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Slug flow modeling for downward inclined pipe flow: theoretical considerations

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Abstract

Slug flow is a very common occurrence in gas–liquid two-phase flow. Usually, it is an unfavorable flow pattern due to its unsteady nature, intermittency and high-pressure drop. For the calculation of pressure drop and void fraction, the normal approach is to separate the slug unit into two zones, a liquid slug zone and a film or gas zone. The pressure drop is calculated using slug flow models that were developed on the basis of a solution of the momentum and continuity equations for these two zones. When applying these models for downward flow, conditions can be encountered where no solutions exist. In this work, we closely examine these conditions and discuss their physical meaning. This includes a detailed description of the slug dissipation process in a downhill section and the calculation of slug dissipation distance.

Keywords: Two-phase flow; Slug flow; Slug dissipation

1. Introduction

Slug flow is one of the most common flow patterns in two-phase pipe flow. Modeling slug flow was first proposed by Dukler and Hubbard (1975). The general approach of Dukler and Hubbard was later used and/or modified by Nicholson et al. (1978), Stanislav et al. (1986) and

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Taitel and Barnea (1990a). Similar models were also proposed for vertical flow by Fernandes et al. (1983), Orell and Rembrand (1986), Sylvester (1987) and Barnea (1990). Thorough reviews of slug flow can be found in Taitel and Barnea (1990b) and Fabre and Liné (1992).

The above mentioned models are very useful for horizontal and upward flows. However, if one tries to apply these models for downward inclined pipes, cases are often encountered in which there are no solutions to this problem. Clearly, this suggests that the flow in the downward section is stratified. Thus, the slug flow model can be used as a means for flow pattern prediction (Bendiksen and Espedal, 1992). This also means that slugs will dissipate in a downhill pipe section.

The present work is aimed at theoretically analyzing these cases, explain the physical phenomena of slug dissipation in downhill pipes, and proposing a method for calculating the downhill dissipation distance.

2. Analysis

2.1. Slug flow modeling

The modeling used for steady slug flow was described in detail in a review paper by Taitel and Barnea (1990b). The analysis assumes identical slugs and the calculations are performed on a single typical slug unit. A schematic geometry of the system is shown in Fig. 1. A typical slug unit consists of a liquid slug zone (that may contain gas bubbles) of length l_s followed by a film (and gas) zone of length l_f.

It is assumed that the translational velocity of the nose of an elongated bubble behind a liquid slug, V_t, can be expressed as a function of the mixture velocity of the slug, U_s, in the form proposed by Nicklin (1962),

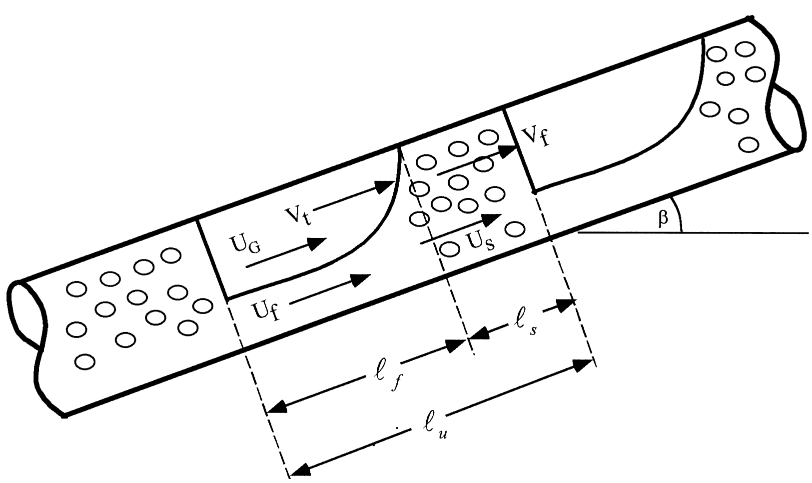

Fig. 1. Slug flow geometry.

$$V_t = CU_s + U_d \tag{1}$$

where the mixture velocity, U_s equals the sum of the liquid and gas superficial velocities, $U_{LS} + U_{GS}$. U_d is the drift velocity, or the velocity of the elongated bubble at the limit of $U_s \rightarrow 0$. C is an empirical velocity distribution parameter that is approximately equal to the ratio of the maximum to the mean fully developed velocity profile. Nicklin (1962) proposed a value of C = 1.2. For laminar flow, C is about 2.0 (Fabre, 1994). For the drift velocity in horizontal and upward inclined pipe flow, Bendiksen (1984) proposed the use of

$$U_d = 0.54\sqrt{gD}\cos\beta + 0.35\sqrt{gD}\sin\beta \tag{2}$$

where D is the pipe diameter, g the acceleration of gravity and β is the inclination angle measured from the horizontal. The theoretical basis for this equation is given by Benjamin (1968) for the horizontal case and by Dumitrescu (1943) for the vertical case. Bendiksen (1984) showed that experimental data quite accurately follows Eq. (2), which uses the horizontal and the vertical formulations multiplied by the cos and the sin of the inclination angle, respectively.

The liquid holdup within a slug, R_s, is assumed to be a function of the liquid mixture velocity. Gregory et al. (1978) proposed the following correlation,

$$R_s = \frac{1}{1 + \left(\dfrac{U_s}{8.66}\right)^{1.39}} \tag{3}$$

Barnea and Brauner (1985) developed the following expression.

$$R_s = 1 - 0.058\left\{2\left[\frac{0.4\sigma}{(\rho_L - \rho_G)g}\right]^{1/2}\left[\frac{2f_s}{D}U_s^3\right]^{2/5}\left[\frac{\rho_L}{\sigma}\right]^{3/5} - 0.725\right\}^2 \tag{4}$$

where σ is the surface tension, f_s is the liquid slug friction factor and ρ_L and ρ_G are the liquid and gas densities. For large U_s, a limiting value of $R_s = 0.48$ is used (Taitel and Barnea, 1990b).

Modeling the liquid film behind the slug is somewhat more complicated and requires a solution of the liquid level profile as a function of the distance from the liquid slug tail (see Taitel and Barnea, 1990b). However, as an approximation that simplifies and speeds calculations, it is common to assume a constant film level equal to the equilibrium level that satisfies the quasi-equilibrium force balance.

$$\frac{\tau_f S_f}{A_f} - \frac{\tau_G S_G}{A_G} - \tau_I S_I\left(\frac{1}{A_f} + \frac{1}{A_G}\right) + (\rho_L - \rho_G)g\sin\beta = 0 \tag{5}$$

along with mass balances for the liquid and the gas relative to the bubble nose velocity, V_t.

$$(V_t - U_f)R_f = R_s(V_t - U_s) \tag{6}$$

$$(V_t - U_G)(1 - R_f) = (1 - R_s)(V_t - U_s) \tag{7}$$

where

$$\tau_G = f_G \frac{\rho_G U_G^2}{2}; \; \tau_f = f_f \frac{\rho_L U_f |U_f|}{2}; \; \tau_I = f_I \frac{\rho_G (U_G - U_f)|U_G - U_f|}{2} \tag{8}$$

In these equations A is area, S, wetted periphery, U is velocity, τ is shear stress, f, friction factor, R holdup and ρ is density. The subscripts G, f, I, s refer to the gas, liquid film, interface and slug, respectively.

For the liquid film and the gas shear stresses, the friction factors, f_f and f_G can be approximated by $f = CRe^{-n}$, where $C = 0.046$, $n = 0.2$ for turbulent flow, and $C = 16$, $n = 1$ for laminar flow. The Reynolds numbers were defined as $Re_f = 4U_f A_f \rho_L / S_f \mu_L$ for the liquid and $Re_G = 4U_G A_G \rho_G / (S_G + S_I)\mu_G$ for the gas (μ is the viscosity). For the interfacial gas–liquid shear stress, we used a constant value $f_I = 0.014$ (Cohen and Hanratty, 1968).

The implicit Eq. (5) is then solved numerically for the liquid holdup in the film, R_f and the liquid velocity, U_f.

The slug length is a fairly constant parameter and it is considered here as having a known value of 30 pipe diameter (Nicholson et al., 1978) while the slug unit length is calculated on the basis of liquid mass balance. Usually, the precise value of the liquid slug length is not important for the calculation of the pressure drop and holdup since the aforementioned variables are primarily effected by the ratio of the liquid slug length to the slug unit length.

Liquid continuity requires that:

$$U_{LS} A = U_L A R_s \frac{l_s}{l_u} + U_f A R_f \frac{l_f}{l_u} \tag{9}$$

where l_s is the length of the liquid slug, l_f, the film length and l_u is the slug unit length ($l_u = l_s + l_f$). Eq. (9) is used to calculate the slug unit length which yields:

$$l_u = l_s \frac{U_L R_s - U_f R_f}{U_{LS} - U_f R_f} \tag{10}$$

2.2. Slug modeling limitations for downward inclination

This model works for horizontal and upward flows. However, for downward flows, there are flow conditions for which a solution of this set of equations does not exist. These cases are analyzed below from both mathematical and physical aspects.

2.2.1. Case 1: no solution to Eq. (5)

Solutions to Eq. (5) (with Eqs. (6) and (7)) may not exist for low liquid and gas flow rates. Clearly, this is the case where steady state flow will be stratified.

Nevertheless, slugs from an upward inclined section can be carried over to a downward inclined section after passing a top elbow, and they are expected to travel some distance in the downward inclined section before they completely dissipate.

The physical meaning of this lack of solution is that the liquid film travels faster than the liquid slug mixture. This can be verified using Eq. (6). As we decrease the liquid flow rate or superficial velocity, U_{LS} (keeping the gas flow rate constant), the liquid film holdup increases until it reaches a maximum, which is equal to unity when the liquid slug is free of gas bubbles, or equals to the liquid slug holdup, R_s. In this case, we reach the limit of the liquid film velocity, which is $U_f = U_s$, as is evident from Eq. (6). Under this condition the tail of the slug will not shed any liquid to the film behind it since the film velocity is larger than the slug velocity. Thus the translational velocity, V_t, of the bubble nose (slug tail) is just $U_{LS} + U_{GS}$.

On the other hand, at the slug front, the liquid will be shed forward and the bubble in front of it will penetrate into the slug. This is the condition Bendiksen (1984) termed as 'bubble turning'. We propose that the slug front velocity can be obtained as a superposition of the two effects, the drift effect and the velocity profile effect. The drift velocity, which is the penetration velocity of the bubble into a stagnant liquid, will be given by Benjamin (1968) and Dumitrescu (1943) theories modified by Bendiksen (1984) in Eq. (2). Unlike the situation at the slug tail where the velocity profile may result in a shedding since slow moving liquid adjacent to the pipe wall can be left behind, the situation is different in the front of the slug. It is assumed that the 'distribution parameter' at the slug front is unity. Thus the front velocity, V_f, in this case will be:

$$V_f = U_s - U_d \tag{11}$$

2.2.2. Case 2: Film length is negative

This is the case for which a solution to Eqs. (5)–(7) does exist but film length l_f calculated by Eq. (10) is negative. This is again the case where steady slug flow does not exist. A negative film length prediction can take place in one of the two cases: (1) if the flow is dispersed bubble flow; and (2) if slugs dissipate downstream. The first sub-case is easy to realize where there is not sufficient gas to form an elongated bubble and the gas moves forward as dispersed bubbles. The second sub-case results from the complete dissipation of slugs in the downhill section.

The following physical process takes place during slug dissipation. When a slug passes a top

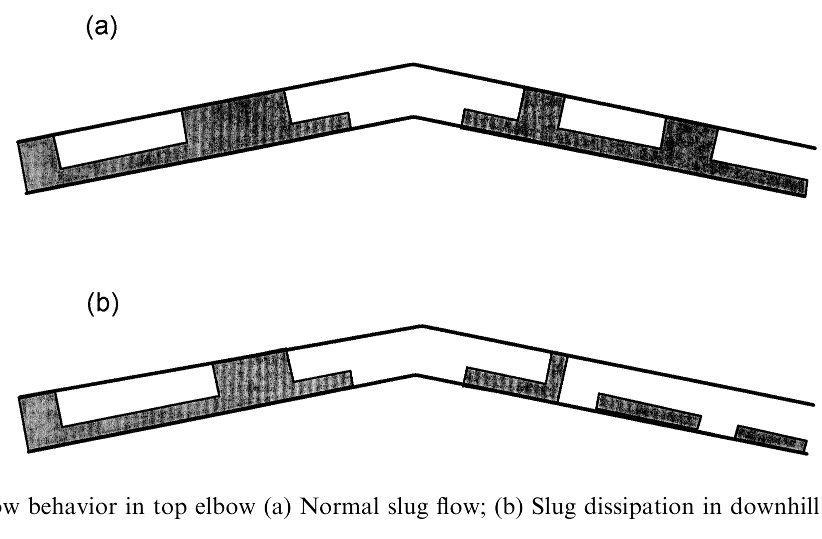

Fig. 2. Slug flow behavior in top elbow (a) Normal slug flow; (b) Slug dissipation in downhill section, case 2.

elbow, the films near the top elbow flow forward in the downward section and backward in the upward section and the zone near the top becomes dry (see Fig. 2). Therefore, the slug front velocity is U_s, that is the velocity of the mixture. This is different from case 1 where the proceeding bubble is assumed to penetrate the liquid slug ('bubble turning') and the film moves faster then the slug mixture velocity. In this case the slug velocity is faster than the film velocity and it would have overtaken and scooped any possible film in front of the liquid slug. The slug tail velocity is equal to the translational velocity given by Eq. (1) which is greater than the front velocity. Thus, the first slug dissipates in the downhill direction. The next approaching slug that passes the top elbow will decrease in length as it passes through the dry zone. If this slug overtakes the film in front of it before completely being dissipated, then a normal slug flow in the downhill section will ensue, but the slug length will be considerably shorter (Fig. 2(a)). However, if the slug dissipates completely before reaching the liquid film, then the flow will be stratified flow and we will get (theoretically) a series of liquid films separated by dry zones (Fig. 2(b)). In practice, these series of films will eventually merge to form a continuous stratified film flow.

This is precisely the case that takes place when the steady state solution for slug flow results in a negative film length. The proof of this is not straightforward. To prove this, we used a slug-tracking program (Zheng et al., 1994; Taitel and Barnea, 1998) which allows one to track normal hydrodynamic slugs and predict their behavior when passing a top elbow.

Indeed, we found that the slug film length, l_f, can change from a positive real solution to a negative false solution as the liquid flow rate is decreased. This is precisely when we move from normal hydrodynamic slug flow in the downhill section (Fig. 2(a)) to the case where slugs dissipate completely in the downhill section resulting in stratified flow (Fig. 2(b)).

At present, determination of the distribution parameter C and the drift velocity U_d for downward flow is not quite clear. Here, we will assume that for downward flow, the distribution parameter will be the same as for upward inclination since it results from the velocity profile, which is the same for downward and upward flows. The more controversial parameter is the drift velocity. We will assume that this velocity is zero for the following reason: for upward flow, the drift velocity is the velocity of a bubble into stagnant liquid. Applying this definition also for downward flow, we note that a bubble on top of stagnant liquid in downward inclined pipe will not move, which means that the drift velocity is zero. Clearly, the validity of Eq. (1) for downward flow is not certain. Yet, it can probably be used as an approximation even if it is not truly valid.

2.2.3. Case 3: drift velocity is negative

Although we do not consider the case where the drift velocity is negative (for the slug tail), there are some claims (Bendiksen, 1984) that the drift velocity in the downward direction may sometimes be negative. A negative drift velocity posses no problem to the solution, provided it is not too large. Expressing Eq. (6) in the following form

$$R_f = \frac{\left[(C-1)(U_{LS}+U_{GS})+U_d\right]R_s}{C(U_{LS}+U_{GS})+U_d-U_f} \tag{12}$$

shows that when the drift velocity is negative and large, that is $|U_d| > (C-1)(U_{LS}+U_{GS})$, the liquid holdup of the liquid film is negative. Obviously, this is not a realistic case. The dominator in Eq. (12) is equal to $(V_t - U_s)R_s$. $V_t = U_s$ means that the translational velocity is equal to the mixture velocity in which case there is no back shedding. Eq. (12) correctly suggests that in this case, R_f is zero and there is no film behind the slug. This case is not a realistic case and we will assume that for downward flow the drift velocity (assuming it is negative, which is not the assumption used here), should satisfy the relation:

$$(C-1)(U_{LS}+U_{GS})+U_d>0 \tag{13}$$

2.2.4. Dissipation length

Once the slug front velocity V_f and tail velocity V_t are known, a dissipation velocity can be defined as $V_{dis} = V_t - V_f$. Assuming that the dissipation velocity is constant, the dissipation time is

$$t_{dis}=\frac{l_s}{V_{dis}}=\frac{l_s}{V_t-V_f} \tag{14}$$

and the dissipation length will be

$$L_{dis}=V_t t_{dis} \tag{15}$$

However, we still need to know the liquid slug length in the downhill section in order to use Eq. (15).

Consider the case of a pipe in which the downward section is preceded with an upward section. In the upward section usually we will have slug flow. In the downward section we may have slug flow; however, usually slugs will be dissipated in the downhill section, resulting in stratified flow. Assuming we know the slug length in the uphill section, we want to know the slug length after the slug has passed the top elbow. Slugs tend to decrease in length as they go through the dry top elbow. Thus, before we use (Eqs. (14) and (15)) to calculate the dissipation distance we need to know the slug length on top of the downward inclined section.

For the case of steady slug flow, the change of slug length as it moves from one section to another was presented by Zheng et al. (1994).

$$\frac{l_{s,II}}{l_{u,I}}=\frac{R_{s,I}-R_{f,I}}{R_{s,II}-R_{f,II}}+\frac{U_{f,I}R_{f,I}-U_{f,II}R_{f,II}}{V_{t,I}\left(R_{s,II}-R_{f,II}\right)}\frac{l_{u,I}}{l_{s,I}} \tag{16}$$

where I refer to the slug properties in one section and II to its properties in the second section. The derivation of Eq. (16) is based on the continuity of liquid flow rate (Eq. (9)) also using continuity across the bubble interface (Eq. (6)) and considering slug frequency constant ($\upsilon = l_u/V_t$). However, Eq. (16) is valid for steady state in which case slugs shrink in size when they move from an uphill section to a downhill section, but do not dissipate completely. When they dissipate completely, we need to know the slug size just after passing the top elbow. This is the slug length when the tail of the slug coincides with the top elbow. This length can be calculated easily considering a slug in the middle of the top dry elbow. The tail velocity is the same as in the uphill section. The front velocity is already in the downhill section and its front velocity can be calculated as in case (1) and (2) (Eq. (11)). The time of passing will be

$l_{s,uphill}/V_{t,uphill}$ in the upward section. Right after this time the tail will coincide with the top elbow and the slug front will be at $l_{s,downhill} = (l_{s,uphill}/V_{t,uphill})V_{f,downhill}$.

3. Results and discussion

In Figs. 3 and 4, we mapped the three cases possible for downward slug flow for a water–air system, at atmospheric pressure, room temperature, 5 cm pipe diameter, and $-1°$ inclination angle. In Fig. 3, we assumed the liquid slug is free of entrained bubbles, $R_s = 1$. As can be seen, for low liquid and gas flow rates, the 'no solution' is due to case 1, while for higher gas flow rates it is due to case 2. For higher liquid flow rate there is a solution for steady slug flow. Thus, at flow conditions of high liquid flow rate, slugs will not dissipate.

Fig. 4 maps the same condition, but allows gas bubbles to be present in the liquid slug zone. Clearly, this is a more realistic condition. The liquid slug holdup, R_s, is calculated using Barnea and Brauner (1985) model. Note that case 2 also appears at the top (high liquid flow rate). As mentioned previously, case 2 consists of 2 sub-cases. The first is when slugs dissipate downhill and the second is the case when the flow is dispersed bubble.

It is not the purpose of this work to consider flow pattern prediction. However, Fig. 5 is a flow pattern map based on Barnea's (1987) model, for the same conditions as in Figs. 3 and 4. It is very surprising that the slug/stratified and slug/dispersed bubble transitions nearly coincide with those predicted by the slug model. Transition to annular is not handled by the slug model. The flow pattern transition and slug models are quite different. In the slug model transition boundaries are determined by a 'no solution' criterion for slug flow i.e. slug

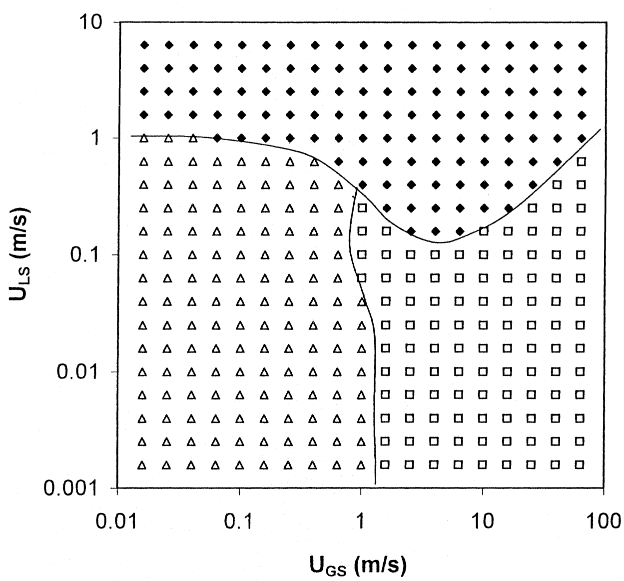

Fig. 3. The regions of no solution for water–air, 5 cm diameter, $-1°$ inclination, $R_s = 1$ (◆ steady slug flow, △ case 1, □ case 2).

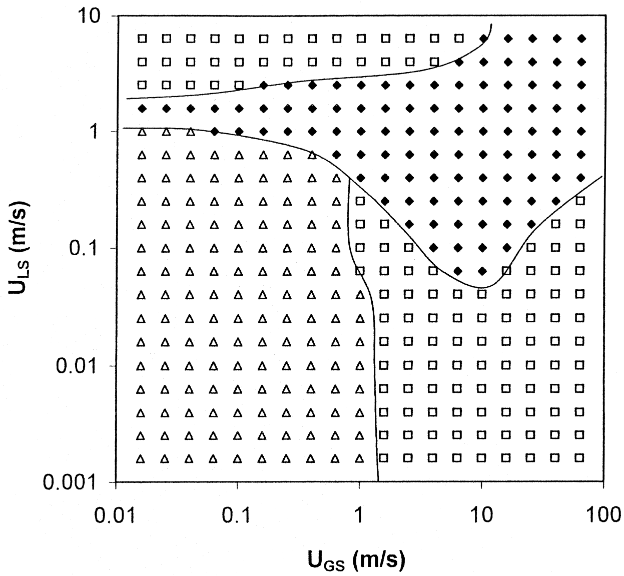

Fig. 4. The regions of no solution for water–air, 5 cm diameter, $-1°$ inclination, R_s by Eq. (4) (◆ steady slug flow, △ case 1, □ case 2).

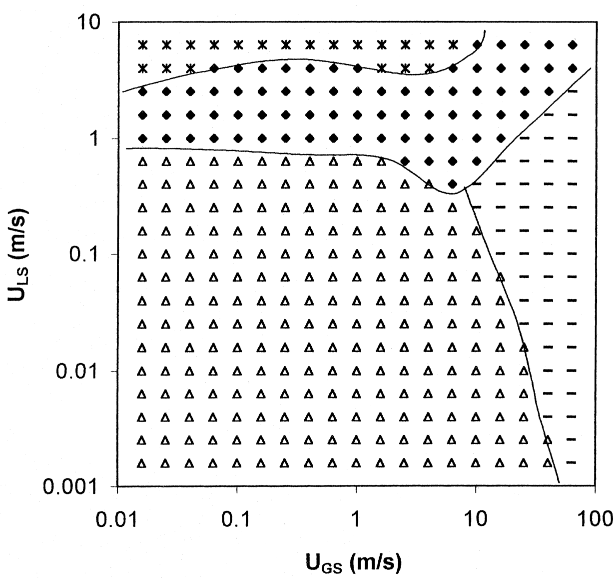

Fig. 5. Flow pattern, water–air, $D = 5$ cm, $-1°$ (downward △ stratified flow, $*$ dispersed bubble, ◆ slug flow, — annular flow).

dissipation, while the Barnea and Brauner (1985) transition to slug flow occurs due to Kelvin–Helmholtz instability. The possibility of considering slug flow dissipation model as a tool to predict stratified/slug flow transition boundary was discussed before (Bendiksen, 1984, Bendiksen and Espedal, 1992 and Bendiksen et al., 1996). Bendiksen and Espedal claimed that the prediction of the slug flow dissipation model is a necessary, but not a sufficient condition, for slug flow to persist. For high-pressure system, they concluded that the slug dissipation mechanism is the more restrictive one and thus could be applied alone to predict stratified/slug transition. The Bendiksen and Espedal slug dissipation model is not the same as the one presented here, although the general idea of examining the stability of slugs is similar. In a later paper, Bendiksen et al. (1996) suggested that the flow pattern depends on the entrance conditions. When the flow is stratified at the entrance then transition to slug flow will take place as a result of Kelvin–Helmholtz instability. However, when flow pattern at the entrance is slug flow, then transition from slug flow to stratified flow will take place as a result of the slug dissipation process. Clearly, the two boundaries are not identical.

Based on the above discussion we see little contradiction between the boundaries in Figs. 4 and 5 and accept Bendiksen et al. (1996) approach. Thus, Fig. 4 predicts the transition from slug flow to stratified flow provided the entrance conditions are slug flow. Similarly, Fig. 5 represents the usual flow pattern boundary starting from stratified flow at the entrance. As a cautionary note, the slug dissipation model in this work was not aimed at providing flow pattern prediction method. It is premature to speculate its applicability for flow pattern prediction.

Fig. 6 shows the calculated slug dissipation length for the same conditions treated before. For these calculations, it is assumed that the slug enters the downhill section from an uphill section of $+1^\circ$ inclination (see Fig. 2) and that in the uphill section the slug length is $30D$ (1.5

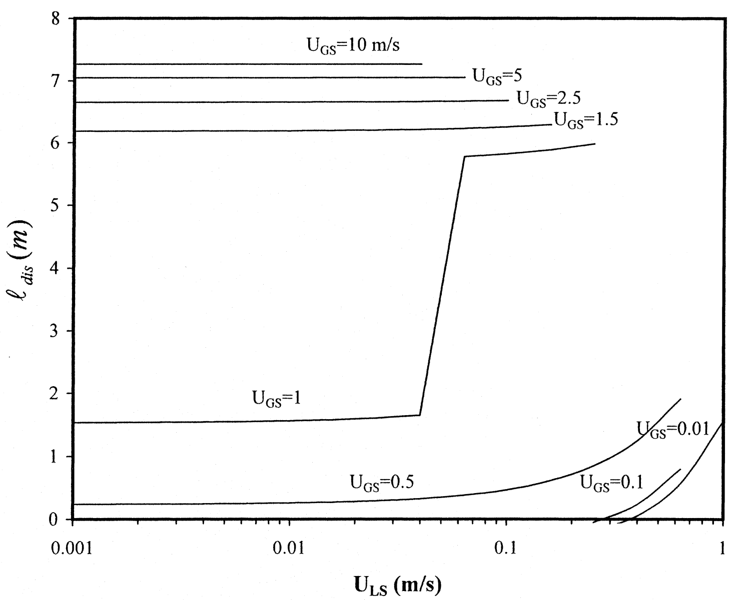

Fig. 6. Slug dissipation length, water–air, $D = 5$ cm, -1° downhill.

m). After passing the top elbow, the slug shrinks in length and its length on the downhill side is calculated as previously outlined. Knowing the tail and front velocities of the slug in the downhill section we can calculate the dissipation distance using Eqs. (14) and (15).

The curves in Fig. 6 show the dissipation lengths as a function of liquid flow rate for various values of gas flow rate. This is equivalent to moving along vertical lines on Fig. 4. The slug dissipation distance increases with increasing gas flow rate. The liquid flow rate has a substantial effect only for low gas flow rates and its effect is negligible for high gas flow rates. The curves are terminated on the 'right' when steady slug flow is possible (see Fig. 4). Note that this termination is based on Fig. 4 and it is not transparent from the slug dissipation length calculation.

In Fig. 6, both case 1 and case 2 are used. As shown in Fig. 4, for flow rates below 1 m/s, case 1 is applicable, while for flow rates above 1 m/s, case 2 is valid. Note that for a gas flow rate of 1 m/s, case 1 occurs at low liquid flow rates and case 2 occurs at higher flow rates. This is reflected in Fig. 6 by the abrupt increase in the slug dissipation length around $U_{LS} \approx 0.6$ m/s. Note also that for very low liquid flow rates and low gas flow rates, the slug dissipation length is zero. That is, slugs are dissipated instantaneously as they pass the top elbow.

4. Summary and conclusions

The 'no solution' for the slug model in downward inclined pipes is analyzed. It is shown that the 'no solution' situation can result for two basic reasons: (1) the film velocity is faster than the mixture velocity, and (2) either a slug passing through a top elbow dissipates before overtaking a film that was shed by the previous slug, or, flow pattern is dispersed bubble.

Both cases result in the dissipation of the slugs in the downhill section and transition to stratified flow takes place. A simple model for the calculation of the slug dissipation length in both cases is presented and a specific example, to demonstrate the applicability of the theory, is included.

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