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TRANSACTIONS OF THE INSTITUTE OF FLUID-FLOW MACHINERY

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Prediction of holdup in liquid slugs

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Abstract

Correlations and models from the literature for the prediction of void fraction in liquid slugs are reviewed. It is shown that a mechanism that can explain the slug aeration in vertical, horizontal and inclined tubes has not yet been established. A new model that attributes the aeration of the liquid slug to a recurrent bubble entrainment from the Taylor bubble (TB) tail is introduced. The bubble fragmentation is related to the rate of turbulent kinetic energy in the shear layer, which is formed at the TB wake as the liquid film plunges into the slug front. The model has been tested against experimental data available from the literature and was found to predict the effects of liquid and gas flow rates and their physical properties, as well as tube diameter and inclination on the void fraction.

Keywords: Slug flow; Holdup; Entrainment; Taylor bubble; Gas-liquid

1 Introduction

Correlations or models for the prediction of the insitu void fraction of liquid slugs in horizontal, inclined and vertical tubes are required as a closure relationship for the modeling of gas-liquid slug flow. The evaluation of the liquid slug holdup is important in particular for the design of vertical and off-vertical inclined systems, since the hydrostatic pressure drop is practically determined by the liquid holdup in the slug.

Several attempts to suggest an experimental correlation for evaluating the void fraction in the slug, ε_{LS} were reported in the literature. A widely used correlation is that of Gregory et al. [1], which is based on their data of oil-air

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slug flow in 25.8 mm and 51.2 mm horizontal pipes. It suggests a dependence only on the mixture velocity; U_m

$$1-\varepsilon_{LS}=\frac{1}{1+(U_m/8.66)^{1.39}}\,. \tag{1}$$

Ferschneider [2], using a larger data bank for horizontal and slightly inclined slug flow, suggested a dimensionless correlation, of the form similar to Eq. (1), in terms of Froude and Eotvos, (Fr, Eo) numbers:

$$1-\varepsilon_{LS}=\frac{1}{(1+C_1\mathrm{Fr}^2\mathrm{Eo}_D^{\gamma})^2}\,, \tag{2}$$

$$\mathrm{Fr}=\frac{U_m}{[(1-\rho_G/\rho_L)gD]^{1/2}}\,;\quad \mathrm{Eo}_D=\frac{(\rho_L-\rho_G)gD^2}{8\sigma} \tag{3}$$

where C_1 and γ are tunable parameters, D is the tube diameter and σ is the surface tension. Other studies, however, indicate a dependence of the slug void fraction on the liquid-cut in the feed, on the fluid properties and on the pipe inclination [3-6]. For instance, the OLGA multi-phase code uses the following correlation for horizontal slug flow, (Malnes [7]), which was fitted to SINTEF laboratories data for high density gas:

$$\varepsilon_{LS}^{h}=c_1[U_m-U_m^{crit}] \tag{4}$$

with

$$c_1=0.15+0.001\rho_G\,;\quad U_m^{crit}=2.57\sqrt{gD}\,. \tag{5}$$

Equation (4) uses dimensional fitting constants and suggests that aerated slugs are obtained when the mixture velocity, U_m exceeds a threshold value, U_m^{crit}, which is dependent on the tube diameter. For vertical slug flow, another correlation of Malnes [8] is used:

$$\varepsilon_{LS}^{v}=\frac{0.3+U_m}{c_2+U_m}\,, \tag{6}$$

$$c_2=\frac{2.2}{1+0.02\rho_G}+2U_{LS}\le 1.8\,, \tag{7}$$

where U_{LS} is the superficial liquid velocity. For inclined systems, the void fraction is estimated in the OLGA code by a superposition of the values obtained for horizontal and vertical systems:

$$\varepsilon_{LS}=\varepsilon_{LS}^{v}\sin^2\beta+\varepsilon_{LS}^{h}\cos^2\beta\,. \tag{8}$$

Only a few studies attempted to model the entrainment of gas bubbles from the

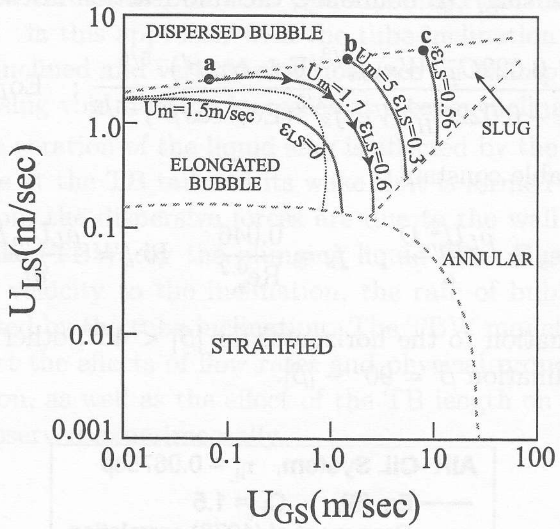


Figure 1. Estimation of the slug void fraction using the Barnea and Brauner [10] approach for air-water flow in 51.2 mm horizontal pipe (dashed lines – flow-pattern boundaries, solid lines – locus of constant void faction in the slug).

Taylor bubble (TB) tail into the liquid slug. The model of Fernandes et al. [9] for vertical slug flow and of Andreussi and Bendiksen [4] for nearly horizontal slug flow, relate the gas entrainment to the liquid film velocity. However, both models practically ignore the effect of surface tension, which must play a role in bubble fragmentation.

Barnea and Brauner's [10] model assumes that the gas in developed liquid slugs appears as dispersed bubbles and that the bubble fragmentation results from the turbulence of the carrying liquid in the slug core. Following this conjecture, the insitu holdup is the same as the holdup on the slug/dispersed-bubble transitional boundary for the same total mixture velocity. The procedure for evaluating ε_{LS} is demonstrated in view of Fig. 1. For instance, starting at point a on the slug/dispersed-bubble flow transitional boundary, where the void fraction is predicted by the homogenous model to be the same as the gas cut in the feed (U_{GS}/U_m); Increasing the gas superficial velocity, U_{GS} results in coalescence of bubbles to form a Taylor bubble, hence transition to slug flow. However, once the mixture velocity is maintained the same, so are the turbulence fragmentation forces in the liquid bridge, hence the gas void fraction in the liquid slug remains essentially the same as at point a. Accordingly, if the slug/DB boundary is known *either form theory or experiments, the void fraction in the slug can be* evaluated following this procedure. Based on the recent model by Brauner[11] for the prediction of slug/DB boundary, the void fraction in the slug is given by:

$$\varepsilon_{LS} = \frac{0.022 C_H^{-1} We_s f_s^{2/3} (\mathrm{Eo}_D \cos\beta')^{-5/6}}{1 + 0.022 C_H^{-1} We_s f_s^{2/3} (\mathrm{Eo}_D \cos\beta')^{-5/6}} \; ; \quad \mathrm{Eo}_D > 5 \, , \tag{9}$$

where C_H is a tunable constant,

$$We_s = \frac{\rho_L U_m^2 D}{\sigma} \; ; \; f_s = \frac{0.046}{\mathrm{Re}_s^{0.2}} \; ; \quad \mathrm{Re}_s = \frac{\rho_L U_m D}{\eta_L}$$

and β' is the inclination to the horizontal for $|\beta| < 45^o$, otherwise it represents the off-vertical inclination $\beta' = 90^o - |\beta|$.

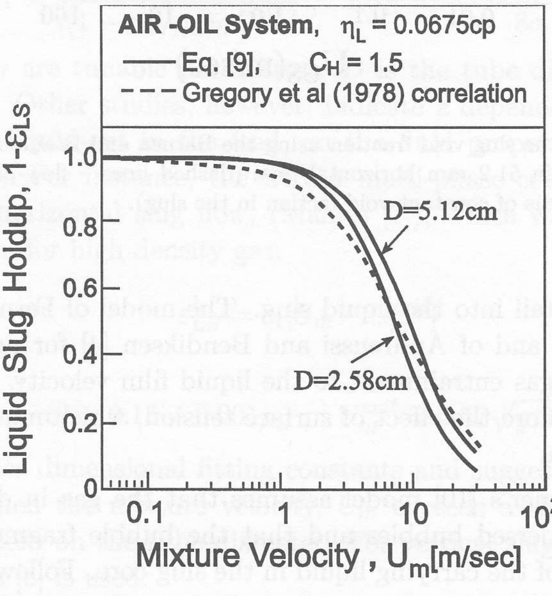


Figure 2. Comparison of the prediction of Eq.(10) with Gregory et al [1] correlation for the liquid holdup in the slug.

Figure 2 shows the predicted slug void fraction vs. the mixture velocity for the oil/air system used by Gregory et al. [1] to develop the experimental correlation Eq. (1). Indeed, the prediction by Eq. (9) is in good agreement with the experimental correlation. The mild dependence on the tube diameter that is indicated by the model of Eq. (9) is not indicated by the experimental correlation, possibly as a result of the rather scattered data which was used to obtain Eq. (1). The main problem with the approach of Barnea and Brauner [10] is that the slug/DB boundary is insensitive to the pipe inclination. This is due to the fact that gravity has a minor role in determining the conditions where a fully dispersed flow can be maintained. Consequently, the resulting variation of the ε_{LS} predicted via this approach with the tube inclination is mild. However, data obtained in inclined and vertical slug flow (see for example [5-6, 12]) clearly indicate that the slug void fraction increases at steeper inclinations.

In general, the aeration of the liquid slug is affected by the dispersion mechanisms taking place at the TB tail and its wake that is formed at the front of the slug. In this region, the dispersive forces are due to the wall jet formed at the Taylor bubble wake (TBW) by the plunging liquid film. Due to the sensitivity of the liquid film velocity to the inclination, the rate of bubble entrainment is significantly affected by the tube inclination. The TBW model introduced herein is shown to predict the effects of flow rates and physical properties of the fluids, the tube inclination, as well as the effect of the TB length on the rate of bubble entrainment as observed experimentally.

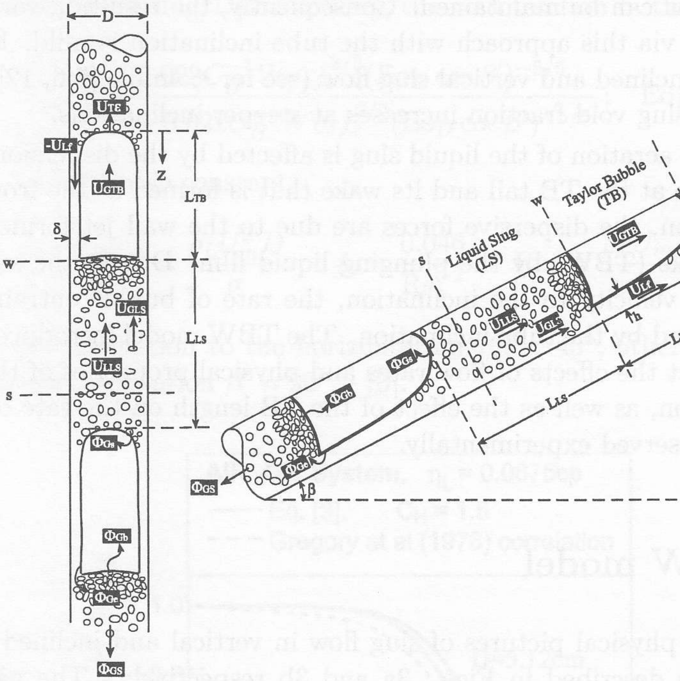
2 The TBW model

The idealized physical pictures of slug flow in vertical and inclined (or horizontal) tubes are described in Figs. 3a and 3b respectively. The gas in the Taylor (elongated) Bubble (TB) moves at a velocity U_{GTB} which is faster than the mixture velocity in the liquid slug, U_m. Therefore, liquid is shed from the back of the slug to form the falling film in the TB region. The small bubbles, which are dispersed in the preceding slug, coalesce with the TB at its nose at a rate Φ_{GS}. Part of the bubbles that are entrained into the TB wake (at a rate Φ_{Ge}) may re-coalesce with the TB tail (at a rate Φ_{Gb}), resulting in a net gas rate of $\Phi_{Ge} - \Phi_{Gb}$, which is shed upstream to the successive TB. In this case, the insitu gas holdup in the TB wake region, ε_{LS}^{W} is higher than the insitu holdup within the liquid slug, ε_{LS}^{S}. In a stable slug flow, the slug length, L_{LS} and the TB length, L_{TB} remain essentially constant in the downstream direction, thus $\Phi_{GS} = \Phi_{Ge} - \Phi_{Gb}$.

The fragmentation of the TB tail and the entrainment of the bubble into the TB wake are due to the dispersive forces induced by the flow of the liquid film as it plunges into the liquid slug front. The flux of surface energy production due to fragmentation of the TB tail into bubbles of a maximal size d_{max} at a rate Φ_{Ge} is given by:

$$\dot{E}_s = \frac{\pi d_{max}^2 \sigma}{\pi d_{max}^3/6} \Phi_{Ge} = \frac{6\sigma}{d_{max}} \Phi_{Ge} \ , \qquad (11)$$

where σ is the surface tension. The flux of this surface energy production is proportional to the flux of turbulent energy supply by the penetrating liquid film



(a) (b)

Figure 3. Schematic description of TBW model for slug flow: a) vertical tube, b) inclined tube.

"jet" at a rate Φ_{Lf}:

$$\frac{1}{2}\rho_L({u'}^2+{v'}^2+{w'}^2)\Phi_{Lf} = C_J\frac{6\sigma}{d_{max}}\Phi_{Ge}\ , \tag{12}$$

where

$$\Phi_{Lf} = (U_T - U_{Lf}^W)(1-\varepsilon_{TB}^W)\ . \tag{13}$$

$C_J = O(1)$ is a constant, and U_T is the TB rise velocity in un-aerated liquid. The latter is obtained by Nicklin et al [13] equation, $U_T = C_0^{TB}U_m + U_0^{TB}$, where C_0^{TB} and U_0^{TB} represent the TB distribution parameter and drift velocity, respectively. The turbulent model for characterizing the dispersive forces in the flow field is that associated with a wall jet and shear layer formed in the liquid slug front, due to the relative velocity, ΔU, between the liquid in the slug front (moving at velocity U_{LLS}^W) and the liquid film at the tail of the preceding TB (moving at velocity U_{Lf}^W, see Fig. 3). The maximal values reported for compound shear layers are, ${u'}^2 = 0.03\Delta U^2$, ${v'}^2 = 0.02\Delta U^2$, ${w'}^2 = 0.013\Delta U^2$ [14]. Here, conservative values ${u'}^2 = {v'}^2 = {w'}^2 = 0.01\Delta U^2$ are taken. Gas entrainment occurs provided the length of the TB, hence the film velocity exceeds a certain threshold value. The threshold value on the film velocity can be estimated assuming it corresponds to a critical Weber number of the order of unity:

$$We'_{crit} = \frac{\rho_L d_{max}(u'^2 + v'^2 + w'^2)_{crit}}{3\sigma} = C' \cong O(1)\,. \quad (14)$$

The maximum stable drop size is of the order the critical size of deformable bubbles, d_{crit} [15], which is expressed in terms of the Eotvos number, $\mathrm{Eo}_D = \Delta\rho g D^2/(8\sigma)$:

$$\tilde{d}_{max} \approx \tilde{d}_{crit} = \frac{d_{crit}}{D} = \left[\frac{0.4\sigma}{(\rho_l - \rho_G) g \cos\beta' D^2}\right]^{1/2} = \frac{0.224}{(\cos\beta' \mathrm{Eo}_D)^{1/2}}\,. \quad (15)$$

Equations (12-15) result in:

$$\frac{\Phi_{Ge}}{\Phi_{Lf}} = \frac{1}{400 C_J}\tilde{d}_{crit}(We - We_C) \;\; ; \;\; We \geq We_C \quad (16.1)$$

$$We = \frac{\rho_L D(U^W_{LLS} - U^W_{Lf})^2}{\sigma} \;\; ; \;\; We_C = \frac{100C'}{\tilde{d}_{crit}} \quad (16.2)$$

C_J and C' are tunable constants ($C_J = 1$, $C' = 2/3$ are used here).

It is worth mentioning at this point that while $U_{LLS} > 0$, the sign of U_{Lf} depends on the tube inclination and the distance from the TB nose. For steep inclinations, U_{Lf} is practically always negative. The liquid film holdup and velocity as function of the distance from the TB nose are obtained by solving the momentum equation for the developing film in a coordinate system attached to the TB velocity. In case of a long TB in vertical or slightly off-vertical slug flow, the asymptotic fully-developed film thickness can be calculated using simple models:

$$\frac{\delta}{(\eta_L^2/\rho_L \Delta\rho\, g \sin\beta)^{1/3}} = 0.909\,\mathrm{Re}_{Lf}^{1/3} \;\; ; \;\; \text{Laminar film [16]} \quad (17.1)$$

$$\frac{\delta}{(\eta_L^2/\rho_L \Delta\rho\, g \sin\beta)^{1/3}} = 0.135\,\mathrm{Re}_{Lf}^{7/12} \;\; ; \;\; \text{Turbulent film [17]} \quad (17.2)$$

where $\mathrm{Re}_{Lf} = \rho U_{LfS} D/\eta_L$ and U_{LfS} is obtained from a mass balance, $U_{LfS} = U_m - \varepsilon_{TB} U_{GTB}$. The gas velocity in the TB is that affected by the rising TB, hence $U_{GTB} = U_T$. The liquid and gas velocities in the slug U_{LLS}, U_{GLS} (both in the wake region (W) and in the slug core (S)) are calculated via the drift flux model, whereby $U_{GLS} = C_0 U_m + U_0$, with C_0 and U_0 representing the bubbles distribution parameter and drift velocity, respectively.

Due to the drift between the bubbles and the liquid, part of the bubbles that are entrained from the TB may re-coalesce with its tail. The instantaneous velocity field as visualized in the TB wake region is very disordered, and the average bubble back-flow may be also a result of the instantaneous secondary velocity components. Here, however, the bubble back-flow is estimated based on the bubbles drift velocity at the TB tail (where the liquid moves at the TB velocity) provided the bubbles reach the TB tail:

$$\Phi_{Gb} = \begin{cases} U_0^W \varepsilon_{LS}^W \varepsilon_{TB}^W & ; \quad U_{GLS}^W > U_{GTB} \\ 0 & ; \quad U_{GLS}^W \leq U_{GTB} \end{cases} \tag{18}$$

The rate of bubbles shed backwards into the liquid slug (and to the successive TB nose) is therefore $\Phi_{GS} = \Phi_{Ge} - \Phi_{Gb}$, for $\Phi_{Ge} > \Phi_{Gb}$, otherwise $\Phi_{GS} = 0$ for $\Phi_{Ge} \leq \Phi_{Gb}$.

The holdup in the TB wake, ε_{LS}^W, and in the slug, ε_{LS}^S, are calculated from a mass balance on the gas in a coordinate system attached to the TB transitional velocity, $U_{T\varepsilon}$. For a non-negligible slip between the liquid and the gas in the slug, U_{GLS} is dependent on the insitu holdup. Therefore, the corresponding equations are written in the implicit form:

$$\varepsilon_{LS}^W - \frac{\Phi_{Ge}}{U_{T\varepsilon} - U_{GLS}^W} = 0 \ ; \ \varepsilon_{LS}^S - \frac{\Phi_{GS}}{U_{T\varepsilon} - U_{GLS}^S} = 0 \, . \tag{19}$$

Also in developed slug flow,

$$\Phi_{GS} = \varepsilon_{TB}^W (U_{T\varepsilon} - U_{GTB}) \, . \tag{20}$$

Equation (20) indicates that in the case of recurrent coalescence of bubbles from the liquid slug with the TB nose and their re-entrainment from the TB tail at a rate $\Phi_{GS} > 0$, the TB translation velocity exceeds the TB rise velocity in un-aerated slug flow [18].

3 Discussion

Figure 4a shows the void fraction in the slug predicted by the TBW model for vertical upward air-water flow, assuming a fully developed liquid film, which is reached asymptotically for sufficiently long TB. The bold curve shows the results obtained without back-flow, since for $D > 5$ cm the entrained bubbles do not reach the TB tail. In this case $\Phi_{GS} = \Phi_{Ge}$ and $\varepsilon_{LS}^S = \varepsilon_{LS}^W$ are predicted. The dashed curves show the results when the backflow, (Eq. 18) is nevertheless included, whereby $\varepsilon_{LS}^W \geq \varepsilon_{LS}^S$. As shown in Fig. 4a, the inclusion of back-flow has a significant effect only for low mixture velocities: for low U_m (< 0.1 m/s), all entrained bubbles are recycled back to the TB tail resulting in $\Phi_{GS} = 0$ and $\varepsilon_{LS}^S = 0$. The value of $\varepsilon_{LS}^W > 0$ implies that for low U_m, the slug aeration is limited to the wake region and the bubbles are not shed backwards to the successive TB noise. However, with increasing U_m, $\varepsilon_{LS}^S \approx \varepsilon_{LS}^W$ and practically the same value is predicted with $\Phi_{Gb} \neq 0$ or $\Phi_{Gb} = 0$.

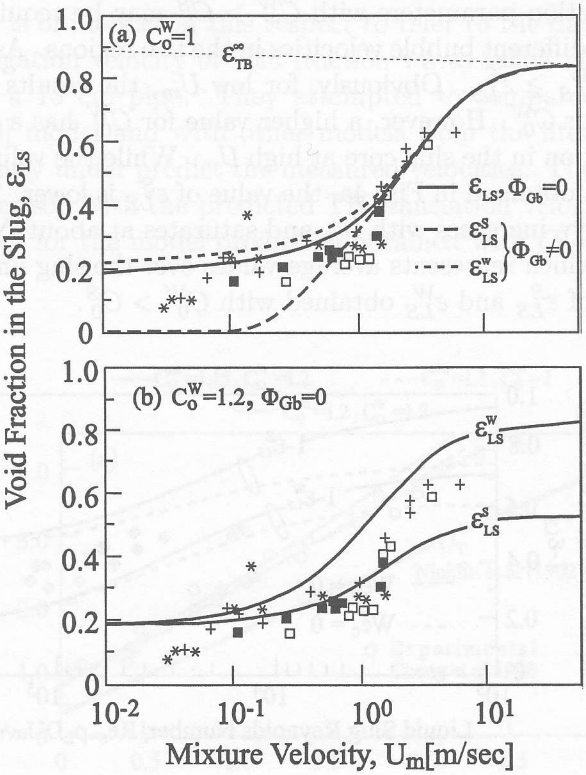


Figure 4. Comparison of the model prediction ($C_0^{TB} = 1.2$, $C_0^S = 1$) for the asymptotic void fraction in the slug with experimental data [12] for vertical air-water system, D = 5.1 cm.

Comparison with the data shown in Fig. 4 is favorable. In particular, the TBW model predictions follow the trend of the steep increase of ε_{LS} for $U_m >$ 1.5 m/s. On the other hand, in the region of low U_m, the experimental values are in between ε_{LS}^S and ε_{LS}^W. In agreement with the experimental data, the model predicts that as $U_m \to 0$, ε_{LS}^W (and ε_{LS}) levels off at a value of $\varepsilon_{LS} \approx 0.2$. It is worth noting that according to the TBW model, the value of ε_{LS} at high U_m approaches asymptotically the value of $\varepsilon_{TB}^\infty = \varepsilon_{TB}^W(L_{TB}^W \to \infty)$, the difference between ε_{LS} and ε_{TB} becomes negligible for $U_m >$ 10 m/sec. This implies that ordered slug flow cannot exist in the region and churning or annular flow is expected in the system.

Bubble back-flow into the TB tail may not be the only reason for the appearance of a high void fraction region at the TB wake. The velocity profile in the wake is highly distorted due to the plunging liquid film. The time-averaged value of the axial velocity in the wake core is higher than in the slug bulk. Hence different distribution parameters with $C_0^W > C_0^S$ may be required to adequately characterize the different bubble velocities in the two regions. As shown in Fig. 4b, this results in $\varepsilon_{LS}^W \geq \varepsilon_{LS}^S$. Obviously, for low U_m, the results are insensitive to the value used for C_0^W. However, a higher value for C_0^W has a pronounced effect on the void fraction in the slug core at high U_m. While the value of ε_{LS}^W is almost the same as that obtained in Fig. 4a, the value of ε_{LS}^S is lower. The difference between ε_{LS}^W and ε_{LS}^S increases with U_m and saturates at about $\Delta\varepsilon_{LS} \approx 0.3$ at high U_m. The data, which represents average values over the slug unit, are in-between the predictions of ε_{LS}^S and ε_{LS}^W obtained with $C_0^W > C_0^S$.

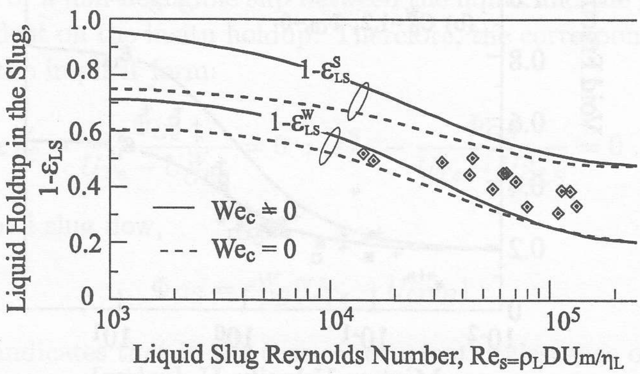


Figure 5. Comparison of the model prediction ($C_0^{TB}, C_0^W = 1.2$, $C_0^S = 1$) of the asymptotic slug void fraction with experimental data [5] for vertical air-kerosene system, $D = 5.1$ cm.

The combined effects of back-flow and $C_0^W > C_0^S$ on the holdup in the slug are demonstrated in Fig. 5 for an air-kerosene system [5]. Here too, the data are shown to be in the range between ε_{LS}^S and ε_{LS}^W. It is worth noting that the gas entrainment rate is predicted to increase proportionally to $\sigma^{-0.5}$. Indeed, for the lower surface tension of air-kerosene ($\sigma = 0.028$ N/m), the slug aeration is somewhat higher than in air-water slug flow. The change is more pronounced at low U_m, whereas at high U_m it turns to be almost insignificant for this surface tension difference. At very high U_m, where $\varepsilon_{LS} \rightarrow \varepsilon_{TB}^W$ is predicted, the surface tension effect is negligible. Another point, which is evident in view of Fig. 5, is that the effect of a threshold value on the Weber number for the onset of bubbles entrainment, We_C, is significant only in the range of relatively low U_m. The lower the critical Weber number is, the higher is the value of ε_{LS} in the limit of

$U_m \to 0$. However, in the range of high U_m, the results obtained with $We_C \neq 0$ or $We_C = 0$ are practically the same.

The TBW model indicates an increase of $U_{T\varepsilon}$ compared to Nicklin's equation, due to the recurrent bubbles coalescence with the TB nose and their entrainment at the TB tail. It is of interest in this respect to refer to the data of Cheng et al [19] for the propagation velocity of void fraction waves taken in vertical upward air-water flow in a 15 cm pipe. They attempted to compare their data with Nicklin et al. [13] model and with other models from the literature. All were found to significantly under predict the measured velocities. Their data is shown in Fig. 6 in comparison with the predicted TB translation velocity. A very good agreement is shown for the model prediction obtained with C_0^{TB} and C_0^W in the range 1÷1.2.

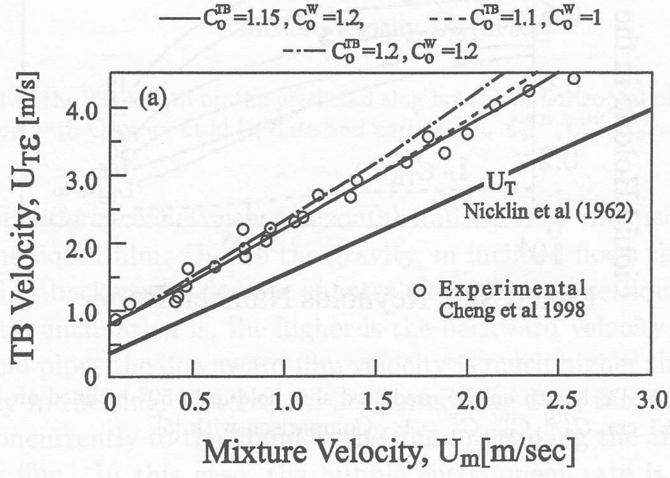


Figure 6. The predicted translation velocity of long TB in a vertical air-water 15 cm tube, $C_0^S = 1$ – Comparison with experimental data [19].

The results shown in Figs. 4 to 6 are for fully developed liquid film corresponding to long TB's. The model explains that variability in ε_{LS} can be expected even when all operational conditions are maintained constant. Variation in the TB length (and in slug length) is associated with variation in the film thickness, hence, in its velocity and the rate of gas entrainment at the TB tail. This, in turn, results in variation of the holdup in the slug, as well as in the TB translation velocity. Any value of ε_{LS} in the range of $0 \leq \varepsilon_{LS} \leq \varepsilon_{LS}(L_{TB} \to \infty)$ actually corresponds to a specific TB length. The variation of ε_{LS} with the TB length is demonstrated in Fig. 7 for an upward inclined air-kerosene system, $\beta = 50°$. The predicted increases with Re_s (or U_m) and with the TB length. The larger the mixture of velocity is, the larger is the feasible range of variation of ε_{LS} due to variation of the TB length, and the longer is the TB length for which the asymptotic values are approached. The data implies L_{TB} of about 10-15D in the range of relatively low Re_s, and an increase of L_{TB} with Re_s. The kerosene and air flow rates corresponding to these data points were not specified in [5]. However, in general, high U_m in slug flow corresponds to high gas-cut, hence longer TB.

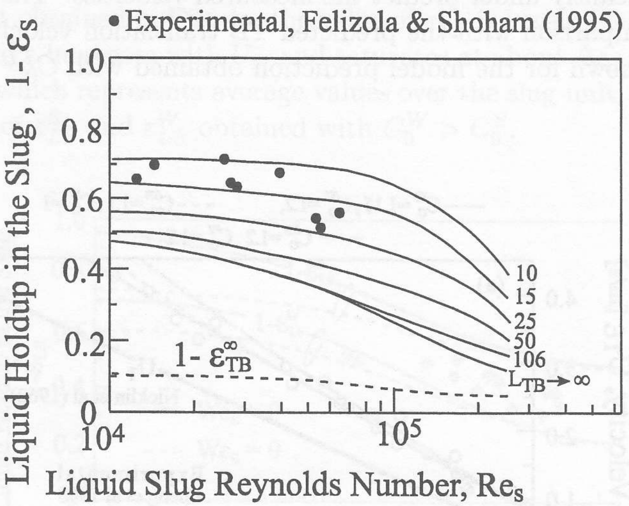


Figure 7. Effect of TB length on the predicted slug holdup in 50° inclined air-kerosene system, $D = 5.1$ cm, $C_0^{TB}, C_0^W, C_0^S = 1$ – Comparison with [5].

Figure 8 shows the results of the TBW model when applied to the air-oil system used by Gregory et al. [1] in $D = 5.12$ cm pipes. Similarly to vertical and inclined flows, the effect of the TB length becomes more pronounced as the mixture velocity is increased and longer TB's are required for approaching the maximal asymptotic holdup. This is implied also by the data that become very scattered for high mixture velocities. In real slug flow, the TB length is non unique even when the input flow rates are maintained constant. Moreover, as the liquid-cut in the feed is increased, the overall mass balance dictates shorter TB's (see for example [5]). In this case, the model predicts higher liquid holdups in the slugs compared to those obtained for the same mixture velocity, but with a lower liquid-cut. Thus, inherent scattering is expected when data of slug holdup is depicted vs. the mixture velocity. In fact, considering the TB length required for approaching fully developed conditions, these may never be reached in practical applications.

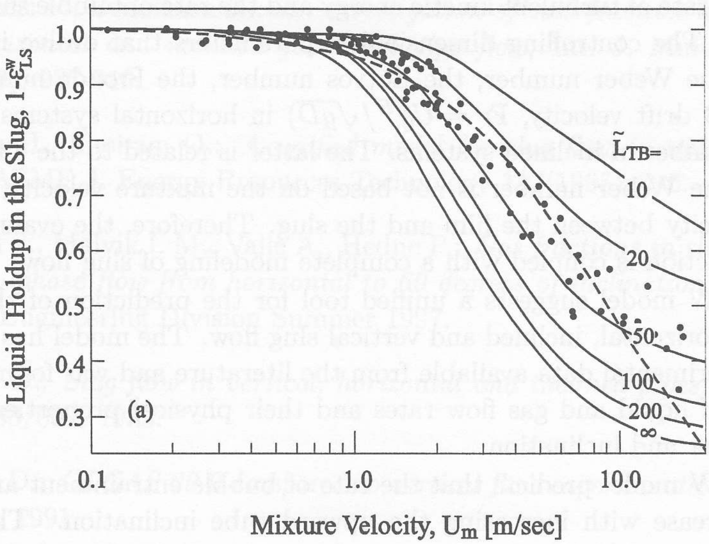


Figure 8. Effect of the TB length on the predicted slug holdup in horizontal oil-air flow – Comparison with Gregory et al [1] data and correlation. $C_0^{TB}, C_0^W, C_0^S = 1.2$; $\mathrm{We}_C = 0$.

The main difference between horizontal and upward inclined flows, is the velocity in the liquid film. Due to the gravity, in inclined flows the liquid in the film is draining backwards, flowing counter-currently to the liquid in the slug. The steeper the inclination is, the higher is the backward velocity in the film. In fact, in vertical pipes the downward film velocity is much higher than the upward liquid velocity in the slug. Whereas in horizontal slug flow, the liquid in the slug front flows concurrently to the liquid in the film, overtaking the almost immobile liquid in the film. In this case, the bubble entrainment rate is dominated by the liquid velocity in the slug. Therefore, the slug becomes un-aerated as the mixture velocity is reduced below a threshold value. However, in upward inclined slug flow, the bubble entrainment rate is dominated by the liquid film velocity. Therefore, aerated slugs can be obtained in the limit of $U_m \to 0$ even with a non-zero value for the critical Weber number.

4 Conclusions

The TBW model introduced in this study attributes slug aeration to a recurrent bubble entrainment from the Taylor bubble (TB) tail and their re-coalescence at the successive TB nose. The bubble fragmentation is due to the turbulence in the shear layer, which is formed at the TB wake as the liquid film penetrates the slug front. The rate of gas entrainment is determined based on energy balance between the rate of turbulent kinetic energy and the rate of bubble surface energy production. The controlling dimensionless parameters that evolve in the TBW model are the Weber number, the Eotvos number, the Froude number (scaled with the TB drift velocity, $\mathrm{Fr} = U_0^{TB}/\sqrt{gD}$) in horizontal systems or the film Reynolds number in inclined systems. The latter is related to the TB rise velocity. Also, the Weber number is not based on the mixture velocity, but on the relative velocity between the film and the slug. Therefore, the evaluation of the slug void fraction is coupled with a complete modeling of slug flow.

The TBW model suggests a unified tool for the prediction of the slug void fraction in horizontal, inclined and vertical slug flow. The model has been tested against experimental data available from the literature and was found to predict the effects of liquid and gas flow rates and their physical properties, as well as tube diameter and inclination.

The TBW model predicts that the rate of bubble entrainment and slug void fraction increase with increasing the upward tube inclination. The effects of tube diameter and liquid viscosity are very modest in horizontal slug flow, but become much more pronounced as the inclination is increased. In inclined flows, the bubble entrainment decreases with increasing the liquid viscosity and/or the reducing tube diameter. Also, regardless of the tube inclination, the bubble entrainment rate and the slug void fraction increase with reducing the surface tension. For low surface tension, foamy slugs can be obtained. Phase inversion is not to be expected, due to the low gas-to-liquid density and viscosity ratios [20]. The maximal slug void fraction is limited by the void fraction at the TB tail. The latter is approached at high mixture velocities and for long TB. In this case, the slug bridge essentially collapses, and the ordered slug flow may no longer be maintained.

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