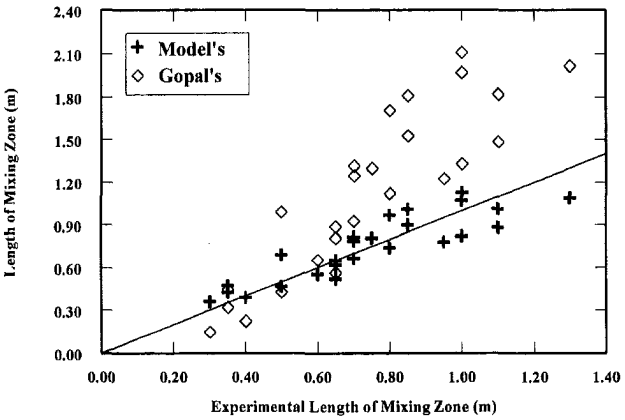

Fig. 20 Model's and Gopal's length of the mixing zone versus experimental length of mixing zone

Conclusions

Slug flow characteristics were studied using water, LVT, a 10.9-cP and a 16.6-cP single-phase mixture of Britol and LVT with nitrogen as the gas phase. The experiments were conducted in a 10.1-cm pipeline at a constant temperature of 40°C and a constant pressure of 0.136 MPa. The nondimensional liquid film height before the slug ranged from 0.28 to 0.40. A stationary slug was used in all experiments.

The results from this study show that as the film Froude number increases the amount of gas entrained in the slug at any given distance also increases. When the liquid film height before the slug increases, so does the liquid holdup at any given distance into the slug. The data also suggest that the higher the viscosity of the fluid, the less gas the slug will entrain at the same film Froude number, and the liquid holdup at the slug front is equal to the nondimensional area of the liquid film height before the slug.

The length of the mixing zone was estimated for each film Froude number by using a visual means of determining the length of the turbulent part of the slug. The length was then determined by studying the liquid holdup data. The end of the mixing zone was determined to be the point where the average liquid holdup became constant. The length of the mixing zone was then plotted against the film Froude number and a linear relationship was observed. There was no effect on the length of the mixing zone when the viscosity of the liquid inside the slug increased, for a viscosity range from 1 to 16.6 cP. An empirical correlation for the length of the mixing zone was developed.

References

Andreussi, P., and Bendiksen, K., 1989, "An Investigation of Void Fraction in Liquid Slugs for Horizontal and Inclined Gas-Liquid Pipe Flow," *International Journal of Multiphase Flow,* Vol. 6, p. 937.

Andreussi, P., Bendiksen, K., and Nydal, O. J., 1993, "Void Distribution in Slug Flow," *International Journal of Multiphase Flow,* Vol. 5, p. 817.

Dukler, A. E., and Hubbard, M. G., 1975, "A Model for Gas-Liquid Slug Flow in Horizontal and Near Horizontal Tubes," *Industrial Engineering Chemistry Fundamentals,* Vol. 14, No. 4, p. 337.

Ferschneider, G., 1983, *Revue de L'Institut Francais du Petrole,* Vol. 38, No. 2, p. 153.

Gopal, M., 1994, "Visualization and Mathematical Modelling of Horizontal Multiphase Slug Flow" dissertation, Ohio University, Aug.

Gopal, M., and Jepson, W. P., 1997, "The Study of Dynamic Slug Flow Characteristics Using Digital Image Analysis," ASME JOURNAL OF ENERGY RESOURCES AND TECHNOLOGY.

Gopal, M., Kaul, A., and Jepson, W. P., 1995, "Mechanisms Contributing to Enhanced Corrosion in Horizontal Three-Phase Oil, Water, and Gas Slug Flow," NACE Paper No. 105.

Green, A. S., Johnson, B. V., and Choi, H., 1990, "Flow-Related Corrosion in Large-Diameter Multiphase Flowlines," SPE 20685, p. 677.

Gregory, G. A., Nicholson, M. K., and Aziz, K., 1978, "Correlation of the Liquid Volume Fraction in the Slug for Horizontal Gas-Liquid Slug Flow," *International Journal of Multiphase Flow,* Vol. 4, p. 33.

Jepson, W. P., 1987, "The Flow Characteristics in Horizontal Slug Flow," *3rd International Conference Multiphase Flow,* Paper F2, p. 187.

Jepson, W. P., and Kouba, G. E., 1987, "The Flow of Slugs in Horizontal, Two Phase Pipeline," *Pipeline Engineering Symposium,* p. 37.

Jepson, W. P., and Taylor, R. E., 1988, "Slug Flow and its Transitions in Large Diameter Horizontal Pipes," AERE-R12992, Harwell Lab., Feb.

Taitel, Y., and Dukler, A. E., 1976, "A Model for Predicting Flow Regime Transitions in Horizontal and Near Horizontal Gas-Liquid Flow," *AIChE Journal,* Vol. 22, No. 1, p. 47.

DISCUSSION

G. E. Kouba[1]

Maley and Jepson (MJ) have used holdup measurements to define the mixing region in slug flow, and, in so doing, present a different picture of the mixing region than previous investigators, (e.g., Dukler and Hubbard, 1975). Three key observations from MJ help to characterize the mixing zone at the slug front:

1 The liquid holdup at the slug front is approximately equal to the holdup in the film immediately in front of the slug.
2 There seems to be a fixed minimum length of the mixing region, represented by the constant in their correlation.
3 The mixing region grows linearly with Froude number and is not a strong function of liquid viscosity.

Although MJ do not offer any mechanistic explanations of the mixing phenomena in slug flow, their data and observations provide insight into the characteristics of the mixing region. This discussion presents a mechanistic interpretation of the mixing region characteristics presented by MJ.

A Mechanistic Model of Slug Mixing Region

The regions of the slug and mixing zone are illustrated in Fig. 21. In this view, the MJ mixing zone is comprised of two axially separated areas, each with a different function, namely entrainment and redistribution.

Entrainment Region. Large-scale turbulent eddies are created as the slug overruns gas and liquid film in the entrainment region. The lead eddy is capable of engulfing both liquid and gas in large gulps rather than scooping, as explained by some investigators. Because the lead eddy throws forward a curtain of liquid which tends to engulf everything in front, the holdup at the beginning of the mixing region tends to equal the holdup of the preceding film region as observed by MJ. The size of the large entrainment lead eddy is of the order of the pipe diameter (D) if all the liquid in the film is entrained, and of order ($D - h_{lf}$) if the slug skates over the film with little entrainment. The second eddy is weaker and rotates counter to the lead eddy. After the second eddy, the turbulence is no longer strong enough to entrain large bubbles; therefore, the rear of the second eddy marks the end of the entrainment region and the beginning of the redistribution region. The entrainment region is bound by the two eddies and is approximately $1.5D$ in length from the start of the slug, i.e., the point at which liquid bridges the top of the pipe.

$$2*(D - h_{lf}) \leq L_e \leq 2*D \qquad (10)$$

Redistribution Region. The magnitude of the large-scale turbulence has declined dramatically by the end of the entrainment region and buoyancy begins to dominate the motion of large bubbles, forcing the redistribution of gas. In the redistribution region, the large gas bubbles migrate upward. The size of bubbles that can be entrained by the decaying turbulence stead-

[1] Chevron Petroleum Technology Company, P.O. Box 446, 1300 Beach Boulevard, La Habra, CA 90631-6374

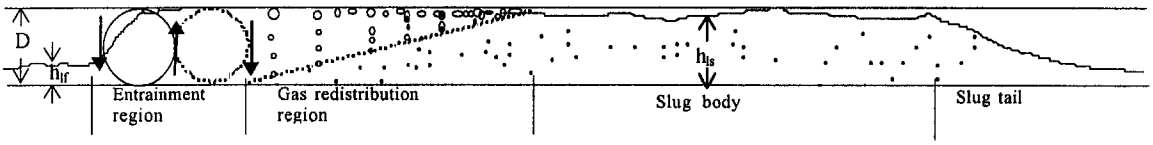

Fig. 21 Regions of mixing zone in liquid slug. Two counterrotating eddies entrain gas and liquid at the slug front. Further back gas redistributes as turbulence decreases.

ily decreases in this region. The turbulence continues to decay toward the residual turbulence in the slug body. The redistribution of the gas is complete at the end of this region and remains essentially unchanged throughout the slug body. A continuous pocket of gas may ride on top of the liquid in the slug, and only those small gas bubbles, capable of being entrained by the residual turbulence, are distributed throughout the liquid.

The liquid holdup increases with distance into the mixing region as the large bubbles migrate out of the high-speed core and accumulate in the low-speed upper wall region. Because the decaying turbulence can entrain less gas, the liquid holdup increases and becomes constant at the end of the redistribution region. The length of the redistribution region can be determined by calculating the axial distance that a moderate-size bubble traverses as it rises from the bottom of the pipe to the gas/liquid interface as follows:

$$L_r = h_{ls}/v_b*(v_t - v_m) \tag{11}$$

where

h_{ls} = liquid height to gas/liquid interface, i.e., vertical traverse distance for bubbles
v_t = translational velocity of slug front
v_m = mixture velocity and axial velocity of bubbles with respect to pipe wall
v_b = rise velocity of a moderate bubble calculated from Eq. (12) (Harmathy, 1960)

$$v_b = 1.53\left[\frac{\sigma g \Delta\rho}{\rho^2}\right]^{1/4} \tag{12}$$

The quantity, $v_t - v_m$, is the axial velocity of the bubble relative to the slug front, and h_{ls}/v_b is the rise time of the bubble.

The total length of the mixing zone is the sum of Eqs. (10) and (11). Assuming the lead eddies are of order D in size and the slug starts where the liquid bridges the top of the pipe, then

$$L_m \cong 1.5D + h_{ls}/v_b*(v_t - v_m) \tag{13}$$

In dimensionless form, Eq. (13) becomes

$$L_m/D \cong 1.5 + h_{ls}/D*(v_t - v_m)/v_b \tag{14}$$

Equation (13) can also be expressed in terms of a slug Froude number, $\mathrm{Fr}_s = (v_t - v_m)/\sqrt{gD}$, which is related to the film Froude number used by MJ.

$$L_m = 1.5D + \frac{h_{ls}\,\mathrm{Fr}_s\sqrt{gD}}{v_b} \tag{15}$$

This representation of the mechanistic model is similar in form to the linear MJ correlation, but with two notable exceptions: neither slope nor intercept is constant.

Results

The mechanistic model of the MJ mixing length can be represented by any of the equivalent forms given by Eqs. (13), (14), or (15). Predictions of mixing length from the mechanistic model and the MJ correlation are compared against MJ data in Fig. 22. The dashed lines indicate a combined uncertainty of ±0.2 m (MJ reported ±0.15 m for each end). With the exception of two data points, the mechanistic model performs as well as the MJ correlation.

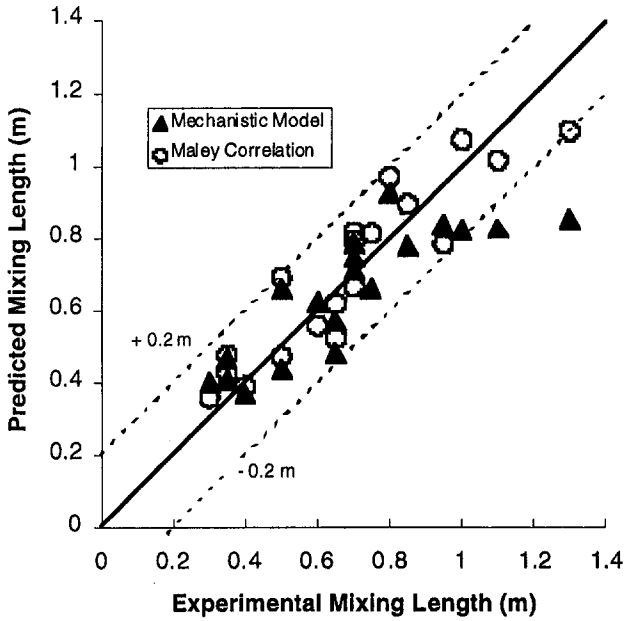

Fig. 22 Comparison of mechanistic model with Maley and Jepson's data and correlation for mixing length

The mechanistic model is consistent with the three observations from MJ. The lead eddy rolls over and entrains the volume of gas and liquid in front of the slug. The minimum length of the mixing region is nearly constant for a given diameter and is governed by the size of the two lead eddies. The growth of the redistribution region is nearly linear with Froude number and is weakly affected by viscosity at low to moderate viscosity.

The advantage of the mechanistic model over the correlation is that it scales with diameter and allows for fluid property effects through the bubble rise velocity, v_b.

Improvements to this simple mechanistic model of entrainment and redistribution regions may result from accounting for bubble penetration depth, hindered rise of bubble swarm and viscous effects, and perhaps calculating rise velocity based on bubble size for small bubbles (<1 mm).

Conclusions

Maley and Jepson's investigation into holdup in slug flow yields insight into the mixing region. A simple mechanistic model has been developed that is consistent with observations and measurements of the mixing region.

Additional References

Dukler, A. E., and Hubbard, M. G., 1975, *Industrial Engineering & Chemistry Fundamentals,* Vol. 14, No. 4, pp. 337–347.

Harmathy, T. Z., 1960, *AIChE Journal,* Vol. 6, p. 281.