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Semi-empirical correlation for counter-current flow limitation at the upper or lower end of sharp-edged vertical pipes

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ABSTRACT

A semi-empirical correlation for CCFL (counter-current flow limitation) in vertical pipes was derived from one-dimensional momentum equations. Available correlations such as the empirical correlations proposed by Wallis (1969) and Zapke and Kröger (1996) can be deduced from the derived fundamental functional form of the semi-empirical correlation in limiting flow conditions. Comparisons between the semi-empirical correlation with available experimental data of CCFL taking place at the sharp-edged lower end of a vertical pipe showed that the correlation is applicable for various fluid properties and pipe diameters. The fundamental functional form of the correlation was also transformed so as to express the characteristics of CCFL occurring at the sharp-edged upper end of a vertical pipe. The present fundamental functional form of CCFL correlation is useful not only to express CCFL data but also to understand how relevant parameters play their roles in the CCFL characteristics.

1. Introduction

A falling liquid film in a vertical pipe and a gas core flowing upward form a two-phase counter-current annular flow. The liquid supplied into the pipe can entirely fall down when the gas volume flux is small. While keeping the liquid inflow constant, the increase in the gas volume flux results in wavy structure on the gas–liquid interface. Some liquid then begins to flow back toward the liquid-inlet side at a certain gas volume flux due to the fast upward motion of the gas (counter-current flow limitation, CCFL). The liquid and gas volume fluxes at the onset of the upward motion of the liquid phase is referred to as the flooding point and the flooding points form the so-called flooding curve. Further increase in the gas volume flux decreases the flow rate of the falling liquid. The relationship between the gas volume flux and the actual liquid flow rate under CCFL is referred to as the CCFL characteristics.

The practical importance of knowledge on the counter-current two-phase flow, especially in nuclear and chemical engineering, has resulted in a large number of studies on the counter-current two-phase flows in vertical pipes (Wallis, 1969; Wallis and Makkenchery, 1974; Richter, 1981; Bharathan and Wallis, 1983; Govan et al., 1991; Bankoff and Lee, 1986; Jeong and No, 1996; Zapke and Kröger, 1996; Zapke and Kröger, 2000; Zapke and Kröger, 2000; Karimi and Kawaji, 2000; Vijayan et al., 2001; Schmidt et al., 2016) (it should be noted that, in the literature, the onset of flooding and the CCFL characteristics were not clearly distinguished and the location of the flow limitation was rarely reported, and therefore, we should be careful when using the available data). For example, CCFL may take place in the steam generator of a pressurized water reactor (PWR) during a reflux-cooling mode, and therefore, CCFL correlations are required to evaluate the flow rate of liquid flowing into the reactor core. Hence we have been investigating the CCFL characteristics in vertical pipes (Kusunoki et al., 2015; Kusunoki et al., 2016; Murase et al., 2016) and proposed some CCFL correlations (Kusunoki et al., 2015), which account for the effects of the fluid properties on the CCFL characteristics. The correlations were however obtained by a purely empirical manner.

In this study, a semi-empirical correlation for CCFL characteristics in vertical pipes is derived from one-dimensional equations for a counter-current annular two-phase flow in a vertical pipe, and its applicability to several data of CCFL characteristics is discussed.

2. Brief review of CCFL correlations

Wallis (1969) proposed the following CCFL correlation based on several experimental data:

$$J_G^{*1/2} + mJ_L^{*1/2} = C \tag{1}$$

where m and C are the slope and the intercept of the $J_L^{*1/2}$-$J_G^{*1/2}$ diagram, the subscripts G and L denote the gas and liquid phases, respectively,

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and J_k^* are the Froude numbers or the so-called Wallis parameters defined by

$$J_k^* = \frac{J_k}{\sqrt{\frac{\Delta\rho g D}{\rho_k}}} \tag{2}$$

Here J is the volume flux, ρ the density, g the magnitude of the acceleration of gravity, D the pipe diameter, and $\Delta\rho$ the density difference, i.e. $\Delta\rho = \rho_L - \rho_G$, between the liquid and gas phases. This correlation has been widely used in correlating CCFL data in vertical pipes. The m and C depend on the inlet and outlet geometries of a vertical pipe and on the inverse viscosity number, N_L, of the liquid phase defined by

$$N_L = \sqrt{\frac{\rho_L \Delta\rho g D^3}{\mu_L^2}} \tag{3}$$

where μ is the viscosity. Eq. (1) represents the balance between the inertial forces of the gas and liquid phases and the gravitational force. The effects of the liquid viscosity and the surface tension are not accounted for. Wallis (1969) took into account the effects of the liquid viscosity on CCFL by introducing N_L by an empirical manner:

$$J_G^{*1/2} + 5.6\left(\frac{J_L^*}{N_L}\right)^{1/2} = 0.725 \tag{4}$$

He also pointed out that this expression is valid for $N_L < 2$ and the slope and the intercept should be functions of N_L for larger N_L.

Wallis (1969) derived the functional form of Eq. (1) by using an annular flow model (Fig. 1), in which the gas and liquid phases are modeled as the cylindrical gas core and the liquid annulus. By assuming that the flows of the two phases are turbulent and the mixing lengths in each phase are constant, the momentum equations of the two phases reduce to

$$\frac{J_G^{*1/2}}{\alpha_G^n} + \frac{J_L^{*1/2}}{\alpha_L^n} = 1 \tag{5}$$

where α is the volume fraction and $\alpha_G + \alpha_L = 1$. The n is 2.5 if the mixing lengths are scaled by the characteristic length scales of each phase, or $n = 3.5$ if they are scaled by D. Eliminating α_k from this equation yields the following envelope:

$$J_G^{*2/(n+1)} + J_L^{*2/(n+1)} = 1 \tag{6}$$

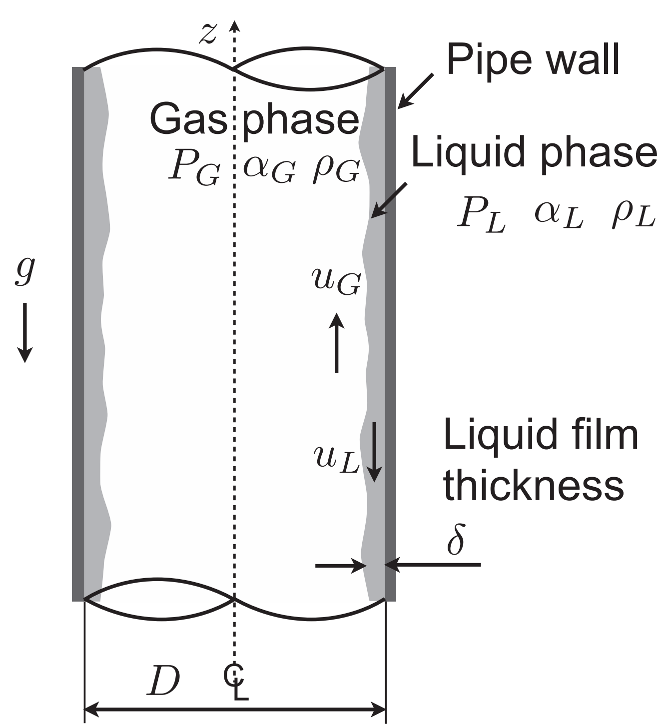

Fig. 1. Annular flow model for counter-current two-phase flow.

If $n = 3$, this equation reduces to Eq. (1) with $m = C = 1$. Bharathan and Wallis (1983) derived the following relation between $J_G^{*1/2}$ and $J_L^{*1/2}$ in terms of α_L and the interfacial friction, f_i, and the wall friction factors, f_W:

$$\left[\frac{2f_i}{(1-\alpha_L)^{5/2}}\right] J_G^{*2} + \left[\frac{2f_W}{\alpha_L^2}\right] J_L^{*2} = \alpha_L \tag{7}$$

The friction factors were given empirically. Since the above equation does not have a simple solution for the Wallis parameters, the envelope was graphically obtained by changing α_L as the parameter. The annular flow model was also applied to the viscous-force-dominant case, Eq. (4) (Wallis, 1969). In this case, the momentum balance reduces to

$$\left(\frac{J_G^{*2}}{\Delta P^*}\right)^{1/n} + \left[\frac{32 J_L^*}{N_L(1-\Delta P^*)}\right]^{1/2} = 1 \tag{8}$$

where ΔP^* is the pressure drop scaled by the buoyancy. The envelope can be obtained parametrically in terms of ΔP^*.

Kusunoki et al. (2015) experimentally investigated the effects of the liquid viscosity on flow limitation at the sharp-edged lower end of a vertical pipe (CCFL-L). In this mode of flow limitation, the liquid flow is limited at the lower end of the pipe and some amount of liquid accumulated there is intermittently brought up by the gas flow (Govan et al., 1991; Kusunoki et al., 2015). The following empirical correlation was proposed to take into account the effects of the gas and liquid viscosities on CCFL-L:

$$\left(\frac{\mu_G}{\mu_L}\right)^{-0.07} J_G^{*1/2} = (1.04 \pm 0.05) - 3.6\Psi + 11\Psi^2 - 16\Psi^3 \tag{9}$$

where

$$\Psi = \left(\frac{\mu_G}{\mu_L}\right)^{0.1} J_L^{*1/2} \tag{10}$$

Zapke and Kröger (1996) investigated the effects of the liquid viscosity and the surface tension σ on CCFL. They showed that their data for various fluid properties can be well correlated by introducing the Ohnesorge number, Oh_L, of the liquid phase into the Wallis-type empirical correlation, i.e.

$$J_G^{*1/2} + J_L^{*1/2} = 0.52 Oh_L^{-0.05} \tag{11}$$

where

$$Oh_L = \sqrt{\frac{\mu_L^2}{\rho_L \sigma D}} \tag{12}$$

The counter-current flow limitation at the sharp-edged upper end of a vertical pipe (CCFL-U) was also investigated in our previous study (Doi et al., 2012). Under CCFL-U, the sharp-edged upper end of the pipe is connected to an upper tank filled with the liquid, and then, the gas blows out to the upper tank as large bubbles, which causes the liquid penetration into the pipe. Thus the bubble generation process plays an important role in the liquid flow rate. The characteristics of CCFL-U is more complicated than CCFL-L since it depends on the tank geometry, the liquid level, h_T, in the upper tank and the gas volume, V_T, in the lower tank. In spite of the complex nature of CCFL-U, the experiments confirmed that the CCFL characteristics are independent of h_T at small V_T and large h_T or are independent of V_T when h_T is small. Doi et al. (2012) also confirmed that the pipe diameter has negligible effects on the CCFL characteristics, and therefore, the following Kutateladze parameter is more appropriate than the Wallis parameters for correlating CCFL-U: