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Drift-flux model for downward two-phase flow

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Abstract

In view of the practical importance of the drift-flux model for two-phase flow analysis in general and in the analysis of nuclear-reactor transients and accidents in particular, the distribution parameter and the drift velocity have been studied for downward two-phase flows. The constitutive equation that specifies the distribution parameter in the downward flow has been derived by taking into account the effect of the downward mixture volumetric flux on the phase distribution. It was assumed that the constitutive equation for the drift velocity developed by Ishii for a vertical upward churn-turbulent flow determined the drift velocity for the downward flow over all of flow regimes. To evaluate the drift-flux model with newly developed constitutive equations, area-averaged void fraction measurement has been extensively performed by employing an impedance void meter for an adiabatic vertical co-current downward air–water two-phase flow in 25.4-mm and 50.8-mm inner diameter round tubes. The newly developed drift-flux model has been validated by 462 data sets obtained in the present study and literatures under various experimental conditions. These data sets cover extensive experimental conditions such as flow system (air–water and steam–water), channel diameter (16–102.3 mm), pressure (0.1–1.5 MPa), and mixture volumetric flux (−0.45 to −24.6 m/s). An excellent agreement has been obtained between the newly developed drift-flux model and the data within an average relative deviation of ±15.4%.

Keywords: Drift-flux model; Distribution parameter; Drift velocity; Downward flow; Impedance void meter; Void fraction; Gas–liquid flow; Multiphase flow

1. Introduction

Two-phase flow is a very widely observed phenomenon for many engineering operations; and thus accurate knowledge of the two-phase flow characteristics has been of great importance over the years. Two-phase flows always involve some relative motion of one phase with respect to the other; therefore, a two-phase flow problem should be formulated in terms of two velocity fields. A general transient two-phase flow problem can be formulated by using a two-fluid model [1,2] or a drift-flux model [3,4], depending on the degree of the dynamic coupling between the phases. The drift-flux model is an approximate formulation in comparison with the more rigorous two-fluid formulation. However, because of its simplicity and applicability to a wide range of two-phase flow problems of practical interest, the drift-flux model is of considerable importance. In view of the practical importance of the drift-flux model for two-phase flow analysis, the drift-flux model has been studied extensively. In the state-of-the-art, the constitutive equations for the drift-flux model have been developed well for vertical upward two-phase flows in conventional-diameter round tubes (25–50 mm) under relatively high flow rate conditions [5]. The constitutive equations obtained

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Nomenclature

a_1	adjustable parameter
a_2	adjustable parameter
C_0	distribution parameter
C_∞	asymptotic value of C_0
$C_{\infty,\mathrm{tr}}$	value of C_0 at $\langle j^*_{\mathrm{tr}}\rangle$
D	diameter of round tube
D_{Sm}	Sauter mean diameter
G	impedance
G^*	non-dimensionalized impedance
G_{f}	impedance of single-phase liquid flow
G_{g}	impedance of single-phase gas flow
G_{m}	impedance of two-phase mixture
g	gravitational acceleration
j	mixture volumetric flux ($= j_{\mathrm{g}} + j_{\mathrm{f}}$)
j^*	non-dimensional mixture volumetric flux
j^*_{tr}	non-dimensional mixture volumetric flux at transition point between dispersed and separated two-phase flows
j_{g}	superficial gas velocity
j_{f}	superficial liquid velocity
L	length scale
Re	Reynolds number
$V_{\mathrm{g}j}$	drift velocity
v_{g}	gas velocity
v^*_{g}	non-dimensional gas velocity
$v_{\mathrm{g}j}$	local drift velocity
z	axial co-ordinate

Greek symbols

α	void fraction
$\Delta\rho$	density difference
ρ_{g}	gas density
ρ_{f}	liquid density
σ	standard deviation

Subscripts

calc.	calculated value
meas.	measured value

Mathematical symbols

$\langle\,\rangle$	area-averaged quantity
$\langle\langle\,\rangle\rangle$	void fraction weighted cross-sectional area-averaged quantity

under the conditions have often been used in computational thermohydraulic codes. The constitutive equations given by Zuber and Findlay [3], or Ishii [4] have been used in the present system codes such as TRAC-P1A, CANAC-II, and ATHOS 3.

Recently, in order to meet the needs of improving the prediction accuracy in various two-phase flow transient analyses, it has been required to develop precise constitutive equations for the distribution parameter and the drift velocity in various two-phase flows; for example, constitutive equations for (1) low flow conditions [6], (2) counter-current flows and downward flows [6], (3) large diameter pipes [6,7], and (4) horizontal flows. Among them, downward two-phase flow is frequently encountered in a number of engineering facilities such as nuclear reactors, chemical process systems, many kinds of boilers, etc. Particularly, the understanding of downward two-phase flow is essential for the safety analysis of the loss of coolant accidents in light water reactors. However, the studies for downward flow are still very limited. In what follows, the studies for downward flow are briefly reviewed.

Clark and Flemmer [8,9] studied the void fraction for downward flow in 52-mm and 100-mm diameter round tubes and evaluated the drift-flux model and its application in predicting the void fraction. They concluded in the first paper [8] that the drift-flux model is applicable to downward flow as well, and moreover, the distribution parameter is not only constant within each flow regime, but also is the same for upward and downward flows. In the second paper [9], they derived another conclusion that the distribution parameter is a function of the void fraction, and proposed distribution parameter for upward and downward flows empirically. Hirao et al. [6] and Kawanishi et al. [10] also studied the drift-flux model parameters by applying the experimental results of co-current and counter-current steam–water two-phase flows taken in 19.7-mm and 102.3-mm diameter round tubes. They empirically presented a variation of the distribution parameter for downward flow with respect to the mixture volumetric flux. Usui and Sato [11] investigated the local void fraction by means of a conductance needle probe and evaluated the drift-flux model for downward flow. Kashinsky and Randin [12] measured local void fraction and liquid velocity in a downward bubbly flow region. In the above studies, the investigators evaluated their own models by limited data sets, which were taken by them under a relatively narrow experimental condition. Thus, the applicability of their models to flow conditions beyond their experimental conditions is still questionable. From this point of view, this study is aiming at the construction of extensive rigorous data base in vertical downward two-phase flow and the development of the drift-flux model, which can be applicable to wide experimental condition.

2. One-dimensional drift-flux model

The drift-flux model is one of the most practical and accurate models for two-phase flow. The model takes into account the relative motion between phases by a constitutive relation. It has been utilized to solve many engineering problems involving two-phase flow dynamics [5]. In particular, its application to forced convection systems has been quite successful. The one-dimensional drift-flux model and its non-dimensional form are given as

$$\frac{\langle j_g \rangle}{\langle \alpha \rangle} = \langle\langle v_g \rangle\rangle = C_0 \langle j \rangle + V_{gj}, \tag{1}$$

or

$$\langle\langle v_g^* \rangle\rangle = C_0 \langle j^* \rangle + 1, \quad \text{where}$$
$$\langle\langle v_g^* \rangle\rangle = \langle\langle v_g \rangle\rangle / V_{gj} \text{ and } \langle j^* \rangle = \langle j \rangle / V_{gj}, \tag{2}$$

where j_g, v_g, and α are the superficial gas velocity, the gas velocity, and the void fraction, respectively. $\langle\,\rangle$ and $\langle\langle\,\rangle\rangle$ mean the area-averaged quantity over cross-sectional flow area and the void-fraction-weighted average quantity, respectively. The distribution parameter, C_0, and the drift velocity, V_{gj}, are given as Eqs. (3) and (4), respectively.

$$C_0 \equiv \frac{\langle \alpha j \rangle}{\langle \alpha \rangle \langle j \rangle}, \tag{3}$$

$$V_{gj} \equiv \frac{\langle v_{gj} \alpha \rangle}{\langle \alpha \rangle}, \tag{4}$$

where v_{gj} is the local drift velocity of a gas phase defined as the velocity of the gas phase, v_g, with respect to that of the volume center to the mixture, j, namely,

$$v_{gj} = v_g - j. \tag{5}$$

The void-fraction-weighted average gas velocity, $\langle j_g \rangle / \langle \alpha \rangle$, and the cross-sectional average mixture volumetric flux, $\langle j \rangle$, are easily obtainable parameters in experiments. Therefore, Eq. (1) suggests a plot of $\langle j_g \rangle / \langle \alpha \rangle$ versus $\langle j \rangle$. An important characteristic of such a plot is that, for two-phase flow regimes with fully developed void and velocity profiles, the data points fall around a straight line. The value of the distribution parameter, C_0, has been obtained indirectly from the slope of the line, whereas the intercept of this line with the void-fraction-weighted average gas velocity axis can be interpreted as the void-fraction-weighted average local drift velocity, V_{gj}.

3. Experimental

3.1. Impedance void meter methodology

An impedance void meter is capable of acquiring the area-averaged signals that represent the structural characteristics of flow. An impedance void meter is a non-intrusive conductance type probe that relies on the different conductivity properties between air and water. Two-pairs of stainless steel are employed as an electrode, and they are flush mounted against the wall. The electrodes span 90° of the cross-section and have 9.53 mm thickness. The thickness was chosen so as to be larger than the dimension of a typical bubble, yet shorter than the length of a cap or a slug bubble. The two-pairs of electrodes are 100 mm apart so that they may allow the investigation of the void propagation velocity. An alternating current is supplied to the electrodes at 100 kHz, and the electrodes are connected to the electrical circuit, which is specially designed so that the output voltage of the circuit becomes proportional to the measured impedance. These impedance signals can also be converted into the area-averaged void fraction with the specific impedance void fraction correlation which should be established by a specific correlation particular to the given impedance void meter. The detailed explanation on the usage of an impedance void meter can be found in the previous studies [14–16].

In the present study, calibration of the impedance void meters was performed with the void fraction measured by a conductivity probe [13]. In order to develop the calibration curve for the impedance void meters, 18 and 21 flow conditions for the 25.4-mm and 50.8-mm diameter round tubes, respectively, were chosen to cover broader impedance value range. The void fractions measured by a conductivity probe in these flow conditions were compared with the corresponding impedance measurements. In order to calibrate the impedance void meters, the measured impedance was normalized by applying

$$G^* = \frac{G_m - G_g}{G_f - G_g}, \tag{6}$$

where G_m, G_g, and G_f are the impedance of two-phase mixture, the impedance of single-phase gas flow, and an impedance of single-phase liquid flow, respectively. Fig. 1 shows non-dimensionalized impedance obtained from the experiment plotted against the area-averaged void fraction, and fitted by a fourth order polynomial. The open and solid circles indicate the data for the 25.4-mm and 50.8-mm diameter tubes, respectively. This best-fitted polynomial is the calibration curve of the given impedance void meter for the present experiment. The calibration curves for the 25.4-mm and 50.8-mm diameter tubes indicated by solid and broken lines, respectively, are represented by

$$\begin{aligned} \langle \alpha \rangle &= -0.984G^{*4} + 1.39G^{*3} - 0.429G^{*2} - 0.981G^* + 1, \\ &\quad \text{for } D = 25.4 \text{ mm}, \\ \langle \alpha \rangle &= -1.33G^{*4} + 2.74G^{*3} - 1.56G^{*2} - 0.853G^* + 1, \\ &\quad \text{for } D = 50.8 \text{ mm}. \end{aligned} \tag{7}$$

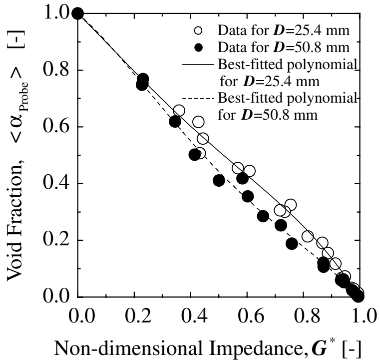

Fig. 1. Calibration of impedance void meter with void fraction measured by conductivity probe.

With the calibration curves given above, the average relative deviation between the impedance void meter and the conductivity probe is ±8.45%.

3.2. Experimental loop

The two-phase flow experiment was performed by using a flow loop installed at Thermal-hydraulics and Reactor Safety Laboratory in Purdue University [17]. Fig. 2 shows the schematic diagram of the two-phase flow loop. The experimental loop consisted of two test sections, which were 25.4-mm and 50.8-mm diameter round acrylic tubes whose total lengths, L, non-dimensionalized by the tube diameter, D, are $L/D = 150$ and 75, respectively. Air was supplied by a compressor and was introduced into a mixing chamber through a porous media with the pore size of 10 μm. The air and purified water were mixed in the mixing chamber and the mixture flowed downwards through the test section. After flowing through the test section, the air was released into the atmosphere through a separator, while the water was circulated by a centrifugal pump. The flow rates of the air and water were measured with a rotameter and a magnetic flow meter, respectively. The void fraction measurements using the impedance void meter were performed at $z/D = 133$ and 66.5 for the 25.4-mm and 50.8-mm diameter test sections, respectively. The sampling frequency of the impedance void meter was set at 500 Hz and the sampling time was 60 s throughout this investigation. These sampling rates were sufficient to reflect the characteristics of certain flow conditions. The range of the area-averaged mixture volumetric flux, $\langle j \rangle$ in this experiment is tabulated in Table 1. It should be noted here that the minus sign in the mixture volumetric flux indicates the downward direction. The flow conditions covered wide flow regimes including bubbly, slug, churn, and annular flows.

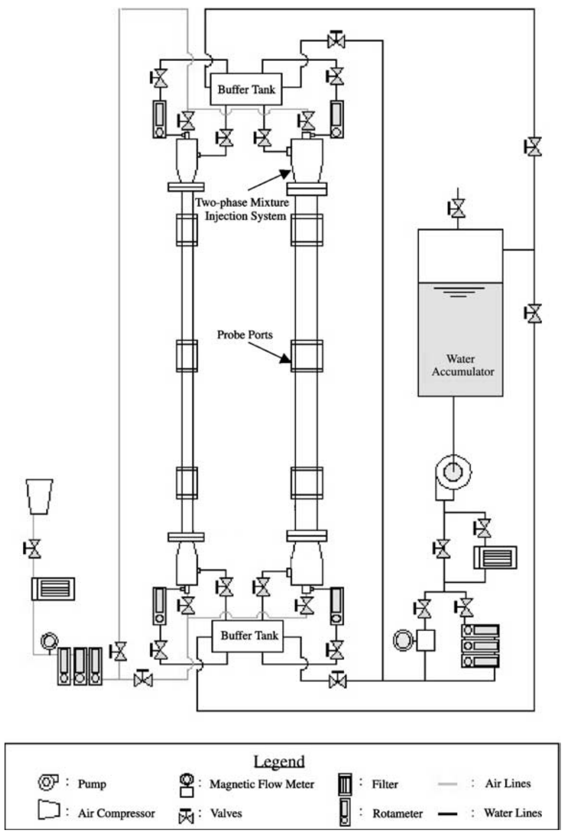

Fig. 2. Schematic diagram of experimental loop.

4. Results and discussion

4.1. Database used to develop drift-flux model in downward two-phase flow

In order to develop the drift-flux model in downward two-phase flow, the present study measured flow parameters of adiabatic downward air–water flows in vertical round tubes with inner diameters of 25.4 and 50.8 mm at the Thermal-hydraulics and Reactor Safety Laboratory in Purdue University. For the 25.4-mm and 50.8-mm diameter round tubes, a total of 284 data sets were acquired. In addition to Purdue's database, four databases [6,8,9,11,12] listed in Table 1 are also available. These databases include gas velocity and mixture volumetric flux, and widely cover extensive experimental conditions such as flow system (air–water and steam–water), channel diameter (16–102.3 mm), pressure (0.1–1.5 MPa), and mixture volumetric flux (−0.45 to −24.6 m/s). Some databases also include local parameters such as void fraction and liquid velocity. The detailed experimental conditions are shown in Table 1. As a result, a total of 462 data sets are available to develop the drift-flux model in downward two-phase flow.

Table 1
Database utilized in this study

Investigators	Tube diameter [mm]	Number of data [–]	Mixture volumetric flux [m/s]	System	Pressure [MPa]	Flow regimes
Clark and Flemmer	50	22	−0.778 to −2.44	Air (g)	0.1	Bubbly-to-slug
	100	45	−0.927 to −2.35	Water (f)	0.1	
Hirao et al.	19.7	20	−0.885 to −9.38	Steam (g)	0.5, 1.5	Bubbly-to-annular
	102.3	15	−0.676 to −3.01	Water (f)	0.5, 1.5	
Usui and Sato	16	22	−0.450 to −2.32	Air (g)	0.1	Bubbly-to-annular
	24	35	−0.407 to −1.35	Water (f)	0.1	
Kashinsky and Randin	42.3	19	−0.519 to −1.09	Air (g)	0.1	Bubbly
				Water (f)	0.1	
Present Work	25.4	143	−1.29 to −24.6	Air (g)	0.1	Bubbly-to-annular
	50.8	141	−1.16 to −6.90	Water (f)	0.1	

4.2. Existing drift-flux model in downward two-phase flow

4.2.1. Correlation of Hirao et al.

In this section, a correlation of Hirao et al. is briefly explained as an example of an existing drift-flux model developed for downward two-phase flow over a relatively wide flow range. Hirao et al. [6] and Kawanishi et al. [10] studied steam–water downward two-phase flows for 19.7-mm and 102.3-mm diameter round tubes, and proposed correlation based on their experimental data. They assumed that the drift velocity for downward two-phase flow would be given by Eq. (8) regardless of the flow regime.

$$V_{gj} = \sqrt{2}\left(\frac{g\sigma\Delta\rho}{\rho_f^2}\right)^{1/4}, \tag{8}$$

where g, σ, $\Delta\rho$, and ρ_f are the gravitational acceleration, the surface tension, the density difference, and the liquid density, respectively. It should be noted here that Eq. (8) is the same functional form as Ishii's equation [4] for the drift velocity of upward churn-turbulent flow. The distribution parameter was empirically determined with respect to the mixture volumetric flux, $\langle j\rangle$, as

$$\begin{aligned} &C_0 = 0.9 + 0.1\sqrt{\frac{\rho_g}{\rho_f}}, \quad \text{for } -2.5 \leqslant \langle j\rangle < 0 \text{ m/s},\\ &C_0 = 0.9 + 0.1\sqrt{\frac{\rho_g}{\rho_f}} - 0.3\left(1-\sqrt{\frac{\rho_g}{\rho_f}}\right)(2.5+\langle j\rangle),\\ &\quad \text{for } -3.5 \leqslant \langle j\rangle < -2.5 \text{ m/s},\\ &C_0 = 1.2 - 0.2\sqrt{\frac{\rho_g}{\rho_f}}, \quad \text{for } \langle j\rangle < -3.5 \text{ m/s}. \end{aligned} \tag{9}$$

The correlation of Hirao et al. reproduced their datasets taken in the region of -10 m/s $< \langle j\rangle$ satisfactorily. However, it should be pointed out here that the correlation for the distribution parameter for $-3.5 \leqslant \langle j\rangle < -2.5$ m/s is in a dimensional form.

4.2.2. Non-dimensionalization of Hirao's correlation

As pointed out in the previous section, Hirao et al. developed the distribution parameter for downward two-phase flow in a dimensional form. Hirao et al. developed the correlation for the distribution parameter, Eq. (9), based on the constant drift velocity, and this constant drift velocity contributed the distribution parameter as an anchor. In other word, the distribution parameter was solely determined by the constant drift velocity to correlate the experimental data. Thus, the correlation may also reflect the effect of the drift velocity. Noting this, the distribution parameter can be non-dimensionalized by employing the drift velocity, V_{gj}, given by Eq. (8). The distribution parameter is then represented in a non-dimensional form as

$$\begin{aligned} &C_0 = 0.9 + 0.1\sqrt{\frac{\rho_g}{\rho_f}}, \quad \text{for } -11 \leqslant \langle j^*\rangle < 0,\\ &C_0 = 0.9 + 0.1\sqrt{\frac{\rho_g}{\rho_f}} - \left(1-\sqrt{\frac{\rho_g}{\rho_f}}\right)(0.75+\langle j^*\rangle),\\ &\quad \text{for } -15 \leqslant \langle j^*\rangle < -11,\\ &C_0 = 1.2 - 0.2\sqrt{\frac{\rho_g}{\rho_f}}, \quad \text{for } \langle j^*\rangle < -15. \end{aligned} \tag{10}$$

While the distribution parameter developed by Hirao et al. agreed well with their experimental data, however, their data were only available up to $\langle j\rangle = -10$ m/s, and did not cover higher downward mixture volumetric flux. Consequently, Hirao et al. suggested that the distribution parameter would become constant as the downward mixture volumetric flux increases as shown in Eq. (9). However, it can be inferred that the distribution parameter may approach to unity as the downward mixture volumetric flux increases from the simple consideration of the flow structure. The flow becomes annular flow if the high downward mixture volumetric flux is a contribution of gas flow, or finely dispersed bubbly flow or homogeneously distributed bubbly flow if it is a contribution of liquid flow because of significantly high turbulence [18]. In both cases, the distribution parameter should approximately be unity. It should be noted here that in reality finely dispersed bubbly flow or homogeneously distributed bubbly flow with the distribution parameter of unity might appear in high downward mixture volumetric flux with unrealistically high liquid flow conditions. Thus, high downward mixture volumetric flux is usually a contribution of gas flow. The drift-flux model proposed by Hirao et al. [6] would fail to predict the gas velocity or void fraction at high downward mixture volumetric flux.

4.3. Development of drift-flux model in downward two-phase flow

Since sufficient understanding of downward two-phase flow structure is not available, it is difficult to develop the detailed drift-flux model. For example, since sufficient data of local flow parameters for gas and liquid phases are not available, the distribution parameter and the drift velocity cannot be determined directly from the definitions presented by Eqs. (3) and (4). For another example, although flow regime transition criteria for downward two-phase flow may be quite different from those for upward two-phase flow [17], they have not been developed. Thus, even though the flow regime dependent drift-flux model can be developed, we cannot practically use it.

In view of these, the approximated drift-flux model, which can be applicable to a wide flow range in downward flow, is developed here. As the first assumption, we approximate the drift velocity over all flow regimes to be Eq. (8), which is the same functional form as Ishii's equation [4] for the drift velocity of upward churn-turbulent flow. It should be noted here that the drift velocity for slug flow would be similar to that for bubbly and churn-turbulent flows for the data base tested in this study. For example, for $D = 50.8$ mm, the drift velocity for slug flow calculated by Ishii's equation (0.247 m/s) is very close to that for churn-turbulent flow calculated by Eq. (8) (0.231 m/s). Even for $D = 16$ mm, the drift velocity for slug flow (0.139 m/s) is close to that for churn-turbulent flow (0.231 m/s). In addition, it can be observed that the slug flow in downward flow is more chaotic, similar to the churn-turbulent flow in upward flow. For large diameter round tubes, slug bubbles cannot be formed due to the surface instability of slug bubbles. For an annular flow regime, the drift velocity effect can be negligible because of large values of the mixture volumetric flux. Thus, in the annular flow regime, the prediction error of V_{gj} by Eq. (8) may not affect the prediction accuracy of the drift-flux model to be developed below. The drift velocity assumed in this study, Eq. (8), may give a good prediction for the drift velocity over all flow regimes, unless Eq. (8) is not applied to estimate the drift velocity in capillary tubes. It should also be pointed out that the error in $\langle\langle v_g^* \rangle\rangle$ estimation due to the uncertainty of this assumption in the drift velocity would be less than ±10% for $\langle j^* \rangle \leqslant -5$ for a conservative estimation.

Ishii [4] developed a simple correlation for the distribution parameter in upward two-phase flow. Ishii first considered a fully developed bubbly flow and assumed that the distribution parameter would depend on the density ratio, ρ_g/ρ_f, and on the Reynolds number, Re. As the density ratio approaches unity, the distribution parameter should become unity. Based on the limit and various experimental data in fully developed flows, the distribution parameter was given approximately by

$$C_0 = C_\infty(Re) - \{C_\infty(Re) - 1\}\sqrt{\rho_g/\rho_f}, \tag{11}$$

where C_∞ is the asymptotic value of C_0. Here, the density group scales the inertia effects of each phase in a transverse void distribution. Physically, Eq. (11) models the tendency of the lighter phase to migrate into a higher-velocity region, thus resulting in a higher void concentration in the central region [4]. Based on a wide range of Reynolds number, Ishii approximated C_∞ to be 1.2 for an upward flow in a round tube [4]. Thus, for a fully developed turbulent flow in a round tube,

$$C_0 = 1.2 - 0.2\sqrt{\rho_g/\rho_f}. \tag{12}$$

Recently, Hibiki and Ishii [19] modified the constitutive equation of the distribution parameter for vertical upward bubbly flow based on the detailed discussion about the bubble dynamics as:

$$C_0 = \left(1.2 - 0.2\sqrt{\rho_g/\rho_f}\right)\{1 - \exp(-22\langle D_{Sm}\rangle/D)\}, \tag{13}$$

where D_{Sm} is the Sauter mean diameter. This modified distribution parameter suggests that the dominant factor to determine the distribution parameter in vertical upward bubbly flow would be the bubble diameter. Ishii [4] also developed the constitutive equation of the distribution parameter for boiling flow based on the detailed discussion on the effect of the nucleate bubbles on the void distribution as:

$$C_0 = \left(1.2 - 0.2\sqrt{\rho_g/\rho_f}\right)\{1 - \exp(-18\langle\alpha\rangle)\}. \tag{14}$$

This modified distribution parameter suggests that the dominant factor to determine the distribution parameter for boiling flow would be the void fraction. Thus, a key to develop the constitutive equation of the distribution parameter is to find a dominant factor to determine the distribution parameter.

Fig. 3 indicates that the distribution parameter may correlate closely with the non-dimensional mixture vol-

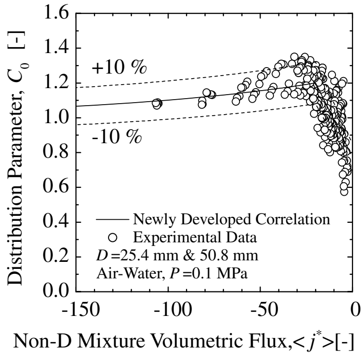

Fig. 3. Dependence of distribution parameter on mixture volumetric flux.

umetric flux. In this figure, the distribution parameters are determined by Eqs. (1) and (8) with void fraction, and superficial gas and liquid velocities measured in this experiment. The experimental result shows that the distribution parameter increases up to a certain value and gradually decreases and eventually approaches to unity as the downward mixture volumetric flux increases. The distribution parameter is likely to have a threshold with respect to the mixture volumetric flux, and this threshold may correspond to the transition point between dispersed and separated two-phase flows. In the dispersed two-phase flow region, the distribution parameter monotonically increases with the downward mixture volumetric flux, whereas in the separated two-phase flow region, the distribution parameter decreases with the downward mixture volumetric flux and finally asymptotically approaches to unity. This trend suggests the following function form for the distribution parameter in downward two-phase flow as:

$$C_\infty = a_1\left(\langle j^*\rangle - \langle j^*_{\mathrm{tr}}\rangle\right) + C_{\infty,\mathrm{tr}}, \quad \text{for } \langle j^*_{\mathrm{tr}}\rangle \leqslant \langle j^*\rangle \leqslant 0,$$

$$\begin{aligned} C_\infty &= C_{\infty,\mathrm{tr}} \exp\left\{a_2\left(\langle j^*\rangle - \langle j^*_{\mathrm{tr}}\rangle\right)\right\} \\ &\quad + 1.0\left[1 - \exp\left\{a_2\left(\langle j^*\rangle - \langle j^*_{\mathrm{tr}}\rangle\right)\right\}\right] \\ &= (C_{\infty,\mathrm{tr}} - 1.0)\exp\left\{a_2\left(\langle j^*\rangle - \langle j^*_{\mathrm{tr}}\rangle\right)\right\} + 1.0, \\ &\quad \text{for } \langle j^*\rangle \leqslant \langle j^*_{\mathrm{tr}}\rangle, \end{aligned} \tag{15}$$

where $\langle j^*_{\mathrm{tr}}\rangle$ and $C_{\infty,\mathrm{tr}}$ are the threshold value of $\langle j^*\rangle$ corresponding to the transition point between dispersed and separated two-phase flows, and the value of C_∞ at $\langle j^*_{\mathrm{tr}}\rangle$, respectively. a_1 and a_2 are adjustable parameters to be determined based on the data. One of the feature of this functional form is that the distribution parameter steeply increases with the downward mixture volumetric flux at the low $\langle j^*\rangle$ range, and asymptotically approaches to unity with increasing the downward mixture volumetric flux. Here, the threshold value of the mixture volumetric flux, $\langle j^*_{\mathrm{tr}}\rangle$, may be approximated to be −20 based on the data graphically. The maximum value of the distribution parameter at the threshold, $C_{\infty,\mathrm{tr}}$, may be assumed to be 1.2, which is the same as that for upward two-phase flow. For extreme cases such as concentrated void profile and sharp liquid velocity profiles around the tube center, the distribution parameter may exceed 1.2. However, as can be seen in Fig. 3, the assumed maximum distribution parameter gives a reasonable value for the maximum distribution parameter measured in the present experiment. From these considerations, the constitutive equation for the distribution parameter in downward two-phase flow are finalized by 284 data sets obtained in this experiment with the least-square method as:

$$\begin{aligned} C_0 &= (-0.0214\langle j^*\rangle + 0.772) + (0.0214\langle j^*\rangle + 0.228)\sqrt{\frac{\rho_{\mathrm{g}}}{\rho_{\mathrm{f}}}}, \\ &\quad \text{for } -20 \leqslant \langle j^*\rangle < 0, \\ C_0 &= \left(0.2\,\mathrm{e}^{0.00848(\langle j^*\rangle+20)} + 1.0\right) - 0.2\,\mathrm{e}^{0.00848(\langle j^*\rangle+20)}\sqrt{\frac{\rho_{\mathrm{g}}}{\rho_{\mathrm{f}}}}, \\ &\quad \text{for } \langle j^*\rangle < -20. \end{aligned} \tag{16}$$

The solid line in Fig. 3 shows the distribution parameter calculated by Eq. (16). The newly developed constitutive equation for the distribution parameter, Eq. (16), gives reasonably good prediction for the distribution parameter over wide range of the mixture volumetric flux. It should be noted here that the distribution parameter at relatively low mixture volumetric flux shows the value lower than unity. It is known that the void fraction profile for downward flow has a core peak in general. Therefore, the reason why the distribution parameters at relatively low mixture volumetric flux are lower than unity may be explained by the liquid velocity profile. However, Kashinsky and Randin [12] recently observed that the liquid velocity profile had a broad peak near the wall for some flow conditions in bubbly flow, namely, relatively low mixture volumetric flux region. This would decrease the distribution parameter.

4.4. Comparison of newly developed drift-flux model with experimental data

In this section, the newly developed drift-flux model for downward two-phase flow is compared with each data listed in Table 1. The drift-flux model proposed by Hirao et al., Eqs. (8) and (10), is also compared with the data.

Fig. 4 shows the comparison of the drift-flux model developed in this study, Eqs. (8) and (16), with the data taken in this study. The solid and broken lines in Fig. 4 indicate the calculated values by the drift-flux models developed in this study and by Hirao et al., respectively. As explained in the previous section, the slope of the drift-flux plot, namely the distribution parameter changes around $\langle j^*\rangle = -20$. For $\langle j^*\rangle \leqslant -20$, the distribution

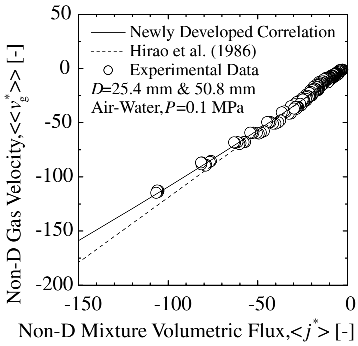

Fig. 4. Evaluation of newly developed drift-flux model with the data taken in the present experiment.

parameter asymptotically approaches to unity. The newly developed drift-flux model can represent this tendency successfully. On the other hand, for $-40 \leqslant \langle j^* \rangle$, the drift-flux model proposed by Hirao et al. gives a good agreement with the data obtained in this study. Since the model of Hirao et al. was validated by their data taken for $-40 \leqslant \langle j^* \rangle$, it would be applicable to the downward flow for $-40 \leqslant \langle j^* \rangle$. However, for $\langle j^* \rangle \leqslant -40$, the prediction by the model of Hirao et al. gradually tends to deviate from the data as the downward mixture volumetric flux increases. Since Hirao et al. did not account for the physical mechanism to determine the distribution parameter for high downward mixture volumetric flux, the model of Hirao et al. is not applicable to the downward flow for $\langle j^* \rangle \leqslant -40$. Fig. 5 shows the comparison of the newly developed drift-flux model with the data taken by Hirao et al. in relatively high pressure steam–water system. The solid and broken lines in Fig. 5 indicate the calculated values by the drift-flux models developed in this study and by Hirao et al., respectively. The newly developed drift-flux model can predict the proper trend and the value of the experimental data very well. It may be concluded that the newly developed drift-

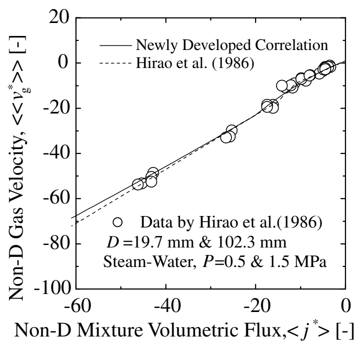

Fig. 5. Evaluation of newly developed drift-flux model with the data taken by Hirao et al. [6].

flux model can also be applicable to relatively high pressure steam–water system. The drift-flux model of Hirao et al. also agrees with their data very well. Figs. 6–8 show the comparison of the newly developed drift-flux model with the data taken by Clark and Flemmer [8,9], Usui and Sato [11], and Kashinsky and Randin [12], respectively. These data were taken in the range of

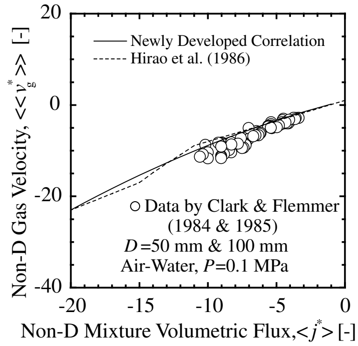

Fig. 6. Evaluation of newly developed drift-flux model with the data taken by Clark and Flemmer [8,9].

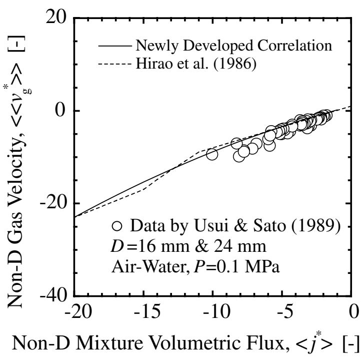

Fig. 7. Evaluation of newly developed drift-flux model with the data taken by Usui and Sato [11].

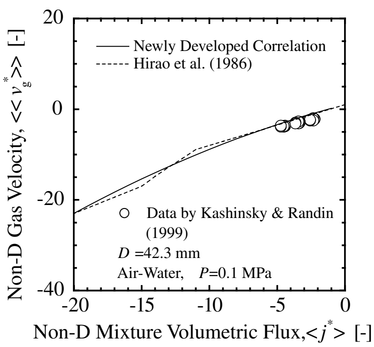

Fig. 8. Evaluation of newly developed drift-flux model with the data taken by Kashinsky and Randin [12].

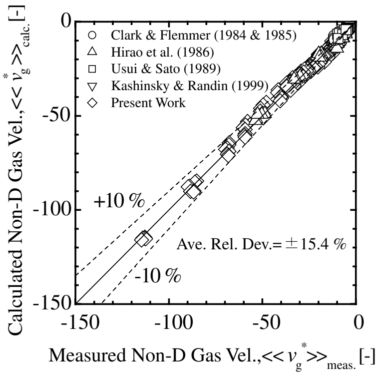

Fig. 9. Comparison between predicted and measured gas velocities.

relatively low downward mixture volumetric flux, $-10 \leqslant \langle j^* \rangle$. The newly developed drift-flux model gives a fairly good agreement with the data. As shown in Fig. 9, the average relative deviation between the newly developed drift-flux model and the data is estimated to be ±15.4%. Thus, the newly developed drift-flux model, Eqs. (8) and (16), has been validated by 462 data sets taken in extensive experimental conditions such as flow system (air–water and steam–water), channel diameter (16–102.3 mm), pressure (0.1–1.5 MPa), and downward mixture volumetric flux (−0.45 to −24.6 m/s).

In this study, the approximated distribution parameter has been developed as given by Eq. (16) and has been validated in downward two-phase flow over wide experimental conditions. Since the correlations for the distribution parameter and the drift velocity in downward two-phase flow have not been validated separately by detailed local flow data, they should not be used individually. In a future study, detailed local measurements of flow parameters for gas and liquid phases are recommended to develop a detailed and more rigorous drift-flux model taking account of the detailed flow structure.

5. Conclusions

In view of the practical importance of the drift-flux model for two-phase flow analysis in general and in the analysis of nuclear-reactor transients and accidents in particular, the distribution parameter and the drift velocity have been studied for downward two-phase flows. The obtained results are as follows:

(1) The constitutive equation, Eq. (16), that specifies the distribution parameter in downward two-phase flow has been derived by taking into account the effect of the downward mixture volumetric flux on the phase distribution.
(2) The constitutive equation for the drift velocity developed by Ishii for upward churn-turbulent flow, Eq. (8), has been assumed to predict the drift velocity for the vertically downward two-phase flow over all of the flow regimes for simplicity. It has been proven that this assumed drift velocity may not affect the prediction accuracy of the drift-flux model for $\langle j^* \rangle \leqslant -5$ significantly.
(3) A comparison of newly developed drift-flux model, Eqs. (8) and (16) with extensive data sets shows a satisfactory agreement within an averaged relative deviation of ±15.4%. These data sets cover extensive experimental conditions such as flow system (air–water and steam–water), channel diameter (16–102.3 mm), pressure (0.1–1.5 MPa), and mixture volumetric flux (−0.45 to −24.6 m/s).

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