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Numerical Study of Void Fraction Distribution Propagation in Gas-Liquid Two-Phase Flow

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Abstract: A dynamic propagation model was developed for waves in two-phase flows by assuming that continuity waves and dynamic waves interact nonlinearly for certain flow conditions. The drift-flux model is solved with the one-dimensional continuity equation for gas-liquid two-phase flows as an initial-boundary value problem solved using the characteristic-curve method. The numerical results give the void fraction distribution propagation in a gas-liquid two-phase flow which shows how the flow pattern transition occurs. The numerical simulations of different flow patterns show that the void fraction distribution propagation is determined by the characteristics of the drift-flux between the liquid and gas flows and the void fraction range. Flow pattern transitions begin around a void fraction of 0.27 and end around 0.58. Flow pattern transitions do not occur for very high void concentrations.

Key words: void fraction distribution; gas-liquid two-phase flow; flow pattern transition

Introduction

The description of gas-liquid two-phase flows in long tubes is complicated by the existence of phase interfaces between the gas and liquid phases. For gas-liquid two-phase flows, the phase interfaces occur in a wide variety of forms depending on the flow rates and the physical properties of the phases as well as the geometry and inclination of the tubes. The different interfacial structures are called flow patterns or flow regimes. Flow pattern transitions have been broadly investigated with numerous reports describing various mechanisms. For example, the various mechanisms suggested for the slug-to-churn flow transition in vertical upward flow include the entrance effect mechanism, the flooding mechanism, the wake effect mechanism, and the bubble coalescence mechanism. Dukler and Taitel[1] treated churn flow as an entrance phenomenon as part of the formation of stable slug flow further downstream in the pipe. McQuillan and Whalley[2] and several others, including Wallis[3], attribute the slug-to-churn transition to flooding of the liquid film surrounding the Taylor bubble in slug flow. Mishima and Ishii[4] attributed the collapse of the liquid slug to the wake effect of Taylor bubbles. They stated that the transition from slug flow to churn flow occurs when the void fraction in the pipe is just greater than the mean void fraction over the Taylor bubble region. Brauner and Barnea[5] attributed the transition to churn flow from slug flow to the formation of highly aerated liquid slugs. When the void fraction in the liquid slug reached 0.52, transition to churn flow occurred as a result of bubble coalescence. There are also various reports on other flow transitions. For instance, Jayanti and Hewitt[6] stated that when the void fraction in the liquid reached 0.25, the bubbly flow transferred to slug flow. However, no methods exist to theoretically predict the flow behavior since

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the mechanisms of bubble breakage-coalescence phenomenon are not clear. Therefore, a new approach is needed to provide insight into this problem.

The wave theory proposed by Lighthill and Whitham[7] helped describe the flow structure and characteristics by focusing on fluctuations in multiphase flow structures. Zuber and Findlay[8] introduced the concept of waves in the study of void fraction fluctuations in gas-liquid two-phase flows. Matuszkiewcz et al.[9] investigated the relationship between the fluctuations and the power spectral density function. Lucas and Walton[10] suggested an approach to measure the flow rate of the bubbly flow based on wave theory utilizing pressure signal characteristics. Jin et al.[11] established an approach to identify flow patterns in oil/water two-phase flows based on wave theory.

These results show that wave theory is a powerful tool for investigating multiphase flows, but no papers have used wave theory to analyze the void fraction distribution propagation in vertical upward gas-liquid flows. This paper analyzes the dynamic propagation of continuity waves in conjunction with dynamic waves which results in a nonlinear system for certain flow conditions.

1 Modeling with the Characteristic-Curve Method

One-dimensional gas-liquid two-phase flows without phase change in a thermal-insulated tube are analyzed in this paper with the drift-flux model, which is essentially a separated-flow model focusing on the relative motion of the phases rather than on the motion of the individual phases. Let α represent the void fraction (volumetric concentration of the gas) while subscripts L and G represent the liquid and the gas phase components, and assume that the liquid and gas densities are constant. The mass conservation equation for each component can then be written in differential form as

$$\frac{\partial \alpha}{\partial t}+\frac{\partial\left(\alpha j_{\mathrm{m}}+H(\alpha)\right)}{\partial z}=0 \tag{1}$$

where j_{m} is a constant representing the averaged volumetric flux of the mixture flow[12].

$H(\alpha)=j_{\mathrm{GL}}=\alpha(1-\alpha)^{n} u_{\infty}$, an empirical formula that has been found to correlate a wide variety of data, is the drift flux of the gas-liquid flow, j_{GL}. The drift-flux, j_{GL}, represents the volumetric flux of the gas phase relative to a surface moving at the volumetric average flux, j_{m}. n is a correlation index, which is a function of a suitably defined Reynolds number, with $n=3$ as a typical value for fluid-particle systems while n is between 1 and 2 for several flow patterns in gas-liquid systems. u_{∞} is the terminal velocity of a single bubble in an infinite fluid.

The drift-flux function, $H(\alpha)$, has a maximum at α_{m} and its derivative with respect to α, $H'(\alpha)$, has a zero at α_{I} (point of inflection) when $n>1$. $H(\alpha)$ has the following properties:

1) $H(0)=0,\ H'(0)=u_{\infty}$;

2) $H(1)=0,\ H'(1)\leq 0$;

3) There exists $0<\alpha_{\mathrm{I}}<1$ such that

$$\begin{cases} H''(\alpha)<0, & 0<\alpha<\alpha_{\mathrm{I}}; \\ H''(\alpha_{\mathrm{I}})=0, & \alpha_{\mathrm{I}}=\dfrac{2}{n+1}; \\ H''(\alpha)>0, & \alpha_{\mathrm{I}}<\alpha<1 \end{cases} \tag{2}$$

Different flow patterns can be compared based on the characteristic void fraction α_{I} for each n to normalize the void fraction.

Table 1 lists the constants in Eq. (1) for various gas-liquid two-phase flows[3]. The first row in Table 1 describes bubbly flows and churn flows. The Reynolds number of the bubbles and the Galileo number for the liquid are defined as:

$$Re_{\mathrm{b}}=\frac{2\rho_{\mathrm{L}} u_{\infty} r_{\mathrm{b}}}{\mu_{\mathrm{L}}} \tag{3}$$

$$G_{\mathrm{L}}=\frac{g \mu_{\mathrm{L}}^{4}}{\rho_{\mathrm{L}} \sigma^{3}} \tag{4}$$

where r_{b} is the equivalent bubble radius, μ_{L} is the viscosity, and σ is the liquid surface tension.

Using the characteristic-curve method to solve the hyperbolic Eq. (1) gives:

$$\alpha(z,t)=\alpha(z_0,0)=\alpha\left(z-\left(\frac{\mathrm{d}j}{\mathrm{d}\alpha}\right)t,0\right) \tag{5}$$

Physically, Eq. (5) means that the initial void concentration at z_0 remains unchanged $(\mathrm{d}\alpha/\mathrm{d}t=0)$ along the characteristic curve in the z-t plane during propagation. This phenomenon can be thought of as a void fraction wave traveling at a speed of $\mathrm{d}j/\mathrm{d}\alpha$. If the initial void fraction distribution is not uniform, the