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Liquid Holdup in Large-Diameter Horizontal Multiphase Pipelines

This paper studies the liquid holdup within the mixing zone of the slug. The results of the study show that the liquid holdup begins at the liquid holdup of the liquid film before the slug and then increases until the end of the mixing zone is reached. Once past the mixing zone of the slug, the average liquid holdup becomes constant. As the height of the liquid film and/or viscosity increases, so does the liquid holdup at any given film Froude number. Since the liquid holdup becomes constant once past the mixing zone of the slug, the mixing zone length was determined for the film Froude numbers studied. The results show that the mixing zone length increases linearly with film Froude number and is independent of the viscosity of the liquid in the slug for a viscosity range of 1 to 16.6 cP.

Introduction

Slug flow is a common flow regime in long-distance multiphase pipelines. When the slug front moves through the pipe, it overruns the slower moving liquid film and accelerates the film to the velocity of the slug. During this process a mixing vortex is created, called the mixing zone. The mixing zone entrains a considerable amount of gas which is released in the form of pulses of bubbles. The pulses of bubbles are shot toward the bottom of the pipe where they can impact and collapse. Figure 1 shows the different regions of the slug. The bubble collapse is believed to increase the corrosion rate and reduce the efficiency of corrosion inhibitors in slug flow. Green et al. (1990) have determined that slug flow causes a higher corrosion rate than wavy/annular. Slug flow can be eliminated if the production is reduced or the gas flow rate is increased. If the production is reduced, a stratified flow regime occurs, which reduces corrosion rate, but reduces the amount of product. If the gas velocity is increased by injecting gas into the pipeline, an annular flow regime occurs. Corrosion rates are reduced, but erosion rates can increase, especially where sand is present within the mixture.

This project uses a stationary slug to study the liquid holdup and length of the mixing zone in a two-phase mixture. Jepson (1987) has shown that the slug characteristics in the mixing zone in a stationary slug are equivalent to moving slugs for the same film Froude numbers. Therefore, this study used a stationary slug for the experiments. The stationary slug allowed the slug characteristics within the mixing zone of the slug to be studied at different distances. Four different liquids were used in this study, water, Conoco LVT200, and two different single-phase mixtures of Britol and Conoco LVT200.

Literature Review

Liquid Holdup. Gregory et al. (1978) developed a correlation for liquid holdup within the slug. The experiments were performed using a light refined oil and air in 2.58-cm and 5.12-cm pipes. To determine the liquid holdup in the slug, they used a capacitance-type liquid volume fraction sensor. The following correlation was developed for liquid holdup, H_L, within the slug:

$$H_L = \frac{1}{1 + \left[\frac{v_M}{8.66}\right]^{1.39}} \tag{1}$$

where v_M is the mixture velocity of the slug and is defined as

$$v_M = v_{SL} + v_{SG} \tag{2}$$

where v_{SL} is the superficial liquid velocity and v_{SG} is the superficial gas velocity. This model gives the average liquid holdup across the entire slug body. The majority of the gas is entrained within the mixing zone of the slug, therefore, the value obtained by using Equation 1 will give a higher liquid holdup value than if only the average liquid holdup within the mixing zone was studied.

Fershneider (1983) also studied liquid holdup in a 0.146-m-dia pipeline using an optical probe. The pressure varied between 10 and 50 bars at ambient temperature. The superficial liquid velocity ranged from 0 to 3 m/s, and the superficial gas velocity ranged from 0 to 7 m/s. The model developed by Fershneider agreed with the data from Gregory et al. (1978). Andreussi and Bendiksen (1989) used air and water to develop a correlation for liquid holdup in horizontal and near horizontal pipelines. They used 5-cm and 9-cm i.d. pipelines ranging from an inclination of -3 to ± 0.5 deg. The data that were collected were used with Gregory et al. (1978) and Fershneider (1983) to develop the correlation. The model used the pipe diameter, inclination, and fluid properties to determine the liquid holdup. However, there were empirical coefficients that were not clearly defined.

Jepson and Kouba (1987) used stationary slugs to perform liquid holdup experiments in a 15-cm pipeline using air and water. They determined that the liquid holdup decreased linearly as the film Froude number increased. The film Froude number is defined in Eq. (6). Jepson and Taylor (1988) performed experiments using air and water in a 30-cm pipeline. They determined that the liquid holdup also was dependent upon the pipe diameter for a gas velocity above 3 m/s.

Gopal (1994) studied the liquid holdup as a function of distance into the slug. He studied two phase slug flow by using water and carbon dioxide mixture, and ARCOPAC90™ and carbon dioxide mixture in a 7.5-cm pipeline at 298 K and 0.101 MPa. Gopal determined that the liquid holdup can be modeled by using a second order process dynamic system. The differential equation which describes this system is

$$\tau^2 \frac{d^2Y}{dt^2} + 2\xi\tau \frac{dY}{dt} + Y(t) = X(t) \tag{3}$$

where τ is a time constant, ξ is the damping ratio, t is time,

Contributed by the Petroleum Division and presented at the Nineteenth Annual Energy-Sources Technology Conference and Exhibition, Houston, Texas, February January 2–6, 1998, of THE AMERICAN SOCIETY OF MECHANICAL ENGINEERS. Manuscript received by the Petroleum Division, October 10, 1997; revised manuscript received June 4, 1998. Technical Editor: J. P. Brill.

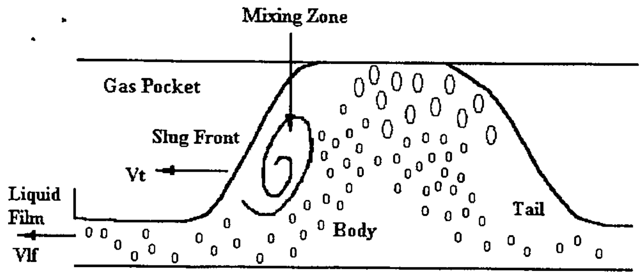

Fig. 1 Profile of different regions of a slug

$X(t)$ is the step input, and $Y(t)$ is the response of the system. Gopal replaced time with distance into the slug, x, and the input was the liquid holdup at x. He determined that the time constant was linearly proportional to the length of the mixing zone

$$\tau = \frac{\text{LMZ}}{4} \tag{4}$$

The damping ratio was determined to be

$$\xi = \frac{\text{Fr}_f}{\sqrt{\text{Re}/\text{Eo}}} \tag{5}$$

The film Froude number is defined as

$$\text{Fr}_f = \frac{v_t - v_{\text{lf}}}{\sqrt{g h_{\text{ef}}}} \tag{6}$$

where v_t is the translational velocity of the slug and equals zero for a stationary slug, v_{lf} is the velocity of the liquid film, g is acceleration due to gravity, and h_{ef} is the effective height of the liquid film. The area of the liquid film can be calculated using equations given by Taitel and Dukler (1976).

Length of Mixing Zone. Early research on slug length modeled the entire length of the slug. Dukler and Hubbard (1975) used air and water in a 3.75-cm pipeline to study the slug length, which was measured using a single electrical contact probe. The data suggested that the slug length was 12–25 pipe diameters. They also suggested that the depth of penetration of the liquid film, the mixing zone, into the slug is dependent upon the velocities of the slug and film. Gopal and Jepson (1997) have shown that Dukler and Hubbard's (1975) model underpredicts the mixing zone length. They have shown that the mixing zone length should be determined by the mixing of the gas and liquid instead of only using the liquid film. Andreussi et al. (1993) suggested that the length of the mixing zone is dependent upon the diameter of the pipe and the liquid holdup of the slug. Andreussi et al. also determined that the slug length was 15–22 pipe diameters.

Gopal (1994) defined the length of the mixing zone as the minimum distance for the void fraction distribution to become a near steady-state profile. He was also the first to correlate the length of the mixing zone, LMZ, with the film Froude number. His studies used water and carbon dioxide and included film Froude numbers of 5 and below with a few film Froude numbers

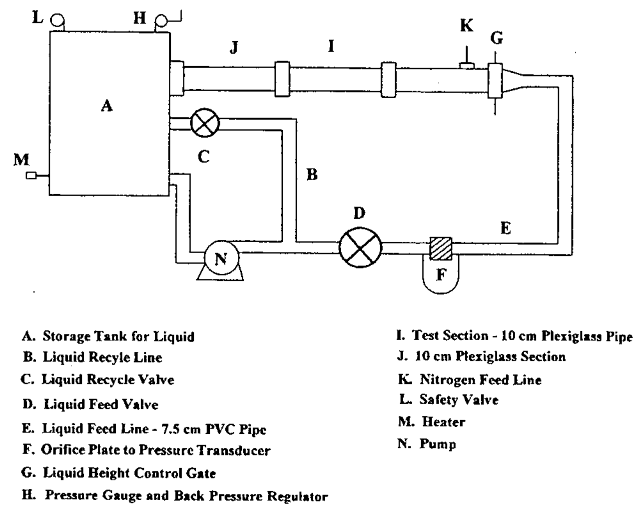

Fig. 2 Experimental layout

between 5 and 10. He found that when the film Froude number increased, the length of the mixing zone increased linearly. The correlation that he developed, with LMZ in meters is

$$\text{LMZ} = 0.13\ \text{Fr}_f - 0.31 \tag{7}$$

This correlation implies that when the film Froude number is equal to 2.5, the length of the mixing zone is zero. However, a slug cannot exist under a film Froude number of approximately 2; therefore, this correlation seems to be valid. Gopal also determined that the total slug length was 5 to 20 pipe diameters.

Experimental Setup

Description of the Flow Loop. The experiments were performed in the system shown in Fig. 2. The experimental layout is 18-m long and is made from PVC and acrylic pipe. The liquid is stored in a 1.3 m^3 stainless steel tank, and using a 7.4-kW centrifugal pump, the liquid is pumped into a 7.6-cm i.d. PVC pipeline. The flow rate of the liquid was controlled using a pump variable speed drive. The liquid then flows through an orifice plate where the pressure drop is measured with an Omega differential pressure transducer with a range of 0 to 5 psi. The liquid then flows into a 10.1-cm i.d. acrylic pipeline where the flow is forced under a gate, and a fast moving liquid film is produced. Three different gate geometries were used in this study. These had ratios of $h/D = 0.28$, $h/D = 0.33$, and $h/D = 0.40$, respectively.

Nitrogen is then introduced into the system. The nitrogen flows from a 5,000 ft^3 storage tank to a pressure regulator at a pressure of 150 psi. The flow rate is controlled by a $\frac{3}{4}$-in. stainless steel needle valve and the gas is injected immediately after the gate. This forms a gas pocket and a hydraulic jump, or slug, is created. The gas flow is adjusted and the slug is moved to the test section and held there. Measurements are then taken.

Nomenclature

A = area of pipe
Eo = Etovos no.
Fr = Froude no.
H = holdup
LMZ = length of mixing zone
Re = Reynolds no.
X = step input
Y = response of second-order system
g = acceleration due to gravity
h = height of liquid film
t = time
v = velocity
α = void fraction
ξ = damping ratio
τ = time constant

Subscripts

M = mixture
SL = superficial liquid
SG = superficial gas
f = film
lf = liquid film
t = translational

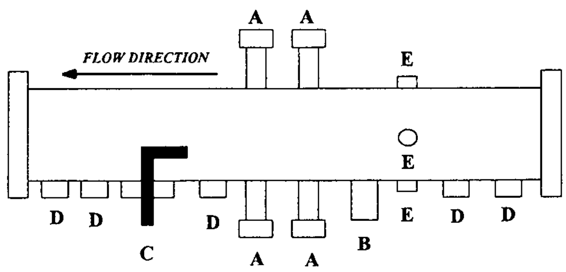

Fig. 3 Test section

The liquid/gas mixture then passes into the tank where the liquid is recycled and the gas is vented to the atmosphere.

The test section, shown in Fig. 3, is 10.1 cm in diameter and 2 m long and is manufactured from acrylic pipe with a 0.64-cm wall thickness. The measurements for this study were taken within the test section. The temperature of the flow was measured by using a type-K thermocouple which is connected to an OMEGA DP3200-TC thermometer. The temperature was held constant at 40°C by using a Wiegand heater with a Wellman thermal system thermostat. The pressure was maintained at 0.136 MPa within the test section by setting the back pressure in the storage tank.

Liquid Holdup. Each liquid holdup sample was withdrawn from the slug by using a 316 stainless steel sampling tube. The sample then flowed into a calibrated tube after simultaneously opening the inlet and outlet valves to the calibrated tube. With the slug held stationary within the test section, an isokinetic sample was withdrawn at a known vertical distance into the slug. At each film Froude number, samples of the flowing mixture, on the center line of the slug, were withdrawn at known distances into the slug.

The number of axial sampling distances was determined by the length of the mixing zone. The method of determining the length of the mixing zone is described in the next section. For each axial point, samples were taken at five different vertical heights across the pipe along the centerline of the pipe. After performing this experiment at five differential vertical heights at each axial location, an average void fraction was then calculated over the cross section of the slug by the following equation:

$$\bar{\alpha} = \frac{\Sigma\, \alpha_i\, dA_i}{A} \tag{8}$$

where α_i is the void fraction at vertical height i, dA_i is the inside differential cross-sectional area of the pipe that α_i represents, and A is the total area of the pipe. After completing the experiment for the entire length of the mixing zone for each film Froude number, the liquid holdup was calculated by subtracting the void fraction from one. The liquid holdup was then plotted against the distance into the slug. For each fluid studied, the liquid holdup experiments were repeated for at least four film Froude numbers.

Length of the Mixing Zone. The length of the mixing zone is determined by two methods. The first method is visual. As shown in Fig. 1, the length of the mixing zone is from the end of the film region to the part of the slug body where the bubbles are not entrained within the mixing vortex. Therefore, the end of the mixing zone can be determined by visually determining where the turbulence created by the mixing vortex is significantly reduced. This could only be determined to ±5 cm for low film Froude numbers, and ±15 cm for the high film Froude numbers.

The second method is based upon the liquid holdup results, and uses the fact that the average void fraction becomes constant once the end of the mixing zone is passed. Therefore, the measurements were taken up to and 30 cm past the visual length. A more accurate end of the mixing zone was then determined when the average liquid holdup became constant.

Results and Discussion

Liquid Holdup. The liquid holdup at a known distance into the slug was measured at five different locations across the cross section of the pipe. Figure 4 shows an example of the local liquid holdup at each of the five locations for a film Froude number of 7.4 for the 16.6 cP mixture. This figure shows that at 7.1 cm from the top of the pipe the liquid holdup is at the maximum value because the sampling probe has penetrated the liquid film. This figure also shows how the liquid holdup values from each of the locations range from 0.29 to 0.84 at a distance 8 cm into the slug and converge to 0.60 to 0.76 before the end of the mixing zone.

The slug front is constantly changing shape due to the high turbulence, therefore, it was difficult to obtain accurate data any closer than 15 cm into the slug front. However, at low film Froude numbers the slug front is not as turbulent as at high film Froude numbers, and a few data points at 8 cm into the slug were obtained. The slug was then moved down the pipe to another known distance and the experiment was repeated until the end of the mixing zone was reached. After obtaining the experimental data, the average liquid holdup was calculated by using a weighted average across the cross section of the pipe. A curve fit was performed through the data to show that the liquid holdup at zero distance into the slug is equal to the nondimensional area of the slug. Video images taken by Gopal et al. (1995) show that the liquid holdup in the slug front is equal to that of the liquid film.

The first fluid that was studied was 100 percent water with a nondimensional liquid gate and film height of 0.33 for a range of film Froude numbers from 4.8 to 18. The nondimensional area of the liquid film, the ratio of the area of the liquid film to the cross-sectional area of the pipe, was 0.29. Since, the liquid holdup is defined as the area of liquid divided by the area of the pipe, the nondimensional area is equal to the liquid holdup of the liquid film before the slug. Therefore, the liquid holdup at zero distance into the slug should be 0.29 for this fluid. The void fraction was plotted against the distance into the slug, as shown in Fig. 5, for a film Froude number of 8.6. The mixing zone length was determined to be 65 cm, and the liquid holdup at zero distance into the slug is 0.31, which is

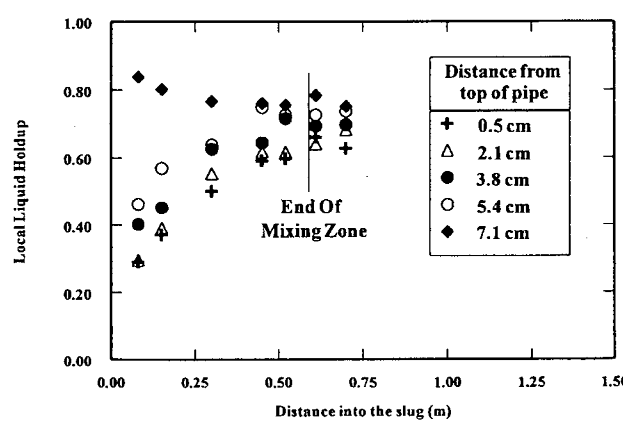

Fig. 4 Local holdup versus distance into the slug for a film Froude number 7.4 for 16.6 cP mixture

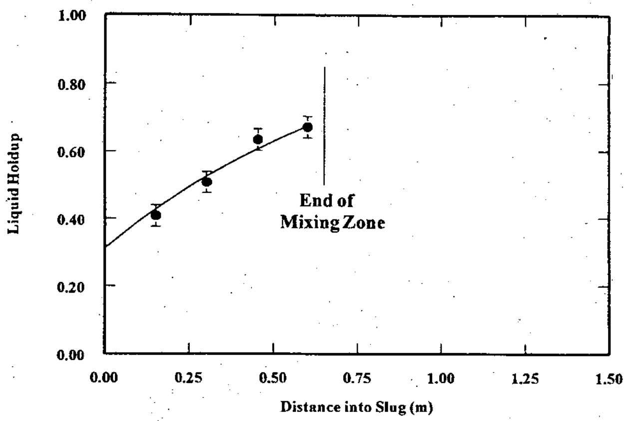

Fig. 5 Liquid holdup versus distance into the slug for film Froude number 8.6 for 100 percent water and a nondimensional liquid film area of 0.29

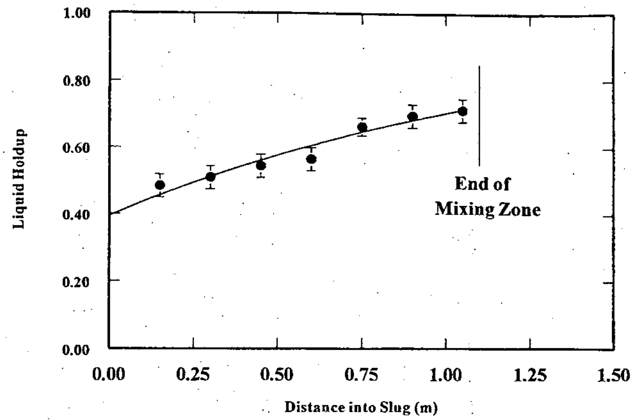

Fig. 7 Liquid holdup versus distance into the slug for film Froude number 13.8 for 100 percent water and a nondimensional liquid film area of 0.37

close to the nondimensional area before the slug. Figure 6 shows the liquid holdup for a film Froude number of 16.4, as a function of distance into the slug. The length of the mixing zone was 110 cm, and the intercept was 0.34. The liquid holdup ranged from 0.40 at 15 cm to 0.60 at 100 cm into the slug.

A second gate with a nondimensional gate height of 0.40 was then used, which also gave a measured nondimensional liquid film height of 0.40. The nondimensional area was determined to be 0.37. Figure 7 shows the data collected for the liquid holdup at a film Froude number of 13.8. The liquid holdup ranged from 0.48 at 15 cm to 71 at 105 cm, and the length of the mixing zone was 110 cm. The liquid holdup at zero distance into the slug, 0.39, was again close to the nondimensional area before the slug.

A third gate with a nondimensional gate height of 0.25 was studied. This gate had a nondimensional liquid film height before the slug of 0.28 and a nondimensional area of 0.23. Figure 8 shows similar results for a film Froude number of 18.6. The intercept was equal to 0.25, and the liquid holdup ranged from 0.30 to 0.54 from 15 cm to 90 cm into the slug. The end of the mixing zone is at 100 cm into the slug.

When a curve fit is performed on the data, the results show that at zero distance into the slug, the liquid holdup is equal to the liquid holdup due to the liquid film, the area of the liquid film divided by the area of the pipe. The results from the three liquid film heights studied, are shown in Fig. 9. This plot shows that the extrapolated intercept is close to the nondimensional area of the liquid film.

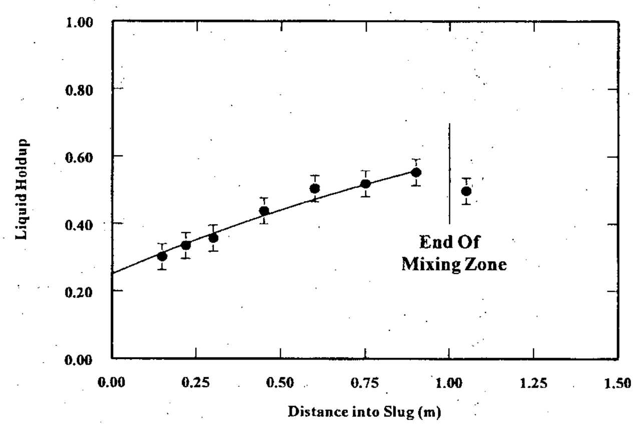

Fig. 8 Liquid holdup versus distance into the slug for film Froude number 18.6 for 100 percent water and a nondimensional liquid film area of 0.23

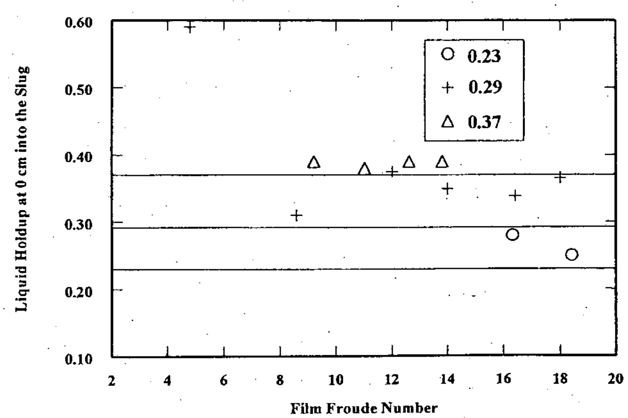

Fig. 9 Liquid holdup at 0 cm into slug versus film Froude number for varying ratios of a_{LF}/A for 100 percent water

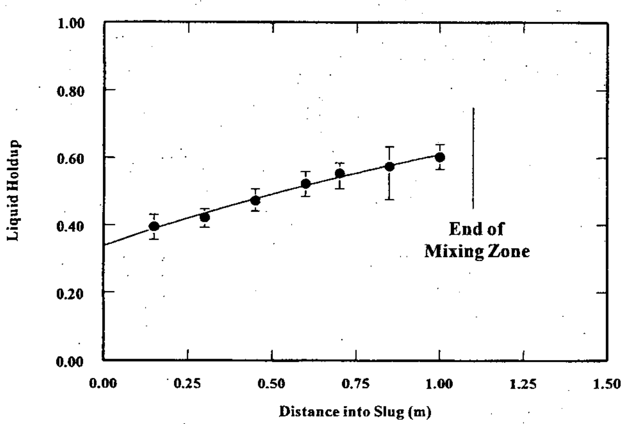

Fig. 6 Liquid holdup versus distance into the slug for film Froude number 16.4 for 100 percent water and a nondimensional liquid film area of 0.29

The second fluid studied was 100 percent LVT which is an oil with a density of 810 kg/m^3, a surface tension of 29.5 dyne/cm, and a viscosity of 2 cP. The nondimensional liquid film height before the slug was 0.35, and the nondimensional area was 0.31. Figure 10 shows an example of the data collected for 100 percent LVT for a film Froude number of 5.7. Figure 10 shows that the liquid holdup at zero distance into the slug was 0.33, and the length of the mixing zone was 50 cm. The liquid

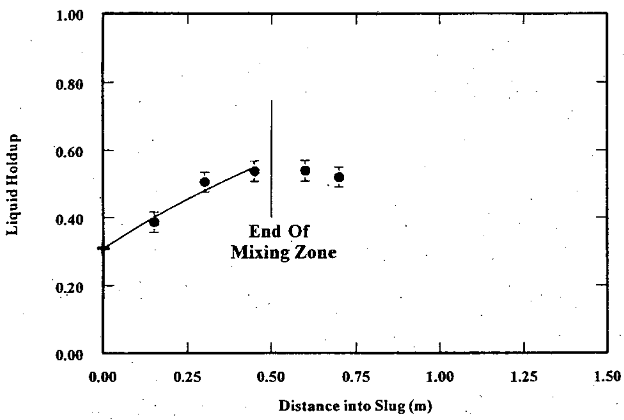

Fig. 10 Liquid holdup versus distance into the slug for film Froude number 5.7 for 100 percent LVT and a nondimensional liquid film area of 0.31

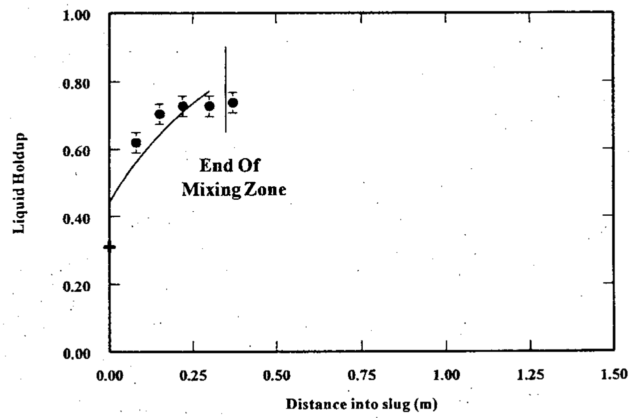

Fig. 12 Liquid holdup versus distance into the slug for a film Froude number of 5.8 for 10.9 cP mixture and a nondimensional liquid film area of 0.31

holdup ranged from 0.38 to 0.54 from 15 to 45 cm into the slug. This figure also shows that past the mixing zone, the liquid holdup becomes constant. At 60 and 70 cm into the slug the liquid holdup is 0.54 and 0.52, respectively. Figure 11 shows the results for a film Froude number of 17.5. This figure shows that the liquid holdup ranges from 0.42 to 0.53, from 15 cm into the slug to 90 cm into the slug. The liquid holdup became constant after 100 cm into the slug, the end of the mixing zone. The liquid holdup at 110 cm was 0.50 and at 135 cm it was 0.49. This plot also shows that at the slug front the liquid holdup was 0.34.

The next fluid to be studied was a mixture of LVT and Britol. The resulting single-phase mixture had a density of 822 kg/m^3, a surface tension of 36.8 dyne/cm, and a viscosity of 10.9 cP. This mixture was studied using a 0.33 nondimensional gate height. The nondimensional liquid film height before the slug was 0.35, and the nondimensional area was 0.31. The results for film Froude number 5.8 is shown in Fig. 12. This figure shows that the liquid holdup increased from 0.62 at 8 cm into the slug to 0.73 at 22 cm into the slug, and once past the mixing zone length of 35 cm, the liquid holdup became constant. The intercept for this graph was 0.44. Figure 13 shows the results for a film Froude number of 12.5. The length of the mixing zone was 70 cm and the liquid holdup at zero distance into the slug was 0.34. The liquid holdup ranged from 0.48 at 15 cm to 0.66 at 52 cm.

A second single-phase mixture which consisted of 50/50 by volume of LVT and Britol was prepared and had a density of 827 kg/m^3, a surface tension of 33.2 dynes/cm, and a viscosity

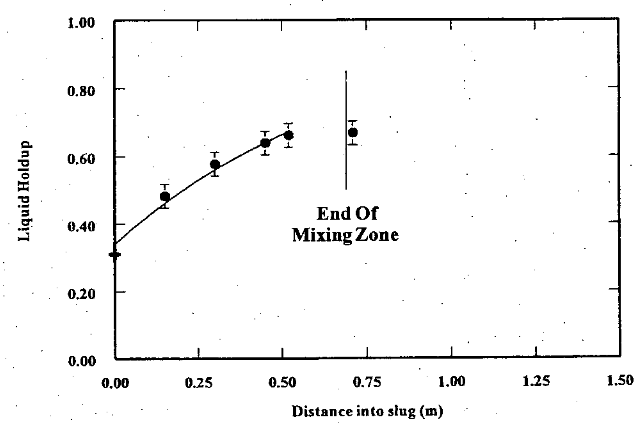

Fig. 13 Liquid holdup versus distance into the slug for film Froude number 12.5 for 10.9 cP mixture and a nondimensional area of 0.31

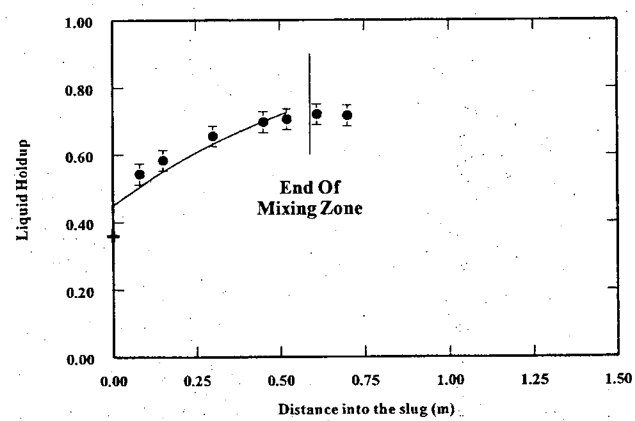

Fig. 14 Liquid holdup versus distance into the slug for film Froude number 7.4 for 16.6 cP mixture and a nondimensional liquid film area of 0.36

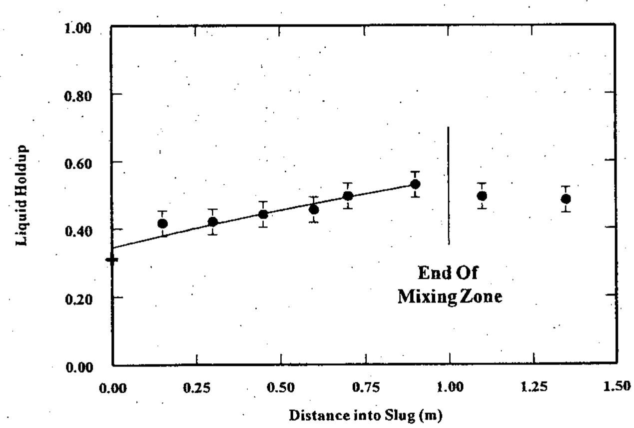

Fig. 11 Liquid holdup versus distance into the slug for a film Froude number of 17.5 for 100 percent LVT and a nondimensional liquid film area of 0.31

of 16.6 cP. The mixture was studied with a nondimensional gate height of 0.33, but the nondimensional liquid film height was determined to be 0.39. The nondimensional area was calculated to be 0.36. Figure 14 shows the results for a film Froude number of 7.4. This figure shows that the liquid holdup at 8 cm was 0.54 and increased to 0.71 at 52 cm. The liquid holdup became constant at a value of 0.72 after the end of the mixing zone was passed at a distance of 60 cm to 70 cm into the slug. The intercept for this graph was 0.45. The results for a film

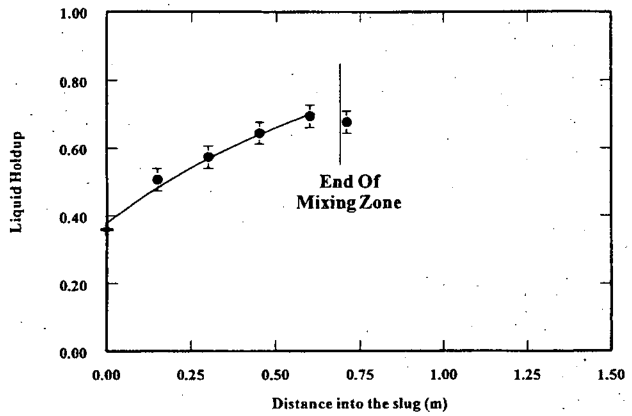

Fig. 15 Liquid holdup versus distance into the slug for film Froude number 9.5 for 16.6 cP mixture and a nondimensional liquid film area of 0.36

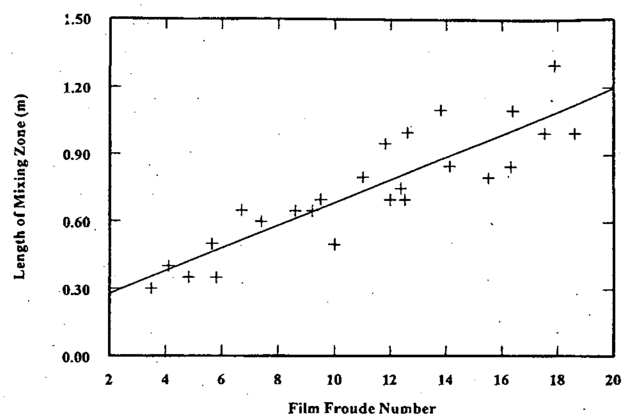

Fig. 18 The length of the mixing zone versus film Froude number

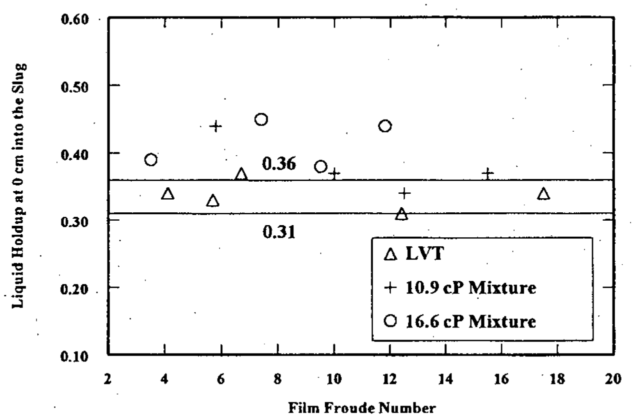

Fig. 16 Liquid holdup at 0 cm into the slug versus film Froude numbers for varying ratios of a_{LF}/A

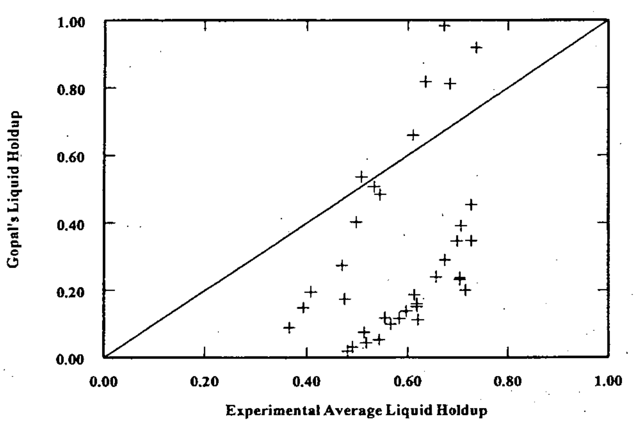

Fig. 17 Gopal's liquid holdup versus experimental average liquid holdup

Froude number of 9.5 are shown in Fig. 15. The liquid holdup was 0.51 at 15 cm and increased to 0.69 at 60 cm into the slug. The length of the mixing zone was 70 cm and the liquid holdup at zero distance into was 0.38.

Figure 16 shows the liquid holdup at zero distance into the slug for each film Froude number for the three different oils studied. This plot shows that the extrapolated intercept for the liquid holdup versus distance into the slug closely resembles the nondimensional area before the slug for each of the oil based slugs studied. Figure 17 compares the experimental results to the results obtained from Gopal's model. This figure shows that Gopal's model normally underpredicts the liquid holdup, which was expected. Gopal's model did not take into account that at the slug front, the liquid holdup should equal the holdup due to the liquid film before the slug.

Length of the Mixing Zone. The length of the mixing zone was determined for all fluids and film Froude numbers studied. When the length of the mixing zone is plotted against the film Froude number for the varying viscosities, it can be seen in Fig. 18 that viscosity does not affect the length of the mixing zone, for a viscosity range from 1 to 16.6 cP. Slugs rarely exist below a film Froude number of 2; therefore, this plot is shown for film Froude numbers ranging from 2 to 20. The correlation that was developed is

$$\mathrm{LMZ} = 0.051\ \mathrm{Fr}_f + 0.18 \tag{9}$$

where the length of the mixing zone, LMZ, is in meters. The results obtained in Eq. (9) were compared to that of the experimental values and the results are shown in Fig. 19. This plot shows that the theoretical values are within the accuracy of the experimental values. However, Eq. (9) was developed for a horizontal system and does not take into account the effect of pipe inclination. In Fig. 20, Gopal's results are added to Fig. 19. Gopal's length of the mixing zone is within the accuracy of the experimental values up to a length of 70 cm. Above a mixing zone length of 70 cm, Gopal's model overpredicts the length of the mixing zone, which was expected. Gopal's model was based upon water and carbon dioxide slugs with film Froude numbers of 10 and less; therefore, as the film Froude number increases above 10, the model becomes less accurate.

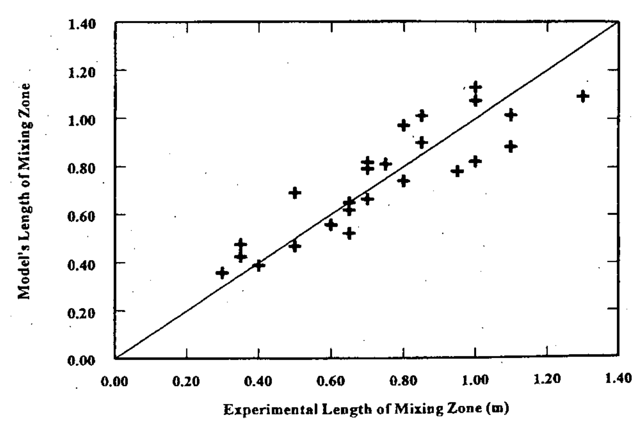

Fig. 19 Model's length of the mixing zone versus experimental length of mixing zone

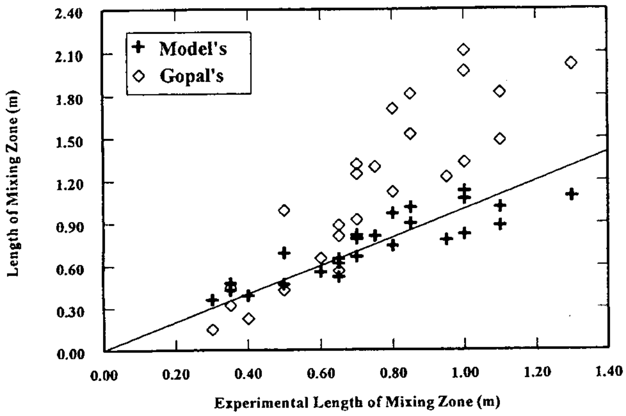

Fig. 20 Model's and Gopal's length of the mixing zone versus experimental length of mixing zone

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.

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DISCUSSION

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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.

$$2*(D - h_{lf}) \le L_e \le 2*D \tag{10}$$

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-

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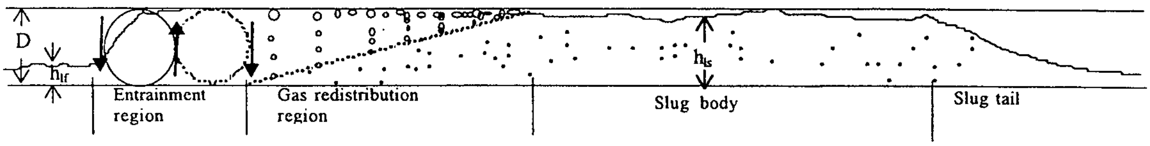

Fig. 21 Regions of mixing zone in liquid slug. Two counterrotating eddies entrain gas and liquid at the slug front. Further back gas redistributes as turbulence decreases.

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, $\text{Fr}_s = (v_t - v_m)/\sqrt{gD}$, which is related to the film Froude number used by MJ.

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

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

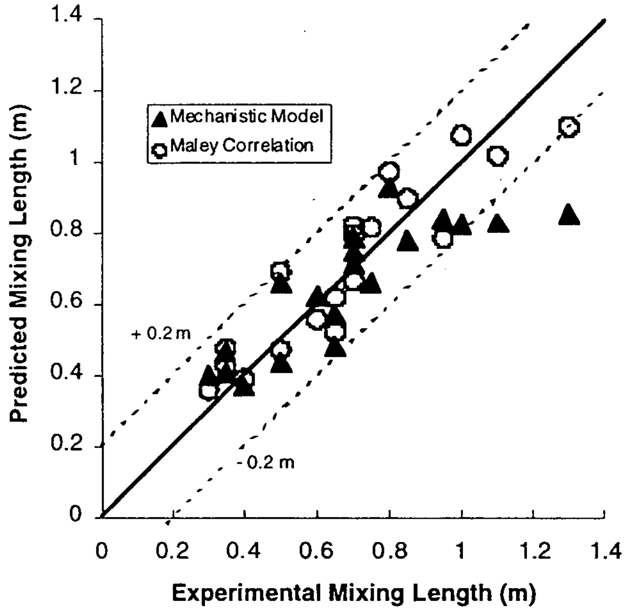

Fig. 22 Comparison of mechanistic model with Maley and Jepson's data and correlation for mixing length

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.

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.

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