A Preliminary Study of Transverse Curvature Effects on Condensation Heat Transfer on Vertical Tube in the Presence of Non-condensable Gas

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1. Introduction

The Passive Containment Cooling System (PCCS) provides passive means to remove the decay heat and protect the integrity of the containment during severe accidents. Korea, in which all the NPPs employ the concrete containment, may adopt a PCCS using internal condensers. In the event of the loss-of-coolant accident (LOCA), steam released from the reactor coolant system is mixed with air inside the containment and condensed on the outer surface of inclined condenser tubes. It is noted that, among previous theoretical and empirical models for condensation on outer wall in the presence of non-condensable gas, no one took into account the effect of a tube diameter. Though the condensation heat transfer coefficient may vary with transverse curvature of condenser tubes, such a curvature effect has not been reported so far. In this study, a preliminary analysis is conducted to calculate the variation in the heat transfer coefficient (HTC) according to the tube diameter based on the study of Cebeci [1]. By applying results of the boundary layer analysis, the transverse curvature effect is predicted.

2. Boundary Layer Analysis of Cebeci

Cebeci obtained solutions to governing equations for free-convective heat transfer on a vertical cylinder and predicted the deviation of the average Nusselt number from that of a flat plate as a result [1]. The governing boundary layer equations for axisymmetric laminar flow are as following:

$$\frac{\partial}{\partial x}(ru)+\frac{\partial}{\partial y}(rv)=0 \qquad (1)$$

$$u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}=g\beta(T-T_\infty)+\frac{\nu}{r}\frac{\partial}{\partial y}\left(r\frac{\partial u}{\partial y}\right) \qquad (2)$$

$$u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}=\frac{\alpha}{r}\frac{\partial}{\partial y}\left(r\frac{\partial T}{\partial y}\right) \qquad (3)$$

By introducing a dimensionless stream function and a similarity parameter, the three dimensionless boundary layer equations are reduced to two ordinary differential equations as:

$$\left(bf''\right)'+3ff''-2\left(f'\right)^2+\frac{T^*}{(\overline{r}_o)^2} = 4x^*\left(f'\frac{\partial f'}{\partial x^*}-f''\frac{\partial f}{\partial x^*}\right) \qquad (4)$$

$$\left(cT^{*\prime}\right)'+3fT^{*\prime}=4x^*\left(f'\frac{\partial T^*}{\partial x^*}-T^{*\prime}\frac{\partial f}{\partial x^*}\right) \qquad (5)$$

See [1] to check the detailed form of b and c, which are expressed in terms of the transverse curvature parameter as:

$$\xi=\frac{2\sqrt{2}}{Gr_x^{1/4}}\left(\frac{x}{r_o}\right) \qquad (6)$$

where r_o denotes the outer radius of a tube. Then the numerical solution for free convection boundary layer equations can be obtained. Cebeci finally derived the expression for the average Nusselt number of a cylinder from that of a flat plate as following:

$$\frac{\overline{Nu}_{x\,cyl}}{\overline{Nu}_{x\,F.P.}}=3\int_0^{\xi}\left[\frac{T_w^{*\prime}(\xi)}{T_w^{*\prime}(0)}\right]\xi^2 d\xi \Big/ \xi^3 \qquad (7)$$

Figure 1 shows calculation results for various values of Prandtl number. At fixed temperature conditions, it is the effective channel length and the outer diameter that determines the parameter ξ. The results indicate that the HTC increases with a decrease of the tube diameter, especially when Pr is low.

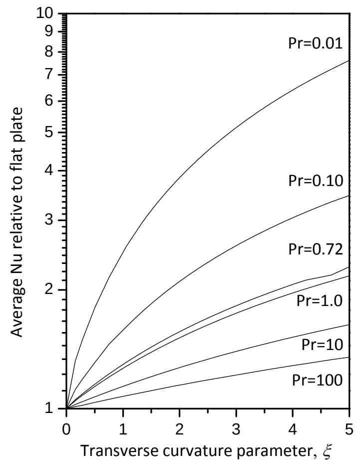

Fig. 1. Average Nu normalized to that of flat plate

3. Application to Condensation

The analysis results of free convective boundary layer equations are applied to predict the variation of the condensation HTC in the presence of a non-condensable gas. The variation of HTC with the tube diameter is obtained at containment condition when the atmospheric air is mixed with steam to reach the design pressure, 4 bar. The temperature difference between the mixture and the wall is set to 35 K.

To calculate the average Nu on a vertical tube using numerical results, one needs the HTC for a flat plate; however, the experimental data for the condensation on a flat plate in the presence of a non-condensable gas is rarely found. Thus, in this study, Nu for a flat plate under the above conditions is indirectly estimated from the HTC correlation by Dehbi [2]. That is, by using the deviation ratio and the HTC for a vertical tube of 38 mm in O.D., Nu for a flat plate is calculated. Then the HTC versus the tube diameter is predicted for given Pr.

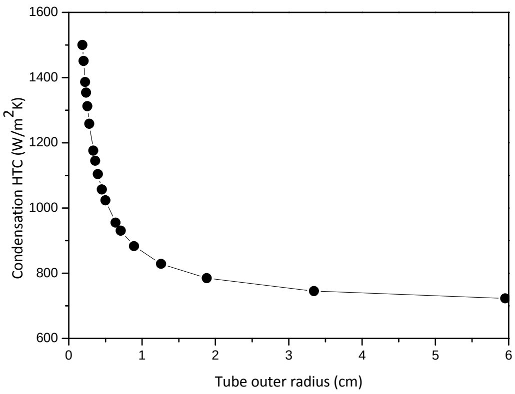

Fig. 2. Curvature effect on condensation HTC

The variation of the condensation HTC with the tube outer radius is plotted in Fig. 2. Calculation results reveal that the heat transfer performance is enhanced as the curvature of condenser tubes is large. When the tube outer radius is 2.24 mm, the HTC is twice that of a flat plate. It is noted that the change of HTC is remarkable as the tube diameter becomes less than 4 cm.

The above calculation is based on the assumption that the laminar free convection boundary layer analysis is also valid to the condensation heat transfer in the presence of air. However, the heat transfer mechanism of the condensation of a steam-air mixture is different from that of a free convective flow. It is accompanied by the phase change, and mathematically described by two interacting boundary layers for the condensate film and the diffusion layer of a steam-air mixture [3]. The quantitative HTC for real condensation heat transfer may differ from the prediction results of this study. Nevertheless, one can gain a qualitative insight that the condensation heat transfer of a steam-air mixture on a vertical tube can be considerably influenced by the transverse curvature of the tube. If this curvature effect is demonstrated through the experiment, it is expected that the outer diameter of condenser tubes will become a crucial parameter in optimizing the design of the PCCS under development.

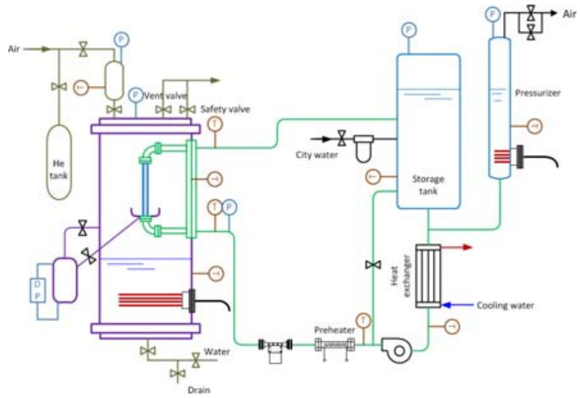

Fig. 3. Schematics of condensation test facility to be constructed in JNU

4. Conclusions

In this study, the effect of the transverse curvature on the condensation HTC on a vertical tube in the presence of air is preliminarily investigated by using the analysis of boundary layer for free convective heat transfer. The results indicate that the heat transfer performance can be enhanced as the outer diameter of condenser tubes is small. To confirm this curvature effect, an experimental program to obtain the condensation heat transfer data for various values of tube diameter is indispensible.

Currently, by a joint research project of Jeju National University and Chung-Ang University, a condensation test facility is being designed and constructed to acquire the condensation HTC data as shown in Fig. 3. From a series of experiment on a single vertical tube, the effects of not only the tube diameter but the inclination, the existence of fins and the local velocity of a bulk mixture by natural circulation will be evaluated precisely. An empirical correlation for the condensation heat transfer of a steam-air mixture will also be developed for design optimization and performance evaluation of the PCCS.

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