

GAS-LIQUID FLOW VOID FRACTION PHASE PATTERN IDENTIFICATION USING SLIPPAGE NUMBER

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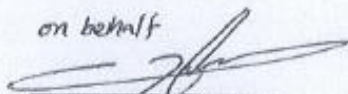
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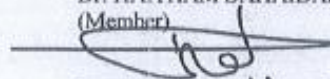
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[To my Parents for their support and trust]

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Abstract

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The characterization and modeling of multi-phase flow is a complex scientific and engineering phenomenon that involves numerous interrelated variables. The introduction of a novel dimensionless parameter for comprehending gas-liquid flow is regarded as a significant advancement toward managing and enhancing the field of multiphase flow. The dimensionless parameter known as Slippage number (SL) was first introduced in literature [1]. It is defined as the ratio between the difference in gravitational forces under slip and no-slip conditions and the inertial force of the gas. Empirical evidence suggests that there is a correlation between Froud mixture number (Frm) and SL, based on a comprehensive dataset. The relationship between SL and Frm yields a single, coherent curve that can be used to understand the dynamics of the gas-liquid flow. This study establishes a numerical correlation between SL and three variables and subsequently verifies the empirical relationship between SL and these new variables through vertical gas-liquid flow experimentation [2]. The utilization of slip velocity (V_{slip}), Frm (Froud mixture number), and a newly introduced dimensionless parameter Froud slip number (Frslip) have enabled the functionalization of SL. Nevertheless, all the relationships have demonstrated identical patterns with SL, exhibiting almost identical behavior as depicted in reference [1]. The parameters V_{slip} , Frm, and Frslip have been obtained through the utilization of fluid condition properties, geometric properties, and experimental data. This process has contributed to the enhancement of the SL, thereby facilitating the identification of flow patterns and void fractions. The present study establishes a quantitative correlation between the SL and Froud mixing numbers in the context of vertical gas-liquid flow and on 2412 experimental data from ten different experimental published researches with various pipe diameters, pipe angles, and fluids properties. Subsequently, the proposed relationship is employed to verify its usefulness in practice. The experimental data have been utilized to generate an enhanced correlation within the drift flux model, and its validity has been confirmed. This thesis presents a methodology for predicting the void fraction in bubbly and annular flow, utilizing the SL/Frm relation. The limitations of this approach are also discussed, along with potential avenues for further research and development.

ملخص الرسالة

الاسم الكامل: جابر مسعود اليامي

عنوان الرسالة: تحديد نمط تدفق الغاز مع السائل ونسبة الغاز باستخدام رقم الانزلاق

التخصص: هندسة موانع وحرارة

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يعد انتقال الغاز والسائل معاً ظاهرة علمية وهندسية معقدة تتضمن العديد من المتغيرات المترابطة مما يجعل إيجاد رقم بدون أبعاد لفهم تدفقها بمثابة تقدم كبير نحو نمذجة وفهم هذا النوع المعقد من التدفق. تم تقديم الرقم بدون الأبعاد (رقم الانزلاق) لأول مرة في المرجع [1]. يتم تعريفه على أنه النسبة بين الفرق في قوى الجاذبية SL المعروف باسم تحت ظروف الانزلاق وعدم الانزلاق على قوة القصور الذاتي للغاز. تشير الأدلة التجريبية إلى وجود علاقة بين رقم منحنى Frم و SL ، بناءً على مجموعة بيانات شاملة. تنتج العلاقة بين SL و Froude (رقم خليط Frم) فرويد وثلاثة SL واحدًا متماسكًا يمكن استخدامه لفهم ديناميكيات تدفق الغاز والسائل. هذه الدراسة تعطي ارتباطاً عددياً بين وهذه المتغيرات الجديدة من خلال تجربة التدفق الرأسي للغاز SL متغيرات ثم تتحقق من العلاقة التجريبية بين (، و الرقم بدون Froude (رقم خليط Frم (سرعة الانزلاق) ، و Vslip و SL والسائل في المرجع [2]. العلاقة بين (وجدت وتم شرحها في هذه الدراسة وأظهرت جميع العلاقات أنماطاً متطابقة Froude (رقم انزلاق Frslip الأبعاد بأنها تعتمد فقط Frslip و Frم و Vslip السلوك و متماثلة تقريباً مع الموضح في المرجع [1]. تتميز المتغيرات على خصائص المائع والخصائص الهندسية للأنابيب والبيانات التجريبية التي يمكن معرفتها. تحدد الدراسة الحالية في سياق التدفق الرأسي للغاز والسائل وعلى 2412 من البيانات التجريبية من Froude و SL ارتباطاً كمياً بين أرقام عشرة أبحاث تجريبية مختلفة بأقطار أنابيب ، زوايا أنابيب وصفات موائع مختلفة. في هذه الدراسة تم الاعتماد على لإيجاد سرعة انتقال الغاز في التدفق ومقارنتها بعشرة علاقات مطروحة في 10 دراسات مختلفة. SL / Frم علاقة تم استخدام البيانات التجريبية لإنشاء علاقة جديدة لإيجاد سرعة الغاز داخل نموذج التدفق، وتم تأكيد صحتها. تقدم هذه وتم مناقشة قيود هذا SL / Frم الأطروحة منهجية للتنبؤ بنسبة الغاز في التدفق الفقاعي والحلقي، باستخدام علاقة النهج أيضاً ، جنباً إلى جنب مع السبل المحتملة لمزيد من البحث والتطوير.

NOMENCLATURE

Symbol	Description
SL	Slippage Dimensionless Number
V_{sg}	superficial Gas Velocity
V_{sl}	superficial Liquid Velocity
V_m	Mixture Velocity
V_g	Gas Velocity
V_{slip}	Slip Velocity
V_l	Liquid Velocity
ρ_G	Gas density
ρ_L	Liquid density
ρ_H	Homogenous density
ρ_{TP}	Two phase density
α or Y_g	Void Fraction
γL	Homogenous Liquid Hold Up
Co	Distribution Coefficient
Re	Reynolds Number
F_{rm}	Froud Mixture Number
F_{rslip}	Froud Slip Number
F_{rsg}	Froud superficial Gas Number
V_{∞}	Terminal rise velocity of bubble
SVR	Superficial Velocity Ratio

CHAPTER 1: INTRODUCTION

1.1 Description

In fluid mechanics, multiphase flow pertains to the simultaneous movement of multiple fluid phases. The utilization of multiphase flow is prevalent in diverse processing technologies, ranging from cavitating pumps and turbines to the production of paper and plastics. Frequent occurrences of the phenomenon above are also observed in the natural world. The previously mentioned transitions may comprise a solitary chemical fluid, such as water and water vapor, or multiple fluid, such as oil and water. A phase is considered continuous if it is present in a spatial region that exhibits uninterrupted flow. Conversely, if the phase is not present in such a region, it is referred to as dispersed. The continuous phase can include either gases or liquids. The type of dispersal phase, whether it is in solid, liquid, or gas form, is at the discretion of the individual. Industrial applications such as power plants, nuclear reactors, boilers, gas well drilling, and so on have been interested in pipes two-phase flow (liquid and gas). As a result of the geometric distribution of the components inside the fluid flow, numerous flow regimes or patterns are met in vertical and horizontal flows [3]. The mass, momentum, and energy transfer rates of the fluid are all affected by this geometric distribution.

1.2 Vertical flow

The well-known flow patterns displayed by flow in vertical pipes are bubbly, slug or plug, churn, annular, and wispy-annular flow, as seen in Fig. 1 below [4].

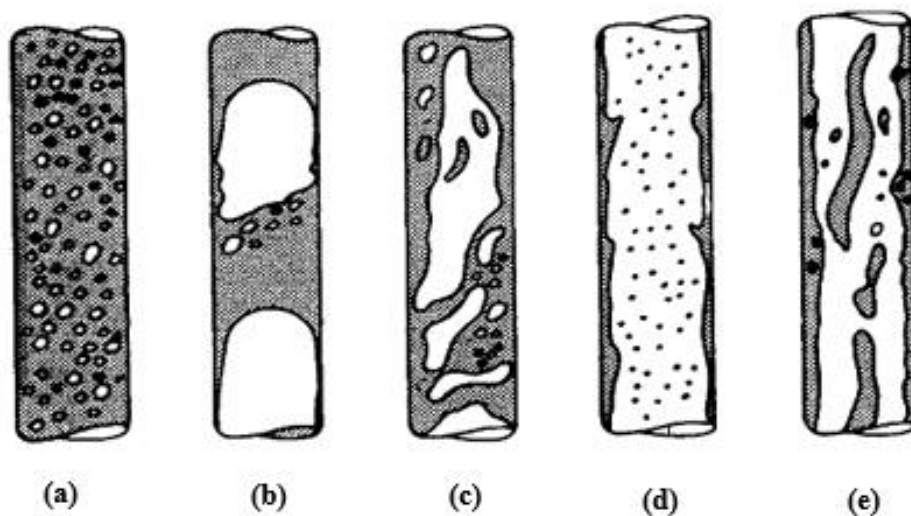


Fig. 1 Flow Regimes in Vertical Upward Two-Phase [4]

1.2.1 Bubbly Flow

Several bubbles are visibly scattered in a continuous liquid phase as distinct bubbles of assorted sizes and forms in bubbly flow, as seen in Fig. 1a. The bubbles are practically spherical in shape and have diameters significantly smaller than the pipes.

1.2.2 Slug Flow

In an upward flow, increasing the gas void percentage leads the bubbles to collide and combine, resulting in bigger bubbles, frequently in the shape of a bullet (Taylor bubbles), as seen in Fig. 1b. Slug flow is the name for this type of flow. Liquid slugs, which may have some tiny bubbles, generally divide the Taylor bubbles. The bubbles are practically the same diameter as the pipe. Between the Taylor bubbles and the pipe wall is a thin liquid layer that might flow downhill under gravity's effect. [5]

1.2.3 Churn Flow

It's a flow regime that exists halfway between slug flow and annular flow. The flow becomes increasingly unstable when the gas's superficial velocity is raised owing to the breaking up of the slug bubbles, resulting in oscillatory action, as seen in Fig. 1c. Due to the relative balance between shear and gravity acting in opposite directions; the liquid phase tends to have an intermittent and up and down flow (albeit there is a net upward flow). Following the description of churn flow, it must be avoided in practice since it can destroy the transportation system (pipes). [5]

1.2.4 Annular Flow

This sort of flow, seen in Fig. 1d, produces a flow pattern with a liquid coating on the pipe sides and a continuous stream of gas in the pipe's center. The liquid layer creates an annular ring around the gas stream as a result. This flow happens as the gas flow rate is increased further. Gas bubbles may or may not be present in the liquid film. Similarly, entrained liquid droplets may or may not be present in the gas stream [5].

1.2.5 Wispy Annular Flow

As the flow rate is increased, the number of entrained droplets in the gas phase increases. As a result, they clump together in the gas core, forming huge lumps or 'wisps' of liquid. See Fig. 1e for further information. [5]

1.2.6 Flow pattern maps

Researchers displayed several empirical maps depicting varied flow patterns. Hewitt and Roberts (1969) created a flow regime map (see Fig. 2) for a 3 cm diameter tube [6]. It was

evaluated for both water/air and water/steam flow at atmospheric pressure and high pressure. The flow patterns mentioned above are quite helpful in classifying the several types of interfacial distribution found in the fluid flow medium [5]. As a result, modeling such a flow becomes easier since a degree of constraint has been applied. Because this study.[6]

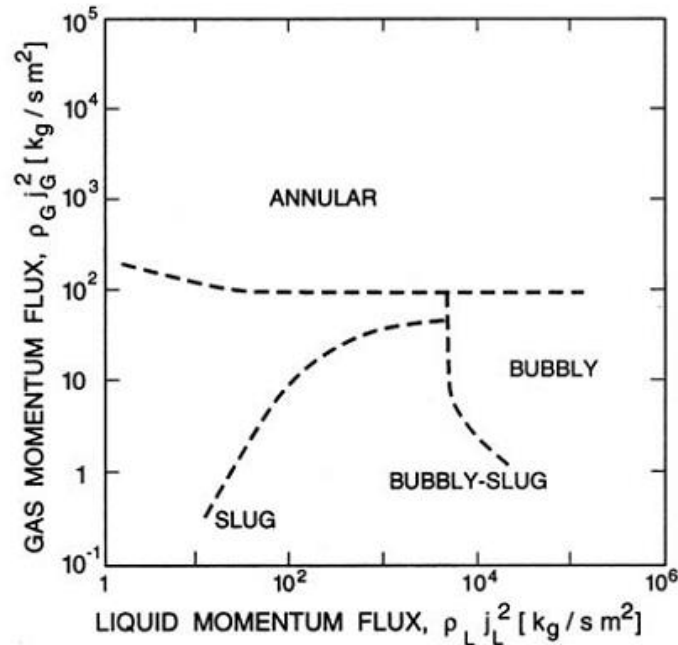


Fig. 2 Vertical Flow Regime Map [6]

1.3 Horizontal Flow

The famous flow pattern presented by flow through horizontal pipes, as shown in Fig. 1 below include, bubbly, slug or plug, churn, annular and stratified flow [7] Where the horizontal flow patterns are widely known in the oil and gas industry with several applications.

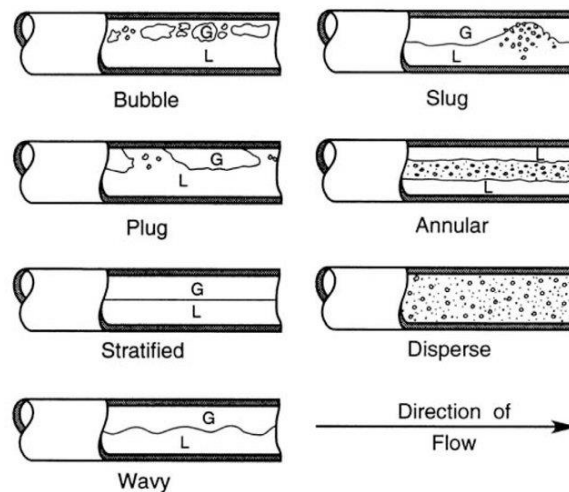


Fig. 3 Flow Regimes in Horizontal Two-Phase [7]

Such as oil pipelines, well oil production, reservoir management, water ,oil gas separation plants.

1.3.1 Bubbly Flow

Bubble flow is a two-phase movement in which little bubbles are scattered or suspended in a liquid continuum as separate entities. Moving and deformable bubble interfaces in time and space domains, as well as complex interactions between the interfaces and between the bubbles and the liquid flow, are typical aspects of this flow. [7]

1.3.2 Slug Flow

Slug Flow is a common two-phase flow in which a wave is picked up occasionally by swiftly flowing gas, forming a frothy slug that travels faster than the normal liquid velocity. [7]

1.3.3 Plug Flow

The plugs are also known as elongated bubbles in horizontal pipelines. The bubbles in plug flow are smaller and travel more slowly than those in slug flow. [7]

1.3.4 Annular Flow

The lighter fluid travels through the middle of the pipe, while the heavier fluid is confined in a thin layer on the pipe wall. [7]

1.3.5 Stratified Flow

When gas and liquid travel in a pipe, certain situations exist where a continuous interface separates the two phases. The gravity force dominates such a flow, causing the liquid to remain at the pipe's bottom. This flow pattern may be seen in pipes the horizontal or sloped pipe structure of the interface's structure, which can be smooth or wavy depending on the gas flow velocity. [7]

1.3.6 Dispersed Flow

The flow in which one phase is diffused in the other continuous phase is known as dispersed flow. This flow arrangement may be found in all forms of two-phase flows (gas-liquid, gas-solid, liquid-liquid, and liquid-solid). Because solid particles never merge with each other in Gas-Solid and Liquid-Solid Flows, the scattered phase is always in solid phase. In Gas-Liquid and Liquid-Liquid Flows, on the other hand, because the interface between the two phases is deformable, the dispersed phase is primarily decided by the flow rates of both phases, and the dispersed phase coalesces and eventually becomes the continuous phase as the flow rate increases. When the gas flow rate is low compared to the liquid flow rate, for

example, the gas phase disperses. When the liquid flow rate is low relative to the gas flow rate, the liquid phase is scattered.

1.3.7 Wavy Flow

Waves arise at the surface between liquid and gas or vapor in a stratified two-phase fluid flow in a horizontal pipe. This kind of fluid flow pattern develops when the surface velocities of the vapor or gas and the liquid differ significantly enough to induce waves. [7]

1.3.8 Flow pattern map

The flow patterns described above are extremely useful in that they help classify the various kinds of interfacial distribution seen in the fluid flow medium (Mandhane, ,1974). Hence modelling such a flow becomes easier since a degree of constraint has been introduced. Fig. 4 depicts the planned flow pattern map. The transition boundaries for the air-water system were principally determined using a log VSL vs. log VSG plot of the 1178 flow pattern data.

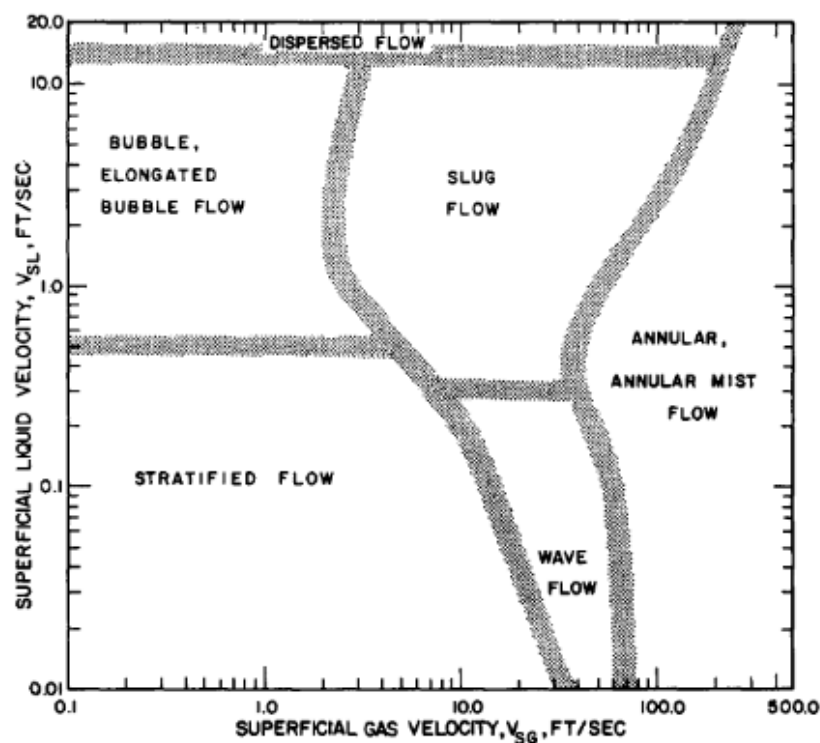


Fig. 4 Horizontal Flow Regime Map [8]

1.4 Inclined Flow

In the context of multiphase flow, it is possible to estimate liquid hold up, pressure drop, and other relevant parameters with a relatively high degree of certainty under conditions of steady-state horizontal flow. However, in the case of inclined pipes, the calculations for liquid hold up and pressure drop become somewhat more complex. According to a study

conducted by Grolman in 1997, the angles of inclination have a significant impact on the liquid holdup and pressure gradient, particularly in the low gas velocity range. The minimum gas flow rate needed for steady-state operation is determined by a critical operating limit, which ensures that liquid can be effectively transported out of lower locations within pipeline systems. Elevated throughput levels have been seen to cause intermittent pipe blockages and disproportionate liquid production at reduced gas flow rates. Figures 5 and 6 depict the holdup, pressure gradient, and wet wall fraction resulting from inclined gas-liquid pipe flow in comparison to those obtained from horizontal flow. The figures demonstrate that minor angles of inclination exert a noteworthy impact, particularly in the lower limits of gas velocities on the surface. The curves were generated through modeling for seven distinct inclination angles (-3, -1, 0, 0.25, 0.5, 1.0, and 3.0) while maintaining a consistent liquid flow rate of 0.25 mL/s. [9]

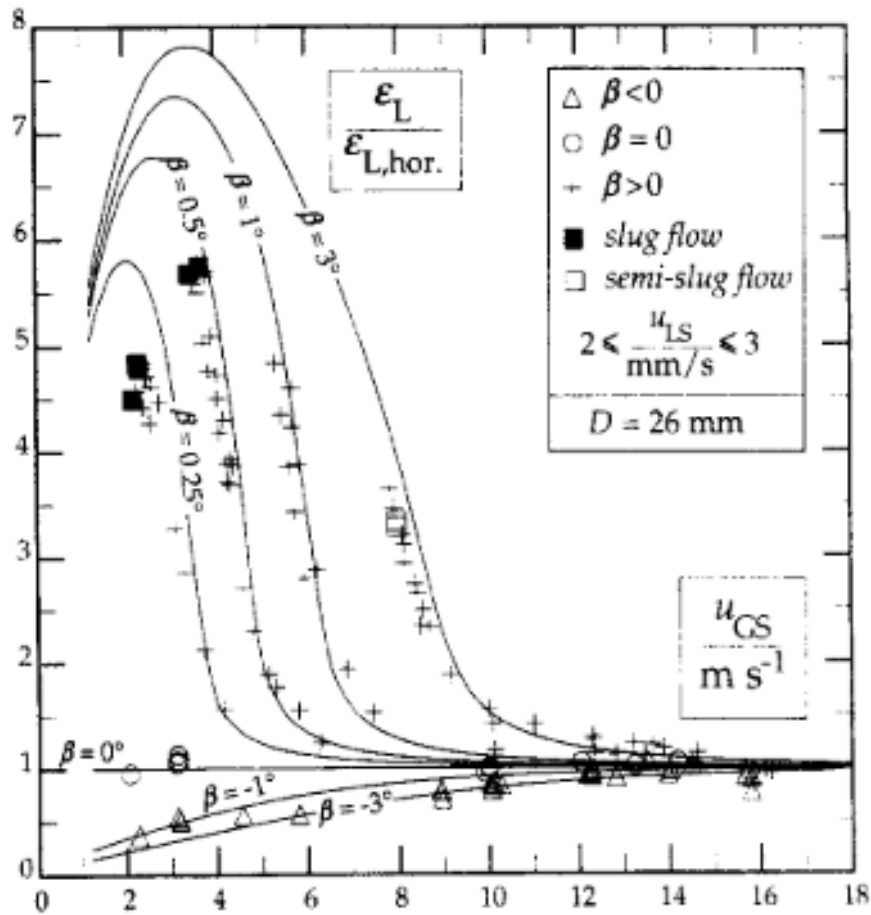


Fig. 5 Inclination effect on the liquid hold up [9]

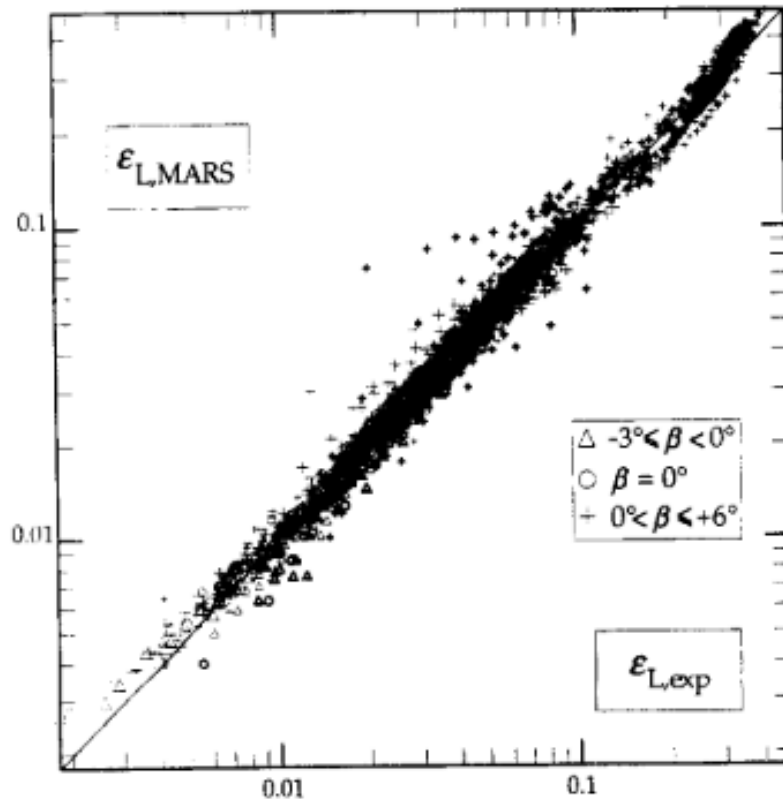


Fig. 6 calculated hold up Vs experimental hold up [9]

CHAPTER 2: LITERATURE REVIEW

2.1 Slippage effect on Gas-Liquid flow

In many published cases the slip ratio (gas velocity / liquid velocity) is considered to be unity following the homogeneous equilibrium model (HEM) of two-phase flow (there is no slip). Most practical and real cases of two-phase flows, on the other hand, have a significant difference in the velocity of the gas and liquid phases. Then Separated flow models will be followed that account for the existence of the slip. It is more convenient to use the flow quality rather than the static quality in two-phase fluid flow. In a two-phase fluid flow, flow quality is defined as: the ratio between the gas mass rate and the mixture mass rate. [9]

where:

S – slip ratio, dimensionless

v – velocity, m/s

V – superficial velocity m/s

α – void fraction, dimensionless

ρ – density of a phase, kg/m³

x – steam quality, dimensionless.

$$S = \frac{v_v}{v_l} = \frac{V_v \cdot (1-\alpha)}{V_l \cdot \alpha} = \frac{\rho_l \cdot x \cdot (1-\alpha)}{\rho_v \cdot \alpha \cdot (1-x)} \quad (1)$$

$$x \equiv \frac{\dot{m}_v}{\dot{m}_v + \dot{m}_l} = \frac{v_v A_v \rho_v}{v_v A_v \rho_v + v_l A_l \rho_l} \quad (2)$$

Slip ratio influences the void fraction flow quality relation as in fig.8. whereby increasing the slip ratio, the void fraction decreases as function of flow quality. Moreover, there are several correlations for the slip ratio and void fraction derived from slip ratio found experimentally [10] few examples are shown in table.1 :

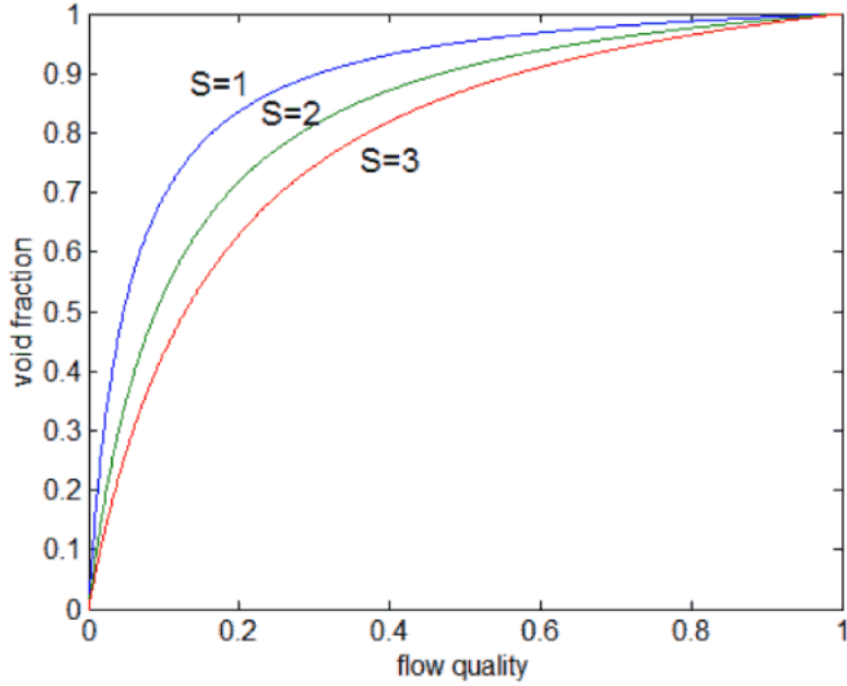


Fig. 7 Slip ratio effect on void fraction vs flow quality [10]

TABLE 1 : Slip Models [10]

Author	Proposed Model
Homogeneous flow model	$S = 1$ (3)
Zivi's Slip Model	$S = \sqrt[3]{\frac{\rho_L}{\rho_G}}$ (4)
Chisholm's slip Model	$S = \sqrt{1 - x \cdot \left(1 - \frac{\rho_L}{\rho_G}\right)}$ (5)
Smith's void model	$S = \left[1 + \frac{\rho_G}{\rho_L} \cdot K \cdot \left(\frac{1-x}{x}\right) + \frac{\rho_G}{\rho_L} \cdot (1-K) \cdot \left(\frac{1-x}{x}\right) \cdot \sqrt{\frac{\rho_G + K \cdot \left(\frac{1-x}{x}\right)}{1 + K \cdot \left(\frac{1-x}{x}\right)}} \right]^{-1}$ (6)

2.2 Drift flux method

Drift flux model is a widely used method to predict and calculate gas void fraction and liquid hold up empirically by comparing the real gas velocity with superficial gas velocity by introducing the distribution factor C_o and the drift velocity V_{dg} under the relation of [11]

$$V_g = C_o * V_m + V_{dg} \quad (7)$$

Initially, this model was introduced by [12], with some inapplicability. However, the model was improved and applied on nuclear reactors [13]. Drift-flux modeling techniques are commonly used to stand for two and three-phase flow in pipes and wellbores.” Unlike mechanistic models, drift-flux models are incessant, differentiable, and relatively fast to compute, so they are well suited for use in wellbore flow models within reservoir simulators. The parameters are found using an optimization technique that minimizes the difference between experimental and model predictions for phase in-situ volume fraction” [14] see fig.9. Slippage dimensionless number proposed by [1], has many advantages and can control especially the gas-liquid flow where it is flow pattern independent, viscosity unbiased and not effected by the pipe angle. The slippage number can be defined as “the ratio of the difference in the gravitational forces between slip and no-slip conditions to the inertial force of the gas.” [1]. However, the Slippage number proposed in this paper depends on the superficial gas velocity and correlated only with Froud mixture number. In this study, the Slippage number is numerically functionalized with Froud mixture number similar to [1] see fig. 10, making this number independent of gas void fraction and depending only on the flow conditions, fluid properties and the geometry.

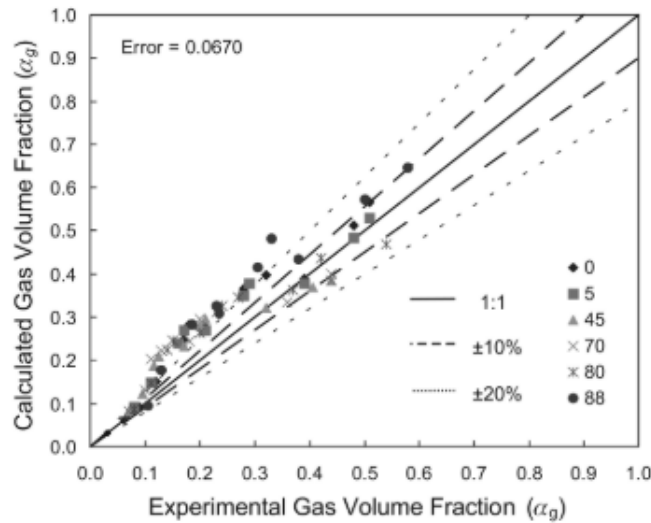


Fig. 8 Predicted in-situ gas volume fraction using original parameters [14]

The drift-flux model was utilized to find the relation between slippage number and the slip velocity as function of flow conditions, fluid properties and the geometry and the experimental gas void fraction to analyze and study the behavior of Slippage number as function of slip velocity.

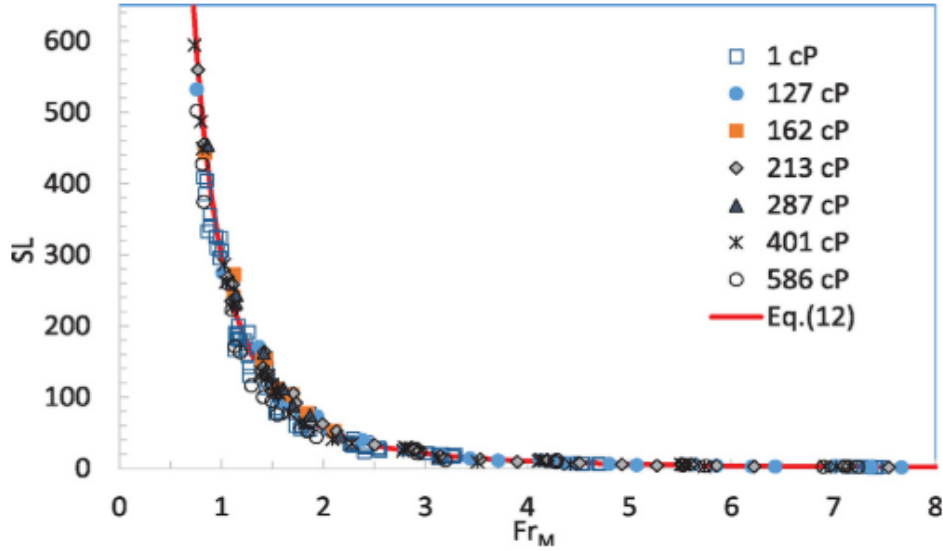


Fig. 9 SL versus Fr_M based on mixture velocity for [2] experimental data [1]

2.3 Slippage Number, SL

Slip-density, ρ_{TP} , differs from the homogeneous or no-slip density of the mixture, ρ_H , in gas-liquid flow. The no-slip mixture density, ρ_H , is easily computed by dividing the volume flow rate of the phases by their ratio, assuming no slippage between them. The slip density, ρ_{TP} , is obtained from the liquid holdup, which may be measured or computed. The suggested dimensionless number is defined as the ratio of the gravitational force differential between slip and no-slip situations to the gas's inertial force (based on the superficial gas velocity or the volumetric flux of the gas) [1]. For a particular pipe diameter and fluids, the value of Slippage Number, SL, is determined by the gas superficial velocity and the difference in mixture densities. The flow pattern and the slippage between the phases play a significant role in the variation in mixture densities. For example, the value will be high for bubbly flow, which is common for low gas superficial velocities. The value of the Slippage number will be extremely low for annular or mist flow at high superficial gas velocities because the slippage is minimal and the liquid droplets are transported by gas, especially for low superficial liquid velocity, V_{sl} or tiny liquid film thicknesses. In a vertical pipe, slug flow involves a descending film and severe phase slippage. As a result of the huge disparity

between the slip and no-slip densities, the Slippage Number is relatively high. Churn flow in a vertical pipe can be detected at faster gas speeds than slug flow. As a result, this figure has a lower value than slug flow. When the liquid slug lacks entrained bubbles, the elongated-bubble movement is a simple example of slug flow. When compared to slug flow, this occurs at lower gas rates. As a result, the slippage between gas and liquid is projected to be greater than slug flow, and therefore the difference in densities, as well as the Slippage Number is greater. Because there is substantially less slippage between phases in a dispersed bubble flow, the Slippage Number is extremely near zero [1]. As a result, this number may be used to identify flow patterns quickly. It may also be useful in simulating gas–liquid fluxes in pipes, particularly in the drift flux technique because the drift flux approach is based on phase slippage.

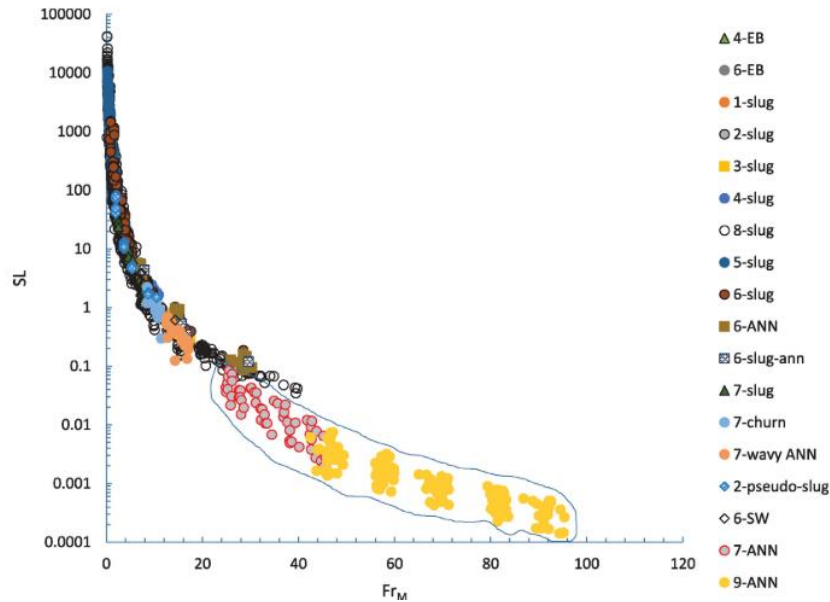


Fig. 10 Slippage Number versus mixture Froude number for gas–liquid flow [1]

CHAPTER 3: OBJECTIVES

The main objective of this work is to enhance using the slippage number for two-phase flow predictions and to fill the gap in this area. The main research gaps are listed below followed by the detailed objectives.

Research Gaps:

- Limited number of investigations on the Slippage number and slip phenomena effect on multi-phase flow field.
- Limited number in method of identifying the void fraction numerically in general .

- Limited research on finding Void fraction or Liquid hold-up with direct relation independent of pipe angle, fluids actual velocities and phase pattern.
- No studies on using Slippage number to find Void fraction and flow pattern.

The main objectives of this thesis are :

- To find a direct relation between the void fraction and flow pattern in gas-liquid flow using explicit multiphase flow parameters such as the input flow conditions (flowrates) , fluid properties and pipe geometry.
- To find various relationships between SL and Froud number , SL and void fraction for different gas-liquid flow cases.
- To functionalize SL with slip velocity (V_{slip}), Froud mixture number (F_{rm}) and a novel dimensionless number F_{rslip} (Froud slip number).
- To find a reliable and new method to predict the gas-liquid flow pattern based on explicit parameters.

CHAPTER 4: PROPOSED MODEL ANALYSIS

4.1 Parameters Modeling Flowchart

4.1.1 Introduction.

The main goal of this work is to optimize the flow pattern and void fraction analysis in gas-liquid multiphase flow for better prediction. In contrast, the void fraction and flow pattern need a unique calculation and flow pattern map for each instance, as stated in the introduction and literature review. Consequently, in the gas-liquid flow, a generalized approach to determine the flow pattern map and the void fraction percentage would be a huge time saver in the multiphase flow area. Furthermore, to fully comprehend the gas-liquid flow in real-world applications, many testing methodologies must be used to provide a complete image of the flow condition.

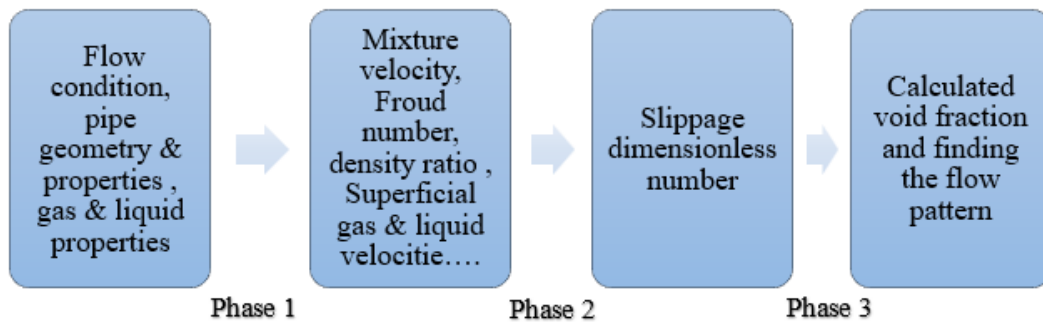


Fig. 11 Parameters Modeling Flowchart

4.1.2 Essential Multiphase Flow Parameters

The input parameters to any prediction tools are liquid and gas properties , pipe geometry, pipe properties and mixture flow rate all are givens and known from the flow testing history where by then they can be used to identify the multiphase flow essential parameters (flow pattern and holdup etc.). the following dimensionless numbers and parameters are essential for the present modeling approach:

$$\textbf{Froud Mixtuer number} : \textbf{Frm} = \sqrt{\frac{vm^2}{D \cdot g}} \quad (8)$$

$$\textbf{Superficial Gas Velocity} : \textbf{Vsg} = \left(\frac{Q_g}{A_p} \right) \quad (9)$$

$$\textbf{Superficial Liquid Velocity} : \textbf{Vsl} = \left(\frac{Q_L}{A_p} \right) \quad (10)$$

$$\textbf{Mixtuer Velocity} : \textbf{Vm} = \textbf{Vsg} + \textbf{Vsl} \quad (11)$$

$$\textbf{Liquid Hold up} : \textbf{HL} = \left(\frac{A_L}{A_p} \right) \quad (12)$$

$$\textbf{Gas void fraction} : \textbf{Y}_g = \left(\frac{A_L}{A_p} \right) \quad (13)$$

4.1.3 Slippage number and further calculations.

The dimensionless slippage number may therefore be derived from the physics and elements of multiphase flow parameters. The slippage dimensionless number, SL, presented by [1] has several benefits and can manage the gas-liquid flow particularly since it is flow pattern independent, viscosity unbiased, and unaffected by pipe angle. The Slippage number is dependent on the superficial gas velocity, and flowing fluids density and is solely connected with the Froud mixing number and all of them are input parameters (known). In this thesis, the Slippage number numerical relation with the Froud mixture number will be validated. The goal is to find gas void fraction through only flow conditions, fluid properties, and geometry. The drift-flux model along with the slippage number and the Froud mixture number relationship is used to determine the void fraction. In gas-liquid flow, the slip-density, ρ_{TP} , is different from the homogeneous ρ_H or no-slip mixture density see Eq.(15) & Eq.(16) [1].

$$\textbf{Slippage Number} : \textbf{SL}_{main} = \left(\frac{\rho_{TP} - \rho_H}{\rho_g Vsg^2} \cdot D \cdot g \right) \quad (14)$$

$$\textbf{In – situ two phase density} : \rho_{TP} = \rho_L \cdot \textbf{HL} + (1 - \textbf{HL}) \cdot \rho_g \quad (15)$$

$$\textbf{Homogenous Density} : \rho_H = \rho_L \cdot \gamma_L + (1 - \gamma_L) \cdot \rho_g \quad (16)$$

$$\textbf{Homogenous Hold up} : \gamma_L = Vsl/Vm = Vsl/(Vsl + Vsg) \quad (17)$$

By dividing the volume flow rate of the phases by their ratio, the no-slip mixture density, ρ_H , may be calculated with ease, supposing that no slippage occurs. Measured or calculated liquid holdup yields the slip density, ρ_{TP} . The slippage number then can be calculated as per Eq.(14) where it is a function of the superficial gas velocity, ρ_H , ρ_{TP} , ρ_g and pipe diameter. Whereby Alsarkhi et al. correlation for the slippage number as a sole function of Mixture Froude number can be estimated for Air-water vertical flow for example of this specific case as in Eq.(18):

$$\text{Alsarkhi et al. correlation } SL_{\text{Alsarkhi}} = 300.13 Fr_m^{-2.425} \quad (18)$$

because densities may vary 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 figure 10. As the drift flux method relies on phase slippage, it may also be immensely 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.

4.1.4 Finding Void fraction from estimated slippage number.

Void fraction can be calculated, from the main slippage number and Alsarkhi correlation, as per below. Validation will be done by calculating back the slippage number and comparing it either to the experimental one or to the correlated one. In [1] and based on [2] data the SL is a sole function of Fr_m proposed in Alsarkhi correlation. Using this suggested correlation will lead to find SL as a single curve of Fr_m that is a function of the mixture velocity and pipe diameter and will ease finding the void fraction. Consequently, SL can be used to find void fraction and predict the flow pattern. The SL/ Fr_m relation will be utilized as a crucial tool in this thesis to demonstrate a novel approach of estimating the void fraction. The SL/ Fr_m relationship will predict SL using just the mixture velocity and pipe diameter. As a result, the void fraction can be calculated by solving the SL number basic function for the void fraction, as shown in Eq.(19). Superficial velocity Ratio SVR Eq.(20) is the ratio between the superficial velocities to indicate the relation between the gas motion to liquid motion in the gas-liquid flow.

$$Y_g = 1 - \frac{1}{(\rho_L - \rho_g)} \left(\frac{SL \rho_g v_{sg}^2}{D \cdot g} + \rho_H - \rho_g \right) \quad (19)$$

$$\text{Superficial velocity Ratio } SVR = \frac{v_{sg}}{v_{sL}} \quad (20)$$

Substituting Eq.(20) in Eq.(14) yields:

$$SL_{SVR} = Fr \, sg^{-2} \cdot \left[\left(\frac{\rho L}{\rho g} \cdot (1 - \alpha) + \alpha \right) - \left(\frac{\frac{\rho L}{\rho g} + SVR}{(1 + SVR)} \right) \right] \quad (21)$$

Equation 21 is the slippage number in terms of the superficial gas to liquid velocities ratio. Where Fr_{sg} is the Froude number based on the superficial gas velocity.

4.2 Slippage number as a function of slip velocity, V_{slip} and Froude number based on slip velocity, Fr_{slip}

Moreover, the study can be extended to find new relations of slippage number where all the relations before are focused on the slippage number as function of Froude mixture number. Consequently, two new relations to be studied to widen the understanding of slippage number effect on the multiphase flow generally and gas-liquid flow specifically. The target of this study is to make SL as function of V_{slip} where the SL_{main} is mainly function of V_{sg} . The drift flux model will be followed to find the relation between SL and V_{slip} numerically and empirically. A definition for the drift velocity of a gas is provided in Equation 22, below. Additionally, a definition for the gas drift flux is given by eq (23). The slip velocity, which represents the relative velocity of the gas to the liquid, is used as an indicator of the gas-liquid flow in Equation 24, which offers a clear indication of the gas-liquid flow [15]. It is possible to incorporate the slip velocity in Eq.(25), which represents the drift flux. As a result, the void fraction is described by the Eq. (26) as a function of the slip velocity. When Eq.(26) is substituted into [eq.14], leads to Eq.(27), which demonstrates that SL as function of Slip Velocity.

$$V_{dg} = V_g - V_m \quad (22)$$

$$J_g = V_{dg} * \alpha = V_{sg} - \alpha * V_m \text{ (where } V_m = V_{sg} + V_{sl}) \quad (23)$$

$$V_{slip} = V_g - V_l \quad (24)$$

$$V_g = C_0 * V_m + (1 - \alpha) * V_{slip} \quad (25)$$

$$\alpha = \frac{V_{sg}}{C_0 * V_m + (1 - \alpha) * V_{slip}} \quad (26)$$

$$SL_{V_{slip}} = \frac{(\rho_{TP} - \rho_H) * g * D}{\rho_g * (\alpha * C_0 * V_m + \alpha * (1 - \alpha) * V_{slip})^2} \quad (27)$$

Furthermore, there are two types of slip velocity based on the drift flux relation [eq.28] and the superficial velocities relation Eq.(29) that are obtained from Eq.(25).

$$V_{slip_{relation}} = \frac{V_{sg}}{(1 - \alpha) * \alpha} - \frac{C_0 * V_m}{(1 - \alpha)} \quad (28)$$

$$Vslip_{math} = \frac{Vsg}{\alpha} - \frac{Vsl}{(1-\alpha)} \quad (29)$$

However, toward dimensionless relations dimensionless transformations have been used to make SL as function of Frm and Frslip. where in [1] the relation between SL and Frm has been found empirically, this study will find SL and Frm also SL and Frslip relations numerically (mathematically) and will be verified empirically relying on the data of [2]. Additionally, SL can be a function of Froud Slip number as in Eq.(31).

$$Frslip = \sqrt{\frac{Vslip^2}{D*g}} \quad (30)$$

$$SL_{Frslip} = \frac{(\rho_{TP}-\rho_H)*(1/Frslip^2)}{\left(\frac{\rho_g}{\rho_l}\right)*(\rho_l-\rho_g)*(\alpha*c_0*\left(\frac{V_m}{Vslip}\right)+\alpha*(1-\alpha))^2} \quad (31)$$

4.3 Void fraction determination using SL number.

Moreover, the SL/Frm relation presented by [1] will be validated using the data in [2], and a new correlation will be developed and tested against additional nine correlations presented in Table 3 with several limitations to demonstrate the strength of this data. As a result, the novel technique will be established utilizing [2] data on Table 2 and will be validated on Table 4 with 2412 bubbly and annular flow experimental data with various pipe inclination angles, flowing conditions, and pipe diameters all in bubbly flow pattern. The presented analysis will determine the method's limitations and how it might be improved. Lastly, this approach will be generalized and will be used as a void fraction calculator and a flow pattern induction tool. The correlation presented in Eq.(18) will be checked first by plotting SL Vs Frm to ensure that the exponential coefficient and the power are appropriate to [1] data by investigating the plot of SL as function Frm shape suggested by [1] and it is accurately presenting the data in [2], the following analysis may proceed.

TABLE 2: (Alruhaimani,2015) data information

Data	Fluids	Pipe degree	Pipe Dia (m)	Flow pattern	Data number
Alruhaimani, 2015 [2]	Oil and Air	90	0.0508	Various pattern	149

As a result, Vg (Vg is equal to 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 the interception from the y-axis (which is representing the drift). Moreover,

the slope is equal to the distribution coefficient, C_o divided by the void fraction, and the y-interception is equal to V_d drift velocity divided by the square root of the pipe diameter multiplied by the gravity acceleration. This technique will provide a new correlation presented in Eq.(32) for the drift flux method and will be used to validate the improved model on additional experiments.

$$V_{sg} = Y_g(1.577V_m + 0.147\sqrt{gD}) \quad (32)$$

Where Y_g is another notation for the void fraction in the literature. The drift flux correlation will next be compared to the experimental results of [2] data, where there are 9 correlations in addition to the newly improved correlation from Eq.(32) [2]. The bubbly and annular flow was selected to eliminate the influence of flow patterns on the study. This technique allows us to compare [2] data and findings to other methodologies and outcomes and discover limits. Zukoski 1966 [15], Benjamin 1968 [16], Weber 1981 [17], and Ben-Mansour et al. 2010 [18] provide further information on drift velocity in Table 3, and the distribution coefficient has been set to 1.2 and 0.92 based on [12-13] C_o value in bubbly and annular flow, respectively. To decide the inaccuracy of each correlation, we will compare the value of V_{sg} predicted by the 10 correlations listed in table 3 to the value of V_{sg} obtained experimentally in [2] data where the average error values are stated in table 9. Table 3 below, gives an overview about the 10 correlations used in this thesis. Where the **limits** are the conditions used to develop each correlation in their original paper, **Fluids** are the fluids used in the experiments in each correlation and **Max Uncertainty** is the maximum error percentage in each correlation using their original data in their published work to give an indication regarding the uncertainty of the correlation development in their original work..

TABLE 3: Drift flux correlations

Data	Correlation	limits	Fluids	Max Uncertainty %
Hasan and Kabir, 1990 [16]	$V_{sg} = Y_g \left(1.2V_m + V_\infty(1 - Y_g)^2 \right)$ $V_\infty = 1.53 \left[\frac{g\sigma(\rho_l - \rho_g)}{\rho_l^2} \right]^{0.25} \quad (33)$	Bubbly flow/vertical pipe	Oil/Water	Max error - $\pm 4.47\%$ in V_{sg} compared to other correlations
Wu et al., 1992 [17]	$V_{sg} = Y_g \left(1.08V_m + 0.9412V_\infty(1 - Y_g)^2 \right)$ $V_\infty = 1.53 \left[\frac{g\sigma(\rho_l - \rho_g)}{\rho_l^2} \right]^{0.25} \quad (34)$	Bubbly flow	Oil/Water	Max error + 19.49% in V_{sg} from average values

Flores, 1997 [18]	$V_{sg} = Y_g \left(1.04V_m + V_\infty (1 - Y_g)^{2.5} \right) \quad (35)$ $V_\infty = 1.53 \left[\frac{g\sigma(\rho_l - \rho_g)}{\rho_l^2} \right]^{0.25}$	Vertical and Inclined pipe	Oil/Water	Max error – 10.24% in Vsg from average values
Han et al., 2017 [19]	$V_{sg} = Y_g \left(1.038V_m + 0.142(1 - Y_g)^{2.5} \right) \quad (36)$	Vertical /Small pipe	Oil/Water	Max error – 25.97% in Vsg from average values
Hao Qin et al, 2022 [20]	$V_{sg} = Y_g(0.8459V_m) + 0.9085V_\infty(1 - Y_g)^2$ $V_\infty = 1.53 \left[\frac{g\sigma(\rho_l - \rho_g)}{\rho_l^2} \right]^{0.25} \quad (37)$	Vertical /Large pipe	Oil/Water	Max error – 5.65% in Vsg from average values
Zukoski, 1966 [21]	$V_{sg} = Y_g(1.2V_m + 0.351\sqrt{gD}) \quad (38)$	Inclined pipe	Water, CO2 tetrachlorid, mercury Glycerin, alcohol	Max error $\pm 5\%$ in Vsg from average values
Benjamin, 1968 [22]	$V_{sg} = Y_g(1.2V_m + 0.542\sqrt{gD}) \quad (39)$	Horizontal pipe	Theoretical study	Max error $\pm 5\%$ in Vsg from average values [21]
Weber, 1981 [23][24]	$V_{sg} = Y_g(1.2V_m + V_d) \quad (40)$ $v_d/\sqrt{gD} = 0.54 - 1.76Eo^{-0.56}$ $\text{Eotvos number } Eo = \rho_g D^2 g / \sigma$	Horizontal/ Inclined/ vertical pipe Bubbly flow	Water, Glycerin, Sucrose	Max error $\pm 10\%$ on Vsg from average values
Ben-Mansour-et-al.,2010 [25]	$V_{sg} = Y_g(1.2V_m + V_d) \quad (41)$ $Fr = \frac{v_d}{\sqrt{gD}}, N_\mu = \frac{\mu}{\rho D^2 g^{\frac{1}{2}}}, Eo = \frac{\rho D^2 g}{\sigma}$ $Fr = 0.53e^{-13.7N_\mu^{0.46}Eo^{-0.1}}$	Horizontal pipe	Air/Heavy Oil	CFD modelling shows an agreement of Vsg with the experiments
The proposed correlation	$V_{sg} = Y_g(1.577V_m + 0.147\sqrt{gD}) \quad (32)$	Vertical pipe	Oil/Air	Max error $\pm 26\%$ in Vsg from average values

Where, Vsg is the superficial velocity of the gas phase, Yg is the actual void fraction, Vm the mixture velocity, Eo is Evotes number, Nμ is the viscosity number, Vinf or V∞ is the terminal rise velocity of bubbles for oil-water bubble flow, 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 et al. correlation Eq.(18) and the SL fundamental equation Eq.(14) 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 and obtained from the input parameters. The

void fraction that found by the SL/Frm relation was evaluated using the bubbly and annular flow obtained from ten different sets of experimental data, as shown in Table 4. Moreover, the data was investigated and analyzed, along with Zukoski 1966 [21], Benjamin 1968 [22], Weber 1981 [23], Ben-Mansour et al. 2010 [24] and Alruhaimani 2015 [2] most recent model found in Table 3 Eq.(32). 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 4, this novel technique of determining void fraction will be tested on 2412 experimental data with 1630 annular flow and 782 bubbly flow. The 10 experimental data in table 4 with varied angles, flowing fluids conditions, 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.

TABLE 4: Bubbly and Annular flow data

Data	Fluids	Pipe degree	Pipe Dia (m)	Flow pattern	Number of data
Sunil Kokal, 1987 [26]	Oil /Air	-90 to 90	0.0512 and 0.0258	Bubbly Annular	133 308
Abduvayt, 2003 [27]	Water/N3	0 to 30	0.1064 and 0.0549	Bubbly Annular	54 8
Barnea, Shoham, 1982 [28]	Water/Air	-90 to 90	0.051 and 0.025	Bubbly Annular	595 1032
P.Y. Lin, T.J. Hanratty, 1985 [29]	Water/Air	0	0.0254 and 0.0954	Annular	31
Van Dresar, N. T., Siegwarth, J. D, 1997 [30]	Helium liquid /Helium gas	1.5	0.00874	Annular	26
Wilkens, R. J. 1997 [31]	Oil/CO2 gas	0 to 2	0.0972	Annular	7
Meng, W. 1999 [32]	Oil/Air	-2 to 2	0.0501	Annular	87
Manabe, R., Zhang, H. [33]	Oil/ Natural gas	0 to 90	0.0549	Annular	89
Mietus, , Matar, 2001 [34]	Oil/Air	0	0.0508	Annular	14
Omebere-Iyari, 2007 [35]	Naphtha/N3	90	0.189	Annular	28

Moreover, SL/Frm relation can be generally written as below:

$$SL = A Frm^{-2.425} \quad (42a)$$

$$VSg^2 = Yg^2(C_0 * Vm + Vdg)^2 \text{ multiply both sides by } \frac{\rho_g}{(\rho_{TP}-\rho_H)*g*D} \quad (42b)$$

Then with manipulations and simplifications and comparing with experimental data the following density factor A is found to give more accurate match with experimental data than a constant value of 300.1 proposed by Alsarkhi et al. [1].

$$A = 2 \times \frac{\frac{(\rho_g + \rho_L)}{2} - \rho_H}{\rho_g} = 1 - \frac{\rho_L}{\rho_g} - \frac{2 \times \rho_H}{\rho_g} \quad (43)$$

Where the A factor is derived by squaring the drift flux equation Eq.(7) and assuming that the relation of SL/Frm as shown in Alsarkhi correlation Eq.(18) is in the form of Eq.(42a). Inverting Eq.(42b) will lead to the SL in Eq.(14) in the left side and a mathematical relation with negative power for Frm in the right side and knowing that based on Alruhaimani data A factor on average equals to 300.13. Consequently, A factors or (density effect factor) has been concluded to Eq.(43) and has been applied to all data derivations.

4.4 (Alruhaimani, 2015) data analyses

(Alruhaimani, 2015) data indicates number of important parameters, such as Vsl, Vsg, Flow pattern, gas density, liquid density, liquid hold up, and extra, were measured experimentally and reported. These include some of the most essential elements. The outcomes of the further calculations were conducted in every step of this study to complete both the numerical and the empirical evaluations are shown in Table 5. **Note:** C_0 (Fréchéou, 1986) [36], C_0 (Lamari, 2001) [37] and C_0 (Petalas and Aziz, 2000) [38] each one used individually to study the effect of C_0 on the SL.

TABLE 5: (Alruhaimani, 2015) data analyses

Variable	Relation
No-slip gas volume fraction, Lemdah-gas	$\gamma_g = Vsg/Vm \quad (44)$
No-slip liquid volume fraction, Lemdah-liq	$\gamma_l = Vsl/Vm \quad (45)$

Void fraction (measured including slip or in-Situ void fraction)	$\alpha = 1 - Hl \quad (46)$
Roh (TP) mixture density based on the in-situ void fraction	$\rho_{TP} = (1 - \alpha) \times \rho_l + \alpha \times \rho_g \quad (47)$
Roh(H) mixture density based on the no slip volume fraction	$\rho_H = (1 - \gamma_g) \times \rho_l + \gamma_g \times \rho_g \quad (48)$
SL main	$SL_{main} = \frac{(\rho_{TP} - \rho_H) \times g \times D}{\rho_g \times Vsg^2} \quad (49)$
Vslip math	$Vslip_{math} = \frac{Vsg}{(1 - \alpha) \times \alpha} - \frac{C_0 \times Vm}{(1 - \alpha)} \quad (50)$
SL vslip math	$SL_{vslip \text{ math}} = \frac{(\rho_{TP} - \rho_H) \times g \times D}{\rho_g * (\alpha \times C_0 \times Vm + \alpha \times (1 - \alpha) \times Vslip_{math})^2} \quad (51)$
Frm	$Frm = \sqrt{\left(\frac{Vm^2}{D \times g}\right)} \quad (52)$
Fr slip	$Fr_{slip} = Sq. \text{ root } \left(\frac{Vslip_{relation}^2}{D \times g} \right) \quad (53)$
Co avg (Lamari, 2001)	$Annular = 0.92, Churn = 1.06, Slug - bubbly = 1.2, Unslug = 1.0$
Co (Fréchou, 1986)	$C_0 \text{ Fréchou (1986)} = 1.2 \times \left(\frac{0.8}{1 + (1 \times 10^{-7} \times Re_{sl})^{2.55}} \right) \quad (54)$ $Re_{sl} = \frac{\rho_l \times Vsl \times D}{\mu L}$
Co (Petalas and Aziz, 2000)	$C_0 \text{ Petalas and Aziz} = 1.2 \times Re_{sl}^{-0.031} \quad (55)$ $Re_{sl} = \frac{\rho_l \times Vsl \times D}{\mu L}$
Vslip relation	$Vslip_{relation} = \frac{Vsg}{\alpha} - \frac{Vsl}{(1 - \alpha)} \quad (56)$
SL vslip relation	$SL_{vslip \text{ relation}} = \frac{(\rho_{TP} - \rho_H) \times g \times D}{\rho_g \times (\alpha \times C_0 \times Vm + \alpha \times (1 - \alpha) \times Vslip_{relation})^2} \quad (57)$
Down part of SL Frm	$Down \ SL_{Frm} = \left(\frac{\rho_g}{\rho_l} \right) \times (\rho_l - \rho_g) \times (\alpha \times C_0 + \alpha \times (1 - \alpha) \times \left(\frac{Vslip}{Vm} \right))^2 \quad (58)$

SL dimen Frm	$SL_{Frm} = (\rho_{TP} - \rho_H) \times \left(\frac{1}{Frm^2}\right) \times \left(\frac{1}{Down SL^* Frm}\right) \quad (59)$
Down part of SL Fr slip	$Down SL_{Frslip} = (\rho_g/\rho_l)(\rho_l - \rho_g) \times (\alpha * C_0 \times \left(\frac{Vm}{Vslip_{relation}}\right) + \alpha \times (1 - \alpha))^2 \quad (60)$
SL Fr slip	$SL_{Frslip} = (\rho_{TP} - \rho_H) \times \left(\frac{1}{Frslip}\right) \times \left(\frac{1}{Down SL^* Frslip}\right) \quad (61)$

4.5 Parametric Study of void fraction, α , superficial velocity ratio, SVR and C_0

This section involves a parametric analysis of the impact of void fraction, superficial velocity ratio, and distribution coefficient on the Slippage number (SL) with respect to the Vslip and Frm relations, utilizing the equations presented in Tables 5 and 6. The study compares the empirical and numerical relations to validate the observed patterns of increment, as reported in references [32] and [33]. Table 6 displays the variables and relations utilized in the analyses. **Note:** C_0 (Fréchou, 1986) [36], C_0 (Lamari, 2001) [37] and C_0 (Petalas and Aziz, 2000) [38] used individually to study the effect of C_0 on the SL.

TABLE 6: α , SVR and C_0 parametric analysis

Variable	Relation
Gas void fraction	$\alpha = \text{between } 0.1 \text{ and } 0.9 \text{ by } 0.1 \text{ increment}$
Vsl	$V_{sl} = \text{between } 0.05 \text{ and } 0.5 \text{ by } 0.03 \text{ increment}$
Vsg	$V_{sl} = \text{between } 0.5 \text{ and } 5 \text{ by } 0.3 \text{ increment}$
Vm	$V_m = Vsl + Vsg \quad (11)$
Lemda Gas	$\gamma_g = Vsg/Vm \quad (62)$
Roh gas	Average (Alruhamiani) data $\rho_g = 2.29 \text{ Kg/m}^3$
Roh liq	Average (Alruhamiani) data $\rho_l = 872.55 \text{ Kg/m}^3$
Roh(TP)	$\rho_{TP} = (1 - \alpha) \times \rho_l + \alpha \times \rho_g \quad (63)$
Roh(H)	$\rho_H = (1 - \gamma_g) \times \rho_l + \gamma_g \times \rho_g \quad (64)$
Re _{sl}	$Re_{sl} = \frac{\rho_g \times Vsl \times D}{\mu L} \quad (65)$
Co avg (Lamari, 2001)	Annular = 0.92, Churn = 1.06, Slug = 1.2, Unslug = 1.0
Co (Fréchou, 1986)	$C_0 \text{ Fréchou (1986)} = 1.2 \times \left(\frac{0.8}{1 + (1 \times 10^{-7} \times Re_{sl}^{2.55})}\right) \quad (66)$

	$Re_{sl} = \frac{\rho_g \times Vsl \times D}{\mu L}$
Co (Petalas and Aziz, 2000)	$C_0 \text{ Petalas and Aziz} = 1.2 \times Re_{sl}^{-0.031} \quad (55)$ $Re_{sl} = \frac{\rho_l \times Vsl \times D}{\mu L}$
Vslip relation	$Vslip_{relation} = \frac{Vsg}{\alpha} - \frac{Vsl}{(1-\alpha)} \quad (67)$
SL vslip relation	$SL_{vslip \text{ relation}} = \frac{(\rho_{TP} - \rho_H) \times g \times D}{\rho_g \times (\alpha \times C_0 \times Vm + \alpha \times (1-\alpha) \times Vslip_{relation})^2} \quad (68)$
Vslip math	$Vslip_{math} = \frac{Vsg}{(1-\alpha) \times \alpha} - \frac{C_0 \times Vm}{(1-\alpha)} \quad (69)$
SL vslip math	$SL_{vslip \text{ math}} = \frac{(\rho_{TP} - \rho_H) \times g \times D}{\rho_g \times (\alpha \times C_0 \times Vm + \alpha \times (1-\alpha) \times Vslip_{math})^2} \quad (70)$
SL main	$SL_{main} = \frac{(\rho_{TP} - \rho_H) \times g \times D}{\rho_g \times Vsg^2} \quad (14)$
Frm	$Frm = \frac{(\rho_l - \rho_g)}{\rho_g} \times (g \times \frac{D}{Vm^2}) \quad (8)$
Down part of SL Frm	$Down \ SL_{Frm} = (\rho_g / \rho_l) (\rho_l - \rho_g) \times (\alpha \times C_0 + \alpha \times (1-\alpha) \times (\frac{Vslip_{relation}}{Vm}))^2 \quad (71)$
SL Frm	$SL_{Frm} = (\rho_{TP} - \rho_H) \times \left(\frac{1}{Frm} \right) \times \left(\frac{1}{Down \ SL_{Frm}^*} \right) \quad (72)$
SL by SVR	$Superficial \ velocity \ Ratio \ SVR = \frac{Vsg}{Vsl} \quad (20)$ $SL_{SVR} = Fr \ sg^{-2} \times \left[\left(\frac{\rho_L}{\rho_g} \times (1-\alpha) + \alpha \right) - \left(\frac{\frac{\rho_L}{\rho_g} + SVR}{(1+SVR)} \right) \right] \quad (21)$
Void fraction by SL	$Yg = 1 - \frac{1}{(\rho_L - \rho_g)} \left(\frac{SL \times \rho_g \times Vsg^2}{D \times g} + \rho_H - \rho_g \right) \quad (19)$

CHAPTER 5: RESULTS AND DISCUSSIONS

5.1 (Alruhaimani, 2015) data results

Figure 12 illustrates the comparison between the empirical method and numerical method of SL/Vslip correlation where Vslip relation and Vslip math are the numerical and empirical relations, respectively. The numerical-based relationship significantly deviates from the Alsarkhi et al. correlation [1] presented in equation 18. Conversely, the Vslip math, an empirical method, exhibits less error and closely approximates the Alsarkhi et al. correlation with high accuracy. The numerical relation gives a more accurate formula than the empirical relation where the difference between both methods is around 4.42% as an average total error, indicating that the SL & Vslip is accepted method. The present study explores the empirical relationship between SL and vslip, as well as the numerical relationship between SL and Vslip. Moreover, the findings indicated that:

$$SL_{\text{vslip relation}} = 161.99 \times Vslip_{\text{relation}}^{-2.005} \quad \text{with } R^2 = 0.8342 \quad (73)$$

$$SL_{\text{vslip math}} = 248.98 \times Vslip_{\text{math}}^{-2.286} \quad \text{with } R^2 = 0.8711 \quad (74)$$

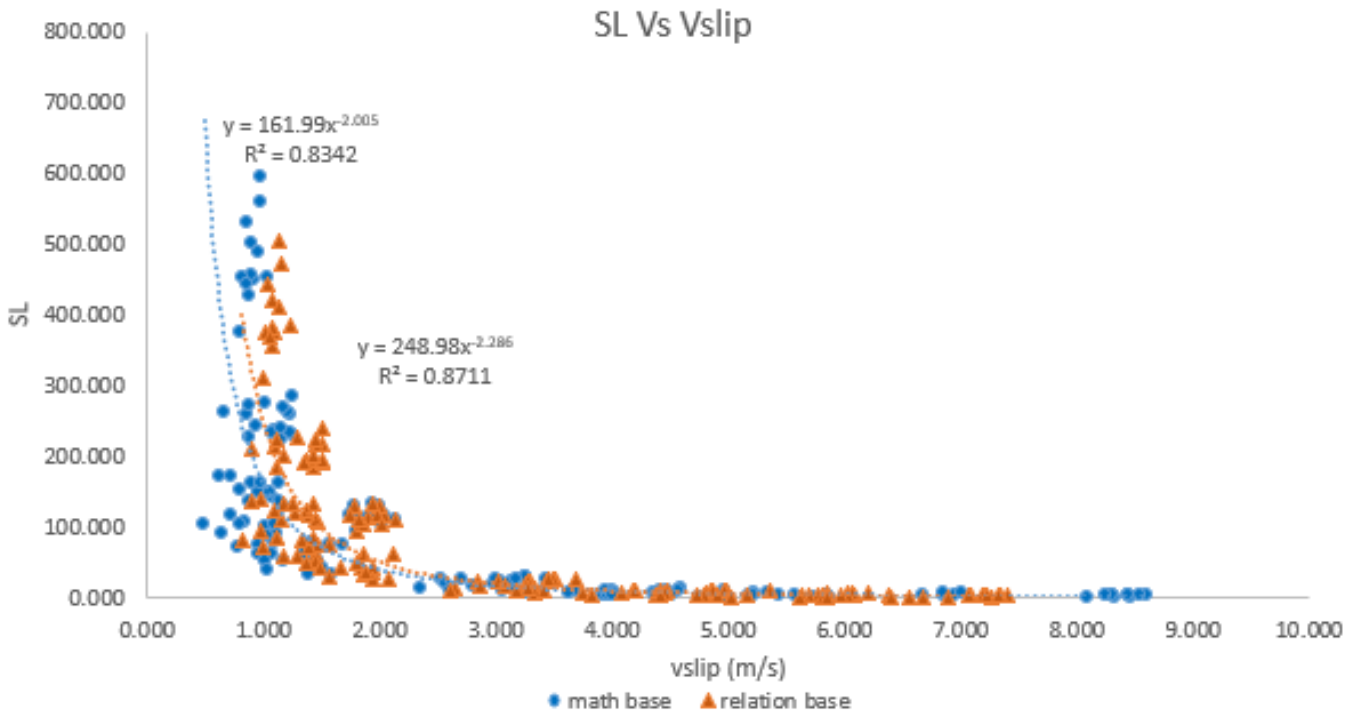


Fig. 12 SL Vs Vslip (math base Eq.(69) relation base Eq. (68))

Figure 13 demonstrates the comparison between the numerical-based relationship of SL Eq.(18) and the empirical relation between SL and Fr_m in Eq.(59). Where Eq.(18) Alsarkhi correlation based on Alruhimiani data and considered as the base of the study and Eq.(59) is SL/ Fr_m including the effect of the distribution coefficient and Co and the void fraction effect to validate the integrity of the proposed correlation by Alsarkhi. Moreover, the findings indicated that the difference between both methods is about 17% and with the below info:

$$SL_{main} = 300 \times Fr_m^{-2.425} \quad \text{with } R^2 = 1 \quad (75)$$

$$SL_{Fr_m} = 247.01 \times Fr_m^{-2.236} \quad \text{with } R^2 = 0.9598 \quad (76)$$

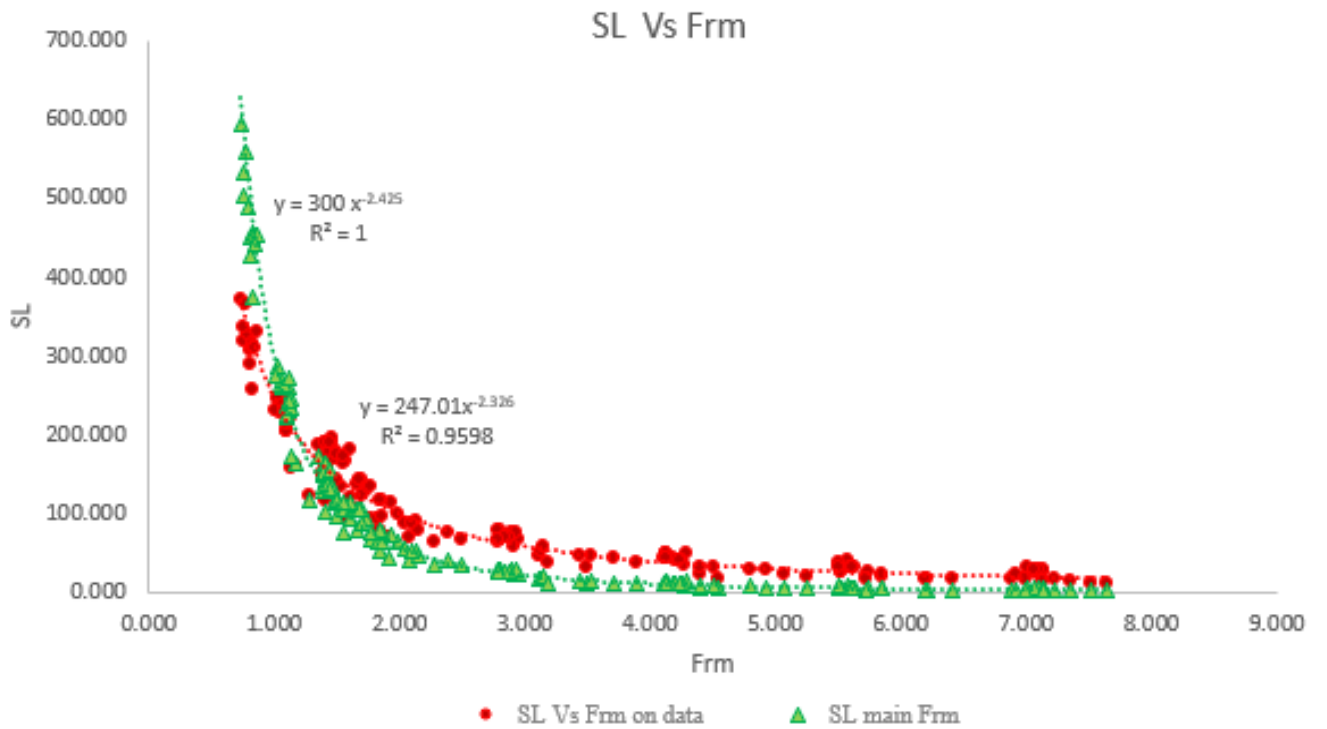


Fig. 13 SL Vs Frm

The 14th figure depicts the empirical relationship and the mathematical relationship between SL and Fr_{slip} . The empirical and numerical relations exhibit a high degree of proximity, with a negligible difference of approximately 2.27%. This suggests that the proposed SL & Fr_{slip} relation is suitable. As a result, this evaluation has the potential to establish a rational dimensionless correlation between the slip ratio and the Froude slip ratio, which is solely dependent on fluid characteristics and flow conditions. Moreover, the findings indicated that:

$$SL_{Frslip \text{ relation}} = 553.6 \times Fr_{slip}^{-1.143} \quad \text{with } R^2 = 0.5088 \quad (78)$$

$$SL_{Frslip \text{ math}} = 712.36 \times Fr_{slip}^{-1.203} \quad \text{with } R^2 = 0.5222 \quad (79)$$

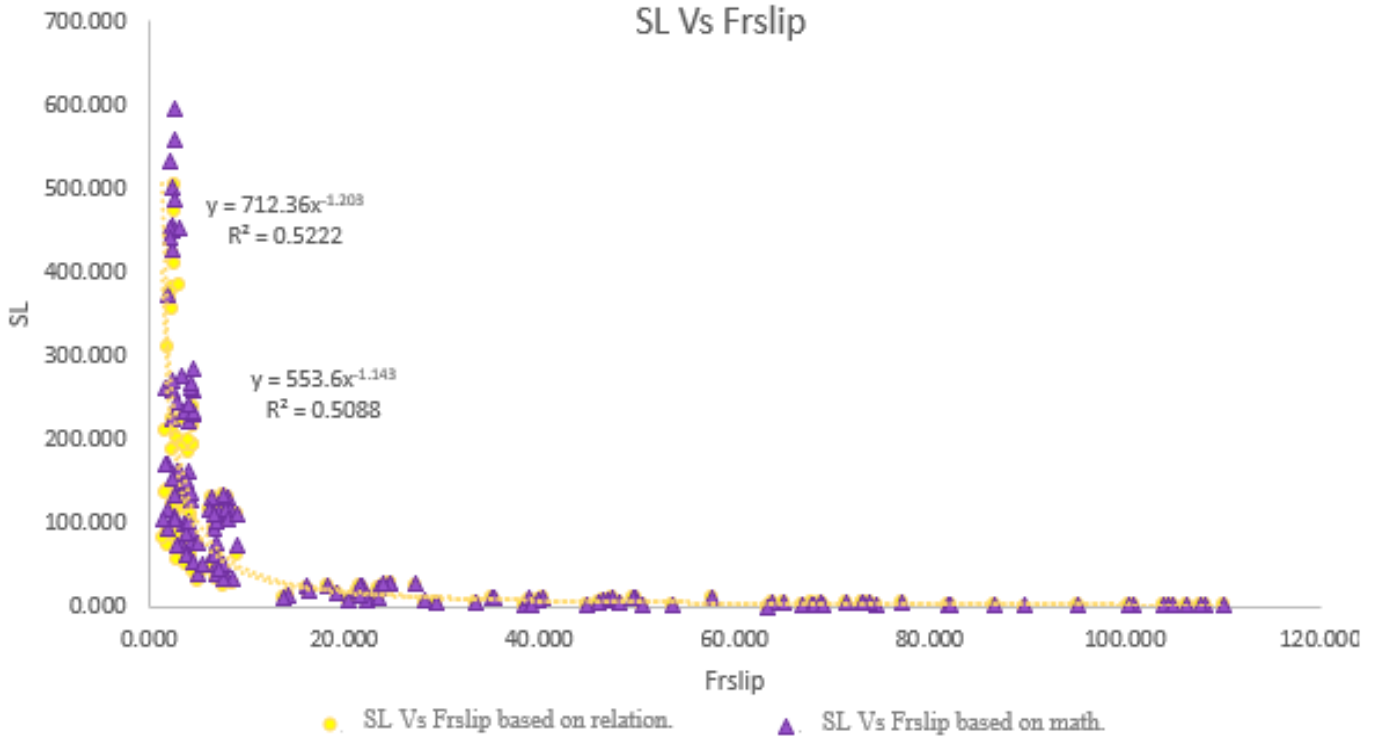


Fig. 14 SL Vs Frslip

Through an analysis of the coefficient and power factor of the connection between SL and Fr_{slip} , as depicted in reference [1], it is possible to utilize the data presented in reference [2] to compute the requisite variables for SL in equation 14, including homogeneous density. Subsequently, SL can be expressed as a function of Fr_{slip} . The power value and coefficient values depicted in Figure 15 and equation 18 exhibit a high degree of similarity. Moreover, the experimental mixture velocity will be graphed against the actual gas velocity, computed by dividing the experimental superficial gas velocity by the experimental void fraction, to enhance a novel drift flux correlation formulated from data in [2] as depicted in Eq.(32). According to the data presented in Figure 16, it can be inferred that the average slope is 0.7002, which suggests that the value of C_o is 1.577. Furthermore, the calculation of drift velocity involves multiplying 0.147 by the square root of the pipe diameter and gravitational acceleration. The updated model is derived in equation 32 by utilizing the data from reference [2].

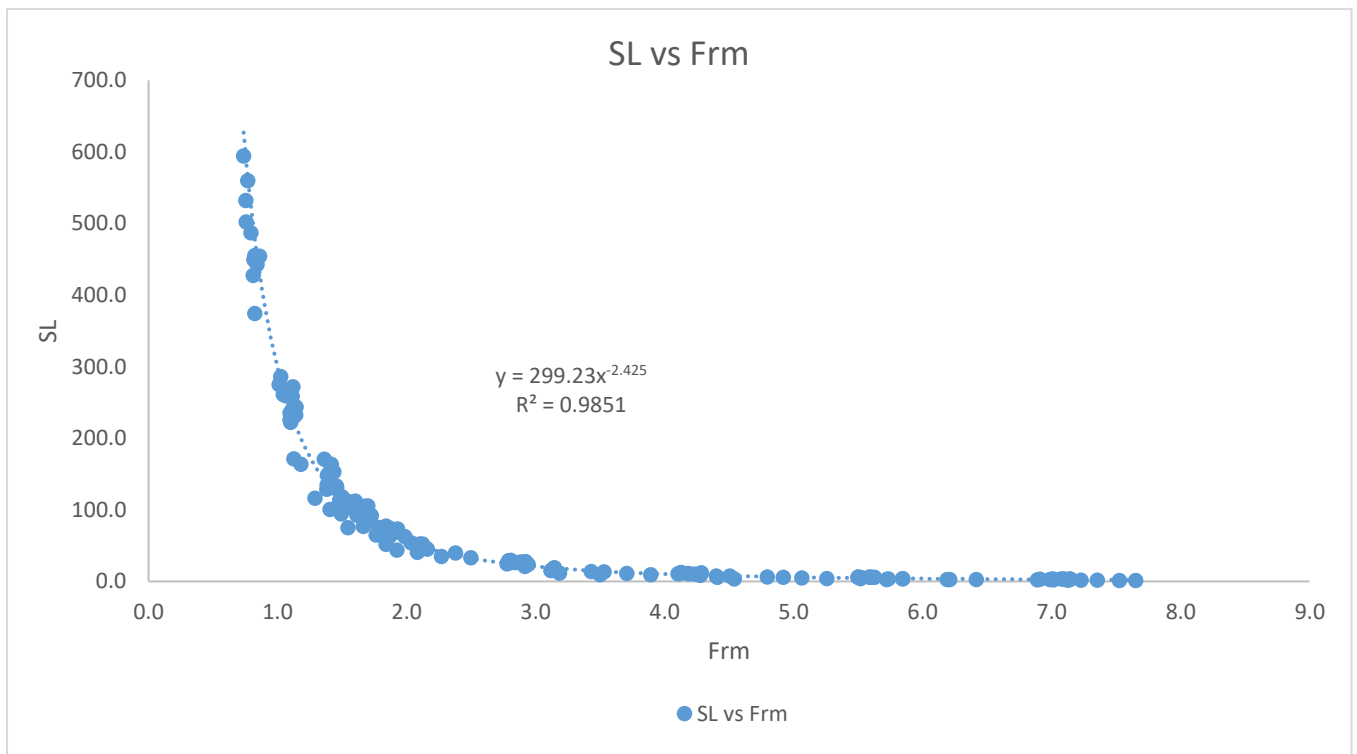


Fig. 15 SL versus Frm based on Abrahamian's (2015) data [2]

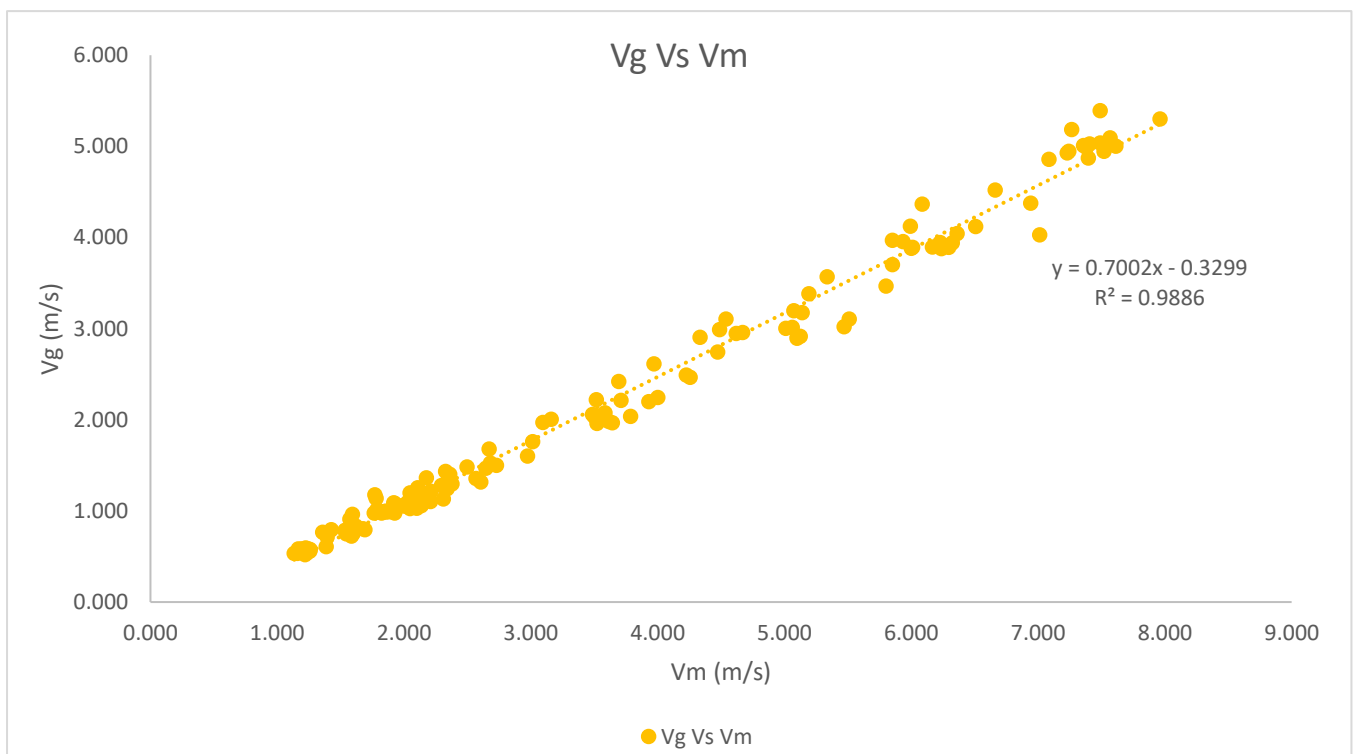


Fig.16 Actual gas velocity Versus mixture velocity based on Alruhaimani's (2015) data [2]

The depicted behavior in Figure 17 was derived by integrating the 10 correlations illustrated in Table 3 to predict V_{sg} , followed by plotting it against the experimental V_{sg} . The behavior showcases the constraints and potential usefulness of the data presented in reference [2], in terms of enhancing our understanding of the SL/Frm relationship derived from said data, as well as the novel correlation established in equation 32 based on the same data. The correlations presented in Figure 17 and Table 3 exhibit larger error values in correlations proposed by Hasan and Kabir (1990) [16], Wu et al. (1992) [17], Flores (1997) [18], Han et al. (2017) [19], and Hao Qin (2022) [20]. (2016) [19], and Lee et al. (2019) [20], among others due to the dependence of drift velocity as a function on void fraction.

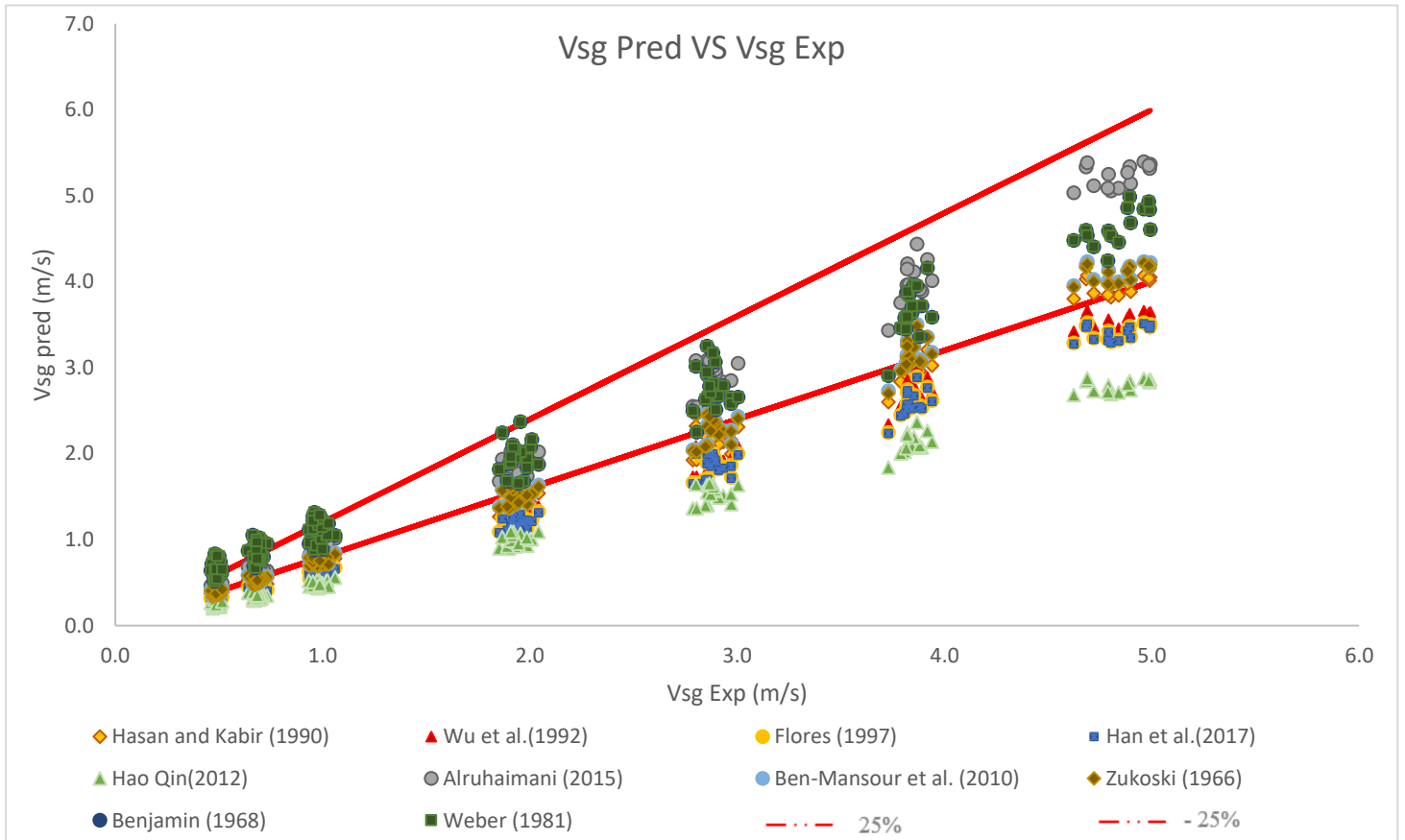


Fig. 17 Predicted superficial gas velocity Vs experimental superficial gas velocity based on Alruhaimani's (2015) data [7]

5.2 Void fraction through SL

For bubbly flow, using Zukoski 1966 [21], Benjamin 1968 [22], Weber 1981 [23], and Ben-Mansour et al. 2010 [24] and Alruhaimani 2015 [2] correlations from Table 3 for which they are common in the high accuracy compared to the other correlations and are not function of void fraction give the advantage to use them on the experimental data from Table 4. With the flow pattern fixed as bubbly flow and varying the pipe diameter and angle with varying

the flowing fluids conditions will show where the limitations are in finding the void fraction using SL utilizing [2] data. The void fraction discovered by SL is displayed versus the void fraction discovered by the relations in Table 3. Figure 18 demonstrates the comparison without A Factor (density effect factor) where the value is set to 300.13 as per [1] and the different fluids densities effect will not be captured. five correlations shows precise behavior where void fraction values predicted by the SL/Frm relation and the void fraction found by table 3 correlations are considerably close to each other with 2 areas showing the discrepancy in the correlations values: 1- The region of Abduvayt's data [27] water/nitrogen flow, where the high density of nitrogen compared to the air is effecting the SL/Frm relation derived from [2] data which is oil /air based making the assumption of the proposed SL weak in this area. 2- Two data points from Ovadia Shoham (1982) [19] in which the values of superficial liquid velocity is low in comparison to the entire data, indicating the influence of low superficial liquid velocity [37]. In figure 19, the A factor effect has been included and the data has been enhanced in the area of Abduvayt's data [27] where the high Nitrogen density effect has been disappeared and still the data points of Ovadia Shoham (1982) [19] are far from the correct path. Figure 20 illustrates the frequency of the SL values in the bubbly flow. Moreover, this figure proved 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 15 according to 80% of the data where Vsg for the bubbly flow varies between 0 and 25 m/s.

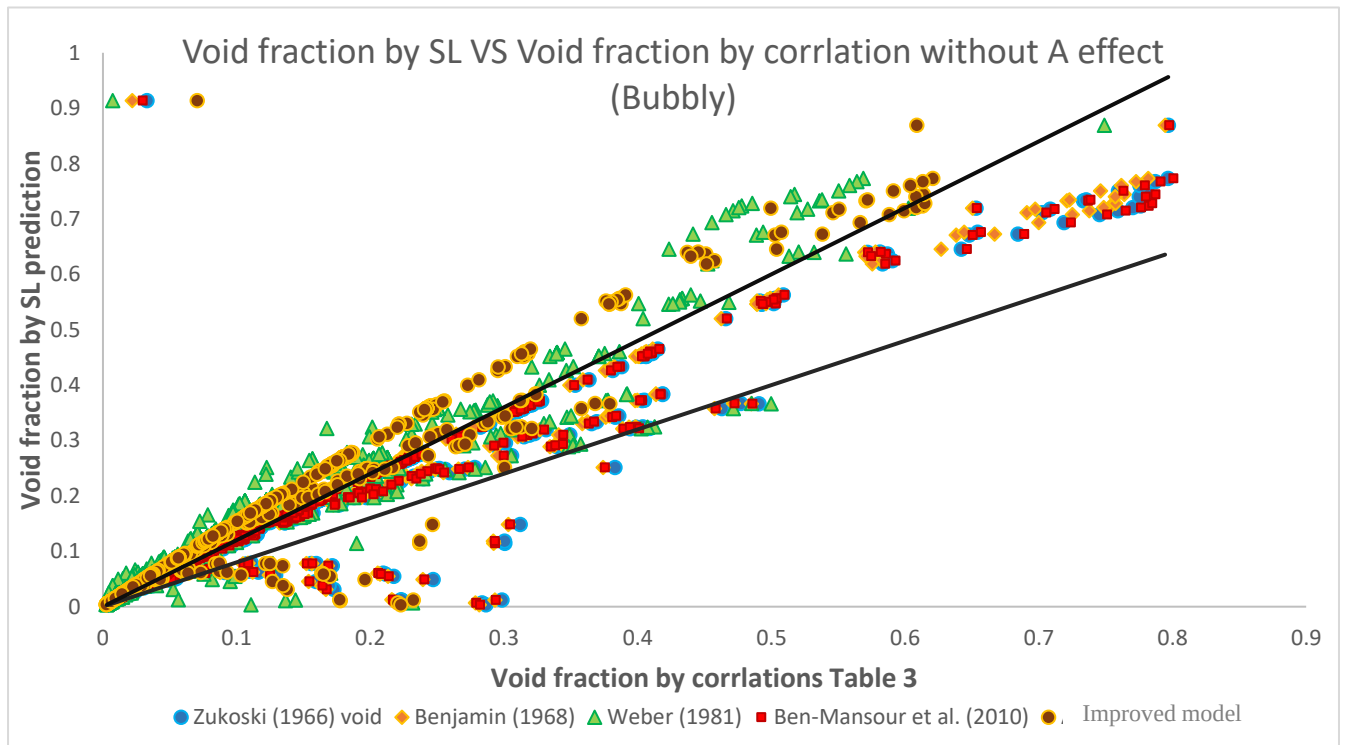


Fig. 18 Void fraction by SL prediction Eq.(18) Vs Void fraction by Table 3 Bubbly flow without A effect

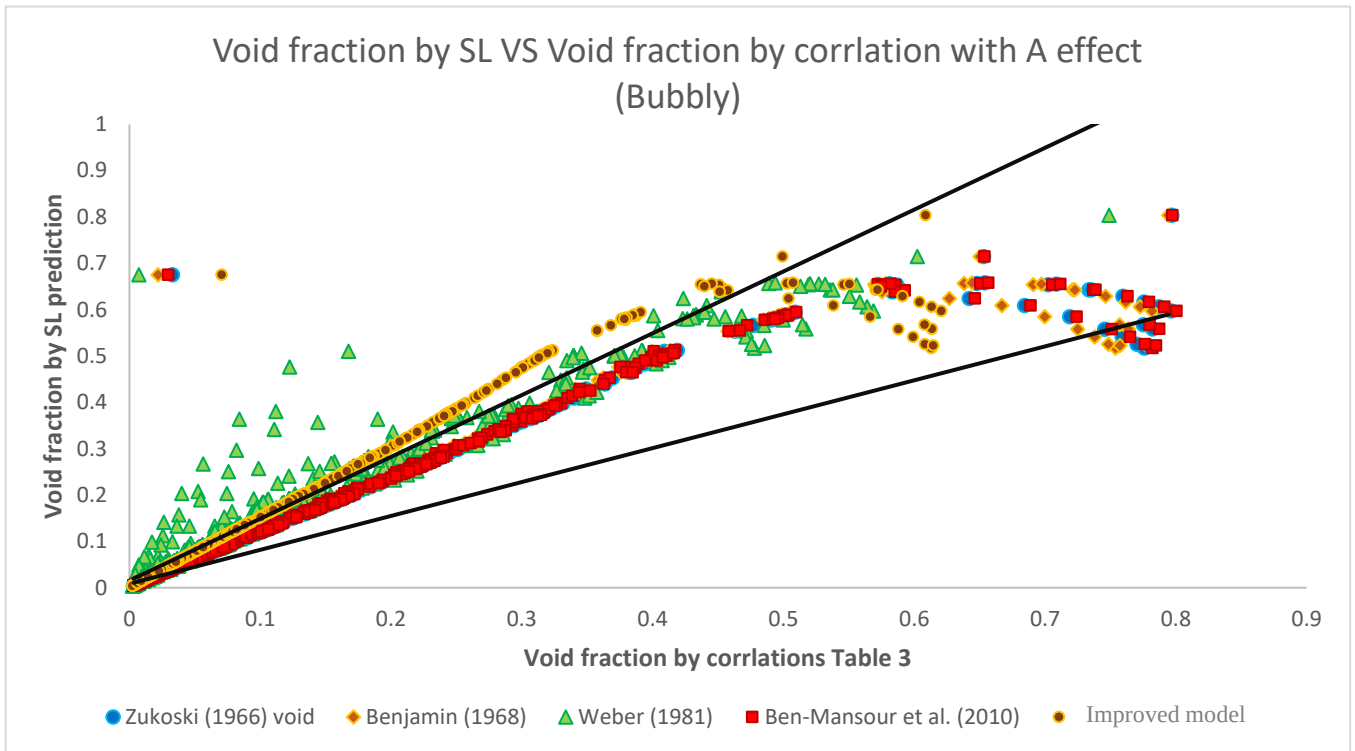


Fig. 19 Void fraction by SL prediction Eq.(18) Vs Void fraction by Table 3 Bubbly flow with A effect

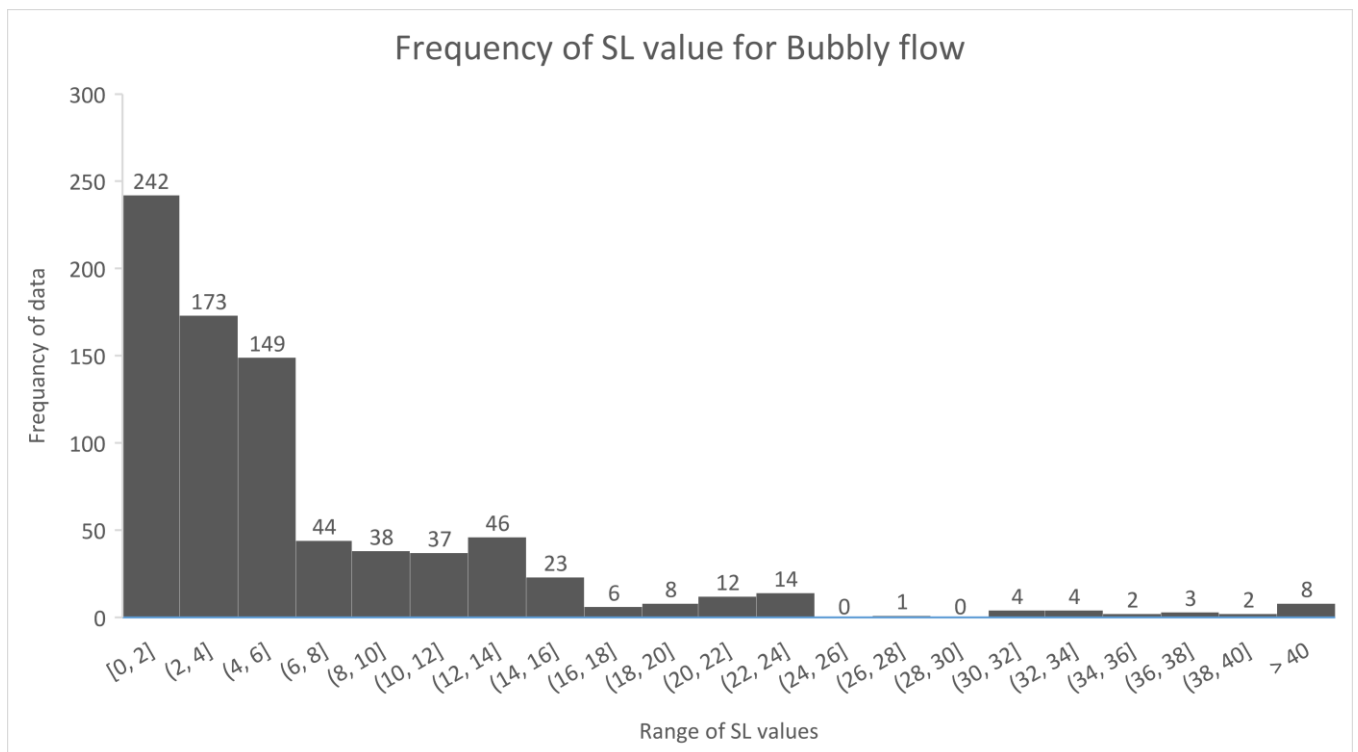


Fig. 20 Frequency of SL values in bubbly flow data Table 4

The utilization of the Zukoski 1966 [21], Benjamin 1968 [22], Weber 1981 [23], and Ben-Mansour et al. 2010 [24] and the improved model from Alruhaimani 2015 [2] correlations listed in Table 3, which exhibit high accuracy and are independent of void fraction, is recommended for the analysis of experimental data presented in Table 4 pertaining to Annular flow. By keeping a fixed flow pattern of annular flow and altering the pipe diameter and angle of inclination while varying the flowing fluids operating conditions, it is possible to identify the constraints in determining the void fraction using SL and the correlation established by the data presented in reference [2]. The void fraction discovered by SL is displayed versus the void fraction found by the relations in Table 3 with the applying A factors (density effect factor). Figure 21 illustrates that the five correlations show imprecise behavior, wherein the void fraction values projected by the SL/Frm relation are significantly close to each other in certain regions, and exceedingly distant in the majority of the data, outstanding to the inadequate consideration of the density effect. The use of A factors (density effect factor) in Figure 22 results in a notably precise performance in contrast to Figure 21, wherein the presence of two regions displays a gap in the correlation values. firstly, The region of Omebere-Iyari, [35] data Naphthene/nitrogen flow, where the high density of nitrogen compared to the air is affecting the SL/Frm relation derived from [7] data which is oil /air based assuming of the proposed SL weak in this area. Secondly, The data regarding (-90 pipe) from Ovadia Shoham's study in 1982 [29] reveals that the values of superficial liquid velocity show minimal fluctuations in comparison to the overall data, suggesting the impact of low superficial liquid velocity [37]. The frequency of SL values in the annular flow is depicted in Figure 23. This figure also showed that the SL in annular flow may be anywhere from 0.02 to 3.57 in general, while it is most often seen in the range of 0 to 0.71 when V_{sg} for the annular flow fluctuates between 16 and 200 m/s (where 90% of the data lies).

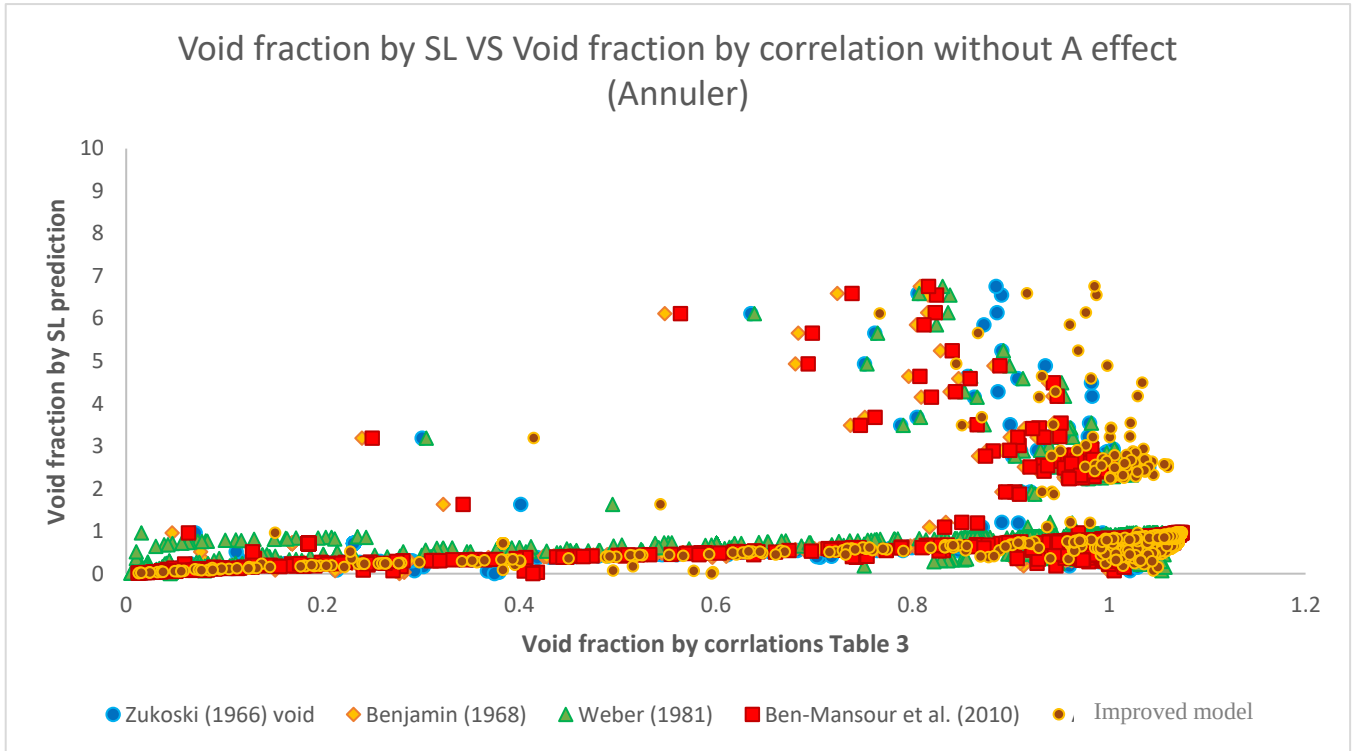


Fig. 21 Void fraction by SL prediction Eq.(18) Vs Void fraction by Table 3 Annular flow without A effect

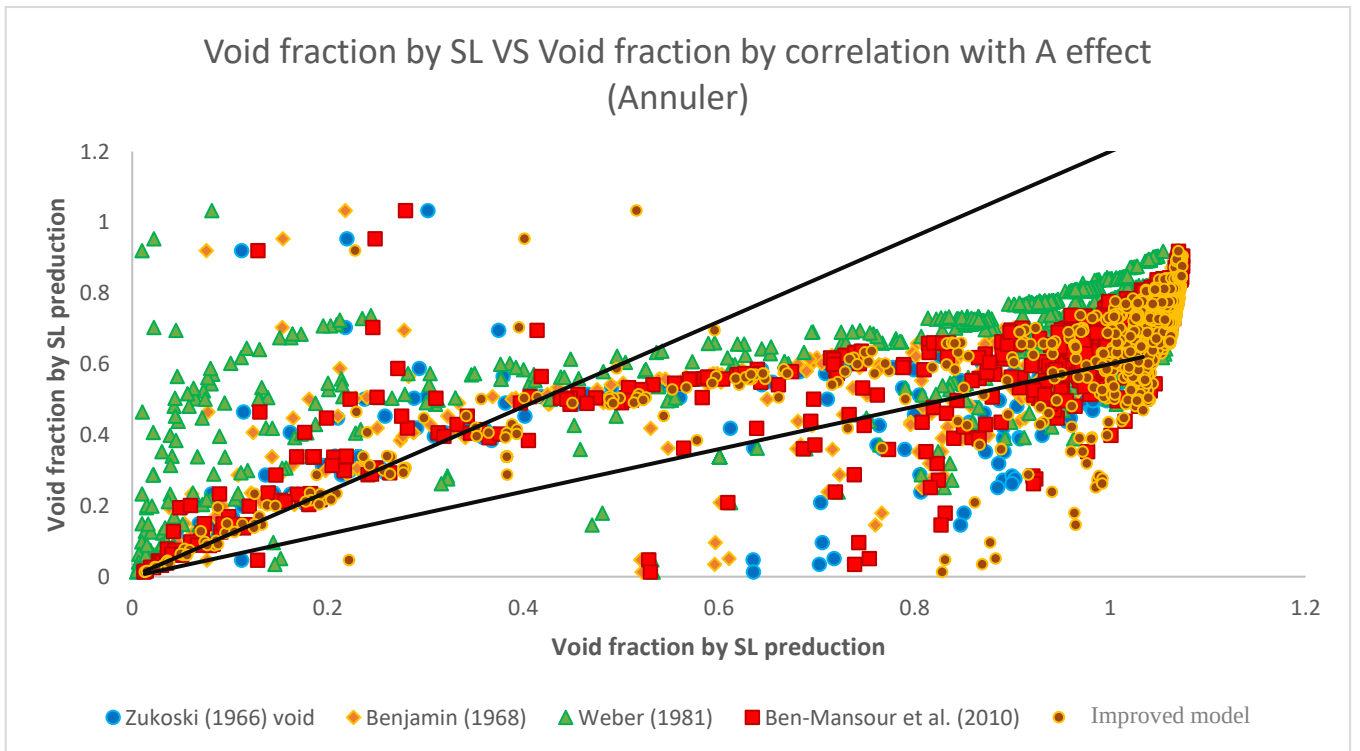


Fig. 22 Void fraction by SL prediction Eq.(18) Vs Void fraction by Table 3 Annular flow with A effect

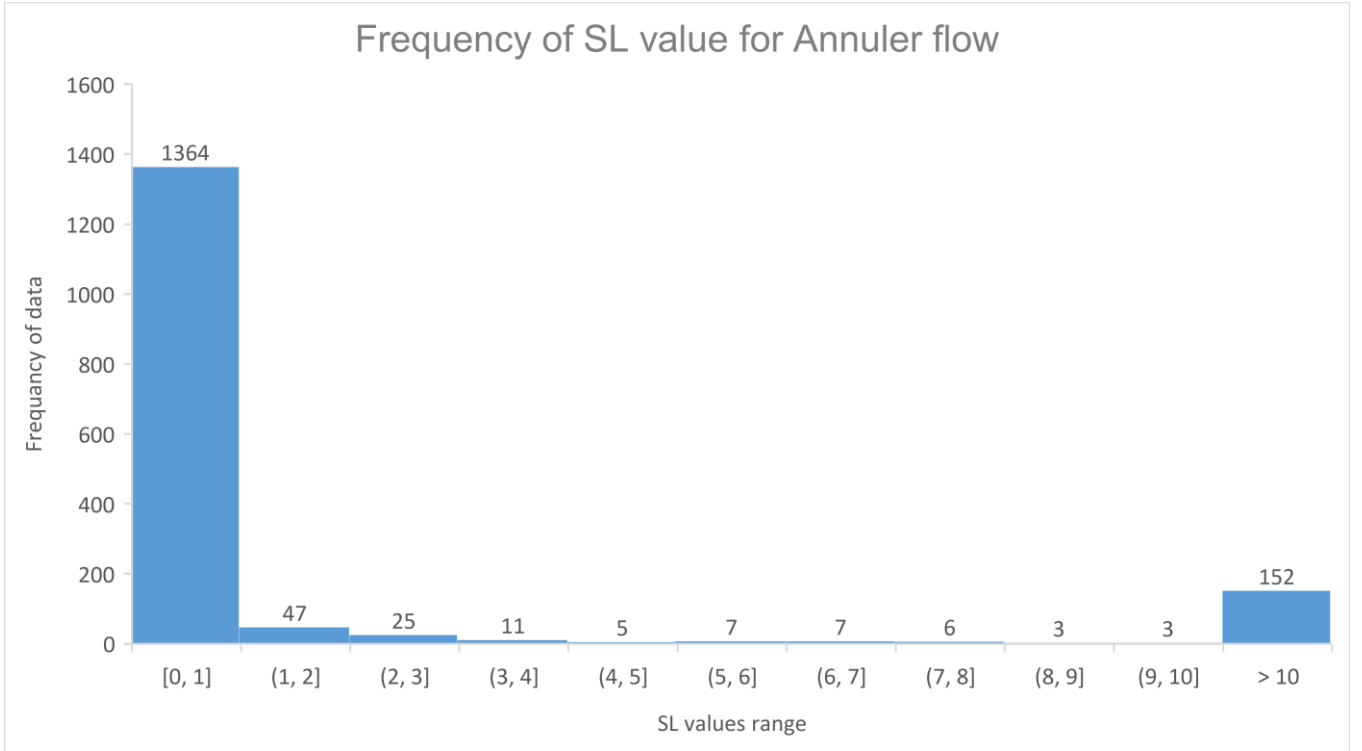


Fig. 23 Frequency of SL values in Annular flow data Table 4

5.3 α , SVR and C_0 parametric results

Figures 24 and 25 show the impact of void fraction on the relationship between SL and Vslip. The empirical relation between SL and Vslip is represented by the dotted lines, while the numerical relation between SL and Vslip is represented by the solid lines. Figure 24, derived from the average C_0 values reported by Lamari (2001), and Figure 25, based on C_0 values reported by Fréchu (1986). The variable void fraction exerts two primary impacts on all relationships: 1-The value of void fraction is inversely proportional to the range of SL, resulting in a reduction in the size of SL function. 2- Increasing the value of the void fraction results in an escalation of the discrepancy between the empirical and numerical relations. This is particularly clear at $\alpha=0.9$, where the deviation between the two relations is most stated. Nevertheless, the disparity among all void fraction values is not significant and conforms to a consistent pattern. The impact of C_0 on SL relationships is singular. Elevating the value of C_0 results to an escalation of the discrepancy between the empirical and numerical relationships. Nevertheless, the discrepancy among all C_0 values is insignificant and adheres to a consistent pattern. Moreover, Figures 24 and 25 illustrate the impact of the C_0 on SL versus Vslip relationship. It is observed that the C_0 avg (Lamari, 2001) [34] exhibits lower deviation between empirical and numerical relations compared to C_0 (Fréchu, 1986).

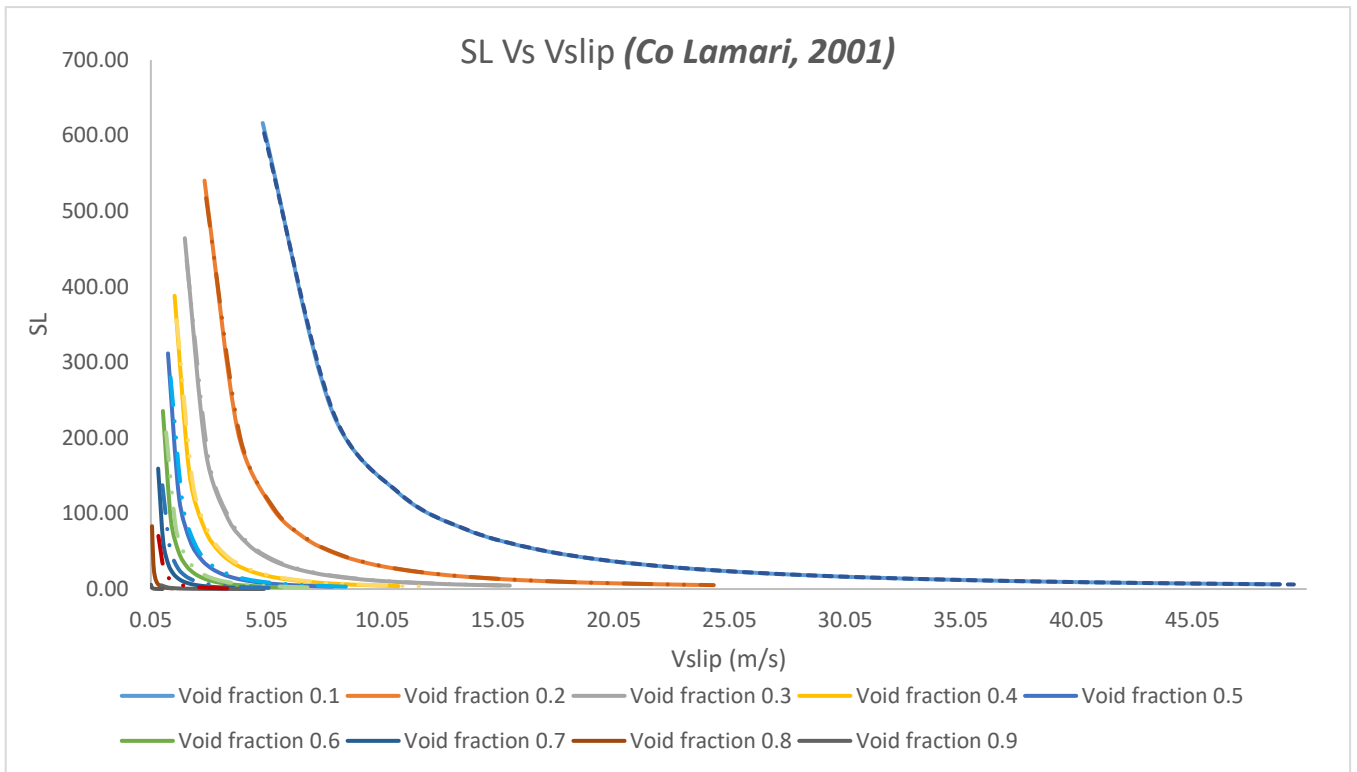


Fig. 24 SL Vs Vslip Co (Lamari, 2001)

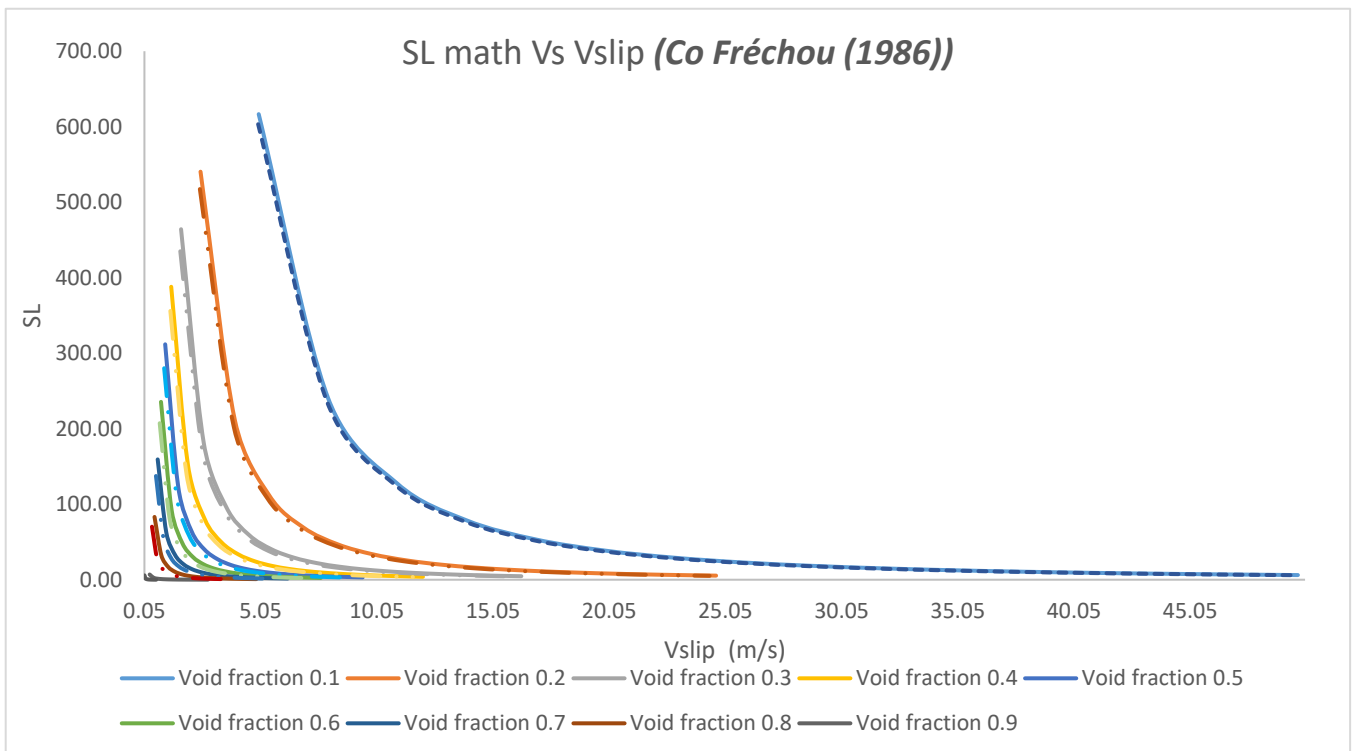


Fig. 25 SL Vs Vslip (Fréchu, 1986)

Figure 26 shows the range of Co (Fréchou, 1986) and Co (Petalas and Aziz, 2000) where both of them are functions of Reynolds number based on the superficial liquid velocity. This evaluation was applied on Table 4 data where the figure shows that Co (Petalas and Aziz, 2000) has a more convenient range between 0.8 and 1.2 as most of the literature. In the other hand Co (Fréchou, 1986) has a wider range from 0 to 1 indicating that it is less accurate than Co (Petalas and Aziz, 2000).

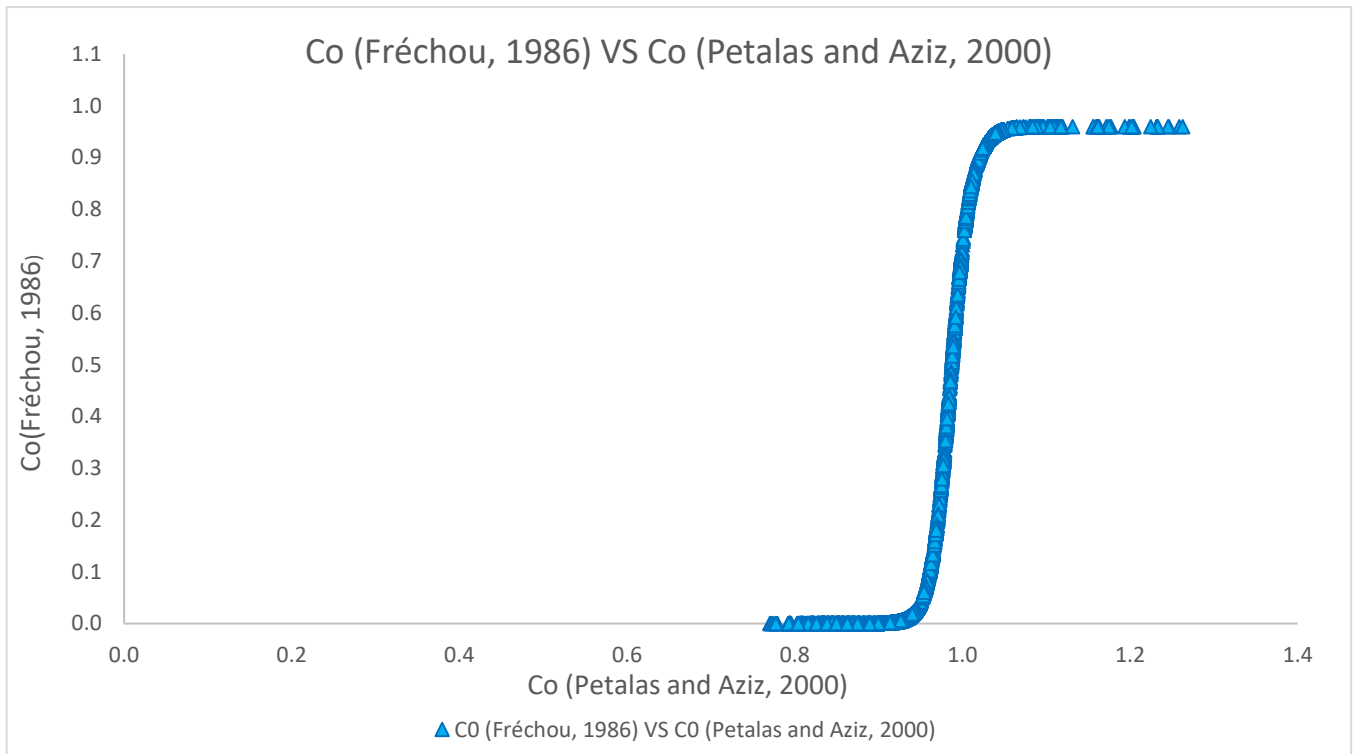


Fig. 26 Co (Fréchou, 1986) VS Co (Petalas and Aziz, 2000) Table 4 data

The method in which SVR modifies the connection between SL and Void fraction is seen below in figure 27. The examination used computational methods to evaluate a variety of factors, some of which were V_{sg} (ranging from 0.1 to 0.99), Void fraction (ranging from 0.1 to 0.9), and SVR (ranging from 0.0 to 100). The following values were used to be the physical constants of the system: $D = 0.051$, $g = 9.81$, and $\rho g = 2.29 \text{ kg/m}^3$. According to Figure 27, a rise in SVR leads to a comparable increase in the SL range as a function of the void fraction. This is the case when there is a positive correlation between the two variables. Figure 28 depicts the effect on the SL/ F_{rm} correlation of altering the void fraction between 0.1 and 0.9 while keeping the other parameters from Figure 27 constant. A rise in the void fraction is connected with a drop in the relation of slippage number Froud mixing number graph and its related constraints. This is proven by the fact that there is an inversible relation between the void fraction and the graph of SL/ F_{rm} , as showed by the trend.

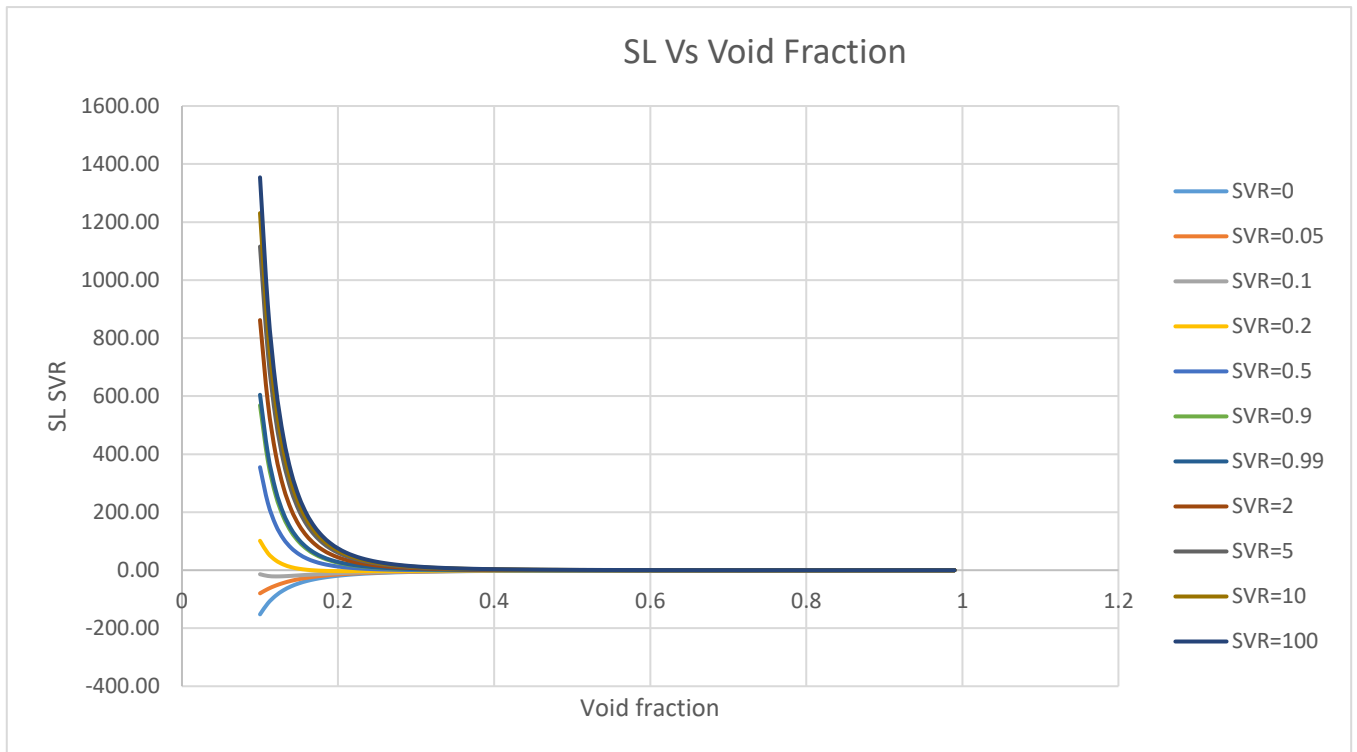


Fig. 27 SL SVR Eq. (21) Vs Void fraction with effect of SVR

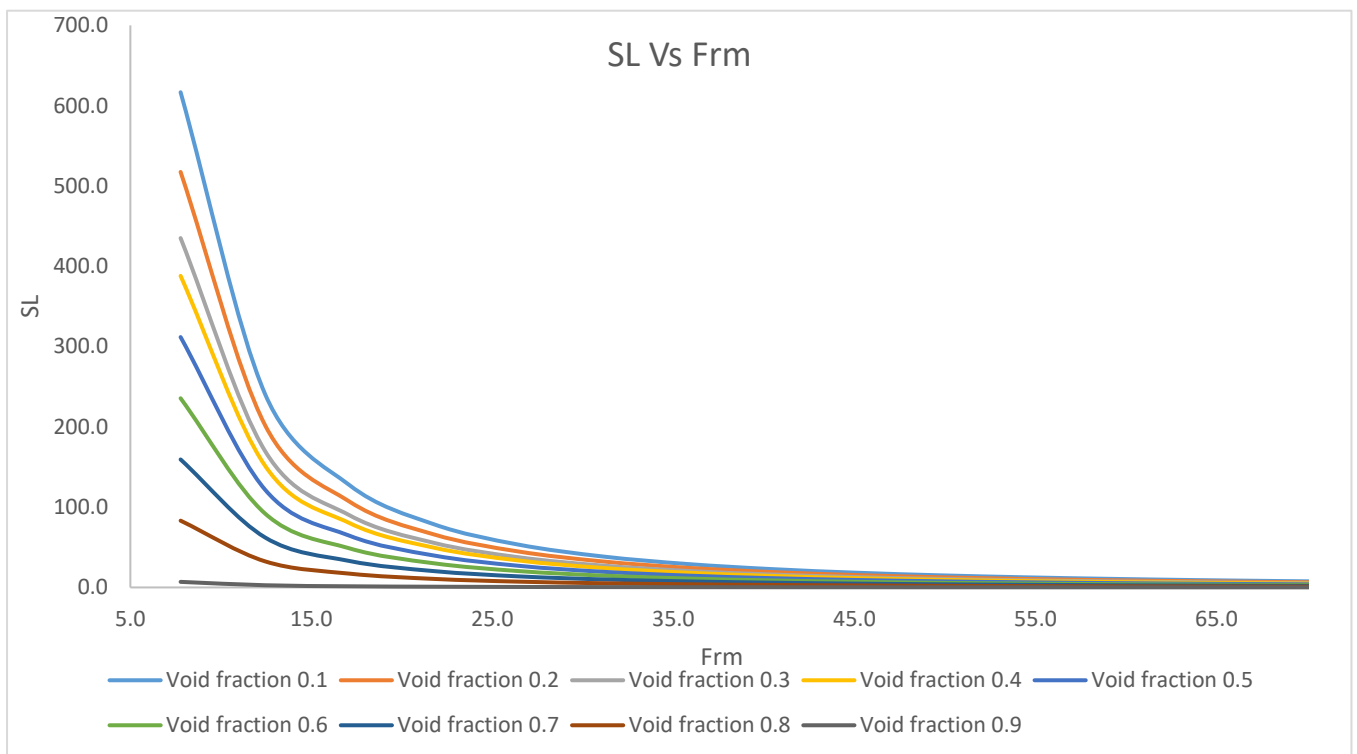


Fig. 28 SL Vs Frm with Void fraction Effect

5.4 SL Error analysis

The empirical analysis in Fig. 29 examines the error associated with the newly proposed Slip number, SL Vslip, by comparing it to SL presented in [1] in Eq.(14) through a graphical representation. The discrepancy in the mathematical calculations of SL Vslip is relatively insignificant in comparison to the SL model postulated by Alsarkhi et al. [1]. The fact that the margin of error is within 0.25% suggests that the newly proposed statistical model is a reasonable and practical option. Table 7 displays the utilized relationships in this section.

TABLE 7: Error Variables

Variable	Relation
Vslip math	$Vslip_{math} = \frac{Vsg}{(1 - \alpha) * \alpha} - \frac{C_0 * Vm}{(1 - \alpha)}$
SL vslip math	$SL_{vslip\ math} = \frac{(\rho_{TP} - \rho_H) * g * D}{\rho_g * (\alpha * C_0 * Vm + \alpha * (1 - \alpha) * Vslip_{math})^2}$
SL main	$SL_{main} = \frac{(\rho_{TP} - \rho_H) * g * D}{\rho_g * Vsg^2}$

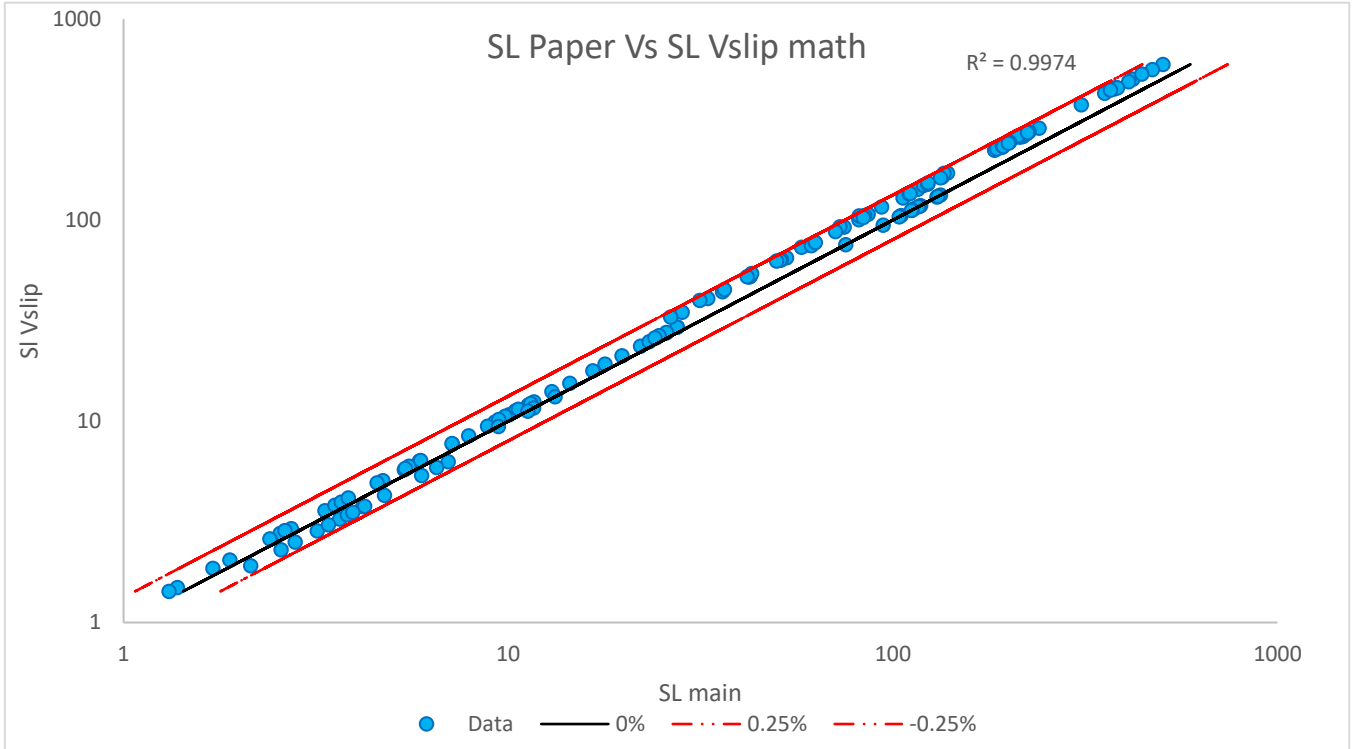


Fig. 29 SL main Vs SL Vslip

The comparison between SL Paper and SL Frslip is shown empirically in Fig. 30 to probe the uncertainty of the recently proposed Slip number (SL by Frslip). When compared to alsarkhi et al. [1] SL presented in eq.(14), the difference in the SL/Frslip relation is considered to be inconsequential. The newly proposed SL has an error rate of 0.87 percent indicates it is validity. The connections that were used to write this can be seen in Table 8.

TABLE 8: Error Variables

Variable	Relation
Vslip relation	$Vslip_{relation} = \frac{Vsg}{\alpha} - \frac{Vsl}{(1 - \alpha)}$
Fr slip	$Frslip = \frac{(\rho_l - \rho_g)}{\rho_g} * (g * \frac{D}{Vslip_{relation}}^2)$
Down part of SL Fr slip	$Down SL^*_{Frslip} = (\rho_g / \rho_l)(\rho_l - \rho_g) * (\alpha * C_0 * (\frac{Vm}{Vslip_{relation}}) + \alpha * (1 - \alpha))^2$
SL Fr slip	$SL^*_{Frslip} = (\rho_{TP} - \rho_H) * (\frac{1}{Frslip}) * (\frac{1}{Down SL^*_{Frslip}})$
SL paper Eq.(14)	$SL = \frac{(\rho_{TP} - \rho_H) * g * D}{\rho_g * Vsg^2}$

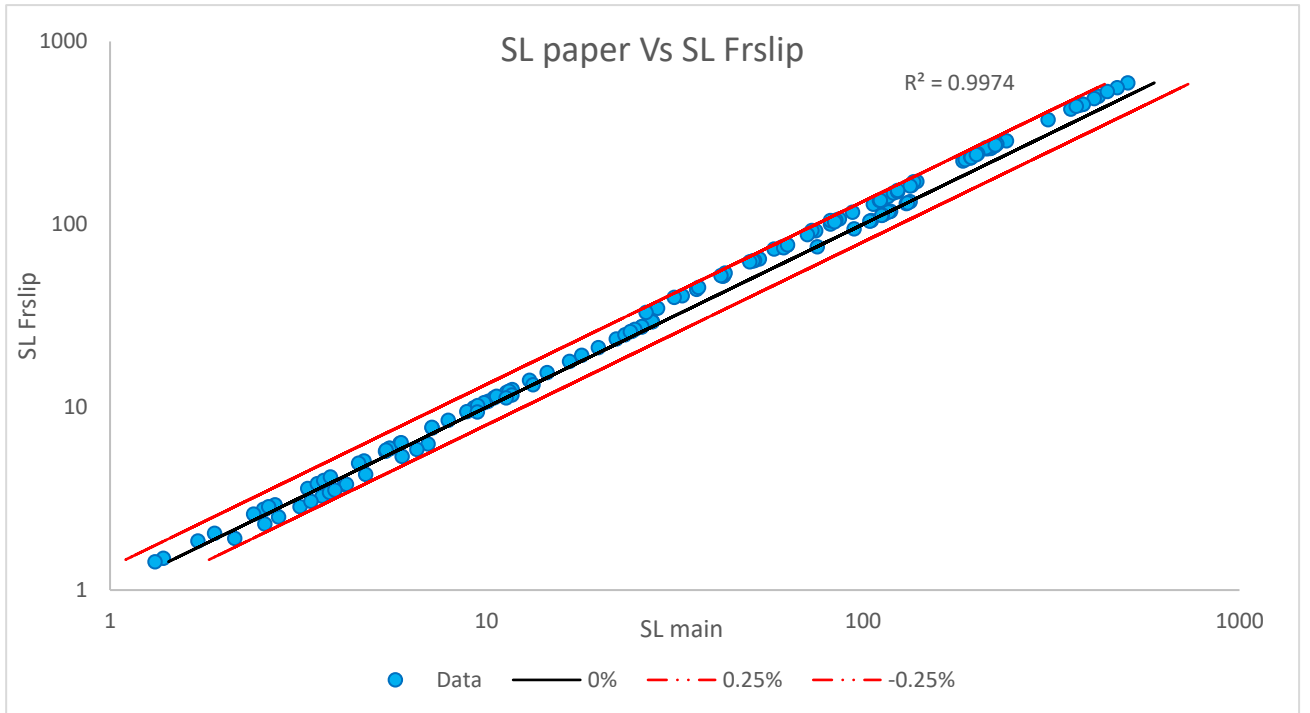


Fig. 30 SL paper Vs SL Frslip

The accuracy of Correlations in Table 3 has been verified based on the experimental data on [2]. It is worth to state that Alruhaimani's (2015) data [2] have been developed on completely different conditions compared to the rest of the experiments in Table 3 such as Benjamin (1968) [22] developed on horizontal pipe. This demonstrates the high quality of Alruhaimani's (2015) data [2], which supports both the theorized SL/Frm relationship by Alsarkhi et al., 2016 [1] and the newly established correlation using Alruhaimani's (2015) data [2] presented in Eq.(32). 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.(80) and Eq.(81) respectively below. Moreover, on both error methods the correlations predicted Vsg can be compared to the experimental Vsg. Note that e_i is the difference between the experimental Vsg and the correlated Vsg, $\bar{E}$ is the average value of the experimental Vsg and n is the number of data.

$$ARE = \frac{1}{n} \sum_{i=1}^n e_i \quad (80) \quad E_2 = \sqrt{\frac{\sum_{i=1}^n (e_i - \bar{E})^2}{n}} \quad (81)$$

TABLE 9: Correlations Error Tested using Alruhaimani's (2015) data Table 2

Data	ARE%	E2%
Hasan and Kabir, 1990 [16]	-18.565	0.815
Wu et al., 1992 [17]	-23.323	0.733
Flores, 1997 [18]	-25.250	0.706
Han et al., 2017 [19]	-26.151	0.706
Hao Qin et al, 2022 [20]	-32.415	0.574
Zukoski, 1966 [21]	-14.323	0.836
Benjamin, 1968 [22]	-10.745	0.846
Weber, 1981 [23][24]	8.999	0.897
Ben-Mansour et al., 2010 [25]	-13.622	0.839
Improved model Eq. (32)	-3.627	1.084

Table 10 displays that all correlations applied on data from table have close and acceptable values, except for 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 somehow similar.

TABLE 10: Correlations Error in Table 4 data

Data	ARE%	E2%
Zukoski, 1966 [21]	-12.352	3.505
Benjamin, 1968 [22]	-9.566	3.440
Weber, 1981 [23]	20.053	1.736
Ben-Mansour et al., 2010 [25][24]	-11.417	3.449
Alruhaimani, 2015 [2]	11.628	2.731

CONCLUSIONS

In summary, the numerical interrelations between SL, Vslip, Frm, and Frslip have been established empirically through the analysis of available data. Additionally, the impact of void fraction, SVR, and **Co** on the proposed relationships was decided and subjected to numerical testing. The variable void fraction is known to have two primary impacts on all relations. First, the value of void fraction is inversely proportional to the range of values of SL, whereby increasing the void fraction numerically in the study the SL values range shrinking more and more resulting in a reduction in the exponential function of SL function. Second, elevating the value of void fraction results in an escalation of the discrepancy between the empirical and numerical relations. As shown in figure 24. The maximum deviation between the numerical relation and empirical relation is maximum at **void fraction**=0.9 Nevertheless, the variation observed in all void fraction values is not significant and conforms to a consistent pattern. The variable **Co** exhibits a singular impact on the SL correlations. The disparity between the empirical and numerical correlations expands as the value of **Co** is elevated knowing that the changeability in **Co** values is minimal and support to predicted SL/Vslip relation. Ultimately, the recently suggested SL values were juxtaposed with the SL values presented in the work of Alsarkhi et al. [1], and the discrepancies were determined to be as follows: A comparison between the Alsarkhi et al. [1], SL and SL by Vslip assessments reveals a marginal error rate of 4.42% where the relationship deemed error-free as it is derived through mathematical means. The evaluation between numerical and empirical relations for SL by Frslip indicates an error rate of 2.27%. Moreover, according to Alsarkhi et al. [1], [1] proposal generated and supported using Alruhaimani's (2015) data [2], the SL is exponentially connected to Frm in the form of **SL = A Frm^B**, where A and B equal 300.13 and -2.475 respectively. In this thesis A has been defined as the density effect factor with relation as $A = 2 \times \frac{(\rho_g + \rho_L)/2 - \rho_H}{\rho_g}$. Additionally, a novel correlation Eq. (32), discovered as a drift flux model and refined using Abrahamian's (2015) data [2], and verified against experimental data, and showed excellent applicability for all flow patterns but only in vertical flow where **Co = 1.577** and **Vd = 0.147√gD**. Moreover, utilizing the bubbly and annular flow data from the trials in table 3 with 2412 experimental data 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 Alruhaimani's (2015)

data [2], where the flowing fluids are oil/air, and the pipe angle is 90 degrees showed a good relation in data with different pipe and fluid conditions. The investigation revealed that the SL/Frm relationship produces poor results in the water/nitrogen region and at low superficial liquid velocity locations if the density effect factor not applied where these weak areas are enhanced by involving the density effect factor. As a result, SL is unaffected by pipe diameter and angle, but is affected by fluid density and flow pattern. In this work, a strong SL/Frm connection was verified and accepted in annular and 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 work shows that the SL for bubbly flow is mostly found when SL between 0 and 15 with V_{sg} varies between 0 and 25 m/s and annular flow when usually SL between 0 and 0.71 with V_{sg} varies between 16 and 200 m/s . As a result, once the SL/Frm relation includes the density impact, the flow pattern and void fraction can be predicted using the SL/Frm relation. Where SL can be found by knowing the mixture velocity and pipe diameter and by knowing the range of V_{sg} flow pattern can be predicted and using eq.(19) the void fraction can be found.

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Vitae

JABER ALYAMI

PROFESSIONAL SUMMARY

One who, despite being just twenty-six years old, has worked as an engineer for three years in the oil and energy industry. This individual is skilled in a multitude of areas, including analysis, technical support, presentation, creative thinking, and problem solving. Engineer with a Master of Science in mechanical engineering from King Fahd University of Petroleum and Minerals (KFUPM).

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WORK HISTORY

Project Engineer, 03/2023 to Current

Aramco

Covering the tie in and non tie in maintain potential projects

Maintenance Engineer, 03/2022 to 03/2023

Aramco

Working as maintenance engineer in ABQQ Plants as support for the OME team

Project Engineer, 08/2021 to 03/2022

Aramco

- As part of SAOO TSD MPU team, supporting coordinating oil and water wells construction in North Ghwar field

Operation Engineer, 07/2020 to 08/2021

Aramco

- Abqaiq Gas oil separation plants as operation engineer where huge experience is gained through following the separation process and monitor the plant production.

Project Engineer, 02/2020 to 07/2020

Aramco

- Covering maintain potential (MP) projects in North Ghawar area, many challenges from squeezed schedule to handling several projects in the same time were great opportunity to learn

CDPNE partner, 09/2018 to 02/2020

Aramco

EDUCATION

Master's degree, Thermal and Fluid Science, Expected in 05/2023

King Fahd University of Petroleum & Minerals - KFUPM

Bachelor's degree, Mechanical Engineering, 2020

King Fahd University of Petroleum & Minerals - KFUPM

with the second honor

CERTIFICATIONS

NCEES FE issued on Feb 2022

SKILLS

- Presentation creation
- Contract negotiation
- Project estimation
- Engineering support
- Equipment installation
- Technical troubleshooting
- Project scheduling
- Process optimisation
- Analytical research
- Self-motivated
- Data analysis