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Droplet entrainment and deposition rates in a horizontal annular flow for SPACE code

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ABSTRACT

Correlations for the droplet entrainment and deposition rates were developed to accurately predict its behavior in a horizontal annular flow. The Lopez de Bertodano et al. droplet entrainment rate correlation was evaluated and then modified based on the experimental data for both vertical and horizontal annular flows. In addition to this, a new droplet deposition coefficient correlation was proposed for a droplet deposition rate. The droplet deposition coefficient is represented by a function of dimensionless parameters considering the effects of the gas and liquid superficial velocities and the pipe inner diameter. Finally, the SPACE code was assessed against various experimental data for droplet mass flow rate of horizontal annular flows obtained from the open literature. The improved SPACE code showed better prediction capability for the droplet behavior in the horizontal annular flow than the original one.

1. Introduction

In a horizontal annular flow, high-velocity gas flows in the pipe core with accompanying liquid droplets, and a continuous liquid flows along the pipe inner wall (see Fig. 1). In this condition, droplets are not only generated from the interfacial wave in the continuous liquid but also deposit to the continuous liquid (Bae et al., 2017). These droplets play an important role for the mass and heat transfer processes in an annular flow. The amount of droplets is determined by the balance of their entrainment and deposition in the flow channel.

The Safety and Performance Analysis Code (SPACE) for an analysis of nuclear reactor safety being developed in Korea adopts two-fluid three-field models, comprising gas, continuous liquid, and droplet fields, for accurate analysis of droplet behavior (Ha et al., 2011). The governing equations for a continuous liquid and a droplet of the SPACE code requires constitutive models for droplet entrainment and deposition rates. However, models for droplet entrainment and deposition rates have not been extensively developed. It is caused by the fact that it is difficult to measure separately the droplet entrainment rate and droplet deposition rate because the phenomena of droplet entrainment and deposition occur at the same time in the flow channel.

Sugawara (1990) proposed new droplet entrainment and deposition rate models to accurately predict 'dry-out' phenomena in a reactor fuel rod. A validation program of the proposed models was conducted with air-water and adiabatic steam-water data of a vertical annular flow using the FIDAS code, which uses three field models. The FIDAS code incorporated with the models had a good capability to predict the behavior of an annular flow. Stevanovic and Studovic (1995) studied droplet entrainment of a developing annular flow in a vertical pipe to understand the droplet behavior inside U-tubes in a steam generator under a postulated SBLOCA (Small Break Loss of Coolant Accident). They applied four correlations for the droplet entrainment rate and droplet deposition rate, respectively, to the STRAP code and tested them against the Hewitt (1987) experiment with a 31.75 mm pipe diameter. The combination of an empirical correlation (Saito et al., 1978) based on Hutchinson and Whalley data for the droplet entrainment rate and a constant droplet deposition coefficient (Saito et al., 1978), for the droplet deposition rate provided the best results. Lee and No (2007) utilized a three-field TRAC-M/F90 code to predict droplet entrainment with optional choosing of the Kataoka et al. (2000) or Würtz (1978) droplet entrainment and deposition rate models in a vertical annular-mist flow. They showed that the Würtz (1978) model accurately predicted the steam-water data of a high-pressure condition up to 9 MPa, but scattering relative to the experimental data was observed in the low-pressure condition. Whereas, the Kataoka et al. (2000) model showed satisfactory agreement with the experimental data in the low-pressure air-water flow and porous-sinter inlet of the test section condition. As in the above cases, most studies on droplet

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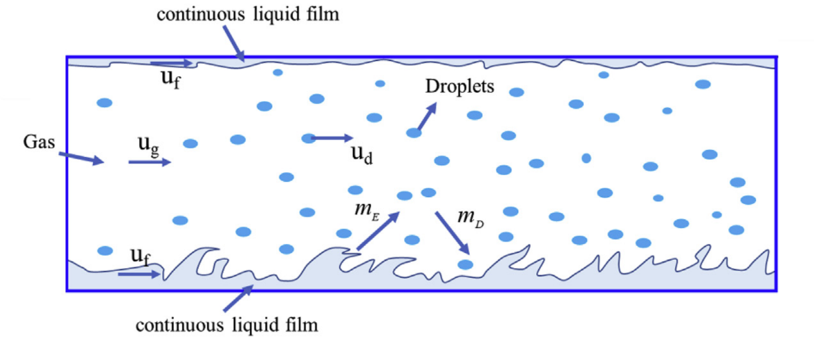

Fig. 1. Schematic of droplet entrainment and deposition in a horizontal annular flow.

entrainment have been mainly performed in a vertical annular flow because of its importance for fuel rods in the reactor core or U tubes in the steam generator in nuclear power plants. However, the development of droplet entrainment and deposition rate models for a horizontal annular flow has been relatively limited.

The SPACE code (2016) adopts the Lopez de Bertodano et al. (1997) droplet entrainment rate correlation for both vertical and horizontal annular flow conditions although this correlation was developed based on experimental data of a vertical annular flow. The rationale for this is that the droplet entrainment behavior of the horizontal annular flow is expected to be similar to that of the vertical annular flow under a high gas velocity condition. In fact, however, the liquid film thickness at the bottom of the pipe in the case of a horizontal flow is thicker than that at the top of the pipe due to a gravity effect. As a result, the droplet distribution in a horizontal flow is also asymmetric. Thus, the Lopez de Bertodano et al. (1997) droplet entrainment rate correlation needs to be evaluated for the experimental data of a horizontal annular flow. As the droplet deposition rate model of the SPACE code, the McCoy and Hanratty (1977) correlation is used for both vertical and horizontal annular flows. However, since this correlation was developed with experimental data using an injection method of mono-dispersed droplets in a vertical upward and downward flow, it is also not suitable originally for the phenomena of deposition for poly-dispersed droplets in a horizontal annular flow.

The main purpose of this study is to evaluate and develop droplet entrainment and deposition rate correlations applicable to a horizontal annular flow for the SPACE code. We then apply the proposed droplet entrainment and deposition rate correlations to the SPACE code. Finally, a code assessment is performed against the droplet mass flow rate data of the horizontal annular flow over a wide range of flow conditions to validate the combined use of new droplet entrainment and deposition rate correlations.

2. The SPACE code

The SPACE code is a transient analysis code being developed in Korea to simulate thermal hydraulic phenomena in pressurized water reactor (PWR) nuclear power plants (Ha et al., 2011). This code treats two-fluid three-field equations, and uses a total of 10 governing equations for mass, momentum, and energy for the vapor, continuous liquid, and droplet, respectively, including mass conservation of non-condensable gas. The time and space averaged one dimensional transient governing equations are summarized in Table 1. The gas field is assumed to be a homogeneous equilibrium mixture of vapor and non-condensable gas. Dividing the liquid phase into the continuous liquid and droplet is physically reasonable way where the liquid can be appeared in both liquid film and droplet forms because thermal and hydraulic behavior of droplets are different from that of liquid film. The two liquid fields exchange mass by droplet entrainment and deposition rate, which are denoted by m_E and m_D, respectively.

The 10 governing equations with the volume conservation of Eq. (1) can obtain the following 11 parameters: the three velocities, the three volume fraction, the three temperatures, the total pressure, and the non-condensable gas pressure.

$$\alpha_g + \alpha_l + \alpha_d = 1 \tag{1}$$

2.1. Droplet entrainment and deposition rate models in the SPACE code

The amount of droplets predicted by the SPACE code is determined by the balance of m_E and m_D, which are required as constitutive relations in the governing equations for a continuous liquid and a droplet. At present, the SPACE code uses the same droplet entrainment and deposition rate models for both vertical and horizontal annular flow conditions under an assumption that the droplet behavior of a horizontal annular flow is similar to those of the vertical annular flow at high gas velocity conditions. It is inevitable choice because there are no useful models of droplet entrainment and deposition rate for a horizontal annular flow in the open literature.

As a droplet entrainment rate model, the correlation reported by Lopez de Bertodano et al. (1997) is adopted in the SPACE code. This correlation was developed focusing on the physical mechanism of the ripple growth rate, as delineated in Eq. (2).

$$m_E = k_E \frac{\mu_l}{D_h}\left[We_g\left(\frac{\rho_l-\rho_g}{\rho_g}\right)^{1/2}(\mathrm{Re}_{lf}-\mathrm{Re}_{lfc})\right]^{0.925}\left(\frac{\mu_g}{\mu_l}\right)^{0.26} \tag{2}$$

where $We_g = \frac{\rho_g j_g^2 D_h}{\sigma_l}$, $\mathrm{Re}_{lf} = \mathrm{Re}_l(1-E)$, $\mathrm{Re}_l = \frac{\rho_l j_l D_h}{\mu_l}$, $E = \frac{m_d}{m_l}$, and $\mathrm{Re}_{lfc} = 80$ for a minimum value of the liquid film Reynolds number for droplet generation. Lopez de Bertodano et al. (1997) also proposed $k_E = 4.47 \times 10^{-7}$ based on the experimental data of an air-water vertical annular flow. The experimental data used for the development of the correlation covers the pressure from 140 to 660 kPa, the gas superficial velocity from 24.5 to 126 m/s and the liquid superficial velocity from 0.074 to 0.54 m/s.

Droplet deposition rate, m_D, is expressed as the product of the droplet concentration C and the droplet deposition coefficient k_D as follows,

$$m_D = Ck_D \tag{3}$$

Here, C is formulated as a function of the mass flow rate, velocity, and density of droplet and gas, as follows,

$$C = \frac{m_d}{\frac{m_g}{\rho_g}\frac{v_d}{v_g} + \frac{m_d}{\rho_d}} \tag{4}$$

By employing the assumption that the droplet velocity is similar to the gas velocity and if $\frac{m_g}{\rho_g} >> \frac{m_d}{\rho_d}$ in the denominator of Eq. (4), C can be simply represented as below.

$$C \approx \rho_g \frac{m_d}{m_g} \tag{5}$$