Research Article

A unified correlation for predicting slug liquid holdup in viscous two-phase flow for pipe inclination from horizontal to vertical

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Abstract

This study presents new measured slug liquid holdup data for liquid viscosity ranging from 200 to 800 mPa s. The experiments were conducted using two different large pipe diameters (0.08 and 0.1 m) and pipe inclination angles of 0°, 30°, 60° and 90° from horizontal. To our best knowledge, most of the existing experimental data were limited to either vertical or horizontal flow and mostly performed using small pipe diameters. Based on the measured data, a new unified empirical correlation is developed to predict slug liquid holdup for viscous two-phase flow in horizontal, vertical and inclined pipes. The proposed correlation is simple and fully consistent with the trends of published experimental data. This study also investigates in details the performance of the existing liquid holdup correlations using different flow conditions. The investigation reveals several discrepancies associated with these correlations. Based on statistical analysis, the proposed correlation performs best as compared to the existing correlations using both the present measured data and data from three independent sources.

List of symbols

A, C   Constants
d   Pipe diameter (m)
g   Acceleration gravity (m/s^2)
N   Dimensionless number
H   Slug liquid holdup
N_f Inverse viscosity number
N_{Re} Reynolds number
T   Temperature (°C)
V   Velocity (m/s)

Greek letters

ε Residual error
ϕ Correlation independent parameter
σ Surface tension (N/m)
μ Viscosity (kg/m s) (Pa s)
ρ Density (kg/m^3)
$\Delta\rho$ Density difference (kg/m^3)
θ Inclination angle from horizontal (°)

Subscripts

Fr   Froude number
g   Gas phase
L   Liquid phase
m   Mixture phase
s   Superficial
LS   Liquid slug
µ   Viscosity
C   Celsius

1 Introduction

Two-phase flow is a common occurrence in oil and gas production and transportation. The most common flow regime, in the pipelines, is the slug flow, which is described by alternating liquid slugs and gas intervals. Many theoretical and experimental studies for predicting flow regimes, liquid holdup and pressure drop in two-phase slug flow

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are available in the literature. Most of these studies were dealing with low viscosity two-phase slug flow. However, new challenges have appeared for the petroleum and chemical industries where high viscosity liquid and gas flows are increasingly occupied. Liquid viscosities were found to significantly affect flow behaviors, such as flow regimes, liquid holdup and hence, the pressure drop. The slug liquid holdup is the liquid fraction in the slug body and is required for the closure of most two-phase slug flow mechanistic models. The prediction of slug liquid holdup has been studied widely; however, it has not been solved yet, especially for inclined pipe and high viscosity systems.

Several theoretical and experimental studies investigated the prediction of the slug liquid holdup. A survey of these studies revealed that the slug liquid holdup (H_{LS}) is a function of several flow parameters, namely, superficial gas velocity (V_{sg}), mixture superficial velocity (V_m), liquid density (ρ_L), angle of inclination from horizontal (θ), superficial liquid velocity (V_{sl}), liquid viscosity (μ_L), surface tension (σ_L) and pipe diameter (d). Observations of Al-Ruhaimani et al. [5], Al-Safran et al. [8], Andreussi and Bendiksen [9], Baba et al. [10], Baba et al. [11], Brito et al. [15], Farsetti et al. [18], Gokcal [20], Gregory et al. [22], Kora et al. [23], Nadler and Mewes [25], Nuland [26], Pan [28], Wang et al. [31], Wen et al. [32], Zhao et al. [34], Zhao et al. [35] showed a clear inverse relationship between H_{LS} and both V_{sg} and V_m. The H_{LS} decreases with the increase of V_{sg}, due to sweeping out the liquid phase from the pipe resulting in more of the gas phase occupying the pipe cross sectional area. On the other hand, there is a slight increase in H_{LS} with the increase of V_{sl}, due to an increase in the input of liquid content in the pipe. It seems that the effect of V_{sg} on H_{LS} is stronger than the effect of V_{sl}, hence the overall effect of V_m (sum of V_{sg} and V_{sl}) is that as the V_m increases the H_{LS} decreases.

Wen et al. [32] investigated the effect of liquid medium, in terms of liquid density and the proportion of heavy components, on the liquid holdup. The authors observed that the H_{LS} is proportional to high content of heavy components and inversely related to ρ_L. The inverse relationship between H_{LS} and ρ_L is also confirmed by the mechanistic model of Barnea and Brauner [12].

Nuland et al. [27] and Gomez et al. [21] observed a slight decrease in H_{LS} as the angle θ increases. Gomez et al. [21] concluded that H_{LS} is maximum at horizontal flow conditions, decreasing as the upward inclination increases, and it is minimum for upward vertical flow. The mechanistic models of Abdul-Majeed and Al-Mashat [3] and Brauner and Ullmann [14] confirmed the decreasing of H_{LS} with increasing of θ from horizontal. Al-Ruhaimani et al. [5] compared their vertical data with Kora et al. [23] horizontal data and observed a decrease in H_{LS} with increasing of θ and a decreasing effect of θ on H_{LS} with increasing of V_m.

The effect of σ_L on H_{LS} was studied by Nadler and Mewes [25], Pereyra et al. [29] and Brito et al. [15] using data of air/water and air/oil with a moderate liquid viscosity (μ_L up to 120 mPa s). These studies revealed that σ_L has a significant effect on H_{LS} for low superficial gas velocity (less than 0.5 m/s). Above this value of V_{sg}, a decreasing effect of σ_L was observed and the effect of μ_L becomes the dominant, resulting in larger values of H_{LS} for air/oil data as compared to air/water data. The effect of σ_L can be explained in terms of gas bubble rise velocity. As the surface tension increases, the bubble rise velocity increases resulting in bubble accumulation, which promotes bubble loss rate and increase liquid holdup.

Regarding the effect of pipe diameter, the observations of Wen et al. [32] and Andreussi and Bendksen [9] and the mechanistic models of Barnea and Brauner [12] and Abdul-Majeed and Al-Mashat [3] indicated a slight increase of H_{LS} with increasing of pipe diameter. Godbole et al. [19] stated that the reason, for this effect, is due to higher bubble rise velocity in larger pipe diameter.

Several experimental studies have been conducted to investigate the effect of μ_L on H_{LS} in vertical and horizontal two-phase flow [5, 8, 10, 11, 15, 20, 23, 25, 26, 28, 31, 34, 35]. All these studies showed that for medium to high liquid viscosity, H_{LS} increases as μ_L increases. The liquid level in the pipe cross section increases when liquid viscosity increases owing to the increase in shear around the pipe wall and resistance to flow, which leads to an increase of H_{LS}. A number of researchers [17, 24, 33] observed a dual effect of liquid viscosity on gas holdup (1-H_{LS}). They found that for low liquid viscosity (up to 3 mPa s.), the gas holdup increases with the increase of liquid viscosity, whereas, above 3 mPa s., the gas holdup decreases with increasing of liquid viscosity. This behavior can be explained by the increase in bubble coalescence due to large drag forces in two-phase flow with liquid viscosity greater than 3 mPa s. For low liquid viscosity, drag forces are not large enough to cause bubbles coalescence, instead these forces could contribute to a more uniform distribution of bubbles resulting in higher gas holdup (lower liquid holdup).

The objective of the present study is to investigate the effect of μ_L on H_{LS} in vertical, horizontal and inclined viscous two-phase flow. At the beginning, the behavior of the existing slug liquid holdup correlations, that accounting for liquid viscosity, is compared with the trends of the published experimental data and also tested against variation of the flow parameters. The correlations included are those of Gomez et al. [21], Abdul-Majeed [2], Kora et al. [23], Al-Safran et al. [8] and Al-Ruhaimani et al. [5]. Other correlations, namely, Abdul-Majeed and Al-Mashat [3], Brauner and Ullmann [14], Al-Safran [7] and Wang et al. [31] are not included due to their complexity. An experimental study is then conducted to provide a new data set

of slug liquid holdup data for viscous two-phase flow covered liquid viscosity ranging from 200 to 800 mPa s. A new unified semi-empirical correlation is proposed to predict H_{LS} for viscous two-phase flow in horizontal, vertical and inclined pipes. Finally, the proposed and the existing correlations are tested against the present experimental data and also against data from three different sources. The following section describes and tests the existing correlations against variation of mixture superficial velocity and liquid viscosity, while keeping other parameter constants (pipe diameter = 0.04 m, liquid density = 850 kg/m³, gas density = 2 kg/m³, gas viscosity = 0.02 mPa s).

1.1 Gomez et al. correlation

Gomez et al. [21] proposed the following correlation for predicting horizontal to vertical upward flow, as a function of the slug Reynolds number (N_{ReSL})

$$H_{LS} = 1.0e^{-\left(0.00784\theta + 2.48 \times 10^{-6} N_{Re_{SL}}\right)} \tag{1}$$

$$N_{Re_{SL}} = \frac{d\rho_L V_m}{\mu_L} \tag{2}$$

where θ is the inclination angle from horizontal in degrees. Figure 1 shows the results of Eq. (1) against liquid viscosity for V_m = 1.5 m/s and θ = 0. The performance of Eq. (1) with the variation of V_m and μ_L is given in Fig. 2. As noted, Eq. (1) shows the expected trend of increasing H_{LS} with increasing of μ_L and decreasing of V_m. However, this correlation tends to yield H_{LS} close to unity for μ_L greater than 100 mPa s, indicating an overestimation of slug liquid
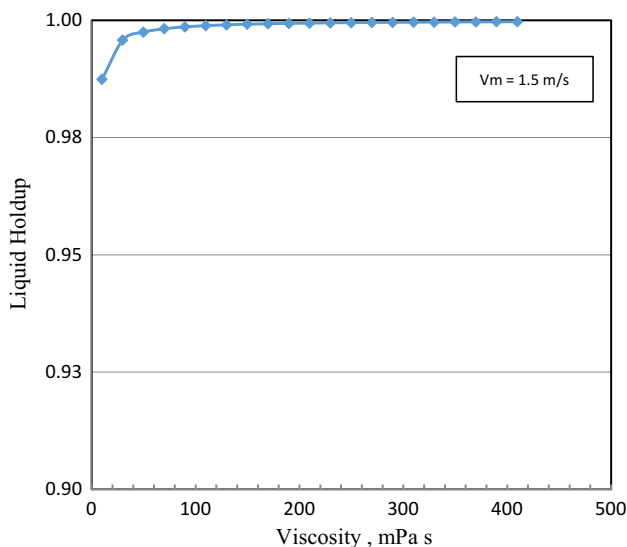

Fig. 1 Liquid viscosity effect on slug liquid holdup predicted by Gomez et al. [21]
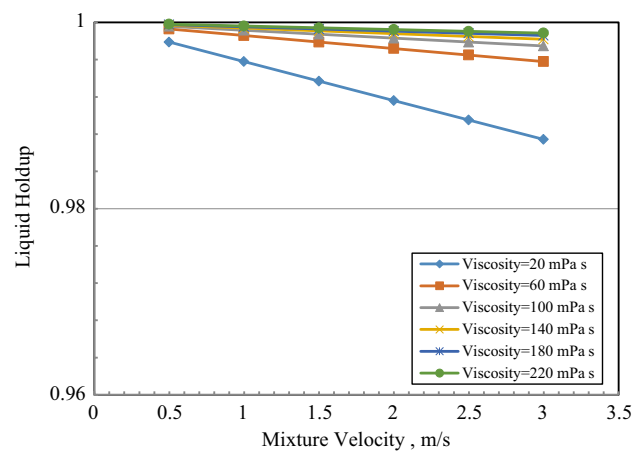

Fig. 2 Performance of Gomez et al. [21] correlation using different liquid viscosities

holdup for viscous two-phase horizontal flow. Figure 2 shows that there is a decreasing effect of V_m on H_{LS} with increasing of μ_L. Analysis of Eqs. (1) and (2) indicates a decrease in H_{LS} with increasing of d, which mismatches with the experimental data of Wen et al. [32], Abdul-Majeed [1] and Andreussi and Bendksen [9].

1.2 Abdul-Majeed correlation

Abdul-Majeed [2] developed a correlation to predict H_{LS} for horizontal and slightly inclined flow:

$$H_{LS} = \left(1 - CV_m\right)A \tag{3}$$

$$C = 0.06 + 1.3377\left(\frac{\mu_g}{\mu_L}\right) \tag{4}$$

$$A = \begin{pmatrix} 1.0 & \theta \leq 0 \\ 1 - \sin\theta & \theta > 0 \end{pmatrix} \tag{5}$$

Performance of Eq. (3) with variation of μ_L for horizontal flow at V_m = 1.5 m/s is shown in Fig. 3. As noted, H_{LS} increases with the increase of μ_L, however for high liquid viscosity, this effect becomes less significant. Figure 4 illustrates the effect of both the μ_L and V_m using Abdul-Majeed [2] correlation. As shown, this correlation does not well account for effect μ_L on H_{LS}. This implies that Eq. (4) needs a revision to reveal the actual effect of μ_L. Analysis of Eq. (5) indicates that H_{LS} decreases with increasing of θ which matches with the experimental data of Nuland et al. [27], Gomez et al. [21] and Al-Ruhaimani et al. [5].

1.3 Kora et al. correlation

Based on experimental data, Kora et al. [23] observed a direct relationship between H_{LS} and μ_L (180–587 mPa s).
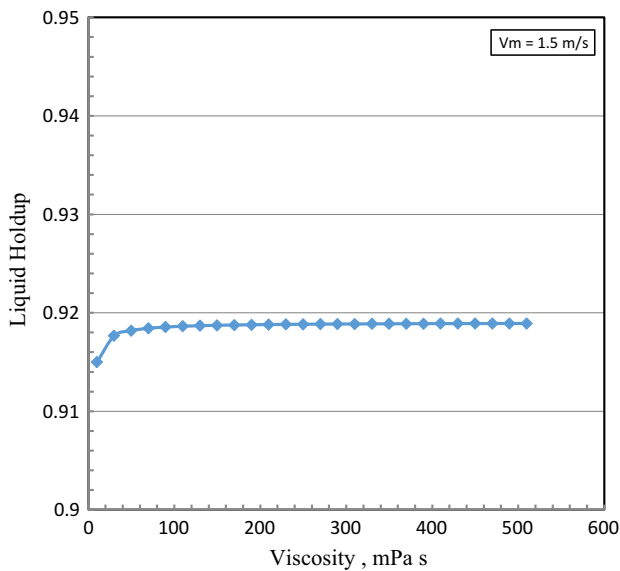
Fig. 3 Liquid viscosity effect on horizontal slug liquid holdup predicted by Abdul-Majeed [2]
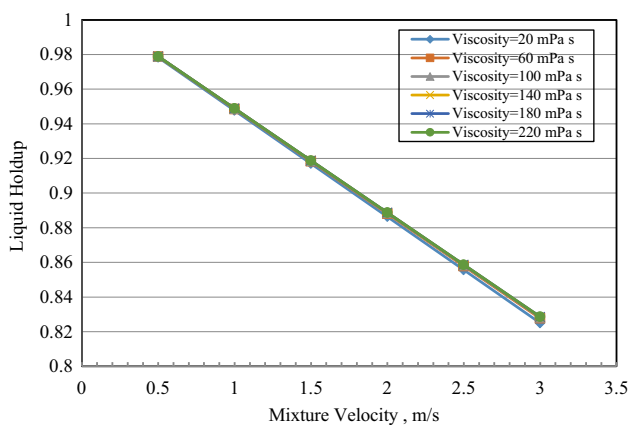
Fig. 4 Performance of Abdul-Majeed [2] correlation using different liquid viscosities

They proposed the following correlations for prediction **H_{LS}** as a function of two dimensionless groups representing Wallis Froude number (**N_{Fr}**) and viscosity number (**N_μ**):

$$H_{LS} = 1.012e^{\left(-0.085 N_{Fr} N_\mu^{0.2}\right)}, \quad 0.15 < N_{Fr} N_\mu^{0.2} < 1.5 \tag{6}$$

$$H_{LS} = 0.9473e^{\left(-0.041 N_{Fr} N_\mu^{0.2}\right)}, \quad N_{Fr} N_\mu^{0.2} \geq 1.5 \tag{7}$$

$$H_{LS} = 1.0, \quad N_{Fr} N_\mu^{0.2} \leq 0.15 \tag{8}$$

where

$$N_{Fr} = \frac{V_m}{(gd)^{0.5}} \sqrt{\frac{\rho_L}{(\rho_L - \rho_g)}} \tag{9}$$

$$N_\mu = \frac{V_m \mu_L}{gd^2 (\rho_L - \rho_g)} \tag{10}$$

The performance of Kora et al. correlation (2011) presented in Fig. 5, shows an inverse relationship between slug liquid holdup and liquid viscosity. This disagrees with the experimental studies and most of the published correlations. To explain this unexpected behavior, the term $N_{Fr} N_\mu^{0.2}$ is simplified as:

$$N_{Fr} N_\mu^{0.2} = \frac{V_m^{1.2} \mu_L^{0.2} \rho_L^{0.5}}{g^{0.7} d^{0.9} \Delta\rho^{0.7}} \tag{11}$$

Equations (6) and (7) can be expressed as:

$$H_{LS} = 1.012e^{\left(\frac{-0.085 V_m^{1.2} \rho_L^{0.5} \mu_L^{0.2}}{g^{0.7} d^{0.9} \Delta\rho^{0.7}}\right)} \tag{12}$$

$$H_{LS} = 0.9473e^{\left(\frac{-0.041 V_m^{1.2} \rho_L^{0.5} \mu_L^{0.2}}{g^{0.7} d^{0.9} \Delta\rho^{0.7}}\right)} \tag{13}$$

Several comments can be drawn from Eqs. (12) and (13). First, the predicted slug liquid holdup increases with decreasing of liquid viscosity, which opposes with the experimental liquid holdup data of Nuland [26], Gokcal [20], Pan [28], Al-Ruhaimani et al. [5] and Baba et al. [10]. Second, the predicted slug liquid holdup is proportional
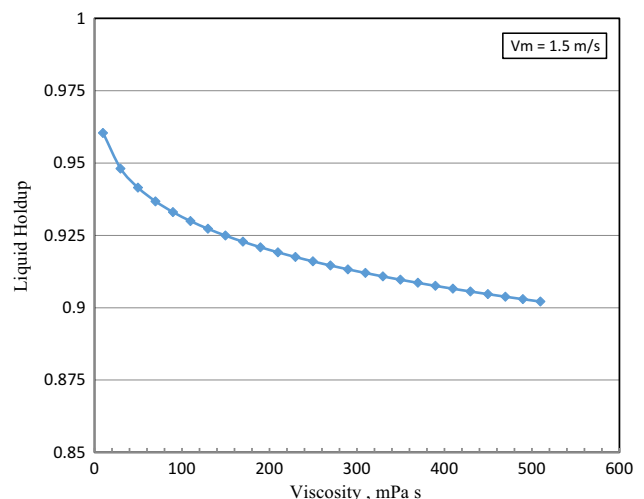
Fig. 5 Liquid viscosity effect on slug liquid holdup predicted by Kora et al. [23]

to liquid density (the net effect of ρ_L and $\Delta\rho$, for $\rho_L \gg \rho_g$), whereas the experimental study of Wen et al. [32] showed an opposite relationship. Also, the mechanistic model of Barnea and Brauner [12] indicated that as the liquid density increases, the slug liquid holdup decreases. Third, the effect of pipe diameter on slug liquid holdup is significant as compared to the effect of liquid viscosity, as shown in Fig. 6. The results of Kora et al. [23] correlation against mixture velocity and liquid viscosity are shown in Fig. 7. As noted, the slug liquid holdup decreases with the increase of both mixture velocity and liquid viscosity. Figure 7 shows a high effect of liquid viscosity for V_m greater than 2 m/s. The effect becomes less significant for V_m values less than 2 m/s.

1.4 Al-Safran et al. correlation

Based on Kora et al. [23] experimental data, Al-Safran et al. [8] developed a better fitting formula using the same term suggested by Kora et al. [23], that is $N_{Fr}N_\mu^{0.2}$. Their correlation is expressed as:

$$H_{LS} = 0.85 - 0.075\emptyset + 0.057\sqrt{\emptyset^2 + 2.27} \tag{14}$$

where

$$\emptyset = \left(N_{Fr}N_\mu^{0.2} - 0.89\right) \tag{15}$$

Figure 8 shows the unexpected trend of decreasing slug liquid holdup with increasing of liquid viscosity. The prediction of Eq. (14) versus mixture velocity for different liquid viscosities is shown in Fig. 9. As noted, Al-Safran et al. [8] correlation shows the same behavior predicted by Kora
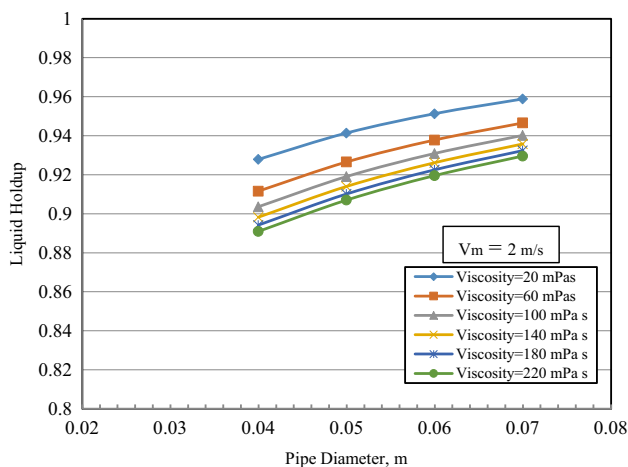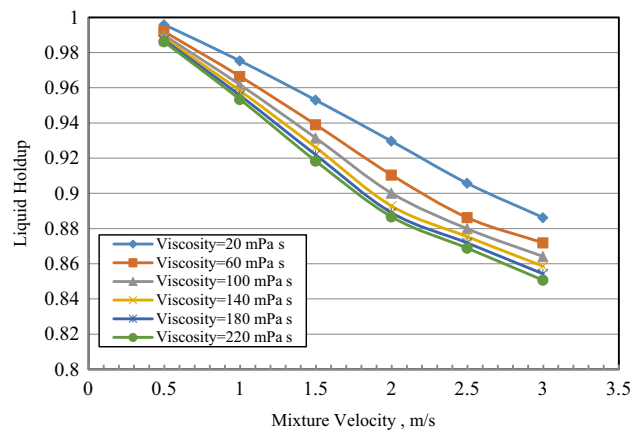
Fig. 7 Performance of Kora et al. [23] correlation using different liquid viscosities

et al. [23]. Detailed calculations of slug liquid holdup indicate that both correlations yield approximately the same results. For completeness and simplification, Eq. (15) can be rewritten as:

$$\emptyset = \left(\frac{V_m^{1.2}\mu_L^{0.2}\rho_L^{0.5}}{g^{0.7}d^{0.9}\Delta\rho_L^{0.7}} - 0.89\right) \tag{16}$$

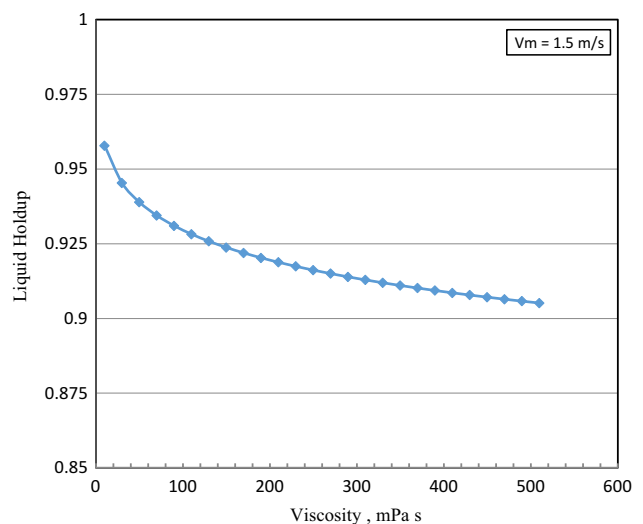Analysis of Eq. (16) reveals the same above three comments associated with Kora et al. correlation (2011).

Fig. 6 Effect of pipe diameter on liquid holdup predicted by Kora et al. [23]

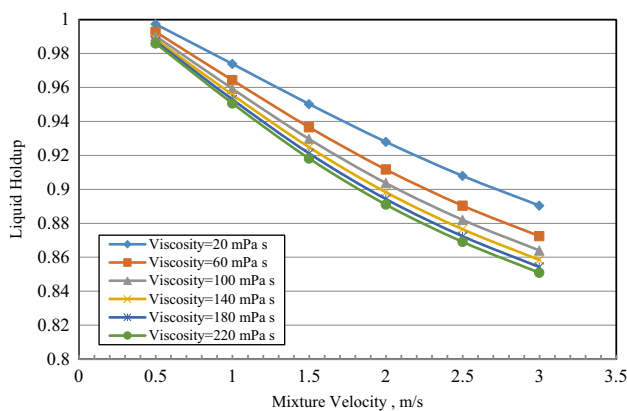**Fig. 8** Liquid viscosity effect on slug liquid holdup predicted by Al-Safran et al. [8]

Fig. 9 Performance of Al-Safran et al. [8] correlation using different liquid viscosities

1.5 Al-Ruhaimani et al. correlation

Based on experimental study of viscous (127–558.7 mPa s) upward two-phase vertical flow, Al-Ruhaimani et al. [5] developed the following correlation for predicting slug liquid holdup:

$$H_{LS} = 0.266 N_{Fr}^{-1} N_f^{-0.5} + 0.912 \tag{17}$$

where N_{Fr} is defined in Eq. (9) and N_f is the inverse viscosity number given by:

$$N_f = \frac{\sqrt{gd^3 \rho_L (\rho_L - \rho_g)}}{\mu_L} \tag{18}$$

Equation (17) can be simplified to:

$$H_{LS} = \frac{0.266 \mu_L^{0.5} g^{0.25} \Delta \rho^{0.25}}{d^{0.25} \rho_L^{0.75} V_m} + 0.912 \tag{19}$$

Equation (19) reveals that the slug liquid holdup increases with increasing of liquid viscosity and decreasing of mixture velocity (see Figs. 10, 11). This agrees with the published horizontal experimental studies [8, 20, 23]. Also, Al-Ruhaimani et al. [5] correlation reveals the correct inverse relationship between slug liquid holdup and liquid density; however, it indicates an increase in liquid holdup with decreasing of pipe diameter which is not in agreement with observations of Wen et al. [32] and Andreussi and Bendksen [9]. Also the mechanistic models of Barnea and Brauner [12] and Abdul-Majeed and Al-Mashat [3] indicated an increase of slug liquid holdup with increasing of pipe diameter. Another worthy note is that Al-Ruhaimani et al. [5] predicts a very narrow range of liquid holdup and always yields slug liquid holdup greater than 0.912. Detailed results show that the first term on the right hand
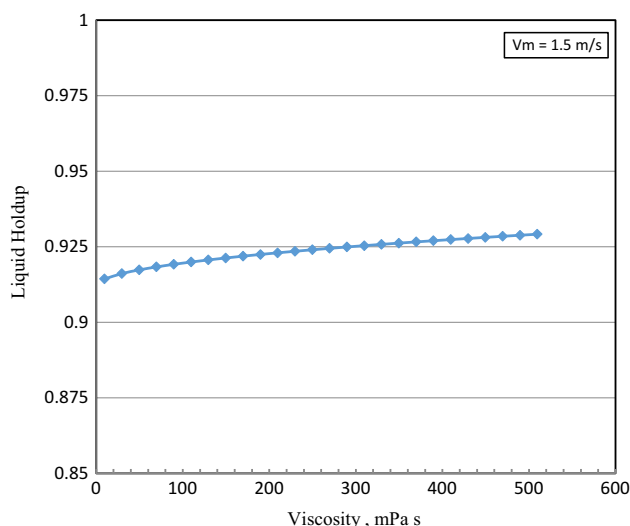

Fig. 10 Liquid viscosity effect on slug liquid holdup predicted by Al-Ruhaimani et al. [5]

side of Eq. (19) predicts very little effect on liquid holdup, for example, for $\mu_L = 100$ mPa s, the term is only 0.0054 and it becomes 0.012 for $\mu_L = 500$ mPa s. Figure 11 shows the results of Eq. (19) against mixture velocity for different liquid viscosities. As noted, the effect of liquid viscosity is significant for low mixture velocity (less than 2 m/s). For greater values of V_m, the effect is less significant. This behavior is exactly the opposite of that shown by both Kora et al. [23] and Al-Safran et al. [8] correlations.

2 New correlations

From the above analysis, it is clear that there is a need for a new correlation that can be simple, accurate, consistent in units and consistent with observations trends. To achieve
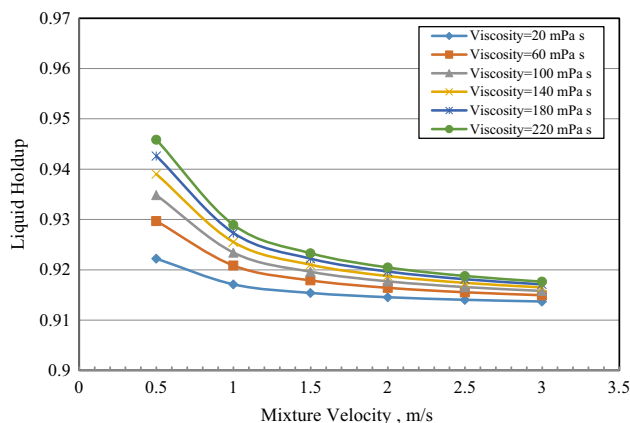

Fig. 11 Performance of Al-Ruhaimani et al. [5] correlation using different liquid viscosities

this goal, we try to correlate the slug liquid holdup with the function $N_{Fr}/N_\mu^{0.2}$, which can be written as:

$$\frac{N_{Fr}}{N_\mu^{0.2}} = \frac{V_m^{0.8} \rho_L^{0.5}}{\mu_L^{0.2} g^{0.3} d^{0.1} \Delta\rho^{0.3}} \qquad (20)$$

It is expected that the slug liquid holdup will be inversely related to the above suggested function. As already mentioned, the effect of each of the flow parameters included in this function is justified by the trends of the observations, as described earlier. The final form of the new correlation is obtained based on new measured slug liquid holdup data created from experiments conducted in two large pipe sizes. The total number of the measured data is 180, distributed as: 60 points for horizontal flow with 0.08 m and 0.1 m pipe diameters, 60 points for the inclined flow of 30 and 60 degree angles from horizontal and 60 points for vertical flow with 0.08 m and 0.1 m pipe diameters. The liquid viscosity range covered by the measured data is (200- 800) mPa s. The experimental setup is explained in the following sections.

2.1 Test fluids

Air and lubricant oil are used as test fluids. The physical properties of lubricating oil at 25 °C are: API gravity = 25.7°; density = 900 kg/m^3; surface tension = 31 mN/m. Gas properties are: density = 1.3 kg/m^3; viscosity = 0.02 mPa s. Two factory calibrated flow meters were used to measure the oil and gas flow rates, with accuracy of ± 0.05% of the scale reading. The oil viscosity is measured using rheometer at different temperature values. Fitting technique is used to

correlate the results and the following empirical equation is obtained (see Fig. 12)

$$\mu_L = 2.5e^{-0.0608Tc} \qquad (21)$$

where Tc is the temperature in °C and $\boldsymbol{\mu_L}$ in Pa s. Oil viscosities of 199, 402, 499, 601 and 802 mPa s were used during measuring liquid holdup. These viscosities were measured at temperatures of 41.6, 30, 26.5, 23.4 and 18.7 °C respectively. This viscosity variation is achieved by heating/cooling system that controls the oil temperature during circulation in the tank. Prior to starting experiments, a circulation process is done by a circulation heater, connected to the storage tank, to achieve a uniform oil viscosity. The experimental heating system is presented in Fig. 13. The oil temperature in the oil tank is increased by the circulation heater, where the desired oil temperature is entered into the heater control panel. On average, the period required to reach each desired oil temperature, is about 3 h. The range of the temperature of the circulation heater is (0–50) °C. The lubricant oil circulates through a pipe connecting the heater and the oil storage tank until the temperature reaches the desired value. For the liquid viscosity range covered, the corresponding range of the densities of the lubricant oil is from 884.7 to 908.3 kg/m^3 and the corresponding range for the lubricant oil-air surface tension is from 29.8 to 31.7 mN/m. The change in the lubricant oil density is less than 3% and the change in surface tension is less than 6%, so that an effect on the slug characteristics due to the change in oil density and surface tension is negligible in comparison to the changes in liquid viscosity.

To make sure that the lubricant oil obeys Newton's law, the flow behavior of three lubricant oil samples (200, 500 and 800 mPa s) were investigated over a wide range of

Fig. 12 Liquid viscosity versus temperature

Inside plot:
$y = 2.5e^{-0.0608x}$
$R^2 = 0.9931$

X-axis: Temperature, °C
Y-axis: Liquid Viscosity, Pa s
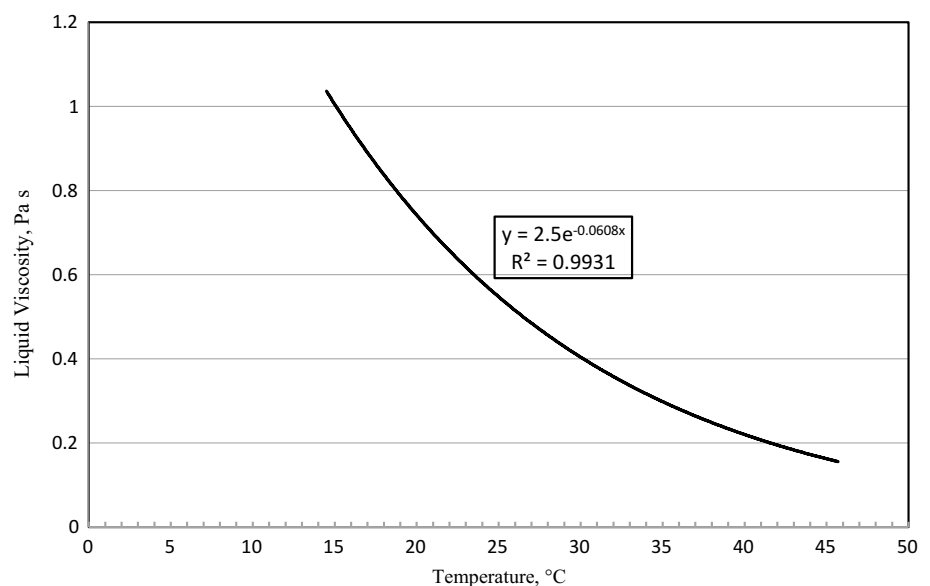
**Fig. 13** Experimental heating system

shear rates at 25 °C. The measurement tests were conducted under the controlled rate (CR) mode of the rheometer, and the values of shear stress and shear rate were obtained. The results are presented in Fig. 14, from which it can be seen that measured shear stress and shear rate of these samples are collated by a linear line, indicating the oil used in this study with viscosity up to 800 mPa s is a Newtonian fluid.

2.2 Test section

Experiments were conducted using two different polycarbonate pipe diameters (0.08 and 0.1 m), each with 18 m length. The testing pipe is connected to a return steel pipe with the same diameter and length. An inclinable boom is connected to the test section to move it up to any inclination angle from 0° to 90° from horizontal. The lubricant oil is stored in a tank of 2 m^3 capacity and feeds using cavity pump of 16 m^3/h maximum capacity. Compressed air is supplied from a screw compressor with a maximum capacity of 400 m^3/h, and with a maximum discharge pressure of

Fig. 14 Shear rate versus shear stress for different liquid viscosities
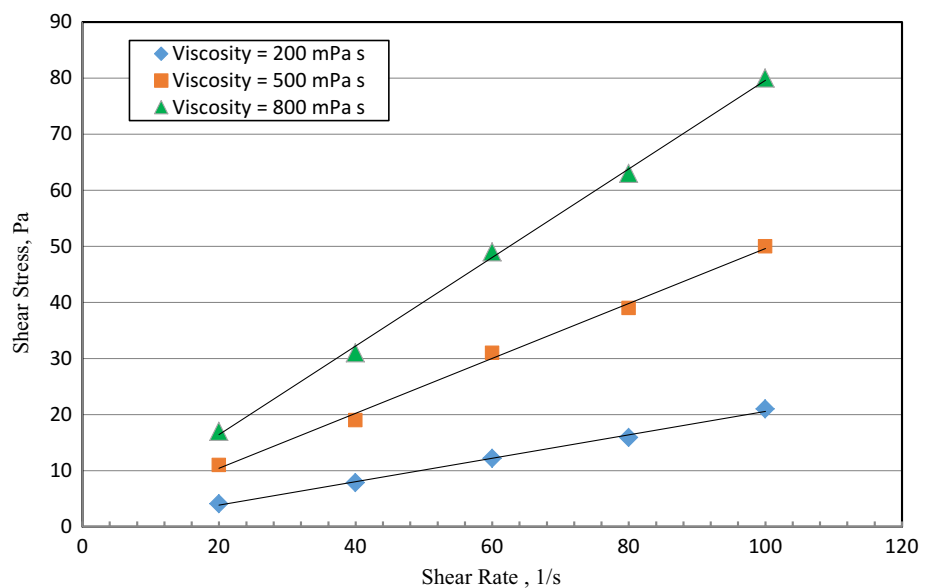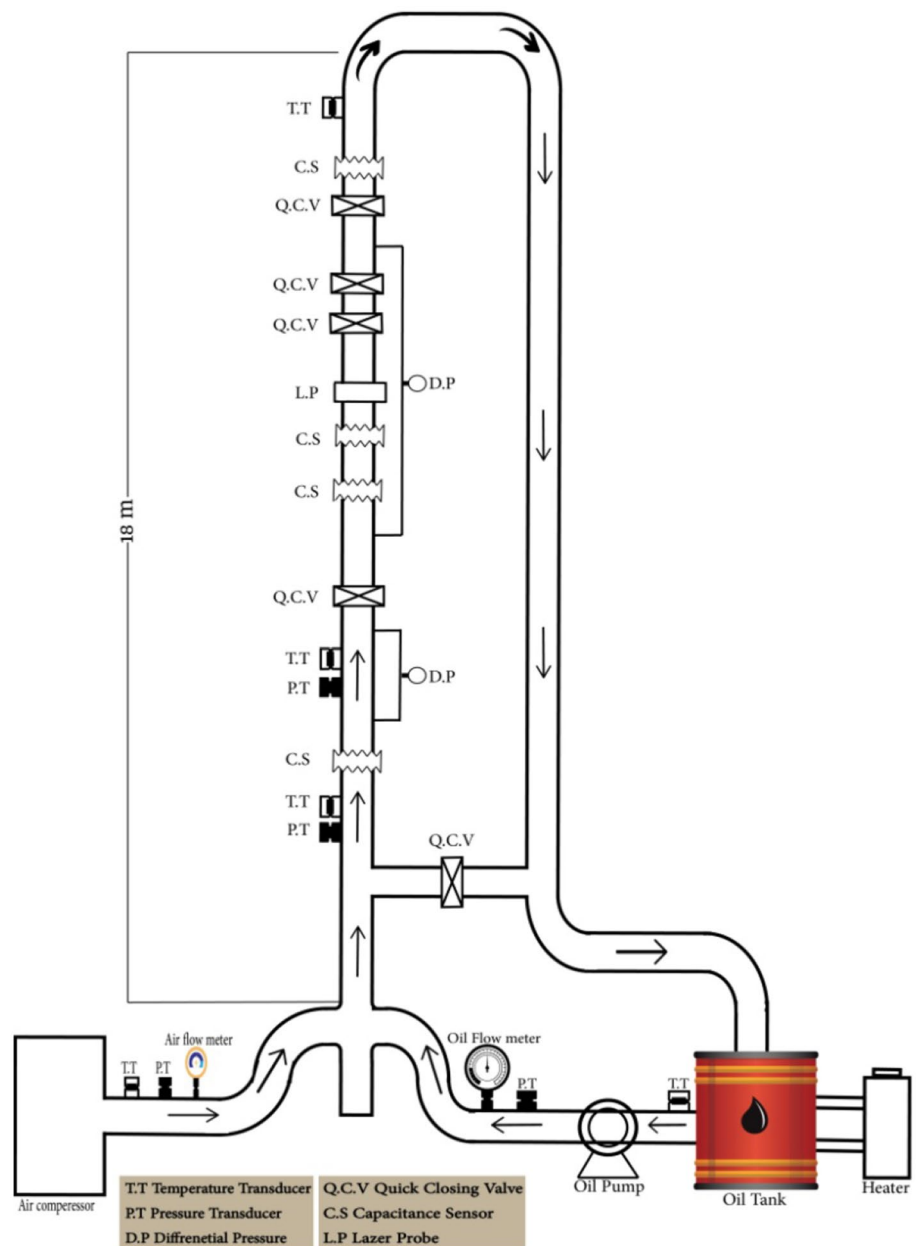
7 barg. Five temperature detectors were used to measure the temperature, three of them located at the test section and two detectors placed in the oil and gas flow lines. The pressure is measured using four pressure transducers, two are placed in the test section, the other two are located on the flow lines of oil and gas. Quick closing valve system was used to trap and determine the slug liquid holdup. Five closing valves are installed in the test section; two of them are dedicated for dynamic calibration of capacitance sensors. Four capacitance sensors (two-wire type) were used to track the development of slug flow in the test section. In addition to the capacitance sensors, there is a laser sensor installed in the test section to detect the

front of the slug and then activate the closing valves. The test platform is shown in Fig. 15. The calibrations of the closing valves and capacitance sensors and uncertainty analysis [16] are given in "Appendix".

2.3 Test matrix

Table 1 shows a description of the fluid and flow parameters covered by the measured data. To our best knowledge, this study is one of the very few studies that present viscous measured liquid holdup data for inclined two-phase flow using large pipe diameters. Most of the existing experimental data were limited to either vertical

Fig. 15 The test platform

T.T Temperature Transducer	**Q.C.V** Quick Closing Valve	
P.T Pressure Transducer	**C.S** Capacitance Sensor	
D.P Diffrenetial Pressure	**L.P** Lazer Probe	

Table 1 Description of the present measured data

V_m (m/s)	Liquid viscosity (mPa s)	Pipe diameter (m)	Inclination angle (°)	No. of data points
0.2–2.7	200–800	0.08–0.1	0	60
0.45–2.0	200–600	0.08–0.1	90	60
0.82–4.14	500	0.08	30, 60	60

or horizontal flow and mostly performed using small pipe diameters. The ranges of the investigated superficial gas and liquid velocities are (0.2–1.85) m/s and (0.05–0.25) m/s for vertical flow, (0.6–3.9) m/s and (0.07–0.39) m/s for inclined flow of 30° from horizontal, (0.6–2.8) m/s and (0.1–0.32) m/s for inclined flow of 60° from horizontal, (0.1–2.4) m/s and (0.1–0.3) m/s for horizontal flow. The upper limits of superficial liquid velocities are determined by the liquid pumping limitation, whereas, the upper limits of superficial gas velocities are controlled to avoid transition from slug flow to another flow pattern. Figures 16, 17 and 18 show comparisons of the measured vertical and inclined data against the flow pattern map proposed by Abdul-Majeed [1]. As can be seen, all the data points are falling within the slug flow. Figure 19 compares the horizontal measured data with Beggs and Brill [13] flow pattern map. As shown, some data points are not predicted well by this flow map and this could be attributed to viscosity and diameter effects. The uncertainties of fluid and flow properties were calculated using Taylor propagation equations as described in detail by Al-Safran [6] and

Al-Ruhaimani [4]. For V_{SL}, V_{Sg}, ρ_L, and μ_L the certainties are 0.5%, 1.9%, 1% and 1% respectively.

## 2.4 Correlations development

The measured vertical data are shown in Fig. 20. As noted, the slug liquid holdup is slightly higher for pipe diameter of 0.1 m as compared to pipe diameter of 0.08 m. This observation agrees with the finding of Wen et al. [32]. It seems that, as the pipe diameter increases in viscous two-phase flow, the bubble rise velocity increases, resulting in reduction of the gas residence time and then reducing the gas void fraction (i.e., increasing of liquid holdup). Figure 21 presents the vertical measured liquid holdup vs. liquid viscosity. The slug liquid holdup increases as the liquid viscosity increases. The scatter is due to the effect of mixture velocity, which varies for vertical flow from 0.45 to 2.0 m/s (as described in Table 1).

Figure 22 shows the measured slug liquid holdup versus $N_{Fr}/N_\mu^{0.2}$ for vertical data. The proposed correlation that can best fit the vertical measured data is:

$$H_{LS} = 0.961 - 0.0083 N_{Fr} N_\mu^{-0.2} \tag{22}$$

Figure 23 displays the measured horizontal data for both pipe diameters 0.08 m and 0.1 m. As can be seen, the slug liquid holdup value increases slightly with increasing of pipe diameter for the same mixture velocity. The measured horizontal slug liquid holdup data are plotted against $N_{Fr}/N_\mu^{0.2}$ as shown in Fig. 24. These data can be represented by the following correlation:
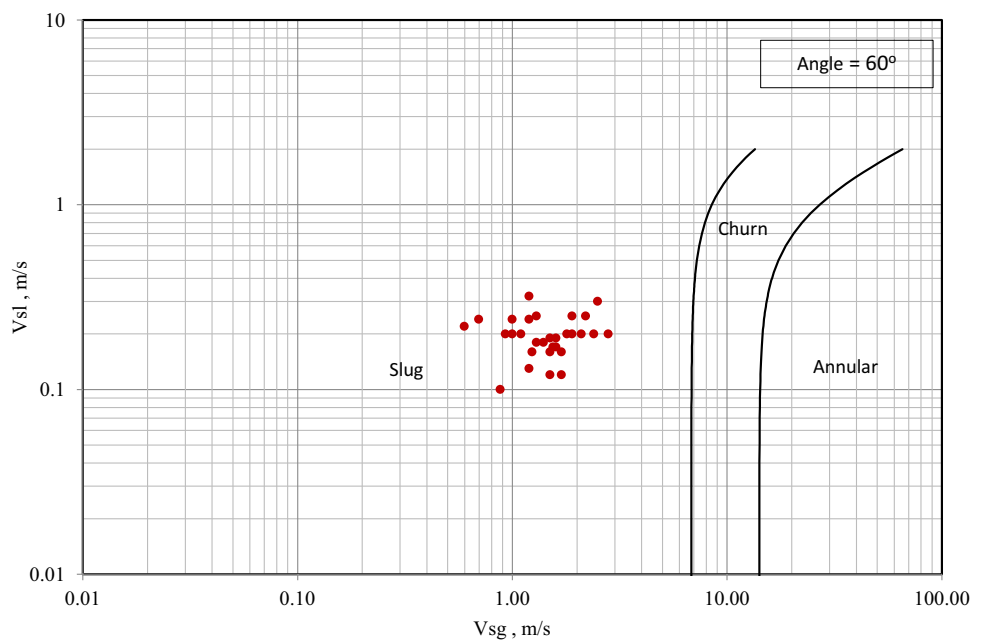
Fig. 16 Measured vertical data superimposed on Abdul-Majeed [1] flow pattern map, using 0.08 m pipe size
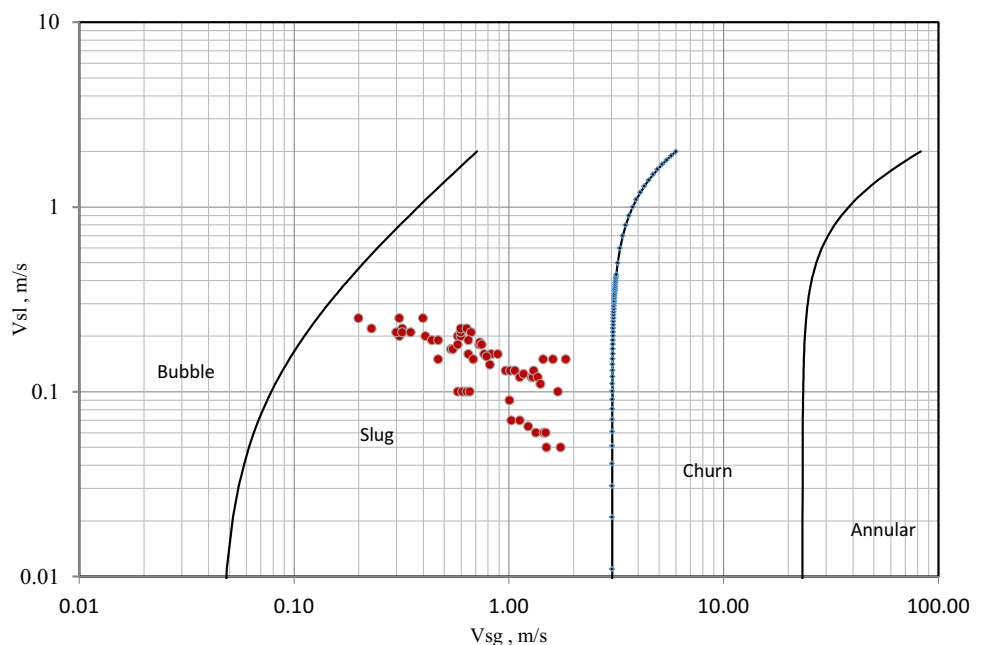
Fig. 17 Measured 30° inclined data superimposed on Abdul-Majeed [1] flow pattern, using 0.08 m pipe size
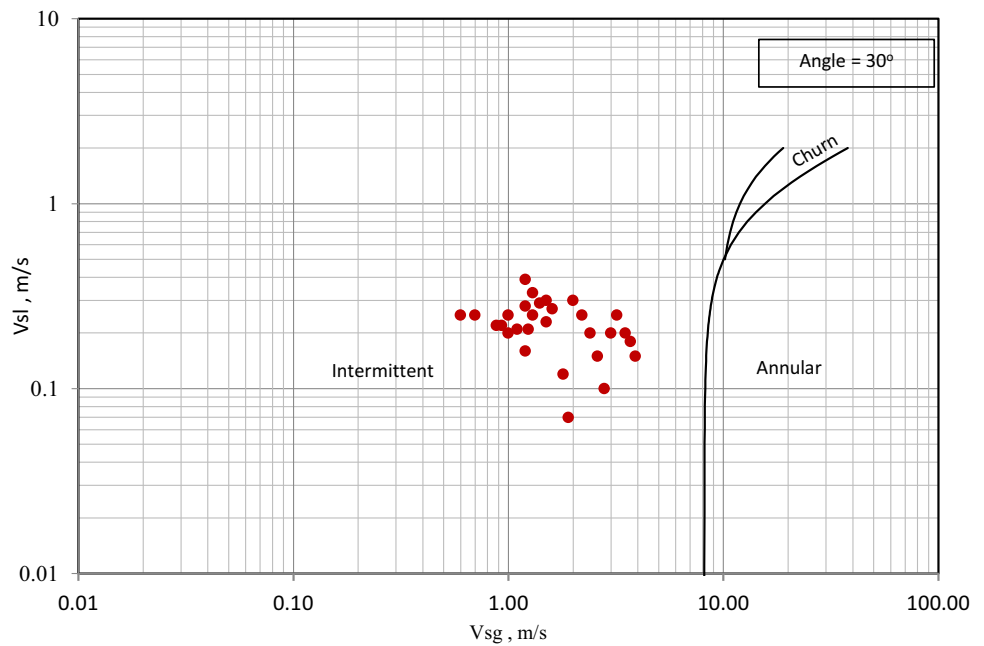
Fig. 18 Measured 60° inclined data superimposed on Abdul-Majeed [1] flow pattern, using 0.08 m pipe size

$$H_{LS} = 1.016 - 0.0195 N_{Fr} N_\mu^{-0.2} \tag{23}$$

The same procedure is used for inclined data. Figures 25 and 26 show the liquid holdup values for pipe angles of 30° and 60° respectively.

The proposed correlation for 30° inclined data is:

$$H_{LS} = 0.9977 - 0.0158 N_{Fr} N_\mu^{-0.2} \tag{24}$$

For inclined data of 60° from horizontal, the following correlation is suggested:

$$H_{LS} = 0.9793 - 0.01206 N_{Fr} N_\mu^{-0.2} \tag{25}$$

To develop a unified correlation that can be used for all ranges of the inclination angle, Eqs. (22) through (25) are combined into one correlation as suggested below:
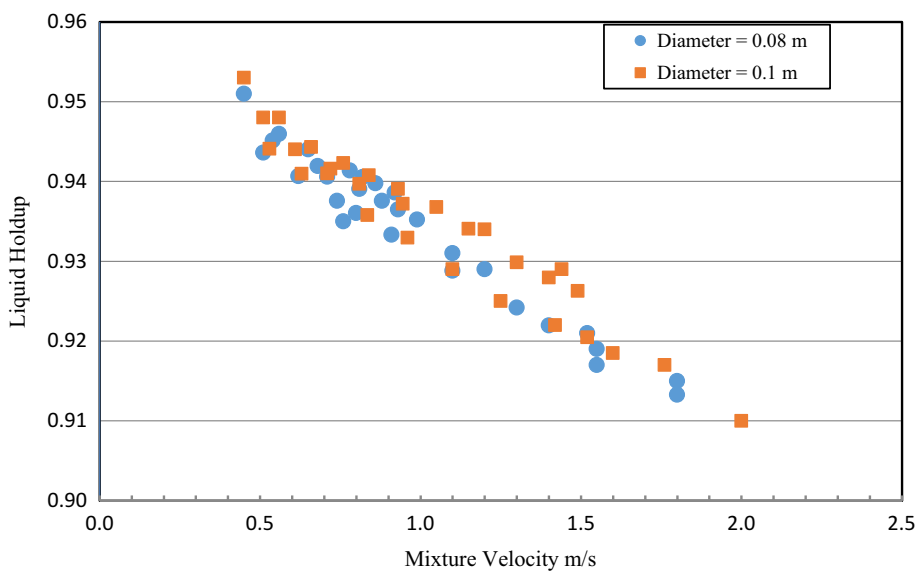
$$H_{LS} = 1.016 - 0.000611\theta + (0.000124\theta - 0.0195) N_{Fr} N_\mu^{-0.2} \tag{26}$$

where $N_{Fr} N_\mu^{-0.2}$ can be calculated from Eq. (20) and θ is the angle of inclination from the horizontal in degree.

Fig. 19 Measured horizontal data superimposed on Beggs and Brill [13] flow pattern map, using 0.08 m pipe size
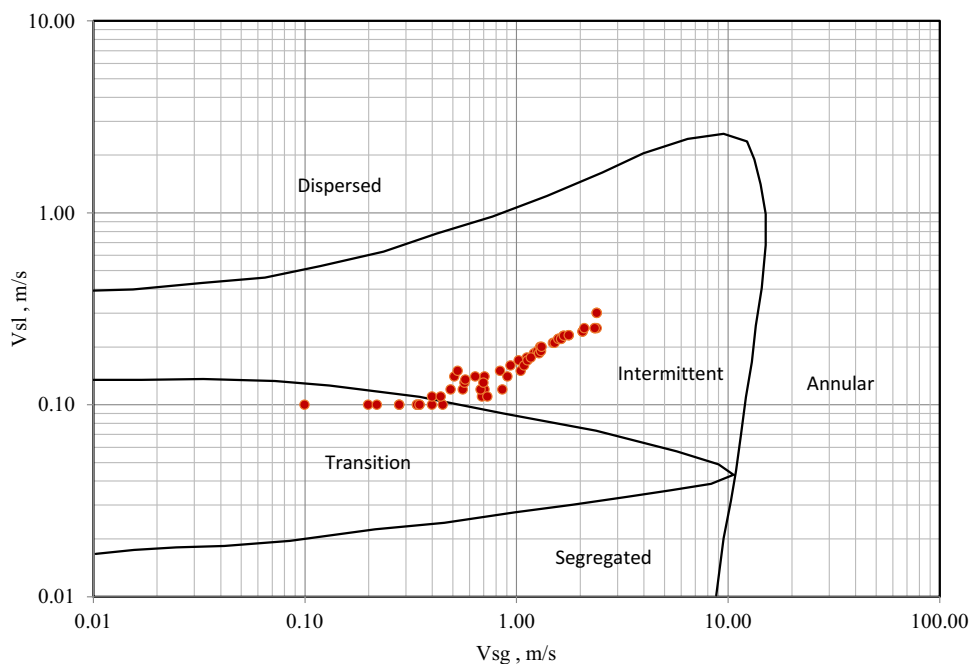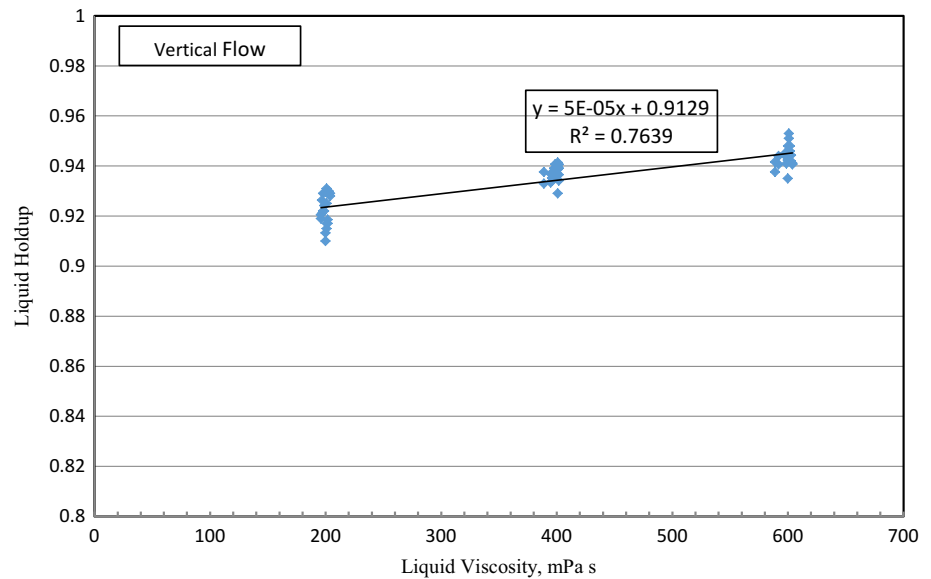

Fig. 20 Measured vertical slug liquid holdup (present study)

The results of the new correlation presented in Fig. 27, indicates an increase in liquid holdup with increasing of liquid viscosity. This is in agreement with the present and previous observations. The performance of the proposed correlation against mixture velocity for different liquid viscosities is illustrated in Fig. 28. As shown, the proposed correlation predicts high effect of liquid viscosity for high mixture velocity.

For comparison purpose, the predictions of all correlations are tested using different flow conditions. Figures 29 and 30 show the predictions for high viscosity with $V_m = 1.5$ and 3 m/s respectively. The other flow parameters are kept constant with the following values: $\rho_L = 850$ kg/m^3, $d = 0.04$ m, $\rho_g = 2$ kg/m^3, $\mu_g = 0.02$ mPa s. For both V_m values Gomez et al. [21] yields the highest liquid holdup values close to unity. For $V_m = 1.5$ m/s, Abdul-Majeed [2] and Al-Ruhaimani et al. [5] correlations give the same trend and approximately the same results for medium liquid viscosity ($\mu_L = 20$–200 mPa s). Correlations of Kora et al. [23] and Al-Safran et al. [8] give very close values. For $V_m = 1.5$ m/s, all the existing correlations yield liquid holdup greater than 0.9, whereas the proposed correlation shows that the predicted holdup can be as low as 0.83 for $\mu_L = 20$ mPa s. It is important to remark that for both mixture velocities, the

Fig. 21 Vertical slug liquid holdup versus liquid viscosity

Fig. 22 Proposed fitting correlation to measured vertical slug liquid holdup data
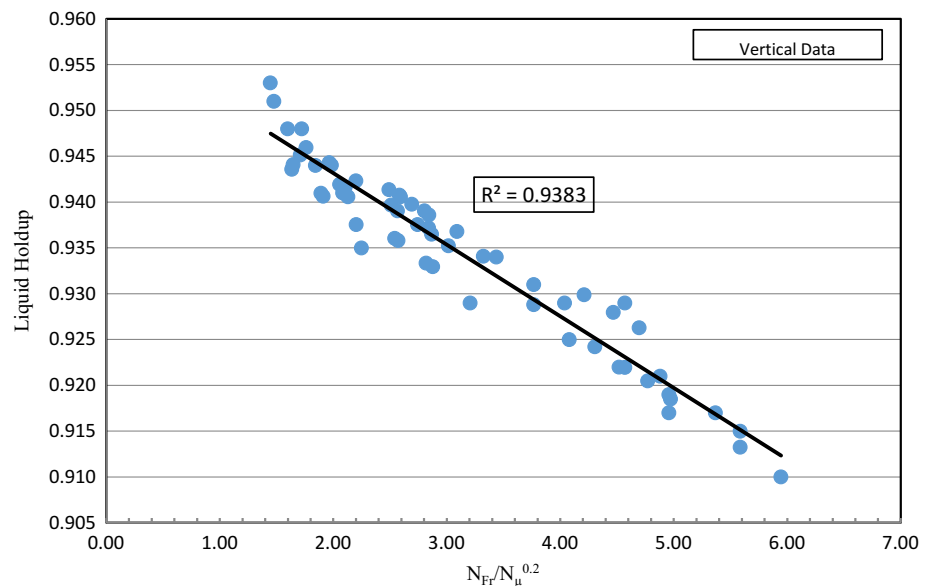
proposed correlation and those of Kora et al. [23] and Al-Safran et al. [8] predict significant effect of liquid viscosity change, but in opposite trend. That is, the proposed correlation shows an increase in liquid holdup while the correlations of Kora et al. [23] and Al-Safran et al. [8] show a decrease in liquid holdup with increasing of liquid viscosity. For both V_m values, the predictions of Gomez et al. [21], Abdul-Majeed [2] and Al-Ruhaimani et al. [5] correlations do not vary significantly. Figure 31 illustrates the prediction with the variation of pipe diameter. Gomez et al. [21] and Al-Ruhaimani et al. [5] correlations predict very slight decrease in holdup with the increase of pipe diameter, which disagrees with the observations of the present study and those of Wen et al. [32]. Abdul-Majeed [2] correlation

predicts constant values since it does not account to pipe diameter. The correlations of Kora et al. [23] and Al-Safran et al. [8] predict very high effect of pipe diameter on liquid holdup, which does not show by any experimental study. The proposed correlation predicts a reasonable increase in holdup with increasing of pipe diameter.
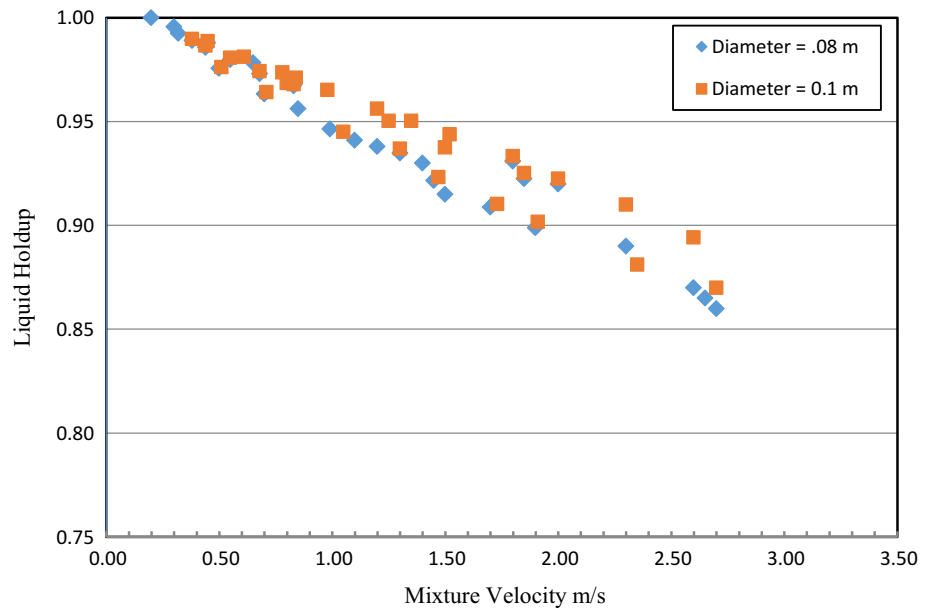
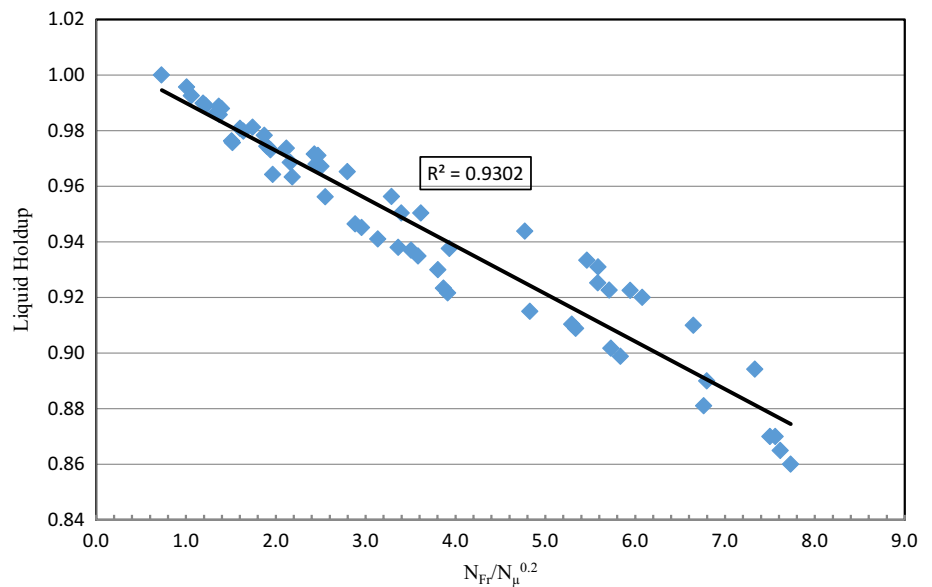## 3 Evaluation and validation

3.1 Evaluation

The proposed and the existing correlations are evaluated using the present measured data. Four statistical

**Fig. 23** Measured horizontal slug liquid holdup data (present study)

**Fig. 24** Proposed fitting correlation to measured horizontal slug liquid holdup data

parameters are selected for evaluation, namely: average relative error (ε_1), absolute average relative error (ε_2), average actual error ($\varepsilon3$) and absolute average actual error ($\varepsilon4$). Refer to Al-Ruhaimani [4] for a detailed description or equations of these parameters. The results for horizontal, vertical and inclined data are listed in Tables 2, 3 and 4 respectively. As shown, the new correlation yields the best performance among all correlations. For vertical flow, Al-Ruhaimani et al. [5] correlation is determined as the second best method. For horizontal flow, Al-Ruhaimani et al. [5] and Abdul-Majeed [2] correlations give better results as compared to Gomez et al. [21], Kora et al. [23] and Al-Safran et al. [8] correlations. For inclined data, Al-Ruhaimani et al.

[5] is again the second best correlation followed by Al-Safran et al. [8] correlation. The worse performance for vertical and inclined flows is shown by Abdul-Majeed [2] and Gomez et al. [21] correlations. It is important to remark that the results of Abdul-Majeed [2] and Gomez et al. [21] correlations can be improved significantly by eliminating the correction factor used by these authors for the effect of inclination angle. For example, for the present vertical data, when using $\theta = 0$ (instead of 90°) in these two correlations, the four statistical parameters become 0.483, 1.242, 0.463, 1.161 for Abdul-Majeed [2] correlation and 6.15, 6.15, 5.736, 5.736 for Gomez et al. [21] correlation (see Table 3 for comparison). The same observation is noticed

Fig. 25 Proposed fitting correlation to measured slug liquid holdup data of 30° inclination angle
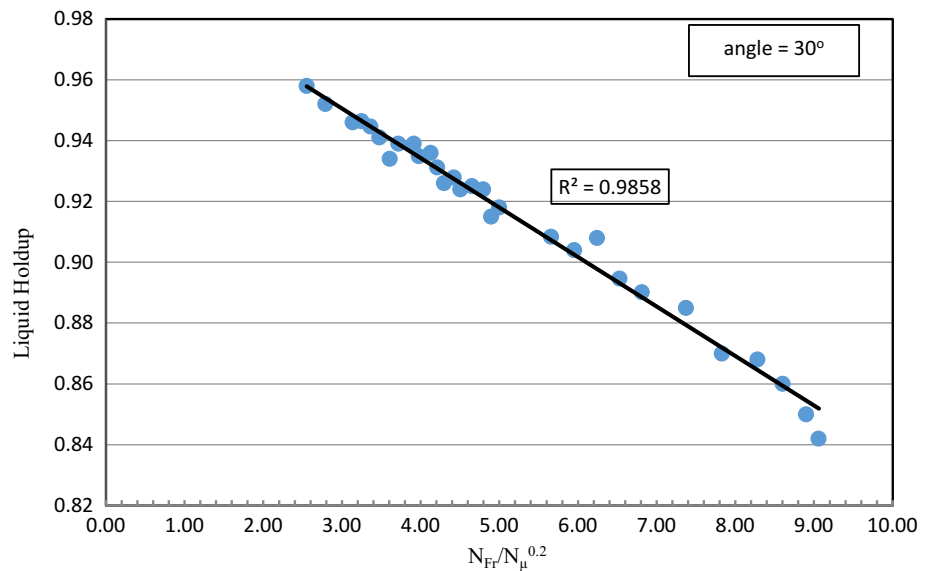
Fig. 26 Proposed fitting correlation to measured slug liquid holdup data of 60° inclination angle
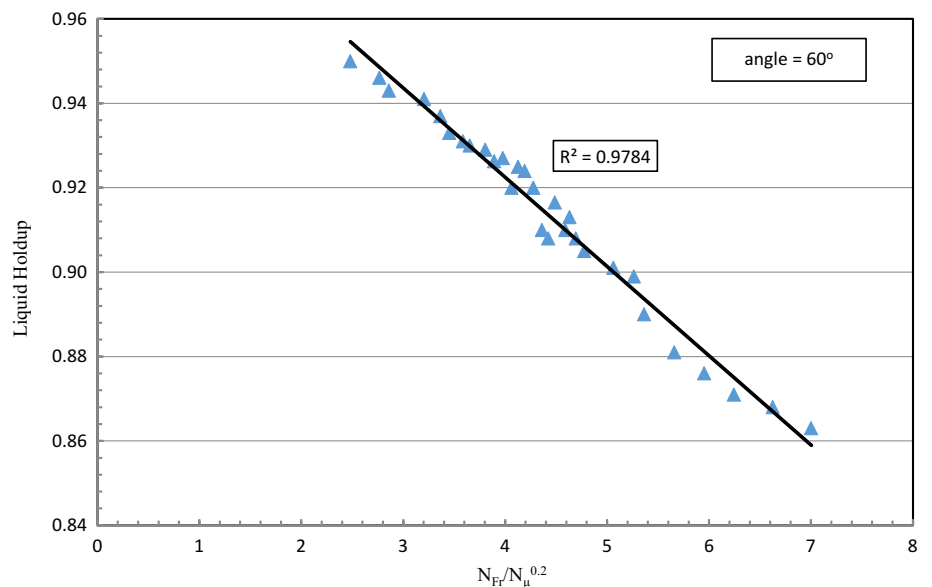

for present inclined data. Following the approach of Shi et al. [30] for performance evaluation, the measured and predicted liquid holdup for all correlations are plotted in Figs. 32, 33 and 34, for horizontal, vertical and inclined data respectively. As indicated, for horizontal and inclined data, the predictions of the proposed correlation fall within the ±3% range. For vertical flow, the prediction of the present correlation falls within the ±1% error range. The existing correlations show predictions with higher error ranges compared to the proposed, as described above and demonstrated in Tables 2, 3 and 4.

3.2 Validation

The newly proposed correlation is also tested against independent, measured data collected from three different sources. These data are those of Nuland [26] for horizontal slug flow (89 data points), Kora et al. [23] for horizontal slug flow (144 data points) and Al-Ruhaimani et al. [5] for vertical slug flow (68 data points). Before starting validation process, we would like to compare Nuland [26] data with Kora et al. [23] data, since they are both for viscous horizontal slug flow. Figure 35 shows a comparison of these two data sets. The present horizontal data points are also shown in this figure. It is noted that for approximately

Fig. 27 Liquid viscosity effect on slug liquid holdup predicted by proposed correlation
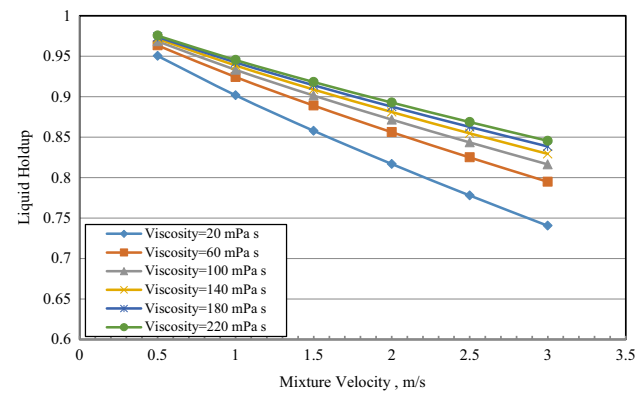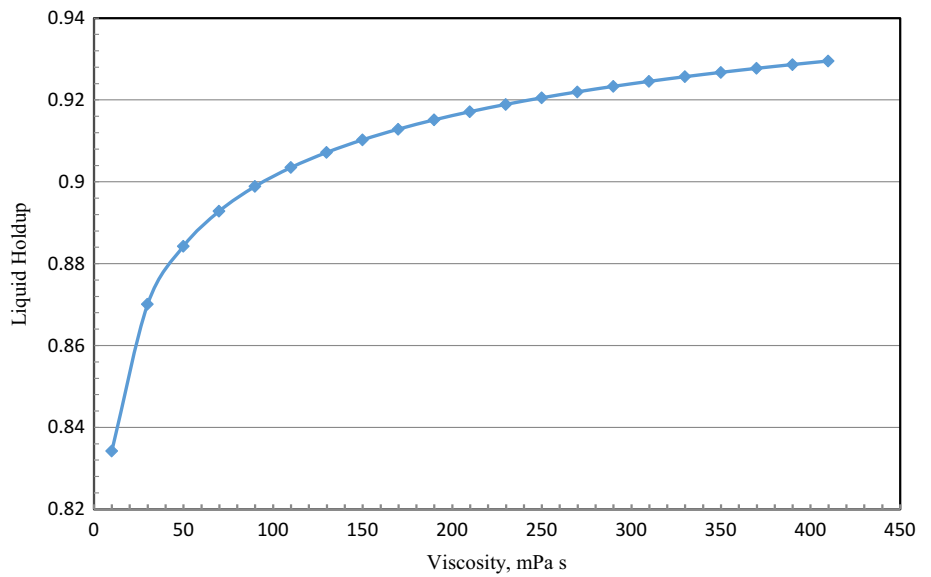
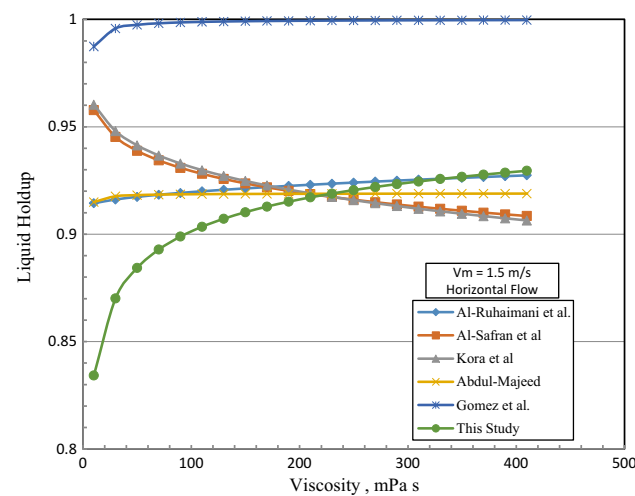**Fig. 28** Performance of proposed correlation using different liquid viscosities
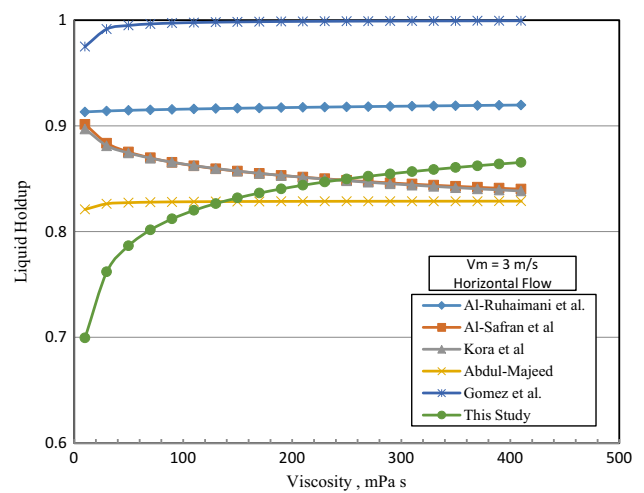
Fig. 30 Comparison of slug liquid holdup correlations for liquid viscosity change at $V_m = 3.0$ m/s

the same values of mixture velocity and liquid viscosity, the three data sets show different measured liquid holdup values. On average, Nuland [26] data are 40% lower than the data of Kora et al. [23] and the present horizontal data. We also compare Nuland [26] data with Gregory et al. [22] horizontal data and observe that Nuland data are 30% lower than those of Gregory et al. [22]. It is expected that this large difference is due to using different liquid holdup measurement instruments. Table 5 summarizes the validation measured data.

Fig. 29 Comparison of slug liquid holdup correlations for liquid viscosity change at $V_m = 1.5$ m/s

Fig. 31 Effect of pipe diameter on the proposed and existing slug liquid holdup correlatioms
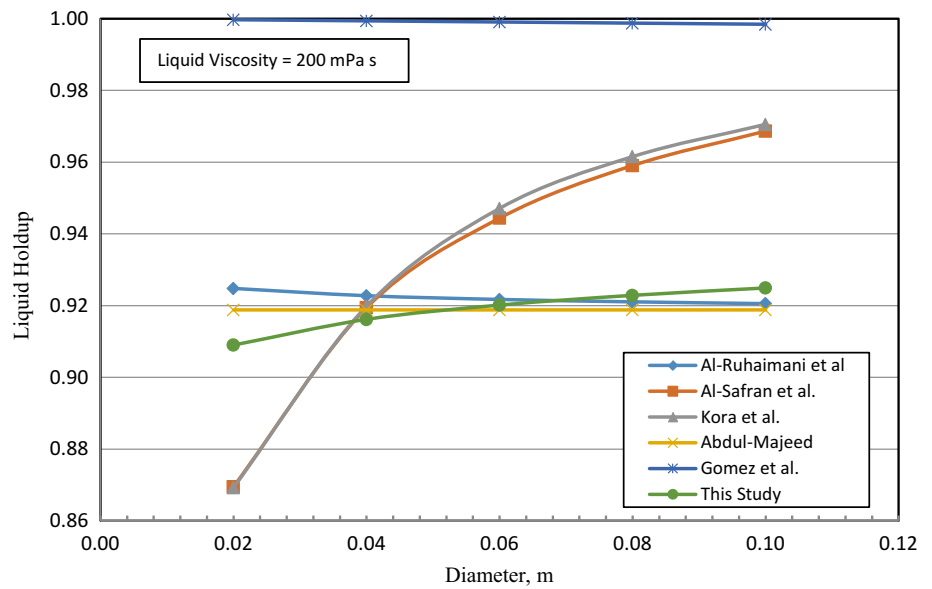
Table 2 Evaluation of slug liquid holdup correlations using present horizontal measured data

Correlation	ε1%	ε2%	ε3	ε4
Gomez et al. [21]	5.9007	5.9008	5.4259	5.4261
Abdul-Majeed [2]	− 2.08631	2.08631	− 1.94970	1.94970
Kora et al. [23]	2.85262	2.85262	2.63749	2.63749
Al-Safran et al. [8]	2.76605	2.76605	2.56049	2.56049
Al-Ruhaimani et al. [5]	− 0.53343	2.08677	− 0.57122	1.95691
Present study	0.03997	0.84661	0.04581	0.79138

Table 4 Evaluation of slug liquid holdup correlations using present inclined measured data

Correlation	ε_1%	ε_2%	ε_3	ε_4
Gomez et al. [21]	− 22.5762	22.5762	− 20.6971	20.6971
Abdul-Majeed [2]	− 22.4324	22.4324	− 20.4577	20.4577
Kora et al. [23]	2.00180	2.48292	1.85531	2.27170
Al-Safran et al. [8]	2.17625	2.19966	1.99426	2.01537
Al-Ruhaimani et al. [5]	1.24392	2.04297	1.06419	1.81766
Present study	0.75710	0.84617	0.67513	0.75659

Table 3 Evaluation of slug liquid holdup correlations using present vertical measured data

Correlation	ε1%	ε2%	ε3	ε4
Gomez et al. [21]	− 41.6269	41.6269	− 38.8957	38.8957
Abdul-Majeed [2]	− 42.0508	42.0508	− 39.2808	39.2808
Kora et al. [23]	4.39140	4.39140	4.10354	4.10354
Al-Safran et al. [8]	4.33777	4.33777	4.05457	4.05457
Al-Ruhaimani et al. [5]	− 0.04118	0.51725	− 0.03761	0.48417
Present study	0.07114	0.21955	0.06648	0.20522

### 3.2.1 Al-Ruhaimani et al. [5] vertical measured data (68 data points)

The statistical parameters of the correlations using, Al-Ruhaimani et al. [5] data, are presented in Table 6. The cross plot of the measured versus predicted liquid holdup is illustrated in Fig. 36. As expected Al-Ruhaimani et al. [5] correlation gives the best results since it was developed using this data set. The proposed correlation yields

excellent results and very closes to Al-Ruhaimani et al. [5]. The correlations of Abdul-Majeed [2] and Gomez et al. [21] are totally unsatisfactory for vertical measured data due to using the correction factor for the effect of inclination angle (as stated previously).

3.2.2 Nuland [26] horizontal data (89 data points)

Table 7 lists the statistical results of the correlations using the horizontal data of Nuland [26]. Figure 37 presents a comparison between measured and predicted liquid holdup data. Recalling the conclusion, mentioned above, that Nuland [26] data are always low as compared to other data sets, it is expected that all correlations over predict Nuland [26] data as shown in Fig. 37 and Table 7. The best performance is shown by the proposed correlation followed by Abdul-Majeed [2] correlation. Gomez et al. [21] correlation over predicts all the 89 data points.

Fig. 32 Comparison between measured and predicted liquid holdup for the present horizontal data set
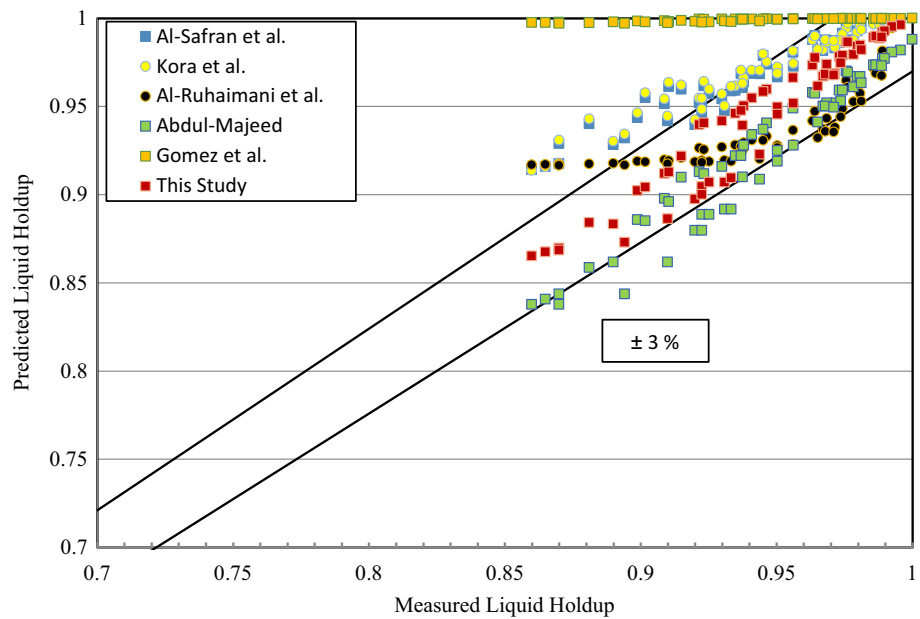
Fig. 33 Comparison between measured and predicted liquid holdup for the present vertical data set
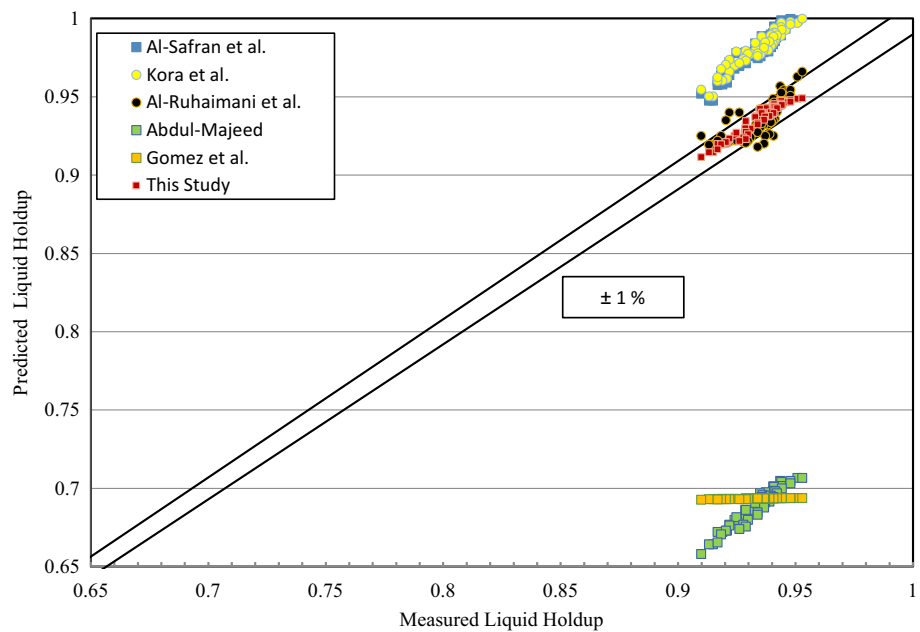
### 3.2.3 Kora et al. [23] horizontal data (144 data points)

Kora et al. [23] dataset consists of 144 data points covering liquid viscosities of 586, 378, 257 and 181 mPa s. Based on fitting techniques, Kora et al. [23] and Al-Safran et al. [8] used these data to develop their empirical correlations. Since these two correlations predict a decrease in liquid holdup with increasing of liquid viscosity, as stated above (see Figs. 5, 8). Therefore, it is important to analyze this data set to see the behavior of liquid holdup with liquid viscosity change. Figure 38 displays the data of Kora et al. [23]. As noted and expected there is an overlap in liquid

holdup measurements. The H_{LS} values for viscosity of 586 mPa s are greater than those for viscosity of 378 mPa s. However, the highest measured H_{LS} values are associated with the lowest liquid viscosity 181 mPa s. This behavior of measured data explains why Kora et al. [23] and Al-Safran et al. [8] show discrepancies in holdup prediction with variation of liquid viscosity.

Table 8 shows the performance of all correlations. Figure 39 shows a cross plot of measured versus predicted liquid holdup data. Kora et al. [23] and Al-Safran et al. [8] correlations have an advantage over other correlations due to the bias they have towards this data set, from which

Fig. 34 Comparison between measured and predicted liquid holdup for the present inclined data set
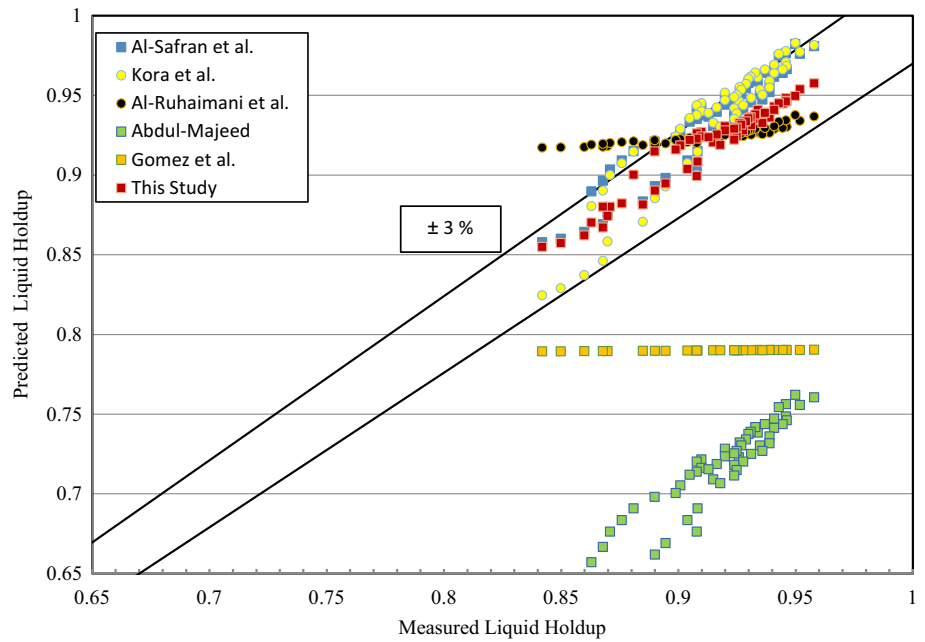
Fig. 35 Comparison between Nuland [26], Kora et al. [23] and present horizontal measured liquid holdup data
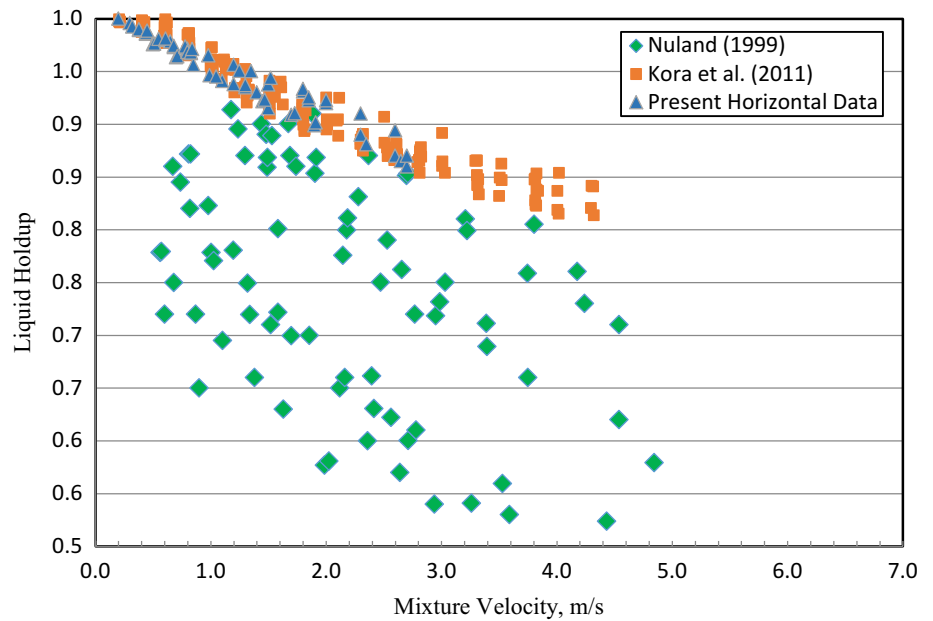
Table 5 Description of the validation measured data

Authors	V_m (m/s)	Liquid holdup	Liquid viscosity (mPa s)	Pipe diameter (m)	Inclination angle (°)	No. of data points
Nuland [26]	0.56–5.8	0.342–0.914	50–400	0.06	0	89
Kora et al. [23]	0.21–4.32	0.813–0.999	181–586	0.0508	0	144
Al-Ruhaimani et al. [5]	0.52–1.76	0.908–0.959	120–598	0.0508	90	68

Table 6 Evaluation of slug liquid holdup correlations using Al-Ruhaimani et al. [5] vertical measured data

Correlation	ε_1%	ε_2%	ε_3	ε_4
Gomez et al. [21]	− 47.0377	47.0377	− 43.8480	43.8480
Abdul-Majeed [2]	− 47.4725	47.4725	− 44.2458	44.2458
Kora et al. [23]	3.31702	3.36514	3.09009	3.13486
Al-Safran et al. [8]	3.13595	3.20257	2.92185	2.98389
Al-Ruhaimani et al. [5]	0.03427	0.42745	0.02936	0.39748
Present study	0.07716	0.51825	0.06745	0.48324

they were developed. Al-Safran et al. [8], as expected, gives the best results. The proposed correlation is shown to be the second best correlation as it yields better results than the rest correlations, including Kora et al. [23] correlation.

3.2.4 All measured validation data (301 data points)

Table 9 presents the statistical parameters of correlations for the entire measured data used for validation. This data set consists of Nuland [26], Kora et al. [23] and Al-Ruhaimani et al. [5] measured data. As can be seen, the proposed correlation shows the best performance for the entire validation data and clearly outperforms all the other correlations. The correlations of Kora et al. [23], Al-Safran et al. [8] and Al-Ruhaimani et al. [5] give approximately the same results.

4 Conclusions

A new measured liquid holdup dataset is presented that covering a wide range of liquid viscosity (200–800 mPa s) and pipe inclination angles (0°, 30°, 60° and 90° from horizontal). The experiments were conducted using two large pipe diameters (0.08 and 0.1 m). Analysis of data indicates that the slug liquid holdup increases as liquid viscosity increases. Comparison of the inclined data with vertical and/or horizontal data reveals a slight decreasing in slug liquid holdup with the increase of inclination angle from horizontal. A predictive analysis of the existing slug liquid holdup correlations against the published observations was conducted and three main conclusions were revealed, namely, none of these correlations is fully consistent with the trends of experimental data; none of
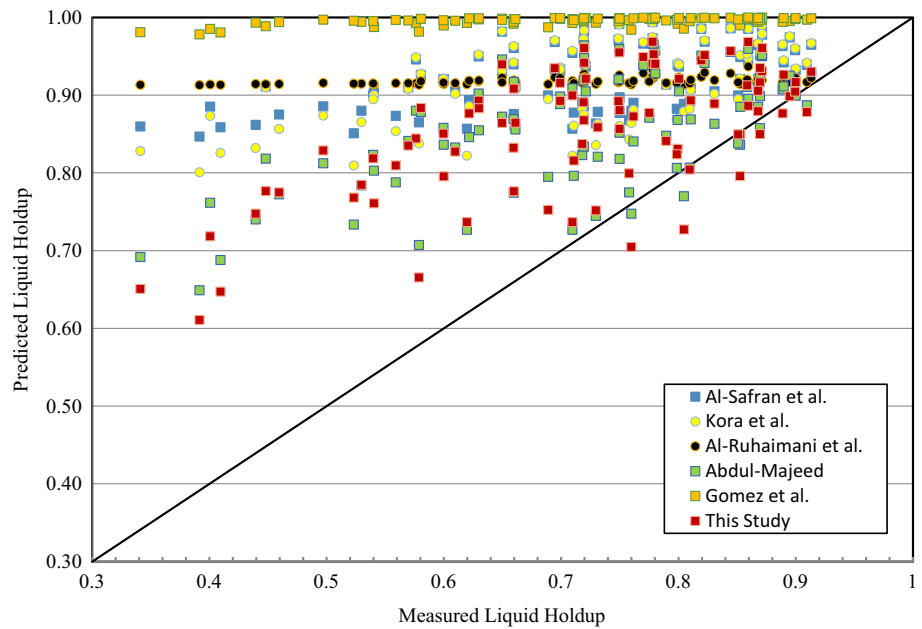
Table 7 Evaluation of slug liquid holdup correlations using Nuland [26] horizontal measured data

| Correlation	ε_1%	ε_2%	ε_3	ε_4
Gomez et al. [21]	45.5716	45.5716	27.9245	27.9245
Abdul-Majeed [2]	23.77676	24.09534	14.14689	14.41385
Kora et al. [23]	33.19377	33.19377	20.11017	20.11017
Al-Safran et al. [8]	34.29729	34.29729	20.69599	20.69599
Al-Ruhaimani et al. [5]	34.32990	34.32990	20.22218	20.22218
Present study	23.13303	23.85979	13.86824	14.46828

Fig. 36 Measured versus predicted liquid holdup for Al-Ruhaimani et al. [5] vertical data set
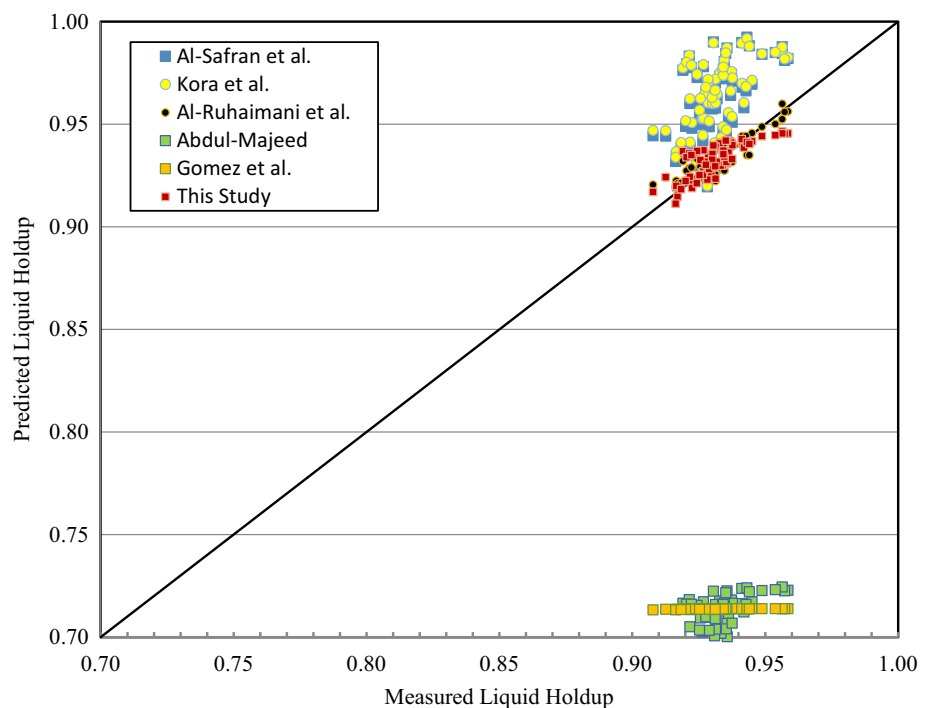
Fig. 37 Measured versus predicted liquid holdup for Nuland [26] horizontal data set

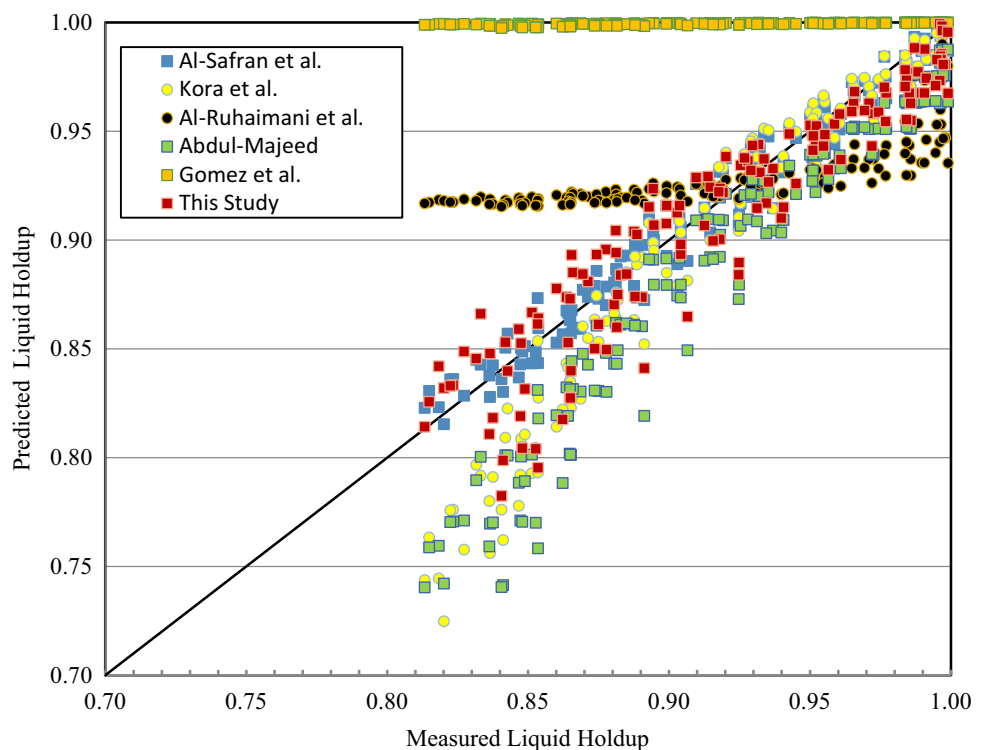**Fig. 38** Kora et al. [23] measured slug liquid holdup data
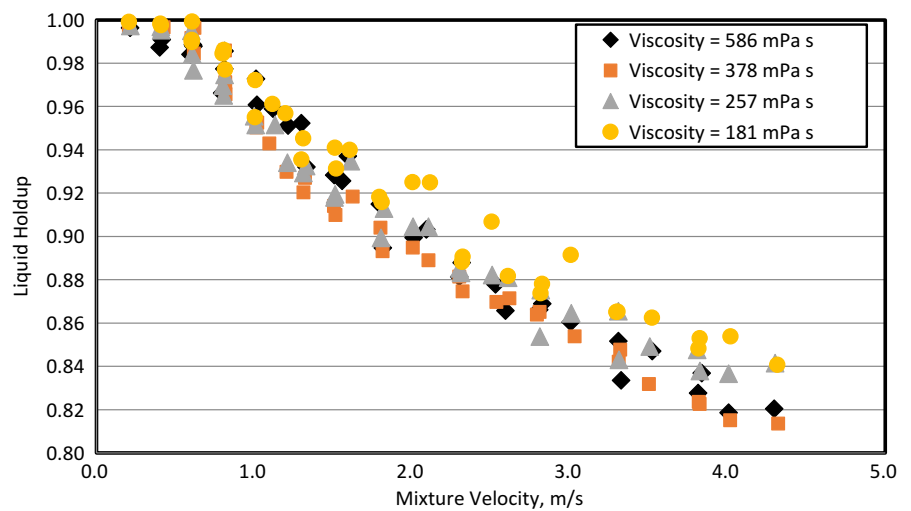
Table 8 Evaluation of slug liquid holdup correlations using Kora et al. [23] horizontal data

Correlation	$\varepsilon_1\%$	$\varepsilon_2\%$	ε_3	ε_4
Gomez et al. [21]	9.4626	9.4626	8.3107	8.3107
Abdul-Majeed [2]	−3.54945	3.55059	−3.16223	3.16328
Kora et al. [23]	−1.61183	2.15137	−1.37044	1.87453
Al-Safran et al. [8]	0.00734	0.83813	−0.00587	0.76567
Al-Ruhaimani et al. [5]	1.69844	4.35963	1.29172	3.89143
Present study	−0.67796	1.76343	−0.64282	1.59237

them accounts for all of the important flow parameters; and they predict different minimum slug liquid holdup (ranging from 0.34 to 0.912). A new unified correlation is proposed to predict liquid holdup in horizontal, vertical and inclined viscous slug flow. The new correlation is simple and totally agrees with observations. The proposed correlation clearly outperforms the existing correlations using the current measured data and data from three independent sources.

Fig. 39 Measured versus predicted liquid holdup for Kora et al. [23] horizontal data set

Table 9 Evaluation of slug liquid holdup correlations using all measured validation data

Correlation	$\varepsilon_1\%$	$\varepsilon_2\%$	ε_3	ε_4
Gomez et al. [21]	7.37518	28.62807	3.92677	22.13850
Abdul-Majeed [2]	− 5.39243	19.54785	− 7.32559	15.77096
Kora et al. [23]	9.79302	11.60423	5.98866	7.55119
Al-Safran et al. [8]	10.85303	11.26553	6.77669	7.15982
Al-Ruhaimani et al. [5]	10.97099	12.33294	6.60391	7.93080
Present study	6.53309	8.01560	3.60829	5.14897

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

Appendix

The calibration of closing valves and capacitance sensors applied to the present measured data is approximately similar to that used by Al-Safran [6] and Al-Ruhaimani et al. [5] with slight differences due to using large pipe diameters compared to 0.0508 m ID used in these studies. The following sections describe the calibrations for vertical slug flow. Similar procedures were conducted for horizontal and inclined slug flows.

Quick closing valves calibration

The requirement of this calibration depends on the accuracy of volume measurements (trap section volume, V_t and vessel volume, V_v). Any possible error in these measurements can lead to a difference between actual liquid holdup and that determined by quick closing valves. Since the volume measurements were repeated several times with quite accuracy, very slight differences were found between the determined and actual liquid holdup. The closing valve calibration of the present measured data was shown in Fig. 40 and could be expressed by:
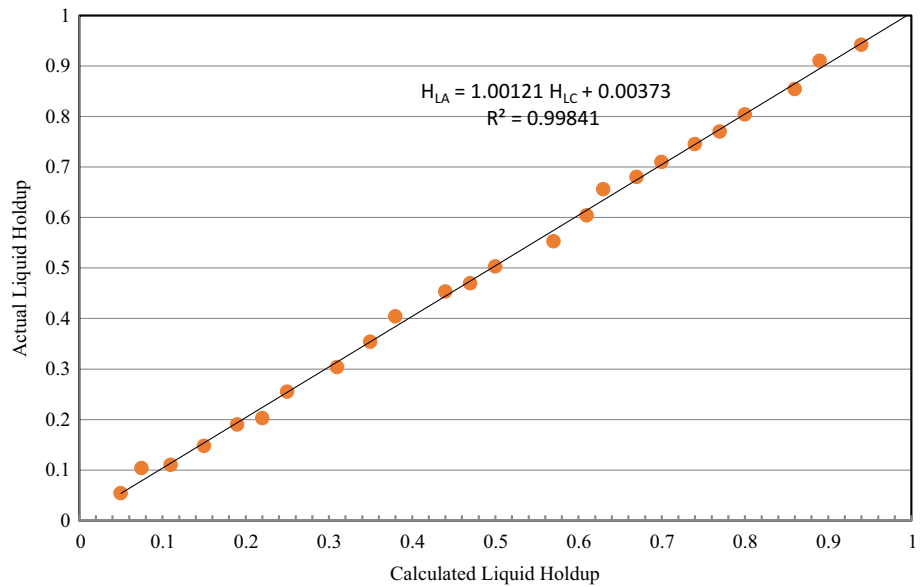
$$H_{LA} = 1.00121 H_{LC} + 0.00373 \qquad (27)$$

The certainty of estimated V_v/V_t, calculated holdup and estimated V_t were calculated according to Al-Ruhaimani et al. [5] procedure. The overall calibration uncertainty of closing valves was found to be 0.0204.

Capacitance sensor static calibration

The static calibration of the capacitance sensor was conducted to define a relationship between the voltage reading of the capacitance sensor and the liquid holdup calculated from this reading voltage, under stratified conditions. The results, of one of the used sensors, were plotted in Fig. 41, with a relation of straight line curve fitting. Table 10 shows the coefficients of the straight lines of the

Fig. 40 Quick closing valve calibration relation

$$H_{LA} = 1.00121 \, H_{LC} + 0.00373$$
$$R^2 = 0.99841$$

Fig. 41 Capacitance Sensor static calibration

$$H_{LSC} = 1.0834 \, \text{Voltage} - 0.0685$$
$$R^2 = 0.9973$$
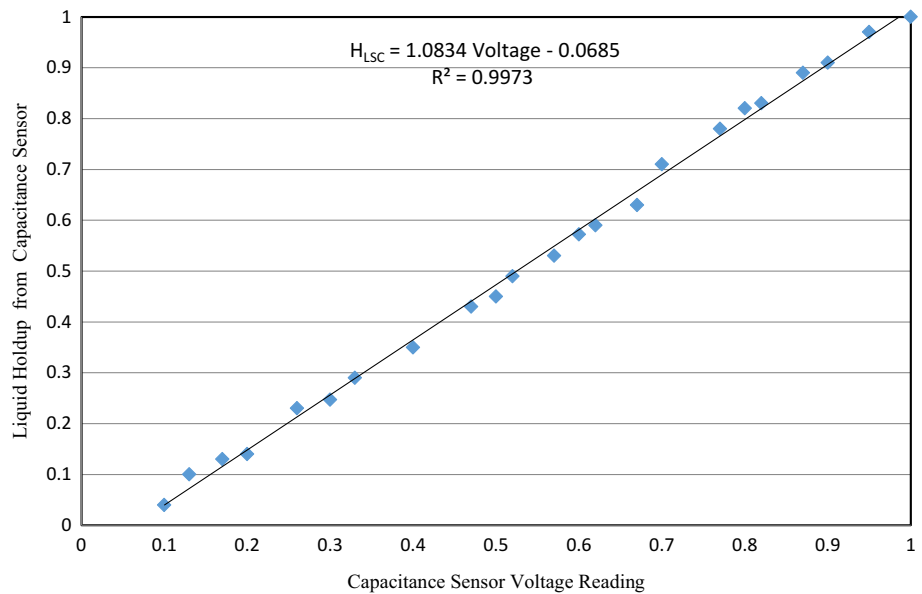
three sensors, in addition to the uncertainties of static calibration of sensors (calculated using the procedure of Al-Ruhaimani et al. [5].

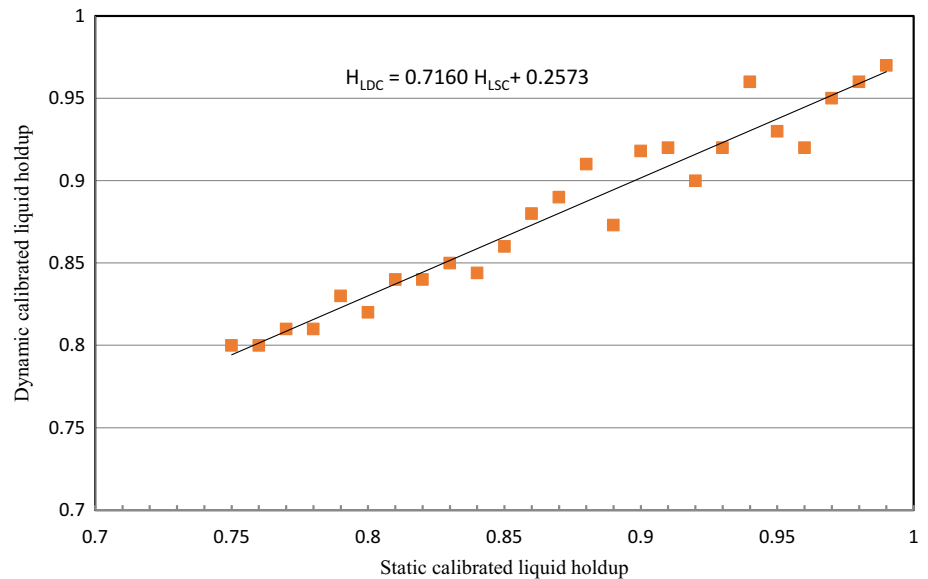## Capacitance sensor dynamic calibration

As mentioned in the test section, two quick closing valves are used for dynamic calibration of the capacitance sensors. This calibration was conducted to define a relationship between the dynamic calibrated liquid holdup and the static calibrated liquid holdup. The need for conducting dynamic calibration to the capacitance sensors is due to the fact that static calibration was performed under

Table 10 Static calibration and uncertainty of capacitance sensors

Capacitance sensor	A coefficient	B coefficient	Calibration uncertainty
First	1.0838	−0.0583	0.0402
Second	1.0834	−0.0685	0.0402
Third	1.0978	−0.0758	0.0403

stratified flow conditions. Al-Safran [6] showed that one capacitance sensor should be dynamically calibrated and this calibration can be applied to all other capacitance

Fig. 42 Capacitance Sensor dynamic calibration

$H_{LDC} = 0.7160\ H_{LSC} + 0.2573$

Table 11 Dynamic calibration and uncertainty of capacitance sensors

Capacitance sensor	A coefficient	B coefficient	Calibration uncertainty
First	0.7160	0.2573	0.0342
Second	0.7160	0.2573	0.0342
Third	0.7160	0.2573	0.0343

sensors. Figure 42 illustrates the dynamic calibration of capacitance sensors. Table 11 presents the dynamic calibration curve fitting coefficients and uncertainties.

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