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Wide pressure range condensation modeling on pure steam/steam-air mixture inside vertical tube

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ABSTRACT

The elimination of active systems and their replacement with passive systems are emphasized to improve a system reliability in advanced nuclear power plants such as SMART. For accident situations, a condensate heat exchanger having vertical tubes is an ultimate heat sink to remove residual heat generated in the core. To adequately analyze the system behaviors, a realistic condensation model with pure steam or a steam-air mixture in the condensate heat exchanger is important for the various thermal hydraulic conditions.

Improved correlations are proposed to analyze the thermal hydraulic behaviors for wide pressure conditions of up to 6 MPa. For a validation of the condensation heat transfer for the condensate heat exchanger tube side, simulations of the UCB (University of California at Berkeley) and POSTECH (Pohang University of Science and Technology) condensation experiment are carried out, and the results are compared with the experimental data. For pure steam conditions, the correlations predict well or underpredict slightly the UCB experimental results and predict the POSTECH experimental results within 25%. The improved correlation predicts that the condensation heat transfer coefficient decreases as the system pressure increases as shown the POSTECH experiment.

1. Introduction

In advanced nuclear power plants, an elimination of active systems and their replacement with passive systems are emphasized to enhance the reliability of the systems after the Fukushima-Daiichi accident. In 100 MWe SMART (System-Integrated Modular Advanced ReacTor) designed by KAERI, many passive features are adopted (Kim et al., 2014). Under an emergency condition, the reactor coolant system (RCS) and the passive residual heat removal system (PRHRS) are naturally circulated by gravity force. The passive residual heat removal system is an ultimate heat sink in the SMART reactor and removes residual heat generated in the core through a condensate heat exchanger. The condensate heat exchanger having a vertical tube bundle is submerged in an emergency cooldown tank filled with water. To adequately analyze the system behaviors including a decay heat removal capability, an optimistic condensation model with pure steam or a steam-air mixture at the condensate heat exchanger is important under the various thermal hydraulic conditions.

The condensation heat transfer phenomenon depends on the geometry type, fluid property, and dynamic conditions. A typical geometry is a vertical, horizontal, or slightly horizontal shape with the tube and shell type. Because the condensate heat exchanger in the SMART plant has a vertical tube type, condensation phenomenon at the vertical tube is focused on this study, although there are many results of achievement for horizontal tubes (Schaffrath et al., 2001; Kim et al., 2013; Caruso et al., 2013; Jeon et al., 2015). Nusselt proposed an analytical solution for laminar condensation of a saturated vapor on an isothermal vertical plate neglecting the effects of interfacial waves and the heat capacity of the fluid (Collier, 1972). This simple model has good prediction results for very thin films of non-metallic fluids such as water. Many authors have extended the condensation phenomena using an analytical or experimental method. Vierow and Schrock (1991) conducted an experiment consisting of an inner diameter of 22 mm and a height of 2.1 m at 0.03 to 0.45 MPa, respectively. They found the effect of non-condensable gas on condensation heat transfer at a high non-condensable gas fraction. Siddique et al. (1993) performed an experiment of steam and air/helium mixture condensation with a height of 2.54 m and an inner diameter of 46 mm at 0.1 to 0.5 MPa to identify a non-condensable gas effect for the condensation. They developed a non-dimensional correlation used Nusselt number, which was correlated by the

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mixture Reynolds number and non-condensable gas mass fraction. A theoretical study of film-wise, annular condensation of a saturated vapor in a turbulent forced flow through a vertical tube was conducted to find the effects of interfacial shear stress on the heat transfer (Chen and Ke, 1993). The interfacial shear stress due to vapor flow has a significant effect on the condensation heat transfer and pressure gradient. A steam condensation experiment with air or helium was performed at a height of 2.4 m and an inner diameter of 47.5 mm at 0.1 to 0.5 MPa, and new correlations were developed using the degradation factor, diffusion layer, and mass transfer conductance modeling (Kuhn et al., 1997). Steam condensation experiments in submerged pool water was performed to complete the condensation (Oh and Revankar, 2006). The tube geometry has a height of 2.4 m and an inner diameter of 26 mm at 0.1 to 0.4 MPa. The condensation heat transfer decreased as the system pressure increased. An experimental study was performed to investigate the local condensation heat transfer coefficients for a small-diameter vertical tube in the presence of non-condensable gas at 0.1 to 0.13 MPa (Lee and Kim, 2008). A new correlation based on dimensionless shear and non-condensable mass fraction variables was developed to calculate the condensation heat transfer with non-condensable gas.

Based on an empirical approach, Shah (1979) generated a correlation as a best curve fit to the available convective condensation heat transfer data for a wide range. Ghiaasiaan et al. (1995) conducted a quasi-steady state correlation of condensation with the non-condensable gas using the two-fluid model. The effect of non-condensable on the heat and mass transfer was accounted by using the stagnant film theory. The developed correlation was compared with the experimental data of Vierow and Schrock (1991) and Siddique et al. (1993). Hassan and Banerjee (1996) developed a correlation to simulate the interface temperature for the steam and non-condensable gas. The degradation factor was proposed and implemented into the RELAP5/MOD3, which was a widely used computer code for the system analysis of a nuclear reactor. In addition, a physical model to calculate the condensation heat transfer coefficient in a vertical condenser tube considering the effects of gravity, liquid viscosity, and vapor flow in the core region of the flow was proposed (Kim et al., 2011).

Most correlations for the condensation were developed at atmospheric or relatively lower pressure conditions as described in the literature review. However, the condensate heat exchanger at the SMART plant is operated under the high pressure condition of 2.0 to 6.0 MPa. In order to apply the condensate heat exchanger at the SMART plant, it is necessary to develop an improved correlation that is appropriate for high pressure conditions. The objective of the present work is to develop a new condensation correlation with pure steam or a steam/non-condensable gas mixture for a high pressure range and demonstrate its agreement with the experimental results.

2. Heat transfer correlations for a condensate heat exchanger

A thermal hydraulic analysis code, TASS/SMR, was developed to apply an analysis of the SMART plant (Chung et al., 2015a). The governing equations were the mixture mass, steam mass, mixture energy, steam energy, and mixture momentum. Various physical models reflecting the design features of the SMART plant were incorporated in the code. One of them is a condensation heat transfer model at the vertical tube inside of the condensate heat exchanger. A schematic diagram of the heat transfer module for the condensate heat exchanger was described by Jun et al. (2014). Condensation heat transfer correlation was initially adopted Nusselt (Collier, 1972) and Shah correlation (Shah, 1979) in the TASS/SMR code.

$$h_{Nusselt} = \frac{k_l}{0.9086}\left(\frac{\mu_f^2 \mathrm{Re}_f}{g\rho_f \Delta\rho}\right)^{-1/3} \tag{1}$$

$$h_{Shah} = 0.023\left(\frac{k_l}{D_h}\right)\mathrm{Re}_l^{0.8}\,\mathrm{Pr}_l^{0.4}(1-x)^{0.8}\left(1+\frac{3.8}{Z^{0.95}}\right) \tag{2}$$

Here Re, Pr, and Z denote the Reynolds number, Prandtl number, and correlating parameter for condensation heat transfer, respectively. This correlation was reasonably predicted for the steam condensation under various tube sizes and thermal properties at the lower pressure condition for the compared experimental data, but was limited to predict the influence of non-condensable gas in steam (Shah, 1979).

The condensation correlation in the TASS/SMR code was modified to better predict the condensation heat transfer with pure steam and a steam-gas mixture under thermal hydraulic conditions including high pressure condition for the operation range of the SMART condensate heat exchanger. The new correlations used are as follows:

$$h_{Modified-Lee} = 1.03 \cdot \tau_g^{0.15} \cdot h_{Nusselt} \tag{3}$$

$$\begin{gathered} \tau_g = \frac{\frac{1}{2}\rho_g u_g^2 f_R}{g\rho_f L} \\ L = (\nu_f^2/g)^{1/3}, \quad f_R = \begin{cases} 0.079\,\mathrm{Re}_g^{-1/4} & \text{for Re} > 2300 \\ 16/\mathrm{Re}_g & \text{for Re} > 2300 \end{cases} \end{gathered} \tag{4}$$

$$h_{KSP} = f_1 \cdot f_2 \cdot h_{Nusselt} \tag{5}$$

$$\begin{aligned} f_1 &= f_{1shear} \times f_{1\mathrm{other}} \\ f_{1shear} &= \delta_f/\delta_{f,o} \\ f_{1\mathrm{other}} &= 1 + 7.32 \times 10^{-4}\,\mathrm{Re}_f \\ f_2 &= \begin{cases} 1 - 2.601 W_{nc}^{0.708} & \text{for } W_{nc} < 0.1 \\ 1 - W_{nc}^{0.292} & \text{for } W_{nc} > 0.1 \end{cases} \end{aligned} \tag{6}$$

Here τ_g and $h_{Nusselt}$ in Eq. (3) denote a dimensionless shear stress that is function of the characteristic length scale (L), degradation factor for pure steam (f_R), and a condensation heat transfer coefficient calculate by Nusselt solution. The coefficients in Eq. (3) are adjusted from the original values proposed by Lee and Kim (2008) using experimental data performed at the high pressure conditions (Yang, 2011; Lee and Kim, 2008). To consider the non-condensable gas effect, the degradation factor proposed by Kuhn et al. (1997) is implemented in the TASS/SMR code. Here, f_1 in Eq. (5) denotes a correlation factor for pure steam, which is a function of the film thickness and Reynolds number, and f_2 represents a factor for a non-condensable gas effect, which is a function of the non-condensable gas mass. δ_f and $\delta_{f,o}$ in Eq. (6) represent the film thickness without and with interfacial shear stress, respectively (Kuhn, 1995). In this work, improvement and validation of the condensation correlation at the vertical tube inside are focused upon because the validation of the heat transfer model for the bundle side was carried out using the experimental data performed by POSTECH and the IIT (Indian Institute of Technology) experimental data (Chung et al., 2015b).

3. Validation of the proposed correlation

3.1. Experimental data for validation

For validation of the condensation heat transfer at the condensate heat exchanger tube side, simulations of the UCB (University of California at Berkeley) and POSTECH condensation experiment