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VOID FRACTION AND FLOW PATTERNS OF TWO-PHASE GAS-LIQUID FLOW IN VARIOUS PIPE INCLINATIONS

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ABSTRACT

Void fraction correlations for various pipe inclinations, both theoretical and empirical, that are widely available in the literature, are compared with experimental data from various sources with different experimental facilities. The discussion here consists of results from collaborated studies on void fraction, which led to the recommendation of a general correlation for various pipe inclinations and working two-phase fluids, and the recommendation of a correlation specifically for upward vertical pipes. The work demonstrated that more accurate predictions can be obtained by giving attention to specific ranges of void fraction in upward vertical pipes. An ongoing study on void fraction in horizontal pipes has led to several correlations, which compared satisfactorily with the experimental data, and the best correlation has yet to be identified. Flow pattern maps of different pipe inclinations that are available in the literature are compared and discussed.

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. In the effort to gain the fundamental understanding of the complexities involved in two-phase flow, void fraction and flow patterns are two of the key pieces to the puzzle.

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, Boiling Water Reactor (BWR) uses light water as neutron moderator and coolant, and void fraction is significant in estimating the reactivity of the nuclear reactor.

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.

Another key toward understanding two-phase flow is the determination of flow patterns. Depending on fluid properties, pipe sizes and orientations, and flow rates, various flow patterns can exist during two-phase flow in a pipe. Since flow patterns influence parameters such as pressure gradient and heat transfer, the knowledge of the flow patterns involved become significant.

Void fraction correlations for various pipe inclinations, both theoretical and empirical, that are widely available in the literature are gathered and analyzed. In addition, measured void fraction data from various sources and experimental facilities is also collected. The collected measured void faction data is used to validate the correlations, and a selected few correlations are recommended based on their predictive performance. In the interest of a fundamental point of view, the comparison of the measured void fraction data with the available correlations encompasses a wide range of gas and liquid flow parameters, flow patterns, and pipe inclinations for different gas-liquid combinations. Flow pattern maps for gas-liquid flow are also discussed. Flow pattern maps of different pipe inclinations available in the literature are compared. Since the assessment of flow patterns in a given gas-liquid system is somewhat subjective, the comparison of flow maps from various sources reveals the similarities and dissimilarities thereof.

NOMENCLATURE

C	[-]	Constant in Wallis' [10] correlation
C_0	[-]	Two-phase distribution coefficient
D	[m]	Pipe inside diameter
g	[m/s]	Gravitational acceleration
m	[-]	Constant in Wallis' [10] correlation
P	[Pa]	Pressure
Re	[-]	Reynolds number
u_{GM}	[m/s]	Drift velocity for gas
V	[m/s]	Velocity
V^*	[-]	Superficial velocity in Wallis' [10] correlation
x	[-]	Flow quality

Special characters

α	[-]	Void fraction
θ	[rad.]	Inclination angle
ρ	[kg/m^3]	Density
σ	[N/m]	Surface tension

Subscripts

atm	Atmosphere
G	Gas
L	Liquid
SG	Superficial gas
SL	Superficial liquid
sys	System

EXPERIMENTAL SETUP FOR HORIZONTAL TO UPWARD AND DOWNWARD VERTICAL FLOW

The recently constructed experimental setup is equipped for measuring heat transfer, pressure drop, 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 [1].

In this writing, only the experimental results of flow patterns and void fraction in upward vertical flow are discussed. The test section for flow visualization and void fraction is illustrated in Figure 1. 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. Pressure taps are included in the flow visualization section for measuring pressure drop across the section.

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 removed in a coalescing filter. The air flow is measured by Emerson Micro Motion Coriolis flow meters (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 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 seconds.

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. Backflow from the mainline into the exit of the bypass line is prevented through the use of a check valve. Air-water mixture trapped in the void fraction section was drained into a Nalgene 8-liter high density polyethylene tank. In order to ensure maximum collection of liquid into the tank, compressed air was used to effectively blow out any remaining liquid inside the void fraction section. The experimental procedure of measuring the void fraction with this experimental setup is also discussed in [1]. The uncertainties associated to the measured void fraction results are estimated to be between ±1.25% and ±4.16%.

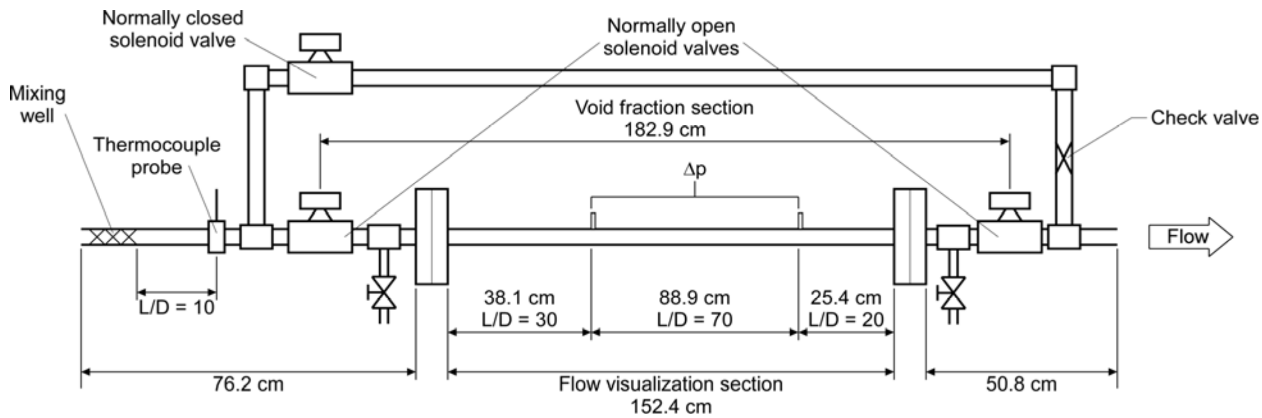

Figure 1 Test section for flow visualization and void fraction

FLOW PATTERNS

Flow Patterns in Horizontal and Upward Inclined Pipes

The various interpretations accorded to the multitude of flow patterns by different investigators are subjective; and no uniform procedure exists at present for describing and classifying them. In this study, the flow pattern identification for the experimental data was based on the procedures suggested by Taitel and Dukler [2], and Kim and Ghajar [3]; and visual observations as deemed appropriate. Note that the flow pattern observations for horizontal and upward inclined pipes, discussed under this heading, were conducted with a different experimental setup of 27.9 mm diameter pipe. The detail of this 27.9 mm diameter pipe experimental setup has been documented in [4-6].

By fixing the water flow rate, flow patterns were observed by varying air flow rates. Flow pattern data were obtained at isothermal condition with the pipe in horizontal position and at 2°, 5°, and 7° inclined positions. These experimental data were plotted and compared using their corresponding values of Re_{SG} and Re_{SL}, and the flow patterns. Representative digital images of each flow pattern were taken using a Nikon D50 digital camera with Nikkor 50 mm f/1.8D lens. Flow patterns that can be observed in horizontal two-phase flow are illustrated in Figure 2. The flow map for horizontal flow with the representative photographs of the various flow patterns is shown in Figure 3. The various flow patterns for horizontal flow depicted in Figure 3 show the capability of our experimental setup to cover multitude of flow patterns. The shaded regions represent the transition boundaries of the observed flow patterns.

The influence of small inclination angles of 2°, 5°, and 7° on the observed flow patterns is shown in Figure 4. As shown in this figure, the flow pattern transition boundaries for horizontal flow were found to be quite different from the flow pattern transition boundaries for inclined flow when slight inclinations of 2°, 5°, and 7° were introduced. The changes in the flow pattern transition boundaries from horizontal to slightly inclined flow are the transition boundaries for stratified flow and slug/wavy flow. When the pipe was inclined from horizontal to slight inclination angles of 2°, 5°, and 7°, the stratified flow region was replaced by slug flow and slug/wavy flow for $Re_{SG} < 4000$ and $4000 < Re_{SG} < 10000$, respectively. Other shifts in the flow pattern transition boundaries were observed in the plug-to-slug boundary and the slug-to-slug/bubbly boundary. In these two cases, the flow pattern transition boundaries were observed to be shifted slightly to the upper left direction as inclination angles were slightly increased from horizontal to 7°. For slightly inclined flow of 2°, 5°, and 7°, there were no drastic changes in the flow pattern transition boundaries.

For verification of the flow pattern map, flow patterns data from Barnea *et al.* [7] was used and compared with the flow pattern maps for horizontal and 2° inclined pipe. Using flow pattern data from Barnea *et al.* [7] for air-water flow in 25.5 mm diameter horizontal pipe, the data points plotted on the flow map for horizontal flow (see Figure 3) are illustrated in Figure 5. The comparison between the data points from Barnea *et al.* [7] and the flow pattern map for horizontal flow showed very satisfactory agreement, especially among the distinctive major flow patterns such as annular, slug and stratified. It should be noted that Barnea *et al.* [7] had successfully compared their horizontal flow pattern data with the flow map proposed by Mandhane *et al.* [8]. In a similar manner, using flow pattern data from Barnea *et al.* [7] for air-water flow in 25.5 mm diameter 2° inclined pipe, the data points plotted on the flow map for 2° inclined flow (see Figure 4) are illustrated in Figure 6. The comparison between the data points from Barnea *et al.* [7] and the flow pattern map for 2° inclined flow also showed very satisfactory agreement.

Flow Patterns in Vertical Pipes

Flow patterns in upward vertical two-phase air-water flow were conducted at isothermal condition using the robust experimental setup capable for pipe orientation from downward vertical to upward vertical. The experimental setup is equipped for measuring heat transfer, pressure drop, 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). All observations for the flow pattern judgments were made at the flow visualization section (see Figure 1). Further discussion on the experimental study of flow pattern in vertical pipe using the test section illustrated in Figure 1 is available in [9].

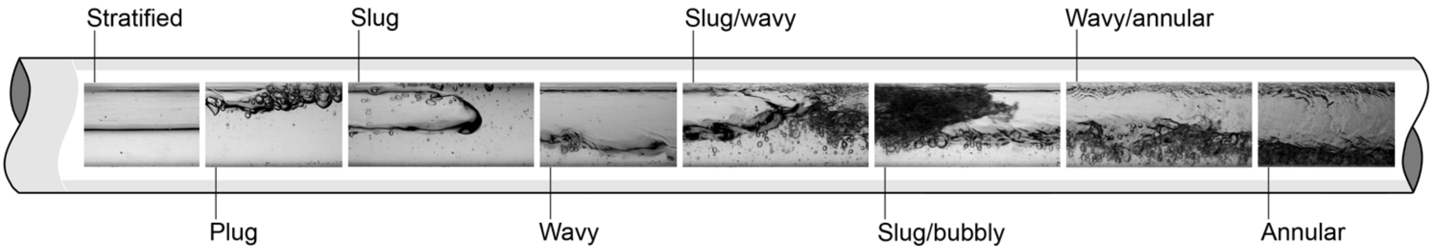

Figure 2 Flow patterns in horizontal two-phase flow

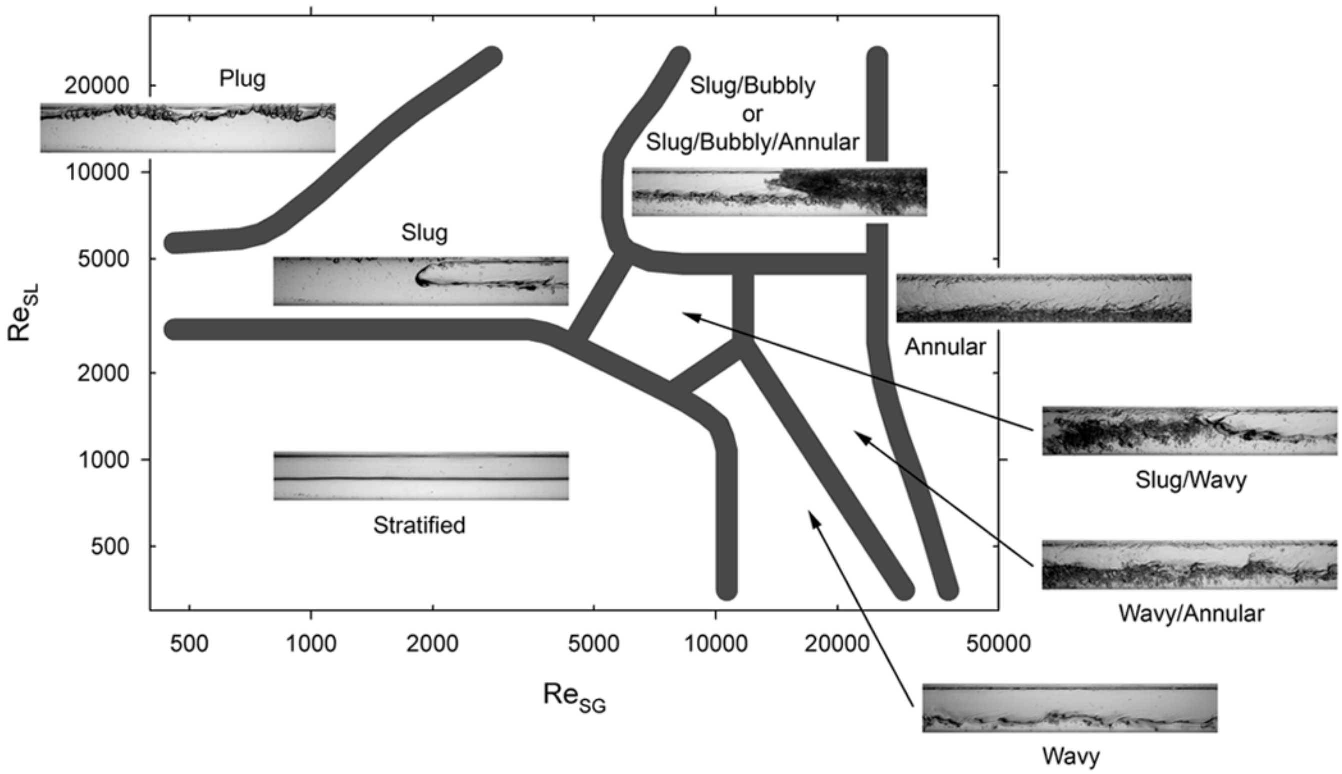

Figure 3 Flow map for horizontal flow with representative photographs of flow patterns

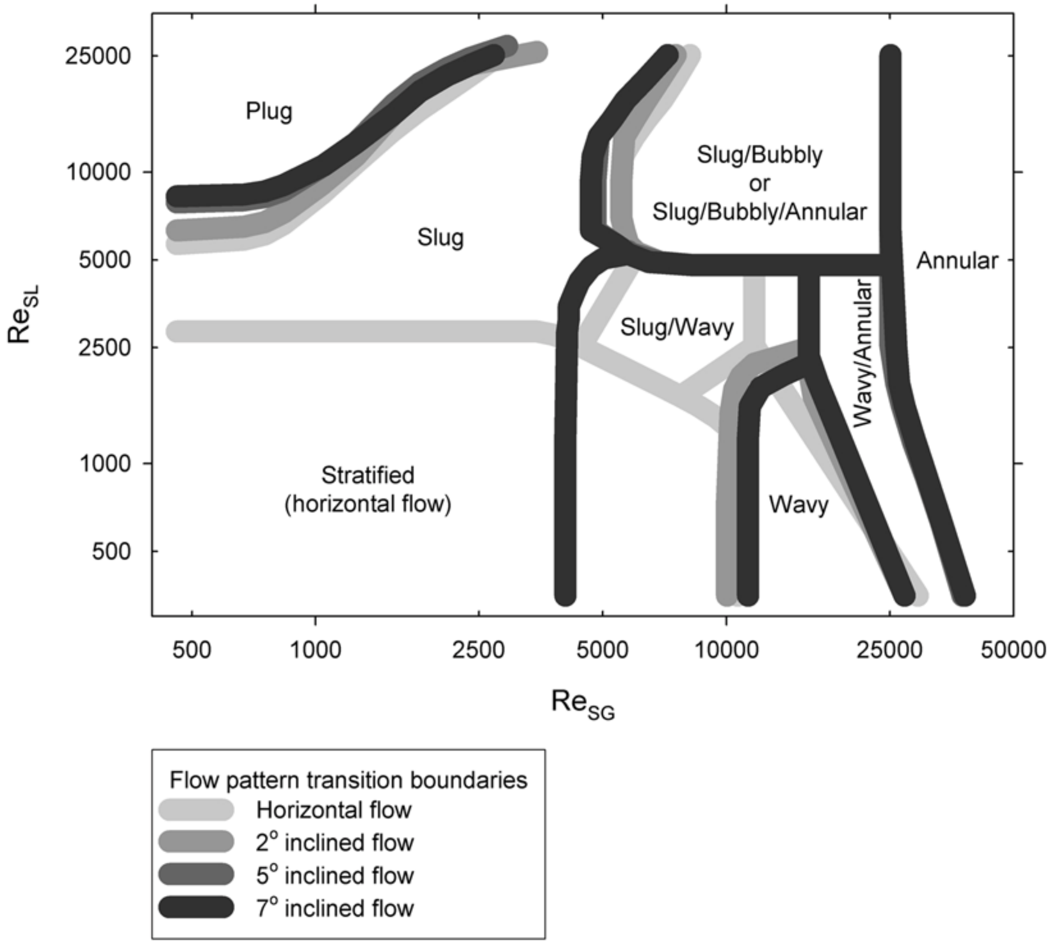

Figure 4 Change of flow pattern transition boundaries as pipe inclined from horizontal position

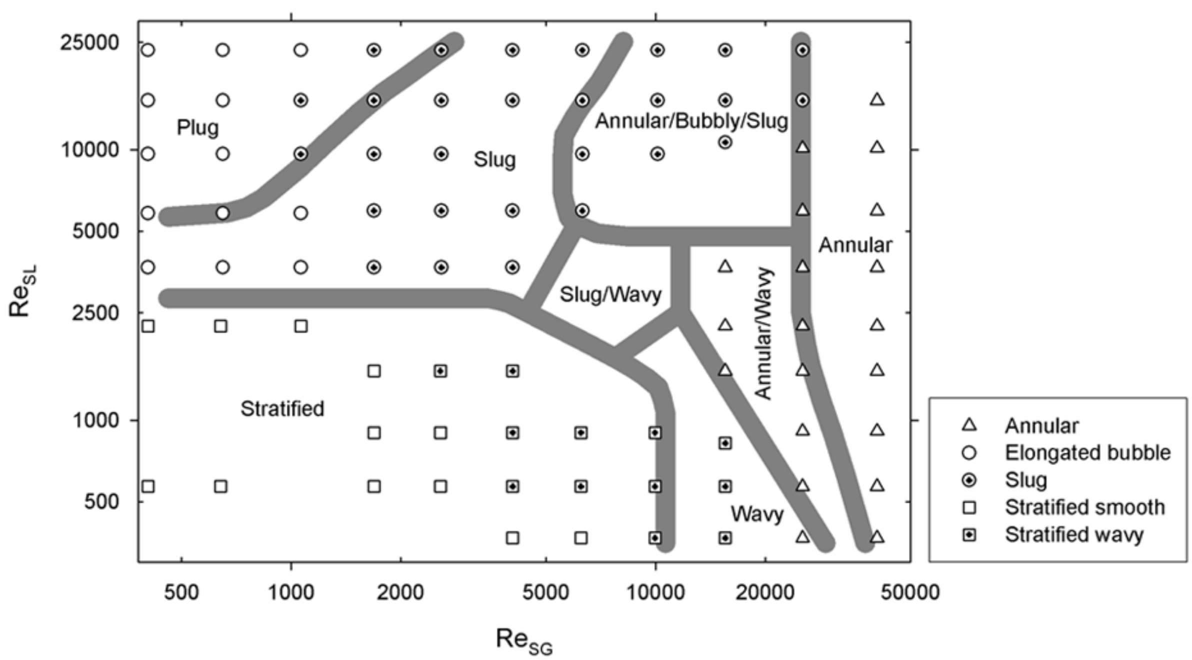

Figure 5 Flow patterns data points from Barnea *et al.* [7] plotted on the flow map for horizontal flow

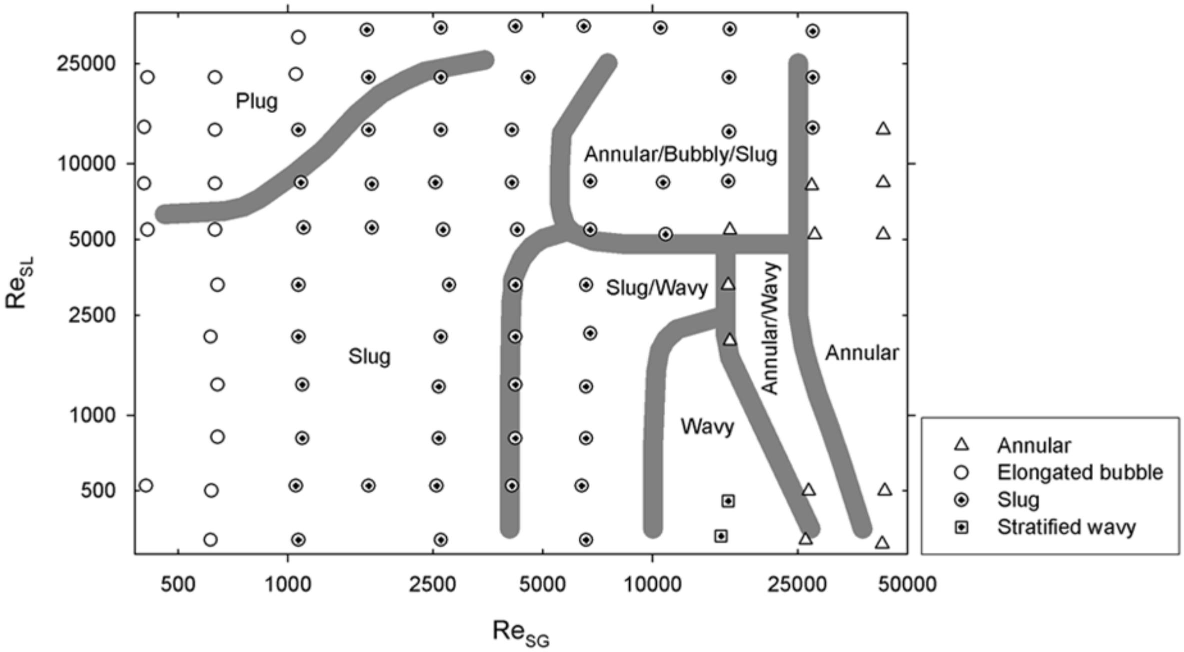

Figure 6 Flow patterns data points from Barnea *et al.* [7] plotted on the flow map for 2° inclined flow

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 recognized and transition boundaries between flow patterns were determined. The five distinctive major flow patterns observed in the upward vertical two-phase flow are dispersed bubble, slug, churn, froth, and annular. 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. The flow map for vertical flow with the representative photographs of the various flow patterns are shown in Figure 7. Flow patterns that can be observed in upward vertical two-phase flow are illustrated in Figure 8. The technique for obtaining the digital images was similar to that employed for horizontal pipe using a Nikon D50 digital camera with Nikkor 50mm f/1.8D lens.

The slug-churn and churn-annular transition boundaries in this experimental study were compared with correlations available in the literature. The correlation suggested by Wallis [10] is widely used and can be written as

$$V_{SL}^{*1/2} + mV_{SG}^{*1/2} = C \tag{1}$$

where the dimensionless superficial velocities for gas and liquid are expressed as

$$V_{SG}^{*} = V_{SG}\rho_G^{1/2}[gD(\rho_L - \rho_G)]^{-1/2} \tag{1a}$$

and

$$V_{SL}^{*} = V_{SL}\rho_L^{1/2}[gD(\rho_L - \rho_G)]^{-1/2} \tag{1b}$$

In Wallis' original expression of Eq. (1), the values of the dimensionless parameters are $C = m = 1$ [10]. 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. The parameters, C and m, vary approximately within the $0.7 \le C \le 1.0$ and $0.8 \le m \le 1.0$ ranges [11]. McQuillan and Whalley [12] applied Wallis' 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 listed in Table 1 and illustrated in Figure 7. The agreement between the experimental data and Eq. (1), with $C = 0.94$ and $m = 1.0$, is satisfactory and the percentage error is within 6%, see Table 1. At the churn-annular transition, the experimental data was compared with the results from McQuillan and Whalley [12], and agreement is also generally good, see Figure 7.

Table 1 Comparison of experimental data with Eq. (1), for the slug-churn transition

V_{SL} [m/s]	V_{SG} [m/s] Experimental	V_{SG} [m/s] Eq. (1) ‡	Error [%]
0.080	1.02	0.975	−4.37
0.165	0.90	0.873	−3.06
0.310	0.70	0.717	2.44
0.460	0.53	0.560	5.73
0.600	0.42	0.417	−0.69

‡ $C = 0.94$ and $m = 1$

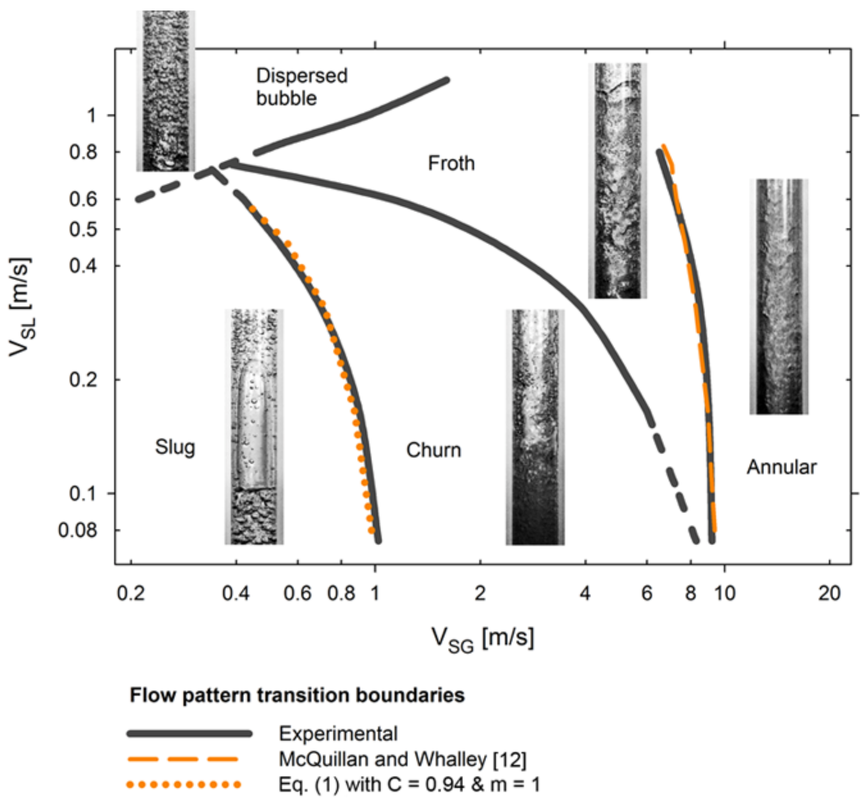

Figure 7 Flow map for vertical flow with representative photographs of flow patterns

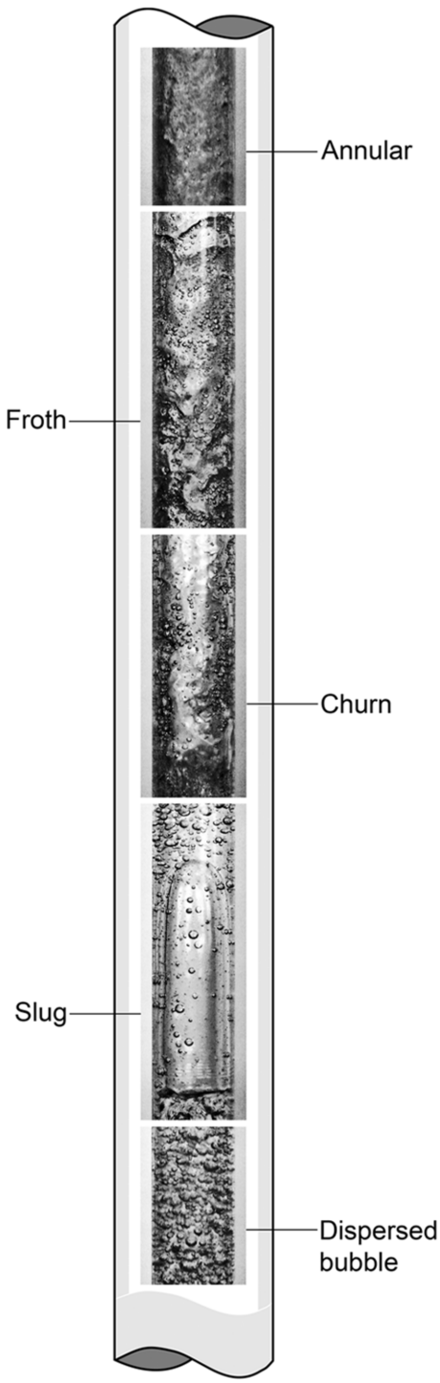

Figure 8 Flow patterns in upward vertical two-phase flow

EXPERIMENTAL RESULTS OF VOID FRACTION IN UPWARD VERTICAL FLOW

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 gas mass flow rate for vertical pipe flow is shown in Figure 9. As liquid mass flow rate increases, the increase in liquid holdup cause the void fraction versus gas mass flow rate curves shift lower. In Figure 9, the groupings of various flow patterns on the variation of void fraction with gas mass flow rate curves are shown. Slug flow is confined to low-range gas mass flow rate with $0.25 < \alpha < 0.72$, while churn and froth flows are found in mid-range gas mass flow rate. At any given gas mass flow rate, churn flow has higher void fraction than froth flow. Annular flow is in the high gas mass flow rate region with $0.72 < \alpha < 0.90$. The range of void fraction values observed in the present study for different flow patterns in upward vertical flow is listed in Table 2.

COMPARISON OF VOID FRACTION CORRELATIONS FOR DIFFERENT FLOW PATTERNS AND PIPE INCLINATIONS

Due to the importance of void fraction in influencing the characteristics of two-phase flow in pipes, Woldesemayat and Ghajar [13] conducted a very extensive comparison of 68 void fraction correlations available in the open literature against 2845 experimental data points. The experimental data points were compiled from various sources with different experimental facilities [14-21]. Out of the 2845 experimental data points, 900 were for horizontal, 1542 for inclined, and 403 for vertical pipe orientations (see Table 3). Based on the comparison with experimental data, six void fraction correlations [22-27] were recommended for acceptably predicting void fraction for horizontal, upward inclined, and vertical pipe orientations regardless of flow patterns. The percentage of data points correctly predicted for the 2845 experimental data points within three error bands for each correlation is summarized in Table 4.

The three more accurate correlations out of the six correlations recommended by Woldesemayat and Ghajar [13] are developed based on drift flux model. A recent discussion on the concept of drift flux is given in [11]. Void fraction correlations based on drift flux model can be expressed generically as

$$V_{SG} = C_0 \alpha (V_{SG} + V_{SL}) + \alpha (u_{GM}) \qquad (2)$$

The gas drift velocity (u_{GM}) represents the local relative velocity between gas and liquid phase. Both the two-phase distribution coefficient (C_0) and the gas drift velocity (u_{GM}) are determined empirically. In the three more accurate correlations recommended by Woldesemayat and Ghajar [13], the appropriate expressions for the two-phase distribution coefficient (C_0) and the gas drift velocity (u_{GM}) are listed in Table 5.

Table 2 Range of void fraction for different flow patterns

Flow pattern	Range of void fraction
Dispersed bubble	0.16 to 0.48
Slug	0.25 to 0.69
Churn	0.35 to 0.77
Froth	0.32 to 0.78
Annular	0.72 to 0.90

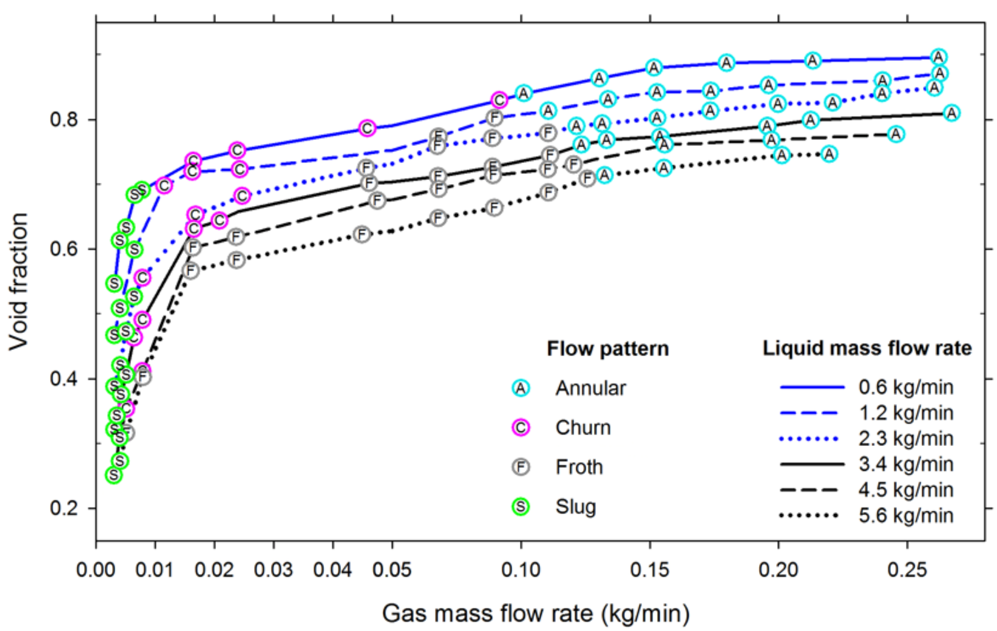

Figure 9 Variation of void fraction with gas mass flow rate for vertical pipe flow

Among the six void fraction correlations recommended by Woldesemayat and Ghajar [13], Dix [23] showed better performance in regards to general overall comparison with the experimental data points summarized in Table 3. The performance of the void fraction correlation by Dix [23] is shown in Figure 10. Woldesemayat and Ghajar [13] proposed an improved void fraction correlation that gives better predictions when compared with available experimental data. The correlation proposed by Woldesemayat and Ghajar [13] was developed based on the drift flux model and takes on the following expression:

$$\alpha = \frac{V_{SG}}{C_0\left(V_{SG}+V_{SL}\right)+u_{GM}} \tag{3}$$

where the two-phase distribution coefficient (C_0) and the gas drift velocity (u_{GM}) are given as

$$C_0 = \frac{V_{SG}}{V_{SG}+V_{SL}}\left[1+(V_{SL}/V_{SG})^{(\rho_G/\rho_L)^{0.1}}\right] \tag{3a}$$

and

$$u_{GM} = 2.9(1.22+1.22\sin\theta)^{P_{atm}/P_{sys}}\left[\frac{gD\sigma(1+\cos\theta)(\rho_L-\rho_G)}{\rho_L^2}\right]^{0.25} \tag{3b}$$

Note that the leading constant value of 2.9 in Eq. (3b) has a unit such that the drift flux velocity (u_{GM}) carries the units of meter per second, and Eq. (3) should be used with parameters conformed to the International System of Units (SI).

Table 3 Summary of experimental database sources, Woldesemayat and Ghajar [13]

Source (*no. of data points*)	Pipe diameter [mm] (*orientation*)	Fluids	Measurement technique
Eaton [14] (*237*)	52.5 & 102 (*H*)	Natural gas-water	Quick-closing valves
Beggs [15] (*291*)	25.4 & 38.1 (*H*, *U*, *V*)	Air-water	Quick-closing valves
Spedding & Nguyen [16] (*1383*)	45.5 (*H*, *U*, *V*)	Air-water	Quick-closing valves
Mukherjee [17] (*558*)	38.1 (*H*, *U*, *V*)	Air-kerosene	Capacitance probes
Minami & Brill [18] (*54 & 57*)	77.9 (*H*)	Air-water & Air-kerosene	Quick-closing valves
Franca & Lahey [19] (*81*)	19.0 (*H*)	Air-water	Quick-closing valves
Abdul-Majeed [20] (*83*)	50.8 (*H*)	Air-kerosene	Quick-closing valves
Sujumnong [21] (*101*)	12.7 (*V*)	Air-water	Quick-closing valves

The pipe orientations are designated with *H*, *U*, and *V* for horizontal, uphill inclined, and vertical, respectively.

The performance of Eq. (3) on the 2845 experimental data points in comparison with the recommended six void fraction correlations is also summarized in Table 4. As shown in Table 4, the void fraction correlation, Eq. (3), introduced by Woldesemayat and Ghajar [13] gives noticeable improvements over the other six correlations. The results of the comparison for Eq. (3) with the 2845 experimental data points are also illustrated in Figure 11. Both Table 4 and Figure 11 show the capability and robustness of Eq. (3) to successfully predict void fraction for various pipe sizes, inclinations, and two-phase fluid mixtures from various sources with different experimental facilities. The benefit of comparing with experimental data from different facilities is the minimization of sample bias.

Table 4 Number and percentage of data points correctly predicted by the six recommended void fraction correlations and Eq. (3) for the entire experimental database summarized in, Woldesemayat and Ghajar [13]

Correlation	No. of data points within		
	±5%	±10%	±15%
Morooka *et al.* [22]	1065 (37.4%)	2137 (75.1%)	2427 (85.3%)
Dix [23]	1597 (56.1%)	2139 (75.2%)	2363 (83.1%)
Rouhani & Axelsson [24]	1082 (38.0%)	2059 (72.4%)	2395 (84.2%)
Hughmark [25]	1244 (43.7%)	2003 (70.4%)	2322 (81.6%)
Premoli *et al.* [26]	1643 (57.8%)	2084 (73.3%)	2304 (81.0%)
Filimonov *et al.* [27]	1369 (48.1%)	1953 (68.6%)	2294 (80.6%)
Woldesemayat & Ghajar [13], Eq. (3)	1718 (60.4%)	2234 (78.5%)	2436 (85.6%)

A total of 2845 experimental data points (see Table 3) were used in this comparison. The number in ( ) represents the percentage of the data points within the error band.

Table 5 Expressions for two-phase distribution coefficient (C_0) and gas drift velocity (u_{GM}) of different void fraction correlations

Source	Two-phase distribution coefficient (C_0) and gas drift velocity (u_{GM})
Morooka *et al.* [22]	$C_0 = 1.08$ $u_{GM} = 0.45$
Dix [23]	$C_0 = \frac{V_{SG}}{V_{SG}+V_{SL}}\left[1+(V_{SL}/V_{SG})^{(\rho_G/\rho_L)^{0.1}}\right]$ $u_{GM} = 2.9\left[\frac{g\sigma(\rho_L-\rho_G)}{\rho_L^2}\right]^{0.25}$
Rouhani & Axelsson [24]	$C_0 = 1+0.2(1-x)$ $u_{GM} = 1.18(1-x)\left[\frac{g\sigma(\rho_L-\rho_G)}{\rho_L^2}\right]^{0.25}$

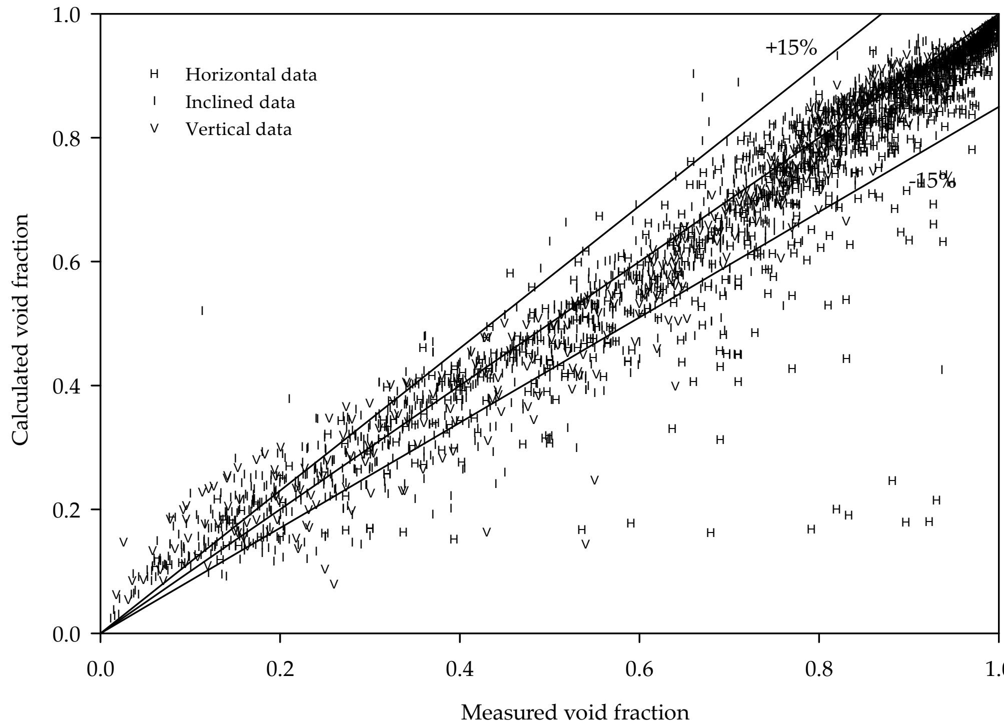

Figure 10 Comparison of void fraction correlation by Dix [23] (see Table 5), with 2845 experimental data points summarized in Table 3, Woldesemayat and Ghajar [13]

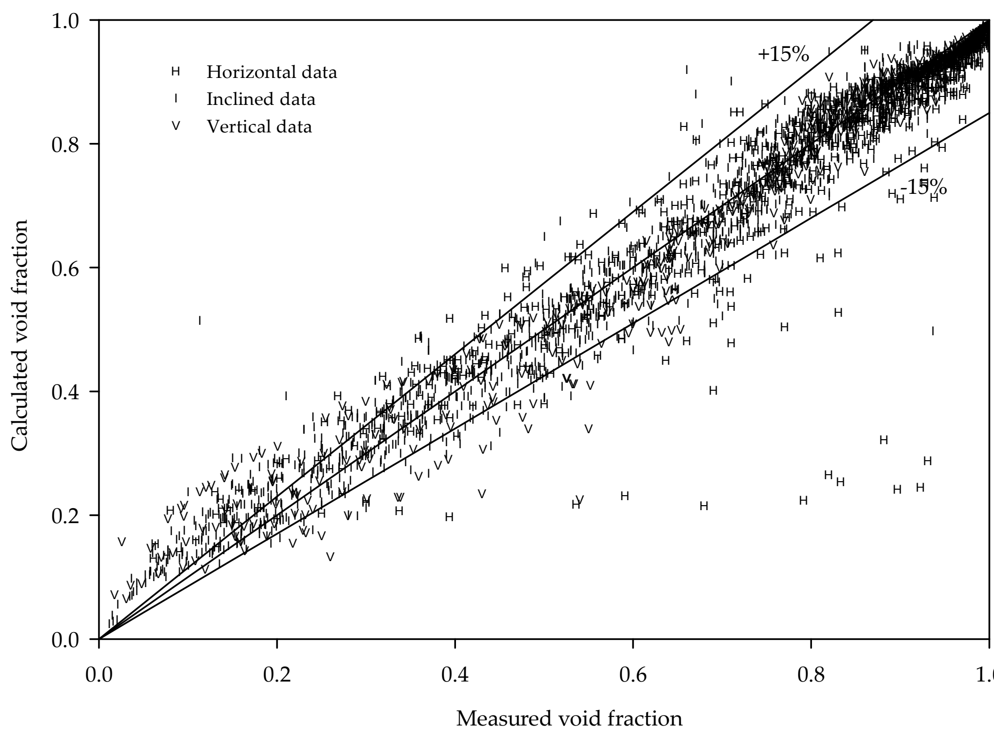

Figure 11 Comparison of void fraction correlation by Woldesemayat and Ghajar [13], Eq. (3), with 2845 experimental data points summarized in Table 3, Woldesemayat and Ghajar [13]

COMPARISON OF VOID FRACTION CORRELATIONS FOR VERTICAL PIPES

Further scrutiny has also been done specifically on the performances of available void fraction correlations with available experimental data for upward vertical two-phase flow. The work demonstrated that more accurate predictions can be obtained by giving attention to specific pipe inclination and ranges of void fraction. The effort resulted in the categorization of void fraction correlations recommended for specific void fraction ranges in upward vertical two-phase flow. Results of these categorical comparisons would allow the access to correlations with higher accuracies for specific void fraction range of interest. Further discussion on the comparison of void fraction correlations for vertical pipe is available in [9].

A database with a total of 1208 experimental data points was used for the comparison with void fraction correlations available in the literature. The database encompasses experimental data points for different gas-liquid combinations and pipe diameters. Table 6 presents a summary of the experimental database, compiled from ten independent sources, for the comparison with void fraction correlations.

In total, 52 flow pattern independent void fraction correlations are considered and compared with data points in the experimental database. Out of the 52 correlations, eleven correlations were considered to be in generally good agreement with the entire experimental database of 1208 data points. The eleven correlations were selected on the basis that their predictions, when compared with the experimental data, have more than 75% and 85% of the predicted data points within ±15% and ±20% error bands, respectively. The sources of the 11 selected correlations are listed in Table 7, along with the results of the comparison.

The eleven correlations listed in Table 7 were selected on the basis of overall performance, which overlooks the strengths and weaknesses in specific ranges of void fraction. Hence, the subsequent logical approach is 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 1.0. The qualitative outcome of the eleven correlations and their performances in each of the four ranges are summarized in Table 8. By comparing the void fraction correlations with experimental data in each of the four specific ranges, the correlation by Rouhani & Axelsson [24] was identified as the best correlation for upward vertical two-phase flow.

Figures 12 and 13 show the comparison of the Rouhani & Axelsson [24] and Nicklin *et al.* [28] correlations with the entire experimental database listed in Table 6. Although Table 7 indicates that the correlation by Nicklin *et al.* [28] has predicted more data points within the error bands of ±15% and ±20% than the correlation by Rouhani & Axelsson [24], it was noted that the Nicklin *et al.* [28] correlation performed unsatisfactorily in the 0.75 to 1.0 void fraction range. The Rouhani & Axelsson [24] correlation, on the other hand, is the only correlation that was found to perform satisfactorily on each of the four void faction ranges (see Table 8).

Table 6 Summary of experimental database for upward vertical two-phase flow (a total of 1208 data points)

Source	Pipe diameter [mm]	Fluids	No. of data points
Present study	12.7	Air-water	153
Schmidt *et al.* [29]	54.5	Nitrogen-water	20
Sujumnong [21]	12.7	Air-water	104
Sujumnong [21]	12.7	Air-glycerin	77
Chokshi [30]	76.0	Air-water	103
Fernandes [31]	50.7	Air-water	88
Mukherjee [17]	38.1	Air-kerosene	65
Spedding & Nguyen [16]	45.5	Air-water	224
Beggs [15]	25.4 & 38.1	Air-water	27
Oshinowo [32]	25.4	Air-water	153
Oshinowo [32]	25.4	Air-glycerin	172
Isbin *et al.* [33]	22.2	Steam-water	22

Table 7 Results of 11 selected correlations for upward vertical two-phase flow that compared satisfactorily with all 1208 experimental data points in Table 6

Correlation	Percentage of data points predicted within the error band of			
	±5%	±10%	±15%	±20%
Nicklin *et al.* [28]	33.1	62.1	84.4	91.7
Hughmark [25]	33.9	58.2	76.7	86.1
Nishino & Yamazaki [34]	43.2	66.6	78.6	84.7
Guzhov *et al.* [35]	28.1	54.6	77.6	88.7
Rouhani & Axelsson [24]	39.9	68.5	83.5	89.3
Bonnecaze *et al.* [36]	33.1	62.1	84.4	91.7
Ishii [37]	37.9	66.6	80.5	87.3
Sun *et al.* [38]	31.3	58.1	78.1	91.1
Kokal & Stanislav [39]	33.0	61.9	84.4	91.6
Morooka *et al.* [22]	32.5	62.1	79.1	87.9
Takeuchi *et al.* [40]	27.6	52.7	78.1	88.6

Table 8 Qualitative performance of 11 selected correlations for upward vertical two-phase flow in four void fraction ranges

Correlation	Void fraction range			
	0.00 to 0.25	0.25 to 0.50	0.50 to 0.75	0.75 to 1.00
Nicklin *et al.* [28]	S	S	S	NS
Hughmark [25]	NS	NS	S	S
Nishino & Yamazaki [34]	NS	NS	S	S
Guzhov *et al.* [35]	S	NS	S	S
Rouhani & Axelsson [24]	S	S	S	S
Bonnecaze *et al.* [36]	S	S	S	NS
Ishii [37]	S	NS	S	S
Sun *et al.* [38]	S	S	S	NS
Kokal & Stanislav [39]	S	S	S	NS
Morooka *et al.* [22]	S	NS	NS	S
Takeuchi *et al.* [40]	S	S	NS	NS

Note: S = satisfactory & NS = not satisfactory

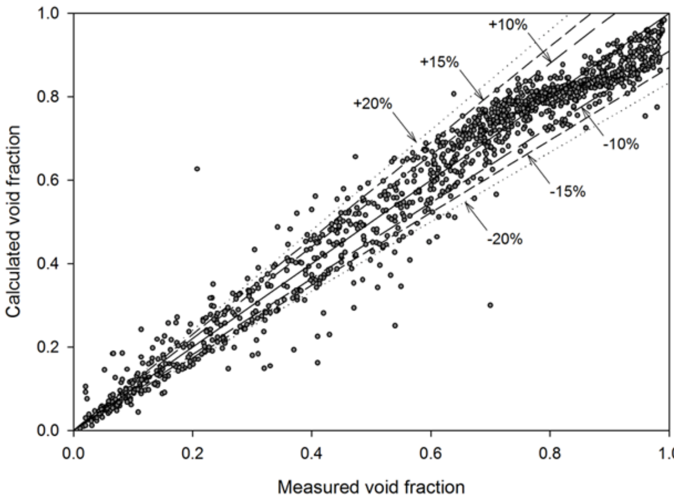

Figure 12 Comparison of void fraction correlation by Rouhani & Axelsson [24] with 1208 experimental data points summarized in Table 6

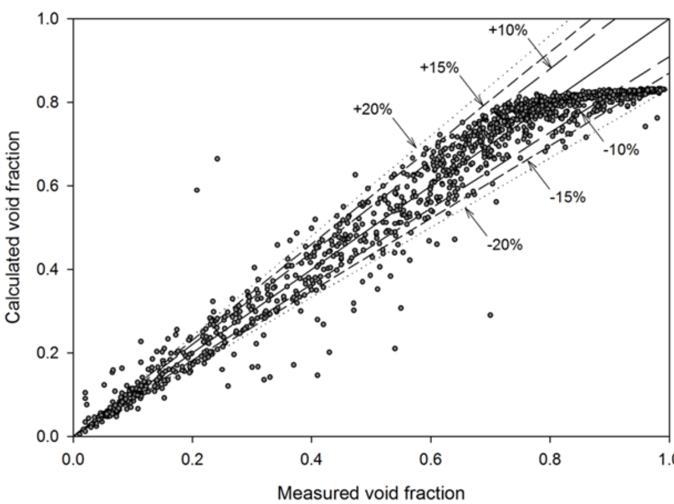

Figure 13 Comparison of void fraction correlation by Nicklin *et al.* [28] with 1208 experimental data points summarized in Table 6

COMPARISON OF VOID FRACTION CORRELATIONS FOR HORIZONTAL PIPES

In addition to upward vertical pipes, further scrutiny on void fraction correlations and experimental data is currently being done specifically for horizontal pipes. The motivation of this effort is to determine the correlations that can give more accurate predictions for horizontal pipes.

Presently, void fraction measurements for horizontal two-phase flow are being conducted using the test section illustrated in Figure 1. In addition to the experimental data points that have been measured thus far, experimental data from other sources has also been compiled. The total number of data points accumulated from experimental measurements as well as from other sources summed up to 968. As summarized in Table 9, the compiled experimental database consists of data from eight independent sources with different pipe sizes, working fluids, and measurement techniques. The compiled experimental database is used for comparison with void fraction correlations.

At this point, there are about fifty independent void fraction correlations, which are applicable for horizontal pipes, have been considered. Out of all the considered void fraction correlations, there are five correlations that have predicted 85% or more of the 968 experimental data points (summarized in Table 9) to within ±15%. The sources of the five selected correlations are listed in Table 10, along with the results of the comparison.

Figures 14 and 15 show the comparison of the correlations by Minami & Brill [18] and Rouhani & Axelsson [24], respectively, with the experimental data listed in Table 9. The correlation by Minami & Brill [18] showed slight tendency of over-predicting the experimental data (see Figure 14). On the other hand, the correlation by Rouhani & Axelsson [24] tends to under-predict the experimental data, conspicuously in the void fraction range of 0.8 to 1.0 (see Figure 15).

Table 9 Summary of experimental database for horizontal two-phase flow (a total of 968 data points)

Source (*no. of data points*)	Pipe diameter [mm]	Fluids	Measurement technique
Eaton [14] (*237*)	52.5 & 102	Natural gas-water	Quick-closing valves
Beggs [15] (*56*)	25.4 & 38.1	Air-water	Quick-closing valves
Spedding & Nguyen [16] (*270*)	45.5	Air-water	Quick-closing valves
Mukherjee [17] (*62*)	38.1	Air-kerosene	Capacitance probes
Minami & Brill [18] (*54 & 57*)	77.9	Air-water & Air-kerosene	Quick-closing valves
Franca & Lahey [19] (*81*)	19.0	Air-water	Quick-closing valves
Abdul-Majeed [20] (*83*)	50.8	Air-kerosene	Quick-closing valves
Present study (*68*)	12.7	Air-water	Quick-closing valves

Table 10 Results of 5 selected correlations for horizontal two-phase flow that compared satisfactorily with all 968 experimental data points in Table 9

Correlation	No. of data points within		
	±5%	±10%	±15%
Minami & Brill [18]	523 (54.0%)	717 (74.1%)	852 (88.0%)
Rouhani & Axelsson [24]	336 (34.7%)	736 (76.0%)	847 (87.5%)
Hughmark [25]	350 (36.2%)	715 (73.9%)	841 (86.9%)
Armand-Massena [41, 42]	456 (47.1%)	745 (77.0%)	830 (85.7%)
Mukherjee [17]	488 (50.4%)	706 (72.9%)	827 (85.4%)

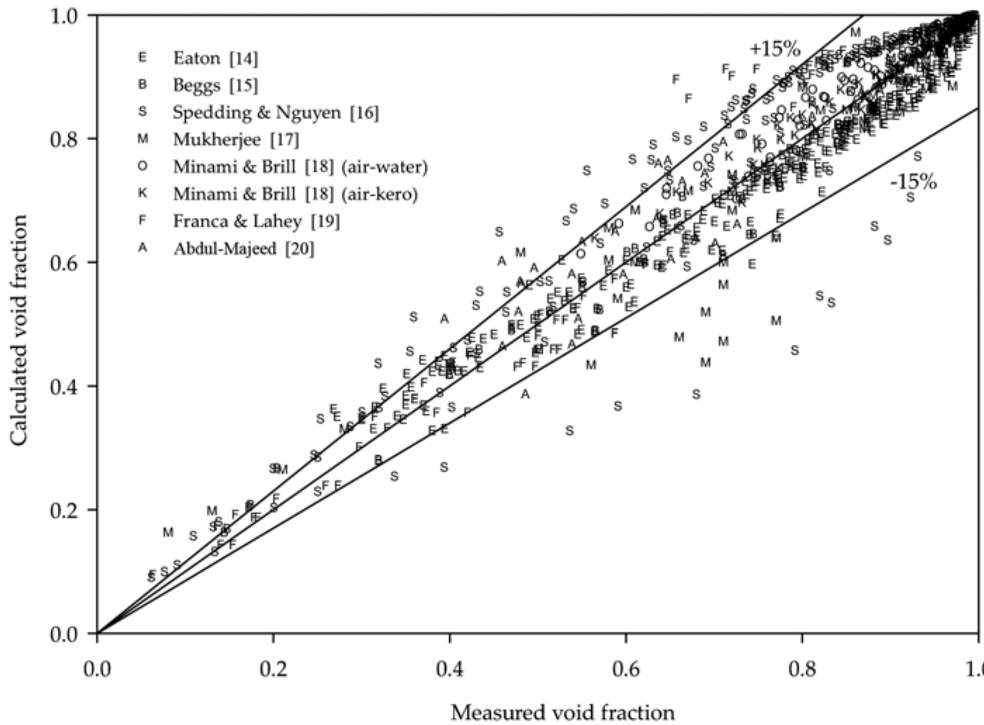

Figure 14 Comparison of void fraction correlation by Minami & Brill [18] with the experimental data points summarized in Table 9

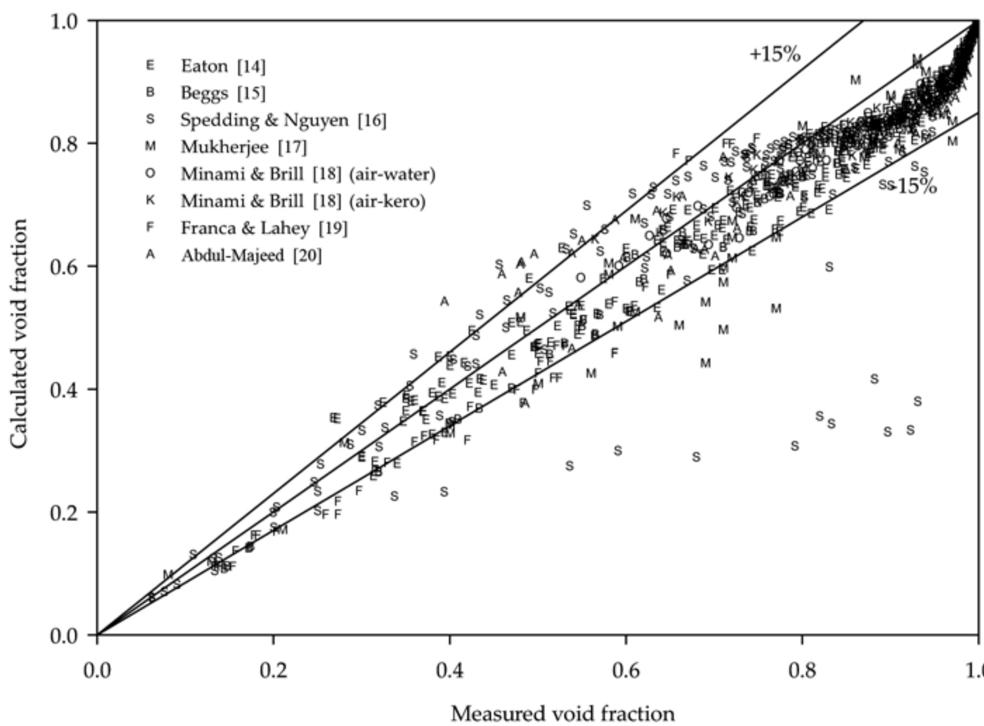

Figure 15 Comparison of void fraction correlation by Rouhani & Axelsson [24] with the experimental data points summarized in Table 9

SUMMARY

Void fraction correlations and experimental data available from the literature are gathered and analyzed. In this ongoing research, void fraction data has also been experimentally measured, for upward vertical and horizontal air-water two-phase flow, and added to the experimental database that consists of data from other sources.

Woldesemayat and Ghajar [13] conducted a very extensive comparison of 68 void fraction correlations, available in the open literature, against experimental data from various sources has resulted in a recommendation of a general void fraction correlation, Eq. (3), that is applicable for different pipe inclinations and working two-phase fluids. The general void fraction correlation, Eq. (3), can be incorporated in analysis for estimating subcooled and saturated water flow boiling pressure drop in small diameter helical coils [43]. Helically coiled tubes are often found in heat transfer equipments that are widely used in nuclear, chemical, cryogenic, food processing and pharmaceutical industries.

The general two-phase void fraction correlation has also shown its applicability in flow boiling of liquid nitrogen in a vertical mini-tube. In an experiment in flow boiling of liquid nitrogen in a vertical mini-tube, Fu et al. [44] showed that the general void fraction correlation, Eq. (3), provided the best prediction in comparison with two other void fraction models. Also, in the development of analytical models, the general two-phase void fraction correlation can be incorporated in the modeling of adiabatic gas-liquid annular two-phase flow in both macroscale [45] and microscale [46] conditions. When compared with their results, Cioncolini et al. [45, 46] noted that the general void fraction correlation, Eq. (3), is among the most accurate general purpose correlations currently available, with most of the data fitted within ±10% for macroscale [45] and ±20% for microscale [46].

Further scrutiny has also been done specifically for upward vertical two-phase flow on the performances of available void fraction correlations. A database of 1208 experimental data points, for different gas-liquid combinations and pipe diameters, was used for the comparison with void fraction correlations available in the literature. The effort resulted in the categorization of void fraction correlations recommended for specific void fraction ranges in upward vertical two-phase flow. Results of these categorical comparisons would allow the access to correlations with higher accuracies for specific void fraction range of interest.

At present stage, the ongoing effort is focused specifically on void fraction in horizontal pipes. Experimentally measured void fraction data, along with experimental results from other sources, are being gathered and compared with correlations available from the literature. Void fraction correlations that compared satisfactorily with the experimental data are identified. Further investigation of this ongoing work will result in recommending correlations that are specifically for horizontal pipes.

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