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Hossein Barati

Takashi Hibiki

Joshua P. Schlegel
Missouri University of Science and Technology, schlegelj@mst.edu

Naofumi Tsukamoto

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Two-group drift-flux model for dispersed gas-liquid flow in large-diameter pipes

Hossein Barati [a], Takashi Hibiki [a,*], Joshua P. Schlegel [b], Naofumi Tsukamoto [c]

[a] Department of Mechanical Engineering, City University of Hong Kong, 83 Tat Chee Avenue, Kowloon Tong, Hong Kong
[b] Department of Nuclear Engineering and Radiation Sciences, Missouri University of Science and Technology, 301W 14th St, Rolla, MO 65401, United States of America
[c] Regulatory Standard and Research Department, Secretariat of Nuclear Regulation Authority, Roppongi First Building, 1-9-9 Roppongi, Minato-ku, Tokyo, 106-8450, Japan

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ABSTRACT

Interfacial heat and mass transfer are prevalent in industrial processes. The interfacial transfer rate can be obtained by the product of their fluxes and interfacial area concentration (IAC) calculated by the interfacial area transport equation (IATE). Bubbles show different behavior according to their sizes. Hence, bubbles are classified into two groups. Consequently, two-group IATE is required causing to use of two gas momentum equations leading to more complexity. The present study suggests a new reliable two-group drift-flux modeling to reduce the two gas momentum equations to one gas mixture momentum equation for gas-liquid flow in large-diameter pipes. The model is developed based on the drift-flux model concept and experimental data. Group-one and group-two distribution parameters and drift velocities are validated through experimental data. The results show that the proposed two-group drift-flux model can support the concept of drift velocity from the bubbly to beyond the bubbly flow and consistency between the one-group and two-group drift-flux models. Moreover, steam-water data are used to validate the applicability of the model in steam-water flows condition. The developed two-group drift-flux model is indispensable for reducing the two gas momentum equations to one gas mixture momentum equation when two-group IATE is implemented into thermal-hydraulic codes to improve the prediction accuracy of IAC.

1. Introduction

Two-phase flows, commonly associated with heat transfer, are involved in various industrial applications including steam generators, heat exchangers, boilers, air conditioners, nuclear reactors, and petroleum production systems [1–4]. A comprehensive understanding of two-phase flow thermal-hydraulic behaviors can significantly improve engineering designs regarding performance and safety. The two-fluid model is the most accurate model for integral system analysis to formulate macroscopic thermo-fluid dynamics of two-phase flows. The two-fluid model considers each phase as a separate phase coupled to each other through mass, momentum, and heat transfer through their interfaces. Additional closure relations are required to predict these mass, momentum, and heat transfers between phases. Therefore, the accuracy of two-fluid model-based analysis codes is strongly influenced by the accuracy of these interaction terms [5,6].

Mass, momentum, and heat transfer between phases depend on their corresponding driving forces and interfacial area concentration (IAC) [7,8]. The latter carries the geometrical effect of the interfacial structure and is defined as the interfacial area per unit volume of a mixture. Thus, IAC is closely linked to the flow regimes [9]. There are two methods to calculate one-dimensional IAC. The first method is conventional, in which IAC is obtained using correlations developed based on experimental data for each flow regime. Because this method is based on experimental data, usually obtained in quasi-fully developed conditions, it suffers from major shortcomings, such as high uncertainties for developing two-phase flows and numerical instabilities close to the flow regime transition zones due to discontinuities [10,11]. Hence, the interfacial area transport equation (IATE) was introduced [12] and has been developed [13] to overcome these shortcomings as the second method to predict the IAC mechanistically.

In gas-liquid two-phase flows, bubbles can be divided into two groups based on their shapes and sizes. Group-one includes spherical and distorted bubbles, whereas group-two includes cap, slug, and churn-turbulent bubbles [14–18]. Each group is subjected to different drag

* Corresponding author at: Department of Mechanical Engineering, City University of Hong Kong, 83 Tat Chee Avenue, Kowloon Tong, Hong Kong.
E-mail address: thibiki@cityu.edu.hk (T. Hibiki).

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Nomenclature

C_0	distribution parameter [-]
C_{01}	group-one distribution parameter [-]
C_{02}	group-two distribution parameter [-]
C_∞	asymptotic value of distribution parameter [-]
$C_{\infty,1}$	asymptotic value of group-one distribution parameter [-]
$C_{\infty,2}$	asymptotic value of group-two distribution parameter [-]
D_{base}	cap bubble base diameter [m]
D^*_{base}	non-dimensional cap bubble base diameter [-]
D_c	maximum cap bubble critical diameter [m]
D_H	hydraulic diameter [m]
D^*_H	non-dimensional hydraulic diameter [-]
$D_{Sm,1}$	group-one Sauter mean diameter [m]
$D_{Sm,2}$	group-two Sauter mean diameter [m]
g	gravitational acceleration [m/s^2]
j	mixture volumetric flux [m/s]
j_f	superficial liquid velocity [m/s]
j_g	superficial gas velocity [m/s]
m_d	mean absolute error [-] or [m/s]
m_{rel}	mean relative error [-]
$m_{rel,\ abs}$	mean relative absolute error [-]
N	number of data [-]
$N_{\mu f}$	viscosity number for liquid phase [-]
N_ρ	density ratio ρ_g/ρ_f [-]
s_d	standard deviation [-] or [m/s]
s_{rel}	relative standard deviation [-] or [m/s]
v_f	liquid velocity [m/s]
v_g	gas velocity [m/s]
v_{g1}	group-one gas velocity [m/s]
v_{g2}	group-two gas velocity [m/s]
v_{gj}	drift velocity [m/s]
v_{gj1}	group-one drift velocity [m/s]
v_{gj2}	group-two drift velocity [m/s]
v_r	relative velocity [m/s]

Greek symbols

α	void fraction [-]
α_1	group-one void fraction [-]
α_2	group-two void fraction [-]
$\Delta\rho$	density difference between gas and liquid phases [kg/m^3]
ρ_f	liquid density [kg/m^3]
ρ_g	gas density [kg/m^3]
σ	surface tension [N/m]
ψ	value [-] or [m/s]

Mathematical symbols

$\langle\rangle$	area-averaged quantity
$\langle\langle\rangle\rangle$	void fraction-weighted mean quantity

Superscripts

$+$	parameter non-dimensionalized by $(\Delta\rho g\sigma/\rho_f^2)^{0.25}$
$*$	parameter non-dimensionalized by Laplace length $(\sigma/g\Delta\rho)^{0.5}$

Subscripts

B	bubbly flow
CT	churn-turbulent flow
Cal.	calculated value
exp.	measured value
HT	value calculated by Hibiki and Tsukamoto's correlation
i	i th data
n	bubble group number
S	slug flow
KI	value calculated by Kataoka and Ishii's correlation

coefficients. Therefore, implementing a two-group IATE model is indispensable for correctly describing the IAC [19,20]. In one-dimensional flows, this will increase the number of equations of the original two-fluid model from six to eight in the modified two-group two-fluid model. One gas momentum equation for each bubble group will lead to higher computational resources and convergence problems [21]. Furthermore, an additional gas momentum equation demands more constitutive relations, which brings more complexity and requires appropriate experimental data to develop those relations. Several researchers have been developing methods to decrease the complexity by reducing the two gas momentum equations to the mixture momentum equation, whereas the two-group bubbles are studied separately with IATE.

Sun et al. [19] proposed a simplified approach based on combining the two gas momentum equations and obtaining the group-one and group-two velocity difference with the steady-state drag force and pressure gradient. In addition, they proposed that the extension of the drift-flux approach for each bubble group can be used as the constitutive equations to solve the set of one-dimensional equations. Brooks et al. [21] assumed a mixture volumetric flux profile to obtain the drift-flux distribution parameter for each group. They extended the original drift-flux expression [22] to obtain a two-group drift-flux model. They evaluated their model with experimental data for flow in the annulus with a hydraulic diameter of 19.0 mm. In another research, Brooks et al. [10] applied the same approach for boiling flow and showed the comparison with boiling steam-water data.

One-group drift-flux model or traditional drift-flux model has been well established [23–25]. Although some research has been done on the two-group drift-flux model, it still needs to be developed well, particularly for two-phase flow through large-diameter pipes. One important reason is that few gas-liquid two-phase flow databases are appropriate for studying two-group bubbles. Therefore, two-group drift-flux modeling for large-diameter pipes is more challenging than usual [26,27]. Measuring local parameters in large-diameter pipes is also difficult due to complex mechanisms such as recirculation [28]. Moreover, turbulence in large-diameter pipes causes void fraction, gas velocity, IAC, and Sauter mean diameter profiles different from those in medium-diameter pipes [29,30]. This implies that the common models in medium-diameter pipes may not perform acceptably for large-diameter pipes [27]. Therefore, two-phase flows in large-diameter pipes call for more reliable experimental databases and investigations to elaborate on their knowledge. Swearingen et al. [31] applied sensitivity analysis for large-diameter pipes by using different models for group-one and group-two distribution parameters and drift velocities to show the importance of selecting group-one and group-two drift-flux models. Meaningful selection can reduce the error significantly in comparison with one-group modeling.

Two-group drift-flux modeling in large-diameter pipes is still an unresolved problem. The primary objective of this study is to propose a model for a two-group drift-flux approach in large-diameter pipes. To this end, the first in a series, a brief review of the current state of the approach is reported. Then, the experimental data used for developing the model are explained. After that, the results of the sensitivity analysis on the two-group drift velocities are presented. Afterward, the group-one and group-two drift velocities are proposed and compared with experimental data. Recently, Hibiki and Tsukamoto [32] developed a well-benchmarked one-group drift-flux model in vertical medium-to-large diameter pipes. The distribution parameters of the two-group drift-flux model are compared with Hibiki and Tsukamoto's (2023) correlations. In addition, the results are compared with other experimental datasets. The applicability of the new two-group drift-flux model was also validated for steam-water flows with steam-water data. The approach used in this study differs from those previously used by other researchers in that consistency between two-group distribution parameters and drift velocities are examined regarding those of one-group.

2. Drift-flux approaches

In this section, a brief overview of drift-flux modeling is presented. Next, two drift-flux models (Kataoka and Ishii [33], Hibiki and Tsukamoto [32]) that form the foundation of this study in large-diameter pipes for vertical two-phase flows are explained. Afterward, the general form of the two-group drift-flux formulation is described.

2.1. Drift-flux general expression

One-group drift-flux formulation was developed by Zuber and Findlay [22] to consider the effect of the non-uniformity of mixture volumetric flux and void fraction profiles across the flow channel and the local relative velocity between phases. They proposed the following general expression as the one-dimensional drift-flux model by applying the area-averaging:

$$\langle\langle v_g \rangle\rangle = C_0 \langle j \rangle + \langle\langle v_{gj} \rangle\rangle, \tag{1}$$

where $\langle\rangle$ and $\langle\langle\rangle\rangle$ represent the area-averaged and void fraction weighted mean values, respectively. v_g and j indicate the local gas velocity and mixture volumetric flux, respectively. C_0 is the distribution parameter, which describes the effect of non-uniform distribution of mixture volumetric flux and void fraction. v_{gj} is the local drift velocity and accounts for the relative velocity between the two phases. The distribution parameter C_0 is defined as:

$$C_0 = \frac{\langle \alpha j \rangle}{\langle \alpha \rangle \langle j \rangle}, \tag{2}$$

where α is void fraction. Eq. (2) shows that the distribution parameter is the covariance of void fraction and mixture volumetric flux. Drift velocity v_{gj} is defined by:

$$v_{gj} = v_g - j. \tag{3}$$

Eq. (4) defines the void fraction weighted mean drift velocity:

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

C_0 and $\langle\langle v_{gj} \rangle\rangle$ must be determined to make Eq. (1) practical. Ishii [34] proposed the following equation for gas-liquid dispersed flows:

$$C_0 = C_\infty - (C_\infty - 1)\sqrt{\frac{\rho_g}{\rho_f}}, \tag{5}$$

where ρ_g and ρ_f represent the gas and liquid densities, respectively. C_∞ is an asymptotic value and depends on the flow channel geometry. For instance, C_∞ is 1.2 for pipes and 1.35 for rectangular channels. Moreover, the value of C_∞ is 1.1 for gas-liquid flows in annuli and rod bundles [21].

Non-dimensional form of Eq. (1) is obtained by using the velocity scale, $(\Delta\rho g\sigma/\rho_f^2)^{0.25}$:

$$\langle\langle v_g^+ \rangle\rangle = C_0 \langle j^+ \rangle + \langle\langle v_{gj}^+ \rangle\rangle, \tag{6}$$

where

$$\langle\langle v_g^+ \rangle\rangle \equiv \frac{\langle\langle v_g \rangle\rangle}{\left(\frac{\Delta\rho g\sigma}{\rho_f^2}\right)^{0.25}}, \tag{7}$$

$$\langle j^+ \rangle \equiv \frac{\langle j \rangle}{\left(\frac{\Delta\rho g\sigma}{\rho_f^2}\right)^{0.25}}, \tag{8}$$

$$\langle\langle v_{gj}^+ \rangle\rangle \equiv \frac{\langle\langle v_{gj} \rangle\rangle}{\left(\frac{\Delta\rho g\sigma}{\rho_f^2}\right)^{0.25}}. \tag{9}$$

Here σ, $\Delta\rho$ and g are surface tension, the density difference between phases, and gravitational acceleration, respectively.

The correlations for drift velocity $\langle\langle v_{gj} \rangle\rangle$ are developed by Ishii [34] in gas-liquid upward flows.

Bubbly flow:

$$\langle\langle v_{gj,B}^+ \rangle\rangle = \sqrt{2}(1 - \langle \alpha \rangle)^{1.75}, \tag{10}$$

Slug flow:

$$\langle\langle v_{gj,S}^+ \rangle\rangle = 0.35 D_H^{*\,0.5}, \tag{11}$$

where D_H^* represents non-dimensional hydraulic diameter.

$$D_H^* = \frac{D_H}{\sqrt{\frac{\sigma}{g\Delta\rho}}}, \tag{12}$$

where D_H is the hydraulic diameter.

Churn-turbulent flow:

$$\langle\langle v_{gj,CT}^+ \rangle\rangle = \sqrt{2}. \tag{13}$$

Eqs. (5) and (10) to (13) describe distribution parameter and drift velocity for medium-sized channel flow, respectively.

2.2. Drift-flux in one-dimensional large-diameter pipes

Kataoka and Ishii [33] explained that slug bubbles are unstable in large-diameter pipes. Slug bubbles spanning over a flow channel cannot form due to the Taylor instability; instead, cap bubbles form after the break up of the slug bubbles. Large-diameter pipes are defined as:

$$D_H^* \geq 30. \tag{14}$$

Kataoka and Ishii [33] developed a constitutive equation for drift velocity $\langle\langle v_{gj} \rangle\rangle$ in medium-to-large diameter pipes for pool conditions.

$$\langle\langle v_{gj,KI}^+ \rangle\rangle = 0.0019 D_H^{*\,0.809} \left(\frac{\rho_g}{\rho_f}\right)^{-0.157} N_{\mu f}^{-0.562} \text{ for } D_H^* \leq 30, \tag{15}$$

$$\langle\langle v_{gj,KI}^+ \rangle\rangle = 0.030 \left(\frac{\rho_g}{\rho_f}\right)^{-0.157} N_{\mu f}^{-0.562} \text{ for } D_H^* \geq 30, \tag{16}$$

where subscript KI denotes Kataoka and Ishii's correlation. $N_{\mu f}$ is viscosity number, which is defined as:

$$N_{\mu f} \equiv \frac{\mu_f}{\left(\rho_f \sigma \sqrt{\frac{\sigma}{g\Delta\rho}}\right)^{0.5}}, \tag{17}$$

where μ_f is the liquid viscosity. Eqs. (15) and (16) are applicable for low-viscosity numbers $N_{\mu f} \leq 2 \times 10^{-3}$. Kataoka and Ishii employed Eq. (5) with $C_\infty = 1.2$ to calculate C_0 for pipes. Therefore, Eqs. (5). (15) and (16) describe Kataoka and Ishii's one-dimensional drift-flux model for medium-to-large diameter pipes with low liquid viscosity. It should be noted that numerous sources of experimental data in the literature have supported the validity of Kataoka and Ishii's drift-flux model. Thus, it is used in several one-dimensional analysis codes, including the USNRC TRACE code [35].

Recently, Hibiki and Tsukamoto [32] explained Kataoka and Ishii's [33] drift-flux correlation prediction performance in the bubbly and beyond bubbly flow regimes. Although this correlation can accurately predict the gas velocity in high mixture volumetric flux conditions, its void fraction prediction in relatively low mixture volumetric flux conditions is underestimated. They found that the drift velocity is being changed continuously in the transition zone from bubbly flow to beyond bubbly flow, particularly in large-diameter pipes. Therefore, Hibiki and Tsukamoto [32] developed a drift-flux model for gas-liquid vertical dispersed flows to follow the flow characteristics in this zone. They developed constitutive equations for the distribution parameter and drift velocity in gas-liquid vertical dispersed flows in medium-to-large pipes. Their model is robust while it preserves simplicity to be applicable in operational conditions. The performance of this model has been validated by comparing it with various sources of experimental data. In this model, the distribution parameter is given by:

$$C_0 = \left\{1.0e^{-60.63\langle\alpha_{KI}\rangle^{2.367}} + 1.2\left(1 - e^{-60.63\langle\alpha_{KI}\rangle^{2.367}}\right)\right\} - \left\{1.0e^{-60.63\langle\alpha_{KI}\rangle^{2.367}} + 1.2\left(1 - e^{-60.63\langle\alpha_{KI}\rangle^{2.367}}\right) - 1\right\}\sqrt{\frac{\rho_g}{\rho_f}}, \tag{18}$$

where $\langle\alpha_{KI}\rangle$ is the void fraction calculated by Kataoka and Ishii's correlation [33], which is given by:

$$\langle\alpha_{KI}\rangle = \frac{\langle j_g^+\rangle}{C_0\langle j^+\rangle + \langle\langle v_{gj,KI}^+\rangle\rangle}. \tag{19}$$

In addition, Hibiki and Tsukamoto [32] proposed the following correlation for the drift velocity:

$$\langle\langle v_{gj,HT}^+\rangle\rangle = \langle\langle v_{gj,B}^+\rangle\rangle e^{-60.63\langle\alpha_{KI}\rangle^{2.367}} + \langle\langle v_{gj,KI}^+\rangle\rangle\left(1 - e^{-60.63\langle\alpha_{KI}\rangle^{2.367}}\right), \tag{20}$$

where subscript HT denotes Hibiki and Tsukamoto's correlation.

The distribution parameter for subcooled boiling flows was modeled by Ishii [34] as follows:

$$C_0 = \left(1.2 - 0.2N_\rho^{0.5}\right)\left(1 - e^{-18\langle\alpha\rangle}\right), \tag{21}$$

Hibiki and Tsukamoto demonstrated that the void fraction in Eq. (21) could be replaced by $\langle\alpha_{CT}\rangle$ which is the void fraction calculated by Ishii's correlation for churn flow.

$$\langle\alpha_{CT}\rangle = \frac{\langle j_g^+\rangle}{\left(1.2 - 0.2N_\rho^{0.5}\right)\langle j^+\rangle + \sqrt{2}}. \tag{22}$$

2.3. Two-group drift-flux modeling

Zuber and Findlay [22] consider all bubbles together, so their model is also known as one-group drift-flux. However, group-one and group-two bubbles show different distribution parameters, drift velocities, and transfer mechanisms due to differences in characteristics such as bubble shape and size. Therefore, it is reasonable if they are treated differently. In a two-group drift-flux model, different distribution parameters and drift velocities are assigned to each group [10]. The two-group drift-flux model in a non-dimensional form is given by:

$$\langle\langle v_{gn}^+\rangle\rangle = C_{0n}\langle j^+\rangle + \langle\langle v_{gjn}^+\rangle\rangle, \tag{23}$$

where

$$C_{0n} \equiv \frac{\langle\alpha_n j\rangle}{\langle\alpha_n\rangle\langle j\rangle}, \tag{24}$$

$$\langle\langle v_{gjn}^+\rangle\rangle \equiv \frac{\langle\alpha_n v_{gjn}^+\rangle}{\langle\alpha_n\rangle}. \tag{25}$$

Here, n indicates the group number and can be 1 or 2 for group-one and group-two bubbles, respectively. Eqs. (26) and (27) are satisfied for the area-averaged void fractions and non-dimensional void fraction weighted mean gas velocities, respectively.

$$\langle\alpha\rangle = \langle\alpha_1\rangle + \langle\alpha_2\rangle, \tag{26}$$

$$\langle\langle v_g^+\rangle\rangle = \frac{\langle\alpha_1\rangle\langle\langle v_{g1}^+\rangle\rangle + \langle\alpha_2\rangle\langle\langle v_{g2}^+\rangle\rangle}{\langle\alpha\rangle}. \tag{27}$$

Therefore, group-one and group-two distribution parameters and non-dimensional void fraction weighted mean drift velocities can be related to those of the one-group model by the following equations, respectively:

$$C_0 = \frac{\langle\alpha_1\rangle C_{01} + \langle\alpha_2\rangle C_{02}}{\langle\alpha\rangle}, \tag{28}$$

$$\langle\langle v_{gj}^+\rangle\rangle = \frac{\langle\alpha_1\rangle\langle\langle v_{gj1}^+\rangle\rangle + \langle\alpha_2\rangle\langle\langle v_{gj2}^+\rangle\rangle}{\langle\alpha\rangle}. \tag{29}$$

Distribution parameter and drift velocity models must be assigned to group-one and group-two bubbles to calculate their gas velocities. Brooks et al. [21] developed a model for two-group drift-flux by suggesting group-one drift velocity as Ishii's correlation for bubbly flow $\langle\langle v_{gj,B}^+\rangle\rangle$ and group-two drift velocity as:

$$\langle\langle v_{gj2}^+\rangle\rangle = 0.54 D_{base}^{*\,0.5}\left(1 - \langle\alpha_2\rangle\right)^{1.5} \; for \; D_{base} < D_c, \tag{30}$$

$$\langle\langle v_{gj2}^+\rangle\rangle = 0.7 C_e^{0.5}\left(1 - \langle\alpha_2\rangle\right)^{1.5} \; for \; D_{base} = D_c, \tag{31}$$

where D_{base} and D_c represent the cap bubble base diameter and maximum cap bubble critical diameter. The non-dimensional cap bubble base diameter is given by:

$$D_{base}^* \equiv \frac{D_{base}}{\sqrt{\frac{\sigma}{g\Delta\rho}}}. \tag{32}$$

The coefficient C_e is given by:

$$C_e = 27.1\left(1 + N_{\mu f}\right)^{0.83}. \tag{33}$$

D_c for the pipe and narrow channel flow, and D_{base} are given by:

$$D_c = 16\sqrt{\frac{\sigma}{g\Delta\rho}} \tag{34}$$

$$D_{base} \approx 2.96\langle D_{Sm,2}\rangle, \tag{35}$$

where $D_{Sm,2}$ is the group-two Sauter mean diameter.

Brooks et al. [21] developed a two-group drift flux model for dispersed flows in annuli. They assumed that the flow characteristics of group-one bubbles are not affected by the presence of group-two bubbles. Moreover, they recommended Hibiki and Ishii's distribution parameter correlation as the group-one distribution parameter.

$$C_{01} = \left(1.1 - 0.1N_\rho^{0.5}\right)\left(1 - e^{\left(-22\langle D_{Sm,1}\rangle/D_H\right)}\right), \tag{36}$$

where $D_{Sm,1}$ is group-one Sauter mean diameter. They suggested Eq. (5) with $C_{\infty,2} = 1.1$ for group-two distribution parameter.

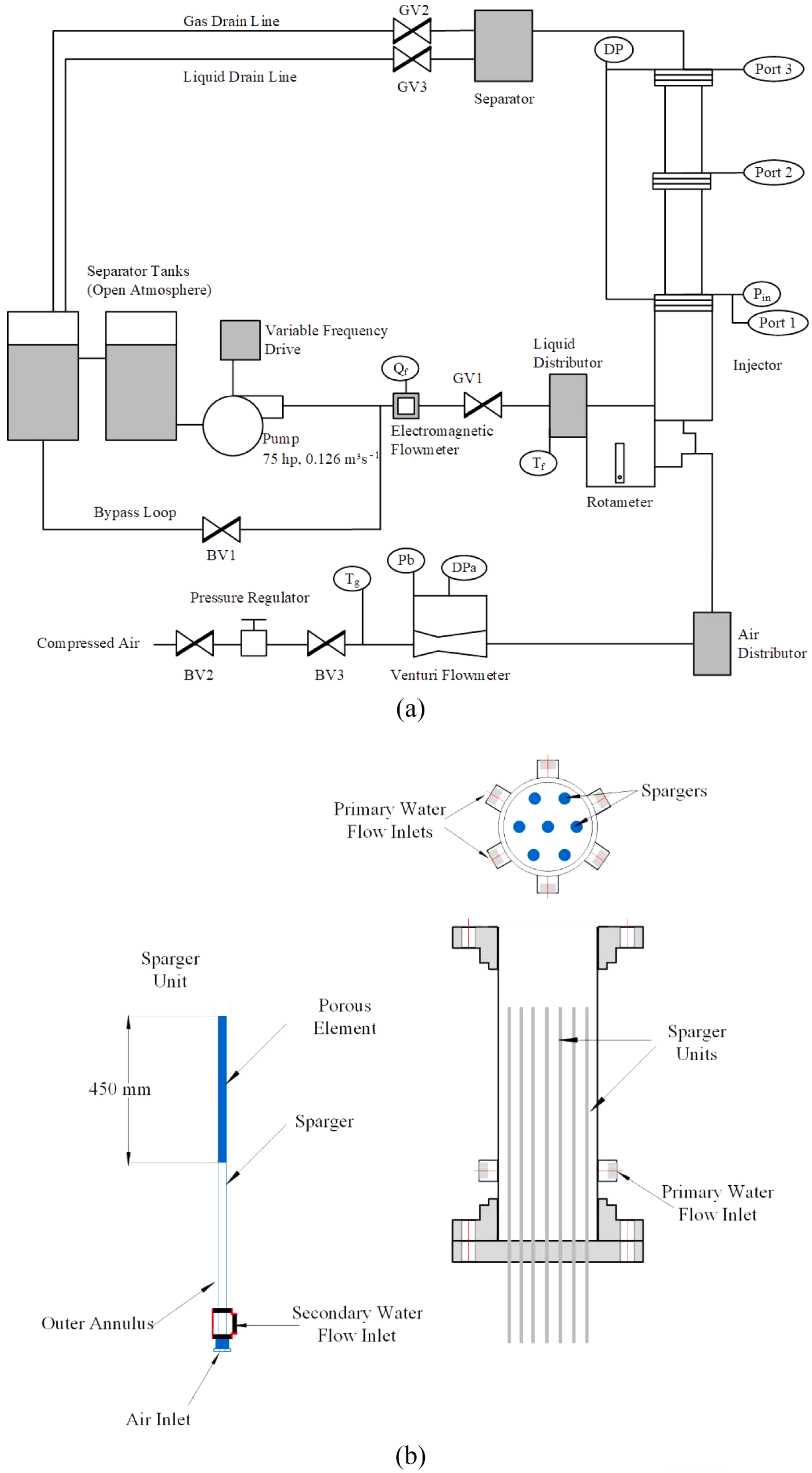


Fig. 1. Schematic diagram of the two-phase flow loop [26,36]. (a) Flow loop design, (b) Gas-liquid two-phase injector design.

3. Experimental database for model development

This section presents the experimental data conditions used for the development and validation of the model and the data quality control method. Experimental data used in this study were obtained by Schlegel et al. [26,36] for large-diameter pipes. The experimental facilities they used are shown in Fig. 1. It was equipped with a gas injector consisting of seven uniformly distributed sparger units. The experiment was carried out for the 4.5 m height test section with 0.152 m and 0.203 m diameter pipes in the bubbly flow injection condition and 0.152 m, 0.203 m, and 0.304 m diameter pipes in the cap-bubbly flow injection condition. The data were collected at three elevations along the 4.4 m height of the test section.

In their experiment, the measurement error of differential pressure transducers was ±0.1 kPa, and the measurement error of the gas volumetric flux measured by the venturi flow meter was ±2%. The gas flow rate was controlled by a compressor with a large tank and pressure regulator to avoid the considerable effect of upstream pressure on the gas flow rate. Moreover, the measurement error of the liquid volumetric flux measured by the magnetic liquid flow meter was ±0.64%. The liquid flow rate was controlled by a centrifugal pump with a variable frequency drive. The mixing process of water and air occurred in an injector unit with sintered elements confined by steel annuli. This configuration could maintain the initial bubble diameter constant by controlling the liquid flow rate through annuli for a wide range of flow conditions. Hence, the data were collected with approximately constant initial bubble diameter due to the constant liquid flow rate in the annuli.

Group-one and group-two local void fractions and interfacial velocities were measured by the four-sensor conductivity probe technique. The conductivity probe technique was introduced by Neal and Bankoff [37] and developed by Kataoka et al. [38] as the four-sensor conductivity probe. However, it had two major shortcomings, including bubbles failing to all sensor penetration and bubble interface deformation arising from probe configuration and bulky structure of the sensor, respectively. Later on, it was improved by employing the miniaturized structure of probe configuration associated with highly conductive and sharp sensor tips [39]. Therefore, the miniaturized configuration probe could measure bubbles with small diameters. In the experiment, the maximum measurement error of the conductivity probe was 12%. The local radial measurements were performed at 15 and 12 local points for the bubbly flow injection condition and cap-bubbly flow injection condition, respectively.

Although notable advances in local measurements have been achieved, the measurement of two-group parameters in large-diameter pipes is extremely difficult due to the local recirculation, which happens in low-liquid flow rate conditions. In addition, the four-sensor conductivity probes generally cannot detect the side interfaces of cap bubbles because the rear sensors may not pierce the interfaces, and sometimes there are some missing bubbles. Moreover, the conductivity sensors measure the interfacial velocity, while for two-group analysis, the gas velocity of each group is required. One solution is that if the deformations of the bubbles are not significant, then the interfacial velocity measured by the probe can be approximated as the gas velocity of the bubbles. This is reasonable for group-one bubbles, which have almost spherical shapes without significant deformation [40].

Because every modeling process is susceptible to data and needs reliable data, data quality control is essential to select proper data for that kind of modeling. Two criteria have been used to remove outlier data. First, if superficial gas velocity measured by gas venturi meter had more than a 20% difference with area-averaged superficial gas velocity measured by conductivity probes, then those data were not considered in the current analysis. Second, if a group-one area-averaged void fraction exceeded a value of 0.36, then that data was removed. This is also consistent with Smith's observation [27] that recirculation strongly affects group-one bubble measurements.

Finally, 156 data were collected after data processing from Schlegel et al. [26,36]. These data consist of 66 and 32 data for 0.152 m and 0.203 m diameter pipes in the bubbly flow injection condition and 23, 13, and 22 data for 0.152 m, 0.203 m, and 0.304 m diameter pipes in the cap-bubbly flow injection condition, respectively. Fig. 2 shows the test matrix for this study. In Fig. 2, the lines indicate the flow regime transition boundaries for upward gas-liquid flow in large-diameter vertical pipes calculated by the model developed by Schlegel et al. [41].

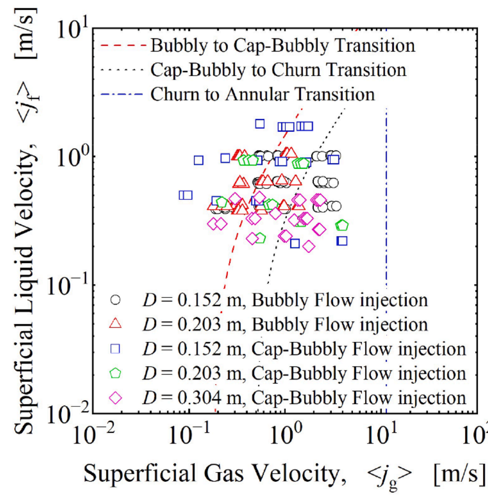


Fig. 2. Test matrix shown on the flow regime map for vertical gas-liquid flows in large diameter pipes.

4. Two-group drift-flux model and its evaluation

This section explains and presents the two-group drift-flux model developed in the present study. To this aim, first, the group-one and group-two drift velocities are discussed according to the sensitivity analysis, consistency with one-group drift-flux, and a comparison with experimental data. Then, the group-one and group-two distribution parameters are discussed using experimental data and comparison to the one-group distribution parameter. After that, group-one, group-two, and total gas velocities and total void fraction are evaluated using various experimental datasets. In the end, the reliability of the model for the steam-water system is examined with experimental data in the literature.

The following types of statistical parameters are used to examine the performance of the drift-flux model in Sections 4.2 to 4.5.

Mean absolute error, m_d

$$m_d = \frac{1}{N}\sum_{i=1}^{N}\left(\psi_{i,Cal.} - \psi_{i,exp.}\right). \tag{37}$$

Standard deviation, s_d

$$s_d = \sqrt{\frac{1}{N-1}\sum_{i=1}^{N}\left(\psi_{i,Cal.} - \psi_{i,exp.} - m_d\right)^2}. \tag{38}$$

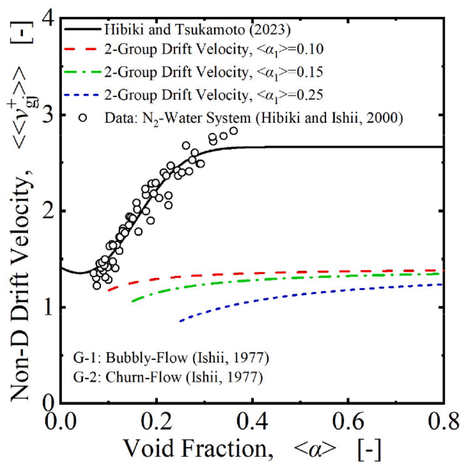
Mean relative error, m_{rel}

$$m_{rel} = \frac{1}{N}\sum_{i=1}^{N}\left(\frac{\psi_{i,Cal.} - \psi_{i,exp.}}{\psi_{i,exp.}}\right) \times 100. \tag{39}$$

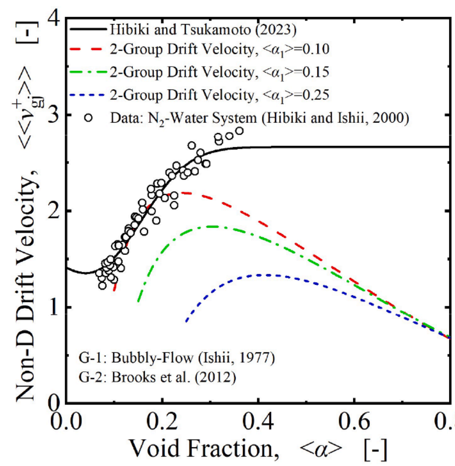
Mean absolute relative error, $m_{rel,abs}$

$$m_{rel,\ abs} = \frac{1}{N}\sum_{i=1}^{N}\left|\frac{\psi_{i,Cal.} - \psi_{i,exp.}}{\psi_{i,exp.}}\right| \times 100. \tag{40}$$

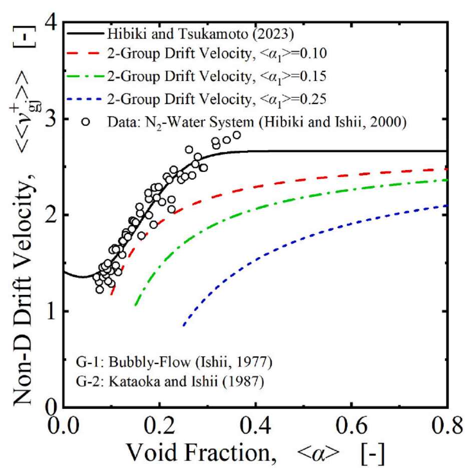
Relative standard deviation, s_{rel}



(a)



(b)



(c)

Fig. 3. Sensitivity analysis on the group-one and group-two drift velocities for (a) G-1 bubbly flow and G-2 churn flow, (b) G-1 bubbly flow and G-2 Brooks et al. correlation, (c) G-1 bubbly flow and G-2 Kataoka-Ishii.

$$s_{\mathrm{rel}} = \sqrt{\frac{1}{N-1}\sum_{i=1}^{N}\left(\frac{\psi_{\mathrm{i,Cal.}}-\psi_{\mathrm{i,exp.}}}{\psi_{\mathrm{i,exp.}}}-m_{\mathrm{rel}}\right)^2} \times 100. \tag{41}$$

Pearson coefficient, r

$$r = \frac{\sum_{\mathrm{i=1}}^{\mathrm{N}}\left(\psi_{\mathrm{i,exp.}}-\overline{\psi_{\mathrm{exp.}}}\right)\left(\psi_{\mathrm{i,Cal.}}-\overline{\psi_{\mathrm{Cal.}}}\right)}{\sqrt{\sum_{\mathrm{i=1}}^{\mathrm{N}}\left(\psi_{\mathrm{i,exp.}}-\overline{\psi_{\mathrm{exp.}}}\right)^2\sum_{\mathrm{i=1}}^{N}\left(\psi_{\mathrm{i,Cal.}}-\overline{\psi_{\mathrm{Cal.}}}\right)^2}}. \tag{42}$$

Root mean square error, *RMSE*

$$RMSE = \sqrt{\frac{\sum_{\mathrm{i=1}}^{\mathrm{N}}\left(\psi_{\mathrm{i,Cal.}}-\psi_{\mathrm{i,exp.}}\right)^2}{N}}. \tag{43}$$

Here, N, $\psi_{\mathrm{i,Cal.}}$ and $\psi_{\mathrm{i,exp.}}$ are the number of data, predicted value, and corresponding experimental data for the i$^{\mathrm{th}}$ datum, respectively. $\overline{\psi_{\mathrm{exp.}}}$ and $\overline{\psi_{\mathrm{Cal.}}}$ denote the average value of experimental data and calculated values. Eq. (40) is commonly used for a simple discussion of a prediction error.

4.1. Two-group drift velocity modeling

Fig. 3 indicates the sensitivity analysis results on the group-one and group-two drift velocities for several different pairs of drift-velocity correlations. It shows the behavior of void fraction weighted mean drift velocity, Eq. (29), with changes in void fraction. This value was obtained for three different group-one void fractions, which are indicated by red dash lines, green dash-dot lines, and blue short dash lines for $\langle\alpha_1\rangle = 0.10$, 0.15, and 0.25, respectively. In Fig. 3(a) to (c), the solid black lines show the non-dimensional drift velocity obtained by Hibiki and Tsukamoto's correlation, $\langle\langle v_{\mathrm{gj,HT}}^{+}\rangle\rangle$, calculated by Eq. (20). Moreover, the open black circles are drift velocity experimental data collected by Hibiki and Ishii [42]. They collected a set of experimental data for nitrogen-water flow in a vertical pipe with a diameter of 0.102 m. Therefore, void fraction weighted mean drift-velocity for different pairs of correlations can be evaluated using these experimental data.

Fig. 3(a) shows the drift velocity obtained by using group-one void fraction, $\langle\langle v_{\mathrm{gj,B}}^{+}\rangle\rangle_1$, defined by Eq. (44), as the group-one drift velocity and Ishii's correlation for churn flow, $\langle\langle v_{\mathrm{gj,CT}}^{+}\rangle\rangle$, calculated by Eq. (13), as the group-two drift velocity.

$$\left\langle\left\langle v_{\mathrm{gj,B}}^{+}\right\rangle\right\rangle_1 = \sqrt{2}\left(1-\langle\alpha_1\rangle\right)^{1.75}. \tag{44}$$

It indicates that as the void fraction increases, the void fraction weighted mean drift velocities for all three group-one void fractions

($\langle\alpha_1\rangle = 0.10,\ 0.15,$ and 0.25) converge to a value less than the drift velocity of the churn flow regime. However, the drift velocity beyond the bubbly flow regime is more than the drift velocity of the churn flow regime, as the experimental data show. It should converge to Hibiki and Tsukamoto's drift velocity. Therefore, this pair of correlations for group-one and group-two bubbles cannot show the behavior of drift-velocity in the transition zone from bubbly to beyond bubbly flow regime and after that.

Similarly, Fig. 3(b) shows the drift velocity obtained by group-one void fraction, $\langle\langle v^+_{gj,B}\rangle\rangle_1$, assigned to the group-one drift velocity. On the other hand, Brooks et al. correlation, Eq. (31), is assigned to the group-two drift velocity. This figure indicates that the void fraction weighted mean drift velocities for all three group-one void fractions ($\langle\alpha_1\rangle = 0.10,\ 0.15,$ and 0.25) increase to a certain point and then decrease with the increase in the void fraction. This trend cannot define the behavior of drift velocity, which is increasing with respect to the group-two void fraction according to the experimental data. Most importantly, after the void fraction increases to higher values, the void fraction weighted mean drift velocity, $\langle\langle v^+_{gj}\rangle\rangle$, corresponding to $\langle\alpha_1\rangle = 0.10$ decreases more than that of the others, corresponding to $\langle\alpha_1\rangle = 0.15$ and 0.25. However, it must not decrease more than the others due to the presence of higher fractions of the group-two bubbles. Hence, this pair of correlations for group-one and group-two bubbles cannot show the behavior of drift velocity during the transition zone and beyond the bubbly flow regime.

Fig. 3(c) shows the void fraction weighted mean drift velocity for the drift velocity obtained by the group-one void fraction, $\langle\langle v^+_{gj,B}\rangle\rangle_1$, as the group-one drift velocity and Kataoka and Ishii's correlation, $\langle\langle v^+_{gj,KI}\rangle\rangle$, as the group-two drift velocity. It shows that as the void fraction increases, the void fraction weighted mean drift velocity increases, $\langle\langle v^+_{gj}\rangle\rangle$; however, it never approaches Hibiki and Tsukamoto's drift velocity value, known as the best estimation of the drift velocity beyond the bubbly flow regime. In fact, this shortcoming can also be pointed out by the comparison to the experimental data. Therefore, this pair of correlations underestimates the value of void fraction weighted mean drift velocity and is not sound.

Fig. 3 shows that these pairs of correlations underestimate the drift velocity. Therefore, drift velocity correlations for group-one or group-two bubbles are underestimated in Fig. 3. Because Kataoka and Ishii's correlation was validated with substantial experimental data, the prediction of group-two bubbles is satisfactorily reliable. It implies that group-one bubbles drift velocity is underestimated in Fig. 3, so the correlation of group-one drift velocity must be improved.

Otake et al. [43] mentioned that in the wake region, there is an effective length in which small bubbles are affected by the larger leading bubble. In fact, a portion of small bubbles, which are flowing in this effective length zone, feel different drag forces in comparison to those small bubbles outside this zone. Wu et al. [13] mentioned that those bubbles would accelerate and maybe collide with the leading one. Therefore, their drift velocity increases. The effect of the wake region on the acceleration of the trailing bubbles was also discussed by several researchers, including Brücker [44], Chai and Cheng [45], and Talvy et al. [46]. This demonstrates that the velocity of small bubbles (group-one bubbles) is influenced by the preceding larger cap bubbles (group-two bubbles).

Hibiki and Tsukamoto [32] employed various databases from different sources to compare the performance of different drift velocity correlations. They found that when the superficial gas velocity was relatively low, Ishii's correlation for bubbly flow [34], $\langle\langle v^+_{gj,B}\rangle\rangle$, could be used to predict gas velocity. The predicted values agreed with the experimental data. However, when superficial gas velocity increased, the predicted values by Ishii's correlation for bubbly flow departed from the experimental data. The predicted values by Kataoka and Ishii's correlation, $\langle\langle v^+_{gj,KI}\rangle\rangle$, agreed with the experimental data at the higher superficial gas velocity conditions. They found this effect significant, particularly in large-diameter pipes, in the transition zone from bubbly flow to beyond bubbly flow.

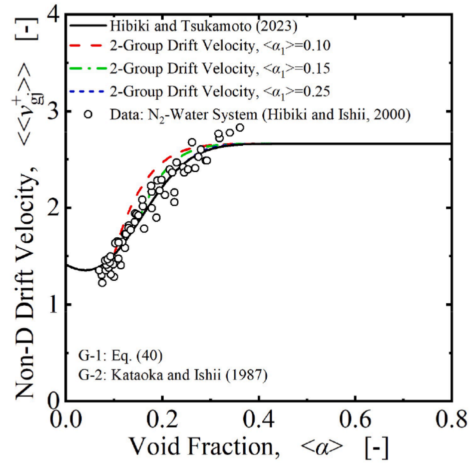


Fig. 4. Comparison of the two-group drift velocity model with experimental data: G-1 Eq. (40) and G-2 Kataoka-Ishii.

Based on the discussions on group-one drift velocity acceleration in the wake region in the literature and Hibiki and Tsukamoto's results [32], one can conclude that group-one drift velocity increases in the transition zone from the bubbly flow to beyond the bubbly flow. This brought motivation to develop a two-group drift-flux model for large-diameter pipes. Hence, in this part, $\langle\langle v^+_{gj1}\rangle\rangle$ and $\langle\langle v^+_{gj2}\rangle\rangle$ correlations are proposed.

The drift velocity of group-one is firmly influenced by the group-two void fraction distribution. Hibiki and Tsukamoto's drift velocity correlation [32], Eq. (20), considers the effect of the void fraction of the group-two bubbles on the group-one drift velocity. The drift velocity of group-one bubbles is approximated as follows:

$$\left\langle\left\langle v^+_{gj1}\right\rangle\right\rangle = \left\langle\left\langle v^+_{gj,B}\right\rangle\right\rangle_1 e^{-60.63\langle\alpha_{KI}\rangle^{2.367}} + \left\langle\left\langle v^+_{gj,KI}\right\rangle\right\rangle\left(1 - e^{-60.63\langle\alpha_{KI}\rangle^{2.367}}\right). \tag{45}$$

In the transition zone, the drift velocity of the group-one obtained by Eq. (45) increases from the drift velocity of bubbly flow (Ishii's correlation for bubbly flow) to that of beyond bubbly flow (Kataoka and Ishii's correlation) as the void fraction increases from the bubbly flow regime to beyond bubbly flow regime.

Hibiki and Tsukamoto [32] demonstrated that Kataoka and Ishii's correlation [33] could accurately predict the drift velocity beyond the bubbly flow. Therefore, Kataoka and Ishii's correlation Eqs. (15) and (16) is used to calculate the drift velocity of group-two bubbles:

$$\left\langle\left\langle v^+_{gj2}\right\rangle\right\rangle = \left\langle\left\langle v^+_{gj,KI}\right\rangle\right\rangle. \tag{46}$$

Fig. 4 shows the proposed group-one drift velocity, Eq. (45), and Kataoka and Ishii's correlation, $\langle\langle v^+_{gj,KI}\rangle\rangle$, as the group-two drift velocity. As this figure indicates, there is a smooth increase in void fraction weighted mean drift velocity, $\langle\langle v^+_{gj}\rangle\rangle$, in the transition zone. After that, it overlaps Hibiki and Tsukamoto's drift velocity beyond the bubbly flow regime. Furthermore, a comparison with the experimental data supports the validity of this pair of correlations for group-one and group-two drift velocity. This figure demonstrates that this pair of correlations can satisfy the drift velocity behavior in the transition zone from bubbly to beyond bubbly flow and after the transition zone.

It should be noted that the void fraction weighted mean values of the group-one and group-two drift velocities, Eq. (29), should be consistent with the one-group drift velocity concept. This value should start from the drift velocity of bubbly flow for very small void fractions. Then, it

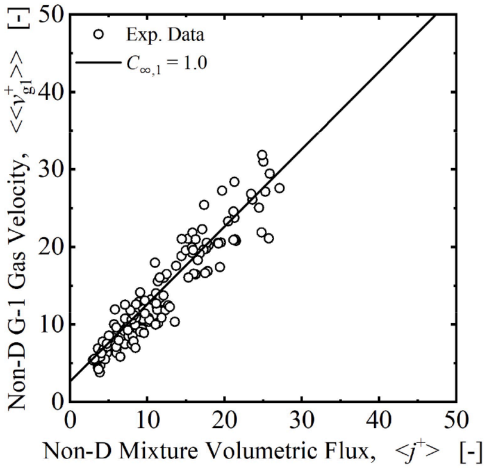


Fig. 5. Comparison between the predicted non-dimensional group-one gas velocities and the non-dimensional group-one gas velocities measured by Schlegel et al. [26,36].

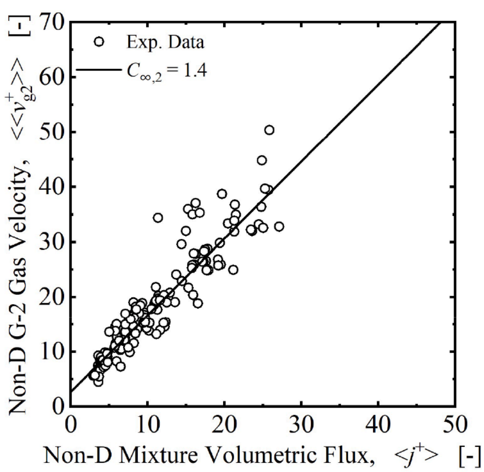


Fig. 6. Comparison between the predicted non-dimensional group-two gas velocities and the non-dimensional group-two gas velocities measured by Schlegel et al. [26,36].

should decrease by increasing void fractions until group-two bubbles start being formed. Eq. (45) can capture this trend. When the transition zone from bubbly flow to beyond bubbly flow begins, one-group drift velocity increases until the transition zone ends. It approaches a certain value which is group-two bubbles drift velocity. These sensitivity analysis and comparison with the experimental data, shown in Figs. 3 and 4, demonstrate that Eq. (45) as the group-one drift velocity and Kataoka and Ishii's correlation as the group-two drift velocity can satisfy the physical behavior of one-group drift velocity.

4.2. Two-group distribution parameter modeling

Figs. 5 and 6 show the drift-flux plot of group-one and group-two bubbles, respectively, for the experimental data collected by Schlegel et al. [26,36]. Distribution parameters for group-one and group-two bubbles should satisfy the drift-flux model of each group, while their void fraction weighted mean value, obtained by Eq. (28), should be consistent with the conventional one-group distribution parameter. Analysis of the experimental data through each group's drift-flux plots shows that $C_{\infty,1}$ and $C_{\infty,2}$ are approximated as constant values equal to 1.0 and 1.4, respectively. Thus, the proposed distribution parameter correlations for group-one and group-two bubbles, based on Eq. (5), are expressed by:

$$C_{01} = 1.0, \tag{47}$$

$$C_{02} = 1.4 - 0.4\sqrt{\frac{\rho_g}{\rho_f}}. \tag{48}$$

Fig. 5 shows all experimental data of $\langle\langle v_{g1}^{+}\rangle\rangle$ in a single plot. The mean relative error and relative standard deviation are 5.69% and 16.9%, respectively. More types of statistical parameters are presented in Table 1. Accordingly, the drift-flux model with $C_{\infty,1} = 1.0$ for group-one bubbles shows a good agreement with experimental data.

Fig. 6 shows all experimental data of $\langle\langle v_{g2}^{+}\rangle\rangle$ in a single plot. The mean relative error and relative standard deviation are −1.88% and 17.2%, respectively. More types of statistical parameters are presented in Table 2. The results indicate that the drift-flux model with $C_{\infty,2} = 1.4$ for group-two bubbles can acceptably predict the experimental values.

The consistency of the proposed distribution parameter for the group-one and group-two bubbles with the one-group distribution parameter is demonstrated in Fig. 7. This figure compares the one-group distribution parameter calculated from the two-group void fraction weighted mean distribution parameter, Eq. (28), and Hibiki and Tsukamoto's correlation. The solid line shows the one-group distribution parameter for the two-phase flows in vertical large-diameter pipes, calculated by Hibiki and Tsukamoto's correlation. The data points indicate the one-group distribution parameters obtained by the void fraction weighted mean of the group-one and group-two bubbles, Eqs. (47) and (48), respectively. Each group's void fractions of the experimental data were used to obtain the mean values of the distribution parameter. Fig. 7 shows that Eqs. (47) and (48) are consistent with the conventional one-group distribution parameter. More interestingly, they also follow the trend in the transition zone from bubbly to beyond bubbly flow regime. It demonstrates that Eqs. (47) and (48) can reproduce the results in the literature reasonably well.

When the developed two-group drift flux correlation is extended to boiling two-phase flows, the wall nucleation effect should be considered in the group-one distribution parameter. Due to limited two-group measurement for boiling two-phase flows in large-diameter pipes, Eq. (49) is tentatively recommended by analogy to Eq. (21) for the group-one distribution parameter.

$$C_{01} = 1.0 \times \left(1 - e^{-18\langle\alpha_{CT}\rangle}\right). \tag{49}$$

Table 1
Performance evaluation of the group-one drift-flux model for non-dimensional group-one gas velocity prediction.

Diameter [m]	N	Injection condition	Non-Dimensional Group-one Gas Velocity, $\langle\langle v_{g,1}\rangle\rangle$, statistical parameters						
			m_d [-]	s_d [-]	m_{rel} [%]	s_{rel} [%]	r [-]	$RMSE$ [-]	$m_{rel,abs}$ [%]
0.152	66	Bubbly flow	1.34	1.39	11.7	11.5	0.976	1.93	12.7
0.203	32	Bubbly flow	1.13	1.74	14.3	20.8	0.818	2.06	19.1
0.152	23	Cap-bubbly flow	−1.93	2.85	−7.20	18.4	0.941	3.45	16.7
0.203	13	Cap-bubbly flow	−0.853	0.790	−6.28	4.99	0.989	1.16	6.82
0.304	22	Cap-bubbly flow	−0.606	1.26	−4.47	9.26	0.966	1.37	8.96
All data	156	–	0.362	2.10	5.69	16.9	0.946	2.14	13.6

Table 2
Performance evaluation of the group-two drift-flux model for non-dimensional group-two gas velocity prediction.

Diameter [m]	N	Injection condition	Non-Dimensional Group-two Gas Velocity, $\langle\langle v_{g,2}\rangle\rangle$, statistical parameters						
			m_d [-]	s_d [-]	m_{rel} [%]	s_{rel} [%]	r [-]	$RMSE$ [-]	$m_{rel,abs}$ [%]
0.152	66	Bubbly flow	0.205	2.29	1.34	11.6	0.965	2.28	9.12
0.203	32	Bubbly flow	−1.11	2.15	−5.41	15.4	0.895	2.39	13.5
0.152	23	Cap-bubbly flow	−4.18	5.73	−7.24	27.6	0.909	7.09	22.3
0.203	13	Cap-bubbly flow	−2.81	2.44	−12.9	7.88	0.968	3.72	12.9
0.304	22	Cap-bubbly flow	0.694	2.83	5.67	18.6	0.897	2.85	15.3
All data	156	–	−0.894	3.50	−1.88	17.2	0.927	3.62	13.2

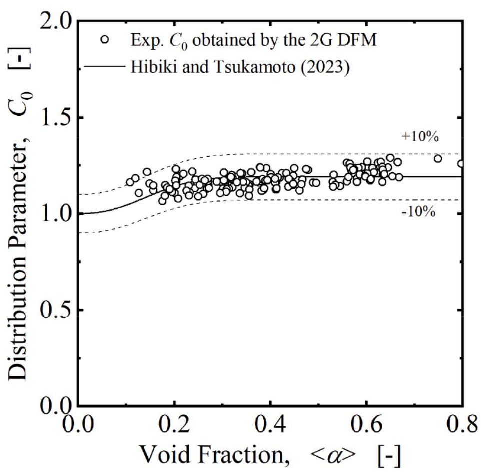


Fig. 7. Comparison between the distribution parameter obtained by the two-group model using Schlegel et al. [26,36] database and Hibiki and Tsukamoto's correlation.

4.3. Two-group gas velocity and void fraction evaluation

Fig. 8 shows the total performance of the two-group drift-flux model. Fig. 8(a) compares the experimental non-dimensional gas velocity data collected by Schlegel et al. [26,36] and the predicted non-dimensional gas velocity obtained by the two-group drift-flux model. The mean relative error and relative standard deviation are 0.940% and 13.5%, respectively. Table 3 presents more statistical parameters for comparison between experimental values and predicted values of the non-dimensional gas velocity. Fig. 8(b) compares the experimental void fraction and predicted void fraction obtained by the two-group drift-flux model. The mean relative error and relative standard deviation of void fraction are 1.44% and 11.4%, respectively. Table 4 presents statistical parameters for the prediction of void fractions. Comparisons with experimental data are satisfactory for both gas velocity and void fraction.

4.4. Validation of the two-group drift-flux model using different datasets

In the previous section, the two-group drift-flux model was proposed and evaluated based on the experimental data of Schlegel et al. [26,36]. In this section, the two-group drift-flux model is evaluated by four other datasets that were not used in the two-group drift-flux model development. Table 5 summarizes the test conditions of the six datasets.

4.4.1. Validation using the database of Hibiki and Ishii [42]

Fig. 9 indicates the non-dimensional drift-flux plot for nitrogen-water two-phase flow data through a 0.102 m diameter pipe under atmospheric pressure and room temperature in different constant superficial gas velocities [42]. The data are shown by different symbols for different superficial gas velocities. Continuously increase in the mixture volumetric flux at the fixed superficial gas velocity leads to a decrease in the void fraction. The lines show the corresponding non-dimensional gas velocity prediction calculated by the two-group drift-flux model for the constant superficial gas velocities. The mean relative error and relative standard deviation of non-dimensional gas velocity prediction are −3.51% and 4.28%, respectively. Other statistical parameters are presented in Tables 6 and 7. This figure demonstrates that the predictions are in good agreement with experimental data in the range of bubbly to

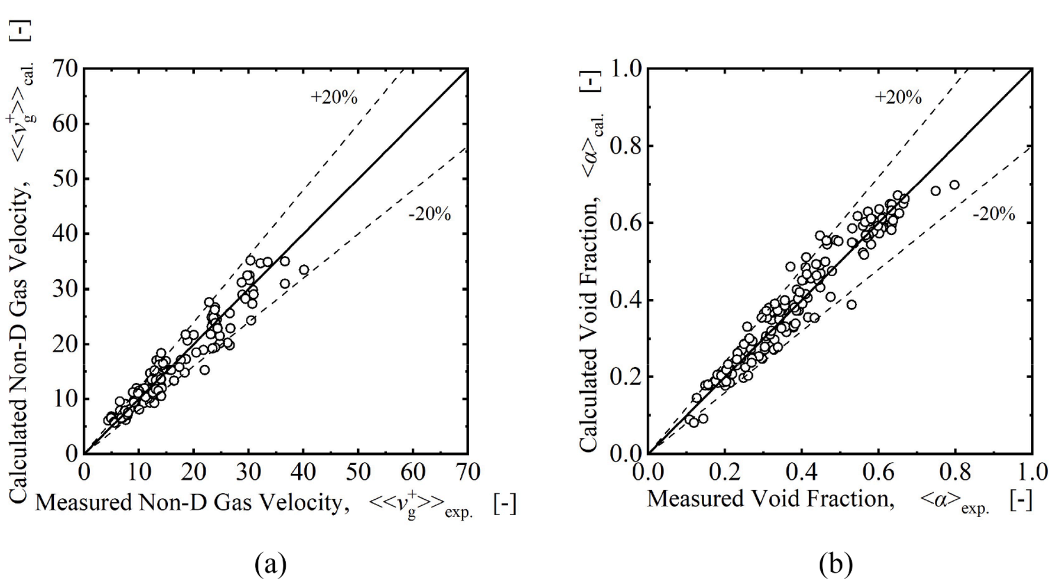


Fig. 8. Validation of the two-group drift-flux model using Schlegel et al. [26,36] database with (a) non-dimensional gas velocities and (b) void fractions.

Table 3
Performance evaluation of the two-group drift-flux model for non-dimensional gas velocity prediction.

Diameter [m]	N	Injection condition	Non-Dimensional Gas Velocity, $\langle\langle v_g\rangle\rangle$, statistical parameters						
			m_d [-]	s_d [-]	m_{rel} [%]	s_{rel} [%]	r [-]	$RMSE$ [-]	$m_{rel,abs}$ [%]
0.152	66	Bubbly flow	0.499	1.18	3.4	8.38	0.988	1.28	6.95
0.203	32	Bubbly flow	−0.064	1.6	1.05	13.5	0.902	1.58	10.6
0.152	23	Cap-bubbly flow	−1.45	2.53	−3.46	20.4	0.963	2.92	16.3
0.203	13	Cap-bubbly flow	−0.643	0.48	−4.44	3.54	0.998	0.796	4.59
0.304	22	Cap-bubbly flow	−0.765	1.16	−6.08	8.07	0.979	1.37	7.95
All data	156	–	−0.147	2.16	0.94	13.5	0.962	2.17	10.5

Table 4
Performance evaluation of the two-group drift-flux model for void fraction prediction.

Diameter [m]	N	Injection condition	Void Fraction, $\langle\alpha\rangle$, statistical parameters						
			m_d [-]	s_d [-]	m_{rel} [%]	s_{rel} [%]	r [-]	$RMSE$ [-]	$m_{rel,abs}$ [%]
0.152	66	Bubbly flow	−0.0107	0.0308	−2.68	7.81	0.976	0.0324	6.54
0.203	32	Bubbly flow	0.00303	0.0474	0.598	12.8	0.907	0.0468	10.4
0.152	23	Cap-bubbly flow	0.0232	0.0489	6.97	17.09	0.968	0.0531	16.25
0.203	13	Cap-bubbly flow	0.0150	0.0120	4.76	3.95	0.997	0.0189	4.94
0.304	22	Cap-bubbly flow	0.0277	0.0380	7.26	9.36	0.971	0.0463	9.01
All data	156	–	0.0047	0.0404	1.44	11.44	0.966	0.0405	8.98

Table 5
Database used for the developed two-group drift-flux model evaluation.

References	Fluid Systems	D [m]	L/D [-]	Data No.	$\langle j_g\rangle$ [m/s]	$\langle j_f\rangle$ [m/s]	$\langle j\rangle$ [m/s]	P [MPa]
Hibiki and Ishii [42]	N_2-Water	0.102	53.9	59	0.0373–0.286	0.0109–0.387	0.0482–0.655	0.1
Hills et al. (Low Flow) [47]	Air-Water	0.149	70.5	301	0.040–0.62	0.0–0.50	0.040–0.85	0.1
Hills et al. (High Flow) [47]	Air-Water	0.149	70.5	93	0.10–3.5	0.0–2.6	0.10–6.1	0.1
Shen et al. [48]	Air-Water	0.200	130	116	0.0178–0.211	0.0504–0.312	0.0731–0.812	0.1
Hashemi et al. [49]	Air-Water	0.305	9.41	40	0.0100–1.16	0.0–0.060	0.0300–1.22	0.1
Omebere-Iyari et al. [50]	Steam-Water	0.194	46.4	10	0.109–0.949	0.100–0.650	0.278–1.59	4.6

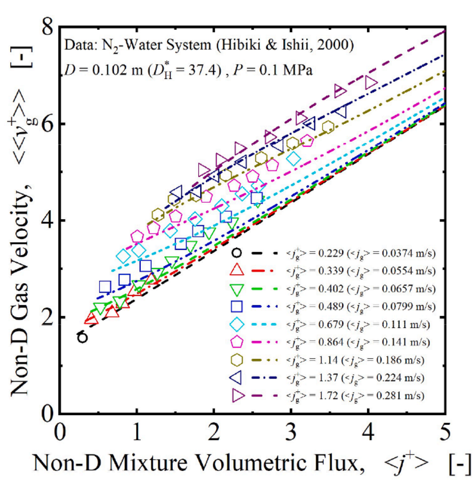


Fig. 9. Non-dimensional drift-flux plot for the dataset collected by Hibiki and Ishii [42].

beyond bubbly flow regime.

4.4.2. Validation using the database of Hills et al. [47]

Fig. 10(a) and 10(b) show the non-dimensional drift-flux plots of two-phase flow experimental data collected by Hills [47] in low and high superficial liquid velocities, respectively. The experiment was performed with air and water as the fluids through a 0.149 m diameter pipe under atmospheric pressure and room temperature condition. The data are indicated by different symbols corresponding to different superficial liquid velocities. The lines show the two-group drift-flux model at different superficial liquid velocities. The mean relative error and relative standard deviation of non-dimensional gas velocity prediction for low flow data are −6.93% and 5.43%, respectively. The corresponding values for high flow data are −0.0495% and 6.64%, respectively. Other statistical parameters are presented in Tables 6 and 7. Fig. 10 demonstrates that the two-group drift-flux model can predict the gas velocity even in low mixture volumetric flux reasonably well.

4.4.3. Validation using the database of Shen et al. [48]

Fig. 11 shows the non-dimensional drift-flux plot of two-phase flow experimental data collected by Shen et al. [48] for flow through a 0.200 m diameter pipe under atmospheric pressure and room temperature condition. The data and model predictions are indicated by different symbols and lines for different superficial liquid velocities. There is a deviation between experimental data and the prediction for the condition of $\langle j_f^+\rangle = 0.308$ and $\langle j^+\rangle \geq 2.5$. This flow condition is almost pool condition. In the pool condition, the two-group drift velocity model approaches Kataoka and Ishii's correlation which has been validated by the substantial amount of data in the literature. There is a likelihood that the measurement uncertainty raises the deviation between the data and the model prediction. Shen et al. [48] explained that increasing the superficial gas velocity at low superficial liquid velocity conditions may lead to multi-dimensional flow behaviors. Hence, measurement uncertainty will increase; however, still, the deviation is less than 20%. Thus, the two-group drift-flux model is reliable for pool conditions. The mean relative error and relative standard deviation of non-dimensional gas velocity prediction are −3.47% and 12.4%, respectively. Other statistical parameters are presented in Tables 6 and 7.

4.4.4. Validation using the database of Hashemi et al. [49]

Fig. 12 indicates the non-dimensional drift-flux plot of two-phase flow experimental data collected by Hashemi et al. [49] for different

Table 6
Performance evaluation of the two-group drift-flux model non-dimensional gas velocity prediction for the dataset collected by other researchers.

Researchers	N	Non-Dimensional Gas Velocity, $\langle\langle v_{gj}\rangle\rangle$, statistical parameters						
		m_d [-]	s_d [-]	m_{rel} [%]	s_{rel} [%]	r [-]	$RMSE$ [-]	$m_{rel,abs}$ [%]
Hibiki and Ishii [42]	59	−0.147	0.171	−3.51	4.28	0.991	0.225	4.64
Hills et al. (Low Flow) [47]	301	−0.374	0.304	−6.93	5.43	0.983	0.482	7.46
Hills et al. (High Flow) [47]	93	0.295	1.16	−0.0495	6.64	0.996	1.19	4.81
Shen et al. [48]	116	−0.311	0.602	−3.47	12.4	0.965	0.675	10.9
Hashemi et al. [49]	40	−0.150	0.472	−5.55	12.1	0.993	0.490	9.30
Omebere-Iyari et al. [50]	10	0.467	0.784	7.02	7.54	0.984	0.879	8.51
All data	619	−0.212	0.633	−4.60	8.34	0.997	0.667	7.56

Table 7
Performance evaluation of the two-group drift-flux model void fraction prediction for the dataset collected by other researchers.

Researchers	N	Void Fraction, $\langle\alpha\rangle$, statistical parameters						
		m_d [-]	s_d [-]	m_{rel} [%]	s_{rel} [%]	r [-]	$RMSE$ [-]	$m_{rel,abs}$ [%]
Hibiki and Ishii [42]	59	−0.00607	0.00716	−3.51	4.28	0.993	0.0093	4.64
Hills et al. (Low Flow) [47]	301	−0.0195	0.0188	−6.93	5.43	0.987	0.0270	7.46
Hills et al. (High Flow) [47]	93	0.00176	0.0200	−0.00495	6.64	0.978	0.0200	4.81
Shen et al. [48]	116	−0.0121	0.0309	−3.47	12.3	0.960	0.0330	10.8
Hashemi et al. [49]	40	−0.00707	0.0262	−5.55	12.1	0.993	0.0268	9.30
Omebere-Iyari et al. [50]	10	0.0261	0.0333	7.02	7.54	0.976	0.0410	8.51
All data	619	−0.0121	0.0236	−4.60	8.34	0.980	0.0265	7.56

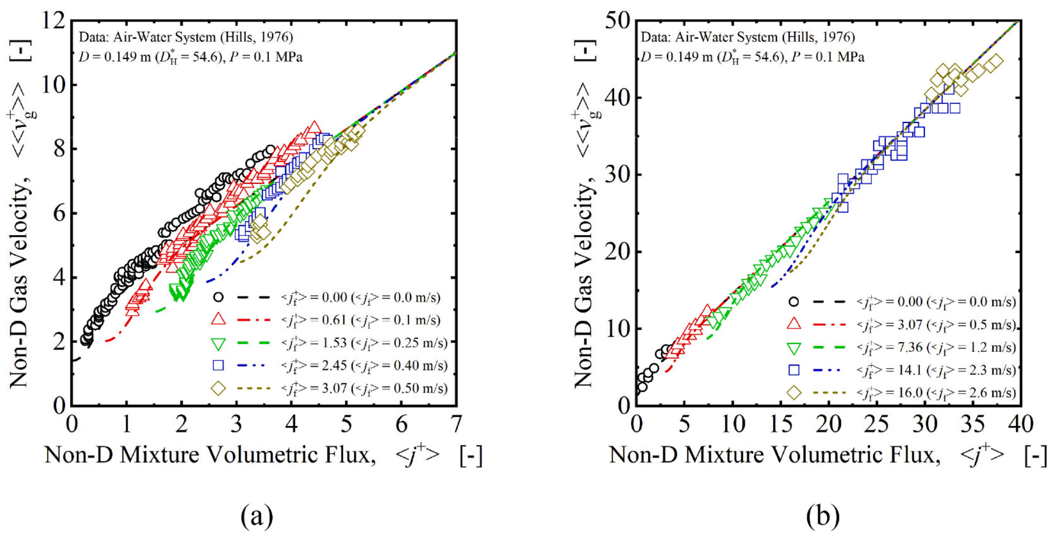


Fig. 10. Non-dimensional drift-flux plot for the (a) low flow dataset and (b) high flow dataset collected by Hills [47].

superficial liquid velocities through a 0.305 diameter pipe with a 2.88 m test section height. The gas was injected into the test section through a horizontal pipe section connected to a riser. The void fraction was measured by a single gamma densitometer with a narrow beam. The data and model predictions are shown by different symbols and lines for different superficial liquid velocities. The experiment was performed under atmospheric conditions. The mean relative error and relative standard deviation of non-dimensional gas velocity prediction are −5.55% and 12.1%, respectively. Other statistical parameters are presented in Tables 6 and 7.

4.5. Application of the proposed two-group drift-flux model in steam-water flow

Steam-water two-phase flow data were used to show the accuracy of the proposed two-group drift-flux model as a common fluid system in cooling processes. Fig. 13(a) and (b) shows the comparison between the steam-water data and the two-group drift flux model for $\langle j_f^+\rangle = 0.708$ and $\langle j_f^+\rangle = 4.60$, respectively. These data were collected by Omebere-Iyari et al. [50] in a 0.194 m diameter pipe at a pressure of 4.6 MPa. The solid black lines indicate non-dimensional gas velocity obtained by the group-one and group-two non-dimensional gas velocities and their corresponding void fractions. The green dash and red dash-dot lines show the group-one and group-two non-dimensional gas velocities, respectively. For Fig. 13(a), a comparison to the experimental data shows that the two-group drift-flux model can follow the trend of the data through a gradually smooth increase in the transition region. The same explanation is also valid for Fig. 13(b). Although these data were not used to develop this two-group drift-flux model, data comparison with the model shows that the model can satisfactorily predict the void fraction weighted mean gas velocity, $\langle\langle v_g^+\rangle\rangle$. It demonstrates the application of the proposed two-group drift-flux model in predicting steam-water two-phase flow through large pipes. The mean relative error and relative standard deviation of non-dimensional gas velocity prediction are −7.02% and 7.54%, respectively. Other statistical parameters are presented in Tables 6 and 7.

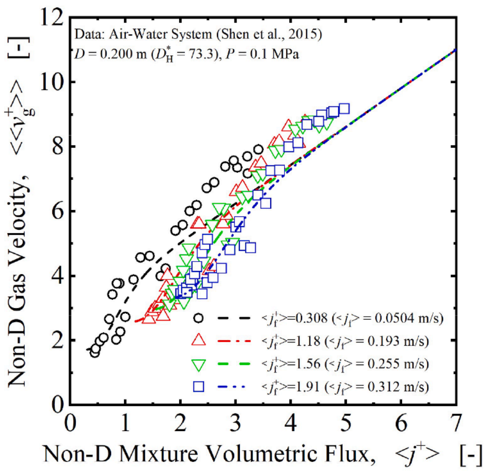


Fig. 11. Non-dimensional drift-flux plot for the dataset collected by Shen et al. [48].

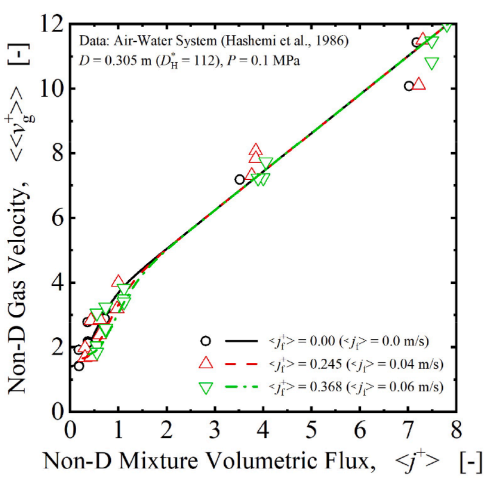


Fig. 12. Non-dimensional drift-flux plot for the dataset collected by Hashemi et al. [49].

Although the datasets mentioned in Sections 4.4 and 4.5 were not used to develop the two-group drift-flux model, the results are reasonably reliable. The mean relative error and relative standard deviation of non-dimensional gas velocity prediction for all data mentioned in these sections are −4.60% and 8.34%, respectively. Other statistical parameters of non-dimensional gas velocity and void fraction prediction are presented in Tables 6 and 7, respectively.

5. Conclusions

This study developed a new reliable two-group drift-flux model for vertical gas-liquid flow in large-diameter pipes. Sensitivity analysis and comparison with nitrogen-water drift velocity experimental data were performed to show the validity of the proposed model for the drift velocity. Asymptotic values for group-one and group-two distribution parameters were proposed, $C_{\infty,1} = 1.0$ and $C_{\infty,2} = 1.4$. The void fraction weighted average of group-one and group-two distribution parameters was compared with the value of the one-group distribution parameter. Moreover, the two-group drift-flux model was evaluated with various databases of two-phase flows through large-diameter pipes. In addition, steam-water two-phase flow data were used to show the reliability of the model for the steam-water flow system in large-diameter pipes. The summary of the advantages of the two-group drift-flux model is listed hereunder.

- Proposed drift velocity correlations for group-one and group-two drift velocities could acceptably predict the one-group drift velocity in the transition zone from the bubbly to beyond the bubbly flow regime.
- The void fraction weighted mean distribution parameters of group-one and group-two bubbles were consistent with one-group distribution parameters both in value ranges and the trend.
- The developed two-group drift-flux model Eqs. (45)-(48) was capable of predicting gas velocity increase behavior against the mixture volumetric flux in the bubbly flow-to-beyond bubbly flow transition with relatively low mixture volumetric flux.
- The performance of the prediction for group-one and group-two gas velocities demonstrated satisfactory accuracy.
- The void fraction weighted mean gas velocities of group-one and group-two could predict the gas velocity reasonably well.
- The two-group drift-flux model was validated in the bubbly flow to beyond the bubbly flow regime with various databases containing void fractions up to 0.80 for large-diameter pipes.

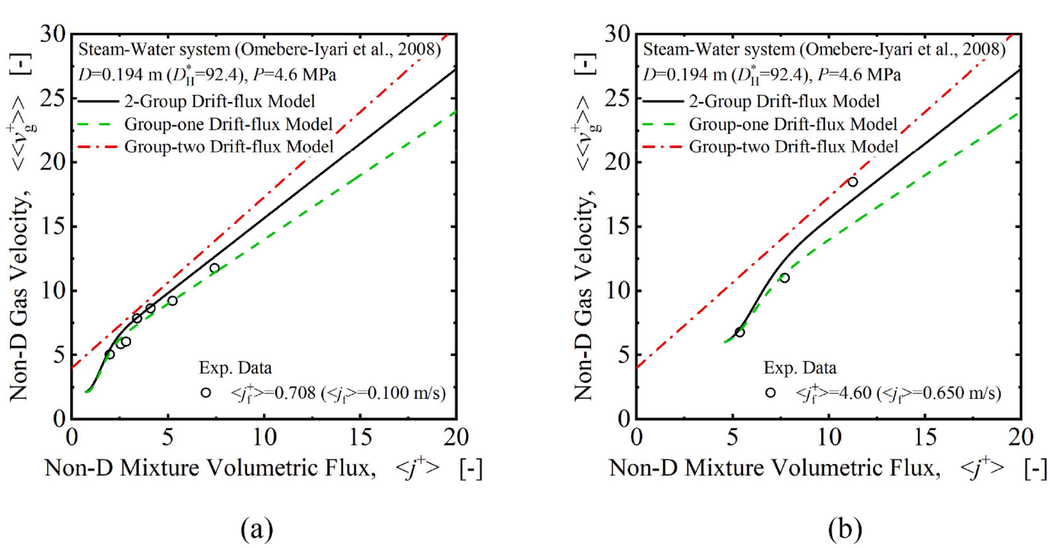


Fig. 13. Non-dimensional drift-flux plot for the steam-water data collected by Omebere-Iyari et al. (2008) [50], (a) $\langle j_f^+ \rangle = 0.708$ and (b) $\langle j_f^+ \rangle = 4.60$.

- Comparisons between model prediction and two-phase flow experimental data for steam-water showed the reliability of the proposed model for two-phase flow in steam-water systems.
- The developed two-group drift-flux model was consistent with one-group drift-flux model and predicts gas velocities well enough.

The developed two-group drift-flux model is indispensable for reducing the two gas momentum equations to one gas mixture momentum equation when two-group IATE is implemented into thermal-hydraulic codes to improve the prediction accuracy of IAC.

CRediT authorship contribution statement

Hossein Barati: Writing – original draft, Methodology, Investigation, Formal analysis, Visualization, Validation. **Takashi Hibiki:** Conceptualization, Formal analysis, Methodology, Writing – original draft, Supervision, Project administration, Data curation, Validation, Funding acquisition. **Joshua P. Schlegel:** Data curation, Conceptualization, Writing – review & editing. **Naofumi Tsukamoto:** Conceptualization, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The authors do not have permission to share data.

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