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Experimental Investigation of Condensation with Bundle Geometry for the Passive Containment Cooling System

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1. Introduction

To enhance safety of the Nuclear Power Plant (NPP), various passive safety features are being developed by nuclear industries. Especially, the integrity of containment building of the Nuclear Power Plant (NPP) has been emphasized after Fukushima accident. Recently, Korean nuclear industry considers an adoption of Passive Containment Cooling System (PCCS) for the design upgrade of APR+ (Advanced Power Reactor Plus). When the postulated loss of coolant accident (LOCA) occurs, steam and water that have high energy are released from the primary side of the Reactor Coolant System (RCS) to containment building and then it causes an increase of pressure of the containment. In this situation, it is required to keep the peak pressure below the design level to maintain integrity of the containment building. The PCCS is designed to replace a conventional active spray system in this accident condition. It makes condense the steam with condensation heat exchanger located inside of the containment building and then reduce the pressure below the design value.

Up to now, lots of condensation experiments on the outside surfaces of plate and single tube have been carried out to be applicable to the analysis of condensation heat exchangers including the PCCS. Uchida [1] proposed a simple correlation for the condensation heat transfer coefficient (HTC) based on the plate. It is widely used for the safety analysis of containment. More recently, condensation experiments on the plate and single tube were conducted by previous investigators such as Dehbi [2], Anderson [3], Liu [4] and Kawakubo [5]. Especially, Dehbi(2015) [6] proposed a useful condensation heat transfer coefficient correlation based on a few experimental data.

However, the PCCS consists of bundle type heat exchanger. Therefore, it is expected that condensation phenomenon for the bundle may be different from the single tube or plate. Unfortunately, we could not find out any condensation experiment as well as heat transfer coefficient model for the bundle type heat exchanger in the open literatures. In the present study, we tried to investigate experimentally condensation phenomena with a tube bundle to explore its bundle effect compared to single tube.

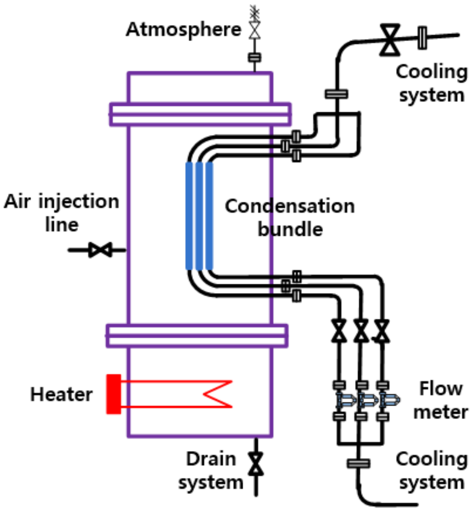

Fig. 1 Schematic diagram of the experimental apparatus

2. Experimental Facility and Measurement Methods

2.1 Experimental status

Experimental facility consists of a containment simulator, a tube bundle, a cooling water supply system, air injection system and a heater for steam generation as shown in Fig.1. The cylindrical containment simulator can be operated up to 10 bar in pressure. The bundle consists of 12 tubes and is a 3*4 array. Steam is generated at the bottom of the vessel by a set of immersion heaters of which maximum heat generation is 50kW. Air is injected through a flexible tube into the vessel.

As shown in Fig.2, coolant temperature and wall temperature are measured by K-type thermocouples (TC) each condensation tube. The surface temperature for the estimation of heat transfer coefficient is calculated with the help of heat conduction equation based on temperature difference measured in different depth at each measurement location.

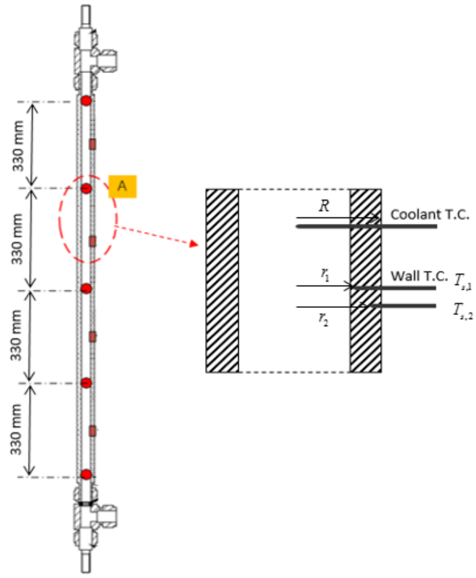

Fig. 2 Schematic diagram of the condensation tube

2.2 Measurement methods

The condensation heat transfer rate of each tube is estimated from the heat transfer rate of coolant as follows,

$$\dot{Q} = \dot{m} c_p \left(T_{coolant,out} - T_{coolant,\mathrm{in}} \right) \tag{1}$$

Finally, the condensation heat transfer coefficient of each tube is obtained from following equation,

$$h = \frac{\dot{m} c_p \left(T_{coolant,out} - T_{coolant,\mathrm{in}} \right)}{\pi D L \left(T_{vessel} - T_{surface} \right)} \tag{2}$$

where h, $\dot{m}$, c_p, d, L are heat transfer coefficient(W/m^{2}K), mass flow rate(kg/s), specific heat(J/kgK), tube outer diameter(m) and tube length(m), respectively.

Here, the $T_{surface}$ is outer surface temperature of a tube and calculated by applying conduction equation as follows,

$$T_{surface} = T_{s,2} + \frac{\ln(R/r_2)}{\ln(r_2/r_1)}(T_{s,2} - T_{s,1}) \tag{3}$$

The average HTC of bundle is calculated by simple arithmetic averaging of those of 12 tubes as follows,

$$h_{bundle} = \frac{h_{tube,1} + h_{tube,2} + \cdots + h_{tube,11} + h_{tube,12}}{12} \tag{4}$$

The air mass fraction is one of the significant parameters affecting condensation rate of the tube bundle. In the present study, the air mass fraction is estimated from the pressure and temperature inside of containment simulator with assumption of saturated steam condition. That is, the air pressure is determined as difference between the total vessel pressure and the steam partial pressure as follow,

$$W = \frac{\rho_{air}}{\rho_{air} + \rho_{steam}(T_{vessel,sat})} \tag{5}$$

3. Experimental results

3.1 Single tube experiments

Condensation experiments on the single tube were carried out for understanding of characteristics of experimental apparatus before bundle experiments. For the pressures of 1.0 and 2.0 bar, the air mass fraction and wall sub-cooling are varied to examine their individual effects. The coolant was preheated at 50, 60 and 70°C for various wall sub-cooling conditions.

The experimental data of the heat transfer on the outside surface of single tube were compared with the prediction of Dehbi's correlation [6]. Since Dehbi's correlation was developed on the plate condition, a conversion factor is need to compare the experimental data of single tube. According to the method proposed by Dehbi, the Cebeci [7] curvature factor was introduced in the correlation for the application to the tube. The difference between the predictions of modified Dehbi's correlation and the experimental data for a single tube is within ±20%, as shown in Fig.3.

$$h_{Dehbi} = 0.185 D^{2/3} \left(\rho_w + \rho_\infty \right) \left(\frac{\rho_w - \rho_\infty}{\mu} \right)^{1/3} \times \frac{h_{fg}}{\left(T_\infty - T_w \right)} \ln \left(\frac{1 - W_{s,w}}{1 - W_{s,\infty}} \right) \tag{6}$$

$$f_{Cebeci} = 1 + 0.3 \left(\sqrt{32} Gr^{-1/4} \frac{L}{d} \right)^{0.909} \tag{7}$$

$$h_{Dehbi,tube} = h_{Dehbi,plate} \times f_{Cebeci} \tag{8}$$

where D, ρ, μ, h_{fg}, W, Gr are diffusion coefficient (cm^2/s), density(kg/m^3), viscosity coefficient(Ns/m^2), latent energy(kJ/kg), air mass fraction and Grashof number.

3.2 Bundle experiments

In bundle experiments, the pressure range covered from 1.5 bar to 4.0 bar. Additionally, the air mass fraction was varied to examine its effect at a given pressure condition. In the experiments, the coolant was preheated to a predetermined temperature 70°C in all cases.

Fig.4 shows the distribution of heat transfer coefficient on the bundle array. The HTC of outside region has higher than that of center. This is because the

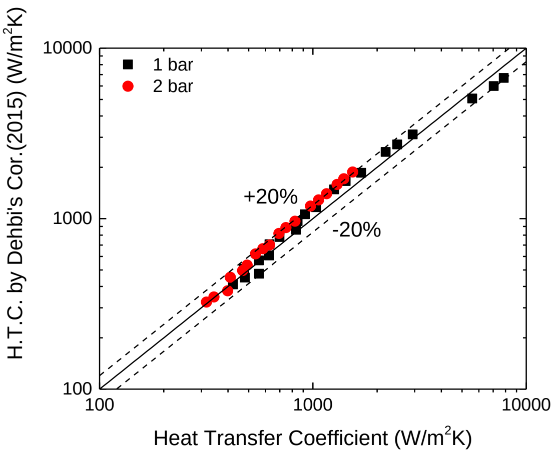

Fig. 3 Comparison of measured condensation heat transfer coefficients with results obtained using the Dehbi correlation

diffusion of gas mixture is activated by suction effect in case of bundle array. The steam of gas mixture mainly condenses on outside tubes. Also, the air is concentrated in middle of bundle and the screening effect occurs. Therefore, the performance of heat transfer of outside tubes is improved. From this reason, there is a little difference between HTC of single tube and bundle array in Fig.5.

The Fig.6 is the comparison results of experimental data with modified Dehbi's correlation. The correlation over-predicts the experimental data within 25%.

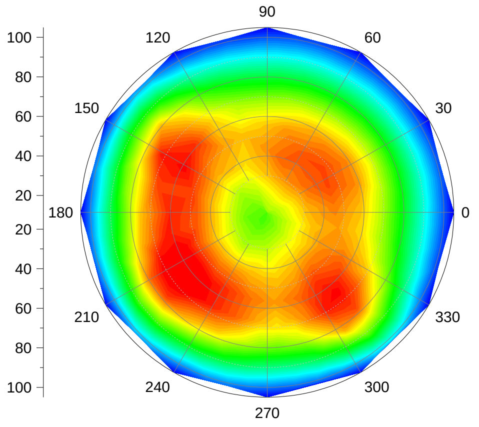

Fig. 4 Distribution of heat transfer coefficient in bundle

3.3 Bundle factor correlation

The bundle factor correlation was proposed for the correction of the deviation between experimental data and modified Dehbi's correlation, as follows:

$$f_{bundle} = \left(1.316 \left(\frac{P}{P_{cr}} \right)^{0.07} \left(\frac{T_{bulk} - T_w}{T_{cr}} \right)^{-0.0145} - 11 \frac{P}{P_{cr}} \right) \times \left(1.08W^2 - 0.945W + 1.12 \right) \quad (8)$$

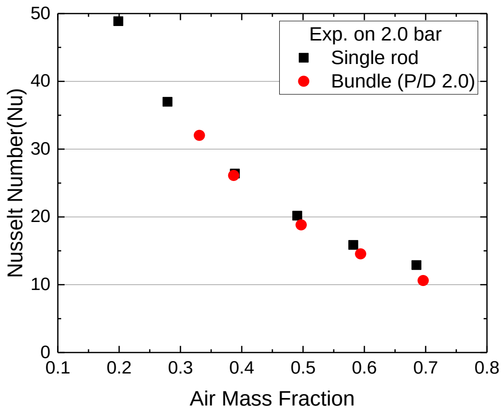

Fig. 5 Comparison of Nusselt number of experimental data on the bundle with one of data on the single tube

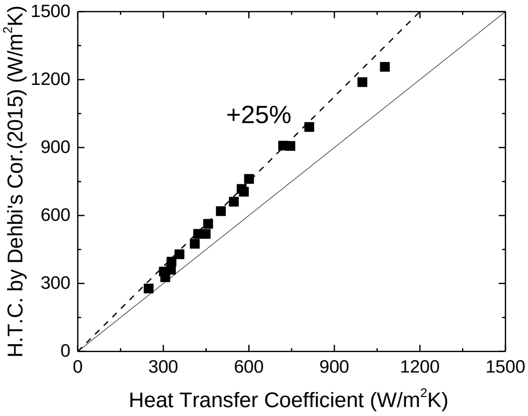

Fig. 6 Comparison of bundle condensation heat transfer coefficients with results obtained using the Dehbi correlation

$$h_{bundle} = h_{Dehbi,tube} \times f_{bundle} \quad (9)$$

The scope of application of Eq.(8) is as follows:

$0.3 \leq W \leq 0.8$; $12 \leq T_{bulk} - T_w \leq 33$℃; $1.5 \leq P \leq 4.0$ bar

The Fig.7 is the comparison results of HTC between a proposed bundle condensation correlation and experimental data. The proposed correlation predicted well within ±4%.

The bundle factor correlation is a quadratic function for the air mass fraction. This explains that the performance of heat transfer on the bundle is increased on low value of air mass fraction.

4. Conclusions

Condensation experiments for PCCS were carried out to investigate bundle effect in the various air mass fraction and pressure condition. There is no significant difference of heat transfer coefficients between on the single tube and bundle. It can be explained that the heat transfer performance of outside tubes of a bundle is improved by suction effect while decrease the heat transfer on the surrounded tubes by screening effect. In

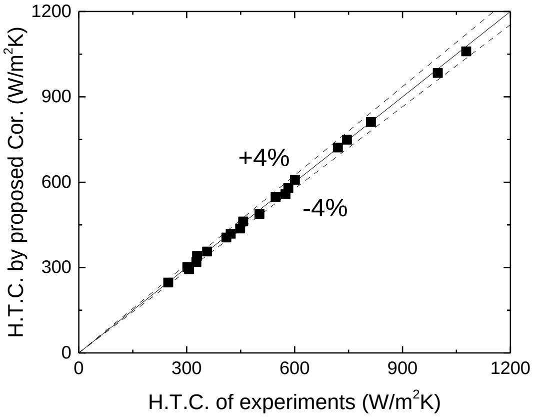

Fig. 7 Comparison of experimental results with results predicted by proposed bundle correlation

the further study, the air fraction effects in bundle will be investigated in detail.

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REFERENCES

[1] H. Uchida, A. Oyama, Y. Togo, Evaluation of post-incident cooling systems of light-water power reactors, in: Proc. Int. Conf. on Peaceful Uses of Atomic Energy, vol. 13, 1965, pp. 93– 102.

[2] A. Dehbi, M.W. Golay, M.S. Kazimi, Condensation experiments in steam– air and steam– air– helium mixtures under turbulent natural convection, in: National Heat Transfer Conf., AIChE, Minneapolis, 1991, pp. 19– 28.

[3] M.H. Anderson, L.H. Herranz, M.L. Corradini, Experimental analysis of heat transfer within the AP600 containment under postulated accident conditions, Nucl. Eng. Des. 185 (1998) 153– 172.

[4] H.-Y. Liu, N.E. Todreas, M.J. Driscoll, An experimental investigation of a passive cooling unit for nuclear plant containment, Nucl. Eng. Des. 199 (2000) 243-255.

[5] Kawakubo, Masahiro, et al. "An Experimental Study on the Cooling Characteristics of passive containment cooling systems." Journal of nuclear science and technology 46.4 (2009): 339-345.

[6] Dehbi, A. "A generalized correlation for steam condensation rates in the presence of air under turbulent free convection." International Journal of Heat and Mass Transfer 86 (2015): 1-15.

[7] R. Cebeci, Laminar free convective heat transfer from the outer surface of a vertical slender circular cylinder, in: Proc. 5th Int. Heat Transfer Conf., vol. 3, Paper NC 1.4, 1974, pp. 15– 19.