An Evaluation and Development of Drift-Flux Correlations for Enhanced Nuclear Reactor Simulations

Sultan Al-Faifi [a*]
[a]King Abdullah City for Atomic and Renewable Energy, Riyadh 12244, Saudi Arabia
*Corresponding author: s.faifi@energy.gov.sa

Abstract - *In the coupled neutronics and thermal-hydraulics analysis, the void fraction plays a significant role in determining various nuclear reactor parameters such as reactor coolant mixture density, neutron moderation, local power distribution, two-phase pressure drop, two-phase flow regimes, and heat transfer coefficient. Consequently, accurate prediction of the void fraction is crucial for nuclear reactor simulations in both steady-state and transient conditions. This research aims to evaluate a range of drift flux correlations frequently employed in the nuclear industry. Initially, a simple and robust one-dimensional two-phase flow code, based on the drift flux approach, was developed and validated to assess the performance of the selected drift-flux correlations. A comprehensive statistical analysis was then conducted, utilizing more than 1,600 experimental tests taken from the open literature. These experiments covered a wide range of vertical and horizontal flow regimes and geometries, including pipes, annulus, and fuel assemblies. The evaluation results identified the Hibiki & Ishii correlation as the most accurate, with a mean absolute error of 16.2%, followed by Toshiba and Antonio correlations, with mean absolute errors of 17.45% and 17.69%, respectively. Additionally, the same experimental dataset was utilized to derive a new drift-flux correlation for various vertical and horizontal flow regimes. The performance assessment of the newly developed correlation showed an overall improvement, with a mean absolute error of 14.6%. The current limitation in the study is the limited availability of experimental datasets in the open literature. To overcome this constraint, future research will aim to access a more extensive dataset, thereby ensuring the development of a more accurate and reliable drift flux correlation for nuclear reactor simulations.*

Keywords: Drift-Flux Correlations, Nuclear Thermal-Hydraulics Codes, Two-Phase Flow

I. Introduction

Demonstration of nuclear reactor safety during the licensing process requires a comprehensive analysis of complex coupled thermal hydraulics-neutronics phenomena for a wide range of transient conditions. Nuclear research institutes have invested a lot of time and money in this field of study. However, the existence of turbulence and two-phase flow, which have a wide spectrum of interacting scales from microscopic to macroscopic, prevent the governing laws of mass, momentum, and energy from being fully solved in complex systems, despite their successful formulation in mathematical equations. Engineers and researchers have worked hard to simplify those governing equations and use them in practical applications. For example, the two-phase flow simulation began with a simple homogenous model that assumed both phases moved at the same speed, progressed to a model that treated the mixture as a whole and took relative velocity into account using algebraic slip correlation, and finally arrived at a more realistic model that treated each phase separately. The latter is currently used by the majority of nuclear thermal hydraulics codes.

The void fraction is a crucial parameter in calculating reactor coolant density, neutron moderation, local power distribution, two-phase pressure drops, two-phase flow regimes, heat transfer coefficients, and other parameters involved in coupled neutronics and thermal-hydraulics analysis.

Accurately predicting the void fraction is, therefore, important for a comprehensive assessment of nuclear reactor performance under both steady-state and transient conditions. As a result, the following are the primary objectives of this paper:

- Develop a new correlation for vertical and horizontal flow by considering different flow regimes and geometries.
- Evaluate multiple drift flux correlations used in the nuclear industry

II. Overview of Drift-Flux Model

The well-known drift-flux model, proposed by Zuber, is a simplified form of the more detailed two-fluid model, which is used in many current thermal-hydraulic system analysis codes [1, 2]. It is a simple and accurate model that describes the complex relative motion in two-phase flow systems as a function of two parameters, namely the distribution parameter and drift velocity. The distribution parameter considers the distribution of the void fraction over the mixture's superficial velocity profile. It simply takes into consideration the non-uniformity of the flow. On the other hand, the drift velocity takes into consideration the local relative velocity between the dispersed phase and the local mixture flux, which is a result of the buoyancy effect. The drift-flux correlation is given by Zuber and Findlay as

$$\langle\langle v_g \rangle\rangle = \frac{\langle j_g \rangle}{\langle \alpha \rangle} = C_0 \langle j \rangle + \langle\langle v_{gj} \rangle\rangle \qquad (1)$$

$$C_0 = \frac{\langle \alpha j \rangle}{\langle j \rangle \langle \alpha \rangle} \qquad (2)$$

$$\langle\langle v_{gj} \rangle\rangle = \frac{\langle \alpha v_{gj} \rangle}{\langle \alpha \rangle} \qquad (3)$$

where v_g, α, C_0, v_{gj}, and j_g are gas velocity, void fraction, distribution parameter, drift velocity, and mixture volumetric flux, respectively. The $\langle\langle\ \rangle\rangle$ and $\langle\ \rangle$ notations represent area-averaged void-weighted mean and area-averaged quantities over the flow channel, respectively. The distribution parameter and drift velocity can be obtained by Eq. (2) and Eq. (3) if the distribution of local void fraction and gas and liquid velocities are measured [3]. However, it is extremely difficult to obtain these values experimentally. Therefore, an alternative method was proposed by Zuber and Findlay to obtain the drift velocity and distribution parameter. If a linear relationship between the area average mixture flux and the void-weighted mean velocity exists in a test condition, then the distribution parameter and drift velocity can be obtained as the slope and intercept in the plot of $\langle j \rangle$ and $\langle\langle v_{gj} \rangle\rangle$, respectively.

The Findlay and Zuber approach has some difficulties determining drift velocity accurately under high mixture flux conditions. Therefore, Ishii and Hibiki came up with the idea of calculating the drift velocity based on the terminal velocity of the disperse phase, which can be derived by balancing the drag force with the buoyancy force in the case of a vertical flow. All correlations that fall under the drift-flux category differ in their terms for the distribution coefficient, drift velocity, or both [4].

II.A. Collected Experimental Data

To assess drift-flux correlations used in the nuclear industry, experimental data for various flow geometries and mass fluxes was gathered. The experimental data were collected under steady-state conditions and encompassed various configurations, including vertical and horizontal pipes, annulus, and fuel assemblies. Table I summarizes the data, and references 5–14 provide further information.

Table I Summary of collected database used in this assessment

Experiment	Diameter (m)	Type	Liquid superficial velocity (m/s)	Gas superficial velocity (m/s)	Fluid Type	Length (m)	Pressure (kPa)
Benjamin [5]	0.05	Vertical (UP)	0.37~1.95	0.055-3.286	Gas-liquid	3	atm-131.7
Stankovic [6]	0.2	Vertical (UP)	0.755	0.788-0.021	Gas-liquid	9.56	101.35-512.27
Almabrok [7]	0.1016	Vertical (UP)	0.07-1.5	8.11-0.04866	Gas-liquid	6	atm
Sujumnong [8]	0.0117	Vertical (UP)	0.0545-8.46	0.546-13.104	Gas-liquid	1.52	101.35-342.66
Caetano [9]	0.0762-0.0422	Vertical Annulus (UP)	0.002-2.9	0.037-22.1	Gas-liquid	13.7	760
Yang [10]	0.0217	Fuel Assembly (UP)	0.088-1.35	0.065-7.12	Gas-liquid	3.258	100.0-300.0
Faris [11]	0.127	Horizontal pipe	0.0-8.6	0.0-28	Gas-liquid	14	atm
Polytech [12]	0.019	Horizontal pipe	0.0-0.5	0.06-7.0	Gas-liquid	4.8	atm
Osamusali [13]	0.051	Horizontal pipe	0.052-0.137	0.35-5.12	Gas-liquid	3.0	atm
Kyungsu [14]	0.1	Horizontal pipe	0.065-0.195	0.00065-0.006	Gas-liquid	7	atm

Table II Selected Drift-flux correlation

Correlation	Distribution Parameter C_0	Drift Velocity v_{gj}
Toshiba Correlation [15]:	$C_0 = 1.08$	$v_{gj} = 0.45$
Hibiki & Ishii Correlation [16]:	For bubbly flow $C_0 = 1.2 - 0.2\sqrt{\frac{\rho_g}{\rho_l}}(1 - \exp(-18\alpha))$	$v_{gj} = 1.41\left[\frac{g\sigma(\rho_l - \rho_g)}{\rho_l^2}\right]^{0.25}(1-\alpha)^{1.75}$
	$C_0 = 1.2 - 0.2\sqrt{\frac{\rho_g}{\rho_l}}$	$v_{gj} = 0.35\left[\frac{gD(\rho_l - \rho_g)}{\rho_l}\right]^{0.5}$
	$C_0 = 1 + \left(\frac{1-\alpha_g}{\alpha_g + 4\sqrt{\frac{\rho_g}{\rho_l}}}\right)$	$v_{gj} = (1-\alpha_g)\left[\alpha_g + 4\frac{\sqrt{\frac{\rho_g}{\rho_l}}\left(\frac{gD(\rho_l-\rho_g)}{\rho_l}\right)^{0.5}}{0.015\rho_g}\right]^{0.5}$
Kokal and Stanislav Correlation [18]:	$C_0 = 1.2$	$v_{gj} = 0.345\left[\frac{gD(\rho_l - \rho_g)}{\rho_l}\right]^{0.5}$
Gomez Correlation [19]:	$C_0 = 1.15$	$v_{gj} = 1.53\left[\frac{g\sigma(\rho_l - \rho_g)}{\rho_l^2}\right]^{0.25}(1-\alpha)^{0.5}$
Antonio Correlation [20]:	$C_0 = 1.0$	$v_{gj} = 1.53\left[\frac{g\sigma(\rho_l - \rho_g)}{\rho_l^2}\right]^{0.25}(1-\alpha)^{0.5}$
	$C_0 = 1.2$	$v_{gj} = 0.64$
Homogenous Model	$C_0 = 1.0$	$v_{gj} = 0.0$

II.B. Selected Drift-Flux Correlations for the Assessment

Within the nuclear industry, drift flux correlations play a crucial role in analyzing coolant behaviors under varying operational conditions, whereas in the oil industry, they provide insights into oil-gas flow in pipelines and reservoirs. For the purposes of this analysis, a select set of the most frequently employed drift flux correlations from these sectors has been chosen. These correlations, along with their coefficients, are detailed in Table II.

III. Two-Phases Drift-Flux Code Development and Validation & Verification

III.A. Code development

The drift-flux code developed for this paper is comprised of two mass conservation equations, a mixture momentum conservation equation, a simplified energy equation, and closure equations. The numerical scheme is based on the advection upstream splitting method (AUSMV), which is a simple and robust transient model that can handle dynamic flow systems accurately. It is a hybrid scheme that combines the advantages of the flux-vector splitting (FVS) scheme and the flux-difference-splitting (FDS) scheme in order to obtain an efficient and accurate prediction. For more comprehensive information about the AUSMV scheme and its implementation, please refer to the references [21, 22].

- Conservation Equations:

1. Liquid mass conservation equation:

The liquid continuity equation can be expressed as follows:

$$\frac{\partial}{\partial t}(\rho_l \alpha_l) + \frac{\partial}{\partial z}(\rho_l u_l) = \Gamma_l \tag{4}$$

2. Vapor mass conservation equation:

The liquid continuity equation can be expressed as follows:

$$\frac{\partial}{\partial t}(\rho_g \alpha_g) + \frac{\partial}{\partial z}(\rho_g u_g) = \Gamma_g \tag{5}$$

3. Mixture momentum conservation equation:

The momentum conservation equations for both liquid and gas can be formulated as follows:

Liquid momentum conservation equation:

$$\frac{\partial}{\partial t}\left[\rho_f(1-\alpha)u_f\right] + \frac{1}{A}\frac{\partial}{\partial z}\left[A\rho_f(1-\alpha){u_f}^2\right] + \Gamma u_I = -(1-\alpha)\frac{\partial P}{\partial z} - F_{wf} - \rho_f g(1-\alpha)\sin\emptyset + F_I - F_{vm} \qquad (6)$$

Gas momentum conservation equation:

$$\frac{\partial}{\partial t}\left[\rho_g \alpha u_g\right] + \frac{1}{A}\frac{\partial}{\partial z}\left[A\rho_g \alpha {u_g}^2\right] - \Gamma u_I = -\alpha\frac{\partial P}{\partial z} - F_{wg} - \rho_g g \alpha \sin\emptyset - F_I + F_{vm} \qquad (7)$$

By adding the liquid momentum equation, Eq. (6), and the gas momentum equation, Eq. (7), the interfacial forces will cancel each other and the following mixture momentum equation can be obtained for two-phase flow:

$$\frac{\partial}{\partial t}\left[\rho_g\alpha_g u_g + \rho_l\alpha_l u_l\right] + \frac{\partial}{\partial z}\left[\rho_g\alpha_g {u_g}^2 + \rho_l\alpha_l {u_l}^2\right] + \frac{\partial P}{\partial z} = \frac{\Delta P_{fric}}{\Delta z} - \left[\rho_l\alpha_l + \rho_g\alpha_g\right]g\sin\emptyset \qquad (8)$$

The conservation equations of mass and momentum can be represented in a conservative vector form as:

$$\frac{\partial}{\partial t}\begin{bmatrix}\rho_g\alpha_g \\ \rho_l\alpha_l \\ \rho_g\alpha_g u_g + \rho_l\alpha_l u_l\end{bmatrix} + \frac{\partial}{\partial z}\begin{bmatrix}\rho_g\alpha_g u_g \\ \rho_l\alpha_l u_l \\ \rho_g\alpha_g {u_g}^2 + \rho_l\alpha_l {u_l}^2 + P\end{bmatrix} = \begin{bmatrix}\Gamma_g \\ \Gamma_l \\ -q\end{bmatrix} \qquad (9)$$

Where
α_l and α_g are volume fractions of liquid and gas
ρ_l and ρ_g are densities of liquid and gas.
v_l and v_g are velocities of liquid and gas.
Γ_g and Γ_l are mass exchanges between liquid and gas phase.
P is pressure term
q is a source term or external forces acting on the fluid (e.g., gravitational force and friction force)

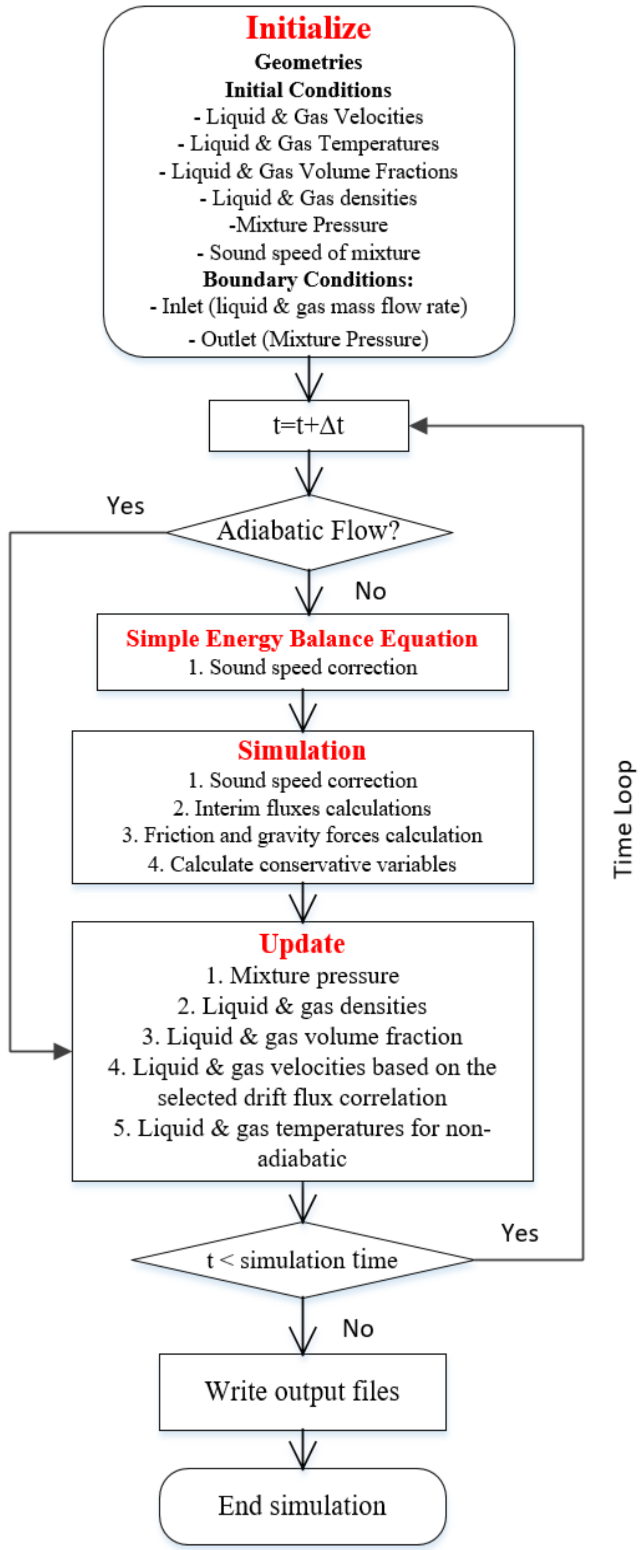

Fig. 1. Flow chart of the two phases flow code based on drift flux approach

Constitutive equations:

Constitutive equations are simplifications used to relate unknown variables with known values. Given that there are seven unknown variables but only three differential equations available, there is a need for four additional constitutive equations to achieve system closure. These constitutive equations include densities, total volume fractions, and slippage equations.

Liquid and gas Density:

The code offers two methods for obtaining liquid and gas densities:

- For a two-phase, single-component mixture (steam-water flow), the values are retrieved from the thermodynamic steam tables, and a linear interpolation function is used.

- For a two-phase, single-component mixture (water and non-condensable), the water density is obtained from the thermodynamic table, and the non-condensable gas density is obtained from the ideal gas law.

$$\rho_g = \frac{P}{R_{spec}T} \tag{10}$$

Volume fraction:

The sum of liquid volume fraction and the gas volume fraction is always equal to one.

$$\alpha_g + \alpha_l = 1 \tag{11}$$

Slippage equation:

The slip velocity proposed by Zuber and Findlay is used to calculate gas velocity based on the area average mixture volumetric flux as

$$\langle\langle v_g \rangle\rangle = C_0 \langle j \rangle + \langle\langle v_{gj} \rangle\rangle \tag{12}$$

where the distribution parameter and drift velocity are calculated based on the selected drift-flux correlations listed in the previous section.

The friction term:

A simple two-phase friction term is used to calculate friction force as

$$F = \frac{f_{TP}}{D_e}\left(\frac{\rho_m j^2}{2}\right) \tag{13}$$

The two-phase friction factor is obtained based on homogenous flow conditions, where $f_{TP} = f_{lo}$, and the liquid only friction factor (f_{lo}) can be calculated using Colebrook correlation [23]

$$\frac{1}{\sqrt{f_{lo}}} = -2\log_{10}\left(\frac{\varepsilon}{3.7D_h} + \frac{2.51}{Re\sqrt{f_{lo}}}\right) \tag{14}$$

where Reynolds number is given as

$$Re = \frac{\rho_l\, abs(v_{mix}) D_c}{\mu_l} \tag{15}$$

The conditions for laminar and turbulent flows are
2000 >Re is Laminar
3000<Re is Turbulent
For 2000 < Re < 3000, an interpolated friction factor is calculated for the transition zone between laminar and turbulent flow as

$$F_{trans} = \left(1 - \frac{Re-2000}{1000}\right) \times F_{lam} + \left(\frac{Re-2000}{1000}\right) \times F_{turb} \tag{16}$$

A detailed flowchart of the code is shown in Fig. 1.

III.B. The Code's Verification and Validation

An excellent test of any numerical solution is to evaluate its prediction for a simplified problem for which an analytical solution can be obtained. Thus, an analytical solution of homogenous and equilibrium two-phase flow in a vertically heated tube with a uniform axial heat flux is used for the validation of the code.

From Fig. 2 and Fig. 3, the numerical solution agrees well with the analytical solution for both the void fraction and the total pressure drop. Hence, the numerical model is verified and can be used for the intended assessment of selected correlations.

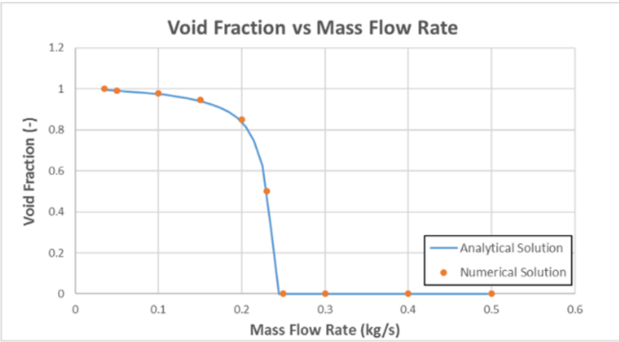

Fig. 2. Void fraction changes with mass flow rate

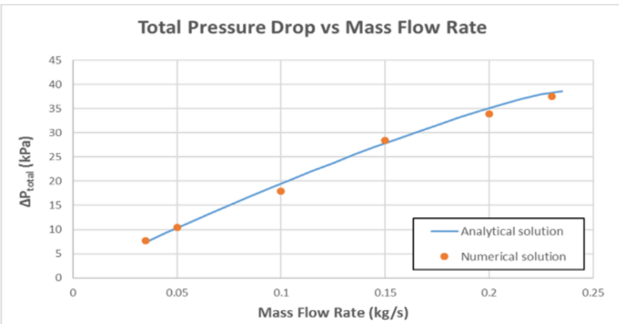

Fig. 3. Total pressure drop along the heated tube at different flow rate

V. New Drift-Flux Correlation Development

V.A. Classification of experimental data into specific flow regimes

Experimental data is categorized into flow regimes using the RELAP5/MOD3 flow regime map for horizontal flow and the Teitel and Dukler flow regime map for vertical flow, as in Fig. 4 and Fig. 5.

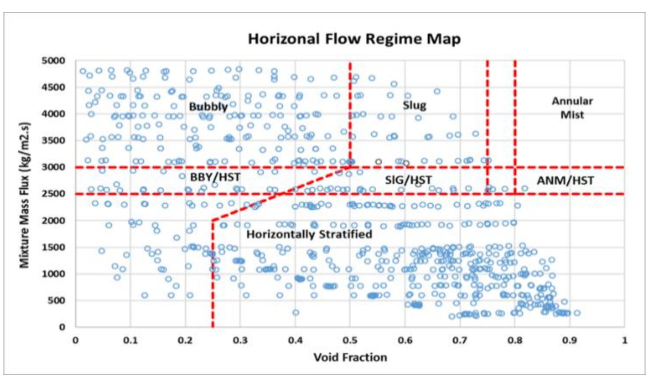

Fig. 4. Experimental data distribution on horizontal flow regime map

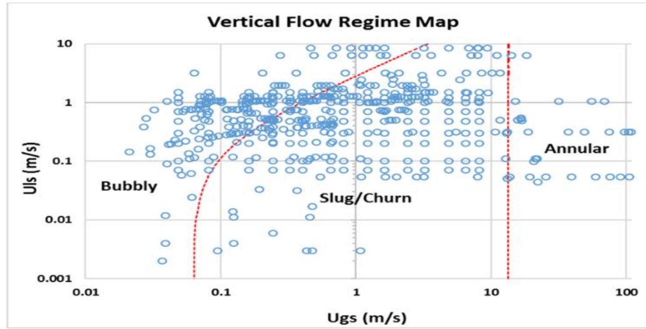

Fig. 5. Experimental data distribution on vertical flow regime map

V.B. Development of drift-flux correlations

- **Horizontal flow regime:**

A simplified drift-flux correlation is proposed for horizontal flow under the assumption that the local drift velocity is zero. A rough estimation of the distribution parameter based on the density ratio and Reynolds Number [26]. Distribution parameters were obtained for vertical flow, and drift velocities for bubbly and slug flow regimes were estimated but ignored for annular flow.

Accurate transition line predictions are necessary for a horizontal flow regime drift-flux correlation. However, it is challenging to precisely estimate the transition lines because of the complicated two-phase flow characteristics of horizontal pipes. As a result, the following assumptions will be used to create a straightforward independent drift-flux correlation: One can simply assume zero local drift velocity as there is no gravitational acceleration in the horizontal plane, and local drift velocity is mostly caused by gravitational acceleration between the two phases along the direction of flow.

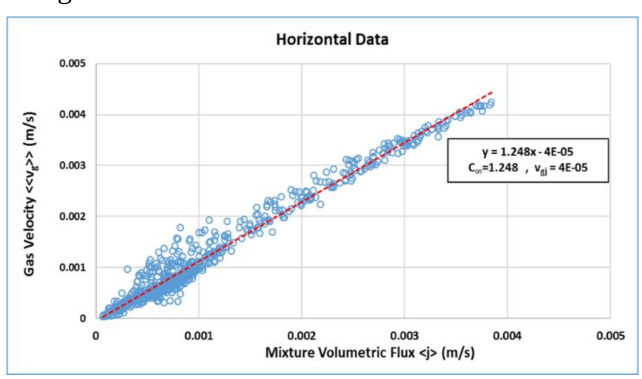

Fig. 6. Horizontal Gas flow velocity compared to the mixture volumetric flux

Since the distribution parameter approaches unity when the density ratio approaches unity, the distribution parameter can be represented approximately by the following asymptotic form:

$$C_0 = C_\infty - (C_\infty - 1)\sqrt{\frac{\rho_g}{\rho_l}} \quad (17)$$

Thus, from Fig. 6, the asymptotic distribution parameter can be calculated as the slope of the linear regression line, and the horizontal flow regime drift-flux correlation can be obtained as:

$$C_0 = 1.25 - 0.25\sqrt{\frac{\rho_g}{\rho_l}} \quad (18)$$

$$v_{gj} = 0.0 \quad (19)$$

- **Vertical Flow regime:**

The distribution parameters for each vertical flow regime can be found by using the same method suggested for the horizontal flow regime. However, the terminal velocity of the disperse phase is used to hypothetically calculate the drift velocities of the bubbly and slug flow regimes. Due to the high mixture volumetric flux in an annular flow regime, the effect of drift velocity can be neglected.

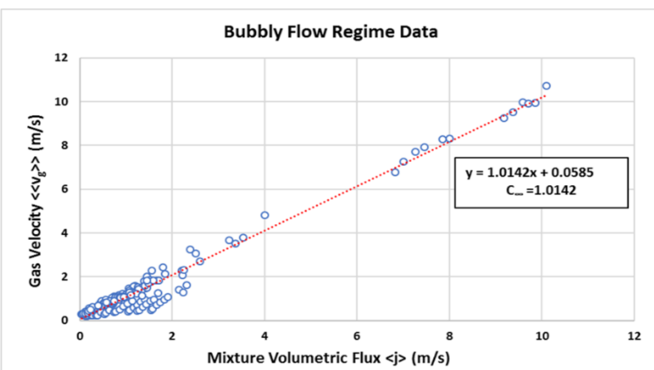

Fig. 7. Vertical bubbly flow velocity compared to the volumetric flux flow

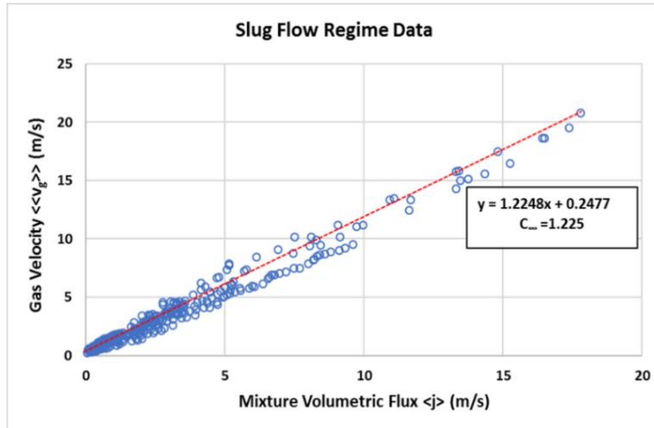

Fig. 8.. Vertical slug flow velocity compared to the volumetric flux flow

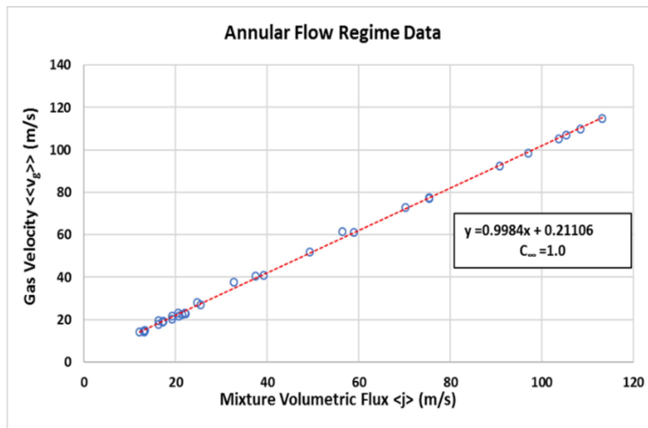

Fig. 9. vertical annular flow velocity compared to the volumetric flux flow

The proposed drift-flux correlation for vertical flow takes the following form:

For bubbly flow

$$C_0 = 1.0142 - 0.0142\sqrt{\frac{\rho_g}{\rho_l}} \quad (20)$$

$$v_{gj} = 1.53\left[\frac{g\sigma(\rho_l-\rho_g)}{{\rho_l}^2}\right]^{0.25}(1-\alpha)^{0.5} \quad (21)$$

For slug flow

$$C_0 = 1.225 - 0.225\sqrt{\frac{\rho_g}{\rho_l}} \quad (22)$$

$$v_{gj} = 0.32\left[\frac{gD(\rho_l-\rho_g)}{\rho_l}\right]^{0.5} \quad (23)$$

For annular flow

$$C_0 = 1.0 \quad (24)$$

$$v_{gj} = 0.0 \quad (25)$$

Since the inclined flow regime is a combination of horizontal and vertical flow regimes, one can generalize the drift-flux correlation for different inclined angles (∅)as follows:

$$v_{gj} = v_{gj0}\, sin(\emptyset) \quad (26)$$

$$C_0 = C_1 sin\,(\emptyset) + Cos\,(\emptyset)\left[1.25 - 0.25\sqrt{\frac{\rho_g}{\rho_l}}\right] \quad (27)$$

Where v_{gj0} and C_1 are obtained for each flow regime as:

For Bubbly flow

$$v_{gj0} = 1.53\left[\frac{g\sigma(\rho_l - \rho_g)}{{\rho_l}^2}\right]^{0.25}(1-\alpha)^{0.5} \quad (28)$$

$$C_1 = 1.0142 - 0.0142\sqrt{\frac{\rho_g}{\rho_l}} \quad (29)$$

For Slug flow

$$v_{gj0} = 0.32\left[\frac{gD(\rho_l - \rho_g)}{\rho_l}\right]^{0.5} \quad (30)$$

$$C_1 = 1.225 - 0.225\sqrt{\frac{\rho_g}{\rho_l}} \quad (31)$$

For Annular flow

$$v_{gj0} = 0.0 \quad (32)$$

$$C_1 = 1.25 - 0.25\sqrt{\frac{\rho_g}{\rho_l}} \quad (33)$$

Assessment of the proposed correlation:

The assessment of the new drift-flux correlation is shown in Fig. 10 & Fig. 11. Both graphs show excellent predictions for all the experimental data analyzed in this assessment.

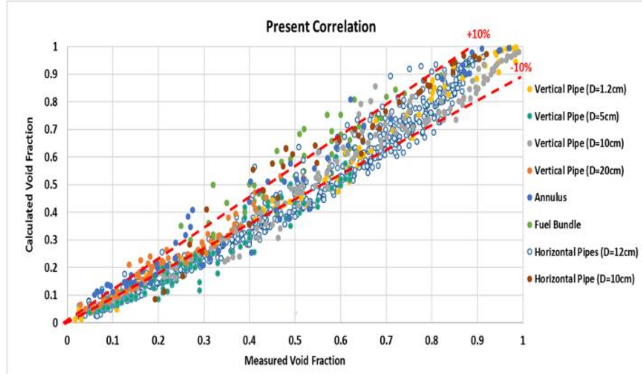

Fig. 10. Present correlation for calculated void fractions vs measured void fraction

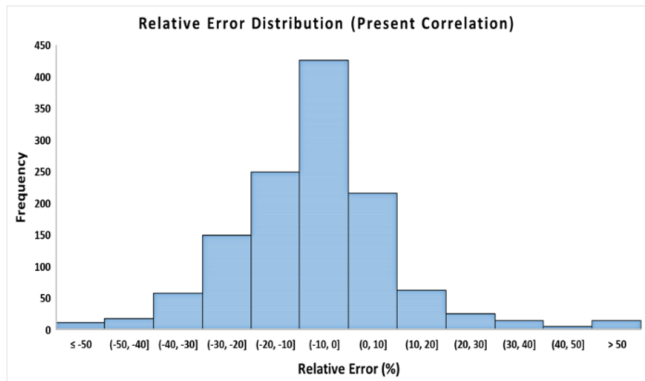

Fig. 11. Error for present correlation for calculated void fractions vs measured void fraction

IV. Assessment Method and Results

Fig. 12–17 include only representative data from all experiments to show graphically the comparison of the predicted and measured void fractions and the error distribution of the predicted values for the top three drift-flux correlations.

Toshiba Correlation:

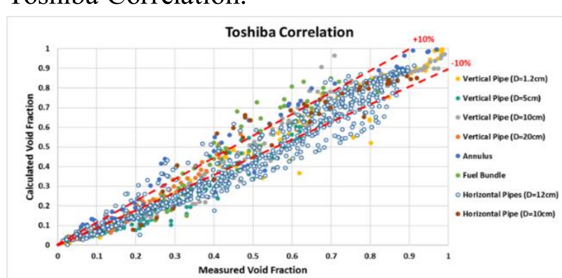

Fig. 12. Comparison between predicted and measured void fractions using Toshiba correlation (Representative data)

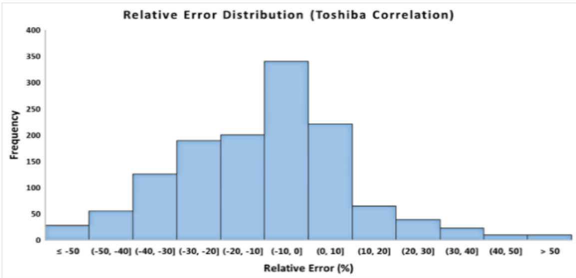

Fig. 13. Error distribution of the predicted void fractions using Toshiba correlation (Representative data)

Hibiki & Ishii Correlation:

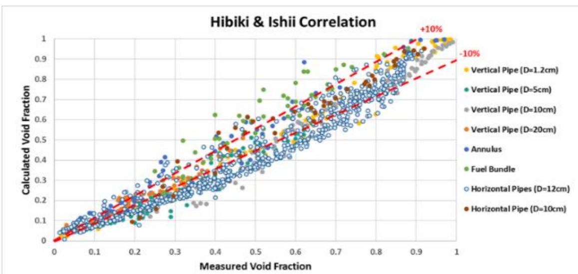

Fig. 14. Comparison between predicted and measured void fractions using Hibiki & Ishii correlation (Representative data)

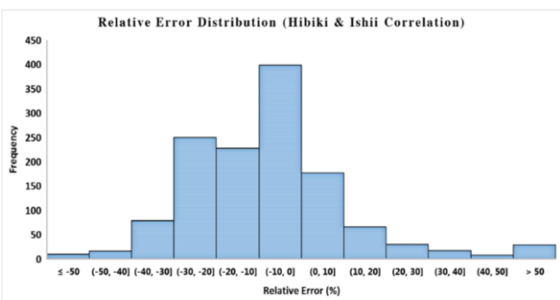

Fig. 15. Error distribution of predicted void fractions using Hibiki & Ishii Correlation (Representative data)

Antonio Correlation:

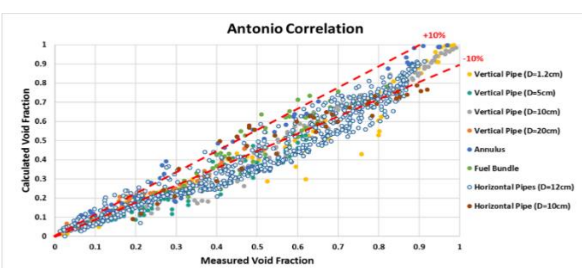

Fig. 16. Comparison between predicted and measured void fractions using Antonio correlation (Representative data)

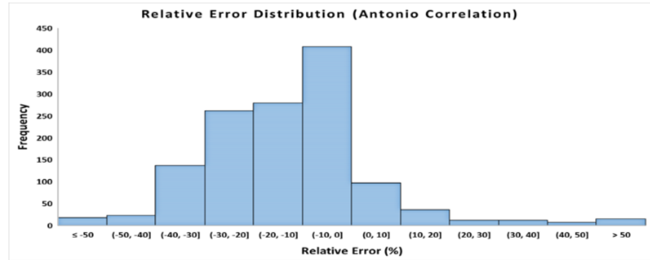

Fig. 17. Error distribution of predicted void fractions using Antonio Correlation (Representative data)

IV. A. *Assessment summary of the selected drift-flux correlations*

Various drift-flux correlations were evaluated based on a statistical analysis that was performed over a wide range of experimental data. Based on the statistical results shown in Table III, the best-performing correlation, which is recommended to be implemented in thermal-hydraulic codes, is the Hibiki and Ishii correlation, followed by the Toshiba correlation and the Antonio correlation. Furthermore, the newly developed correlation shows excellent prediction for all experimental data compared to the other correlations.

Table III Summary of All Drift Flux Correlations' Performance

All Experimental Data					
#	Correlation Name	Mean Error %	Mean of Absolute Error	R.M.S. Error	Standard Deviation
1	Present Correlation	-7.31	14.65	20.08	16.75
2	Hibiki & Ishii	-9.40	16.20	21.11	16.59
3	Toshiba	-11.77	17.45	22.50	16.87
4	Antonio	-14.70	17.69	21.79	14.84
5	Kokal and Stanislav	-13.78	18.51	23.17	15.64
6	Bonnecaze	-14.00	18.69	23.36	15.71
7	Gomez	-6.41	17.51	23.37	19.29
8	Homogenous	13.79	24.88	51.94	41.88

VII. Conclusion

The goal of this paper is to assess several drift-flux correlations used in the nuclear and oil sectors and to develop a new correlation for a two-phase flow with various inclination angles, flow regimes, and flow geometries.

To assess the performance of the selected drift-flux correlations, a simple and robust two-phase transient code was developed and validated. The code is based on a two-phase mixture momentum equation. The performance evaluation was carried out using over 1,600 experimental data points, and the results show that the Hibiki and Ishii correlation is relatively the most accurate, with a mean absolute error of 16.20%, followed by the Toshiba correlation and the Antonio correlation, with mean absolute errors of 17.45% and 17.69%, respectively.

Furthermore, for various vertical and horizontal flow regimes, the same experimental dataset was utilized to construct a novel drift-flux correlation. To acquire the necessary distribution parameters and drift velocities, the experimental dataset was first categorized according to distinct flow regimes. The slope of the linear regression of gas velocities versus mixture volumetric fluxes was used to calculate the distribution parameters, while the drift velocities were calculated using the terminal velocities of the dispersion phases. The novel correlation outperforms previous drift-flux correlations in terms of accuracy, with an overall mean absolute error of 14.6%.

References

1) Zuber, N., Findlay, J.A, 1965. Average volumetric concentration in two-phase flow systems. J. Heat
2) Hibiki, T., Ishii, M., 2002. Distribution parameter and drift velocity of drift-flux model in bubbly flow. Int. J. Heat and Mass Trans. 45, 707–721.
3) Hibiki, T., Ishii, M., 2003. One-dimensional drift-flux model for two-phase flow in a large diameter pipe. Int. J. Heat and Mass Trans. 46, 1773–1790
4) Woldesemayat, Melkamu A., and Afshin J. Ghajar. “Comparison of Void Fraction Correlations for Different Flow Patterns in Horizontal and Upward Inclined Pipes.” International Journal of Multiphase Flow, vol. 33, no. 4, 2007, pp. 347–370., doi:10.1016/j.ijmultiphaseflow.2006.09.004.
5) Doup, Benjamin Casey, and Xiaodong Sun. “Methodology Development of a Gas-Liquid Dynamic Flow Regime Transition Model.” *Ohio State University*, 2014.
6) Stankovic, Branko. “An Experimental Study on the Local Void Fraction Measurements in Large-Diameter Vertical Pipes Using Optical Fiber Probes.” *McMaster*, 1997.
7) Almabrok, A. A., & Yeung, H. C. (n.d.). 2013. Gas-liquid two-phase flow in up and down vertical pipes (dissertation).
8) Sujumnong, Manit. “Heat Transfer, Pressure Drop and Void Fraction in Two-Phase, Two-Component Flow in a Vertical Tube.” *University of Manitoba, Spring*, 1997.
9) Caetano, E. F., Shoham, O., & Brill, J. P. (1992). Upward Vertical Two-Phase Flow Through an Annulus—Part II: Modeling Bubble, Slug, and Annular Flow. Journal of Energy Resources Technology, 114(1), 14–30. https://doi.org/10.1115/1.2905916
10) Yang, X., Schlegel, J. P., Liu, Y., Paranjape, S., Hibiki, T., & Ishii, M. (2012). Measurement and modeling of two-phase flow parameters in scaled 8×8 BWR rod bundle. International Journal of Heat and Fluid Flow, 34, 85–97. https://doi.org/10.1016/j.ijheatfluidflow.2012.02.001
11) Al-SAMARRA'E, Faris Abdulaziz. “Studies Of Heterogeneous Two Phase Flow In Large Diameter Horizontal Pipelines.” *Strathclyde*, 1977.
12) Osamusali, S. I. (1990). Study of gas-liquid two-phase flow pattern transitions in horizontal pipe, annulus and nuclear fuel type rod bundle flow systems (dissertation). National Library of Canada, Ottawa.
13) Lee, Kyungsu, et al. “Experimental Investigation on the Velocity Structure and Its Effect on the Flow Patterns of Air-Water Two-Phase Flow in a Horizontal Pipe.” *KSCE Journal of Civil Engineering*, vol. 22, no. 9, 2018, pp. 3363–3372., doi:10.1007/s12205-018-1037-z.
14) P. Coddington, R. Macian, ‘‘A study of the performance of void fraction correlations used in the context of drift-flux two-phase flow models,’’ Nucl. Eng. Des., 215, 199–216 (2002).
15) Hibiki, Takashi, Ishii, Mamoru, 2003. One-dimensional drift-flux model and constitutive equations for relative motion between phases in various two-phase flow regimes. Int. J. Heat Mass Tran. 46 (25), 4935–4948.v
16) Bonnecaze, R.H., Erskine, W and Greskovich, E.J. (1971), Holdup and pressure drop for two phase

slug flow in inclined pipes, AIChE Journal, Vol.17, pp.1109- 1113.

17) Kokal, S.L. and Stanislav, J.F. (1989), an experimental study of two phase flow in slightly inclined pipes-II. Liquid holdup and pressure drop, Chemical Engineering Science, Vol.44, No.3, pp.681-693

18) Antonio C.V.M. Lage, Rune W. Time – "An Experimental And Theoretical Investigation Of Upward Two-Phase Flow In Annuli" – 64525-Ms, Spe Asia Pacific Oil And Gas Conference And Exhibition, Brisbane, Australia, 16-18 October – 2000

19) Fang, Meng, Wei, Xu and Li, 2019. A Hydraulic Model for Multiphase Flow Based on the Drift Flux Model in Managed Pressure Drilling. *Energies*, 12(20), p.3930.

20) Evje, S., & Fjelde, K. K. (2002). Hybrid flux-splitting schemes for a two-phase flow model. *J. Comput. Phys.*, *175*(2), 674-701. doi:10.1006/jcph.2001.6962

21) Y. Taitel, D. Bornea, and A. E. Dukler. "Modeling Flow Pattern Transitions for Steady Upward

22) Gas-Liquid Flow in Vertical Tubes." *AIChE Journal*. *26*. 3. 1980. pp. 345-354.

23) Ranson, V. H. et al., RELAP5/MOD1 Code Manual, Vols. 1 & 2, NUREG/CR-1826, EGG 2070, March 1982.

24) Ishii, M., 1977. One-Dimensional Drift-Flux Model and Constitutive Equations for Relative Motion between Phases in Various Two-Phase Flow Regimes. ANL-77-47, USA.

25) Hewitt, G. F., and N. S. Hall-Taylor, Annular Two-Phase-Flow, Pergamon Press, Oxford (1970)

26) Wallis, G. B., One-Dimensional Two-Phase flow, pp. 390-393, McGraw-Hill, New York (1969)