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Comparison of Void Fraction Correlations for Different Flow Patterns in Upward Vertical Two-Phase Flow

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A comparison of the performance of 52 void fraction correlations was made based on an unbiased experimental data set of 1208 data points. A comprehensive literature search was undertaken for the available void fraction correlations and experimental void fraction data for upward vertical two-phase flow. The performance of the correlations in correctly predicting the diverse data set was evaluated. Comparisons between the correlations were made and appropriate recommendations were drawn. The analysis showed that most of the correlations developed are very restricted in terms of handling a wide variety of data sets. Based on this analysis, void fraction correlations with the best predictive capability are highlighted.

INTRODUCTION

Practical applications of gas–liquid flow, of two different components or a single substance, are commonly encountered in the petroleum, nuclear, and process industries. The two gas and liquid phases may exist in flow of different components (e.g., air and water) and/or in the event of phase change due to evaporation and condensation of a single fluid. Void fraction (α) is one of the most important parameters in characterizing two-phase flow. Void fraction is the key physical parameter for determining other two-phase parameters, namely, two-phase density, and gas and liquid velocities. In addition, void fraction plays an important role in the modeling of two-phase pressure drop, flow pattern transition, and heat transfer. For example, in modeling and correlating convective heat transfer coefficient in gas–liquid flow without phase change, void fraction is one of the indispensable parameters [1, 2]. Another example of the usefulness of experimental void fraction results is in aiding the development of two-phase flow models, such as a recently developed unified annular flow model, which integrated together models for predicting the entrained liquid fraction, the wall shear stress, and the velocity profile in the annular liquid film [3].

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For industrial applications where two-phase flow is involved, the task of sizing the equipment for gathering, pumping, transporting, and storing such a two-phase mixture requires the formidable task of predicting the phase distribution in the system from given operating conditions. The ability to quantify void fraction is of considerable importance in systems involving two-phase flow. For example, in nuclear reactor technology, the boiling water reactor (BWR) uses light water as a neutron moderator and coolant, and the void fraction is significant in estimating the reactivity of the nuclear reactor.

The seemingly benign issue of determining the phase distribution from input conditions in a given pipe turns out to be a formidable task due to the slippage between the gas and the liquid phases. Currently, there is a plethora of void fraction correlations available in the literature. The fact that there are numerous correlations available would not be a concern had it not been for the fact that most of the correlations have some form of restrictions attached to them. For instance, one of the most common restrictions to the correlations, flow pattern dependency, is sometimes a purely subjective judgment of the investigator, especially for those points on or near flow pattern boundaries. Another pitfall is that many void fraction correlations have only been validated with experimental data that is limited to specific conditions, such as pipe orientation, flow pattern, and gas–liquid combination. As a result, engineers are faced with the daunting task of choosing the appropriate correlation among the plethora of correlations available.

Further advancement in the development of better and more accurate void fraction correlations would not be proper if the tedious process of scrutinizing available correlations is disregarded or circumvented. Comparison of the correlations with the measured results provides a stepping-stone for further developments of more accurate and improved correlations. The purpose of this work is to identify void fraction correlations that could acceptably predict most of the experimental data collected for upward vertical two-phase flow. A comprehensive search has been made in the literature to collect available void fraction correlations as well as the measured void fraction data from various sources. Experimental void fraction data were also measured, rather than being solely dependent upon the data from other sources. Based on the analysis, the best performing correlations for upward vertical two-phase flow were selected and recommendations were drawn based on their strengths and weaknesses. Since the main focus of this study is not on the development of void fraction correlations but rather on identifying the best performing correlations, detailed discussions on the physics that affect void fraction are not within the scope of this study. The physics behind most of the correlations cited in this paper are available in the referenced sources.

EXPERIMENTAL SETUP

The experimental setup is equipped for measuring heat transfer, pressure drop, and void fraction, and also conducting flow visualization in air–water flow for all major flow patterns and inclination angles from 0° (horizontal) to ±90° (vertical). The capabilities of the new experimental setup allow an undertaking that combines the study of heat transfer, flow patterns, pressure drop, void fraction, and inclination effects. Detail discussions on the design, construction, and functionality of this experimental setup are documented by Cook [4]. The schematic of the overall experimental setup for flow pattern visualization and void fraction for the present study is given in Figure 1. The details of the test section are illustrated in Figure 2. The flow visualization section is the central portion of the void fraction section. The flow visualization section is constructed from a polycarbonate tube with an inner diameter of 12.7 mm.

The fluids used in the test loop are air and water. The water is distilled and stored in a 55-gallon cylindrical polyethylene tank. A Bell & Gosset series 1535 coupled centrifugal pump was used to pump the water through an Aqua-Pure AP12T water filter. An ITT Standard model BCF 4063 one-shell and two-tube-pass heat exchanger removes the pump heat and the heat added during the test to maintain a constant inlet water temperature. From the heat exchanger, the water passes through an Emerson Micro Motion Coriolis flow meter (model CMF100) connected to a digital Field-Mount Transmitter (model RFT9739) that conditions the flow information for the data acquisition system. From the Coriolis flow meter it then flows into the test section.

Air is supplied via an Ingersoll-Rand T30 (model 2545) industrial air compressor. The air passes through a copper coil submerged in a vessel of water to lower the temperature of the air to room temperature. The air is then filtered and condensation is removed in a coalescing filter. The air flow is measured by Emerson Micro Motion Coriolis flowmeters (model CMF025 for high flow rates and model LMF3M for low flow rates). Both flow meters are connected to a Micro Motion 1700 transmitter. Air is regulated by a needle valve and is delivered to the test section by flexible tubing.

The inlet liquid and gas temperatures and the exit bulk temperature were measured by Omega TMQSS-06U-6 thermocouple probes. Calibration of thermocouple probes showed that they were accurate within ±0.5°C. Two static mixers, one at the inlet and another at the outlet of the test section, are used to ensure that air and water are properly mixed such that accurate temperature of the mixture can be measured by the thermocouple probes. Upon exiting the test section, the water and air mixture is returned to the reservoir, where it is separated and the water recycled.

The void fraction section is constructed to trap a mixture of two-phase flow in order to measure the volume of the liquid portion. With the known volume of the void fraction section and the measured volume of the liquid portion, the value of the void fraction can be determined. To trap the two-phase mixture in the void fraction section, three quick closing valves are used. Two normally open valves are used for controlling fluid movement at the inlet and exit of the void fraction section, while a normally closed valve is for controlling the entry of fluid into a bypass line. The quick closing valves are W. E. Anderson model ABV1DA101 pneumatic ball valves, and they exhibit a positive seal when closed and have a closing time of 0.03 s.

When the valves are triggered, the two normally open valves close and the normally closed valve opens simultaneously. In this manner, a two-phase sample is trapped in the void fraction section, while the air–water mixture is allowed to continue flowing through the bypass line. Air-water mixture trapped in the void fraction section was drained, and the volume of the liquid is measured. With the measured volume of the liquid (V_l), the void fraction (α) can be determined from the total volume of the test section (V_t) using $\alpha = 1 - V_l/V_t$. The uncertainty associated with the volume of the liquid is ±0.5 cm^3, and the uncertainty associated with the total volume of the test section is ±2 cm^3. Using the procedure prescribed by Kline and McClintock [5], the uncertainties associated with the measured void fraction results were estimated to be between ±1.25 and ±4.16%.

Flow patterns observations in upward vertical two-phase air–water flow were conducted as well. All observations for the flow pattern judgments were made at the flow visualization section (Figure 1). By fixing the water flow rate, flow patterns were observed by varying air flow rates. Using visual observation and digital photography, distinctive flow patterns were

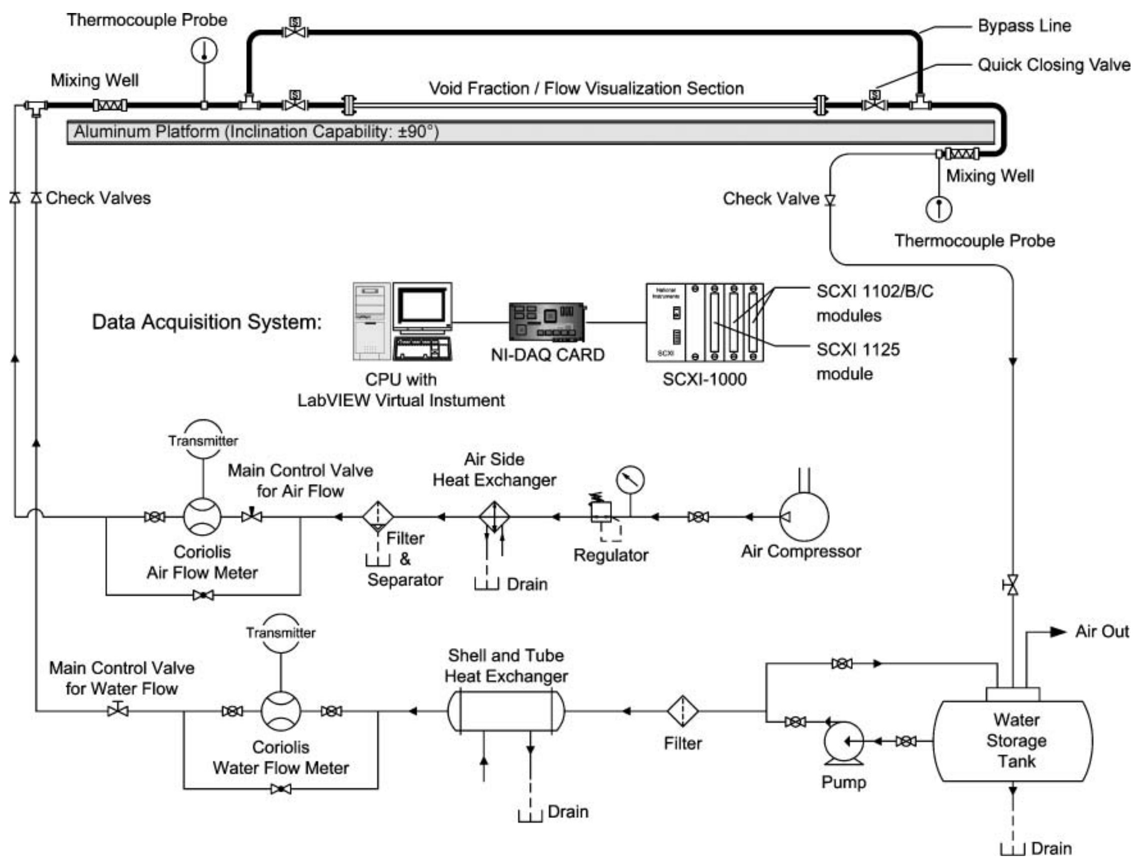

Figure 1 Schematic of experimental setup.

recognized and transition boundaries between flow patterns were determined.

EXPERIMENTAL FLOW PATTERN AND VOID FRACTION RESULTS

Flow Pattern Results

The main purpose of conducting experiments on flow patterns was to determine the region in which each observed flow pattern is located on a flow pattern map. The location of each flow pattern region was then compared with established flow pattern maps. In short, the purpose of this flow pattern experiment was to verify that the experimental setup has the capability of observing flow patterns similar to those reported in the literature. Flow patterns are affected by pipe diameter as well as the types of two-phase fluids; therefore, the transition boundaries of one flow pattern to another are often debatable. However, the general locations of major flow pattern regions are often similar.

By fixing the water flow rate, flow patterns were observed by varying air flow rates. Using visual observation and

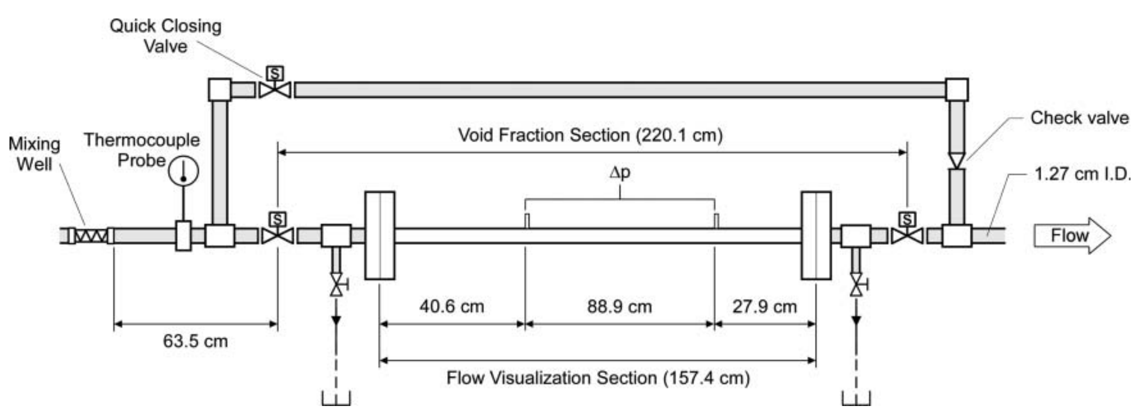

Figure 2 Test section for void fraction and flow visualization.

digital photography, distinctive flow patterns were recognized and transition boundaries between flow patterns were determined. The distinctive major flow patterns observed in the upward vertical two-phase flow are dispersed bubble, slug, churn/froth, and annular. The general locations of dispersed bubble, slug, churn/froth, and annular are in relative agreement with flow pattern map of Taitel et al. [6]. Based on the experimentally documented flow patterns and flow pattern transition boundaries, the two-phase flow pattern map for the upward vertical pipe was delineated. Representative digital images of each flow pattern were taken using a Nikon D50 digital camera with a Nikkor 50 mm f/1.8D lens. The flow pattern map for vertical flow with the representative photographs of the various flow patterns is shown in Figure 3.

The slug–churn and churn/froth–annular transition boundaries in this experimental study were compared with correlations available in the literature. For the transition from slug flow, McQuillan and Whalley [7] suggested that the correlation of Wallis [8], used to predict the flooding gas and liquid flow rates, can be used to predict the transition boundary between plug flow and churn flow:

$$U_{sl}^{*1/2} + mU_{sg}^{*1/2} = C \tag{1}$$

where the dimensionless superficial velocities for gas (U_{sg}^*) and liquid (U_{sl}^*) are expressed in terms of superficial velocities of gas (U_{sg}) and liquid (U_{sl}), densities of gas (ρ_g) and liquid (ρ_l), pipe diameter (D), and gravitational acceleration (g) as

$$U_{sg}^* = U_{sg}\rho_g^{1/2}[gD(\rho_l - \rho_g)]^{-1/2}$$

and

$$U_{sl}^* = U_{sl}\rho_l^{1/2}[gD(\rho_l - \rho_g)]^{-1/2}$$

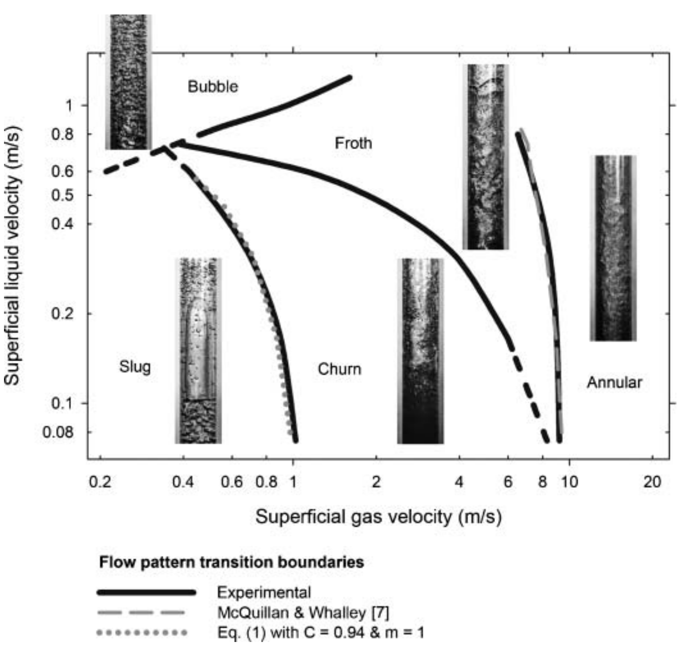

Figure 3 Flow map for vertical flow with representative photographs of flow patterns.

In the original expression of Eq. (1) by Wallis [8], the values of the dimensionless parameters are $C = m = 1$. Equation (1) may be treated as an empirical correlation where the parameters C and m depend on the flow conditions at the inlet and outlet as well as geometry. Ghiaasiaan [9] reported that the parameters C and m vary approximately within the $0.7 \leq C \leq 1$ and $0.8 \leq m \leq 1$ ranges. McQuillan and Whalley [7] applied Wallis's correlation, Eq. (1), and showed generally good agreement with experimental flow pattern data. The comparison of the experimentally documented slug–churn transition with Eq. (1) is illustrated in Figure 3. The agreement between the experimental data and Eq. (1), with $C = 0.94$ and $m = 1$, is satisfactory and the percentage error is within 6%.

Annular flow is observed when the gas flow rate becomes sufficiently high. For the transition to annular flow, McQuillan and Whalley [7] proposed the following simple relation to predict the transition boundary for annular flow:

$$U_{sg}\rho_g^{1/2}[gD(\rho_l - \rho_g)]^{-1/2} \geq 1 \tag{2}$$

McQuillan and Whalley [7] reported that their proposed Eq. (2) compared reasonably well with experimental data from several sources, including Taitel et al. [6] and Weisman and Kang [10]. At the churn/froth–annular transition, the experimental data was compared with the equation of McQuillan and Whalley [7], Eq. (2), and agreement is also generally good; see Figure 3.

Void Fraction Results

The void fraction experiments were conducted to meet several objectives. First, the measured void fraction results were to be used for validation of experimental data from other sources. Since the uncertainties associated with the measured void fractions from this study are determinable, they can be used to validate experimental data compiled from other sources. This validation is especially informative, since not all the sources reported detailed experimental uncertainties. Second, the measured void fraction results were to be used to fill in the gaps in regions that were not measured by other sources. For example, the experimental results from this study have provided 26% of data points to the data compiled from other sources for $0.25 \leq \alpha \leq 0.5$. Also, experimental results from this study have added 67 data points to the 58 data points compiled from other sources for churn/froth flow. Third, the measured void fraction results were to be used to evaluate variation of void fraction with superficial velocities of gas and liquid and groupings of various flow patterns for $0 < \alpha < 1$.

The experimental results of void fraction in upward vertical flow were measured from the test section for flow visualization and void fraction illustrated in Figure 1. The variation of void fraction with superficial gas velocity for vertical pipe flow is shown in Figure 4. As superficial liquid velocity increases, the increase in liquid holdup causes the void fraction versus superficial gas velocity curves to shift lower. At low superficial gas velocities ($U_{sg} < 2$ m/s), a small increase in superficial

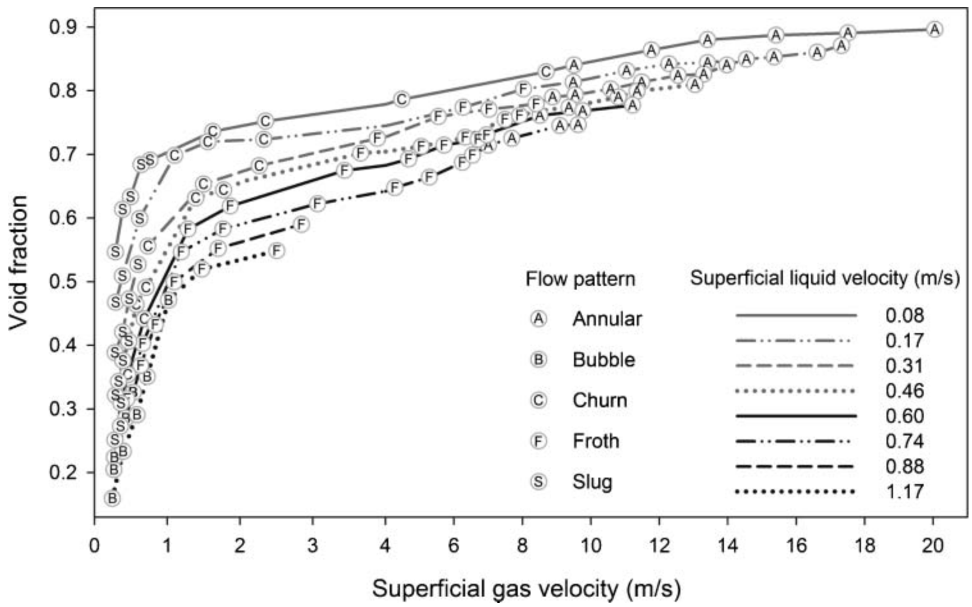

Figure 4 Variation of void fraction with superficial gas velocity for upward vertical pipe flow.

gas velocity caused rapid increase in the void fraction. The rapid increase in the void fraction suggests difficulty in correlating void fraction accurately in this low superficial gas velocity region.

For $U_{sg} > 2$ m/s, void fraction increases gradually with increasing superficial gas velocity. The aforementioned void fraction trends observed in these experimental results are similar to the observations of other reported works [11–14]. In Figure 4, the groupings of various flow patterns on the variation of void fraction with superficial gas velocity curves are shown. From the measured void fraction of this study, bubble and slug flows are confined to low-range superficial gas velocity with void fraction ranges of $0.05 < \alpha < 0.5$ and $0.2 < \alpha < 0.7$, respectively. Churn/froth flow is found in mid-range superficial gas velocity with a void fraction range of $0.3 < \alpha < 0.8$. At a given superficial gas velocity, churn flow has a higher void fraction than froth flow. Annular flow is in the high superficial gas velocity region with a void fraction range of $0.7 < \alpha < 0.9$.

EXPERIMENTAL DATABASE

In an effort to make the evaluation of void fraction correlations unbiased, experimental data from various sources were compiled. Including the experimental data measured for present study, a total of 1208 experimental data points from 10 different sources was compiled. The compiled experimental data were measured at different experimental facilities with various measurement techniques, which include quick-closing valve, capacitance sensor, and gamma-ray absorption. As summarized in Table 1, the experimental data include void fraction measurements in pipe diameters ranging from 12.7 to 76 mm, and

Table 1 Experimental database used for comparison with void fraction correlations

Source	Pipe diameter (mm)	Fluids	No. of data points	Operating pressure (kPa)
Present study [1]	12.7	Air–water	153	114–260
Beggs [37][1]	25.4 & 38.1	Air–water	27	527–677
Chokshi [38][2]	76.0	Air–water	103	1218–3410
Fernandes [39][1]	50.7	Air–water	88	
Isbin et al. [40][2]	22.1	Steam–water	22	101
Mukherjee [12][3]	38.1	Air–kerosene	65	267–609
Nguyen [41][1]	45.5	Air–water	224	107–125
Oshinowo [42][1]	25.4	Air–water	153	134–206
	25.4	Air–glycerin	172	141–199
Schmidt et al. [15][2]	54.5	Nitrogen–water	20	
Sujumnong [13][1]	12.7	Air–water	104	101–343
	12.7	Air–glycerin	77	102–307

[1]Quick-closing valve.
[2]Gamma-ray absorption.
[3]Capacitance sensor.

operating pressures ranging from 101 to 3410 kPa, with different gas–liquid combinations of upward vertical two-phase flow. Based on sources with reported experimental uncertainties, the experimental data have associated uncertainties of less than 10%.

Experimental data measured for the present study were compared with experimental data from other sources at similar superficial velocities of gas and liquid for upward vertical flows. In total, 210 experimental data points from other sources with similar superficial gas and liquid velocities were identified and compared with experimental data measured for the present study. The 210 experimental data points from eight different sources were measured at different experimental facilities for various pipe diameters (12.7 to 76 mm), various operating pressures (101 to 3410 kPa), and different gas–liquid flows. All 210 experimental data points are within ±10% agreement with the experimental data from present study. The result of this comparison is shown in Figure 5. The comparison of the experimental data from present study and other sources, for this flow orientation, has a root-mean-square (RMS) error of 4.2%, and 77% of the 210 experimental data points are within ±5% agreement. The RMS error found from the comparisons of experimental data from other sources and present study is 4.2%, which is comparable with the uncertainties associated with the experimental data of present study that is within ±4.16%. The agreement between the experimental data from present study and other sources validated the goodness of the data compiled for this study.

The results from the comparisons of experimental data from other sources and present study (Figure 5) also suggest, at least within the confines of these comparisons, that void fraction is not affected by pipe diameter (12.7 to 76 mm), operating pressure (101 to 3410 kPa), and type of gas–liquid flow. In addition, referring to the information listed in Table 1, results shown in Figure 5 indicate that experimental void fraction results measured via different techniques are generally in good agreement. This observation confirms with the findings of Jiang and Rezkallah [11] and Schmidt et al. [15], which had compared void fractions measured by gamma-ray absorption technique and quick-closing valve technique.

EVALUATION OF VOID FRACTION CORRELATIONS WITH EXPERIMENTAL DATA

Fifty-two void fraction correlations have been identified from the literature and are considered in this analysis. These correlations were considered due to the reason that complete information on input parameters is available from the compiled experimental database, such that these correlations can be used to calculate void fractions and compared with measured results. Very few of the void fraction correlations identified for this study have been compared with experimental data that are as extensive as is the data summarized in Table 1. Many of the correlations are "specialized" correlations and were originally proposed for specific conditions such as pipe orientation and flow pattern. Thus, their performances outside their specified conditions have not been scrutinized. In the interest of determining the "best" correlation for upward vertical flow, the correlations were subjected to three levels of assessment.

The first level is the evaluation of the correlations with experimental data on the basis of the overall performance, where the results predicted by the correlations for an entire database ($0 < \alpha < 1$) of each pipe orientation were compared with the

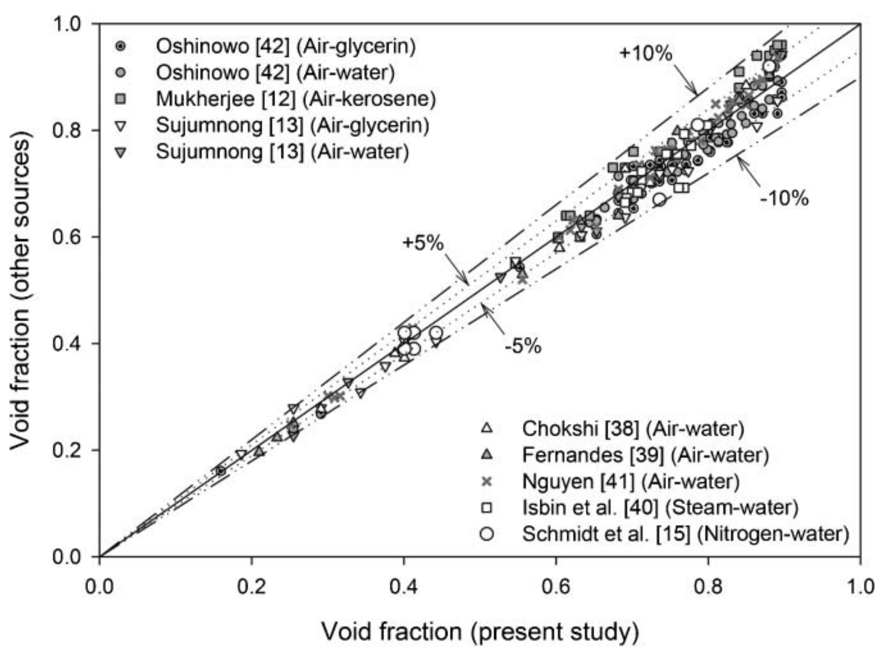

Figure 5 Comparison between experimental data from present study and other sources (see Table 1) for upward vertical flow.

measured results. The first level of assessment by itself is perfunctory, since it overlooks the strengths and weaknesses of the correlations in specific ranges of void fraction. The number of experimental data points is not uniformly distributed throughout the entire void fraction range of $0 < \alpha < 1$ (majority of the data points are in $0.75 < \alpha < 1$); hence, relying solely on overall performances of the correlations could lead to biased interpretations. Subsequently, the second level of assessment is the analysis of the correlations in smaller void fraction ranges, by dividing the entire void fraction range into four categories: 0 to 0.25, 0.25 to 0.5, 0.5 to 0.75, and 0.75 to 1. Dividing the analysis into specific void fraction ranges would also reveal the most accurate correlations for each specific range, thus allowing access to correlations with higher accuracies in specific void fraction range of interest. Finally, the third level of assessment is taking the "best" correlation that has been identified from the first two levels of assessment and comparing it with the performances of flow-pattern-specific void fraction correlations.

Out of the 52 void fraction correlations considered, 18 are mentioned in this article because they were found to compare satisfactorily with the compiled experimental results. Table 2 lists the 18 void fraction correlations discussed in this article, and the reasons for which these correlations were selected are explained in this section. The sources for the other correlations that were analyzed and evaluated but not discussed here, because of unsatisfactory comparison with experimental results, are listed in Table 3. Detailed analysis on the performance of all 52 correlations is discussed by Godbole [16].

Performance of Correlations for the Entire Void Fraction Range

The 52 void fraction correlations considered in this analysis were compared with the data points in the experimental database summarized in Table 1. Out of 52 void fraction correlations compared with the experimental data, 8 correlations predicted the experimental data with a root-mean-square (RMS) error of less than 30%, and at least 85 and 75% of the data points were within ±20 and ±15% error bands of the experimental data, respectively. The sources of the eight correlations along with the results of the comparison are listed in Table 4. The equations for these eight correlations are shown in Table 2. Of these eight selected correlations, all of them are based on the drift flux model, with the exception of Guzhov et al. [17] correlation, Eq. (9). Among the correlations listed in Table 4, the Guzhov et al. [17] correlation predicted the least number of data points within ±10 and ±15% agreement with the experimental results. In the drift flux model, the void fraction (α) is expressed as a function of distribution parameter (C_0), gas-phase drift velocity (u_{gu}), and superficial velocities of gas (U_{sg}) and liquid (U_{sl}): $\alpha = U_{sg} [C_0 (U_{sg} + U_{sl}) + u_{gu}]^{-1}$. Although a correlation that resembles the drift flux model has been presented earlier by Nicklin et al. [18], the principal analysis to the drift flux model is due to Zuber and Findlay [19].

The correlations of Bonnecaze et al. [20], Kokal and Stanislav [21], and Nicklin et al. [18], Eqs. (4), (12), and (15), predicted among the highest number of data points within ±20% agreement with the experimental data. It should be noted that the correlations of Bonnecaze et al. [20] and Kokal and Stanislav [21] are slight variants of the Nicklin et al. [18] correlation; hence, all three correlations produced very similar results when compared with the experimental data. The only variation between these three correlations is the relation for gas-phase drift velocity (u_{gu}). Comparing the correlations of Nicklin et al. [18] and Bonnecaze et al. [20], there is an added term of $(1-\rho_g/\rho_l)$ in the gas-phase drift velocity (u_{gu}) relation of the Bonnecaze et al. [20] correlation. In a similar manner, the Kokal and Stanislav [21] correlation has an added term of $(1-\rho_g/\rho_l)^{0.5}$ in the gas-phase drift velocity (u_{gu}) relation of their correlation. Both additional terms in the gas-phase drift velocity (u_{gu}) relations of the Bonnecaze et al. [20] and Kokal and Stanislav [21] correlations do not impact the results significantly, since the density ratio (ρ_g/ρ_l) is very small for most gas–liquid combinations. Both Nicklin et al. [18] and Bonnecaze et al. [20] predicted 1108 (91.7%) data points within the ±20% error band of the experimental data, while Kokal and Stanislav [21] predicted 1107 (91.6%) data points within the same error band. All three correlations predicted 1019 (84.4%) data points within the ±15% error band of the experimental data.

For the number of data points predicted within the ±10% error band of the experimental data, the correlation of Rouhani and Axelsson [22], Eq. (16), performed the best, with 856 (70.9%) data points predicted within the error band. Following Rouhani and Axelsson [22], the correlation of Ishii [23], Eq. (11), predicted 806 (66.7%) data points within the same error band. A notable observation was made that the correlations of Rouhani and Axelsson [22] and Ishii [23] are the only correlations, among the 52 correlations considered in this study, that predicted at least 85, 75, and 65% of the data points within the ±20, ±15, and ±10% error bands of the experimental data, respectively. Another observation that is worth commenting is that none of the 52 correlations predicted at least 50% of the 1208 experimental data points within ±5% agreement.

The overall comparison of the void fraction correlations with the experimental data for $0 < \alpha < 1$ yielded eight correlations that predicted at least 85 and 75% of the data points within the ±20 and ±15% error bands of the experimental data, respectively, as well as with an RMS error of less than 30%. Out of the eight correlations, there are two correlations that predicted 65% or more of the experimental data points within ±10% agreement. The choice of which correlation to use, based on the evaluation thus far, lies with the user's interest of the accuracy in the correlation. If the interest of accuracy is between the ±15 and ±20% error bands of the experimental data, then the correlation of Nicklin et al. [18], Eq. (15), is preferable. If the interest is for higher accuracy with error bands of the experimental data between ±10 and ±15%, then the correlation of Rouhani and Axelsson [22], Eq. (16), is preferable.

Table 2 Void fraction correlations that performed satisfactorily and are discussed in this study

Source	Correlation	
Armand [26]—Massena [27]	$\alpha = (0.833 + 0.167x)\left(1 + \frac{1-x}{x}\frac{\rho_g}{\rho_l}\right)^{-1}$	(3)
Bonnecaze et al. [20]	$\alpha = \frac{U_{sg}}{C_0(U_{sg}+U_{sl})+u_{gu}}$ where $C_0 = 1.2$	(4)
	$u_{gu} = 0.35\sqrt{gD}\,(1-\rho_g/\rho_l)$	
Dix [28]	$\alpha = \frac{U_{sg}}{C_0(U_{sg}+U_{sl})+u_{gu}}$	(5)
	$C_0 = \frac{U_{sg}}{U_{sg}+U_{sl}}[1 + (U_{sl}/U_{sg})^b]$, $b = (\rho_g/\rho_l)^{0.1}$	
	$u_{gu} = 2.9\left(g\sigma\frac{\rho_l-\rho_g}{\rho_l^2}\right)^{0.25}$	
El-Boher et al. [29]	$\alpha = \left[1 + 0.27\left(\frac{x}{1-x}\frac{\rho_l}{\rho_g}\right)^{-0.69}(Fr_{sl})^{-0.177}\left(\frac{\mu_l}{\mu_g}\right)^{0.378}\left(\frac{Re_{sl}}{We_{sl}}\right)^{0.067}\right]^{-1}$	(6)
	$Fr_{sl} = \frac{U_{sl}^2}{gD}$, $Re_{sl} = \frac{\rho_l U_{sl} D}{\mu_l}$, $We_{sl} = \frac{\rho_l U_{sl}^2 D}{\sigma}$	
Gomez et al. [32]	$\alpha = \frac{U_{sg}}{C_0(U_{sg}+U_{sl})+u_{gu}}$ where $C_0 = 1.15$	(7)
	$u_{gu} = 1.53\left(g\sigma\frac{\rho_l-\rho_g}{\rho_l^2}\right)^{0.25}(1-\alpha)^{0.5}\sin\theta$	
Greskovich and Cooper [24]	$\alpha = \frac{U_{sg}}{C_0(U_{sg}+U_{sl})+u_{gu}}$ where $C_0 = 1.0$	(8)
	$u_{gu} = 0.671\sqrt{gD}\,(\sin\theta)^{0.263}$	
Guzhov et al. [17]	$\alpha = 0.81\frac{U_{sg}}{U_{sg}+U_{sl}}\left(1 - e^{-2.2\sqrt{Fr}}\right)$ where $Fr = \frac{(U_{sg}+U_{sl})^2}{gD}$	(9)
Hibiki and Ishii [33]	$\alpha = \frac{U_{sg}}{C_0(U_{sg}+U_{sl})+u_{gu}}$	(10)
	$C_0 = (1.2 - 0.2\sqrt{\rho_g/\rho_l})(1 - e^{-18\alpha})$	
	$u_{gu} = \left(4\,g\,\sigma\,\frac{\rho_l-\rho_g}{\rho_l^2}\right)^{0.25}(1-\alpha)^{1.75}$	
Ishii [23][1]	$\alpha = \frac{U_{sg}}{C_0(U_{sg}+U_{sl})+u_{gu}}$ where $C_0 = \min(C_{01},\ C_{02})$	(11)
	$u_{gu} = \min(u_{gu1},\ u_{gu2})$	
	See Ohkawa and Lahey [43] for C_{01}, C_{02}, u_{gu1}, and u_{gu2}	
Kokal and Stanislav [21]	$\alpha = \frac{U_{sg}}{C_0(U_{sg}+U_{sl})+u_{gu}}$ where $C_0 = 1.2$	(12)
	$u_{gu} = 0.345\,[gD\,(1-\rho_g/\rho_l)]^{0.5}$	
Lockhart and Martinelli [35][2]	$\alpha = \left[1 + 0.28\left(\frac{1-x}{x}\right)^{0.64}\left(\frac{\rho_g}{\rho_l}\right)^{0.36}\left(\frac{\mu_l}{\mu_g}\right)^{0.07}\right]^{-1}$	(13)
Morooka et al. [30]	$\alpha = \frac{U_{sg}}{C_0(U_{sg}+U_{sl})+u_{gu}}$ where $C_0 = 1.08$, $u_{gu} = 0.45$	(14)
Nicklin et al. [18]	$\alpha = \frac{U_{sg}}{C_0(U_{sg}+U_{sl})+u_{gu}}$ where $C_0 = 1.2$, $u_{gu} = 0.35\sqrt{gD}$	(15)
Orell and Rembrand [34]	This model requires the solving of 7 governing equations	
	See Orell and Rembrand [34] for details of this model	
Rouhani and Axelsson [22]	$\alpha = \frac{U_{sg}}{C_0(U_{sg}+U_{sl})+u_{gu}}$	(16)
	$C_0 = 1 + 0.2\,(1-x)(gD\rho_l^2/G^2)^{0.25}$	(16*a*)[3]
	$C_0 = 1 + 0.2(1-x)$	(16*b*)[4]
	$u_{gu} = 1.18\left(g\sigma\frac{\rho_l-\rho_g}{\rho_l^2}\right)^{0.25}$	
Smith [36]	$\alpha = \left\{1 + \frac{\rho_g}{\rho_l}\left(\frac{1-x}{x}\right)\left[0.4 + 0.6\left(\frac{\rho_l/\rho_g + 0.4\,(1/x-1)}{1+0.4\,(1/x-1)}\right)^{0.5}\right]\right\}^{-1}$	(17)
Sun et al. [25]	$\alpha = \frac{U_{sg}}{C_0(U_{sg}+U_{sl})+u_{gu}}$ where $C_0 = [0.82 + 0.18\,(p_{sys}/p_{cr})]^{-1}$	(18)
	$u_{gu} = 1.41\left(g\sigma\frac{\rho_l-\rho_g}{\rho_l^2}\right)^{0.25}$	
Woldesemayat and Ghajar [31]	$\alpha = \frac{U_{sg}}{C_0(U_{sg}+U_{sl})+u_{gu}}$	(19)
	$C_0 = \frac{U_{sg}}{U_{sg}+U_{sl}}\left[1 + \left(\frac{U_{sl}}{U_{sg}}\right)^{(\rho_g/\rho_l)^{0.1}}\right]$	
	$u_{gu} = 2.9\,(1.22 + 1.22\sin\theta)^{p_{atm}/p_{sys}}\left[\frac{g\,D\,\sigma\,(1+\cos\theta)(\rho_l-\rho_g)}{\rho_l^2}\right]^{0.25}$	
	The leading constant of 2.9 in the above equation for u_{gu} carries a unit of $m^{-0.25}$	

[1]As given by Ohkawa and Lahey [43].
[2]As given by Butterworth [44].
[3]As given by Rouhani [45] and Diener and Friedel [46]; in this analysis, Eq. (16a) is used for $0 < \alpha \le 0.25$.
[4]As given by Woldesemayat and Ghajar [31] and Diener and Friedel [46]; in this analysis, Eq. (16b) is used for $\alpha > 0.25$.

Table 3 Sources for void fraction correlations that were evaluated but did not perform satisfactorily

Source	Source	Source
Armand [26]–Chisholm [47][1]	Bankoff [48][1]	Baroczy [49][1,2]
Bestion [50] [1, 3]	Chisholm [51][1]	Czop et al. [52] [1]
Dimentiev et al. [53] [1, 4]	Filimonov et al. [54] [1]	Gardner [55] [1]
Hughmark [56] [1]	Huq and Loth [57] [1]	Inoue et al. [58] [1, 3]
Jowitt et al. [59] [1, 3]	Kowalczewski [1, 5]	Kütüçüğlu [1, 5]
Lahey and Moody [60] [6, 7]	Madsen [61] [1]	Maier and Coddington [62] [1, 3]
Mattar and Gregory [63] [1]	Moussali [1, 5]	Mukherjee [12] [1]
Neal and Bankoff [64] [1]	Ohkawa and Lahey [43] [7]	Premoli et al. [65] [1]
Shvarts et al. [66] [7]	Sonnenburg [67] [3, 7]	Spedding and Chen [68] [1]
Spedding et al. [69] [1]	Sterman [70] [1]	Takeuchi et al. [71] [7]
Thom [72] [1, 2]	Wilson et al. [73][1]	Yamazaki and Yamaguchi [74][1]
Yeh and Hochreiter [75][7]		

[1]Also given by Woldesemayat and Ghajar [31].
[2]Also given by Butterworth [44].
[3]Also given by Coddington and Macian [76].
[4]Also given by Kataoka and Ishii [77].
[5]Also given by Isbin and Biddle [78].
[6]Also given by Ohkawa and Lahey [43].
[7]Also given by Godbole [16].

The evaluation of the void fraction correlations with experimental data so far was done on the basis of the overall performance, which overlooks the strengths and weaknesses of the correlations in specific ranges of void fraction. Hence, the subsequent logical approach is to analyze the correlations in ranges, by dividing the entire void fraction range into four ranges: 0 to 0.25, 0.25 to 0.5, 0.5 to 0.75, and 0.75 to 1. There are fewer experimental data points for the $0 < \alpha \leq 0.5$ range (199 data points for $0 < \alpha \leq 0.25$ and 190 data points for $0.25 < \alpha \leq 0.5$) than for the $0.5 < \alpha < 1$ (351 data points for $0.5 < \alpha \leq 0.75$ and 468 data points for $0.75 < \alpha < 1$). Hence, relying solely on overall comparison of correlations and experimental results could lead to biased interpretations. Dividing the analysis into specific void fraction ranges would also reveal the most accurate correlations for each specific range, thus allowing access to correlations with higher accuracies in specific void fraction range of interest.

Performance of Correlations for $0 < \alpha \leq 0.25$

In total, 199 experimental data points from the entire database were categorized in the void fraction range of $0 < \alpha \leq 0.25$. Due to lower values of void fraction, the percentage error in prediction with respect to measured data was expected to be more prominent than for the case with higher void fraction values. The high percentage error from the correlations in this region is in part a result of the rapid increase in void fraction at low superficial gas velocity (Figure 4). The rapid increase in void fraction makes correlating void fraction accurately in this region difficult. Due to the relatively higher percentage error in prediction with respect to experimental data in this low range of $0 < \alpha \leq 0.25$, a correlation is considered satisfactory when it predicted at least 80% of the experimental data points within ±30% agreement and with RMS error of less than 60%.

Table 4 Results of 8 correlations that compared satisfactorily with the entire experimental database

	Percentage of data points predicted within			
Correlations	±10%	±15%	±20%	RMS error (%)
Bonnecaze et al. [20], Eq. (4)	62.4	84.4	91.7	23.9
Guzhov et al. [17], Eq. (9)	55.0	77.6	88.7	24.6
Ishii [23], Eq. (11)	66.7	80.5	87.3	28.0
Kokal and Stanislav [21], Eq. (12)	62.3	84.4	91.6	24.0
Morooka et al. [30], Eq. (14)	62.3	79.1	87.8	23.6
Nicklin et al. [18], Eq. (15)	62.4	84.4	91.7	23.9
Rouhani and Axelsson [22], Eq. (16)	70.9	86.8	91.1	25.2
Sun et al. [25], Eq. (18)	58.4	78.1	91.1	23.9

$$\text{RMS error} = \sqrt{\frac{1}{N-1}\sum_{i=1}^{N}\left\{\frac{(\alpha_{\text{calc}})_i-(\alpha_{\text{meas}})_i}{(\alpha_{\text{meas}})_i}\right\}^2} \times 100\%$$

where N is the number of experimental data points

Table 5 Qualitative performance of eight selected correlations for upward vertical two-phase flow in four void fraction ranges

	Void fraction range			
Correlations	0.00 to 0.25	0.25 to 0.50	0.50 to 0.75	0.75 to 1.00
Bonnecaze et al. [20]	S	S	S	NS
Guzhov et al. [17]	NS	NS	S	NS
Ishii [23]	NS	NS	S	S
Kokal and Stanislav [21]	S	S	S	NS
Morooka et al. [30]	S	NS	NS	S
Nicklin et al. [18]	S	S	S	NS
Rouhani and Axelsson [22]	S	S	S	S
Sun et al. [25]	S	S	S	NS

Note. NS, not satisfactory; S, satisfactory.

Six correlations that are listed in Table 4 performed satisfactorily in the $0 < \alpha \leq 0.25$ range (see Table 5). Among the correlations that performed satisfactorily, there are only few correlations that could predict more than 70% of the experimental data points within ±20% agreement with the experimental results, namely, those of Bonnecaze et al. [20], Kokal and Stanislav [21], Nicklin et al. [18], and Rouhani and Axelsson [22]. The correlation of Rouhani and Axelsson [22] is the only correlation that predicted at least 70 and 60% of the 199 experimental data points within the respective ±20 and ±15% error bands.

Among the 52 correlations considered in this study, the correlations of Greskovich and Cooper [24], Nicklin et al. [18], and Rouhani and Axelsson [22], Eqs. (8), (15), and (16), are among the three best correlations in the $0 < \alpha \leq 0.25$ range. The results of the comparison of the three aforementioned correlations with experimental data are listed in Table 6. The performances of both the Nicklin et al. [18] and Rouhani and Axelsson [22] correlations are listed in Table 4. Although the performance of the Greskovich and Cooper [24] correlation, Eq. (8), is not listed in Table 4, it is among the three best correlations in the void fraction range of $0 < \alpha \leq 0.25$ and it predicted the highest number of experimental data points within ±10% error band. The equations for all three correlations are listed in Table 2. The comparison of Rouhani and Axelsson [22] and Greskovich and Cooper [24] correlations with the experimental data is shown in Figure 6.

Performance of Correlations for $0.25 < \alpha \leq 0.5$

In total, 190 experimental data points from the entire database were categorized in the void fraction range of $0.25 < \alpha \leq 0.5$. Unlike the lower range void fraction, the percentage error in prediction with respect to experimental data decreased. In this range of $0.25 < \alpha \leq 0.5$, a correlation is considered to have satisfactory performance when it predicted at least 80% of the experimental data points within ±20% agreement as well as with a RMS error of less than 20%.

Five correlations that are listed in Table 4 performed satisfactorily in the $0.25 < \alpha \leq 0.5$ range (Table 5). Among the 52 correlations considered in this study, there are three correlations that predicted at least 80% of the experimental data points within ±15% agreement, namely, those of Bonnecaze et al. [20], Kokal and Stanislav [21], and Nicklin et al. [18]. Only three correlations predicted at least 85% of the 190 experimental data points within ±20% agreement, namely, those of Nicklin et al. [18], Bonnecaze et al. [20], and Sun et al. [25]. Although the correlation of Sun et al. [25], Eq. (18), performed well in the ±20% error band of the experimental data, its performance deteriorated significantly in the ±15 and ±10% error bands. Sun et al. [25] predicted less than 70 and 50% of the 190 data points within ±15 and ±10% error bands, respectively.

Among the 52 correlations considered in this study, the correlations of Bonnecaze et al. [20], Kokal and Stanislav [21], and Nicklin et al. [18], Eqs. (4), (12), and (15), are among the three best correlations in the $0.25 < \alpha \leq 0.5$ range, and their performances with the experimental data are listed in Table 6. It should be noted that the correlation of Rouhani and Axelsson [22], Eq. (16), which has among the best overall performance discussed earlier, predicted 159 (83.7%) and 135 (71.1%) data points within the ±20 and ±15% error bands, respectively. The comparison of Nicklin et al. [18] (best correlation for $0.25 < \alpha \leq 0.5$), and Rouhani and Axelsson [22] correlations with the experimental data is shown in Figure 6.

Table 6 Results of comparison with experimental data for three best correlations in specific void fraction ranges

	Percentage of data points predicted within			
Correlations	±10%	±15%	±20%	RMS error (%)
$0 < \alpha \leq 0.25$ (199 data points)				
Greskovich and Cooper [24]	45.2	57.8	67.8	55.1
Nicklin et al. [18]	37.2	54.3	70.9	53.4
Rouhani and Axelsson [22]	40.2	62.8	71.9	56.5
$0.25 < \alpha \leq 0.5$ (190 data points)				
Bonnecaze et al. [20]	53.2	80.5	85.3	16.9
Kokal and Stanislav [21]	53.2	81.6	84.7	16.9
Nicklin et al. [18]	53.2	80.5	85.3	16.8
$0.5 < \alpha \leq 0.75$ (351 data points)				
Bonnecaze et al. [20]	80.3	93.4	96.6	9.7
Kokal and Stanislav [21]	80.1	93.2	96.6	9.7
Nicklin et al. [18]	80.3	93.4	96.6	9.7
$0.75 < \alpha < 1$ (468 data points)				
Armand [26]–Massena [27]	94.7	99.4	100	5.3
Dix [28]	93.8	98.7	99.8	5.2
Rouhani and Axelsson [22]	94.0	99.4	99.6	5.6

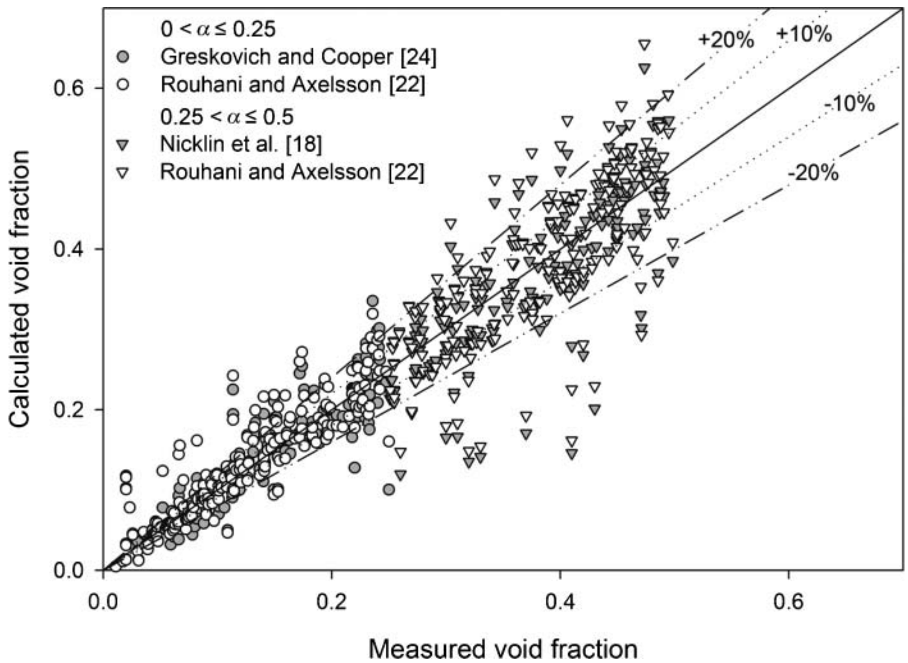

Figure 6 Comparison of Nicklin et al. [18], Rouhani and Axelsson [22], and Greskovich and Cooper [24] correlations with experimental data for $0 < \alpha \leq 0.5$.

Performance of Correlations for $0.5 < \alpha \leq 0.75$

In total, 351 experimental data points from the entire database were categorized in the void fraction range of $0.5 < \alpha \leq 0.75$. As the void fraction value increases, accuracy of the correlations also increases. With the increased accuracy of the correlations in the $0.5 < \alpha \leq 0.75$ range, a correlation is considered satisfactory when it predicted at least 80% of the experimental data points within ±15% agreement and with a RMS error of less than 15%. Seven correlations that are listed in Table 4 performed satisfactorily in the $0.5 < \alpha \leq 0.75$ range (Table 5). Altogether, there are four correlations that predicted at least 95, 90, and 80% of the experimental data points within the respective ±20, ±15, and ±10% error bands, namely, those of Nicklin et al. [18], Bonnecaze et al. [20], Sun et al. [25], and Kokal and Stanislav [21].

Out of the 52 correlations considered in this study, the correlations of Bonnecaze et al. [20], Kokal and Stanislav [21], and Nicklin et al. [18], Eqs. (4), (12), and (15), are among the three best correlations in the $0.5 < \alpha \leq 0.75$ range. The results of the comparison of the three aforementioned correlations with experimental data are listed in Table 6. The correlation of Rouhani and Axelsson [22], Eq. (16), which has overall performance among the best discussed earlier, predicted 336 (95.7%) and 322 (91.7%) data points within the ±20 and ±15% error bands, respectively. The comparison of Nicklin et al. [18] (best correlation for $0.5 < \alpha \leq 0.75$) and Rouhani and Axelsson [22] correlations with the experimental data is shown in Figure 7.

Performance of Correlations for $0.75 < \alpha < 1$

In total, 468 experimental data points from the entire database were categorized in the void fraction range of $0.75 < \alpha < 1$. The correlations performed significantly better in this high range of void fraction. With significant increase in the accuracy of correlations within the $0.75 < \alpha < 1$ range, a correlation is considered satisfactory when it predicted at least 80% of the experimental data points within ±10% agreement as well as with a RMS error of less than 10%. Out of the eight correlations listed in Table 4, only three correlations performed satisfactorily in the $0.75 < \alpha < 1$ range (Table 5). This finding is revealed as a result of dividing the void fraction into specific ranges and analyzing the correlations within them.

Considering all the 52 correlations, only six correlations predicted at least 97 and 90% of the experimental data points within the respective ±15 and ±10% error bands, namely, those of Armand [26]–Massena [27], Rouhani and Axelsson [22], Dix [28], El-Boher et al. [29], Morooka et al. [30], and Woldesemayat and Ghajar [31]. Among these six correlations, the performance of the Armand [26]–Massena [27], Dix [28], El-Boher et al. [29], and Woldesemayat and Ghajar [31] correlations, Eqs. (3), (5), (6), and (19), are not listed in Table 4. However, their correlations are given in Table 2.

Out of all the correlations considered in this study, correlations of Armand [26]–Massena [27], Dix [28], and Rouhani and Axelsson [22], Eqs. (3), (5), and (16), are among the three best correlations in the $0.75 < \alpha < 1$ range. The results of the comparison of the three aforementioned correlations with experimental

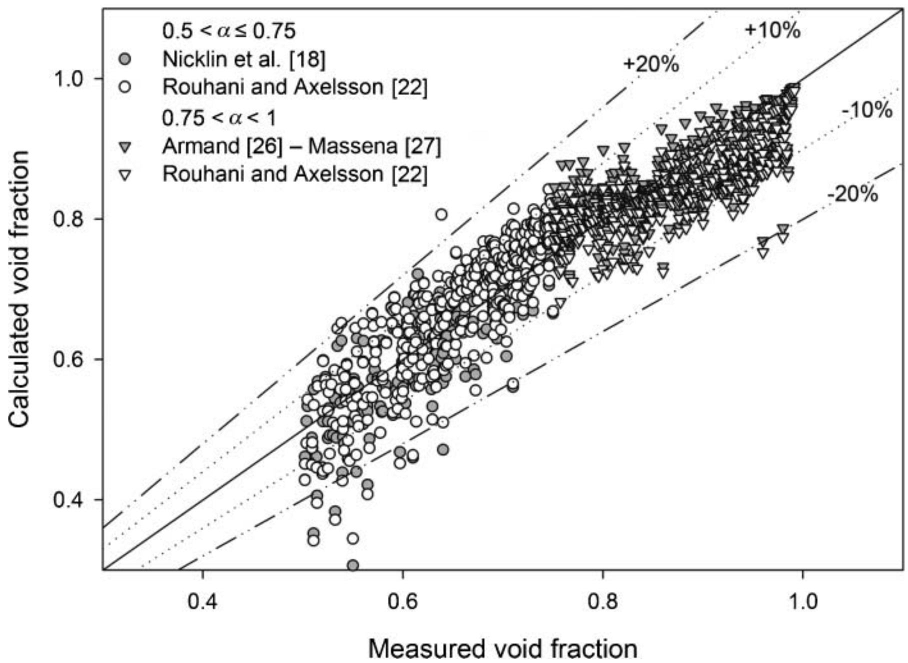

Figure 7 Comparison of Armand [26] – Massena [27], Nicklin et al. [18], and Rouhani and Axelsson [22] correlations with experimental data for $0.5 < \alpha < 1$.

data are listed in Table 6. The correlation of Nicklin et al. [18], which has overall performance among the best discussed earlier, predicted 434 (92.7%) and 297 (63.5%) data points within the ±15 and ±10% error bands, respectively. The comparison of Armand [26]–Massena [27] (best correlation for $0.75 < \alpha < 1$) and Rouhani and Axelsson [22] correlations with the experimental data is shown in Figure 7. The Rouhani and Axelsson [22] correlation showed more of a tendency of underpredicting the experimental data than the Armand [26]–Massena [27] correlation. The Rouhani and Axelsson [22] correlation underpredicted 75% of the data points, while the correlation of Armand [26]–Massena [27] underpredicted 60% of the data points.

Performance of Flow-Pattern-Specific Correlations

Flow-pattern-specific correlations are void fraction correlations developed and recommended for estimating void fraction in specific flow pattern regions. Flow-pattern-specific correlations were compared with void fraction data experimentally measured in that flow pattern region. In total, 550 experimentally measured void fraction data points were used for the comparison with flow-pattern-specific correlations. Since flow patterns are often subject to experimental setup and investigators' observations, the transition boundaries of one flow pattern to another are often debatable. Thus, correlations developed for a specific flow pattern were also used to compare with experimental data for the adjacent flow pattern region. For example, correlations developed for slug flow were also used to compare with experimental data for churn/froth flow. The flow patterns are categorized as bubble, slug, churn, froth, and annular. The experimental data used in this comparison were compiled from different sources with pipe diameters ranging from 12.7 to 50.7 mm and two-phase combinations of air and three different liquids (Table 7). The 550 experimental void fraction data points summarized in Table 7 along with their respective flow patterns were compiled from the original studies.

In the bubble flow region, in total, 111 experimental data points were used for comparison with correlations developed for this flow pattern. Although the bubble flow region has been subcategorized into dispersed bubble and bubbly flow, the discussion presented here makes no such distinction and considered both in the bubble flow region. Based on all the experimental data compiled in this study, the void fraction range for bubble flow is $0.02 < \alpha < 0.5$. Four void fraction correlations, developed for either dispersed bubble or bubbly flow, are considered to be applicable in the bubble flow region. Among the two best correlations developed for bubble flow are the correlations of Gomez et al. [32] and Hibiki and Ishii [33], Eqs. (7) and (10), and their equations are shown in Table 2. The correlation of Gomez et al. [32] has more accurate prediction than the correlation of Hibiki and Ishii [33]. The Gomez et al. [32] correlation predicted 76.6% of the experimental data points within ±20% error band, while the Hibiki and Ishii [33] correlation predicted 72.1% of the experimental data points within the same error band. Although the correlations of Gomez et al. [32] and Hibiki and Ishii [33] were developed for bubble flow, the correlation by Rouhani and Axelsson [22], Eq. (16), which is not a flow-pattern-specific correlation, predicted better results. The results of the comparison are listed in Table 8.

In total, 175 experimental data points in the slug flow region were used for comparison with correlations developed for this flow pattern. Based on all the experimental data compiled in this study, the void fraction range for slug flow is $0.1 < \alpha < 0.8$.

Table 7 Summary of experimental void fraction data for specific flow pattern

Source	Diameter (mm)	Fluids	Number of data points in				
			Bubble	Slug	Churn	Froth	Annular
Present study	12.7	Air–water	25	21	24	43	36
Fernandes [39]	50.7	Air–water	29	16	10	—	19
Mukherjee [12]	38.1	Air–kerosene	17	32	—	—	12
Oshinowo [42]	25.4	Air–water	15	—	—	—	—
	25.4	Air–glycerin	12	86	—	25	34
Sujumnong [13]	12.7	Air–water	13	20	12	11	38

Among the 10 correlations developed for slug flow, the two best performing void fraction correlations are the Bonnecaze et al. [20] and Nicklin et al. [18] correlations, Eqs. (4) and (15). Both correlations predicted 93.7% of the 175 experimental data points within ±20% agreement. The performances of the Bonnecaze et al. [20] and Nicklin et al. [18] correlations are very similar (Table 8), because the correlation of Bonnecaze et al. [20] is simply a slight variation of the Nicklin et al. [18] correlation for upward vertical pipe.

Table 8 Results of best flow pattern specific correlations and their comparisons with Rouhani and Axelsson [22]

Correlations	Percentage of data points predicted within			RMS error (%)
	±10%	±15%	±20%	
Bubble flow (111 data points)				
Gomez et al. [32]	36.0	64.0	76.6	59.3
Hibiki and Ishii [33]	31.5	56.8	72.1	58.3
Rouhani and Axelsson [22]*	37.8	66.7	78.4	63.5
Slug flow (175 data points)				
Bonnecaze et al. [20]	67.4	86.9	93.7	24.5
Nicklin et al. [18]	67.4	86.9	93.7	24.5
Rouhani and Axelsson [22]*	58.9	83.4	94.3	25.5
Churn flow (46 data points)				
Nicklin et al. [18]	87.0	95.7	97.8	6.8
Orell and Rembrand [34]	87.0	97.8	100	6.2
Rouhani and Axelsson [22]*	82.6	93.5	97.8	7.8
Froth flow (79 data points)				
Nicklin et al. [18]	81.0	94.9	96.2	8.1
Orell and Rembrand [34]	92.4	94.9	97.5	7.1
Rouhani and Axelsson [22]*	72.2	88.6	94.9	9.6
Annular flow (139 data points)				
Lockhart and Martinelli [35]	90.6	94.2	97.8	6.5
Rouhani and Axelsson [22]*	92.8	100	100	5.2
Smith [36]	95.7	100	100	5.6

*Not flow-pattern-specific correlation.

In the churn and froth regions, totals of 46 and 79 experimental data points, for respective flow pattern region, were used for comparison with the correlations. Based on all the experimental data compiled in this study, the void fraction range for churn/froth flow is $0.3 < \alpha < 0.9$. For both churn and froth flow patterns, the correlations of Nicklin et al. [18] and Orell and Rembrand [34] showed the best performances (Table 8). The Nicklin et al. [18] correlation predicted 97.8 and 96.2% of the experimental data within ±20% agreement for churn and froth flow patterns, respectively. The Orell and Rembrand [34] correlation has more accurate results, with 100 and 97.5% of the experimental data predicted within ±20% agreement for churn and froth flow patterns, respectively. Although Orell and Rembrand [34] is listed in Table 2, their correlation is not provided since it involves seven different equations.

In total, 139 experimental data points in the annular flow region were used for comparison with the correlations developed for this flow pattern. Based on all the experimental data compiled in this study, the void fraction range for annular flow is $0.65 < \alpha < 0.98$. Among the two best correlations developed for annular flow, are the correlations of Lockhart and Martinelli [35] and Smith [36], Eqs. (13) and (17), and their equations are shown in Table 2. The correlation of Smith [36] has more accurate prediction than the correlation of Lockhart and Martinelli [35] (Table 8). The correlation of Lockhart and Martinelli [35] predicted 97.8% of the experimental data within the ±20% error band, while the Smith [36] correlation predicted all the experimental data within the same error band.

Summary of Correlations Performances

The eight correlations listed in Table 4 were selected on the basis of overall performance, which overlooks the strengths and weaknesses in specific ranges of void fraction. This overall comparison with the experimental data yielded two correlations with

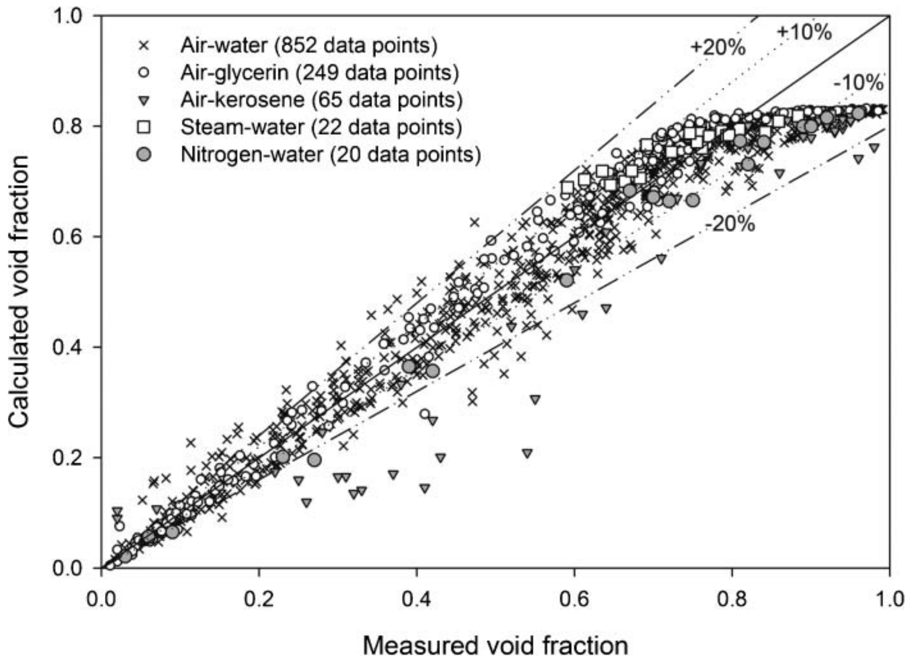

Figure 8 Comparison of Nicklin et al. [18] correlation with all 1208 experimental data points.

best prediction of experimental data, namely, the correlations of Nicklin et al. [18] and Rouhani and Axelsson [22]. The subsequent logical approach was to analyze the selected correlations in ranges, by dividing the entire void fraction range into four ranges: 0 to 0.25, 0.25 to 0.5, 0.5 to 0.75, and 0.75 to 1. The qualitative outcomes of the eight correlations and their performances in each of the four ranges were summarized in Table 5. By comparing the void fraction correlations with experimental data in each of the four specific ranges, the correlation of Rouhani and Axelsson [22], Eq. (16), was identified as the best correlation for upward vertical two-phase flow. It is worthwhile to note that the Nicklin et al. [18] correlation, Eq. (15), performed best for predicting void fraction within the $0.25 \leq \alpha \leq 0.75$ range.

Figures 8 and 9 show the comparison of the Nicklin et al. [18] and Rouhani and Axelsson [22] correlations with the entire

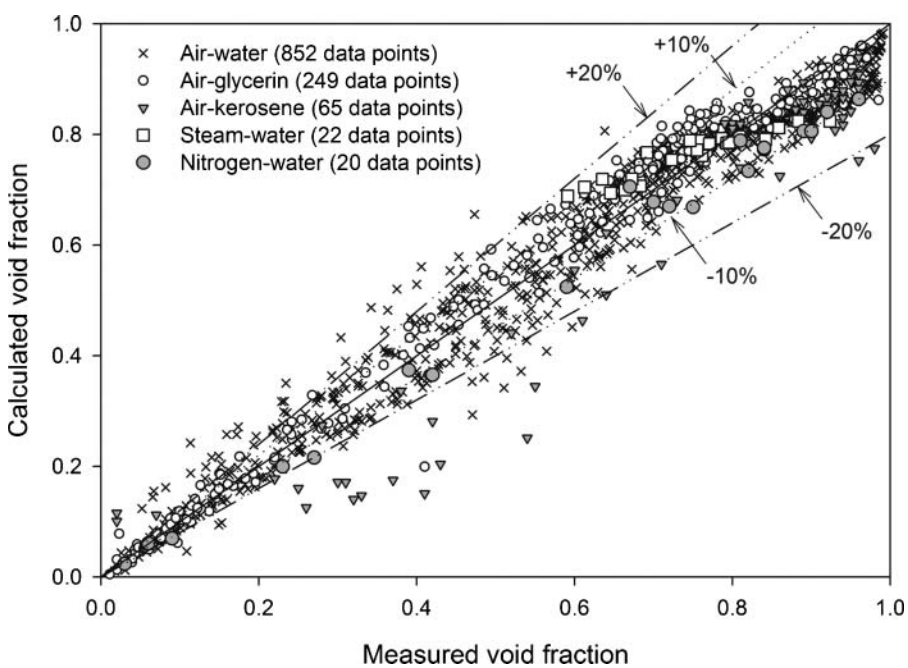

Figure 9 Comparison of Rouhani and Axelsson [22] correlation with all 1208 experimental data points.

experimental database of 1208 data points. Table 4 indicates that the Nicklin et al. [18] correlation has predicted more experimental data points within the error band of ±20% than Rouhani and Axelsson [22] correlation. However, it is shown in Figure 8 that the Nicklin et al. [18] correlation performed unsatisfactorily in the 0.75 to 1 void fraction range, and conspicuously underpredicted the experimental data in this range. The reason that the Nicklin et al. [18] correlation performed unsatisfactorily in the 0.75 to 1 void fraction range is because the correlation uses a constant distribution parameter ($C_0 = 1.2$). It is worth noting that the Nicklin et al. [18] correlation was originally developed for slug flow, and this analysis showed that it is the best performing correlation for slug and churn/froth flows. The correlation of Rouhani and Axelsson [22], on the other hand, is the only correlation that is found to perform satisfactorily in each of the four void fraction ranges (Table 5). Figure 9 also showed that the Rouhani and Axelsson [22] correlation predicted the experimental data generally well for different pipe diameters (12.7–76 mm), operating pressures (101–3410 kPa), and gas–liquid combinations.

The final analysis was the comparison of Rouhani and Axelsson [22] correlation with flow pattern specific correlations and the experimental results available for the corresponding flow pattern. The comparison showed that the correlation of Rouhani and Axelsson [22] compares satisfactorily with flow-pattern-specific correlations and experimental results for the corresponding flow pattern (Table 8). The Rouhani and Axelsson [22] correlation performed better than correlations developed for bubble flow. For slug and churn/froth flows, the Nicklin et al. [18] correlation performed better than the Rouhani and Axelsson [22] correlation. This is to be expected, since most of the experimental data points for slug and churn/froth flows lie in the $0.25 \leq \alpha \leq 0.75$ range. For annular flow, the performance of the Rouhani and Axelsson [22] correlation is comparable to that of Smith [36], which is the best correlation for annular flow.

CONCLUSIONS

A very extensive comparison of most of the void fraction correlations available in the open literature was made against 1208 experimental data points for upward vertical two-phase flow. The best performing correlations considering the total number of data points predicted, as well as their relative consistency in performance, were highlighted. Furthermore, the best correlations for four different void fraction ranges, namely, 0 to 0.25, 0.25 to 0.5, 0.5 to 0.75, and 0.75 to 1, were highlighted, as well as the best flow-pattern-specific correlations.

From this analysis, it can be concluded that the correlations based on the drift flux model are among the most accurate correlations for upward vertical two-phase flow, which is consistent with the finding of Woldesemayat and Ghajar [31]. This discovery suggests that developers for better and more accurate void fraction correlations should perhaps begin with the drift flux model. In addition to identifying correlations with minimum disparity when compared to experimental data, the effort of this undertaking also resulted in the compilation of an extensive experimental void fraction database. The experimental database is useful not only for validating void fraction correlations, but also for extending the understanding of the physics of two-phase flow that includes the hydrodynamic and heat transfer aspects.

NOMENCLATURE

C_0	two-phase distribution parameter, dimensionless
D	pipe inside diameter, m
Fr	Froude number, dimensionless
G	mass flux or mass velocity, kg m^{-2} s^{-1}
g	gravitational acceleration, m s^{-2}
p	pressure, Pa
Re	Reynolds number, dimensionless
U	velocity, m s^{-1}
u_{gu}	gas phase drift velocity, m s^{-1}
V	volume, m^3
We	Weber number, dimensionless
x	flow quality, dimensionless

Greek Symbols

α	void fraction, dimensionless
θ	inclination angle, radians
μ	dynamic viscosity, kg m^{-1} s^{-1}
ρ	density, kg m^{-3}
σ	surface tension, N m^{-1}

Subscripts

atm	atmosphere
cr	critical
g	gas
l	liquid
sg	superficial gas
sl	superficial liquid
sys	system or operating
t	total

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