Prediction of Gas-Liquid Holdup for Inclined Flows

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The accurate prediction of in situ liquid holdup during two-phase, gas-liquid flows in long distance pipelines is a necessity for design purposes. Since a major portion of the overall line pressure drop is due to ascending portions of the pipelines, the accurate prediction of inclined (hereafter used to mean positive inclinations) liquid holdups is extremely important for design and subsequent line operation. In view of the total number of miles of such pipes already built and those in the planning stages, the prediction of inclined holdups becomes, in most probability, the single most important task for the design engineer.

At present, few articles in the literature consider inclined flows. Early work by Flannigan (1958) demonstrated the contribution of the hills to the overall line pressure drop. A number of investigators, as summarized by Gouse (1963, 1964, 1966), have discussed the importance of uphill flows but rarely presented any design data or correlations useful for scale-up. More recently, a number of papers have appeared in the Russian literature concentrating in the area of two-phase, gas-liquid pipeline analysis. Articles by Mamaev (1965), Gallyamov and Goldzberg (1967, 1968), Isupov and Mamaev (1968), and Guzhov et al. (1967) represent a sizeable research effort in this area. In similar fashion, American authors such as Bonnecaze et al. (1969, 1971), Greskovich (1972), and Bonderson (1969) have also considered the subject of inclined two-phase flows.

A particular method for correlating actual liquid holdup with flowing liquid quality has been discussed by most of the above Russian investigators and expanded upon by Greskovich et al. (1969), Greskovich and Shrier (1971), and Greskovich (1972). The correlation utilizes only the mixture Froude number as a parameter and has been shown by Greskovich and Shrier (1971) to be quite accurate for horizontal flows. The only reported use of such a correlation for inclined flows is made by Guzhov et al. (1967) for a pipe inclined 9° from the horizontal. Liquid holdup data presented in Figure 1 are based on the Russian results. Conversion of gas holdup data from Guzhov to liquid holdups was made for our purposes.

It is noted in Figure 1 that for all data presented, the true liquid content is greater than the input liquid content indicating a positive slip velocity. Furthermore, as the input liquid content approaches 100%, the true liquid content approaches 100% as expected. However, as the input liquid content approaches zero, the true liquid content takes on different intercept values depending on the value of the mixture Froude number. But since the liquid rate is zero, the mixture Froude number essentially reduces to a gas Froude number. The physical situation is that of gas moving through a stagnant liquid in slug flow.

EXPERIMENTAL PROCEDURE

Recognizing the value of the intercept and also noting that all the data correlated with the mixture Froude number could be represented by straight lines, work was undertaken in our laboratory to confirm the data of Guzhov by only measuring true liquid holdups at zero liquid rates. The experimental procedure was to utilize a 2.54-cm glass pipe inclined at 9° from the horizontal, initially fill the pipe with water, pass carbon dioxide through the liquid until equilibrium was achieved, and then with the gas rate turned off, measure the liquid content in the pipe. In order to assure a minimum of end effects, the actual liquid holdup was measured for a specified Froude number using a 1.52-m length of pipe. An additional 1.52-m length of pipe was added and the run was repeated. The value of the true liquid content increased. A third section of pipe (the same length) was added, making the overall pipe length 4.57 m. The run was repeated and the true liquid content was approximately the same as that for the 3.05-m section indicating a sufficient pipe length for study. The data reported here represent an average of three runs at the same conditions.

RESULTS AND DISCUSSION

The data obtained in our laboratory for a pipe inclination of 9° from the horizontal are presented in Figure 1. There is reasonable agreement between our data and the data of Guzhov et al. (1967) at the intercepts for Froude numbers of 0.4, 0.8, and 2.0. Of course, all one needs to do to extend intercept data over the range of gas and liquid flow rates is to draw a straight line from the intercept to η and $\lambda = 1$ for each Froude number.

Additional intercept data obtained from our laboratory for other pipe inclinations are presented in Table 1. To the best of my knowledge, no literature data are available with which to compare these numbers; however, they appear to be consistent based on the bubble rise correlation of Bonderson (1969). Using data based on the works of Runge and Wallis (1965), and Zukoski (1966), Bonderson developed an expression for predicting the void fraction for gas-liquid flow in inclined pipes using the following expressions:

$$\alpha = Q_G/(Q_G + Q_F + V_b A) \quad (1)$$

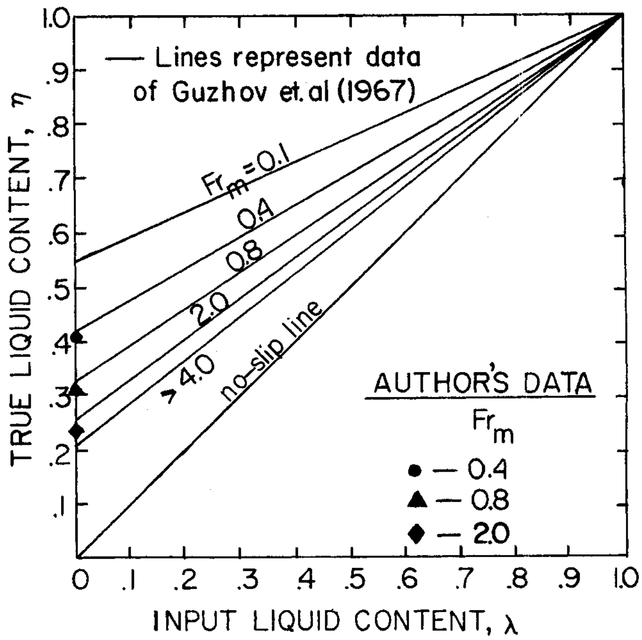

Fig. 1. Dependence of true liquid content on input liquid content and mixture Froude number for gas-liquid flow at 9° from the horizontal.

TABLE 1. LIQUID HOLDUP DATA AT VARIOUS PIPE INCLINATIONS AND MIXTURE FROUDE NUMBERS

θ	$\eta_{\lambda=0}$	Fr_m
2°	0.13	0.4
	0.22	0.8
	0.32	2.0
6°	0.19	0.4
	0.28	0.8
	0.39	2.0
10°	0.22	0.4
	0.31	0.8
	0.41	2.0

TABLE 2. COMPARISON OF LIQUID HOLDUP DATA

θ	Fr	$\eta_{\lambda=0}$	η_B
9°	0.1	0.56	0.56
	0.4	0.42	0.42
	0.8	0.33	0.36
	2.0	0.26	0.30

where

$$V_b = K_2 V + 0.35\ K_3\ (g \Delta\rho D/\rho_f)^{1/2} \qquad (2)$$

These equations are similar to earlier expressions for vertical two-phase flow by Griffith and Wallis (1961) and Nicklin et al. (1962), and for horizontal flows by Hughmark (1965). Bonderson adapted the equation specifically to consider the case of inclined flows. Using Equations (1) and (2) with values of $K_2 = 0.2$ and $K_3 = 1.0$, the true liquid content for a pipe inclination of 9° and at $\lambda = 0$ is calculated and given in Table 2 as η_B. This is accomplished by noting that from continuity, $\alpha + \eta = 1$.

The Bonderson (1969) model agrees well with the data of Guzhov et al. (1967) as indicated in Table 2 as well as data from our laboratory. However, it can be noted that the values for K_2 and K_3 in the Bonderson model are ideal values for a pipe inclination of approximately 10°. When the angle is reduced to approximately 2° as noted in Table 1, the values for $\eta_{\lambda=0}$ are sizeably smaller by 20 to 40% than those for 10°. It is not certain that the Bonderson model can account for these differences.

CONCLUSIONS AND RECOMMENDATIONS

The correlation of true liquid content with input liquid quality and mixture Froude number is convenient and accurate for two-phase flows including inclined flows. In a similar fashion, Greskovich (1972) has shown that the input liquid quality and mixture Froude number are also useful in correlating slug frequency.

Rather than spend an exhaustive amount of time and money on collecting holdup data for two-phase flows, it is recommended that holdups at $\lambda = 0$ be collected and lines extrapolated to $\lambda = 1$, $\eta = 1$ for any desirable mixture Froude number. This can be especially useful when experimental data are collected from large diameter pipes for scale-up purposes. Of course, it may be possible to use the Bonderson model to predict liquid holdup in inclined lines; however, verification of this model must be made for small inclinations and large pipe diameters before it can be recommended for general scale-up purposes.

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NOTATION

- A = pipe cross-sectional area, m²
- D = pipe diameter, m
- Fr = mixture Froude number, V^2/Dg
- g = gravitational constant
- K_2, K_3 = constants in Equation (2)
- Q_G, Q_F = gas and liquid flow rates, respectively, m/s
- V = mixture velocity, $Q_G + Q_F/A$
- V_b = bubble rise velocity given by Equation (2)

Greek Letters

- α = gas void fraction
- η = true liquid holdup, fraction
- $\eta_{\lambda=0}$ = true liquid holdup at zero liquid rate
- η = true liquid holdup calculated by Equation (1)
- λ = input liquid quality, $Q_F/Q_F + Q_G$
- ρ = liquid density, kg/m³
- $\Delta\rho$ = density difference between liquid and gas, kg/m³

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