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Brief communication

Prediction of slug liquid holdup: horizontal to upward vertical flow

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1. Introduction

The prediction of the liquid holdup in the slug body for two-phase gas–liquid slug flow is important for the accurate calculations of the pressure drop. In particular, its evaluation is important for inclined and vertical pipes, since the liquid holdup in the slug body is the main contributor to the hydrostatic pressure drop that can be quite significant for inclined and vertical flows.

The early models for slug flow presented by Dukler and Hubbard (1975) and Nicholson et al. (1978) for horizontal flows are not complete predictive tools, as supplementary data for the slug liquid holdup are needed as a closure relationship in these models. Gregory et al. (1978) presented a correlation for the liquid holdup in horizontal slug flow and showed that the holdup is correlated quite well with respect to the slug mixture velocity.

For the case vertical flows Fernandes et al. (1983) developed a semi-mechanistic model for the prediction of the liquid holdup. The results are close to the approximate value of 0.7 that is usually taken for vertical flows (Taitel and Barnea, 1990), based the concept of probable packing of bubbles in vertical bubbly flow. Sylvester (1987) modified the Fernandes et al. slug flow model and introduced a new correlation for the liquid holdup.

Felizola (1992) and Felizola and Shoham (1995) attempted to develop a unified correlation for the entire range of inclination angles (0–90°). However, it is based on their own data only,

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Table 1
Summary of experimental database for slug liquid holdup

Data source	Inclination	Pipe diameter	Fluids	Liquid phase		Gas phase	Data points
				Density (kg/m^3)	Viscosity (kg/ms)	Pressure kpa	
Kouba (1986)	$\theta = 0^\circ$	7.6 cm	Air–Kerosene	800	1.5×10^{-3}	350	53
Rothe et al. (1986)	$\theta = 0^\circ$	17.8 cm	Freon–water and Air–water	1000	1.0×10^{-3}	550 & 150	14
Brandt and Fuches (1989)	$\theta = 0^\circ$	20.3 cm	Nitrogen–diesel	800	2.0×10^{-3}	2000	8
Kokal (1987)	$0^\circ < \theta < 9^\circ$	5.1 & 7.6 cm	Air–oil	800	6.5×10^{-3}	250	103
Felizola (1992)	$0^\circ < \theta < 90^\circ$	5.1 cm	Air–Kerosene	800	1.5×10^{-3}	250	90
Schmidt (1977)	$\theta = 90^\circ$	5.1 cm	Air–Kerosene	800	1.5×10^{-3}	225	15
							Total = 283

it is complicated (15 coefficients are needed for the different angles) and does not give the right trend for horizontal flow.

Barnea and Brauner (1985) introduced the idea that the slug liquid holdup is the same as the holdup on the slug-dispersed bubble transition boundary, for the same total mixture superficial velocity. The model compares fairly well with a limited vertical upflow and horizontal data. Although this model does take the angle of inclination into consideration, its accuracy is sensitive to the correct bubble-slug transition boundary, which is not readily available with sufficient accuracy.

Experimental data acquired for inclined and vertical slug flow (Kokal, 1987; Felizola, 1992; Schmidt, 1977) have shown that the effect of the angle of inclination on the slug holdup cannot be ignored. The objective of this work is to present a correlation based on up-to-date data that is simple, presented in a dimensionless form and takes correctly the inclination effect.

2. Analysis and results

Data from six different slug flow studies have been used for the development of the present study correlation. A summary of the experimental database for the liquid holdup in the slug is given in Table 1. As can be seen, the 283 data points include pipe diameters between 5.1–20.3 cm and different fluids, including high-density gases. The data have been acquired for the entire inclination angle range, from horizontal to vertical.

The experimental data show that the liquid holdup in the slug, R_S, varies with the inclination angle. It is maximum at horizontal flow conditions, decreasing as the upward inclination increases, and it is minimum for upward vertical flow. The data also reveal that R_S is also a function of the mixture velocity and the viscosity of the liquid phase. The liquid phase

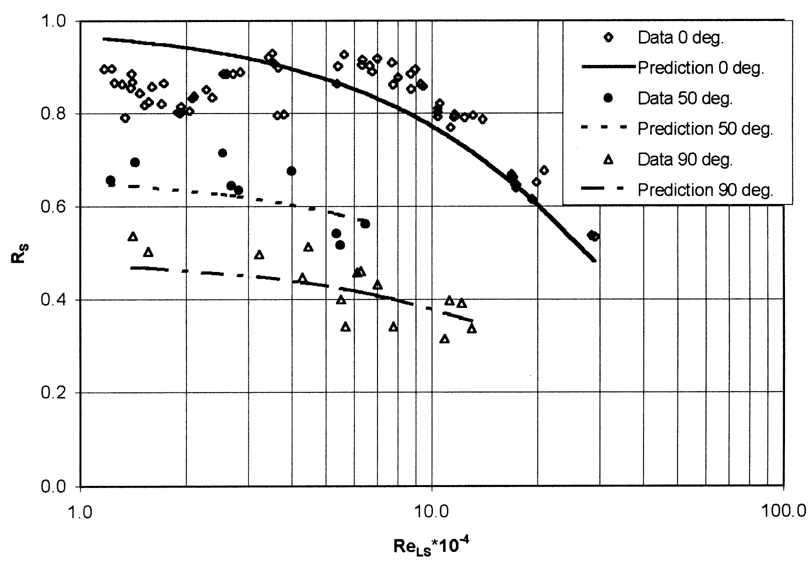

Fig. 1. Comparison between predicted and measured slug liquid holdup.

is the continuous phase in the slug, affecting the entrainment and motion of the gas bubbles. As reported by Su and Metcalfe (1997), the surface tension does not have as significant effect on the liquid holdup in the slug, as compared to the effect of the liquid viscosity.

Based on the above phenomena, it is suggested that the liquid holdup in the slug is a function of the inclination angle θ (in radians) and the slug Reynolds number, Re_{LS}, defined as

$$Re_{LS} = \frac{\rho_L V_M D}{\mu_L} \tag{1}$$

where ρ_L and μ_L are the density and viscosity of the liquid phase, D is the pipe diameter and V_M is the mixture velocity. The developed correlation is

$$R_S = 1.0\ \mathrm{e}^{-\left(0.45\theta_R + 2.48\cdot 10^{-6} Re_{LS}\right)} \quad 0 \leq \theta_R \leq 1.57 \tag{2}$$

where θ_R is the inclination angle in radians.

A typical comparison between experimental data and the prediction of the proposed correlation is given in Fig. 1. The comparison is given for horizontal flow, 0° (data from Kouba, 1986; Rothe et al., 1986; Brandt and Fuches, 1989; Kokal, 1987), inclined upward flow, 50° (data from Felizola, 1992) and vertical upward flow, 90° (data from Schmidt, 1977 and Felizola, 1992). As can be seen, the correlation captures the main trends of the data, namely, decreasing liquid holdup values with increasing Reynolds number and upward inclination angle. The variance of the data about the regression line was calculated to be 0.00676, which is equivalent to a 95% confidence interval of ± 0.16.

Finally, the developed correlation is evaluated against the new experimental results presented by Nuland et al. (1997). These data were not used in the development of the present correlation. It includes results for 10, 20, 45 and 60° inclination angles. The experimental data

Table 2
Comparison between slug liquid holdup predictions and Nuland et al. (1997)

Inclination (degree)	V_{SL} (m/s)	V_{SG} (m/s)	R_S (measured)	R_S (predicted)	Error (%)
10	0.50	1.00	0.75	0.77	3.0
10	0.50	2.00	0.56	0.69	23.2
10	1.00	1.98	0.56	0.65	16.7
20	0.51	0.99	0.67	0.71	6.6
20	0.50	2.01	0.57	0.64	11.8
20	1.00	1.01	0.63	0.67	7.0
20	1.02	2.04	0.54	0.60	10.9
20	1.02	3.02	0.42	0.54	27.7
45	0.50	1.07	0.54	0.58	7.8
45	0.50	2.22	0.40	0.51	27.8
45	0.10	1.00	0.54	0.61	13.7
45	0.20	1.00	0.60	0.61	1.1
60	0.10	1.05	0.42	0.54	29.2
60	0.20	1.05	0.48	0.54	11.8
Average absolute error (%)					14.2

and the prediction of the proposed correlation are given in Table 2. Five data points with very low liquid holdup have been excluded in this study, since it is believed that these data do not represent fully developed slugs but rather aerated proto-slugs. The correlation seems to overpredict the data with an average absolute error of 14.2%. It is possible that the experimental measurements for this set of data are consistently low.

3. Summary and conclusions

A new dimensionless correlation for the liquid holdup in the slug body is developed. The correlation incorporates the mixture velocity, liquid viscosity, pipe diameter and inclination angle. The correlation is based on six up-to-date data sets.

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