SAUDI INTERNATIONAL CONFERENCE
ON NUCLEAR POWER ENGINEERING

Proceedings of SCOPE
13-15 Nov. 2023 – KFUPM
Paper XXXXX

Gas-Liquid Flow Void Fraction Identification Using Slippage Number Froud Mixture Number Relation in Bubbly Flow

Author Name(s): ALYAMI, JABER M.[1 2], ALSRKHI, ABDELSALAM H.[1]

Affiliation: 1 Mechanical Engineering Department in KFUPM, 2 Saudi Aramco

Address: Saudi Arabia, Dhahran
Email(s): g201553450@kfupm.edu.sa, alsarkhi@kfupm.edu.sa

Abstract**—** Characterizing and modeling multi-phase flow is a complicated scientific and technical phenomenon represented by a variety of interrelated elements. Yet, the introduction of dimensionless numbers used to grasp gas-liquid flow is a significant step in controlling and improving the multi-phase flow area. SL (Slippage number) for instance is a strong dimensionless number defined as the ratio of the difference in gravitational forces between slip and no-slip conditions to the inertial force of the gas. The fact that plotting SL versus Frm provides a single acceptable curve for all the data provided proves that SL may be used to realize the behavior of gas-liquid flow. This paper creates a numerical link between SL and Froud mixing number using vertical gas-liquid flow, and then utilizes that relationship to validate its reliability in practice. An improved correlation in drift flux model generated from the experimental data, and its rationality has been verified. In this paper a new approach for predicting the void fraction in bubbly flow, through SL/Frm relation and the limitations of this method, as well as areas for development, are stated. This study improves the overall vision in liquid gas flow part where many of nuclear plants. Understanding and controlling the liquid gas flow can enhance both the design and the efficiency of nuclear power plants.

Keywords**—** Multiphase flow, gas-liquid flow, slippage, void fraction.

I. INTRODUCTION

THE drift flux model is frequently used approach for empirically predicting and calculating gas void fraction or liquid hold up by comparing actual gas velocity with superficial gas velocity incorporating the distribution factor $\boldsymbol{C_0}$and the drift velocity $\boldsymbol{Vd}$ in [eq.1] [1].

$$\boldsymbol{Vg} = \boldsymbol{C_0} * \boldsymbol{Vm} + \boldsymbol{Vdg} \tag{1}$$

This concept was first proposed by [2] with certain limitations. Nonetheless, the model was enhanced and used to nuclear reactors in [3]. Drift-flux modeling methods are extensively employed in pipelines and wellbores to describe two- and three-phase flow. " Unlike mechanistic models, drift-flux models are continuous, differentiable, and reasonably rapid to calculate, making them ideal for use in well-bore flow models inside reservoir simulators. The parameters are calculated by minimizing the discrepancy between experimental and model. predictions for phase in-situ volume percent." [4] Fig 1 is an example of calculated gas void fraction predicted by drift flux model compared with the experimental void fraction [4]. The slippage dimensionless number, SL, presented by (Abdelsalam, 2016) [5] has several benefits and can manage particularly the gas-liquid flow since it is flow pattern independent, viscosity unbiased, and is unaffected by pipe angle. The slippage number is "the ratio of the difference in gravitational forces between slip and no-slip situations to the gas's inertial force."[5]. The Slippage number presented in this paper, on the other hand, is dependent on the superficial gas velocity, flowing fluids density and is solely connected with the Froud mixing number. In this paper, the Slippage number numerical relation with Froud mixture number will be validated [5] see Figure 2. The goal is to find gas void fraction through only flow conditions, fluid properties, and geometry. The drift-flux model along with slippage number and the Froud mixture number relationship are used to determine the void fraction.

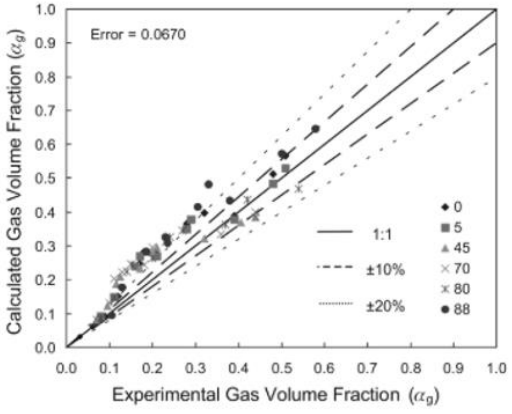

Fig.1 Predicted in-situ gas volume fraction using original parameters [4]

ALYAMI, JABER M is an Engineer in Saudi Aramco company and a Master degree student in King Fahd University for Petroleum and Minerals , (phone: +966-56-9362686; e-mail: jaber.alyami.2@aramco.com).

ALSRKHI, ABDELSALAM H., is a Mechanical engineering Professor in King Fahd University for Petroleum and Minerals (e-mail: alsrkhi@kfupm.edu.sa)

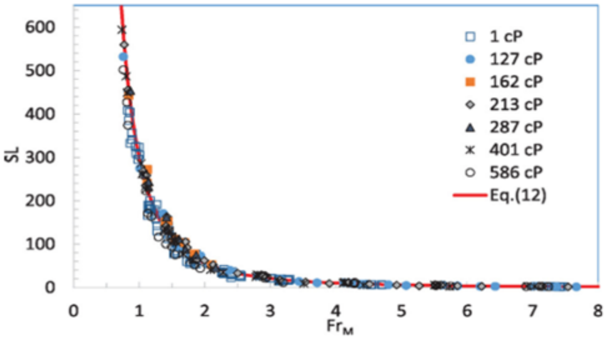

Fig.2 Slippage Number versus mixture Froude number for gas–liquid flow (Abdelsalam, 2016) [5].

In gas-liquid flow, the slip-density, ρTP, is different from the homogeneous ρH or no-slip mixture density see [eq.2,3&4] [6].

$$\textit{Two phase density}:\ \rho TP = \rho L \cdot HL + (1 - HL) \cdot \rho g \qquad (2)$$

$$\textit{Homogenous Density}:\ \rho H = \rho L \cdot \gamma L + (1 - \gamma L) \cdot \rho g \qquad (3)$$

$$\textit{Homogenous Hold up}:\ \gamma L = VsL/Vm = VsL/(VsL + Vsg) \qquad (4)$$

By dividing the volume flow rate of the phases by their ratio, the no-slip mixture density, ρH, may be calculated with ease, supposing that no slippage occurs. Measured or calculated liquid holdup yields the slip density, ρTP. The slippage number then can be calculated as per (eq.5) where it is a function of the superficial gas velocity , ρH, ρTP, ρg and pipe diameter.

$$SL = \left(\frac{\rho TP - \rho H}{\rho g\, Vsg^2} \cdot D \cdot g\right) \qquad (5)$$

because densities may vary greatly depending on factors including the flow pattern and phase slippage. In the case of bubbly flow, which is typical for slow gas superficial velocity, the slippage is limited, and the gas bubbles are carried by liquid where the value of the slippage number will be relatively small similar to the case in this paper see figure 3.

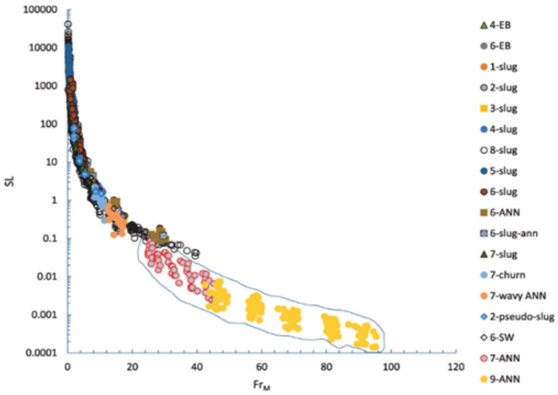

Fig. 3 Slippage Number versus Froude number based on mixture velocity for [7] experimental data [5].

As the drift flux method relies on phase slippage, it may also be very helpful in modelling gas-liquid flow in pipes. In fluid mechanics, the Froude Number is a dimensionless number used to indicate the influence of gravity on fluid motion.

$$Frm = \sqrt{\left(\frac{Vm^2}{D * g}\right)} \qquad (6)$$

In [5] and based on [7] data the SL is function of Frm proposed in Alsarkhi correlation. Using this suggested correlation will lead to find SL as a single curve of Frm that is function of the mixture velocity and pipe diameter and will ease finding the void fraction, consequently, can be used to find void fraction and predict the flow pattern. The SL/Frm relation will be used as a crucial tool in this paper to demonstrate a novel approach of estimating the void fraction. The SL/Frm relationship will predicted SL using just the mixture velocity and pipe diameter. As a result, the void fraction can be calculated by modifying the SL number basic function, as shown in [eq.8].

$$SL = 300.13\ Frm^{-2.425} \qquad (7)$$

$$Yg = 1 - \frac{1}{(\rho L - \rho g)}\left(\frac{SL\, \rho g\, Vsg^2}{D \cdot g} + \rho H - \rho g\right) \qquad (8)$$

Moreover, the SL/Frm relation presented by [5] will be validated using [7] data, and a new correlation will be developed and tested against additional 9 correlations with several limitations to demonstrate the strength of this data. As a result, the novel technique will be established utilizing [7] data and will be validated on Table III 816 bubbly flow experimental data with various pipe angles, flowing fluid characteristics, and pipe diameters all on bubbly pattern. Where the analysis will determine the method's limitations and how it might be improved. Lastly, this approach will be generalized and can be used as void fraction calculator and flow pattern induction tool.

II. METHODOLGY

Before starting the study, the correlation (eq.7) will be checked by plotting SL Vs Frm to ensure that the exponential coefficient and power are appropriate to [7] data see Table I When the chart revealed that SL as function Frm suggested by [5] is accurately presenting the data in [7], the following analysis may proceed.

TABLE I: ALRUHAIMANI,2015 DATA INFORMATION

DATA	FLUIDS	PIPE DEGREE	PIPE DIA (M)	FLOW PATTERN
Alruhaimani, 2015 [7]	Oil and Air	90	0.0508	Various pattern

As a result, Vg (Vsg superficial gas velocity divided by Void fraction) will be plotted against Vm mixture velocity, and the linear relationship will be used to examine the slope and y-intercept. Moreover, the slope is equal to ***C0*** divided by the void fraction, and the y-intercept is equal to Vd drift velocity divided by the square root of the pipe diameter multiplied by the gravity acceleration. This technique will provide a new correlation in (eq.9) for the drift flux method and will be used to validate the improved model on additional experimental data.

$$\boldsymbol{V_{sg} = Y_g\left(1.577V_m + 0.147\sqrt{gD}\right)} \quad (9)$$

The drift flux correlation will next be compared to the experimental findings of [7] data, where there are 9 correlations in addition to the newly improved correlation from (eq.9) [7]. The bubbly flow was selected to eliminate the influence of flow patterns on the study. This technique allows us to compare [7] data and findings to other methodologies and outcomes and discover limits. Zukoski 1966 [8], Benjamin 1968 [9], Weber 1981 [10], and Ben-Mansour et al. 2010 [11] provide further information on drift velocity in table II, and the distribution coefficient has been set to 1.2 based on [2] ***C0*** value in bubbly flow. In order to determine the inaccuracy of each correlation, we will compare the value of Vsg predicted by the 10 correlations listed in table II to the value of Vsg obtained experimentally.

TABLE II: DRIFT FLUX CORRELATIONS

DATA	CORRELATION	LIMITS
Hasan and Kabir, 1990 [3] [eq.10]	$V_{sg} = Y_g\left(1.2V_m + V_\infty(1-Y_g)^2\right)(10)$ $V_\infty = 1.53\left[\frac{g\sigma(\rho_l-\rho_g)}{\rho_l^2}\right]^{0.25}$	BUBBLY FLOW
Wu et al., 1992 [12] [eq.11]	$V_{sg} = Y_g\left(1.08V_m + 0.9412V_\infty(1-Y_g)^2\right)(11)$ $V_\infty = 1.53\left[\frac{g\sigma(\rho_l-\rho_g)}{\rho_l^2}\right]^{0.25}$	BUBBLY FLOW
Flores, 1997 [8] [eq.12]	$V_{sg} = Y_g\left(1.04V_m + V_\infty(1-Y_g)^{2.5}\right)(12)$ $V_\infty = 1.53\left[\frac{g\sigma(\rho_l-\rho_g)}{\rho_l^2}\right]^{0.25}$	BUBBLY FLOW
Han et al., 2017 [14] [eq.13]	$V_{sg} = Y_g\left(1.038V_m + 0.142(1-Y_g)^{2.5}\right)(13)$	BUBBLY FLOW
Hao Qin et al, 2022 [15] [eq.14]	$V_{sg} = Y_g\left(0.8459V_m + 0.9085V_\infty(1-Y_g)^2\right)(14)$ $V_\infty = 1.53\left[\frac{g\sigma(\rho_l-\rho_g)}{\rho_l^2}\right]^{0.25}$	BUBBLY FLOW
Zukoski, 1966 [8] [eq.15]	$V_{sg} = Y_g\left(1.2V_m + 0.351\sqrt{gD}\right)(15)$	INCLINED PIPE
Benjamin, 1968 [9] [eq.16]	$V_{sg} = Y_g\left(1.2V_m + 0.542\sqrt{gD}\right)(16)$	HORIZONTAL PIPE
Weber, 1981 [10][16] [eq.17]	$v_d/\sqrt{gD} = 0.54 - 1.76Eo^{-0.56}$, Eotvos number $Eo = \rho_g D^2 g/\sigma$ $V_{sg} = Y_g(1.2V_m + V_d)(17)$	HORIZONTAL PIPE
Ben-Mansour et al., 2010 [11] [eq.18]	$Fr = \frac{v_d}{\sqrt{gD}}, N_\mu = \frac{\mu}{\rho D^{\frac{3}{2}} g^{\frac{1}{2}}}, Eo = \frac{\rho D^2 g}{\sigma}$ $Fr = 0.53e^{-13.7N_\mu{}^{0.46}Eo^{-0.1}}$ $V_{sg} = Y_g(1.2V_m + V_d)(18)$	HORIZONTAL PIPE
Improved model from [7] [eq.9]	$V_{sg} = Y_g\left(1.577V_m + 0.147\sqrt{gD}\right)(9)$	VERTICAL PIPE

Where, Vsg is the light fluid superficial velocity, Yg is the void fraction, Vm the mixture velocity, Eo is Evote's number, Nm is the viscosity number, Vinf is the terminal rise velocity of bubbles for oil-water bubble flow the ,g is the gravity acceleration and D is the internal pipe diameter.Following the validation of the Relation between SL and Frm, void fraction can be calculated using Alsarkhi correlation [eq.7] and the SL fundamental equation [Eq.8] with knowing the gas superficial velocity, pipe diameter, liquid and gas densities . This method is convenient since Frm is a function of mixture velocity, which can be readily seen in practice. The void fraction that found by the SL/Frm relation was tested using the bubbly flow obtained from three different sets of experimental data, as shown in table III. Moreover, the data was investigated and analyzed, along with Zukoski 1966 [8], Benjamin 1968 [9], Weber 1981 [10], and Ben-Mansour et al. 2010 [11] and Alruhaimani 2015 [7] most recent model found in table II (eq.9). By comparing the void fraction that was calculated by utilizing the correlations to the void fraction that was determined by using the SL, the new method to find void fraction using the SL/Frm relation can be proved. This methodology will demonstrate not only the areas in which the improved SL/Frm relationship grow well, but also the areas in which it falls short. As indicated in table III, this novel technique of determining void fraction will be tested on Sunil Kokal (1987) [17], Abduvayt (2003) [18], and Ovadia Shoham (1982) [19] with varied angles, flowing fluids, and pipe diameters. The correlations that employ the void fraction to calculate drift velocity will not be used in this data analysis since the void fraction is not given experimentally. As a result, these data will be evaluated by Zukoski 1966 [8], Benjamin 1968 [9], Weber 1981 [10], and Ben-Mansour et al. 2010 [11] and Alruhaimani 2015 [7] correlations.

TABLE III: BUBBLY FLOW DATA

DATA	FLUIDS	PIPE DEGREE	PIPE DIA (M)	FLOW PATTERN
SUNIL KOKAL, 1987 [17]	OIL AIR	-90 TO 90	0.0512 AND 0.0258	DISPERSED BUBBLY
ABDUVAYT, 2003 [18]	WATER NITROGEN	0 TO 30	0.1064 AND 0.0549	DISPERSED BUBBLY
OVADIA SHOHAM, 1982 [19]	WATER AIR	-90 TO 90	0.051 AND 0.025	DISPERSED BUBBLY

III. RESULTS AND DISCUSSIONS

Using [7] data, and by calculating the required variables for SL in (eq.5), such as homogenous density, and plot it as a function of Frm to examine the coefficient and power factor of the relationship between SL and Frm presented by [5]. The plot revealed virtually comparable coefficient values and the same power value as seen in figure 4 and (eq.7). Furthermore, to improve a new drift flux correlation derived from [7] data as in [eq.9] the experimental superficial gas velocity will be divided by the experimental void fraction to obtain the real gas velocity,

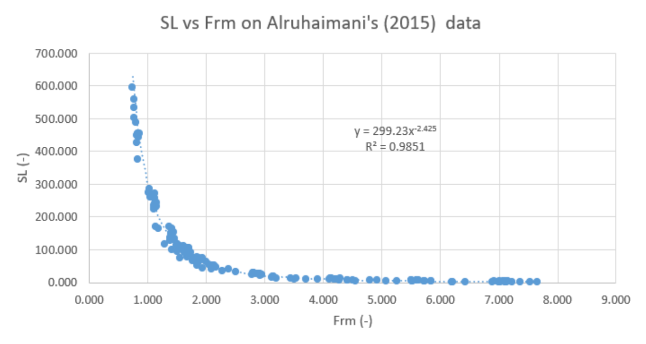

Fig. 4 Slippage Number versus mixture Froude number based on data [7].

which will be plotted with the mixture velocity, whose value is the sum of the experimental superficial gas velocity and the superficial liquid velocity. According to Figure 5, the slope is 0.7002, hence Co is 1.577 on average . Moreover, the drift velocity is 0.147 multiplied by the square root of the pipe diameter multiplied by the gravitational acceleration. As a result, we arrive to the improved model from [7] data in [eq.9].

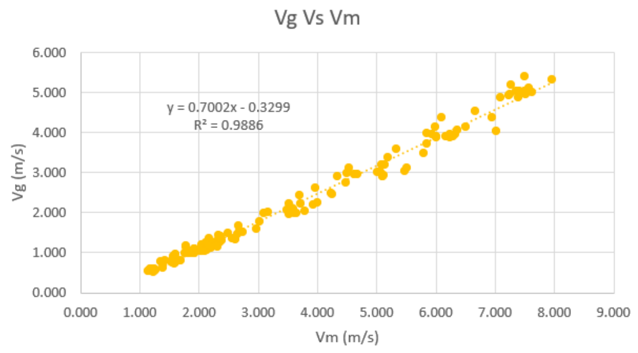

Fig.5 Real gas velocity Vs mixture velocity based on [7] data.

The below behavior in figure 6 indicates the limitation and the applicability of [7] data to add value on both the SL/Frm relation found from this data and the new correlation developed in (eq.9) from this data and is the result of incorporating the 10 correlations in table II it to predict Vsg and plot it versus experimental Vsg. The figure 6 and table IV demonstrate that Hasan and Kabir (1990) [7], Wu et al. (1992)[12], Flores (1997) [8], Han et al. (2017) [14], and Hao Qin (2022) [15] have greater error values, where they all have drift velocity as a function of void fraction in common.The other correlations, on the other hand, have significantly less inaccuracy since they were established in settings other than Alruhaimani's (2015) data [7], such as Benjamin (1968) [9] developed on horizontal pipe. This demonstrates the high quality of Alruhaimani's (2015) data [3], which supports both the theorized SL/Frm relationship by Abdelsalam, 2016 [5] and the newly established correlation using Alruhaimani's (2015) data [7]. In addition the average relative error (ARE) is a statistic used to evaluate how close the calculated values are to the actual ones and E2 is the standard deviation [eq.19] ARE and [eq.20] E2 respectively below. Basied on both error methods the correlations predicted Vsg can be compared to the experimental Vsg.

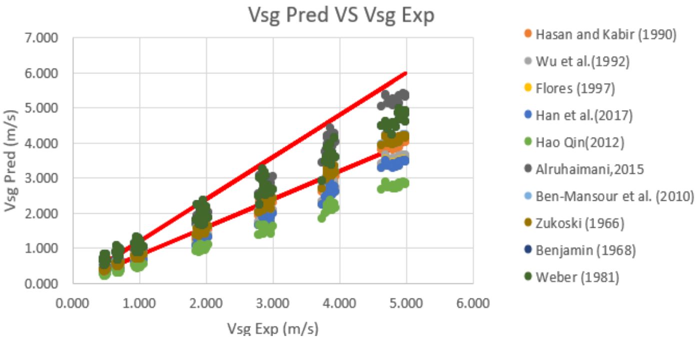

Fig. 6 Predicted superficial gas velocity Vs experimental superficial gas velocity based on Alruhaimani's (2015) data [7].

$$ARE = \frac{1}{n}\sum_{i=1}^{n} e_i \quad (19) \qquad E_2 = \sqrt{\frac{\sum_1^n (e_i - \bar{E})^2}{n}} \quad (20)$$

TABLE IV: CORRELATIONS ERROR APPLIED ON ALRUHAIMANI'S (2015) DATA [7]

DATA	ARE%	E2%
Hasan and Kabir, 1990 [3]	-18.565	0.815
Wu et al., 1992 [12]	-23.323	0.733
Flores, 1997 [8]	-25.250	0.706
Han et al., 2017 [14]	-26.151	0.706
Hao Qin et al, 2022 [15]	-32.415	0.574
Zukoski, 1966 [8]	-14.323	0.836
Benjamin, 1968 [9]	-10.745	0.846
Weber, 1981 [10][16]	8.999	0.897
Ben-Mansour et al., 2010 [11]	-13.622	0.839
Improved model Alruhaimani,2015 [7]	-3.627	1.084

Using Zukoski 1966 [8], Benjamin 1968 [9], Weber 1981 [10], and Ben-Mansour et al. 2010 [11] and Alruhaimani 2015 [7] correlations on table III data with the flow pattern fixed as

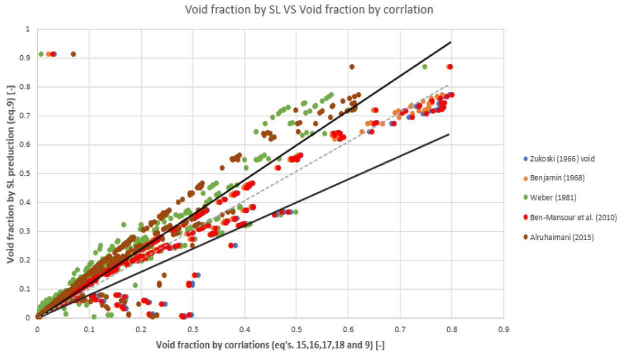

Fig. 7 Void fraction by SL prediction [eq.8] Vs Void fraction by correlations Table II.

bubbly flow and varying the pipe diameter and angle with varying the flowing fluids will show where are the limitations in finding the void fraction using SL and the relationship found by [7] data . The void fraction discovered by SL is displayed versus the void fraction discovered by the relations in table II. Figure 7 demonstrates that all five correlations with the precise behavior where void fraction values predicted by the SL/Frm relation are considerably close to each other with 2 areas showing the discrepancy in the correlations values: 1- The region of Abduvayt's data [18] water/nitrogen flow, where the high density of nitrogen compared to the air is effecting the SL/Frm relation derived from [7] data which is oil /air based mading the assumption of the proposed SL week in this area. 2- Two data points from Ovadia Shoham (1982) [19] in which the values of superficial liquid velocity fluctuate little in comparison to the entire data, indicating the influence of low superficial liquid velocity.

Table V displays that all correlations have close and acceptable values, with the exception of Weber (1981) [10], which is restricted to only the horizontal flow and requires a specific procedure of find void fraction. Despite this limit, the error is not particularly large in comparison to the remaining correlations, and its behavior is identical.

TABLE V: CORRELATIONS ERROR IN [7] DATA

DATA	ARE%	E2%
ZUKOSKI, 1966 [8]	-12.352	3.505
BENJAMIN, 1968 [9]	-9.566	3.440
WEBER, 1981 [10][16]	20.053	1.736
BEN-MANSOUR ET AL., 2010 [11]	-11.417	3.449
ALRUHAIMANI,2015 [7]	11.628	2.731

Figure 8 illustrates the frequency of the SL values in the bubbly flow. Moreover, this figure demonstrated that the SL in bubbly flow may range anywhere from 0.02 to 41 in general, although it is most often found in the range of 0.02 to 7 according to 80% of the data.

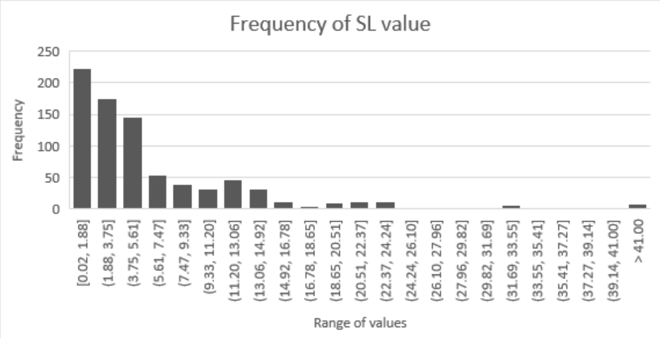

Fig. 8 Frequency of SL values in bubbly flow data.

IV. CONCLUSIONS

To summarize, according to [5] proposal generated and supported in this paper using Alruhaimani's (2015) data [7], the SL is exponentially connected to Frm in the form of $\boldsymbol{SL = A\,Frm^{B}}$, where A and B equal 300 and -2.475, respectively. Novel correlation discovered and refined using [7] data , verified against experimental data, and shown excellent applicability for all flow patterns but only on vertical flow where **C0= 1.577** and **Vd=** $\boldsymbol{0.147\sqrt{gD}}$. Moreover, utilizing the bubbly flow data from the trials in table 3 involving varied pipe diameter and angle, as well as different flowing fluids, provided a clearer picture of the applicability of the SL approach to predict void fraction. As a result, the SL/Frm relationship was constructed using [7] data, where the flowing fluids are water/air and the pipe angle is 90 degrees showed good in oil/air and water/air data with different pipe conditions. The investigation revealed that the SL/Frm relationship produces poor results in the water/nitrogen region and at low superficial liquid velocity locations. As a result, SL is unaffected by pipe diameter and angle, but is impacted by fluid density and flow pattern. In this work, a strong SL/Frm connection was verified and accepted in water/air bubbly flow applications, as well as a novel technique of determining void fraction using only quantifiable factors such as mixture velocity, superficial gas velocity, pipe diameter, and fluid density. By generalizing this technique to incorporate flow patterns and fluid density effects, we can analyze any gas-liquid flow and predict the void fraction and flow patterns. This paper shows that the SL for bubbly flow is often found between 0.02 and 7. As a result, once the SL/Frm relation includes the density impact, the flow pattern can be predicted using the SL/Frm relation as well as the void fraction.

ACKNOWLEDGMENT

King Fahd University of Petroleum and Minerals are to be appreciated for providing us with the opportunity and support we need.

REFERENCES

[1] Fran, F., & Lahey Jr, R. T. (1992). THE USE OF DRIFT-FLUX TECHNIQUES FOR THE ANALYSIS OF HORIZONTAL TWO-PHASE FLOWS. In Int. J. Multiphase Flow (Vol. 18, Issue 6).

[2] Zuber, N., Findley, J., 1965. Average volumetric concentration in two-phase flow systems. J. Heat Transfer 87, 453–468.

[3] Hasan A.R., Kabir C.S., 1990. A New Model for Two-Phase Oil/Water Flow: Production Log Interpretation and Tubular Calculations. SPE Production Engineering. 5(2), 193-199. https://doi.org/10.2118/18216-PA.

[4] Shi, H., Holmes, J., GeoQuest, S., Durlofsky, L., Etc, C., Aziz, K., Diaz, L., Alkaya, B., & Oddie, G. (2005). Drift-Flux Modeling of Two-Phase Flow in Wellbores. http://onepetro.org/SJ/article-pdf/10/01/24/2124951/spe-84228-pa.pdf.

[5] Abdelsalam, A., Cem, S., & Eduardo, P. (2016). New dimensionless number for gas-liquid flow in pipes. International Journal of Multiphase Flow, 81, 15–19. https://doi.org/10.1016/j.ijmultiphaseflow.2015.12.

[6] Faghri, A. and Zhang, Y. (2006), Transport Phenomena in Multiphase Systems, Elsevier, 1st Edition, ISBN: 1123706106, 855 pp.

[7] Alruhaimani, F.A., 2015. Experimental Analysis and Theoretical Modeling of High Liquid Viscosity Two-Phase Upward Vertical Pipe Flow. The University of Tulsa Ph.D. Dissertation.\

[8] Zukoski, E.E. 1966. Influence of viscosity, surface tension, and inclination angle on motion of long bubbles in closed tubes. J. Fluid Mech. 25 (4): 821–837. DOI: 10.1017/S0022112066000442.

[9] Benjamin, T. B., 1968. Gravity Currents and Related Phenomena, J. Fluid. Mech. 31, Part 2, 209-248.

[10] Weber, M.E., Alarie, A., and Ryan, M. E., 1986. Velocities of Extended Bubbles in Inclined Tubes," Chem. Eng. Sci. 41, 2235-2240.

[11] Ben-Mansour, A. Sharma, B. Jeyachandra, B. Gokcal, A. Al-sarkhi, C. Sarica, 2010. Effect of Pipe diameter and high oil viscosity on drift velocity for horizontal pipes, 7th North American Conference on Multiphase Technology, Banff, Canada-2nd -4th June.

[12] Wu, X.L., Wang, L., Tang, K.N, Shi, X.L., 1992. Two-phase Flow Interpretation Model for Production Log. WLT. 16(5), 381-388. https://doi.org/10.16489/j.issn.1004-1338.1992.05.016.

[13] Flores, J.G., 1997. Oil-water flow in vertical and deviated wells. The university of Tulsa. Thesis of Doctor of philosophy.

[14] Han, Y. F., Jin, N.D., Zhai, L.S., Zhang, H.X., Ren, Y.Y., 2017. Flow pattern and holdup phenomena of low velocity oil-water flows in a vertical upward small diameter pipe. Journal of Petroleum Science and Engineering. 159, 387-408. https://doi.org/10.1016/j.petrol.2017.09.052.

[15] Hao Qin , Jinbin Wan , Chaowei Duan , Chunlei Liu , Yuxi Qin , Xin Liu Yubo Liu. An improved drift-flux model for oil-water two-phase flow in vertical large-diameter pipes with low flowrate and high water holdup. Journal of Petroleum Exploration and Production Technology. (2022)

[16] Weber, M.E., 1981. Drift in Intermittent Two-Phase Flow in Horizontal Pipes, Can. J. Chem. Eng.59, 398-399.

[17] Kokal, S. L. (1987). An Experimental study of two phase flow in inclined pipes (Unpublished doctoral thesis). University of Calgary, Calgary, AB. doi:10.11575/PRISM/14066.

[18] Abduvayt, P., Manabe, R., and N. Arihara. "Effects of Pressure and Pipe Diameter on Gas-Liquid Two-Phase Flow Behavior in Pipelines." Paper presented at the SPE Annual Technical Conference and Exhibition, Denver, Colorado, October 2003. doi: https://doi.org/10.2118/84229-MS.

[19] Barnea D, Shoham O, Taitel Y, Flow pattern transition for downward inclined two phase flow; horizontal to vertical Chemical Engineering Science, 1982.

Symbol	**Description**
SL	Slippage Dimensionless Number
Vsg	superficial Gas Velocity
Vsl	superficial Liquid Velocity
Vm	Mixture Velocity
Vg	Gas Velocity
Vslip	Slip Velocity
Vl	Liquid Velocity
ρG	Gas density
ρL	Liquid density
ρH	Homogenous density
ρTP	Two phase density
α or Yg	Void Fraction
γL	Homogenous Liquid Hold Up
Co	Distribution Coefficient
Re	Reynolds Number
Frm	Froud Mixture Number
Frslip	Froud Slip Number
Frsg	Froud superficial Gas Number
V_∞	Terminal rise velocity of bubble
SVR	Superficial Velocity Ratio