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THE FRONT SHAPE OF A SPHERE-PROPELLED LIQUID SLUG IN A NATURAL-GAS PIPELINE

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Abstract—A simple calculation model has been developed for predicting the conditions under which a sphere-propelled liquid slug will maintain a full-bore configuration when travelling in a natural-gas pipeline running through hilly terrain. The model also predicts, among other things, the curvature, length and volume of the sloping front end of the slug. Results from laboratory studies in which a sphered slug is simulated by sending a batch of water through a horizontal or inclined perspex pipe, thereby displacing the air in the pipe, are in good agreement with the model predictions up to a slug velocity of 2 m/s. Above this velocity the measured sloping front end is longer than predicted. This is due to air entrainment in the front end, a phenomenon ignored in the calculation model. The model has also been applied to a large-diameter natural-gas pipeline through which a sphere-propelled slug of hydrocarbon liquid moves.

Key Words: natural-gas pipeline, sphered slug, slug front

1. INTRODUCTION

Natural gas produced offshore is usually transported through long pipelines to gas-treating facilities on shore. This gas mostly contains traces of water, which will partly condense together with the heavier hydrocarbons during transport. This could lead to hydrate formation. Moreover, in particular, in the presence of carbon dioxide, corrosion is likely to occur in this system if no preventive measures are taken. One way to combat such corrosion and hydrate formation is to inject continuously glycol/methanol into the pipeline, as this will absorb the condensing water [see, for instance, Campbell (1981)].

As far as corrosion protection of the pipeline is concerned, an alternative approach is to inject, on a regular basis, a hydrocarbon slug with a suitable composition, in which a corrosion inhibitor has been dissolved. It is essential that this slug passes the line as a full-bore slug, enabling the corrosion inhibitor to reach every part of the pipe wall. This could be achieved by launching a sphere immediately after the injection of the liquid hydrocarbon or condensate slug with corrosion inhibitor. However, in particular, in downward-sloping parts of the pipeline at low gas velocities, it may be difficult to maintain a full-bore slug in front of the sphere as a result of stratification. With a sufficiently steep downward slope the velocity of the pig-propelled slug may even be too low for the slug to catch up with the liquid running down the slope as a stratified layer. Under these conditions a full-bore slug will NEVER be generated.

It is essential to have a reliable method available to predict for given pipe conditions (e.g. pipe route profile) and gas velocity whether a full-bore slug can be generated by sphering and, if so, the minimum quantity of slug required, which of course should be more than the volume of the stratified front of the slug. Also, allowance should be made for the fact that part of the liquid will leak along the sphere and will remain on the pipe wall as a thin liquid layer. If we use the results of Baker (1967) for slippage past a sphere, the thickness of such a layer in a 0.9 m dia pipe is estimated as 0.1 mm, which amounts to a loss of 27 m^3 per 100 km. A quantity of this size cannot be neglected.

As far as the authors are aware, there is no direct information available in the open literature regarding the front shape of a full-bore sphere-propelled slug. Nor are any direct criteria given for

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the critical sphering velocity above which a full-bore slug can be maintained in downward-sloping pipelines. Most of the publications on the slug shape deal with natural slugs as they are generated in a two-phase flow pipeline in the slug flow regime. A characteristic feature of such a slug flow is that fast-moving liquid slugs alternate with gas slugs, with a slow-moving liquid layer below the gas slugs.

Markovich (1983) published an experimental study on the structure of the leading edge of such a natural liquid slug. The front end of the slug was simulated by sending a water batch through a horizontal tube in which a stagnant water layer was already present. In the study, particular attention was given to the interaction of this stagnant layer with the front of the slug. The resemblance to a hydraulic jump was noted.

Kouba & Jepson (1989) also suggested that natural slugs, as they are generated in two-phase pipe flow, are hydraulic jumps propagating along the pipeline. They showed experimentally that at the slug front a change takes place from supercritical flow (in the liquid film) to subcritical flow (in the slug body), which is consistent with the existence of a hydraulic jump.

Dukler & Hubbard (1975) were among the first to formulate a model for a natural slug. Their model is based on the observation that a fast-moving slug outruns the slow liquid film in front of it. This liquid film is accelerated to the full slug velocity in a mixing eddy located at the front of the slug. This mixing eddy will also draw gas into the slug front. Their study has been followed by many other publications in which more refined models have been presented (e.g. Nicholson *et al.* 1978; Moalem-Maron *et al.* 1982).

The above-mentioned approaches all have in common that a liquid film has to be present in front of the slug. With sphere-propelled slugs this is not always the case.

Nydal & Andreussi (1991) published an experimental study of the aeration of a water slug moving over a slow-moving water layer in a slightly inclined transparent pipe in which a water film was flowing downwards in steady motion. The water slug was created by the sudden introduction of a water flow into the pipe in a more or less similar manner to that described by Markovich (1983), as discussed above. A slug generated in this way simulates very well a sphere-propelled slug. The gas entrainment in the front of the slug was monitored by means of a conductance method (Andreussi & Bendiksen 1989). A few experiments were also carried out with no liquid layer present. One important conclusion from this study was that substantial gas entrainment only occurred if a liquid layer was present ahead of the advancing slug.

As far as the stability of a full-bore slug in a downward-sloping pipe is concerned, a criterion can be derived from the study by Bendiksen (1984) on the motion of long bubbles in inclined tubes. The reasoning is that the transition from a full-bore slug to a stratified layer in a downward-sloping line below a critical slug velocity can also be modelled as the propagation of a long bubble countercurrent to the slug. Bendiksen performed a series of experiments to determine the effect of tube inclination on bubble motion with the liquid Reynolds and Froude numbers and tube diameter as the most important parameters. Air bubbles were introduced in an inclined transparent pipe, through which water was flowing at a constant rate, occupying the whole cross-section of the pipe.

In the case of a negative pipe inclination (liquid flowing downwards) Bendiksen observed that, below a critical liquid velocity, the bubble was moving in the opposite direction to the liquid flow. The bubble velocity relative to the slug flow was equal to the bubble propagation speed prevailing in the limiting case, whereby the pipe was filled with stagnant liquid. [A comprehensive data set on bubble propagation in inclined tubes filled with stagnant liquid is given by Zukoski (1966).] Above the critical velocity it was observed that the bubble changed direction and moved downwards at an absolute velocity higher than the liquid velocity.

This phenomenon can be explained by the fact that the liquid flow underneath the bubble changes from accelerating to decelerating flow when the liquid velocity exceeds the critical value. This will cause an increase in the thickness of this liquid layer underneath the bubble and consequently a "squeezing-out" of the bubble in the direction of the liquid flow.

At present there is no model available to describe the front length of a sphere-propelled slug. Since full-bore, sphere-propelled slugs are the most commonly used industrial means of protecting the inside of pipelines against corrosion, an appropriate model is presented in this paper.

This calculation model assesses the conditions under which a full-bore liquid slug can be maintained in front of a sphere in a hilly terrain pipeline. The model also predicts, among other things, the curvature, length and volume of the sloping front end of the slug. Subsequently, a description is given of laboratory experiments carried out to verify the calculation method.

A comparison is made of the model predictions with the results of the experiments and the relevant findings and observations in literature. Finally, the model has been applied to natural-gas pipeline conditions.

2. THE CALCULATION MODEL

In figure 1 the propagation of a sphered liquid slug in a pipeline is visualized. The slug has a stratified or sloping front end, the length of which is a function of, among other things, the pipeline slope and sphering velocity.

A control volume ACDB in the pipe has been defined.

At time *t* the front end of the slug just reaches A [figure 1(a)].

At time *t′* the front end of the slug just reaches C, whereas the full-bore part is about to pass the line AB or boundary 1 [figure 1(b)].

The following initial assumptions are made:

1. Steady-state conditions have been established (the shape and length of the slug front are time-independent).
2. There is no liquid film upstream of the slug.
3. The velocity is constant at any place in the pipe, both in the gas and in the slug.
4. There is no gas entrainment in the slug. (If the slug velocity is high, this assumption may not be valid.)
5. Constant shear stresses are assumed along the slug front.
6. The presence of the liquid in the control volume will not influence the gas-filled part of the control volume. In other words, in an observation point in the gas-filled part no difference in local pressure will be noticed until the gas/liquid interface passes this observation point. This is a rather crude assumption.

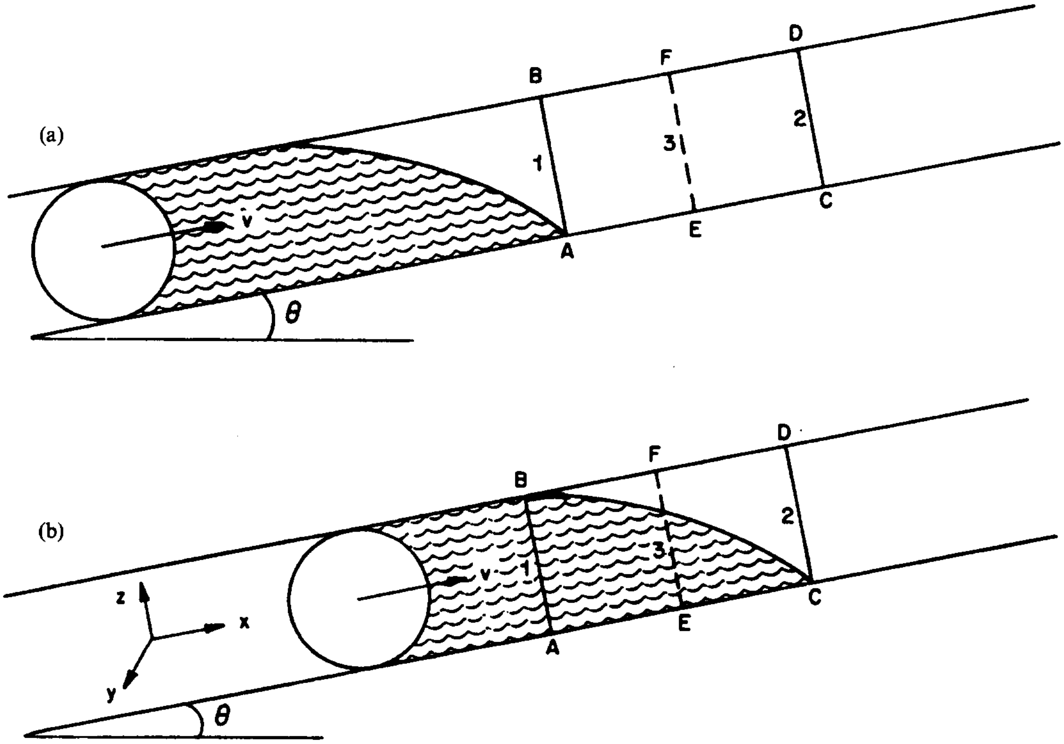

Figure 1. The movement of a sphere-propelled slug through a pipeline: (a) situation at time *t*, (b) situation at time *t′*.

From the force balance over the control volume it is derived that at time t:

$$\underset{\text{(pressure)}}{\bar{p}_1 - \bar{p}_2} = \underset{\text{(gravity)}}{L\rho_G g \sin\theta} + \underset{\text{(friction)}}{2f_G \rho_G v^2 L/D}, \qquad [1]$$

where $\bar{p}_1$ and $\bar{p}_2$ are the averaged gas pressures at boundaries 1 and 2 (AB and CD, respectively) at time t, L is the length of the sloping front end, ρ_G is the density of the gas, g is the gravity constant, θ is angle of the pipe central axis to the horizontal plane, f_G is the Fanning friction factor for the gas flow in the pipe, v is the slug velocity and D is the inner diameter of the pipeline.

At time t',

$$\bar{p}_1' - \bar{p}_2' = \alpha L \rho_L g \sin\theta + (1-\alpha) L g \rho_G \sin\theta + 2\rho_G f_G v^2 (1-\beta) L/D + 2\rho_L f_L v^2 \beta L/D, \qquad [2]$$

where $\bar{p}_1'$ and $\bar{p}_2'$ are the averaged gas pressures at boundaries 1 and 2, respectively at time t', ρ_L is the liquid density, α is the fraction of the control volume occupied by liquid, β is the fraction of the surface of the control volume covered with liquid and f_L is the Fanning friction factor for the liquid flow. Both f_G and f_L are assumed to be constant along the slug front.

Combining [1] and [2], and realizing that $\bar{p}_2' = \bar{p}_2$, we have:

$$\bar{p}_1' - \bar{p}_1 = \alpha L(\rho_L - \rho_G) g \sin\theta + 2\beta v^2 (\rho_L f_L - \rho_G f_G) L/D. \qquad [3]$$

For $\bar{p}_1' - \bar{p}_1$ another expression can also be derived:

$$\bar{p}_1' - \bar{p}_1 = (p_A' - p_A)/2 \qquad [4]$$

(because $\bar{p}_1' = (p_A' + p_B')/2$, $\bar{p}_1 = (p_A + p_B)/2$ and $p_B = p_B'$), p_A and p_A' are the pressures in A at times t and t', respectively, and p_B and p_B' are the pressures in B at times t and t', respectively; and

$$p_A' - p_A = (\rho_L - \rho_G) g D \cos\theta \qquad [5]$$

(because $p_A' - p_B' = \rho_L g D \cos\theta$, $p_A - p_B = \rho_G g D \cos\theta$ and $p_B = p_B'$).
Substitution of [5] into [4] yields

$$\bar{p}_1' - \bar{p}_1 = 0.5(\rho_L - \rho_G) g D \cos\theta. \qquad [6]$$

Combination of [3] and [4] gives

$$L = gD(\rho_L - \rho_G)\cos\theta / [2\alpha g \sin\theta(\rho_L - \rho_G) + 4\beta v^2 (\rho_L f_L - \rho_G f_G)/D]. \qquad [7]$$

If the assumption is made that the gas/slug-front interface is straight, then

$$\alpha = \beta = 0.5$$

and [7] simplifies to

$$L = gD(\rho_L - \rho_G)\cos\theta / [g \sin\theta(\rho_L - \rho_G) + 2v^2 (\rho_L f_L - \rho_G f_G)/D]. \qquad [8]$$

In reality the interface is curved. It is assumed that the surface of the interface is represented by

$$h/D = (1 - x/L)^{\gamma}, \qquad [9]$$

where h is the height of the liquid at the centre of the cross-section of the stratified front end and γ is defined as the curvature index of the slug-front end.

If $0 < \gamma < 1$, the surface is convex (from an observation point in the gas phase). For $\gamma > 1$, the surface is concave; α and β are both unique functions of γ.

To assess γ, the calculations have to be extended. A control volume ECDF is defined which has half the volume of control volume ACDB (see also figure 1). Note that at location EF: $h = (0.5)^{\gamma} D$.

At time t,

$$\bar{p}_3 - \bar{p}_2 = 0.5 L \rho_G g \sin\theta + f_G \rho_G v^2 L/D; \qquad [10]$$

and at time t',

$$\bar{p}_3' - \bar{p}_2' = 0.5\alpha^* L\rho_L g \sin\theta + 0.5(1-\alpha^*)Lg\rho_G \sin\theta + \rho_G f_G v^2(1-\beta^*)L/D + \rho_L f_L v^2 \beta^* L/D; \qquad [11]$$

where $\bar{p}_3$ and $\bar{p}_3'$ are the averaged pressures at boundary 3 (EF) at time t and t', respectively, α^* is the fraction of the control volume ECDF occupied by liquid and β^* is the fraction of the surface of the control volume ECDF covered with liquid.

Because $\bar{p}_2' = \bar{p}_2$, combination of [10] and [11] gives the following expression for L:

$$L = (\bar{p}_3' - \bar{p}_3)/[0.5\alpha^* g \sin\theta(\rho_L - \rho_G) + \beta^* v^2(\rho_L f_L - \rho_G f_G)/D]. \qquad [12]$$

For $\bar{p}_3' - \bar{p}_3$ we derive:

$$\begin{aligned}\bar{p}_3' - \bar{p}_3 &= \frac{4}{(\pi D^2)}(\rho_L - \rho_G)g\cos\theta \int_0^h 2\sqrt{(zD - z^2)}(h-z)\,\mathrm{d}z \\ &= \frac{4}{(\pi D^2)}(\rho_L - \rho_G)g\cos\theta\{(h - 0.5D)^2\sqrt{(hD - h^2)} \\ &\quad + 0.25D^2(h - 0.5D)[\arcsin(2h/D) - 1 + 0.5\pi] + \sqrt{(hD - h^2)^3}/1.5\}. \qquad [13]\end{aligned}$$

An iteration procedure is followed to determine L. γ is varied stepwise. For a given γ the parameters α, α^*, β and β^* are also known since they are only a function of γ (see figure 2 for their dependence

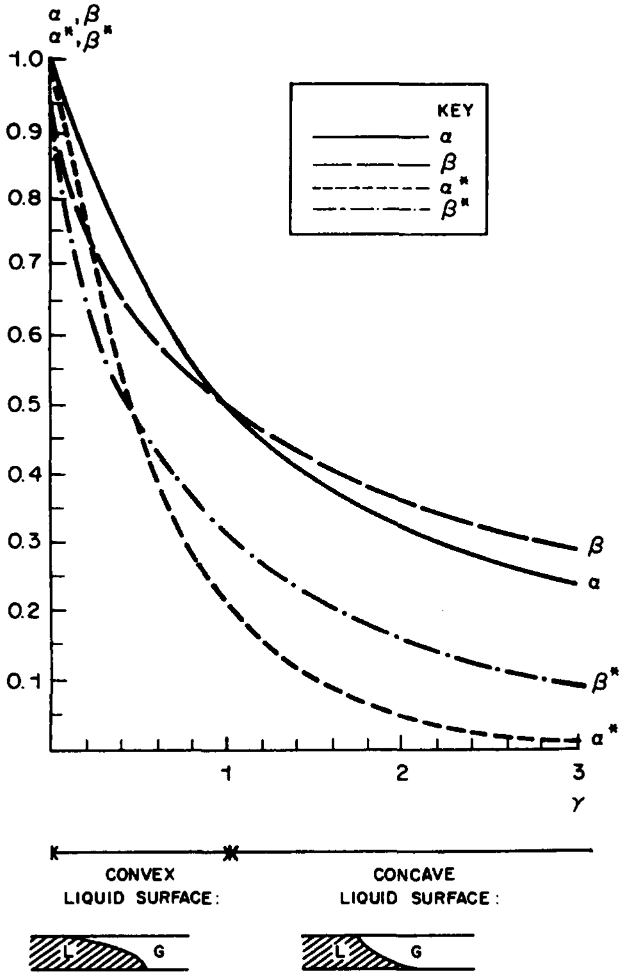

Figure 2. α, β, α^* and β^* as a function of the curvature index γ.

on γ). Also h (at location EF) is then fixed. Thus, it is possible to calculate L following two routes: either according to [7] or according to the combination of [12] and [13]. The criterion for the correct γ is that both approaches should result in the same L (within a given tolerance).

Although the choice of half the control volume ACDB for control ECDF seems logical, it has to be realized that this is still an arbitrary choice. Since [9] is an approximate description of the slug-front interface, the γ value to be found by the matching process will still be a function of the choice of volume ECDF.

Finally, the volume of the stratified slug front, $\mathrm{Vol}_{\mathrm{strat}}$, is then given by

$$\mathrm{Vol}_{\mathrm{strat}} = \alpha\pi D^2 L/4. \qquad [14]$$

3. EXPERIMENTAL VERIFICATION

3.1. Experimental setup

To check the predictions of the calculation model, laboratory experiments have been carried out with a 26 m long perspex pipeline with an inner diameter of 5 cm. The sphered slug was simulated by sending a water flow from the laboratory water-main through the pipe, thereby displacing the air in the pipe. The inclination [100 tan θ (%)] of the pipe was either -2% (downflow mode), 0% (horizontal) or $+2\%$ (upflow mode). A measuring pipe section with tiny conductivity probes inserted in the pipe wall could be placed at any desired location in the pipe. For the location of the probes in the measuring section see figure 3.

When the slug front passes the trigger probe pair, the measurement is started ($t = 0$). If, subsequently, the slug front passes a measuring probe pair the local breakthrough time is measured because of the locally increased conductivity between the two probes of the pair. From the various breakthrough times, with the location of the probes and the slug velocity being taken into account, both the length and the shape of the water front are determined.

The standard location of the measuring section was 17 m downstream of the pipe inlet. In addition, several tests were performed with the measuring section upstream in the pipe, at 10 m from the inlet.

These tests showed that after 10 m the equilibrium slug-front length was reached for slug fronts up to a length of 7 m.

To check further whether the presence of the probes influenced the measurements, photographs were taken when the measuring section was not installed. It was found that the probes did not affect the measurements (e.g. length of sloping front) so it was justified to employ this measuring method.

3.2. Results

Figure 4 (reproduction of a photograph) shows a typical example of the front end of a slug generated in the test pipe (pipe in the horizontal position).

The curvature of the slug front is shown by means of the straight reference line. It is further seen that small waves are superimposed on the interface.

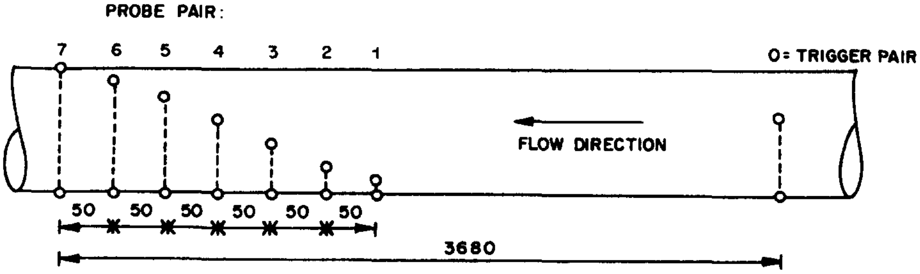

Figure 3. The measuring section (all dimensions in mm).

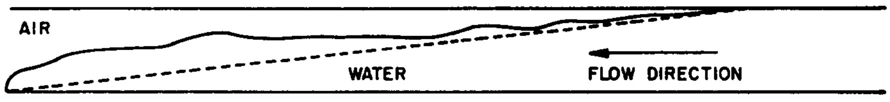

Figure 4. Example of a slug front generated in the model pipe (horizontal).

In figures 5 and 6 the measured front length, L, and the curvature index, γ, respectively, are presented as a function of the slug velocity for the three pipe inclinations. In these figures the theoretical solution is also presented.

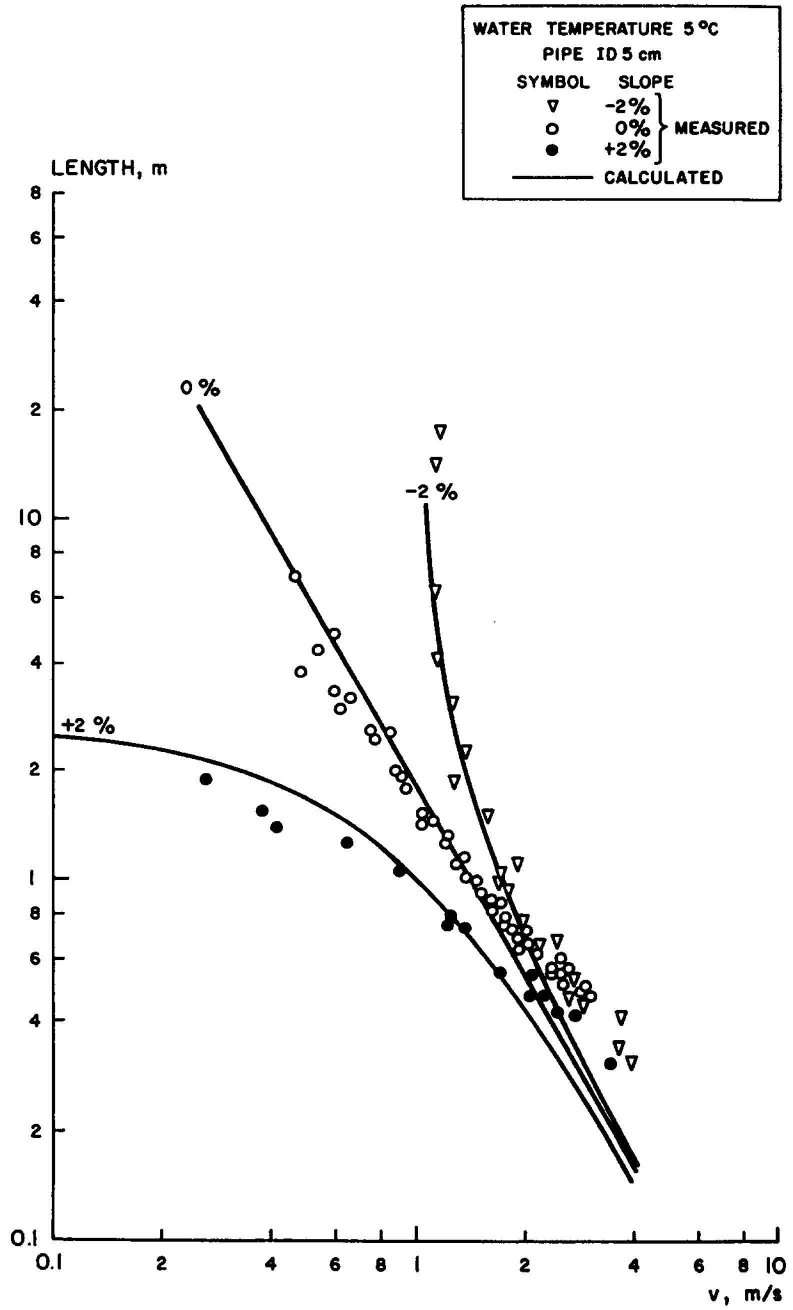

Figure 5. Influence of the pipe inclination and slug velocity on the slug-front length.

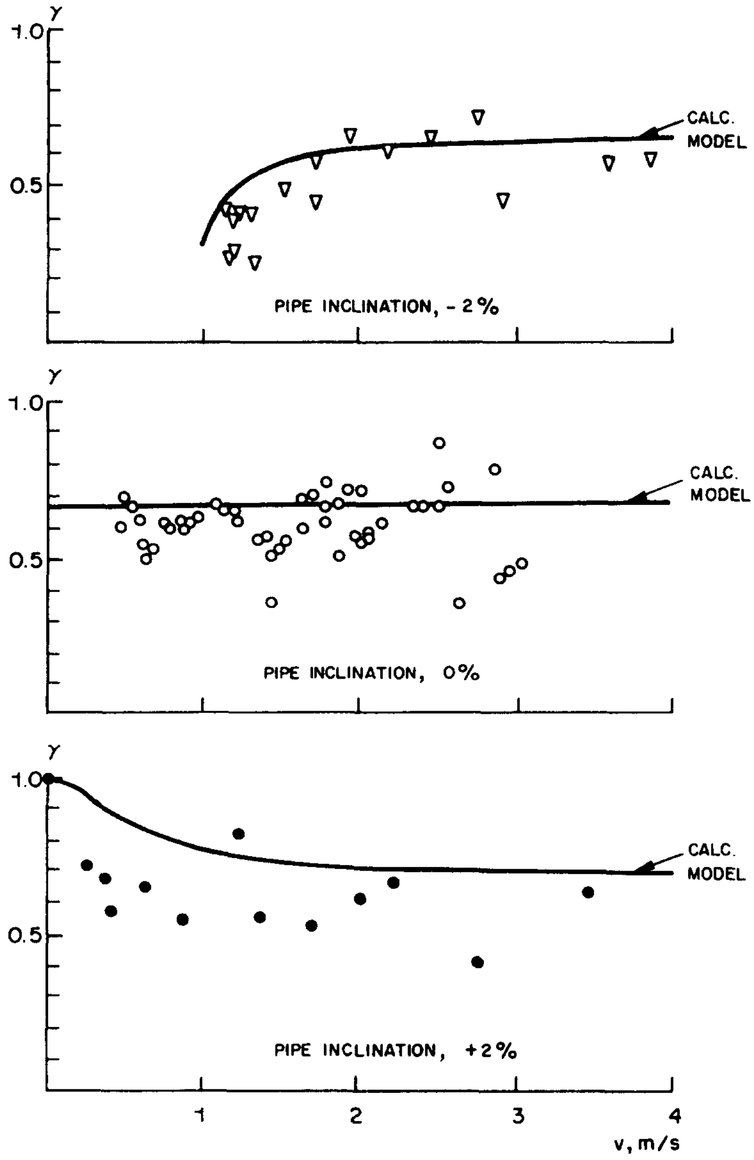

Figure 6. Comparison of the predicted and measured curvature indexes for pipe inclinations of −2, 0 and 2%.

3.3. *Comparison with the predictions of the model and findings from literature*

Figure 5 shows that, up to a slug velocity of 2 m/s, the calculation model gives a fairly good prediction for the front-end length, in particular for the pipe inclinations of 0 and −2%.

Both the model and experiments show that, for all conditions, $\gamma < 1$. In other words, the front end of the slug is always convex. This is in line with the observations of other investigators (e.g. Kouba & Jepson 1989), although, admittedly, these nearly always concern the front end of a natural slug with, upstream of it, a slow-moving liquid film. The presence of this layer, having a "braking" effect, will promote the convexity of the slug-front end.

As far as the curvature index γ is concerned, there is a trend in our experiments that the values observed experimentally are lower than calculated, i.e. the front end is more convex than predicted, in particular for the positive pipe inclination.

The experimental results for the case of a negative pipe inclination show that the closer the slug velocity is to the velocity below which no full-bore slug is possible, the lower γ. It can be seen from figure 6 that the values of γ as predicted by the calculation model follow rather closely the same trend. Apparently, despite the number of simplifications we made in the model, it is still able to predict this feature reasonably well.

As indicated earlier in this paper, it is possible, in principle, to derive from the bubble direction-changing criteria, as formulated by Bendiksen (1984), the value of the velocity below which no full-bore slug is possible. Using these criteria, is has been calculated that, in the case of a water–air system with a pipe with an internal diameter of 5 cm and a negative pipe inclination of -2%, the critical velocity is 0.95 m/s, which is in good agreement with the prediction of our model and our experimental results (see figures 5 and 6). For liquid velocities lower than this value, stratification will take place. This is equivalent to a bubble propagating countercurrently relative to the slug. Based on Zukoski's (1966) data it is calculated that, for our particular case, the speed of this bubble relative to the slug is 0.26 m/s for liquid velocities below the critical value.

Figure 5 shows that, for slug velocities >2 m/s, the calculation model underestimates the front length. A high-speed film showed that, above a slug velocity of about 2 m/s, air starts to entrain in the slug front, so it is likely that this phenomenon is the cause of the observed discrepancy. The gas bubbles escaping from the slug front will accumulate in the upper part of the pipe, thus extending the length of gas/liquid interface and therefore also the effective front length.

As has been stated earlier in this paper, data from the literature (Nydal & Andreussi 1991) suggest that the amount of air entrained in the slug is very small if no liquid film is present in front of the slug. The presence of a slow-moving liquid layer in front of the slug, though, promotes strongly the entrainment of air into the slug because, in the process of the film accelerating to the slug velocity, a mixing eddy is formed which also will draw air into the slug. From the data presented in figure 6 of their publication, it has been assessed via extrapolation that, for a 5 cm dia pipe, below a slug velocity of about 4 m/s no air entrainment takes place, or is still at such a low level that it cannot be detected by their conductance method. This velocity level is significantly higher than that observed by us.

One of the reasons for this discrepancy could be that, although from visual observation it seems that, at slug velocities <4 m/s, a significant amount of air has been entrained in the slug front, this in fact takes place preferentially at the pipe wall, with the gas fraction in the bulk of the slug front still being quite low.

Additional model calculations have been carried out in an attempt to explain the discrepancy between the experimentally observed and predicted slug length at higher slug velocities from the effect of the aeration on the slug viscosity and density. In these calculations both the effective slug density and the viscosity have been varied systematically between the values holding for air and water.

In figure 7 the results are shown in a contour plot for a pipe inclination of -2% and a slug velocity of 4 m/s. The experimentally observed value of the slug-front length was 35 ± 5 cm. It is seen that a DECREASE in the density, due to aeration, for instance, also DECREASES the front length, whereas a DECREASE in the viscosity INCREASES the front length.

If, in the calculation model, a density and viscosity were used as defined by the shaded area in figure 7, the model would have given a good estimate of the front length. This suggests that the effective viscosity is close to that of air, whereas the effective density is still relatively high. This could mean physically that the major part of the gas entrained in the slug is located in the vicinity of the wall, where it would have the greatest impact on the effective slug viscosity. This is consistent with our explanation of the discrepancy between the experimental results of Nydal & Andreussi (1991) and the present results concerning the onset of air entrainment in the slug front.

4. PRACTICAL IMPLICATIONS

The calculation model has been used to assess the minimum size of a slug which, under flow equilibrium conditions, will just provide full-bore wetting of large-diameter natural-gas pipelines. This minimum size is equivalent to the liquid volume of the stratified front end of the slug. Figure 8 gives, for an existing submarine natural-gas pipeline, this theoretical minimum size as a function

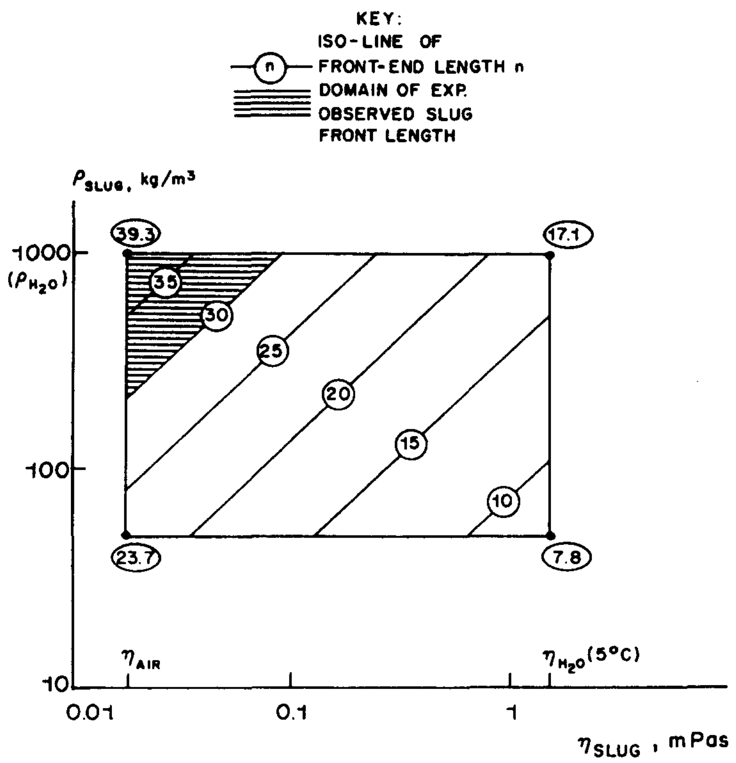

Figure 7. Calculated influence of the slug viscosity and density on the length of the slug-front end (length in cm); slug velocity = 4 m/s, pipe inclination = −2%.

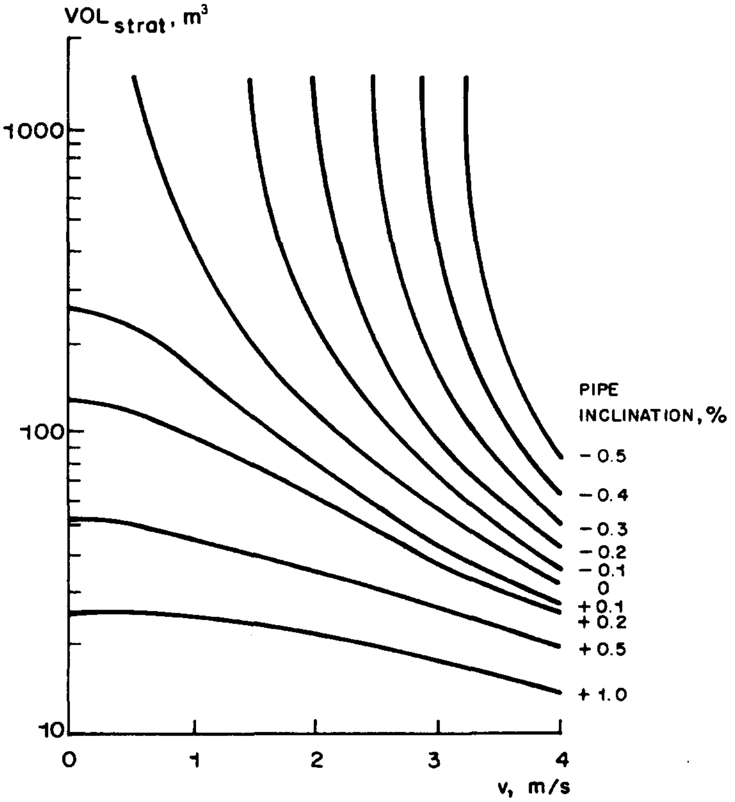

Figure 8. The calculated volume of the slug front of a sphered slug in a natural-gas pipeline as a function of the slug velocity and pipe inclination (for pipe and flow conditions, see the main text).

of the slug velocity up to 4 m/s for several local pipe inclinations, ranging between -0.5 and $+1.0\%$.

The relevant pipeline and flow conditions are as follows:

Pipe:	inner diameter:	0.87 m
	wall roughness:	0.018 mm
Condensate:	dynamic viscosity:	8.5×10^{-5} Ns/m^2
	density:	418 kg/m^3
Gas:	dynamic viscosity:	1.8×10^{-5} Ns/m^2
	density:	158 kg/m^3.

Figure 8 indicates further that, for pipe inclinations $\leqslant 0\%$, it is not possible to maintain a stable full-bore slug below a critical slug velocity, v_{crit}.

For this particular case, v_{crit} is approximately the following function of the pipe inclination, incl (incl expressed in %):

$$v_{\text{crit}} = -10.42(\text{incl}) - 7.73(\text{incl})^2. \qquad [15]$$

The coefficients on the right-hand side of the equation have the dimension [m/s].

5. CONCLUSIONS

It has been demonstrated that the calculation model developed to describe the front end of a sphere-propelled liquid slug gives good results, despite the number of approximations made.

Comparison of the predictions of the model with the literature data and the results of our slug simulation experiments shows the following:

1. Up to a slug velocity of 2 m/s, under conditions whereby a full-bore slug can be maintained, the model predicts the length of the slug-front end very well for the pipe inclinations investigated: -2, 0 and 2%. Above this velocity, air starts to entrain into the slug front. The model underpredicts the length of the front for those velocities if the effect of the air entrainment on the slug viscosity and density has not been taken into account.
2. The change in convexity of the slug front is predicted fairly well in the case of a negative pipe inclination under full-bore slug conditions when the slug velocity is decreasing to the critical value at which a full-bore slug can no longer be maintained.
3. The prediction of this critical velocity is in good agreement with the results of our slug simulating experiments and also in line with the prediction based on the bubble direction-changing criterion as formulated in the literature.

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