Prediction of Void Fraction and Interfacial Area Concentration in a Vertical Two-Phase Flow

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Introduction

In the formulation of two-fluid model, appropriate constitutive relations for interfacial transfer terms are required to close the phasic balance equations. In general, the interfacial transfer terms are proportional to the interfacial area concentration (IAC), which is defined as the interface area per unit fluid volume. Therefore, the interfacial area concentration is one of the most important parameters in the two-fluid model.

In the local approach of the modeling of IAC, bubble size distributions are predicted by modeling the breakup and coalescence process of bubbles.[1] This leads to so-called population balance equation. And, the bubble number density transport equation is obtained by integrating the population balance equation over the volume of all sizes of particles. For most two-phase flow studies, the detailed bubble volume dependent number density equation is considered as being too complicated for use in the field equations. But, the more detail bubble size effect should be considered because the bubble size influences the inter-phase heat and mass transfer through the IAC and momentum drag terms.

To constitutive the number density transport equation, the source and sink terms due to the bubble coalescence, breakup and bubble expansion/contraction should be modeled properly.

In this study, the two-fluid model is coupled with the number density transport equation in which the coalescence and breakup models are modified. The number density for various bubble sizes is calculated in order to consider the detailed bubble volume effect. Comparisons of the void fraction and IAC for the various flow conditions are performed against recent experimental data in air/water loop.[2] The schematic diagram of the air/water loop is shown in Fig. 1.

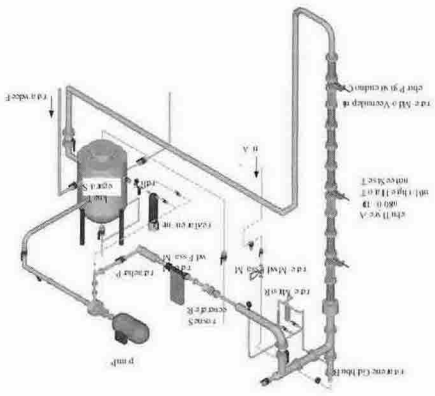

Fig. 1. Air/Water Test Loop

Calculation of the flow parameters

In this study, a multi-dimensional code is set up by using the two-fluid model and the number density transport equation. The velocity information is obtained by using the two-fluid model and the local parameters such as the void fraction and IAC are calculated with the number density transport equation. The two-fluid model and the number density transport equation are coupled systematically with each other. The two-fluid model treats each phase separately in terms of two sets of the conservation equations of mass, momentum and energy with proper averaging methods. In order to solve the momentum conservation equation, the constitutive relations such as drag force, virtual mass force, lift force should be included.

The flow parameters obtained by using the number density transport equation are inserted into the two-fluid model newly at every time step. In order to obtain the flow parameters, the number density transport equation can be derived as follows[3]:

$$\frac{\partial n}{\partial t}+\nabla\cdot\left(\bar{u}_g\, n\right)=-\frac{\bar{u}_g}{\rho_g}\cdot\nabla\rho_g\cdot n+S_{BC}+S_{BR}+S_{WE}\quad,\qquad(1)$$

where n, $\bar{u}$ and ρ are the number density, gas velocity and gas density. S_{BC}, S_{BR} and S_{WE} are the source and sink term of bubble coalescence, breakup and wake entrainment. The first term of the right-hand side of equation (1) considers the gas expansion due to the changes in gas density along the bubble path. The expansion of the gas phase has to be included when the gas density changes considerably such as this study.

The coalescence due to random collision and the breakup due to turbulent effect are modified following the reference study.[4] The coalescence due to random collision mainly results from the turbulence of the continuous phase and is shown as below,

$$S_{BC}=\frac{1}{2}\sum_{i=1}^{N}\sum_{j=1}^{N}\Gamma_{ij},\quad\begin{cases}\Gamma_{ij}=\Gamma_{ij} & : V_i+V_j=V_k\\ \Gamma_{ij}=0 & : V_i+V_j\neq V_k\end{cases}\qquad(2)$$

$$S_{BR}=\sum_{j=1}^{N}\Gamma_{ij}$$

$$\Gamma_{ij}\approx n_i n_j\cdot\left(d_i+d_j\right)^2\cdot\varepsilon^{1/3}\cdot\left|d_i^{2/3}+d_j^{2/3}\right|\cdot\exp\left(-\frac{\rho_f r_{ij}^3\varepsilon^2}{\sigma}\right)$$

: the coalescence rate of the bubble i and the bubble j, where d, N, V, $r_{ij}=0.5\left(r_i^3+r_j^3\right)^{1/3}$, ε, ρ_f and σ are the bubble diameter, total bubble group number, bubble volume, equivalent radius, energy dissipation, liquid density and surface tension respectively.

The breakup due to the turbulent effect is mainly caused by the collision with the turbulent eddy of

similar size to the bubble and is given by,

$$S_{con,ij} = \sum_{k=1}^{N} \Gamma_{ik,kj} , \qquad S_{brk,i} = \sum_{j=1}^{N} \Gamma_{ij,m} \tag{3}$$

$$\Gamma_{ij,m} \approx n_i n_j \varepsilon^{2/3} \left(d_i^{2/3} + \frac{d_i^{2/3} - \lambda_c^{2/3}}{d_i - \lambda_c} \right) S_p \frac{V_j}{V_i} \cdot \exp\left(-\frac{E}{E_{avg}} \right)$$

: the producing rate of bubble j after colliding the any bubble i with the eddy

where n , $E_{avg} \approx \int_{\lambda_c}^{\infty} \rho_f \lambda^{11/3} \varepsilon^{2/3} d\lambda \Big/ \int_{\lambda_c}^{\infty} d\lambda$,

$E \approx \sigma(d_i^2 + d_j^2 - d_c^2)$, $S_p \approx \int_{\lambda_c}^{\infty} (d_i + \lambda)^2 d\lambda \Big/ \int_{\lambda_c}^{\infty} d\lambda$ and λ_c

are the eddy number density, the eddy energy, the surface tension energy, the area of breakup and the minimum eddy diameter for breakup respectively.

The wake entrainment is a phenomenon that a bubble following a large bubble is accelerated by the wake that the large bubble makes in its rear side, then is collided to and coalesced with the preceding large bubble. The wake entrainment considering the velocity of the proceeding cap/slug bubble is derived as follows:

$$S_{con,ij} = \sum_{k=1}^{N} \sum_{l=k}^{N} \Gamma_{ik,kl} , \quad \begin{cases} \Gamma_{ik,kl} = \Gamma_{ik,kl} & : V_k + V_l = V_i \\ \Gamma_{ik,kl} = 0 & : V_k + V_l \neq V_i \end{cases} \tag{4}$$

$$S_{brk,i} = \sum_{j=1}^{N} \Gamma_{ij,n} + \sum_{j=1}^{N} \Gamma_{ij,0}$$

$$\Gamma_{ij,0} \approx n_i n_j d_i^2 u_i \cdot \exp\left(-\frac{\rho_f r_{ij}^3 \varepsilon^{2/3}}{\sigma d_i^{2/3}} \right)$$

: the coalescence rate of the proceeding bubble i and the trailing bubble j.

Results and Discussion

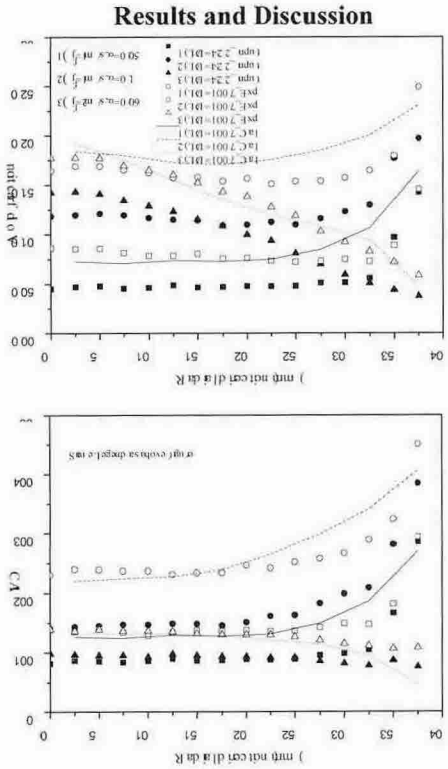

Fig. 2 Comparison results of void fraction & IAC

To evaluate the number density transport equation that is coupled with the two-fluid model, the comparison of the prediction of void fraction and IAC with the experimental data was performed as typically shown in Fig.2 shows at the L/D=100.7 of test section. The number density, which is calculated at the L/D=42.2, is used as the input condition. The void fraction and the IAC can be obtained as follows,

$$\alpha = \sum_{i} V_i \cdot n_i , \quad a = \sum_{i} A_i \cdot n_i , \tag{5}$$

where A is the bubble area.

As shown in the Fig. 2, the wall peaking is observed in the case of 1) and 2). On the contrary, the core peaking is shown in the case of 3). The void fraction is increased along the flow path due to the decrease in the system pressure. The local distribution of the IAC is similar to that of the void fraction. In general, this results from the fact that the IAC is proportional to the void fraction. The void fractions predicted by the number density transport equation are larger than the experimental data in the case of 1) and 2). Since the average bubble diameter and the turbulent intensity are small relatively, the coalescence due to random collision and pressure effect are expected to be dominant than the breakup and wake entrainment. In order to obtain more accurate results, the proper adjustment of calculation constants is required in the breakup and wake-entrainment terms. In the case of 3), the number density transport equation seems to predict the void fraction and the IAC well. Consequently, although there are relatively large errors in the results, the trend of the predictions followed those of the experimental data. The predicted errors of the void fraction are 19.4%, 14% and 9.7%, respectively in three cases. The predicted errors of the IAC are 11%, 10.3% and 21.2%, respectively in three cases.

Conclusion

The code, in which the two-fluid model is coupled with the number density transport equation, is developed to obtain the flow parameters in a two-phase flow. The predictive capability seems to be reasonable in void fraction and IAC. The developed code and model could be utilized in studies of IAC effectively.

Acknowledgement

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Reference

[1] F. Lehr, D. Mewes, "A transport equation for the interfacial area density applied to bubble columns", Chem.Eng.Sci, vol. 56, pp. 1159-1166, 2001

[2] D.J. Euh et al, "Transport phenomena of the two-phase flow parameters in adiabatic bubbly and slug flow conditions", KNS autumn meeting, 2004

[3] M. Millies, D. Mewes, "Interfacial area density in bubbly flow", Chem.Eng.Pro, vol. 38, pp. 309-319, 1999

[4] M.J. Prince et al., "Bubble Coalescence and Break-up in Air-Sparged Bubble Columns, AIChE, vol. 36, No. 10, 1990