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CORRELATION OF THE LIQUID VOLUME FRACTION IN THE SLUG FOR HORIZONTAL GAS–LIQUID SLUG FLOW

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Abstract—Experimental data for gas holdup in liquid slugs are reported for two different pipe sizes (2.58 cm and 5.12 cm I.D.). A simple empirical correlation is developed and is shown to be a significant improvement over the only other published correlation proposed by Hubbard (1965). The results of this investigation are important for the development of a mechanistic model for the prediction of pressure drop and holdup for slug flow in pipes.

INTRODUCTION

Two principal attempts to provide mechanistic models for horizontal gas–liquid slug flow have appeared in the literature. The first of these due to Kordyban (1961) and Kordyban & Ranov (1963) was not very successful due to several simplifying assumptions inherent in these authors' analysis.

Primarily, it was assumed that liquid slugs moved at the gas velocity and slipped over the top of a slower moving liquid film. Agreement between their model and experimental data was generally poor.

In the second study, Hubbard (1965) and Dukler & Hubbard (1975) presented a considerably more detailed analysis, in which it was noted that:

(a) the liquid slug scooped up the liquid film ahead of it and redeposited a new film in its wake; and

(b) in the process of the scooping action, some gas entrainment occurred within the slug.

In the Kordyban (1961) model, any such entrainment was neglected, and the density of the fluid in the slug was taken simply as that of the liquid. However, in the Dukler & Hubbard (1975) model, the pressure drop calculation is based on the actual density of the mixture in the high velocity slug section, and the effect of the entrained gas is accounted for by the use of a mixture density defined as,

$$\begin{aligned}\rho_M &= \rho_L E_{LS} + \rho_G(1 - E_{LS})\\ &\simeq \rho_L E_{LS}\end{aligned} \qquad [1]$$

where ρ_M is the density of the two phase mixture, and E_{LS} is the liquid volume fraction in the liquid slug.

Unfortunately, no theoretical method is available for the prediction of E_{LS} and an empirical correlation was sought.

Hubbard (1965) attempted to measure E_{LS} through the use of an impact probe system. This proved to be very difficult and the results he obtained showed little consistency and reproductibility was poor. Consequently, only a very crude correlation was proposed which has represented a basic weakness in the overall Dukler & Hubbard (1975) model.

It should be noted however, that a modelling study for horizontal slug flow currently in progress at The University of Calgary, has confirmed the need for a reliable method of predicting E_{LS}.

THIS STUDY

Experimental values of E_{LS} for this study were obtained using the capacitance-type liquid volume fraction sensors that have been described in an earlier paper by Gregory & Mattar (1972). These sensors used in conjunction with an IKOR Model 545 Vapor–Liquid meter,† provided a continuous record of the *in situ* liquid volume fraction. They have a sufficiently fast response that the average liquid volume fraction may be recorded for each slug as it passes through the approx. 15 cm long sensor. The average lengths of the liquid slugs have been observed by the authors to vary between a factor of 10 and 125 times the length of the sensor and thus, the measurements may be considered as representative averages rather than as single point determinations. The sensing elements are located on the outside wall of the pipe and thus do not cause any disruption to, or interference with, the flow.

Several series of experiments were performed using a light refined oil, with air as the gas phase. The density and viscosity of the oil were 858 kg/m^3, and 6.75 mP sec respectively, both measured at the average system temperature of 23°C. Two horizontal test sections were used, having inside diameters of 2.58 cm and 5.12 cm respectively. In the 2.58 cm test section, a length of approx 575 pipe diameters was provided upstream of the liquid volume fraction sensor to minimize entrance effects from the flow. In the 5.12 cm test section, the entrance length was approx. 340 dia. The total length of the flow system is approx. 30 m, and thus the measuring points were also located well upstream of the point where the flow leaves the test section and enters the separator. The average mid-point pressure, which was maintained relatively constant for all flow rates investigated, was 345 kPa for the 2.58 cm pipe, and 255 kPa for the 5.12 cm pipe. The range of flow rates investigated, expressed in terms of the liquid and gas superficial velocities, V_{SL} and V_{SG} respectively, were:

$$0.030 \le V_{SL} \le 2.316 \text{ m/sec};$$

$$0.088 \le V_{SG} \le 15.376 \text{ m/sec}.$$

These ranges cover virtually the entire region of slug flow that can be observed in the flow loop. A detailed description of the overall flow loop is reported elsewhere (Aziz & Gregory, 1976).

RESULTS AND DISCUSSION

The measured values of E_{LS} and the corresponding phase velocities obtained with the 2.58 cm I.D. pipe are given in table 1, while table 2 contains the data for the 5.12 cm I.D. test section. It should be noted that each value of E_{LS} reported in these tables actually represents an average for approximately 30 slugs observed at each set of flow rates. However variations in the values of E_{LS} for individual slugs were small, and the standard deviations for the samples were generally about 0.01.

When the data were plotted as E_{LS} vs log V_M, where V_M, the mixture velocity is defined as,

$$V_M = V_{SL} + V_{SG} \qquad [2]$$

a definite correlation was apparent, the general form of which could be represented by

$$E_{LS} = \frac{1}{1 + \left(\frac{V_M}{\alpha}\right)^{\beta}} \qquad [3]$$

where α and β are constants.

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Table 1. Detailed data for runs performed in 2.58 cm I.D. horizontal pipe

Pipe diameter = 2.58 cm			Pipe diameter = 2.58 cm		
V_{SL} (h/sec)	V_{SG} (h/sec)	E_{LS}	V_{SL} (h/sec)	V_{SG} (h/sec)	E_{LS}
0.030	0.088	1.000	0.610	0.088	0.958
0.030	0.140	1.000	0.610	0.140	0.961
0.030	0.244	1.000	0.610	0.247	0.942
0.030	0.460	0.983	0.610	0.460	0.948
0.030	0.930	0.963	0.610	0.911	0.942
0.030	1.838	0.897	0.610	1.807	0.889
0.061	0.088	0.998	0.610	2.914	0.788
0.061	0.140	1.000	0.610	5.437	0.699
0.061	0.244	0.998	0.914	0.088	0.968
0.061	0.460	0.986	0.914	0.140	0.962
0.061	0.927	0.985	0.914	0.247	0.942
0.061	1.835	0.922	0.914	0.460	0.930
0.122	0.088	1.000	0.914	0.911	0.899
0.122	0.140	0.999	0.914	1.807	0.876
0.122	0.241	0.998	0.914	3.042	0.746
0.122	0.460	0.938	0.914	5.337	0.674
0.122	0.923	0.924	0.914	10.293	0.578
0.122	1.820	0.913	0.914	15.626	0.519
0.122	2.917	0.869	1.372	0.244	0.934
0.213	0.088	1.000	1.372	0.457	0.907
0.213	0.140	0.997	1.372	0.917	0.834
0.213	0.241	0.963	1.372	1.643	0.790
0.213	0.460	0.953	1.372	3.011	0.723
0.213	0.927	0.935	1.372	5.605	0.640
0.213	1.838	0.878	1.372	11.195	0.532
0.213	2.825	0.849	2.133	1.667	0.671
0.366	0.088	0.989	2.133	2.987	0.621
0.366	0.140	0.953	2.133	5.922	0.557
0.366	0.241	0.935			
0.366	0.460	0.937			
0.366	0.923	0.934			
0.366	1.813	0.866			
0.366	3.151	0.807			
0.366	5.111	0.680			

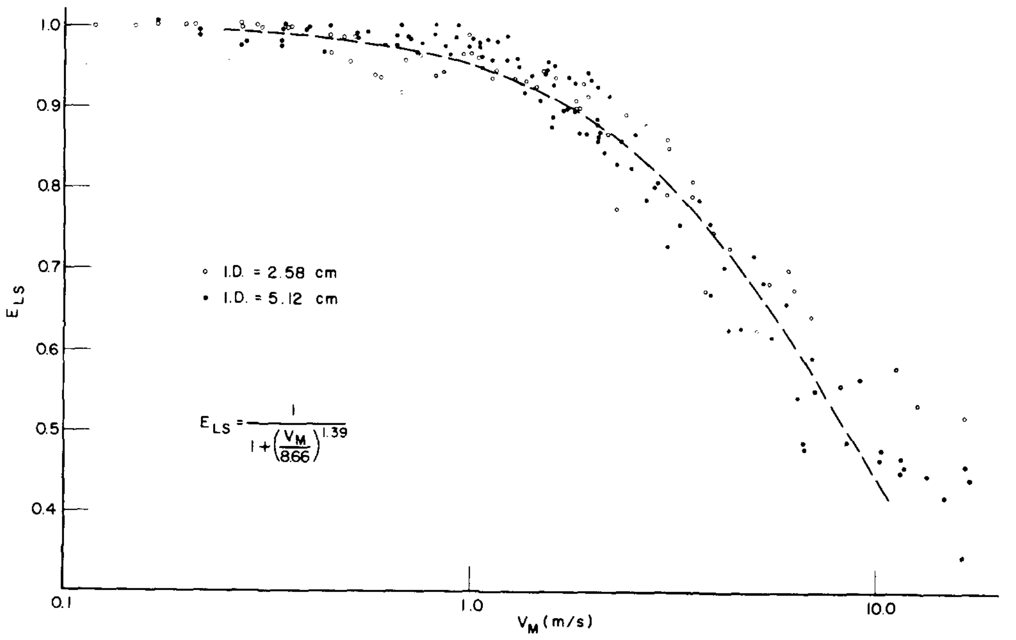

Figure 1. Measured values of E_{LS} vs mixture velocity for air–oil slug flow in horizontal 2.58 and 5.12 cm I.D. pipes.

Table 2. Detailed data for runs performed in 5.12 cm I.D. horizontal pipe

Pipe diameter = 5.12 cm			Pipe diameter = 5.12 cm			Pipe diameter = 5.12 cm		
V_{SL} (h/sec)	V_{SG} (h/sec)	E_{LS}	V_{SL} (h/sec)	V_{SG} (h/sec)	E_{LS}	V_{SL} (h/sec)	V_{SG} (h/sec)	E_{LS}
0.061	0.283	0.980	0.610	0.046	0.989	1.372	0.216	0.926
0.061	0.823	0.963	0.610	0.046	0.975	1.372	0.311	0.894
0.061	1.490	0.956	0.610	0.091	0.985	1.372	0.436	0.896
0.061	1.908	0.941	0.610	0.094	0.983	1.372	0.564	0.863
0.061	1.929	0.931	0.610	0.146	0.978	1.372	0.680	0.855
0.122	0.046	1.000	0.610	0.216	0.987	1.372	0.683	0.862
0.122	0.094	0.986	0.610	0.308	0.992	1.372	0.802	0.844
0.122	0.094	0.994	0.610	0.436	0.971	1.372	0.933	0.825
0.122	0.152	0.975	0.610	0.558	0.979	1.372	1.137	0.822
0.122	0.155	0.978	0.610	0.680	0.959	1.372	1.457	0.800
0.122	0.216	0.997	0.610	0.808	0.939	1.372	2.874	0.702
0.122	0.216	0.974	0.610	0.933	0.944	1.372	4.179	0.616
0.122	0.311	0.969	0.610	1.198	0.930	1.372	5.751	0.550
0.122	0.436	0.994	0.610	1.448	0.886	1.372	8.961	0.465
0.122	0.558	1.000	0.610	1.929	0.866	1.372	12.057	0.444
0.122	0.680	1.000	0.610	3.002	0.783	1.372	15.480	0.456
0.122	0.683	1.000	0.610	4.368	0.716	1.823	15.303	0.442
0.122	0.805	1.000	0.610	5.407	0.658	1.856	2.024	0.670
0.122	0.927	0.976	0.610	8.537	0.563	1.856	4.596	0.541
0.122	1.192	0.949	0.610	10.948	0.469	1.862	0.832	0.789
0.122	1.481	0.950	0.914	0.091	0.983	1.865	1.201	0.727
0.122	1.951	0.924	0.914	0.155	0.964	1.868	9.683	0.450
0.305	0.046	1.000	0.914	0.219	0.958	1.871	12.774	0.417
0.305	0.094	0.998	0.914	0.314	0.958	2.316	2.009	0.623
0.305	0.094	0.996	0.914	0.439	0.916	2.316	4.246	0.485
0.305	0.146	1.000	0.914	0.561	0.906			
0.305	0.216	0.985	0.914	0.683	0.883			
0.305	0.219	0.988	0.914	0.689	0.872			
0.305	0.308	0.973	0.914	0.811	0.896			
0.305	0.433	0.965	0.914	0.927	0.867			
0.305	0.564	0.973	0.914	1.158	0.868			
0.305	0.686	0.971	0.914	1.439	0.858			
0.305	0.808	0.985	0.914	1.941	0.803			
0.305	0.939	0.986	0.914	2.911	0.757			
0.305	1.204	0.941	0.914	4.325	0.686			
0.305	1.442	0.935	0.914	6.053	0.590			
0.305	1.911	0.911	0.914	9.390	0.479			
0.305	2.941	0.754	0.914	10.628	0.450			
0.305	4.383	0.626	0.914	15.376	0.342			
0.305	6.388	0.479						
0.305	8.689	0.487						

Values of α and β were determined for various subsets of the data using a method of non-linear least squares, and the results of these calculations are given in table 3.

All of the 167 data points are shown in figure 1 as a semi-log plot of E_{LS} vs V_M. The dashed line in figure 1 is given by the relation,

$$E_{LS} = \frac{1}{1+\left(\frac{V_M}{8.66}\right)^{1.39}} \qquad [4]$$

where the mixture velocity, V_M has units of (m/sec).

Equation [4] is actually based on a culled data set in which all observations where $V_{SG} > 10$ m/sec have been discarded. These points are included in figure 1, however. The basis for neglecting these points in the evaluation of α and β lies in the observations from a detailed investigation of flow pattern transitions for the same oil/air system and flow loop used in this study. Gregory *et al.* (1977) noted that the transition from intermittent (i.e. slug) flow to annular flow generally lies within the region of $10 \leq V_{SG} \leq 15$ m/sec. A similar observation can be made

Table 3. Comparison of the values of α and β in [3] calculated using various data subsets

$$\text{Model: } E_{LS} = \frac{1}{1 + \left(\frac{V_M}{\alpha}\right)^{\beta}}$$

$$d_i = (E_{LS})_{i,\text{pred}} - (E_{LS})_{i,\text{obs}}$$

$$\bar{d} = \frac{\sum_{i=1}^{n} d_i}{n}$$

$$S = \frac{\sum_{i=1}^{n} d_i^2}{n-1}$$

Description of data	Number of data points	α	β	$\bar{d}$	S
All data for 2.58 and 5.12 cm I.D. pipes	167	10.2	1.21	−0.006	0.042
All data for 2.58 cm I.D. pipe	62	12.8	1.06	−0.004	0.035
All data for 5.12 cm I.D. pipe	105	9.48	1.26	−0.008	0.042
$V_{SG} < 10$ m/sec for 2.58 and 5.12 cm I.D. pipes	157	8.66	1.39	−0.002	0.034
$V_{SG} < 10$ m/sec for 2.58 cm I.D. pipe	59	9.95	1.27	−0.004	0.029
$V_{SG} < 10$ m/sec for 5.12 cm I.D. pipe	98	8.30	1.42	−0.005	0.035

with the generalized flow pattern map that has been proposed by Mandhane *et al.* (1974). The relatively wider data scatter that is evident in figure 1 for $V_M > 10$ m/sec is thus thought to be due to the somewhat unstable nature of slug flow as the transition to annular flow is approached. It is significant that E_{LS} values in this region are of the order of 0.45, indicating that the slug is in fact a very frothy mixture under these conditions. It is clear from table 3 that the 10 observations which lie in or very close to the transition region exert a substantial effect on the values of α and β.

Examination of figure 1 and table 3 suggests the existence of a modest diameter effect, with values of E_{LS} tending to be slightly higher for the 2.58 cm pipe at values of $V_M > 1.0$ m/sec, and slightly lower when $V_M < 1.0$ m/sec. If, in fact, [3] is rewritten as

$$E_{LS} = \frac{\alpha^{\beta}}{\alpha^{\beta} + V_M^{\beta}}$$

it can be noted that there is only a small difference between the values of α^{β} for the culled 2.58 and 5.12 cm I.D. data sets (i.e. 18.5 and 20.2 respectively). Thus it is possible that α^{β} represents a single constant for the two diameters and any true diameter effect is reflected solely in the value of β. Detailed examination of the data in tables 1 and 2 also suggests that there might be a modest effect on E_{LS} due to V_{SG}. However, in view of the general degree of data scatter, the

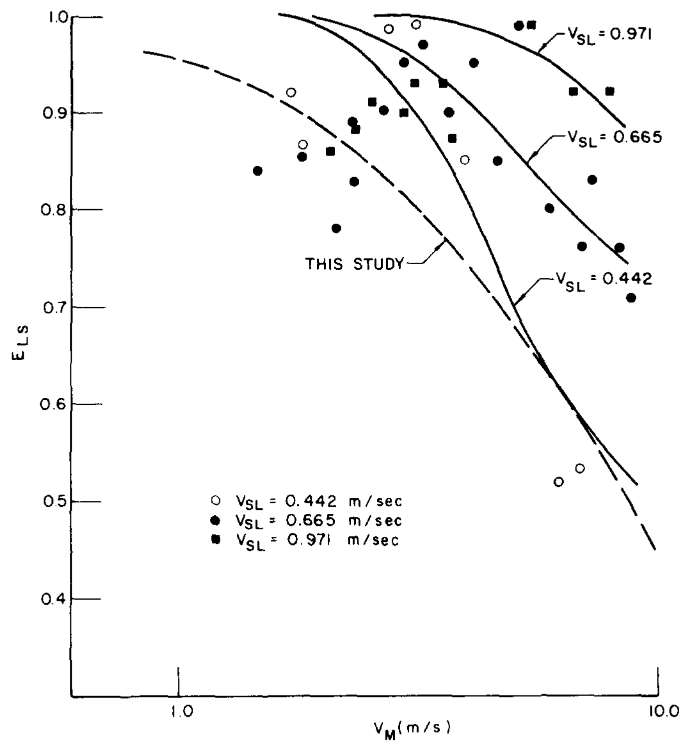

Figure 2. Comparison of the correlation proposed in this study with the data of Hubbard (1965).

fact that only two diameters have been considered, and the simplicity of [4], no attempt has been made at this time to quantify these effects.

Finally, it is of interest to compare the E_{LS} data of Hubbard (1965) referred to earlier with the correlation represented by [4]. This comparison is shown in figure 2 in which [4] is shown by the dashed line. It must be noted that Hubbard's data were obtained in a 3.81 cm I.D. pipe with the air–water system and the different fluid system may account for at least some of the data shift to the right. However, the scatter is so bad that any explanation is tenuous. The solid lines in figure 2 represent the "smoothed" fit to the data for the various indicated values of V_{SL} which were used by Hubbard for the purposes of testing his model. The correlation and data presented in this paper are an obvious improvement over those of Hubbard, which have been the only data known by the present authors to have been reported in the literature up to this time.

CONCLUSIONS

1. The capacitance-type *in situ* liquid volume fraction sensors described by Gregory & Mattar (1972) are capable of providing reasonably reproducible measurements of E_{LS} when used with a non-electrolyte system such as air–oil.

2. A correlation has been proposed which can be used to predict E_{LS} over the entire range of flow rates in which slug flow occurs.

3. The form of the correlation might eventually have to be modified to include a diameter, flow rate and possible fluid property effect as appropriate data become available.

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NOMENCLATURE

$\bar{d}$ mean deviation between predicted and observed values of E_{LS};

E_{LS} liquid volume fraction in the slug under flowing conditions;

S standard deviation between predicted and observed values;
V_M mixture velocity, $= V_{SL} + V_{SG}$ (m/sec);
V_{SG} superficial velocity of the gas phase (m/sec);
V_{SL} superficial velocity of the liquid phase (m/sec);
α parameter in [3];
β parameter in [3];
ρ_G density of the gas phase (kg/m^3);
ρ_L density of the liquid phase (kg/m^3);
ρ_M density of the gas–liquid mixture, defined by [1], (kg/m^3).

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