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Improved Drift Flux Void Fraction Model for Horizontal Gas-liquid Intermittent Flow

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ABSTRACT

Drift Flux model is widely used in literature to predict void fraction in two-phase gas-liquid flow. Drift flux model has been used for all flow regimes. The distribution parameter implemented in the model is very crucial for the accuracy of the model. A new distribution parameter was developed in this paper as a function of two dimensionless parameters and flow regime (slug or plug). The new model showed a superior predicted void fraction accuracy over all available models in literature. In this paper, the influence of the flow regimes was implemented in the formulation of the drift flux model distribution parameter for the first time in literature. The drift velocity was found to be negligible in the horizontal configuration. The proposed model was validated using unbiased data from literature from different sources and for a wide range of liquid viscosity from water up to high viscosity oil (600 cP) and pipe diameter from 19 mm up to 152 mm. The mean relative absolute error of the proposed model using all data bank is around 16% while the least error model available in literature is around 19%. Moreover, the most recent models of Rassame and Hibiki (2018) and Kong et al. (2018b) give 33% and 50%, respectively.

Keywords: Gas-liquid Two-phase flow; Void fraction; Drift Flux; Plug and Slug flow; Horizontal configuration.

NOMENCLATURE

A	cross sectional area of the pipe	n	number of samples
C_0	distribution parameter	Q	volumetric flow rate of the fluid
C_∞	asymptotic value of the distribution parameter	V_{gr}	drift velocity parameter
D	pipe diameter	V_{sg}	gas superficial velocity
D_h	hydraulic equivalent diameter	V_{sl}	liquid superficial velocity
g	gravitational acceleration	x_i	absolute error normalized by the measured value
H_L	liquid holdup		

Greek Letters

α	void fraction	ρ	average density of the fluid
σ	surface tension	μ	dynamic viscosity

Non-Dimensional Numbers

Re	Reynolds number	Fr	Froude number

Subscripts

g	gas	m	mixture
l	liquid	TP	two-phase flow

Superscripts

+	non-dimensional quantity

Abbreviations

ABE	mean relative absolute error	DFM	Drift-Flux Model
RMS	Root Mean Square	TFM	Two-Fluid Model

1. INTRODUCTION

Two-phase flows can be seen in various industrial devices such as production and transportation of gas and oil in petroleum and gas industry, heat exchangers and nuclear reactors.

Analysing the available two-phase flow models reveals the followings: the homogenous model, neglects the slippage between phases, and it doesn't give reliable results. The Two-Fluid Model (TFM) is based on separate mass, momentum, and energy conservation equations for each phase. Additional terms (in form of closer relationships) due to the phase interactions are needed in these equations because the flowing phases are dependent of each another. The Drift-Flux Model (DFM) differs from TFM by replacing the interaction terms by the mixture momentum equation specifying the relative motion between phases. This simplification gives the DFM many advantages such as being continuous, differentiable and relatively easy to compute (Shi *et al.* 2005).

The DFM is widely used to predict the one-dimensional (or area-averaged) gas void fraction, α, or the liquid holdup, H_L. The two parameters refer to the ratio of the gas phase volume and liquid phase volume fraction, respectively, to the two-phase mixture volume at a given time. Thus, the void fraction and liquid holdup are related by the equation $\alpha + H_L = 1$. In the present work, the terminology void fraction is used, since it is the most popular. The void fraction is one of the most important parameters to characterize the gas-liquid two-phase flow. It is used to calculate the two-phase flow mixture density and viscosity and the average velocities of the two phases. In the DFM, the void fraction is given as a function of two drift-flux parameters which are the distribution parameter, C_0, and the drift velocity, V_{gd}. The latter parameter refers to the relative velocity between gas phase and mixture, while distribution parameters characterize the concentration profile of void fraction on the cross-section pipe, or the effect of local phase distribution and velocity on area-averaged void fraction. The two parameters can be obtained from the measurements of local void fraction and gas and liquid velocities distributions.

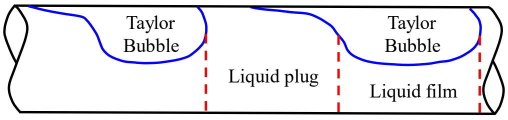
The DFM was originally introduced by Zuber and Findley (1965), the authors applied it to a vertical upward two-phase flow. The authors have also proposed a simple technique to estimate the distribution parameter and drift velocity through presenting the data using V_g-V_m plane, where V_m and V_g refers respectively to mixture and gas velocities, respectively. If the collected data give a linear fit, the slope and the intercept point represent the distribution parameter and drift velocity, respectively.

Ishii (1977) proposed a model to calculate the two drift-flux parameters for different vertical upward flow regimes such as bubbly, slug, churn and annular. Through the years, different drift flux void fraction models were proposed for different channel configuration, flow direction, or a specific flow regime, (Hibiki and Ishii 2003a), (Kong *et al.* 2018b), (Hibiki 2019), (Dong *et al.* 2020). After thorough review of the existing void fraction models and analysing their prediction through a confrontation with an experimental database collected from the open literature, Woldesemayat and Ghajar (2007) proposed a void fraction model based on DFM. This model considers the effect of phasic superficial velocities, the physical properties of the two phases, the working pressure as well the diameter and the inclination of the pipe.

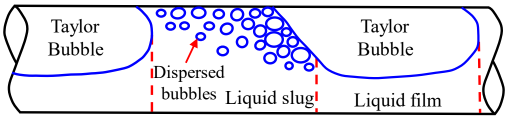
França and Lahey (1992) were the first to apply the DFM to horizontal pipe. The study was carried out using 19 mm ID pipe and air-water mixture. The experimental measurements of void fraction, obtained using quick-closing valves, for stratified, plug, slug and annular flows were evaluated using DFM analysis. It was found that the standard variable V_g and V_m can be used to correlate the void fraction for plug and slug flow. In other hand, α/(1-α) and $\beta = V_{sg}/V_m$ are more suitable for segregated regime. It was also reported that the distribution parameters and drift velocity are constant and dependant of the flow regime. Lamari (2001) and Kong *et al.* (2018b) also proposed a void fraction correlation in which the two drift-flux parameters are constant and flow regime dependant. Based on the work of Fabre and Liné (1992), Choi *et al.* (2012) correlated the distribution coefficient with mixture Reynolds number. Rassame and Hibiki (2018) examined the existing DFM models for horizontal pipes. The authors concluded that the distribution coefficient is flow-regime-dependent constant in most of them, which implies that the distribution parameter doesn't include the effect of physical properties and the dynamic of the flow. From the performed statement, Rassame and Hibiki (2018) proposed a flow regime independent drift-flux model to predict the void fraction based on the model of Ishii (1977). Using a collected database composed of 566 data points, the authors correlated the distribution parameter with the densities of the two phases and the ratio of non-dimensional superficial gas velocity to non-dimensional mixture volumetric flux. The mean drift velocity was considered equal to zero by the authors as there is no gravitational acceleration in the horizontal direction. For validation purpose, Rassame and Hibiki (2018) assessed the performance of the proposed model, as well as the model of Chexal *et al*. (1992), with the collected database. It was found that most of void fraction measurements were predicted within about ±20% uncertainty. Considering this performance, which is similar to those given by the model of Chexal *et al.* (1992), and the simplicity of the proposed model comparatively to the latter, the performance of the developed model was considered excellent by Rassame and Hibiki (2018). In their study, the authors also studied the prediction level of their model for different flow regimes. The mean absolute relative errors were found equal to 13.8%, 5.34%, 3.89%, 0.074% and 37.8%, for stratified smooth (SS), stratified wavy (SW), annular flow with dispersed liquid droplets (AD), dispersed bubble (DB), and intermittent flow (I) respectively. For the intermittent flow, if the data collected for $V_m \leq 3$ m/s are not considered, the mean absolute relative errors decreases to 16.6%. The same behaviour was observed with the model of Chexal *et al.* (1992). Rassame and Hibiki (2018) have made an assumption that the insufficient measurement accuracy is the reason behind the discrepancy for this range of mixture velocity. As mentioned above, this behaviour was not reported for bubbly flow data. Considering that void fraction values are generally smaller in this flow regime compare to the intermittent flow (Ghajar 2020), (Kong *et al.* 2018b), and thus, more sensible to the strong uncertainties, this explanation is questionable.

As mentioned above, Rassame and Hibiki (2018) correlated the distribution parameter with all collected data, and thus by including the intermittent flow with other flow regimes data. Also doubts may arise concerning this approach. Indeed, the intermittent flow, regardless of the pipe inclination, has specific features, including his intermittent nature and chaotic behaviour, that distinguishes it from other flow regimes (Fabre and Liné 1992), (Mohmmed *et al.* 2021). The existence of different shapes of the intermittent flow, called sub-regimes add more difficulties to this flow, (Thaker and Banerjee 2015), (Arabi *et al.* 2020a, b), (Arabi *et al.* 2021). It also exists drift flux models when the authors have correlated the two drift-flux parameters of the intermittent flow separately from other flow regimes. This is the case for the model of Hibiki and Ishii (2003a) for vertical upward flow and those of França and Lahey (1992), Lamari (2001) and Kong *et al.* (2018b) for horizontal pipe.

In all DFM models developed for horizontal intermittent flow, the authors have considered both drift flux parameters as constant. A visualization of void fraction profile collected by Kong *et al.* (2018b) using four-sensor conductivity probe technique for different liquid and gas superficial velocities, depicted in Fig. 1 (a) and (b), respectively, demonstrates that both gas and liquid superficial velocities influence the distribution of void fraction along the pipe cross-section. Thus, it seems important to consider the effect of flow conditions in the distribution parameter.



(a) Plug configuration



(b) Slug configuration

Fig. 1. Examples of (a) plug and (b) slug flows.

In horizontal configuration, the intermittent flow is traditionally divided into two different sub-regimes namely plug and slug flows, (Kong *et al.* 2018a), (Arabi *et al.* 2020a), (Arabi *et al.* 2021), (Thaker and Banerjee 2017), (Sassi *et al.* 2022). In plug flow, the liquid slugs are free or carried out small quantities of gas bubbles and the interface liquid slugs/elongated bubbles are laminar (Fig. 1 (a)). Increasing of superficial gas velocities induce an increment of gas bubbles presence inside the liquid slugs, and thus a transition to slug flow, as shown in Fig. 1 (b).

Recently, Arabi *et al.* (2021) have demonstrated that the hydrodynamic parameters are different for plug and slug flows.

The present paper aims to improve the drift flux void fraction model developed by Rassame and Hibiki (2018) for horizontal plug and slug gas-liquid two-phase flows. in order to achieve this goal, i.e. given an approval void fraction model, the parameters that is influencing the void fraction in the intermittent plug and slug two-phase flow have been investigated. Therefore, within the one-dimensional drift-flux study, the impacts of the flow pattern, the pipe geometry, the physical proprieties of the two fluids and the inlet flow conditions (liquid and gas velocity) were considered. The predicted void fraction performance of the proposed model is compared with those of different void fraction drift flux models including the correlation of Rassame and Hibiki (2018) and showed better performance.

2. BACKGROUND ON DFM FORMULATION AND REVIEW OF EXISTING DFM CORRELATIONS

2.1 Theoretical Background

The concept of "drift velocity" was first developed by Zuber and Findley (1965) in order to account the difference in velocity between the two phases. The local drift velocity, V_{gr}, is described as the result of the difference in gas velocity, V_g, and the volumetric flux of the mixture, V_m. The local drift velocity is expressed as:

$$V_{gr} = V_g - V_m \tag{1}$$

By including the mean area cross-section "< >" and the mean weighted void fraction area "<< >>":

$$<f> = \frac{1}{A}\int_f f\,dA \tag{2}$$

$$\ll f \gg = \frac{<\alpha f>}{<\alpha f>} = \frac{\frac{1}{A}\int_f \alpha f\,dA}{\frac{1}{A}\int_f \alpha\,dA} \tag{3}$$

The average of equation (1) over a whole flow channel yields the following unidimensional drift flow model:

$$V_g = C_0 V_m + V_{gr} \tag{4}$$

The gas velocity, V_g, is given by Eq. (5).

$$V_g = \frac{V_{sg}}{\alpha} \tag{5}$$

where V_{sg} is the superficial gas velocity and α is the average void fraction.

The volumetric flow of the mixture, or mixture velocity, V_m, is the sum of the gas and liquid superficial velocities (Eq. (6)).

$$V_m = V_{sg} + V_{sl} \qquad (6)$$

By combining Eq. (4) and (5), a global drift flow model equation for predicting the void fraction becomes:

$$\alpha = \frac{V_{sg}}{C_0 V_m + V_{gr}} \qquad (7)$$

Considering Eq. (7) for calculating the void fraction, both distribution parameter, C_0, and the drift velocity V_{gr} are needed. However, such parameters are not always attainable. some authors such as Zuber and Findley (1965), Hibiki and Ishii (2001), Rassame and Hibiki (2018) suggested an alternative approach to estimate these two parameters by taking into account the linear relationship between V_m and V_g as stated in the Eq. (4). The distribution parameter and the drift velocity represent the slope and y-intercept of V_m and V_g plot, respectively. Nevertheless, a calculation of the uncertainty must be involved in this method where both the distribution parameter and the drift velocity are calculated. The accuracy of one parameter, e.g., C_0, has a direct impact on the second, e.g., V_{gr}. If the measurements are made under a wide test conditions range of gas and liquid superficial velocities, i.e., more than one two-phase flow regime, it is hard to accurately estimate the distribution parameter and the drift velocity using V_m and V_g plot. Therefore, any attempt to model the distribution parameter and the drift velocity should take into consideration the nature of the flow pattern.

2.3 Existing Gas-liquid two-phase drift-flux models in The Literature

The available drift-flow correlations that have been developed so far to estimate the void fraction will be presented/discussed in this section. Table 1 presents the available drift-flux correlations to predict the void fraction. As discussed in section 1, some models are also independent with respect to the flow conditions and/or phases properties. Additionally, the drift-flux correlations can be flow regime dependant or independent. It's worth noting that only independent flow regime or the ones developed for the intermittent flow correlations, such as that of Silva *et al.* (2011), are reported in the table. In addition to the later, the correlations of França and Lahey (1992), Lamari (2001), Rassame and Hibiki (2018) and Kong *et al.* (2018b) are the only ones that have been developed from an experimental database collected only using horizontal pipes. We can remark that the models of Ishii (1977), Clark and Flemmer (1986), Gomez *et al.* (2000) and Choi *et al.* (2012) consider the void fraction as input parameter in the equation of the drift flux parameters, which complicates the calculation of the void fraction (Dong *et al.* 2020).

2.3 Distribution Parameter of the Horizontally Oriented Pipe

In order to consider the influence of the inertial force, Ishii (Ishii 1977) proposed the following equation of the distribution parameter.

$$C_0 = C_\infty - (C_\infty - 1)\sqrt{\frac{\rho_g}{\rho_l}} \qquad (8)$$

where C_∞ is an asymptotic value of the distribution parameter, ρ_g and ρ_l are the gas and liquid densities. However, the shape of the Eq. (8) ensures that the distribution parameter approximates unity when the density ratio is close to 1. By combining Eq. (4) and (8) with the assumption of the drift velocity $V_{gr} = 0$, the asymptotic value of the distribution parameter is expressed as:

$$C_\infty = \frac{\dfrac{V_g}{V_m} - \sqrt{\dfrac{\rho_g}{\rho_l}}}{1 - \sqrt{\dfrac{\rho_g}{\rho_l}}} \qquad (9)$$

The main challenge raised in Eq. (9) is the prediction of the gas velocity, which is directly dependent on the void fraction (Eq. (5)). Thus, an appropriate prediction of the asymptotic value of the distribution parameter is required to resolve the issue.

3. EXPERIMENTAL DATABASE IN HORIZONTAL TWO-PHASE FLOW

Similar to the work of Rassame and Hibiki (2018), this study will be performed using a collected database from the open literature to be unbiased. The detail of 367 void fraction measurements collected from six data sources are summarised in Table 2. To the best knowledge of the authors, the latter (367) data are those obtained during studies of horizontal intermittent gas-liquid flows by distinguishing between the plug and slug flows. The fluid system, pipe diameter, number of data and the range of superficial gas and liquid velocities are also given in Table 2. These experiments were carried out using air-water, air-light refined machine oil, air-high viscosity oil (up to 600 cP) and air-silicone oil. The pipe diameters ranges of the database are between 19 and 152.4 mm, and thus referring to Lu *et al.* (2018), includes moderate (10 mm < ID < 100 mm) and large (ID>100 mm) diameter pipes.

The collected experimental database are plotted on the flow pattern map of Mandhane *et al.* (1974), which is considered as one of the reference flow pattern maps for horizontal gas-liquid two-phase flow. Figure 2 (a) displays test conditions for the air-water mixture. From this figure, one can observe that all data are located in intermittent flow, i.e., the plug and the slug flow. We can also report that, the transition line of the flow pattern map between plug and slug flow matches well with the experimental data for both flow configurations. Figure 2 (b) depicts the test conditions for the air-silicone oil and air-oil mixtures, which corresponds to the data of

Table 1 Existing drift-flux correlations developed for (vertical / horizontal) gas-liquid two-phase flow

Author	C_0	V_{gr}
Zuber and Findlay (1965)	1.2	$1.53\left(\frac{g\sigma\Delta\rho}{\rho_l^2}\right)^{0.25}$
Rouhani and Axelsson (1970)	For: $\alpha \leq 0.1$ $1+0.2(1\text{-}x)\left(\frac{gD\rho_l^2}{G^2}\right)^{0.25}$ For: $\alpha > 0.1$ $1+0.2(1\text{-}x)$	$1.18\left(\frac{g\sigma\Delta\rho}{\rho_l^2}\right)^{0.25}$
Mattar and Gregory (1974)	1.3	0.7
Greskovich and Cooper (1975)	1	$0.671\sqrt{gD}(\sin\theta)^{0.263}$
Ishii (1977)	$1.2 - 0.2\left(1\text{-}\exp(\text{-}18\alpha)\right)\sqrt{\frac{\rho_g}{\rho_l}}$	$(C_0\text{-}1)V_m+\sqrt{2}\left(\frac{g\sigma\Delta\rho}{\rho_l^2}\right)^{0.25}$
Clark and Flemmer (1986)	$0.934\ (1+1.42\alpha)$	$1.53\left(\frac{g\sigma\Delta\rho}{\rho_l^2}\right)^{0.25}$
Beattie and Sugawara (1986)	$1+2.6\sqrt{\left(0.0716\ Re_{TP}^{-0.237}+0.008\right)}$	$0.35\sqrt{\frac{gD\Delta\rho}{\rho_l}}$
Kataoka and Ishii (1987)	$1.2 - 0.2\sqrt{\frac{\rho_g}{\rho_l}}$	For: $D_h^* \leq 40$ $0.03\left(\frac{\rho_g}{\rho_l}\right)^{-0.157}\left(\frac{g\sigma\Delta\rho}{\rho_l^2}\right)^{0.25} N_{ul}^{-0.562}$ For: $D_h^* > 40$ $0.92\left(\frac{\rho_g}{\rho_l}\right)^{-0.157}\left(\frac{g\sigma\Delta\rho}{\rho_l^2}\right)^{0.25} N_{ul}^{-0.562}$ $D_h^*=D_h/\sqrt{\sigma/g\Delta\rho}$ $N_{ul}=\mu_l/\left(\rho_l\sigma\sqrt{\sigma/g\Delta\rho}\right)^{0.}$
França and Lahey (1992)	1.0 (Plug flow) 1.2 (Slug flow)	0.16 (Plug flow) -0.20 (Slug flow)
Mishima and Hibiki (1996)	$1.2 + 0.51\exp(\text{-}0.691\ D)$	0
Gomez *et al.* (2000)	1.15	$1.53\left(\frac{g\sigma\Delta\rho}{\rho_l^2}\right)^{0.25}\sqrt{1\text{-}\alpha}\ \sin\theta$
Lamari (2001)	0.98 (Plug flow) 1.06 (Slug flow)	0.068 (Plug flow) 0.991 (Slug flow)
Woldesemayat and Ghajar (2007)	$\left[1+\left(\frac{V_{sl}}{V_{sg}}\right)^{\left(\frac{\rho_g}{\rho_l}\right)^{0.1}}\right]\left(\frac{V_{sg}}{V_m}\right)$	$2.9\left[\frac{gD\sigma\ (1+\cos\theta)\Delta\rho}{\rho_l^2}\right]^{0.25}$ $1.22(1+\sin\theta)^{\left(\frac{P_{atm}}{P_{sys}}\right)}$
Da Silva *et al.* (2011)	1.18	0.34
Choi *et al.* (2012)	$\frac{2}{1+(Re/1000)^2}+$ $\frac{1.2 - 0.2\sqrt{\rho_g/\rho_l}\left(1\text{-}\exp(\text{-}18\alpha)\right)}{1+(1000/Re)^2}$	$0.024\cos\theta+1.60\left(\frac{g\sigma\Delta\rho}{\rho_l^2}\right)^{0.25}\sin\theta$

Rassame and Hibiki (2018)	For $0 \leq \frac{(V_{sg})^{+}}{(V_m)^{+}} < 0.9$ $0.8\exp\left\{0.815\left(\frac{(V_{sg})^{+}}{0.9(V_m)^{+}}\right)^{1.50}\right\} -$ $\left[0.8\exp\left\{0.815\left(\frac{(V_{sg})^{+}}{0.9(V_m)^{+}}\right)^{1.50}\right\} -1\right]\sqrt{\frac{\rho_g}{\rho_l}}$ For $0.9 \leq \frac{(V_{sg})^{+}}{(V_m)^{+}} \leq 1$ $\left(\frac{-8.08(V_{sg})^{+}}{(V_m)^{+}} + 9.08\right) +$ $8.08\left(\frac{(V_{sg})^{+}}{(V_m)^{+}} -1\right)\sqrt{\frac{\rho_g}{\rho_l}}$	0
Kong *et al.* (2018b)	0.77 (Plug flow) 0.98 (Slug flow)	0.16 (Plug flow) -0.10 (Slug flow)

Table 2 Details of the collected database.

Authors	Fluids	Pipe ID [mm]	V_{sl} [m/s]	V_{sg} [m/s]	Nº of Data
Kokal and Stanislav (1989)	Air-Oil	25.8, 51.2 and 76.3	0.03-3.0	0.05-15.30	224
França and Lahey (1992)	Air-Water	19	0.20-1.49	0.13-2.35	37
Gokcal *et al.* (2008)	Oil-Air	50.8	0.01-1.75	0-20	32
Abdulkadir *et al.* (2018)	Air-Silicone oil	67	0.05-0.38	0.05-0.94	32
Kong (2018)	Air-Water	38.1 and 101.6	1.0-4.0	0.25-5.23	13
Kong *et al.* (2018b)	Air-Water	50.8	2.0-3.0	0.12-2.38	07
Dang *et al.* (2018)	Air-Water	152	0.69-2.97	0.06-9.22	54

Abdulkadir *et al.* (2018) and Kokal and Stanislav (1989), respectively. The air-silicone oil data, i.e., the "empty" and "solid" symbols, do not match with the "plug" and "slug" regions respectively. The air and oil data are well bounded by the transition line of plug/slug and do not meet with the transition line of stratified/slug. In fact, unlike the air-water combination, a slower superficial velocity for the liquid is needed to establish the intermittent flow, i.e., the plug and the slug flow, in the air-oil combination. Such a performance has been reported by Andritsos *et al.* (1989).

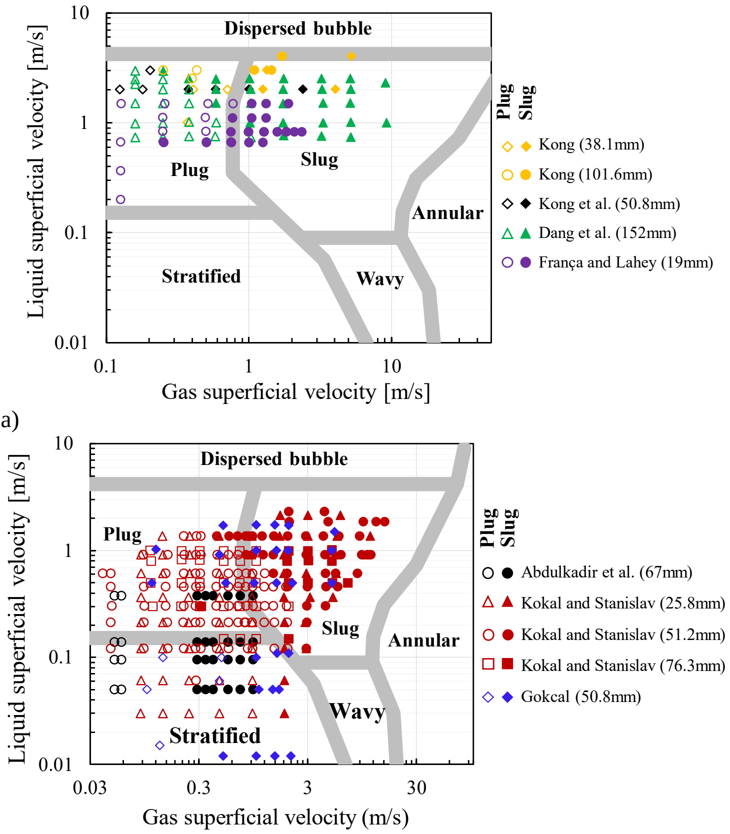
4. RESULTS AND DISCUSSION

4.1 Assessment of the drift flow formulation in horizontal configuration

In this section, the concept introduced by Zuber and Findley (1965) that is expressed in Eq. (4) has been assessed in order to investigate the relation between the gas velocity and the volumetric flux of the mixture, also to confirm the assumption of the negligible value of drift velocity, V_{gr}, in horizontal intermittent two-phase flow.

The collected database is represented using the V_g-V_m plane in Fig. 3. Following the recommendation of Arabi *et al.* (2021), we have represented the data of plug and slug flow separately. It appears from the figure that the experimental data in the intermittent flow regime, i.e., plug and slug flow, are in clear linear alignment with some degree of deviation. This finding was already reported for horizontal intermittent flow in the literature (França and Lahey (1992), Abdulkadir *et al.* (2018), Rassame and Hibiki (2018), Kong *et al.* (2018b), *Arabi et al.* (2021). For each flow pattern, a linear fit, with the assumption of V_{gr} = 0, was applied to the whole database. The obtained fit equation is also depicted in Fig. 3 (a) and (b).

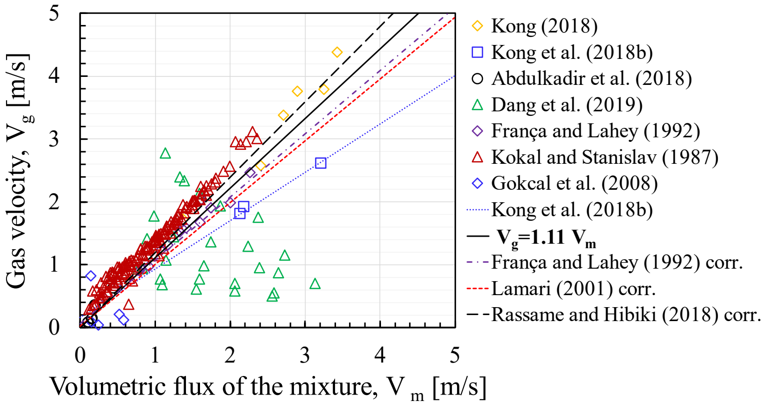
The correlation proposed by Lamari (2001) denoted by a dashed red line appears to underestimate the experimental data for the plug flow (Fig. 3 (a)) and fairly well predicted of the slug flow data (Fig. 3 (b)). While the correlation of França and Lahey (1992) fits well with the experimental data for the slug flow (Fig. 3 (b)) and underestimates the data points for the plug flow (Fig. 3 (a)). Comparatively to existing ones, it appears clearly that the correlation of Rassame and Hibiki (2018) is the one that shows the best prediction. The latter correlation turned out to be identical to the obtained fits for the slug flow and slightly different to the proposed correlation for plug flow. A great dispersion of the data is observed on both sides of the two proposed linear fit equations. This behaviour can be explained by the fact that the gathered data were acquired for various fluid



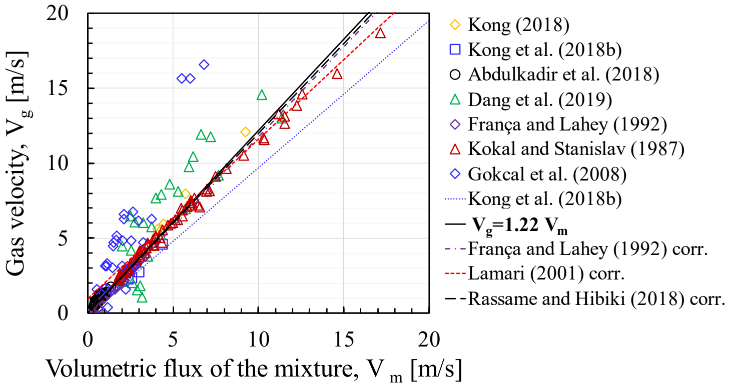
(a)

(b)

Fig. 2. Experimental test conditions of the collected data, plotted in the flow maps of Mandhane *et al.* (1974). (a) air-water mixture. (b) air-silicone oil and air-oil mixtures.



(a) Plug flow



(b) Slug flow

Fig. 3. Gas velocity versus volumetric flux of the mixture.

mixture, different diameters and important range of phase superficial velocities, as mentioned in Table 2.

These reported findings, using the experimental (collected) database, allow us to confirm firstly that the assumption to consider the drift velocity equal to zero is valid. In addition, they highlight the need to develop a drift flux model which considers the physical properties of the two fluids, the pipe diameter as well the flow parameters.

4.2 Development of New Drift-Flux Correlation for Horizontal Flow

This section emphases on the prediction of the distributed parameter, C_0. The latter is directly related to the asymptotic value of the distribution parameter, C_∞, in Eq. (8). The first step is to perform a thorough analysis of the variables that is influencing the asymptotic value of the distribution parameter, C_∞. This analysis allows to evaluate the effect of the inertial and viscous forces of the two-phase flow. These two parameters are directly set in the two-phase mixture Froude number and the two-phase Reynolds number which are defined as follows.

$$Fr_m = \frac{V_m}{\sqrt{gD}}\sqrt{\frac{\rho_l}{\rho_l - \rho_g}} \tag{10}$$

$$Re_{TP} = \frac{V_m\, D\, \rho_l}{\mu_l} \tag{11}$$

On the other hand, the ratio of the dimensionless superficial velocity of the gas to the dimensionless volumetric flux of the mixture should also be evaluated, as suggested by Hibiki and Ishii (2003b). The dimensionless superficial velocity, $(V_{sg})^+$, of the gas and the volumetric flux of the mixture, $(V_m)^+$, are expressed by Eq. (12) and (13), respectively.

$$(V_{sg})^+ = \frac{V_{sg}}{\left(\frac{\Delta\rho\, g\, \sigma}{\rho_l^2}\right)^{0.25}} \tag{12}$$

$$(V_m)^+ = \frac{V_m}{\left(\frac{\Delta\rho\, g\, \sigma}{\rho_l^2}\right)^{0.25}} \tag{13}$$

where $\Delta\rho$ is the difference between liquid and gas densities, g is the gravitational acceleration and σ is the surface tension.

Figure 4 (a) to (c), illustrates the plots of the asymptotic distribution parameter, C_∞, as function of the velocity ratio $(V_{sg})^+/(V_m)^+$, the mixture Froude number, Fr_m, and the two-phase Reynolds number, Re_{TP}, respectively. The open symbols indicate the experimental data for plug flow while solid symbols are those representing slug flow. It can be seen from this figure that the asymptotic distribution parameter data tends to increase slightly with the velocity ratio $(V_{sg})^+/(V_m)^+$, and slightly decreases with the mixture Froude number, Fr_m, and the two-phase Reynolds number, Re_{TP}. The scattering of the experimental data can be explained by the intermittent nature of the plug and slugs flow which reflects by the existence of strong fluctuations in void fraction time series Abdulkadir *et al.* (2016). Thus, it seems challenging to hold the asymptotic distribution parameter to a well-defined shape. However, the best fitting curve of the asymptotic distribution parameter was found to have a power-liked behavior. The two fitting curves for the plug and the slug, depicted in the figures, behave in the same way. Nevertheless, a small difference has been detected between both of them, which confirm the statement made in section 3.1. Thus, to achieve the maximum accuracy, both two-phase flow configurations i.e., plug and slug flow should be correlated independently.

By considering Ishii's approach and all previous insights, the asymptotic distribution parameter, C_∞, must be a function of $(V_{sg})^+/(V_m)^+$ and Re_{TP}. The Froude number of the mixture, Fr_M, is not included,

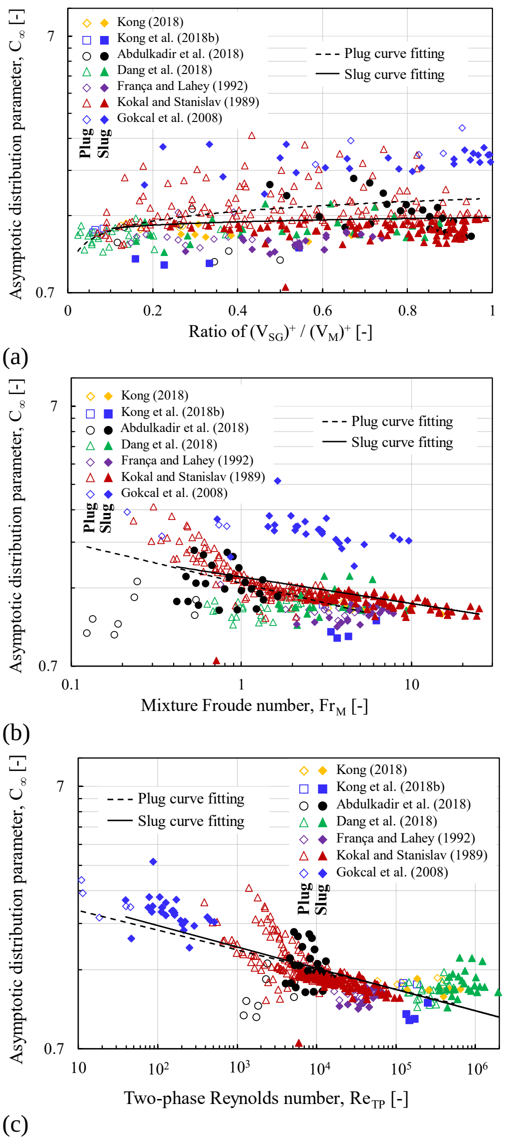
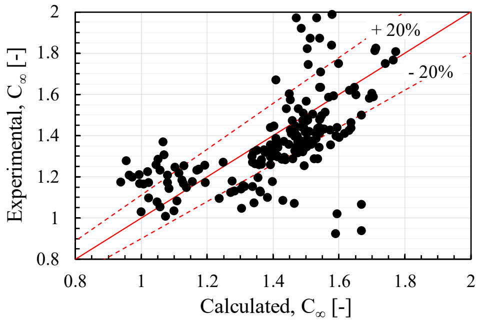
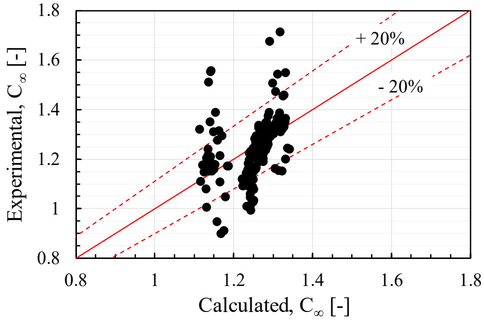


Fig. 4. Relationship between the asymptotic distribution parameter C_∞, and (a) the ratio of $(V_{sg})^+/(V_m)^+$; (b) the mixture Froude number Fr_M; (c) Two-phase Reynolds number Re_{TP}.



(a) Plug flow



(b) Slug flow

Fig. 5. Comparison between the experimental and the new correlation of the asymptotic distribution parameter C∞.

as inertial forces are already considered in the Ishii's equation, as it appears in Eq. (8), and the gravitational forces are negligible in the case of horizontal configuration. In addition, the power law form of the proposed correlation must be followed for the distinct flow regimes plug and slug.

The following correlations of the asymptotic distribution parameter, C∞, are proposed.

For Plug flow:

$$C_\infty = 3.08479\left[\frac{(V_{sg})^+/(V_m)^+}{Re_{TP}}\right]^{0.07546} \tag{14}$$

For Slug flow:

$$C_\infty = 3.69352\left[\frac{(V_{sg})^+/(V_m)^+}{Re_{TP}}\right]^{0.097585} \tag{15}$$

Figure 5 depicts a comparison between the experimental asymptotic distribution parameter, C∞, which was derived by using Eq. (9), and the calculated asymptotic distribution parameter obtained from the new correlations (Eq. (14) and (15)). In Fig. 5 (a) and (b), the experimental data for plug and slug flow shows good agreement with the proposed new correlations. Most of data are found to be near to the diagonal line (45° line), i.e., within the dashed lines which denotes a deviation of ± 20 %. Thus showing, the accuracy of the proposed correlation.

By combining equations (11), (12) and (13) into equations (14) and (15). The equations of asymptotic distribution parameter, C∞, can be arranged as follows:

For Plug flow:

$$C_\infty = 3.08479\left[\frac{V_{sg}\,\mu_l}{V_m^2\,D\,\rho_l}\right]^{0.07546} \tag{16}$$

For Slug flow:

$$C_\infty = 3.69352\left[\frac{V_{sg}\,\mu_l}{V_m^2\,D\,\rho_l}\right]^{0.097585} \tag{17}$$

After substituting the correlation of the asymptotic distribution parameter C∞ into equation (Eq. (8)), The resulting formulation of the distribution parameter for a gas-liquid two-phase flow in a horizontal pipe becomes:

For Plug flow:

$$C_0 = 3.084\left[\frac{V_{sg}\,\mu_l}{V_m^2\,D\,\rho_l}\right]^{0.075} - \left[\left(3.084\left[\frac{V_{sg}\,\mu_l}{V_m^2\,D\,\rho_l}\right]^{0.075}\right) - 1\right]\sqrt{\frac{\rho_g}{\rho_l}} \tag{18}$$

For Slug flow:

$$C_0 = 3.693\left[\frac{V_{sg}\,\mu_l}{V_m^2\,D\,\rho_l}\right]^{0.097} - \left[\left(3.693\left[\frac{V_{sg}\,\mu_l}{V_m^2\,D\,\rho_l}\right]^{0.097}\right) - 1\right]\sqrt{\frac{\rho_g}{\rho_l}} \tag{19}$$

Figure 7 shows the ratio between the theoretical and experimental void fraction as a function of the experimental void fraction data. The circular and triangular symbols indicate the ratio calculated by the new proposed correlation and the ones of Rassame and Hibiki, respectively. As can be seen in this figure, both correlations show comparable predictive ability for a small range of the void fraction, i.e., $0.4 \leq \alpha_{Exp.} \leq 0.6$. However, the intermittent plug-and-slug flow is the most persistent configuration in the horizontal two-phase flow, and the spectrum of the void fraction corresponding to this kind of flow configuration exceeds the boundaries of $0.4 \leq \alpha_{Exp.} \leq 0.6$. Furthermore, the majority of the data derived from the new correlation are located around unity and within the dashed lines that indicates a deviation of ± 20 %. The correlation

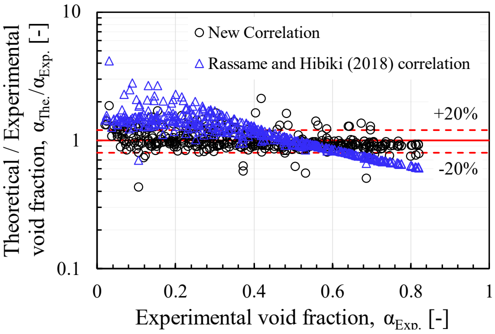


Fig. 6. Descriptive performance of the new proposed correlation and those of Rassame and Hibiki (2018) correlation for all tested experimental data.

of Rassame and Hibiki (2018) tends to overestimate and underestimate the measurement in the ranges of $0.4 > \alpha_{Exp}$ and $\alpha_{Exp} > 0.6$, respectively. This plot demonstrates that the proposed correlation surpasses the model of Rassame and Hibiki (2018).

It is worthy to remember that the correlation of Rassame and Hibiki considers only the ratio $(V_{sg})^+/(V_m)^+$ as a variable parameter and ignores the impact of the two-phase flow pattern.

Additionally, the prediction given by the proposed correlation is also compared with those obtained by various existing void fraction drift-flux models. In order to perform this comparison, two statistical parameters were used. The first is the root mean square (RMS) and the second is the mean relative absolute error (ABE), which are calculated through the equations (20) to (22) (Zeghloul *et al.* 2020).

$$RMS=\sqrt{\frac{1}{n}\sum_{i=0}^{n}\left[\frac{\alpha_{i,calculated}-\alpha_{i,measured}}{\alpha_{i,measured}}\right]^2} \tag{20}$$

$$x_i=\frac{\left|\alpha_{i,calculated}-\alpha_{i,measured}\right|}{\alpha_{i,measured}} \tag{21}$$

$$ABE=\frac{1}{n}\sum_{i=0}^{n}x_i \tag{22}$$

Where $\alpha_{i,calculated}$ is the predicted void fraction, $\alpha_{i,measured}$ is the experimental void fraction and n, is the number of data.

Table 3 provides a synthesis of the computed RMS and ABE results for various void fraction drift flux correlations (i.e. Mattar and Gregory (1974), Greskovich and Cooper (1975), França and Lahey (1992), Mishima and Hibiki (1996), Lamari (2001), Woldesemayat and Ghajar (2007), Da Silva *et al.* (2011), Rassame and Hibiki (2018) and Kong et al. (2018b)) as well the developed one. For each model, the two statistical parameters are given for each flow pattern data as well for the whole database.

Considering Table 3, it appears that the new proposed drift flux correlation yields to the smallest deviations, which match the total (RMS) and (ABE) values of 23% and 16%, respectively. Furthermore, an admissible deviation was attained for Silva *et al.* (2011) correlation, which is consistent with the close results for (RMS) and (ABE) to the proposed correlation. While the remaining tested correlations were found to be less effective in the prediction of the experimental data. Furthermore, the most tested correlations from the literature as well as the newly proposed correlation seems to work more accurately in slug flow than in plug flow, as confirmed by the obtained (RMS) and (ABE) results corresponding to the two flow configurations. It is worth noticing that less than 25% deviation error may be regarded as very interesting values for two-phase flow.

5. CONCLUSION

New proposed model for the distribution parameters in drift flux model was developed and showed a superior accuracy over all available models in literature. The model was developed in a notion to improve the model of Rassame and Hibiki (2018) and turned to have the best accuracy when it is compared to 9 available models for the distribution parameters. The proposed model was validated using unbiased experimental data bank from different resources available in literature covering wide range of pipe diameter up to 152 mm and viscosity up to 600 cP. The main conclusions of the present work can be summarized in the following two points:

1) The drift flux model is reformulated for plug and slug flow separately for the first time in literature.
2) The asymptotic distribution parameter, C_∞, which is very crucial for the drift flux model was found to be a function of two dimensionless parameters, namely, $(V_{sg})^+/(V_m)^+$ and Re_{TP} and the flow regime (whether plug or slug).
3) The proposed model showed more accurate results than all available models.
4) The new model results in a mean relative absolute error for all data bank of around 16% while the closest model (Da Silva *et al.* (2011)**)** gives around 19% and the most recent models of Rassame and Hibiki (2018) and Kong *et al.* (2018b) give 33% and 50%, respectively.

Table 3 Values of RMS and ABE (%) for two-phase Void fraction.

Author	Plug		Slug		Total	
	RMS	ABE	RMS	ABE	RMS	ABE
New correlation*	23.87%*	16.49%*	28.63%*	16.91%*	26.30%*	16.70%*
Mattar and Gregory (1974)	41.90%	38.22%	29.61%	26.01%	36.43%	32.27%
Greskovich and Cooper (1975)	59.74%	49.09%	59.46%	43.00%	59.83%	46.12%
França and Lahey (1992)	31.04%	24.80%	56.43%	35.25%	45.23%	29.89%
Mishima and Hibiki (1996)	31.87%	25.84%	30.72%	27.86%	31.31%	26.83%
Lamari (2001)	44.70%	38.57%	30.67%	23.49%	38.50%	31.22%
Woldesemayat and Ghajar (2007)	36.08%	24.27%	45.66%	25.18%	41.03%	24.72%
Da Silva *et al.* (2011)	27.39%	18.88%	31.15%	20.24%	29.28%	19.54%
Rassame and Hibiki (2018)	50.15%	39.37%	42.58%	27.16%	46.62%	33.42%
Kong *et al.* (2018b)	51.41%	47.34%	73.14%	54.75%	62.94%	50.95%

REFERENCES

Abdulkadir, M., V. Hernandez-Perez, C. A. Kwatia, and B. J. Azzopardi (2018). Interrogating flow development and phase distribution in vertical and horizontal pipes using advanced instrumentation. *Chemical Engineering Science* 186, 152-167.

Abdulkadir, M., V. Hernandez-Perez, I. S. Lowndes, B. J. Azzopardi and E. Sam-Mbomah (2016). Experimental study of the hydrodynamic behaviour of slug flow in a horizontal pipe. *Chemical Engineering Science* 156, 147-161.

Andritsos, N., L. Williams and T. J. Hanratty (1989). Effect of liquid viscosity on the stratified-slug transition in horizontal pipe flow. *International Journal of Multiphase Flow* 15, 877-892.

Arabi, A., A. Azzi, R. Kadi, A. Al-Sarkhi and B. Hewakandamby (2021). Empirical modelization of intermittent gas/liquid flow hydrodynamic parameters: the importance of distinguishing between plug and slug flows. *SPE Production & Operations* 36, 703-720.

Arabi, A., Y. Salhi, Y. Zenati, E. K. Si-Ahmed and J. Legrand (2020a). On gas-liquid intermittent flow in a horizontal pipe: Influence of sub-regime on slug frequency. *Chemical Engineering Science* 211.

Arabi, A., K. Ragui, Y. Salhi and A. Filali (2020b). Slug frequency for a gas-liquid plug flow: Review and development of a new correlation. *International Communications in Heat and Mass Transfer* 118.

Beattie, D. R. H. and S. Sugawara (1986). Steam-water void fraction for vertical upflow in a 73.9 mm pipe. *International Journal of Multiphase Flow* 12, 641-653.

Chexal, B., G. Lellouche, J. Horowitz and J. Healzer (1992). A void fraction correlation for generalized applications. *Progress in Nuclear Energy* 27, 255-295.

Choi, J., E. Pereyra, C. Sarica, C. Park and J. M. Kang (2012). An efficient drift-flux closure relationship to estimate liquid holdups of gas-liquid two-phase flow in pipes. *Energies* 5, 5294-5306.

Clark, N. and R. Flemmer (1986). The effect of varying gas voidage distributions on average holdup in vertical bubble flow. *International Journal of Multiphase Flow* 12, 299-302.

Da Silva, M. J., U. H. De Helmholtz, Z. Dresden-Rossendorf, C. E. F. Do Amaral and R. E. M. Morales (2011). Experimental investigation of horizontal gas-liquid slug flow by means of wire-mesh sensor. *Journal of the Brazilian Society of Mechanical Sciences and Engineering* 33, 234-242.

Dang, Z., Z. Yang, X. Yang and M. Ishii (2018). Experimental study of vertical and horizontal two-phase pipe flow through double 90 degree elbows. *International Journal of Heat and Mass Transfer* 120, 861-869.

Dong, C., S. Rassame, L. Zhang and T. Hibiki (2020). Drift-flux correlation for upward two-phase flow in inclined pipes. *Chemical Engineering Science* 213.

Fabre, J. and A. Liné 1992. Modeling of Two-Phase Slug Flow. *Annual Review of Fluid Mechanics* 24, 21-46.

França, F. and R. T. Lahey (1992). The use of drift-flux techniques for the analysis of horizontal two-phase flows. *International Journal of Multiphase Flow* 18, 787-801.

Ghajar, A. J. (2020). *Two-Phase Gas-Liquid Flow in Pipes With Different Orientations*, 1st ed. ed. Springer, Switzerland.

Gokcal, B., Q. Wang, H. Q. Zhang and C. Sarica (2008). Effects of high oil viscosity on oil/gas flow behavior in horizontal pipes. *SPE Projects, Facilities & Construction* 3, 1-11.

Gomez, L. E., O. Shoham, Z. Schmidt, R. N. Chokshi and T. Northug (2000). Unified mechanistic model for steady-state two-phase flow: horizontal to vertical upward flow. *SPE Journal* 5, 339-350.

Greskovich, E. J. and W. T. Cooper (1975). Correlation and prediction of gas-liquid holdups in inclined upflows. *AIChE Journal* 21, 1189-1192.

Hibiki, T. (2019). One-dimensional drift-flux correlations for two-phase flow in medium-size channels. *Experimental and Computational Multiphase Flow* 1, 85-100.

Hibiki, T. and M. Ishii (2001). Distribution parameter and drift velocity of drift-flux model in bubbly flow. *International Journal of Heat and Mass Transfer* 45, 707-721.

Hibiki, T. and M. Ishii (2003a). One-dimensional drift-flux model and constitutive equations for relative motion between phases in various two-phase flow regimes. *International Journal of Heat and Mass Transfer* 46, 4935-4948.

Hibiki, T. and M. Ishii (2003b). One-dimensional drift–flux model for two-phase flow in a large diameter pipe. *International Journal of Heat and Mass Transfer* 46, 1773-1790.

Ishii, M. (1977). *One-Dimensional Drift-Flux Model and Constitutive Equations for Relative Motion Between Phases in Various Two-Phase Flow Regimes.* Argonne Natl. Lab., IL, USA.

Kataoka, I. and M. Ishii (1987). Drift flux model for large diameter pipe and new correlation for pool void fraction. *International Journal of Heat and Mass Transfer* 30, 1927-1939.

Kokal, S. L. and J. F. Stanislav (1989). An experimental study of two-phase flow in slightly inclined pipes—I. Flow patterns. *Chemical Engineering Science* 44, 665-679.

Kong, R. (2018). *Characterization of Horizontal Air-Water Two-Phase Flow in Different Pipe Sizes.* Open Access Diss. Purdue University, West Lafayette, Indiana.

Kong, R., A. Rau, S. Kim, S. Bajorek, K. Tien and C. Hoxie (2018a). Experimental study of horizontal air-water plug-to-slug transition flow in different pipe sizes. *International Journal of Heat and Mass Transfer* 123, 1005-1020.

Kong, R., Q. Zhu, S. Kim, M. Ishii, S. Bajorek, K. Tien and C. Hoxie (2018b). Void fraction prediction and one-dimensional drift-flux analysis for horizontal two-phase flow in different pipe sizes. *Experimental Thermal and Fluid Science* 99, 433-445.

Lamari, M. L. (2001). *An Experimental Investigation of Two-Phase (Air-Water) Flow Regimes in a Horizontal Tube at Near Atmospheric Conditions.* The Ottawa-Carleton Institute for Mechanical and Aerospace Engineering, Ottawa, Ontario.

Lu, C., R. Kong, S. Qiao, J. Larimer, S. Kim, S. Bajorek, K. Tien and C. Hoxie (2018). Frictional pressure drop analysis for horizontal and vertical air-water two-phase flows in different pipe sizes. *Nuclear Engineering and Design* 332, 147-161.

Mandhane, J. M., G. A. Gregory and K. Aziz (1974). A flow pattern map for gas—liquid flow in horizontal pipes. *International Journal of Multiphase Flow* 1, 537-553.

Mattar, L. and G. A Gregory, (1974). Air-Oil Slug Flow in An Upward-Inclined Pipe - 1: Slug Velocity, Holdup and Pressure Gradient. *Journal of Canadian Petroleum Technology* 13, 69-76.

Mishima, K. and T. Hibiki (1996). Some characteristics of air-water two-phase flow in small diameter vertical tubes. *International Journal of Multiphase Flow* 22, 703-712.

Mohmmed, A. O., H. H. Al-Kayiem and A. B. Osman (2021). Investigations on the slug two-phase flow in horizontal pipes: Past, presents, and future directives. *Chemical Engineering Science* 238, 116611.

Rassame, S. and T. Hibiki (2018). Drift-flux correlation for gas-liquid two-phase flow in a horizontal pipe. *International Journal of Heat and Mass Transfer* 69, 33-42.

Rouhani, S. Z. and E. Axelsson (1970). Calculation of void volume fraction in the subcooled and quality boiling regions. *International Journal of Heat and Mass Transfer* 13, 383-393.

Sassi, P., G. Fernández, Y. Stiriba and J. Pallarès (2022). Effect of solid particles on the slug frequency, bubble velocity and bubble length of intermittent gas–liquid two-phase flows in horizontal pipelines. *International Journal of Multiphase Flow* 149, 103985.

Shi, H., J. A. Holmes, L. J. Durlofsky, K. Aziz, L. R. Diaz Teran Ortegon, B. Alkaya and G. Oddie (2005). Drift-flux modeling of two-phase flow in wellbores. *SPE Journal* 10, 24-33.

Thaker, J. and J. Banerjee (2015). Characterization of two-phase slug flow sub-regimes using flow visualization. *Journal of Petroleum Science and Engineering* 135, 561-576.

Thaker, J. and J. Banerjee (2017). Transition of plug to slug flow and associated fluid dynamics. *International Journal of Multiphase Flow* 91, 63-75.

Woldesemayat, M. A. and A. J. Ghajar (2007). Comparison of void fraction correlations for different flow patterns in horizontal and upward inclined pipes. *International Journal of Multiphase Flow* 4, 347-370.

Zeghloul, A., A. Messilem, N. Ghendour, A. Al-sarkhi, A. Azzi and A. Hasan (2020). Theoretical study and experimental measurement of the gas liquid two-phase flow through a vertical Venturi meter. *Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science* 0, 1-18.

Zuber, N. and J. A. Findlay (1965). Average volumetric concentration in two-phase flow systems. *ASME Journal of Heat and Mass Transfer* 87, 453-468.