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Original Article

VOID FRACTION PREDICTION FOR SEPARATED FLOWS IN THE NEARLY HORIZONTAL TUBES

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ABSTRACT

A mechanistic model for void fraction prediction with improved interfacial friction factor in nearly horizontal tubes has been proposed in connection with the development of a condensation model package for the passive auxiliary feedwater system of the Korean Advanced Power Reactor Plus. The model is based on two-phase momentum balance equations to cover various types of fluids, flow conditions, and inclination angles of the flow channel in a separated flow. The void fraction is calculated without any discontinuity at flow regime transitions by considering continuous changes of the interfacial geometric characteristics and interfacial friction factors across three typical separated flows, namely stratified–smooth, stratified–wavy, and annular flows. An evaluation of the proposed model against available experimental data covering various types of fluids and flow regimes showed a satisfactory agreement.

1. Introduction

The Korean Advanced Nuclear Power Plant Plus (APR+) is expected to adopt a passive auxiliary feedwater system (PAFS) consisting of a condensation heat exchanger having nearly horizontal tubes (3° downward) as one of the passive safety systems. Recently, many experimental studies and analyses have been conducted to verify the cooling performance of PAFS. These comprehensive evaluations revealed that most of the existing models underestimate the condensation heat transfer coefficient in the horizontal tubes of a condensing heat exchanger similar to that of PAFS [1–3]. This is because most condensation heat transfer models of the horizontal tubes are based on empirical correlations that are not applicable to a variety of conditions including the types of flowing fluids and inclination angle of the heat exchanger tube. As an alternative approach to achieve better predictions, a mechanistic condensation model is considered applicable to the nearly horizontal tubes by distinguishing two different heat transfer

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mechanisms in the separated flow regimes typically observed in the PAFS heat exchanger tubes [4]. For such an approach, estimation of void fractions is of crucial importance in considering different heat transfer mechanisms in nearly horizontal condensing tubes.

To predict the void fraction in a two-phase flow, empirical correlations that consider slip ratio parameters have typically been used [5,6]. These methods are applicable to some dispersed flows such as bubbly flow and intermittent flow but not to separated flows whose slip ratios are usually large or non-negligible [7]. By contrast, a mechanistic model proposed by Taitel and Dukler [8] is widely used to predict the void fraction by iterative schemes for separated flow in horizontal tubes. However, this model is only applicable to fully stratified flow with the assumption that the gas–liquid interface is flat. Barnea et al [9] predicted the void fraction by a separated flow model that used geometric parameters applicable to annular flow. Ullmann and Brauner [10] and Chen et al [11] proposed improved geometric models for a curved interface caused by large interfacial shear stress in a stratified–wavy flow. The interfacial friction factor, another important parameter for the mechanistic prediction of the void fraction, has been widely studied for the stratified–smooth, stratified–wavy, and annular flows [8,12,13]. Ottens et al [14] reviewed such correlations and reported that some had large errors when compared with experimental data owing to limitations in their applicability depending on the flow conditions. Moreover, the use of different models for the friction factor and geometric characteristics according to flow regime may also lead to discontinuities at flow regime transitions in the void fraction calculations.

As mentioned above, accurate prediction of the void fraction in such separated flows requires sophisticated constitutive models on the interfacial characteristics. Therefore, the objective of this study is to develop a new mechanistic model for better prediction of the void fraction under separated flows in a nearly horizontal tube, especially focusing on the continuous changes in geometric shape and friction factor at the phase interface. That is, the geometric relations that assume an ideal arc for the curved interface were used to define the continuous flow regime transition from stratified to annular flows with the improved interfacial friction factors.

2. Void fraction prediction model

The proposed model is based on the concept of equilibrium-separated flow, proposed by Taitel and Dukler [8]. The configuration of the ideal separated flow, which is typically generated in the nearly horizontal tube, is schematically depicted in Fig. 1. The separated flow model used in this study focused on the simple adiabatic conditions of negligible phase change and droplet entrainment. Therefore, the momentum balance equations for the two phases with the assumption of fully developed flow in the steady state condition are as follows:

$$-A\alpha\left(\frac{dP}{dz}\right)_g - \tau_{wg}S_g - \tau_i S_i - \rho_g A\alpha g\sin\theta = 0 \quad (1)$$

$$-A(1-\alpha)\left(\frac{dP}{dz}\right)_l - \tau_{wl}S_l + \tau_i S_i - \rho_l A(1-\alpha)g\sin\theta = 0 \quad (2)$$

Assuming equal pressure difference between the two phases, the combined momentum equation for the separated flow is finally obtained as follows:

$$\frac{\tau_{wg}S_g}{A\alpha} - \frac{\tau_{wl}S_l}{A(1-\alpha)} + \frac{\tau_i S_i}{A\alpha(1-\alpha)} - \left(\rho_l - \rho_g\right)g\sin\theta = 0 \quad (3)$$

To determine the void fraction by using Eq. (3), it is necessary to define the constitutive equations for the shear stresses τ_{wg}, τ_{wl} for each phase at the wall and τ_i (positive when $u_g > u_l$) at the phase interface, as well as for the contact perimeters S_g, S_l, and S_i over which the shear stresses act.

The shear stress terms for the wall and interface are calculated by applying single-phase expressions as follows:

$$\tau_{wg} = \frac{1}{2}f_g\rho_g u_g^2 \quad (4)$$

$$\tau_{wl} = \frac{1}{2}f_l\rho_l u_l^2 \quad (5)$$

$$\tau_i = \frac{1}{2}f_i\rho_g|u_g - u_l|(u_g - u_l) \quad (6)$$

where the actual velocities u_g and u_l are expressed by the superficial velocities j_g and j_l of gas and liquid phases, respectively, as well as functions of the mass flux G, flow quality x, and void fraction α as follows:

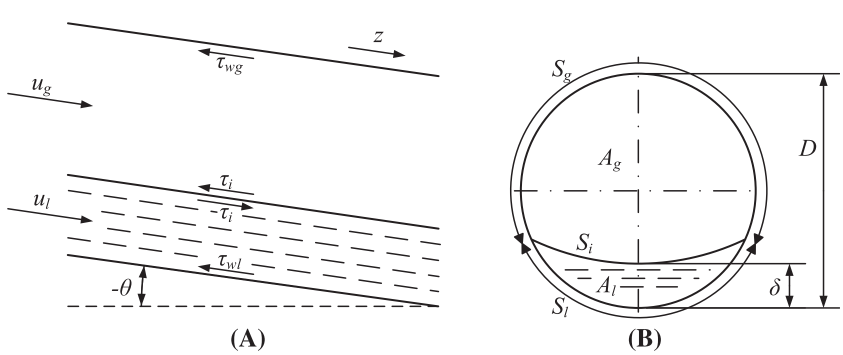

Fig. 1 – Schematic depiction of the configuration and coordinates of the separated flow. (A) Flow parameters. (B) Geometric parameters.