. Nusselt, The Surface Condensation of Water Vapor, Ziescrhift Ver. Deut. Ing., Vol. 60, p. 541, 1916.

[6] P. F. Peterson, V. E. Schrock, T. Kageyama, Diffusion Layer Theory for Turbulent Vapor Condensation with Noncondensable Gases, ASME Journal of Heat Transfer, Vol. 115, p. 998–1003, 1993.

[7] P. F. Peterson, Theoretical Basis for the Uchida Correlation for Condensation in Reactor Containments, Nuclear Engineering and Design, Vol. 162, p. 301-306, 1996.