Computational Study for the Diameter Effect on Condensation Heat Transfer on Outer Surface of a Heat Exchanger Tube

Chang-Won Lee, Hyoung-Kyu Cho, Goon-Cherl Park*
Dept. of nuclear engineering, Seoul National Univ., 1 Gwanak-ro, Gwanak-gu, Seoul 08826
**Corresponding author: chohk@snu.ac.kr*

1. Introduction

After the Fukushima accident, need for passive system has been arising, and in Korea, PCCS (Passive Containment Cooling System) comprised of heat exchanger tubes were devised for iPOWER (innovative Power Reactor) concept design [1]. To guarantee the cooling performance of the PCCS, the condensation heat transfer needs to be accurately calculated. However, there are no generalized condensation heat transfer coefficient correlations [2] because the new concept system can have various curvature shapes depending on the diameter of the heat exchanger. Thus, the relation between diameter of PCCS heat exchanger and condensation heat transfer coefficient has been investigated in the present study and the heat exchanger design was selected based on the JNU (Jeju National University) experiment [3].

A curvature effect correction factor was derived by Popiel [4] and Dehbi [2] used the parameter when proposing his generalized condensation heat transfer coefficient correlations. However, the correction factor of Popiel is derived for single-phase natural convection heat transfer phenomena [4]. Thus, it should be confirmed if the correlation is applicable to condensation phenomena as there can be differences between the single phase and condensation heat transfers. In this study, the applicability of the Popiel's correlation to the condensation phenomena was investigated with CFD analyses and a preliminary form of the curvature effect correction factor for the condensation phenomena was proposed.

2. CFD analysis

2.1. Reproduction of Popiel's correlation with CFD.

Curvature effect on single-phase heat transfer phenomena was numerically studied by Popiel [4] for a natural convective laminar flow. The proposed heat transfer coefficient ratio of a cylindrical heat exchanger to a flat plate was expressed as follows:

$$\frac{Nu_{cyl}}{Nu_{flat}} = 1 + 0.3 \cdot \left(\sqrt{32} \cdot Gr^{-\frac{1}{4}} \frac{L}{D}\right)^{0.909} \quad (1)$$

where L is height of the heat exchanger and D is diameter of the heat exchanger. For the reproduction of Popiel's correlation with STAR-CCM+, a single-phase heat transfer simulation was conducted. As described in Fig.1, the diameter of the pressure vessel was set according to the conditions of JNU experimental facility. For simulations of the cylinder heat exchanger, computational domain made up of 1/12 symmetry volume for the air-steam gas mixture was used. For the investigation of curvature effect, the simulations were conducted varying the diameter of the heat exchanger from 10 mm to 40 mm. And the rectangular channel for simulating the plate heat exchanger has the same cross-sectional flow area as the cylinder heat exchanger. Fig. 2 shows comparison of the curvature effect parameters which was predicted by the Popiel's correlation and calculated by the CFD code. The curvature effect parameter is defined as the relative difference between Nu of the cylindrical heat exchanger and that of the flat plate heat exchanger as follows.

$$curvature\ effect\ prarameter = \frac{|Nu_{cyl} - Nu_{flat}|}{Nu_{flat}} \quad (2)$$

As plotted in Fig.2, with the computational domain, the CFD calculation results of the single-phase heat transfer phenomena show good agreement with Popiel's correlation and it was successfully reproduced using the present CFD model.

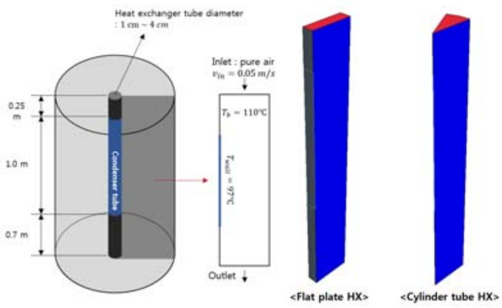

Fig. 1. Schematics of concept geometry and computational domain

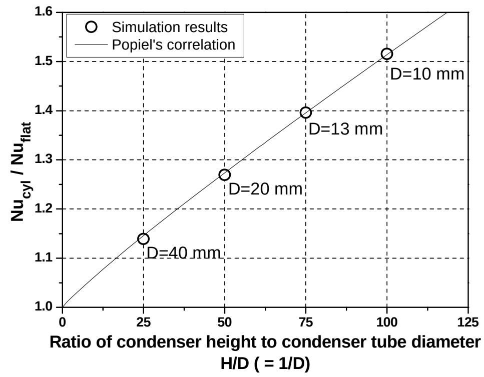

Fig. 2. Comparison of curvature effect parameter between CFD and the correlation by Popiel

Table. 1. Conditions of condensation CFD simulations

Pressure (bar)	Wall temp. (℃)	Bulk temp. (℃)	Gr
4	97	110	2.22E+10
4	97	120	3.83E+10
4	97	130	5.36E+10
4	80	130	8.47E+10
4	70	110	7.48E+10
3	70	130	5.84E+10
3	70	120	5.08E+10
3	70	110	4.26E+10
3	70	100	3.35E+10
2	80	110	1.41E+10
2	80	100	9.83E+09
2	70	110	1.97E+10
2	70	90	1.07E+10
2	70	80	5.63E+09
2	60	100	2.15E+10

2.2. Curvature effect on condensation phenomena.

The similar analysis was repeated using the same computational domain. But, for condensation simulations, the condensation model with the fluid liquid film model [5] was applied for the STAR-CCM+. The fluid film model is the model which can handle a thin liquid film on a wall and it has been validated against the condensation heat transfer experiment such as COPAIN experiments by Lee et al. [6].

The inlet temperature of the steam-air mixture is at the saturation temperature. The condenser wall temperature was set constantly to 97 °C while various bulk temperatures were imposed depending on cases. The simulation conditions are listed in Table 1. Meshes were similar to that of the previous sections and y+ was maintained smaller than 1 for whole computational domain.

As presented in Fig. 3, Popiel’s correlation overestimates curvature effect by 20% approximately. If the diameter of the heat exchanger is large, the ratio of the area of the wall to the volume of the surrounding air is small, so that the temperature boundary layer becomes thick. Thus, when the diameter is large, the temperature gradient and the heat flux is relatively small. However, in the condensation phenomena, due to the radial velocity as presented in Fig. 4, the boundary layer is thinner than that of the single-phase heat transfer phenomena and has a large temperature gradient. Therefore, in the condensation heat transfer phenomena, the relative change of the temperature gradient along the diameter is smaller than that in the single-phase heat transfer phenomena.

And the over-prediction increases with the gas mixture bulk temperature. If the bulk temperature increases, the density difference of the mixture between the bulk and the interface becomes larger and accordingly, the downward velocity becomes more accelerated. Since that, as seen in Fig. 4, the suction toward wall occurs and then, relatively high velocity towards the condenser wall appears in condensation phenomena. Hence, as bulk temperature increases, the difference from the single phase phenomena increases in condensation conditions.

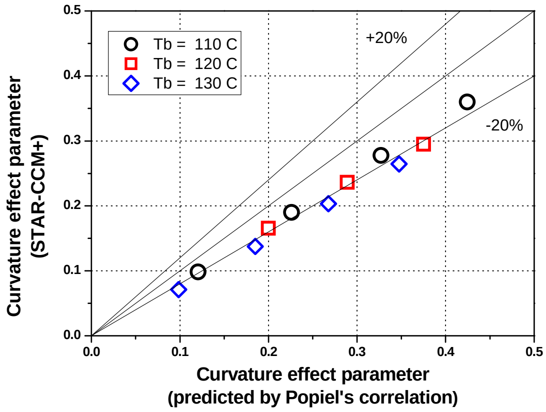

Fig. 3. Comparison of curvature effect parameter between the correlation and CFD

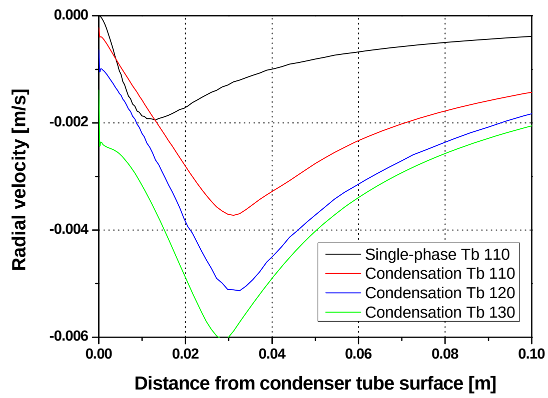

Fig. 4. Radial velocity profile at the lower end of condenser wall

2.3. Curvature effect correction factor for condensation phenomena.

The curvature effect on the heat transfer phenomena in the condensation condition has different trend from that in the single-phase condition. Therefore, for the curvature correction factor, condensation parameter needs be considered. As discussed in the previous section, large density difference of the mixture between the bulk and the interface leads to the curvature effect decreases. Therefore, Bird correction factor [7], which is widely used to consider the suction effect, was applied to the factor modification. Bird correction factor, θ_B, is the suction correction factor by considering the vigor of condensation as follows:

$$\theta_B = \frac{ln(1+B)}{B} \tag{2}$$

In the above, the so-called Bird suction parameter, B, is defined as follows:

$$B \equiv \frac{W_{s,i}-W_{s,\infty}}{1-W_{s,i}} \quad (3)$$

Based on the Popiel equation, the curvature effect parameter considering the condensation phenomena is fitted as follows:

$$\frac{Nu_{cyl}-Nu_{flat}}{Nu_{flat}} = 2.35 \cdot \theta^{-0.259} Gr^{-0.266} \left(\frac{H}{D}\right)^{0.94} \quad (4)$$

Fig. 5 shows a comparison of calculation results between CFD analysis and Popiel's correlations. The average difference between the correlation of Popiel and CFD results is about 20% and the standard deviation is approximately 7%. The comparing results of the predicted curvature effect parameters between the CFD analysis and the modified model are plotted in Fig. 6. The modified correction factor removes the bias of the original parameter and shows better prediction. In addition, the modified correction factor reduces the standard deviation by 3% as the Bird correction factor is applied.

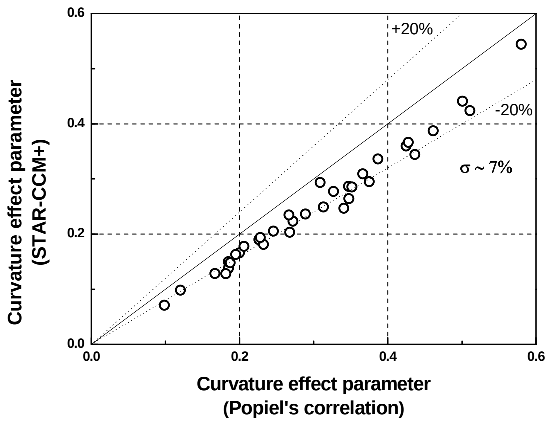

Fig. 5. Comparison of curvature effect parameter between the Popiel's correlation and CFD

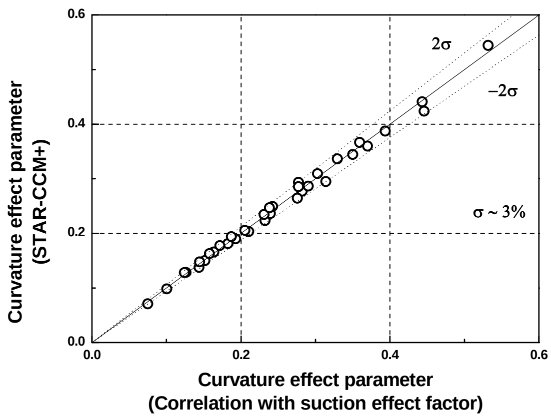

Fig. 6. Comparison of curvature effect parameter between the modified correction factor and CFD

3. Conclusion

In this study, the condensation phenomena simulations were performed to derive the curvature effect correction factor applicable to the condensation phenomena. Based on the CFD analysis results, Bird correction factor was selected as a parameter for condensation phenomena. The fitting equation was introduced which shows good agreement with CFD results. The modified correlation can be expected to be applicable as a curvature effect correction factor when deriving generalized condensation heat transfer coefficient correlations. For the further works, as validation of modified curvature effect correction factor, quantitative comparison between the modified curvature effect correction factor and the experimental results of curvature effect on condensation [3] will be conducted.

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