AIAA JOURNAL
Vol. 44, No. 7, July 2006

One-Dimensional Drift-Flux Model at Reduced Gravity Conditions

Takashi Hibiki*
Kyoto University, Osaka 590-0494, Japan
Tomoji Takamasa†
Tokyo University of Marine Science and Technology, Tokyo 135-8533, Japan
Mamoru Ishii‡
Purdue University, West Lafayette, Indiana 47907-2017
and
Kamiel S. Gabriel§
University of Ontario Institute of Technology, Oshawa, Ontario L1H 7K4, Canada

The drift-flux model is of practical importance for two-phase flow analyses at reduced gravity conditions. In view of this, the drift-flux model, which takes the gravity effect into account, is studied in detail. The constitutive equation of the distribution parameter for bubbly flow, which takes the gravity effect into account, has been proposed, and the constitutive equations for slug, churn, and annular flows, which can be applicable to reduced gravity conditions, are recommended based on existing experimental and analytical studies. The previously derived constitutive equations of the drift velocity in various two-phase flow regimes, which takes the frictional pressure loss into account, are adopted in this study. A comparison of the model with various experimental data over various flow regimes and a wide range of flow parameters taken at microgravity conditions shows a satisfactory agreement. The drift-flux model has been applied to reduced gravity conditions such as 1.62 and 3.71 m/s^2, which correspond to the lunar and Martian surface gravities, respectively, and the effect of the gravity on the void fraction in two-phase flow systems has been discussed.

Nomenclature

A = cross-sectional area
C_0 = distribution parameter
C_∞ = asymptotic value of C_0
c = coefficient
D = diameter of pipe
D_H = hydraulic equivalent diameter of flow channel
D_{SM} = Sauter mean diameter
$\tilde{D}_{SM}$ = nondimensional Sauter mean diameter
F = quantity
f = friction factor
g = gravitational acceleration
g_N = normal gravitational acceleration
j = superficial velocity
Lo = Laplace length
$\tilde{L}o$ = nondimensional Laplace length
M_F = frictional pressure gradient in multiparticle system
$M_{F\infty}$ = frictional pressure gradient in single-particle system
p = pressure
Re = Reynolds number
$\tilde{R}e$ = bubble Reynolds number
V_{gj} = drift velocity of gas phase
v = velocity
v_r = relative velocity between phases in multiparticle system
z = axial distance
α = void fraction
$\Delta\rho$ = density difference between phases
ε = energy dissipation rate per unit mass
ν = kinematic viscosity
ρ = density
σ = surface tension
$\langle\,\rangle$ = area-averaged value
$\langle\langle\,\rangle\rangle$ = weighted mean value

Subscripts

f = liquid phase
g = gas phase
l = laminar flow
t = turbulent flow
z = z component

Received 31 August 2004; revision received 23 May 2005; accepted for publication 1 November 2005.

*Associate Professor, Research Reactor Institute, Kumatori, Sennan.
†Professor, Faculty of Marine Technology, Etchujima, Koto.
‡Walter H. Zinn Distinguished Professor, School of Nuclear Engineering, 400 Central Drive.
§Associate Provost, Research and Graduate Programs, 2000 Simcoe Street North.

Introduction

IN view of the great importance to the thermal-hydraulic design of thermal-control systems at reduced gravity conditions, a number of experiments have been performed for two-phase flows at reduced gravity conditions by means of a drop tower and an aircraft.[1–7] The flow characteristics measured at reduced gravity conditions include flow regime, void fraction, interfacial area concentration, and pressure drop. Because of the difficulty in estimating the effect of gravity on the flow characteristics theoretically, correlation-type constitutive equations have been developed mainly to predict the flow parameters. For example, at normal gravity conditions, the drift-flux model[8] is often used to predict void fractions by setting parameters such as superficial gas and liquid velocities. The constitutive equations of the distribution parameter and the drift velocity at normal gravity conditions have been modeled rigorously based on assumed phase distribution and similarity hypotheses on the drag coefficient in multiparticle systems, respectively,[9,10] and the validity of the constitutive equations has been verified by extensive one-dimensional data as well as two-dimensional data. The constitutive equations at normal gravity conditions have been extended to two-phase flows in large-diameter pipes,[11] downward flows,[12] and internally heated annuli.[13] However, the drift-flux model at reduced gravity conditions has not been well established yet. The major efforts focus on the experimental determination of the distribution parameter and the drift velocity from the one-dimensional flow parameters. In the regression analysis, some scientists assumed the drift velocity to be zero,[1] and others relaxed it as a fitting parameter.[7] The former case corresponds to extended application of the drift-flux model developed at normal gravity conditions[9] to microgravity conditions, whereas in the latter case the negative drift velocity, which was not physically sound, was reported.[7] Thus, the systematic development of the drift-flux model has not been done at reduced gravity conditions yet.

Recently, breakthrough experimental and analytical studies at microgravity conditions were performed to address the effect of the gravity on bubble dynamics.[5,14] A sophisticated experiment performed in bubbly flows at low liquid Reynolds number[5] clearly indicated the difference in void fraction between normal and microgravity flows and nonzero drift velocity. On the other hand, the relative velocity between a single bubble and a liquid flow in a confined channel was derived by taking the effect of a frictional pressure gradient due to a liquid flow[14] into account. This analysis implied that the frictional pressure gradient due to the liquid flow might be regarded as an additional source of buoyancy and the effective body acceleration would be expressed by the linear superposition of gravitational acceleration and flow-induced body acceleration. These studies inspired the detailed formulation of drift velocity considering the wall shear stress,[15] which can be applied to reduced gravity conditions.

In view of the practical importance of the drift-flux model for two-phase flow analyses at reduced gravity conditions, this study aims at detailed discussion of the drift-flux model taking the gravity effect into account. First, the constitutive equations of the drift velocity developed by considering the wall shear stress will be described briefly, as was done in a previous study.[15] Next, to close the drift-flux model, the constitutive equation of the distribution parameter for bubbly flow, which takes the gravity effect into account, will be proposed, and the constitutive equations for slug, churn, and annular flows, which can be applicable to reduced gravity conditions, will be recommended based on existing experimental and analytical studies. Finally, the drift-flux model is applied to reduced gravity conditions that correspond to lunar and Martian surface gravities, and the effect of the gravity on the void fraction in two-phase flow systems is discussed.

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 the relative motion between phases into account by a constitutive relation. The drift-flux model has been utilized to solve many engineering problems involving two-phase flow dynamics. In particular, its application to forced convection systems has been quite successful. In what follows, the derivation of the one-dimensional drift flux model will be demonstrated by averaging the local drift velocity over the channel cross section.[8,9] The rational approach to obtain a one-dimensional model is to integrate the three-dimensional model over a cross-sectional area and then to introduce proper mean values.

The drift velocity of a gas phase V_{gj} is defined as the velocity of the gas phase v_g with respect to the volume center to the mixture j:

$$V_{gj} = v_g - j = (1-\alpha)(v_g - v_f) = (1-\alpha)v_r \tag{1}$$

where v_f and v_r are the liquid velocity and the relative velocity between phases, respectively. The void-fraction-weighted mean drift velocity $\langle\langle V_{gj}\rangle\rangle$ is given by

$$\begin{aligned}\langle\langle V_{gj}\rangle\rangle &\equiv \langle \alpha V_{gj}\rangle/\langle\alpha\rangle = \langle \alpha v_g\rangle/\langle\alpha\rangle - \langle\alpha j\rangle/\langle\alpha\rangle \\ &= \langle j_g\rangle/\langle\alpha\rangle - \langle\alpha j\rangle/\langle\alpha\rangle \end{aligned}\tag{2}$$

where a simple area average of a quantity F over the cross-sectional area A is defined by

$$\langle F\rangle = \frac{1}{A}\int_A F\,\mathrm{d}A \tag{3}$$

The one-dimensional drift-flux model can be derived by recasting Eq. (2) as

$$\begin{aligned}\langle\langle v_g\rangle\rangle &= \langle j_g\rangle/\langle\alpha\rangle = [\langle\alpha j\rangle/(\langle\alpha\rangle\langle j\rangle)]\langle j\rangle + \langle\alpha V_{gj}\rangle/\langle\alpha\rangle \\ &= C_0\langle j\rangle + \langle\langle V_{gj}\rangle\rangle\end{aligned}\tag{4}$$

where C_0 is defined by

$$C_0 \equiv \langle\alpha j\rangle/(\langle\alpha\rangle\langle j\rangle) \tag{5}$$

Constitutive Equations of Distribution Parameter and Drift Velocity

Constitutive Equations of Drift Velocity in Various Flow Regimes

For a dispersed two-phase flow, the one-dimensional drift velocity can be derived by the averaged interfacial drag and the drag coefficient in multiparticle system.[15] In an annular two-phase flow, the relative motions between phases are governed by the interfacial geometry, the body-force field, and the interfacial momentum transfer. The constitutive equation for the gas-drift velocity in annular two-phase flows has been developed by taking those macroscopic effects of the structured two-phase flows into account.[9]

The derived drift velocities in various flow regimes are summarized in Table 1. In Table 1, g_z, σ, ρ_f, and D are the gravitational acceleration, the surface tension, the liquid density, and the channel diameter, respectively. The frictional pressure gradients in a single-particle system $M_{F\infty}$ and in a multiparticle system M_F are defined as in Eqs. (6) and (7), respectively,

$$M_{F\infty} \equiv [f/(2D)]\rho_f\langle v_f\rangle^2 \tag{6}$$

where f is the wall friction factor, and

$$M_F \equiv \left(-\frac{\mathrm{d}p}{\mathrm{d}z}\right)_F \tag{7}$$

For gravity-dominant flows where the frictional pressure gradients can be neglected, the constitutive equations of the drift velocity are simplified to Ishii's equations.[9]

Constitutive Equations of Distribution Parameter in Various Flow Regimes

For a dispersed two-phase flow, Ishii[9] developed a simple correlation for the distribution parameter. 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 defined by $\langle j_f\rangle D/\nu_f$. 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

$$C_0 = C_\infty - (C_\infty - 1)\sqrt{\rho_g/\rho_f} \tag{8}$$

Here, the density group scales the inertia effects of each phase in a transverse void distribution. Physically, Eq. (8) 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.

The distribution parameters in various flow regimes are modeled based on Eq. (8) as follows.

Bubbly Flow

In the bubbly flow regime, the asymptotic value of the distribution parameter is given by[15]

$$C_\infty = C_{\infty,l}\exp(-0.000584Re) + C_{\infty,t}[1-\exp(-0.000584Re)] \tag{9}$$

Table 1 Drift-flux parameters taking gravity effect into account

Flow regimes	Void-fraction-weighted mean drift velocities	Distribution parameters
Bubbly flow	$\langle\langle V_{gj}\rangle\rangle = \sqrt{2}\left\{\frac{(\Delta\rho g_z + M_{F\infty})\sigma}{\rho_f^2}\right\}^{\frac{1}{4}} \times \frac{18.67(1-\langle\alpha\rangle)^2\left\{\frac{\Delta\rho g_z(1-\langle\alpha\rangle)+M_F}{\Delta\rho g_z + M_{F\infty}}\right\}}{1+17.67(1-\langle\alpha\rangle)^{\frac{6}{7}}\left\{\frac{\Delta\rho g_z(1-\langle\alpha\rangle)+M_F}{\Delta\rho g_z + M_{F\infty}}\right\}^{\frac{3}{7}}}$	$C_0 = 2.0\exp(-0.000584Re) + \left(1.2\exp\left[-5.55(g/g_N)^3\right] + 1.2[1-\exp(-22\langle D_{SM}\rangle/D)]\left\{1-\exp\left[-5.55(g/g_N)^3\right]\right\}\right) \times [1-\exp(-0.000584Re)] - \left[2.0\exp(-0.000584Re) + \left(1.2\exp\left[-5.55(g/g_N)^3\right] + 1.2[1-\exp(-22\langle D_{SM}\rangle/D)] \times \left\{1-\exp\left[-5.55(g/g_N)^3\right]\right\}\right)[1-\exp(-0.000584Re)] - 1\right]\sqrt{\rho_g/\rho_f}$
Slug flow	$\langle\langle V_{gj}\rangle\rangle = 0.35\left\{\frac{[\Delta\rho g_z(1-\langle\alpha\rangle)+M_F]D}{\rho_f(1-\langle\alpha\rangle)}\right\}^{\frac{1}{2}}$	$C_0 = 1.2 - 0.2\sqrt{\rho_g/\rho_f}$
Churn flow	$\langle\langle V_{gj}\rangle\rangle = \sqrt{2}\left[\frac{(\Delta\rho g_z + M_{F\infty})\sigma}{\rho_f^2}\right]^{\frac{1}{4}} \times \left[\frac{\Delta\rho g_z(1-\langle\alpha\rangle)+M_F}{\Delta\rho g_z + M_{F\infty}}\right]^{\frac{1}{4}}$	$C_0 = 1.2 - 0.2\sqrt{\rho_g/\rho_f}$
Annular flow	$\langle\langle V_{gj}\rangle\rangle \approx 0$	$C_0 \approx \frac{1-\langle\alpha\rangle}{\langle\alpha\rangle + \left\{\frac{1+75(1-\langle\alpha\rangle)}{\sqrt{\langle\alpha\rangle}}\frac{\rho_g}{\rho_f}\right\}^{\frac{1}{2}}}\left[1+\frac{\sqrt{\frac{\Delta\rho g_z D(1-\langle\alpha\rangle)}{0.015\rho_f}}}{\langle j\rangle}\right] + 1$

where $C_{\infty,l}$ and $C_{\infty,t}$ are the asymptotic values of the distribution parameter for laminar and turbulent flows, respectively. For a laminar flow, $C_{\infty,l} = 2$ regardless of gravity conditions,[9] whereas for a turbulent flow under normal gravity conditions, $C_{\infty,t}$ is obtained by considering the bubble lateral migration characteristics as[10]

$$C_{\infty,t}^{1-g} = 1.2[1-\exp(\langle D_{SM}\rangle/D)] \tag{10}$$

where D_{SM} is the bubble Sauter mean diameter, which can be predicted by the following correlation[16]:

$$\tilde{D}_{SM} = 1.99\tilde{L}o^{-0.335}\tilde{R}e^{-0.239} \tag{11}$$

where $\tilde{D}_{SM} \equiv \langle D_{SM}\rangle/Lo$, $Lo \equiv \sqrt{[\sigma/(g\Delta\rho)]}$, $\tilde{L}o \equiv Lo/D_H$, and $\tilde{R}e \equiv (\langle\varepsilon\rangle^{1/3}Lo^{1/3})Lo/\nu_f$. The energy dissipation rate per unit mass ε can be given by[16]

$$\langle\varepsilon\rangle = g_N\langle j_g\rangle\exp(-0.000584Re) + \frac{\langle j\rangle}{\rho_m}\left(-\frac{dp}{dz}\right)_F[1-\exp(-0.000584Re)] \tag{12}$$

where $g_N = 9.8$ m/s^2. The pressure loss per unit length due to friction can be calculated from Lockhart–Martinelli's correlation.[17] The applicability of Eq. (10) has been confirmed[10] for experimental conditions such as 0.262 m/s $\leq\langle j_f\rangle\leq$ 5.00 m/s, 25.4 mm $\leq D \leq$ 60 mm, and 1.40 mm $\leq\langle D_{SM}\rangle$. Because Eq. (10) is rather complicated, and its applicability is limited by the validated experimental range, $C_{\infty,t}^{1-g} = 1.2$ proposed by Ishii[9] or $C_{\infty,t}^{1-g} = 1.0$ based on available distribution parameters determined by local flow measurements[10] may still be utilized by accepting a certain prediction error for simplicity. On the other hand, experimental results obtained at microgravity conditions[1,6] indicate that the asymptotic value of the distribution parameter for a turbulent bubbly flow at microgravity conditions is approximated to be 1.2. Thus, a general form of the asymptotic value of the distribution parameter may be approximated by

$$C_{\infty,t} = 1.2\exp\left[c(g/g_N)^3\right] + 1.2\{1-\exp[-22\langle D_{SM}\rangle/D]\}\left\{1-\exp\left[c(g/g_N)^3\right]\right\} \tag{13}$$

where c is approximated to be -5.55 from $\exp[c(g/g_N)^3] = 0.5$ at $g/g_N = 0.5$. Thus, the distribution parameter in the bubbly flow regime is given by

$$C_0 = 2.0\exp(-0.000584Re) + \left(1.2\exp\left[-5.55(g/g_N)^3\right] + 1.2[1-\exp(-22\langle D_{SM}\rangle/D)]\left\{1-\exp\left[-5.55(g/g_N)^3\right]\right\}\right) \times [1-\exp(-0.000584Re)] - \left[2.0\exp(-0.000584Re) + \left(1.2\exp\left[-5.55(g/g_N)^3\right] + 1.2[1-\exp(-22\langle D_{SM}\rangle/D)] \times \left\{1-\exp\left[-5.55(g/g_N)^3\right]\right\}\right)[1-\exp(-0.000584Re)] - 1\right] \times\sqrt{\rho_g/\rho_f} \tag{14}$$

Slug Flow

In the slug-flow regime, the asymptotic value of the distribution parameter is approximated to be 1.2 regardless of gravity conditions.[1,9] Thus,

$$C_0 = 1.2 - 0.2\sqrt{\rho_g/\rho_f} \tag{15}$$

Churn Flow

In the churn-flow regime, the asymptotic value of the distribution parameter may be approximated to be 1.2 regardless of gravity conditions.[3,9] Thus,

$$C_0 = 1.2 - 0.2\sqrt{\rho_g/\rho_f} \tag{16}$$

Annular Flow

In separated flows, the local relative velocity between two phases cannot be defined.[15] If small liquid particles are entrained in the gas core or small gas bubbles are entrained in the liquid film, the local relative velocity may be approximated to be zero, resulting in $\langle\langle V_{gj}\rangle\rangle \approx 0$. This approximation is acceptable in annular two-phase flows where the entrainment of liquid from the film to the gas-core flow is negligibly small. Thus, we have

$$C_0 \approx \frac{1-\langle\alpha\rangle}{\langle\alpha\rangle + \left\{\frac{1+75(1-\langle\alpha\rangle)}{\sqrt{\langle\alpha\rangle}}\frac{\rho_g}{\rho_f}\right\}^{\frac{1}{2}}} \times \left[1 + \frac{\sqrt{\frac{\Delta\rho g_z D(1-\langle\alpha\rangle)}{0.015\rho_f}}}{\langle j\rangle}\right] + 1 \qquad (17)$$

Results and Discussion

Evaluation of Drift-Flux Model Taking Gravity Effect into Account

The constitutive equations of the distribution parameter and the drift velocity, which have been obtained by taking the gravity effect into account, are summarized in Table 1. The newly developed drift-flux model given in Table 1 will be evaluated using an existing database taken at microgravity conditions. The experimental conditions of the data sources are given in Table 2. A total of 206 data sets are available to evaluate the drift-flux model. The reported errors for these databases are about $\pm 10-15\%$. Thus, the error bars of $\pm 15\%$ will be indicated as follows.

Figure 1 shows a comparison of the newly developed drift-flux model, taking the gravity effect into account, with the Takamasa et al.[5] data. They obtained the data at normal and microgravity conditions, and, thus, these data sets can be used to discuss the effect of reduced gravity on the flow parameters. In Fig. 1, open and solid symbols indicate the data sets taken at normal and microgravity conditions, respectively. Solid, broken, and dotted lines also indicate the values calculated by the newly developed drift-flux model at normal gravity conditions, the newly developed drift-flux model at microgravity conditions, and the following empirical correlation at microgravity conditions proposed by Colin et al.,[1] respectively:

$$\langle\langle v_g\rangle\rangle = 1.2\langle j\rangle \qquad (18)$$

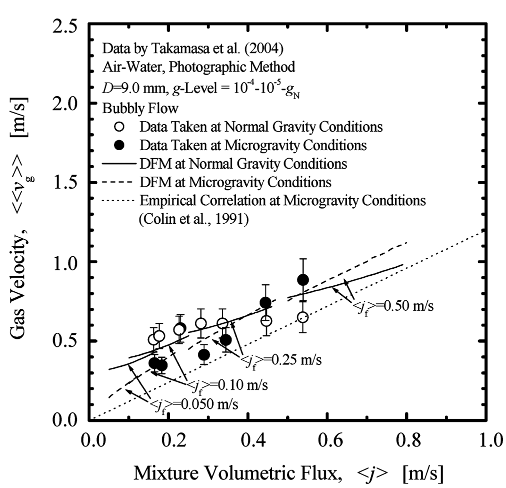

Fig. 1 Comparison of drift-flux model taking gravity effect into account with bubbly flow data by Takamasa et al.[5]

Here, the calculations derived by the newly developed drift-flux model were made at given liquid velocities and in the range of $\langle\alpha\rangle \leq 0.3$. A fairly good agreement is obtained between the data and the newly developed drift-flux model at normal gravity conditions. Here, because Eq. (10) may not be applicable to the experimental condition such as $D = 9.0$ mm, $C_{\infty,t}^{1-g}$ in the newly developed drift-flux model at normal gravity conditions is assumed to be 1.0 based on local-phase distributions obtained in two-phase flow experiments at normal gravity conditions.[18] The newly developed drift-flux model at microgravity conditions also agrees very well with the data.

Note that the gas velocities measured at microgravity conditions are higher than those at normal gravity conditions for a relatively higher mixture volumetric flux, and the reverse tendency is observed for a relatively lower mixture volumetric flux. The difference between the data obtained at normal and microgravity conditions is attributed to the difference in the local slip and phase distribution effects between normal and microgravity conditions. For high mixture volumetric flux, the distribution parameter effect is more pronounced. Because the wall peaking in the void fraction distribution is observed at normal gravity conditions,[18] the distribution parameter at normal gravity conditions is lower than that at microgravity conditions. The dominant distribution parameter effect, namely, $C_0\langle j\rangle \gg \langle\langle V_{gj}\rangle\rangle$, and C_0 at microgravity conditions higher than C_0 at normal gravity conditions result in the gas velocities at microgravity conditions being higher than those at normal gravity conditions for a relatively high mixture volumetric flux. On the other hand, for low mixture volumetric flux, the local slip effect is more pronounced. The drift velocity at normal gravity conditions is higher than that at microgravity conditions. The pronounced local slip effect and the $\langle\langle V_{gj}\rangle\rangle$ at normal gravity conditions higher than $\langle\langle V_{gj}\rangle\rangle$ at microgravity conditions result in the gas velocities at microgravity conditions being lower than those at normal gravity conditions. The newly developed drift-flux model can represent this tendency very well. Unfortunately, Eq. (18) systematically underestimates the experimental data obtained at microgravity conditions. This is attributed to the improper assumption of negligible drift velocity in Eq. (18), which causes a significant estimation error at low mixture volumetric flux conditions.

In Fig. 2, the measured void fractions are compared with the predictions of the newly developed drift-flux model at microgravity conditions and with that of Eq. (18). The newly developed drift-flux model agrees with the data within an averaged prediction error of $\pm 13.9\%$, whereas Eq. (18) agrees with the data within an averaged prediction error of $\pm 53.7\%$. This also suggests that the drift velocity at microgravity conditions may not be assumed to be zero and that the newly developed drift-flux model at microgravity conditions can represent the local slip effect properly.

Figures 3 and 4 compare the newly developed drift-flux model at microgravity conditions and Eq. (18) with the Colin et al.[1] data. The newly developed drift-flux model at microgravity conditions

Table 2 Databases used to evaluate drift-flux model under microgravity conditions

Parameter	Colin et al.[1]	Bousman et al.[2]	Fujii et al.[3]	Elkow and Rezkallah[4]	Choi et al.[7]	Takamasa et al.[5]
Pipe size	40	12.7	10.5	9.53	10.0	9.00
Gas	Air	Air	N_2	Air	Air	N_2
Liquid	Water	Water	Water	Water	Water	Water
Number of data	44 (Bubbly) 44 (Slug)	11 (Bubbly) 33 (Slug)	3 (Bubbly) 2 (Slug) 8 (Churn)	10 (Bubbly) 20 (Slug) 13 (Churn) 6 (Annular)	20 (Bubbly) 18 (Taylor bubbly) 12 (Slug)	7 (Bubbly)
Total number of data	88	44	13	49	50	7
Technique	Conductance probe	Conductance probe	DC current	Conductance probe	Electrical resistance probe	Photograph
μg Facility	Parabolic flight	Parabolic flight	Parabolic flight	Parabolic flight	Parabolic flight	Drop tower
g Level	<0.03-g_N	<0.02-g_N	<0.01-g_N	<0.01-g_N	<0.01-g_N	10^{-4}–10^{-5}-g_N

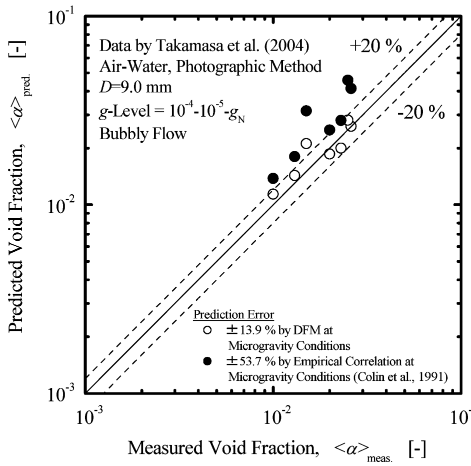

Fig. 2 Comparison of prediction accuracy by drift-flux model at microgravity conditions with empirical correlation proposed by Colin et al.[1]

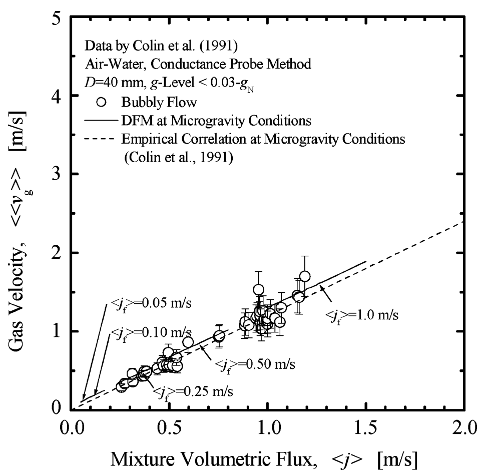

Fig. 3 Comparison of drift-flux model at microgravity conditions with bubbly flow data by Colin et al.[1]

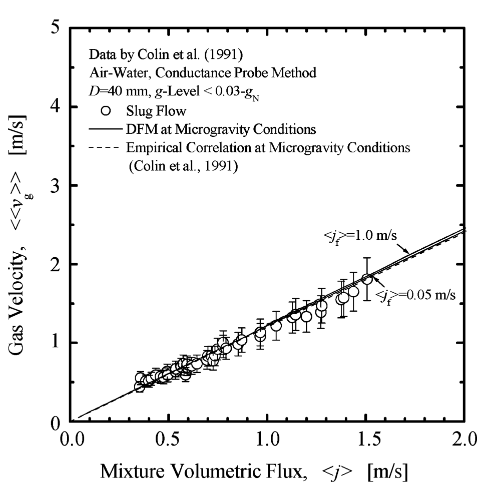

Fig. 4 Comparison of drift-flux model at microgravity conditions with slug flow data by Colin et al.[1]

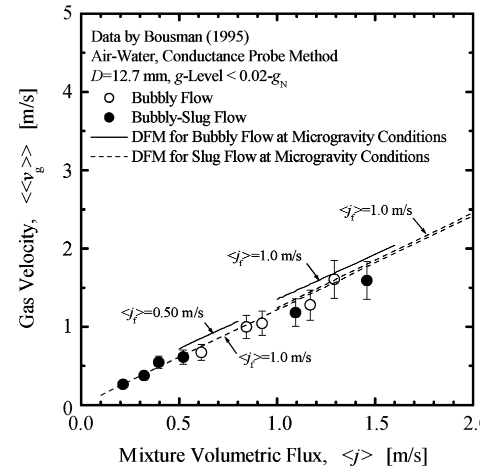

Fig. 5 Comparison of drift-flux model at microgravity conditions with bubbly flow data by Bousman.[2]

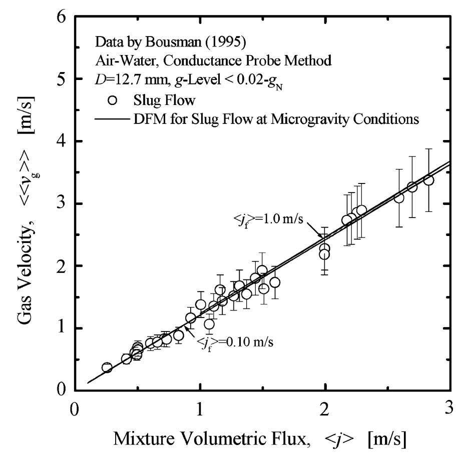

Fig. 6 Comparison of drift-flux model at microgravity conditions with slug flow data by Bousman.[2]

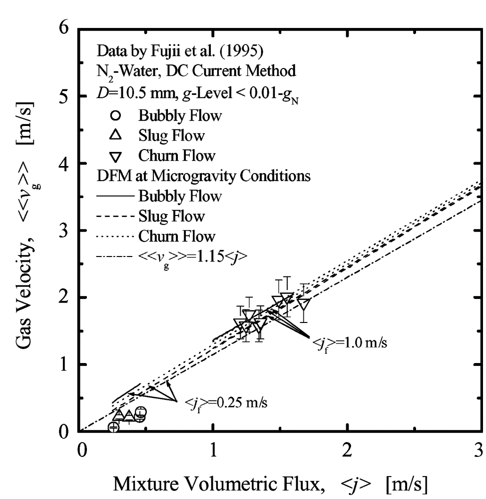

Fig. 7 Comparison of drift-flux model at microgravity conditions with data by Fujii et al.[3]

and Eq. (18) are compared with bubbly and slug-flow data in Figs. 3 and 4, respectively. In Figs. 3 and 4, solid and broken lines indicate the values calculated by the newly developed drift-flux model at microgravity conditions and Eq. (18) proposed by Colin et al.,[1] respectively. The calculations in the bubbly flow regime are conducted at given superficial liquid velocities and in the range of $\langle\alpha\rangle \leq 0.3$. The newly developed drift-flux model at microgravity conditions predicts the bubbly and slug-flow data very well. As expected, the newly developed drift-flux model at microgravity conditions gives predictions similar to those of Eq. (18) in relatively high liquid-flow conditions where the assumption of negligible drift velocity may be sound.

Figures 5 and 6 show a comparison of the newly developed drift-flux model at microgravity conditions with the data by Bousman.[2] The drift-flux model at microgravity conditions is compared with bubbly and slug-flow data in Figs. 5 and 6, respectively. The calculations in the bubbly flow regime are conducted at given superficial

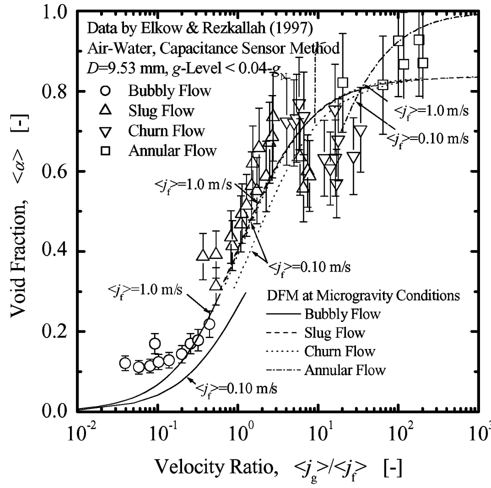

Fig. 8 Comparison of drift-flux model at microgravity conditions with data by Elkow and Rezkallah.[4]

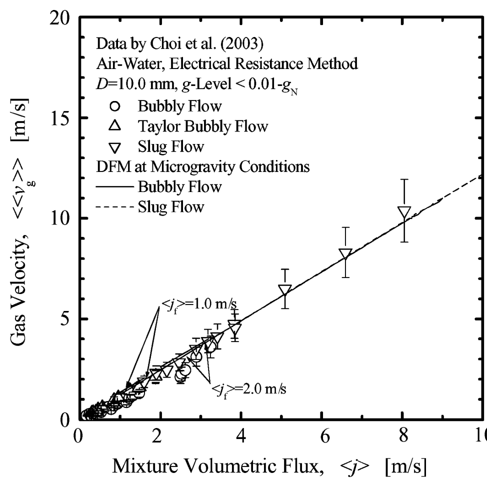

Fig. 9 Comparison of drift-flux model at microgravity conditions with data by Choi et al.[7]

liquid velocities and in the range of $\langle\alpha\rangle \leq 0.3$. The drift-flux model at microgravity conditions predicts the bubbly and slug-flow data very well.

Figure 7 shows a comparison of the newly developed drift-flux model at microgravity conditions with the Fujii et al.[3] data, which are reproduced from their original figure. Because the data points for bubbly and slug flows are too crowded in the original figure, the reproducibility of these data may not be of excellent quality. The drift-flux model at microgravity conditions is compared with bubbly, slug-, and churn-flow data in Fig. 7. The calculations in the bubbly flow regime are conducted at given superficial liquid velocities and in the range of $\langle\alpha\rangle \leq 0.3$. The drift-flux model at microgravity conditions predicts the churn-flow data very well. Fujii et al.[3] concluded that all of the data, including bubbly, slug-, and churn-flow data, can be approximated with a regression line of $\langle\langle v_g\rangle\rangle = 1.15\langle j\rangle$. Because the drift-flux model at microgravity conditions gives similar predictions to the regression line, it may be concluded that the drift-flux model at microgravity conditions also predicts the bubbly and slug-flow data fairly well.

Figure 8 shows a comparison of the newly developed drift-flux model at microgravity conditions with the data by Elkow and Rezkallah,[4] which are reproduced from their original figure plotted in the $\langle j_g\rangle/\langle j\rangle$ vs $\langle\alpha\rangle$ plane. The drift-flux model at microgravity conditions is compared with bubbly, slug-, churn-, and annular-flow data. Note that flow reversal was observed in the churn-flow regime and could greatly deteriorate the void fraction measurement accuracy in this regime.[4] Although the data scatter is rather large, the drift-flux model at microgravity conditions can predict the data tendency very well.

Figure 9 shows a comparison of the newly developed drift-flux model at microgravity conditions with the Choi et al.[7] data, which are reproduced from their original figures. The drift-flux model at microgravity conditions is compared with bubbly, Taylor bubbly, and slug-flow data in Fig. 9. The calculations in the bubbly flow regime are conducted at given superficial liquid velocities and in the range of $\langle\alpha\rangle \leq 0.3$. Choi et al.[7] characterized the Taylor bubbly flow as bullet-shaped bubbles with a smooth nose, flowing with no or few small bubbles in the liquid slugs. The drift-flux model for slug flow may be approximately applicable to the Taylor bubbly flow. The drift-flux model at microgravity conditions predicts the data reasonably well.

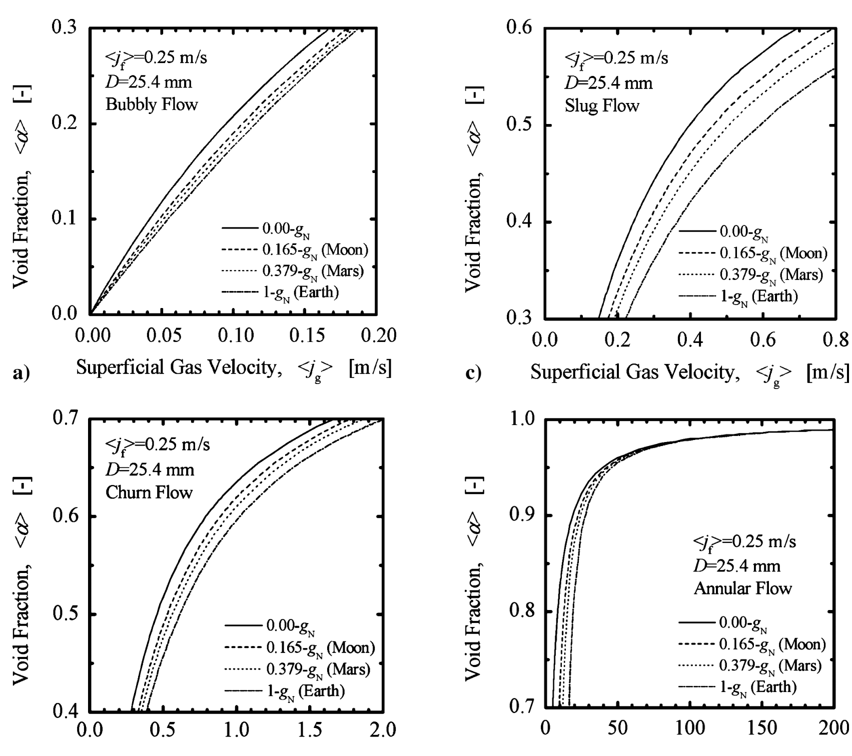

Fig. 10 Example computation of drift-flux model in various two-phase flow regimes for $\langle j_f\rangle$ = 0.25 m/s at reduced gravity conditions.

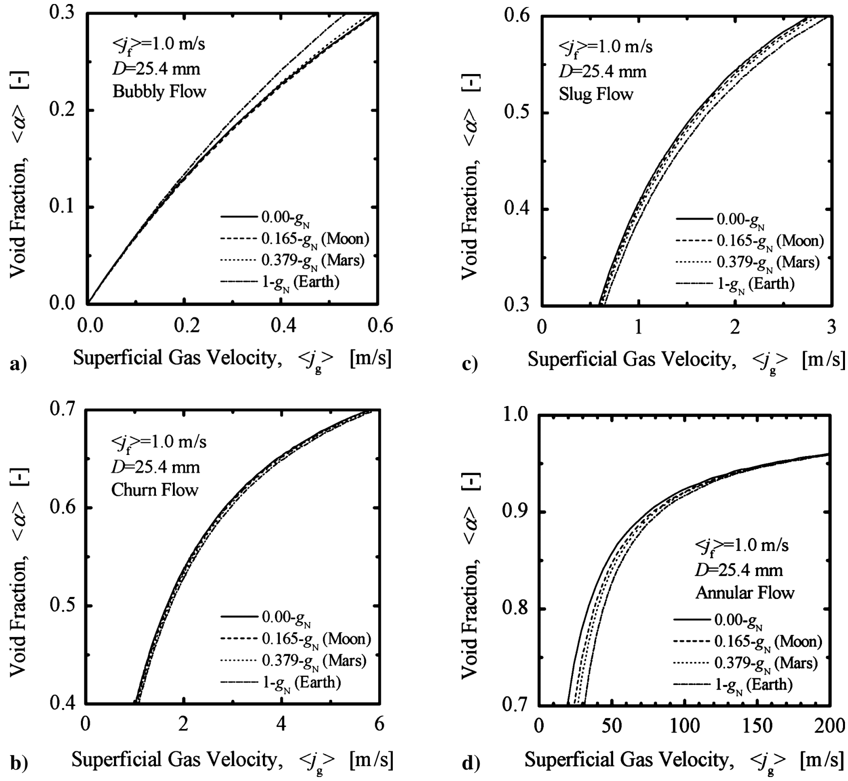

Fig. 11 Example computation of drift-flux model in various two-phase flow regimes for $\langle j_f \rangle$ = 1.0 m/s at reduced gravity conditions.

The foregoing comparisons validate the applicability of the drift-flux model given in Table 1 to adiabatic air–water and nitrogen–water flows. The applicability of the drift-flux model to other fluid systems should be evaluated by extensive data sets to be taken in various flow systems in a future study. In addition to this, note that the distribution parameter in an adiabatic flow can be different from that in a subcooled boiling flow because the bubbles are generally localized near a heater surface in a subcooled boiling flow.[9,13] Thus, the constitutive equations of the distribution parameter should be modified by considering the bubble localization effect when they are applied to subcooled boiling systems.

Example Computations of Drift-Flux Model at Reduced Gravity Conditions

To examine the effect of the gravity on the void fraction in two-phase flow systems, example computations of the newly developed drift-flux model in various flow regimes are performed for various flow regimes in a 25.4-mm-diam pipe, which is approximately the median value of the pipes listed in Table 2. Here, $\langle j_f \rangle = 0.25$ and 1.0 m/s are, respectively, chosen as typical low and high liquid velocity conditions in which the local slip and phase distribution effects are more pronounced. Figures 10 and 11 show the calculated results for $\langle j_f \rangle = 0.25$ and 1.0 m/s, respectively. In each of Figs. 10 and 11, Figs. 10a and 11a, 10c and 11c, 10b and 11b, and 10d and 11d indicate the calculations for bubbly, slug, churn, and annular flows, respectively. Solid, broken, dotted, and chain lines indicate the calculated void fractions for $0g_N$ (0.00 m/s^2), $0.165g_N$ (1.62 m/s^2), $0.379g_N$ (3.71 m/s^2), and $1g_N$ (9.80 m/s^2) corresponding to zero gravity and the gravity levels on the moon, on Mars, and on Earth, respectively.

Figure 10 shows that, for $\langle j_f \rangle = 0.25$ m/s, the void fractions are increased by decreasing the gravity, and the rate of the increased void fraction due to the reduced gravity can reach tens of a percentage at relatively lower void fractions. In the bubbly flow regime, the void fraction at $1g_N$ is lower than that at $0g_N$ due to the insignificant distribution parameter effect and similar values in the distribution parameter between normal and microgravity conditions for $\langle j_f \rangle = 0.25$ m/s. In such low liquid velocity and low mixture volumetric flux conditions, a core void peaking is observed at normal gravity conditions,[19] resulting in $C_0 \approx 1.2$. In fact, Eq. (10) predicts the distribution parameter to be about 1.18. Thus, the lower void fraction at $1g_N$ is mainly attributed to the higher drift velocity at $1g_N$. In slug-flow and churn-flow regimes, the void fractions are increased by decreasing the gravity due to the decreased drift velocity because the distribution parameters in these flow regimes may not depend on the gravity. In the annular-flow regime, the void fractions are increased by decreasing the gravity due to the decreased distribution parameter. The gravity effect becomes insignificant in the annular-flow regime with void fractions higher than 0.9.

Note from Fig. 11 that the effect of the gravity on the void fraction becomes insignificant for higher superficial liquid velocities such as $\langle j_f \rangle = 1.0$ m/s, namely, for higher mixture volumetric flux. Note that the void fraction at $1g_N$ is higher than that at $0g_N$ in the bubbly flow regime due to the pronounced distribution parameter effect for $\langle j_f \rangle = 1.0$ m/s. The distribution parameter at $1g_N$ is expected to be lower than that at $0g_N$ due to wall peaking in the void fraction distribution.[18] In fact, Eq. (10) predicts the distribution parameter to be about 1.10. Figure 11 indicates that the rate of the decreased void fraction due to the reduced gravity is rather small. Thus, the effect of the gravity on the void fraction in two-phase flow systems is more pronounced for low liquid flow and low mixture volumetric flux conditions, whereas the gravity effect may be ignored for high liquid velocity conditions, namely, high volumetric flux conditions.

In general, the distribution parameter effect is much larger than the local slip effect in relatively high mixture volumetric flux conditions. Then, negligible drift velocity may be assumed for practical purposes. However, in detailed and precise simulations using the drift-flux model, the detailed formulation of the distribution parameter and the drift velocity would be indispensable. In a future study, extensive experimental work on accurate measurements of local flow parameters should be addressed to evaluate the drift-flux model given in Table 1.

Conclusions

The drift-flux model is of practical importance for two-phase flow analyses at reduced gravity conditions. In view of this, the drift-flux model, which takes the gravity effect into account, is studied in detail. The obtained results are as follows:

1) The constitutive equation of the distribution parameter for bubbly flow, which takes the gravity effect into account, has been proposed, and the constitutive equations for slug, churn, and annular flows, which can be applicable to normal and microgravity conditions, are recommended based on existing experimental and analytical studies.

2) The drift-flux model considering the gravity effect has been finalized by the recommended constitutive equations of the distribution parameter and the constitutive equations of the drift velocity previously derived by taking the effect of the wall friction on the relative velocity between phases into account.

3) A comparison of the newly developed drift-flux model with various experimental data over various flow regimes and a wide range of flow parameters taken at microgravity conditions shows satisfactory agreement.

4) An example computation of the newly developed drift-flux model has been performed at various reduced gravity conditions. It has been revealed that the effect of the gravity on the void fraction in two-phase flow system is more pronounced for low liquid flow and low mixture volumetric flux conditions, whereas the gravity effect may be ignored for high mixture volumetric flux conditions.

Acknowledgments

Part of this work was supported by a Grant-in-Aid for Scientific Research from the Japan Society for the Promotion of Science (No. 14580542) and the ground-based research program for space utilization promoted by the Japan Space Forum.

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H. Chelliah
Associate Editor