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STATISTICAL CHARACTERIZATION OF SLUG FLOW IN HORIZONTAL PIPES

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Abstract—Air/water slug flow in 53 and 90 mm i.d. horizontal pipes has been investigated for a large range of gas and liquid velocities. For this purpose a special instrumentation with simultaneous data acquisition and analysis has been developed. This has been used to determine the mean slug characteristics (length, holdup and velocity) and their statistical distributions.

Key Words: slug flow, statistical distributions, void in slugs, slug velocity

1. INTRODUCTION

Slug flow in horizontal pipes can be described as the flow of aerated slugs, travelling at high velocity, separated by flow regions in which the gas and the liquid assume a stratified configuration. With the introduction of the concept of oil and gas transportation in long pipelines for the exploitation of subsea reservoirs the research on slug flow has been intensified during the last decade, as the phenomenon of slugging introduces fluctuations of an unstable nature that must be considered in the design of two-phase flow systems.

In modelling slug flow, an averaged, one-dimensional model is usually selected. This approach is based on the assumption that slug flow can be described as a sequence of identical slug units travelling at a constant translational velocity (Dukler & Hubbard 1975). In this type of model the length, the translational velocity and the mean liquid holdup in the slug body are computed by means of empirically based closure relations. The mean holdup in the pipe, the length of the slug unit and the pressure gradient can then be computed by a set of mass and momentum conservation equations. Recent works on slug flow (Fernandes 1981; Malnes 1983; Andreussi & Bendiksen 1989) have provided some improvement to the model of Dukler & Hubbard (1975), but there is still a need for more data for a better assessment of the equations used as closure relations.

Considering the stochastic features of slug flow, an experimental investigation of this flow regime should be based on extensive and accurate measurements of the main slug parameters, such as length, velocity and mean void. It should also be remarked that before slug flow data can be used for the assessment of closure relations, it should be ensured that the flow is well-developed and independent of the inlet conditions. In principle, this can be done taking data at different locations in the pipe and, eventually, varying inlet conditions, with the consequence that the number of data required increases appreciably.

In this paper we present an experimental investigation on the statistical properties of slug flow. Statistical distributions of the slug parameters are obtained for different pipe lengths and inlet conditions, and correlation functions are computed as indications of the statistical relations between the parameters. A special instrument has been designed for the direct measurement of slug flow parameters. Signals from three conductance probes are processed online in a PC equipped with an ADC working at high sampling rates. Only key parameters are computed and stored for each slug unit: the slug front velocity, the slug bubble velocity, the slug length and the slug holdup.

The concept of simultaneous data acquisition and analysis allows the combination of high sampling rates with long acquisition times. This makes it possible also to characterize slug flow at flow rates where the slug frequency is low.

2. EXPERIMENTAL SETUP

2.1. Flow loop

The experiments are relative to air/water flow at atmospheric conditions in two horizontal pipes of 52.9 mm i.d. (stainless steel) and 90 mm i.d. (acrylic). The ranges of liquid and gas superficial velocities covered in the experiments are

$$J_L = 0.6 \text{ to } 3.5 \text{ m/s}$$

and

$$J_G = 0.5 \text{ to } 20 \text{ m/s}.$$

All reported superficial gas velocities are at standard conditions (1 bar, 20°C).

The experimental setup is shown schematically in figure 1. A bench supporting the 17 m long test sections can be inclined continuously between $\pm 3°$ with respect to the horizontal position by a motorized support. Tap water is circulated by centrifugal pumps and the air is supplied by a compressor at a controlled pressure of 6 bar. Single-phase flow rates are measured with calibrated rotameters before the mixing section. The pressure at the gas rotameters is set at 2 bar.

The design of the inlet section is also shown in figure 1. As can be seen, at the pipe inlet stratified flow conditions are obtained by injecting the gas phase parallel to the liquid from the top of the pipe.

2.2. Instrumentation

The instrumentation adopted in this investigation is based on the conductance method. The central probe is made of two conducting rings spaced 2.5 pipe diameters apart. This probe has been described in detail and tested by Andreussi *et al.* (1988) and is used in the present experiments to measure the instantaneous liquid holdup. Two trigger probes are positioned on each side of the rings to monitor the conditions at which the holdup in the central probe is recorded. As shown in figure 2, the triggers are made of two quarters of a ring and face each other vertically at a given cross-section of the pipe. As for the holdup probe, the trigger probes are carefully grooved into the pipe section so that the conducting elements are flush with the pipe wall. The overall distance between the triggers is about 8 pipe diameters.

The triggers and holdup probe operate in a system of simultaneous data acquisition and analysis. The online data analysis is controlled by the values of voltage signals from the triggers. Logical flags are associated with the triggers, with flag values set to one (high) when the output

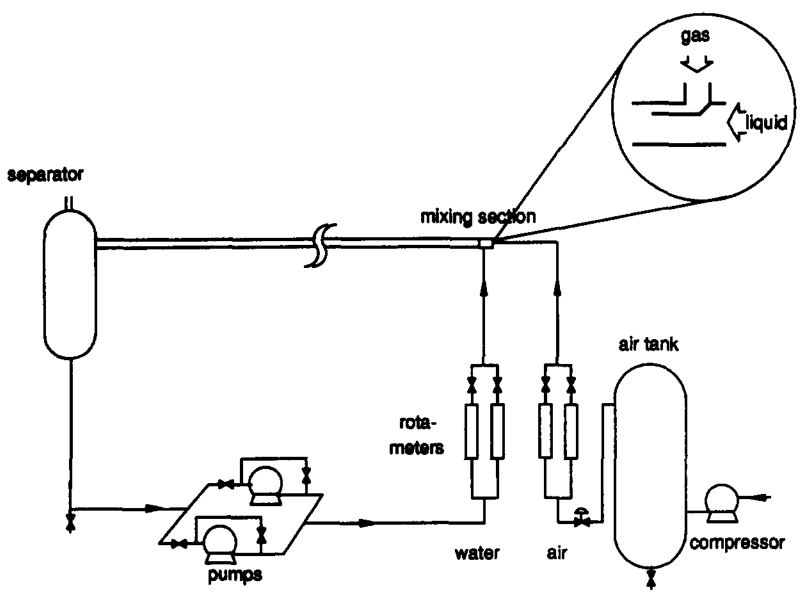

Figure 1. Experimental setup for slug flow experiments. Test section: 17 m, 53.90 mm i.d.

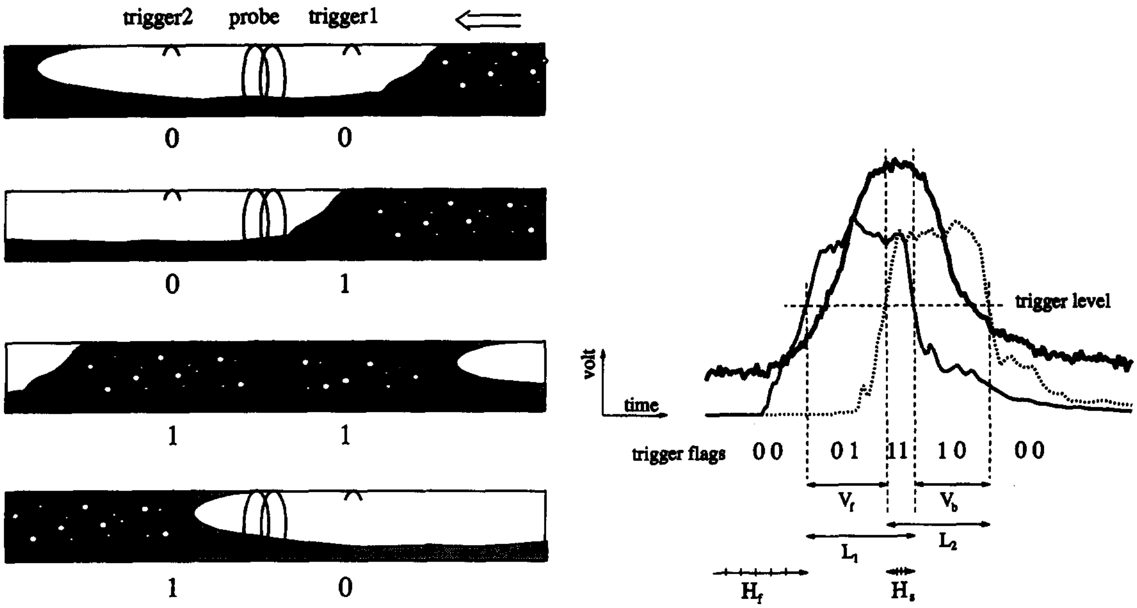

Figure 2. Trigger flag values for a slug that passes the measuring station and output signals from the holdup and the trigger probes.

voltage exceeds a prescribed value and to zero (low) when the voltage signal is below this value. The sequence of flag values when a slug is passing through the measuring station is shown in figure 2, together with examples of the probe signals that are recorded and analysed by the system.

The discrimination level indicated in the figure defines the flag values. In figure 2 this level is a line, but in the presence of noise this line can be split into a band (noise rejection band). In this way, the potential problem that small fluctuations modify flag values is eliminated. It should also be noticed that holdup disturbances shorter than the distance between the triggers will not be considered in the analysis.

Figure 2 also shows the regions of the time traces where the slug parameters are computed: the front and tail velocities (U_t, U_b) are computed from the transit time of the front and the tail between the triggers; the slug length L_s is computed for both triggers from the transit time of the slug and the mean value of the front and tail velocity; the final length of the slug is taken as the mean value from the two triggers.

The mean liquid holdup in the slugs can be computed either as the mean value relative to the entire slug (full averaging), or as the mean value relative to a limited number of data samples (reduced averaging). In both cases, the mean holdup is only computed when both logical flags are up, but in the second case a sequence of mean values is computed and the user can choose which value should be stored. In most cases, the differences between the holdup in the central region and in the region with maximum holdup were small.

The program is written in Assembler to obtain a high sampling rate and accurate control of the sampling frequency. Each cycle of data sampling and analysis involves the same number of operations. The system has been carefully calibrated with a signal generator and gives a sampling rate per channel of 6.700 kHz.

As input to the online program the following parameters must be given: total acquisition time; trigger level; trigger band value; and input for full or reduced averaging for the slug holdup. The determination of these input values is done with the aid of an oscilloscope. It was ensured on the oscilloscope that the discrimination band was low enough for the system to capture all phenomena that blocked the pipe.

The number of samples for the mean holdup computations was estimated to correspond to 1–2 diameters of length based on the front velocity. The acquisition time was chosen to give a total number of recorded slugs between 100 and 500.

In addition to the online data recording, the local pressure in the pipe was measured with two absolute pressure transducers. One was positioned at the measuring station and the other 2 m upstream. In a distinct set of experiments, the local void distribution in the slug body has been determined by a fibreglass optical probe. The tip of this probe was 0.7 mm in diameter and the characteristics of the probe are described in detail by Annunziato (1986).

Since raw data are lost and only computed parameters are saved, the system was carefully tested and compared with other experimental methods. In particular, the computational method was checked with a separate program for a time trace analysis of the triggers and the central probe. This has proved an efficient way of testing the system, as the sensitivity analysis could be performed by software instead of conducting a large number of experiments.

The results relative to slug holdup measurements have been compared with the results obtained with a different time trace analysis. The probability density function of the complete holdup signal, including the stratified region between slugs, shows two peaks: a low holdup peak relative to the mean holdup in the stratified region; and a high holdup peak relative to the mean slug holdup. The online results agree very well with the peak values from this analysis at low flow rates. At high flow rates, probability density functions of the complete signal are not accurate, since the peaks in the histogram are no longer well-defined, due to the presence of waves and developing slugs, and since the limited computer memory allows only a few slugs to be recorded when the sampling rate is high. For these reasons, the present method of analysis appears more accurate and efficient than the use of the probability density distribution of the entire holdup time trace.

3. RESULTS

3.1. *Developing slugs*

The system developed for online data analysis allows the acquisition and processing of large samples. This gives excellent reproducibility of the mean slug characteristics (typically better than 2%).

A special phenomenon that has been observed and studied with the present experimental method is the occurrence of two types of slugs: the regular slugs and a different type of slugs, shorter and more aerated, which can be described as non-developed slugs. These slugs block the entire pipe cross-section and propagate at approximately the same velocity as regular slugs. They can easily be distinguished from waves, as waves only occasionally block the pipe and travel at a lower velocity. Eventually, non-developed slugs may decay, but the present observations suggest that, on the average, they evolve into regular slugs. For this reason it seems appropriate to call these slugs developing slugs.

Developing slugs are clearly observed as a second peak in the statistical distribution of the slug holdup. The presence of this peak allows us to distinguish developing from regular slugs in the analysis of slug characteristics. The second peak emerges in two cases: when the gas velocity is increased or when the measuring station is moved upstream, closer to the region in the pipe where

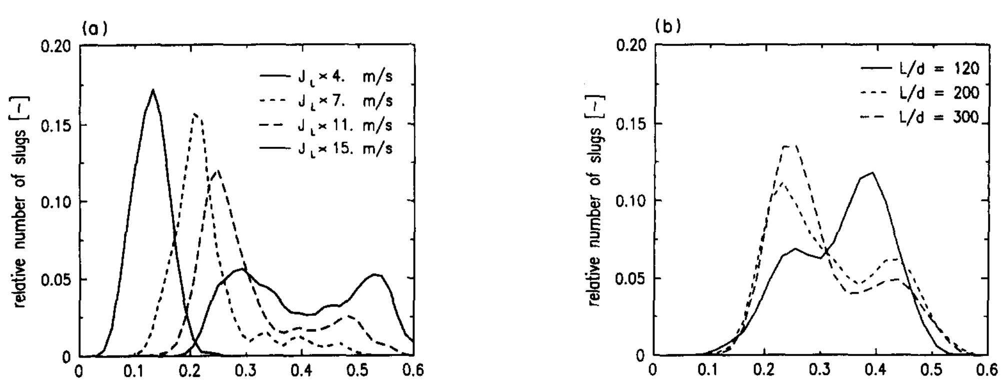

Figure 3. Statistical distributions of the void fraction in slugs. (a) Increasing gas velocities; $L/d = 300$, $d = 5$ cm, $J_L = 1.2$ m/s. (b) Increasing distance from the pipe inlet; $J_G = 9.3$ m/s, $J_L = 0.6$ m/s, $d = 5$ cm.

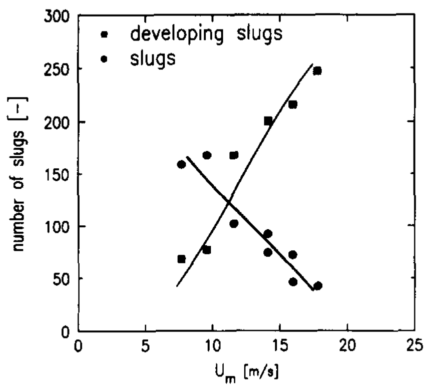

Figure 4. Number of slugs and developing slugs for increasing gas velocity; $J_L = 0.6$ m/s, $d = 5$ cm, $L/d = 300$.

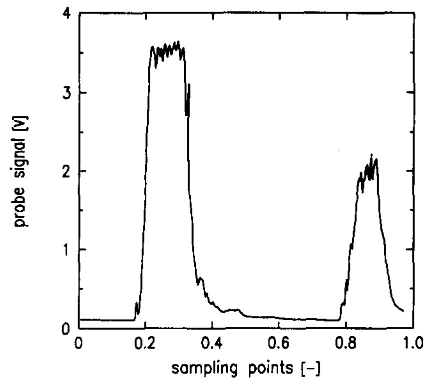

Figure 5. Time trace from the conductance probe showing a slug and a developing slug; $J_L = 1.2$ m/s, $J_G = 9.0$ m/s, $d = 5$ cm.

the slugs are formed. Figure 3 shows examples of histograms for the two cases and figure 4 shows the corresponding number of slugs and developing slugs.

Several characteristics of developing slugs have been observed:

- *They are highly aerated.* An example of a time trace representing a developing and a regular slug is shown in figure 5.

  Figure 6 shows the mean void fraction for slugs and developing slugs as a function of the superficial mixture velocity.

  Single phenomena have been investigated with the optical probe for local void fraction measurements. It was observed that developing slugs can easily be distinguished from waves as gas bubbles and a continuous liquid phase could be detected over the whole pipe cross-section. These slugs are more aerated than regular slugs at all positions, both close to the top and the bottom of the pipe.
- *Developing slugs are shorter.* Although statistical distributions of the slug length show a single peak, discrimination of the slugs according to the slug holdup reveals that developing slugs are shorter. The results are shown in figure 7.
- *Developing slugs evolve into regular slugs.* After an initial formation zone, the total slug frequency is fairly constant along the length of the pipe, see figure 8. This was also confirmed in experiments where the pipe length was doubled; the frequency of developing slugs at the outlet decreased but the frequency of all phenomena was about constant. On average, developing slugs do not decay or coalesce with other slugs, but they seem to grow and transform into regular slugs.
- *Developing slugs travel at the same velocity as regular slugs*, as shown in figure 9.

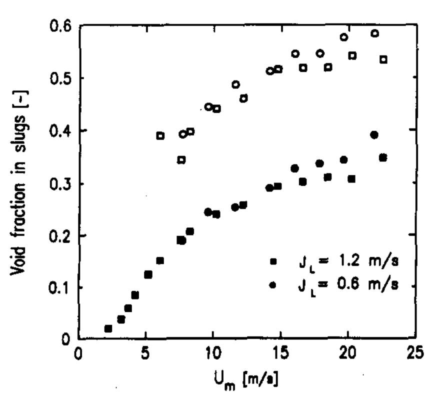

Figure 6. Mean void fractions in slugs (filled symbols) and developing slugs (open symbols); $d = 5$ cm.

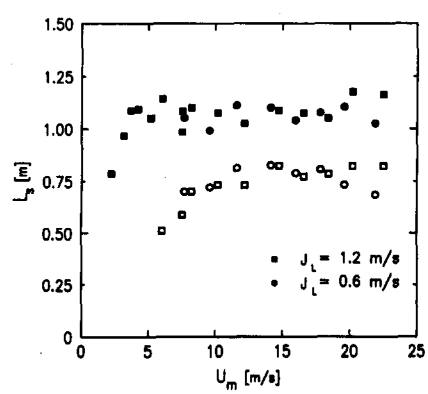

Figure 7. Mean slug lengths for slugs (filled symbols) and developing slugs (open symbols), $d = 5$ cm.

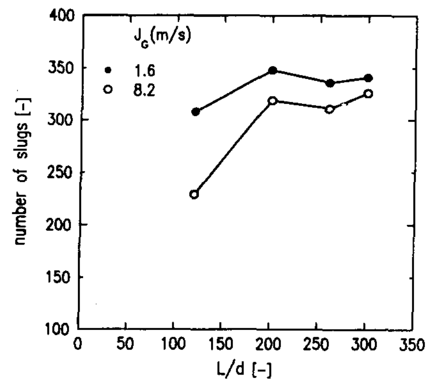

Figure 8. Number of slugs at various locations of the measuring station. Acquisition time 12 min; $J_L = 0.6$ m/s, $d = 5$ cm.

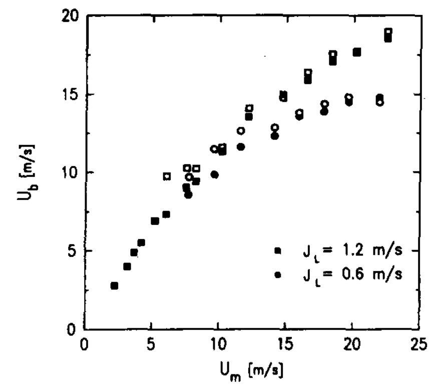

Figure 9. Mean slug bubble velocities for slugs (filled symbols) and developing slugs (open symbols); $d = 5$ cm.

- *Pressure recordings of developing slugs show the same characteristics as those of regular slugs.* The pressure signal from a regular slug typically consists of three regions: an initial sharp rise in the pressure corresponding to the acceleration of the film ahead of the slug to the liquid velocity in the slug; a moderate increase in the pressure due to the frictional pressure drop along the slug body; and, finally, a fairly constant pressure in the slug bubble that follows the slug.

  To give an example, in an experiment with $J_G = 1.1$ m/s and $J_L = 1.2$ m/s the mean value of the pressure peak after a developing slug was 19% less than the value relative to regular slugs. The somewhat smaller pressure may be related to the different length and void in the two cases. The pressure response of a wave is negligible when compared with that of a slug.

3.2. *Developing length for slug flow*

3.2.1. Pipe length. Slug flow can be described as a sequence of identical slug units (Dukler & Hubbard 1975). However, the presence of developing slugs is a clear indication that two qualitatively different types of slugs may coexist in the pipe. This experimental observation appears to be related to pipe length; it is then necessary to verify if the flow is fully developed at the measuring station, before the data obtained can be used to develop or verify closure relations. Great care is needed, in particular, in the measurement of the mean void in the slugs, as the main difference between regular slugs and developing slugs concerns this parameter.

The existence of fully developed slug flow in pipes operating close to atmospheric conditions is a matter of definition, as gas expansion due to pressure losses along the pipe will cause an increase in the mixture velocity. Nevertheless, it seems possible to distinguish between an entrance region, in which the slugs are formed, and a quasi-developed region, in which the flow characteristics of a slug unit change slowly along the pipe and mostly depend on the local value of the gas velocity rather than on the previous history of the flow.

In the present experiments, in order to avoid the recording of developing slugs, the measurements must be taken sufficiently far from the inlet, or the gas flow rate must be sufficiently low. In figure 10 the conditions at which only one peak is present in the histograms of the slug holdup are shown. These are the flow rates and pipe lengths at which developing slugs are not recorded. For example, an inspection of the histogram for $J_L = 0.6$ m/s and $J_G = 6.0$ m/s indicates that a tail in the histogram corresponding to the presence of developing slugs vanishes when the pipe length is doubled from 300 to 600 diameters.

A well-defined statistical distribution of the slug holdup, with only one peak, may be regarded as a necessary condition for developed slug flow. It is not a sufficient condition, it only indicates the pipe length at which all slugs have similar characteristics at given flow rates.

On the other hand, it has been reported (Scott *et al.* 1987) that in long pipelines the slug frequency decreases and the mean slug length increases. These slow changes of slug frequency and length should be considered as compatible with the definition of quasi-developed slug flow.

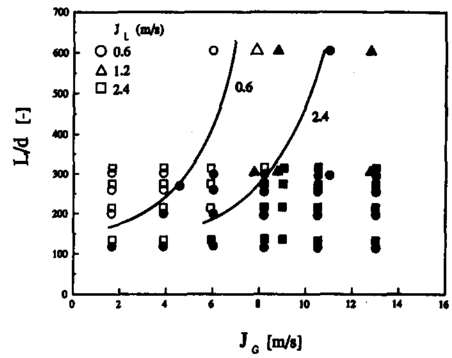

Figure 10. Pipe length in number of diameters where the statistical distributions of the slug holdup show only one peak (open symbols).

From figure 10, it is easy to detect an appreciable effect of the liquid flow rate on the developing length for slug flow. As can be seen, at low liquid flows, it takes a longer distance to obtain developed flow.

3.2.2. Inlet conditions. In order to assess the effect of inlet conditions on main slug parameters, the mixing section was inverted (see figure 1). Two series of experiments with 10 gas velocities in the range $J_G = 0.5$ to 10 m/s and $J_L = 1.2$ m/s were performed with the gas being injected at the top and the bottom of the pipe. With the gas on the bottom the frequency was 3–6% lower and the slug length 5–10% higher than with the gas on the top. The holdup in the slugs and the velocities were the same for both inlet conditions (relative mean differences were generally <2%). Although inlet conditions are important for the transition to slug flow (Bendiksen & Malnes 1987), the flow structure is not greatly affected by the geometry of the mixing section for velocities well inside the slug flow region.

3.3. Statistical distributions

In the analysis of the experimental results, regular slugs were distinguished from developing slugs by means of the statistical distributions of the slug holdup, as indicated in the examples shown in figure 3. The shape of the statistical distributions of measured slug parameters has been determined only in the velocity range of developed slug flow.

3.3.1. Slug length. The statistical distribution of the slug length appears to be well-fitted by a lognormal distribution, as also noted by Brill *et al.* (1981) and recently by Sæther *et al.* (1990). Figure 11 shows that the tail in the distribution corresponding to long slugs is better fitted with a lognormal rather than with a normal distribution.

3.3.2. Slug void fraction. The distribution of the slug void fraction is often lognormal, as in the case shown in figure 11.

For small void fractions, the difference between the lognormal and the normal distribution is small. At higher gas flow rates and higher void fractions the shorter and more aerated developing slugs emerge. In acquisitions where short slugs were discriminated, the slug void fraction tended to be normally distributed.

3.3.3. Slug bubble velocities. At moderate superficial gas velocities the slug bubble velocity is normally distributed, as shown in figure 11. The slug velocity fluctuates mainly because the film holdup ahead of the slug varies. In addition, a decompression wave propagates through the pipe whenever a slug enters into the separator. In addition to the physical spread in the velocity, fluctuations in the front and tail of the slug will contribute to the scatter in the measured values when the trigger distance is small and the slug velocity large. An experiment with velocity measurements over 40 diameters gave less scatter, but equal mean values compared with the online results with a trigger distance of 8 diameters (3% difference with $J_G = 11$ m/s and $J_L = 1.2$ m/s). Slug bubble velocities were then seen to be normally distributed.

3.4. Statistical correlations

The measured slug parameters H_s, L_s and U_b fluctuate within characteristic spreads due to the unstable nature of the flow. An interesting question is whether these parameters for each slug are statistically related to each other. Is there, for example, a tendency for long slugs to have particularly high or low holdups or velocities?

A statistical measure of the dependency between two stochastic variables x and y is the covariance, $\mathrm{covar}(x, y)$, defined as

$$\mathrm{covar}(x, y) = \int_{-\infty}^{+\infty} [p_x(x) - \mu_x][p_y(y) - \mu_y]\,\mathrm{d}x\,\mathrm{d}y, \qquad [1]$$

where μ is the expected value and p is the probability density. The correlation coefficient $R(x, y)$ is defined as the covariance normalized with respect to the standard deviations σ_x and σ_y:

$$R(x, y) = \frac{\mathrm{covar}(x, y)}{\sigma_x \sigma_y}. \qquad [2]$$

If the variables are statistically independent the correlation coefficient is zero.

The empirical correlation coefficient is used as a measure of the linear dependency between two measured variables:

$$r(x, y) = \frac{1}{n} \frac{\sum_{i=1}^{n} (x_i - \bar{x})(y_i - \bar{y})}{s_{xx} s_{yy}} \qquad [3]$$

with the empirical standard deviations:

$$s_{xx} = \sqrt{\frac{1}{n} \sum_{i=1}^{n} (x_i - \bar{x})^2}. \qquad [4]$$

The empirical correlation coefficients have been computed for several pairs of measured slug parameters. In these computations, developing slugs were to a large degree avoided by excluding the phenomena relative to the high void fraction peak in the histograms.

Figure 12 shows the empirical correlation coefficient between the holdup in the slug and the slug length, $r(H_s, L_s)$. These results indicate that at intermediate mixture velocities longer slugs have a tendency to have higher holdup. This may correspond to the experimental observations of a small decrease of the void fraction along the slug.

The correlation coefficient between the slug length and the slug bubble velocity, $r(L_s, U_b)$, were small, with values <0.2. This means that slugs are in general long enough to develop a steady velocity profile at the tail. The following slug bubbles then, on an average, see the same upstream conditions, independently of the slug length.

The characteristic slug period and the slug frequency may be obtained from the autocorrelation function and the power spectrum of holdup time traces. The autocorrelation of a holdup time trace represents a peak corresponding to the slug period and a similar peak in the power spectrum will correspond to the slug frequency.

Similarly, if there is a pattern in a sequence of slug lengths it will emerge as peaks in the autocorrelation function and the power spectrum of the sequence. On the other hand, if the slugs are independent, the functions will be flat.

The autocorrelation function was computed for sequences of slug lengths and slug holdups in a number of cases. In a sequence of m slugs the autocorrelation was computed from

$$G_n = \frac{1}{m} \sum_{k=-m/2}^{m/2} x_k x_{k+n}, \qquad [5]$$

where x is the length or the holdup. In all cases the spectra were flat and the autocorrelation close to zero, as for the example in figure 13.

At high gas velocity, a conditional probability density function was also constructed. Slugs with void fraction in the range 0.27–0.3 were marked and the probability density distributions of the

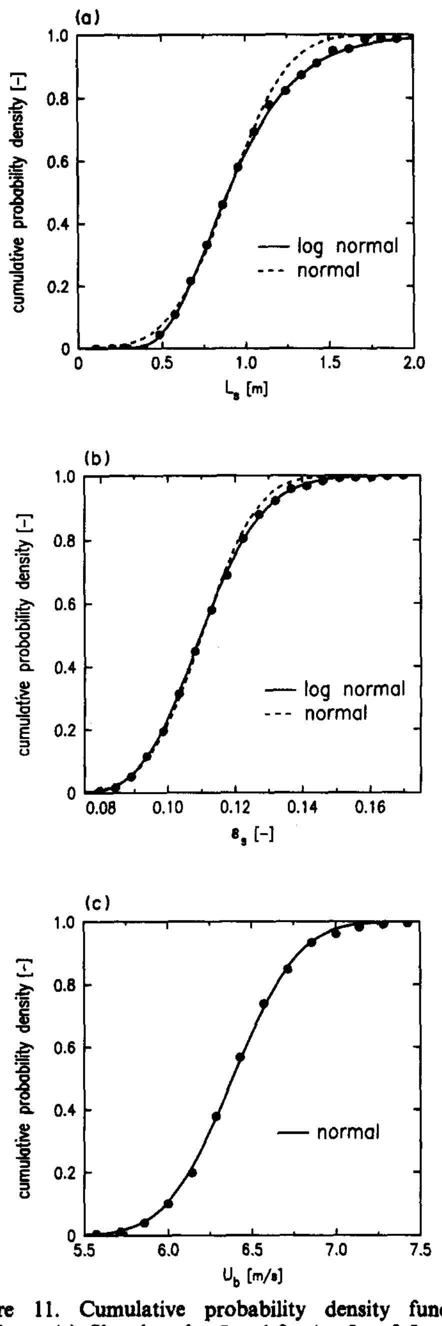

Figure 11. Cumulative probability density functions; $d = 5$ cm. (a) Slug length; $J_L = 1.2$ m/s, $J_G = 2.5$ m/s. (b) Slug void fraction; $J_L = 2.4$ m/s, $J_G = 3.04$ m/s. (c) Slug bubble velocity; $J_L = 2.4$ m/s, $J_G = 3.04$ m/s.

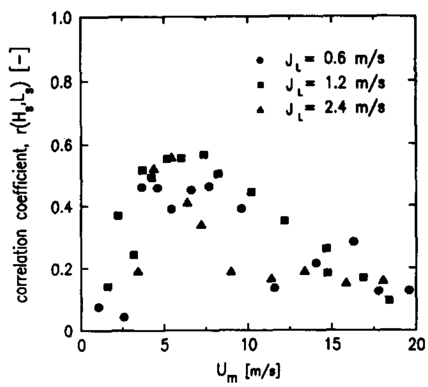

Figure 12. Empirical correlation coefficient between slug length and holdup; $d = 5$ cm.

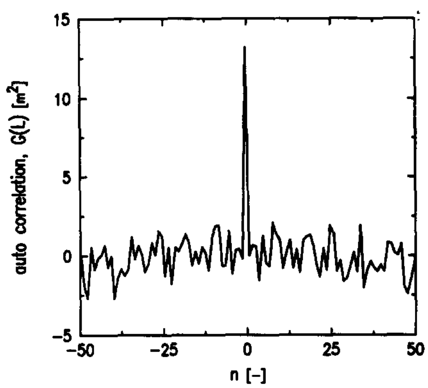

Figure 13. Autocorrelation function of slug length; $J_L = 2.4$ m/s, $J_G = 3.5$ m/s, $d = 5$ cm.

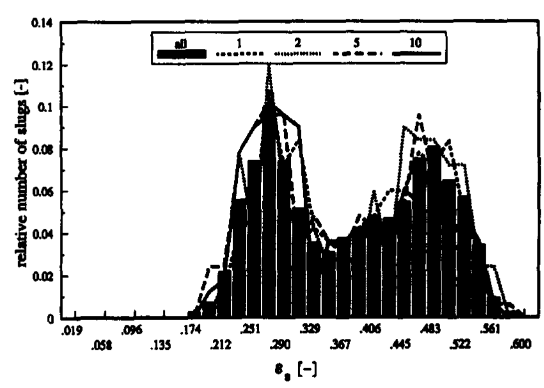

Figure 14. Conditional probability density functions for the void fraction in slugs; $J_L = 0.06$ m/s, $J_G = 13.0$ m/s, $d = 5$ cm, $L/d = 600$. The lines are the distributions of the first, second, fifth and tenth following slugs with void fraction in the range 0.27–0.3.

following first, second, fifth and tenth slug were computed. As shown in figure 14, the distributions are about equal to the distribution of all slugs. If a slug with a specific void fraction is detected, the following slugs will not have a characteristic different void fraction.

In conclusion, there seems to be no evident pattern in the sequence of slugs, the characteristics of one slug have no clear influence on the characteristics of other slugs.

These results are not entirely consisent with the work of Sæther *et al.* (1990), where the methods of fractal statistics have been used to quantify the dependency between slugs. It was seen that the degree of dependency between slug lengths increased with increasing gas velocity. When the present data was analysed with the same method (rescaled range analysis) no dependency was found.

At high gas velocities there is, on average, only one slug present in the pipe at a time, and it may be expected that the characteristics of one slug are independent of the preceding slug that left the pipe. The present result, that the slugs occur independently also at high slug frequencies, may be more surprising. Since this is an issue of practical interest, it should be investigated further in future research.

3.5. Standard deviations

Figure 15 shows the standard deviations from the mean for the slug parameters. The standard deviations are obtained from acquisitions where developing slugs have been discriminated.

The spread in the slug void fraction increases with increasing flow rate, and there is a slight trend for the standard deviations to reduce with increasing liquid flow rate.

At high flow rates the spread in the slug length will depend on the trigger discrimination level, a low level will result in large mean slug lengths with large standard deviations. The decreasing spread in the slug length at high velocities is probably an effect of the increasing trigger level that was used to discriminate waves and developing slugs. The relative spread in the measured slug velocities (mean of the front and back velocities) is quite high and increases with increasing flow rate. At high mixture velocities the measuring uncertainties are appreciable since the velocities are determined over a short distance (8 pipe diameters). The characteristic time for fluctuations in the front and tail of the slug is then not negligible compared with the transit time of the slug between the stations.

4. MEAN SLUG CHARACTERISTICS

4.1. Void fraction in the slug

In the evaluation of mean slug characteristics developing slugs are not considered. Regular slugs are selected by means of the probability density function of the void fraction in the slugs. When these functions are bimodal, only slugs relative to the low void peak are considered in the analysis. The void fraction data shown in figure 16 are the mean values for regular slugs.

From figure 16 it is seen that the superficial mixture velocity must exceed a minimum threshold value before the gas can be entrained into the slug body. The void fraction is mainly a function of the mixture velocity, but a weaker effect of the liquid flow rate is also observed. In particular, at increasing liquid flows, the mixture velocity at the onset of gas entrainment in the slugs also increases. Moreover, in the range of low mixture velocities, the void is larger for low liquid flows. The diameter effect, if any, is small. Measurements with 5 and 9 cm i.d. pipes show very similar results.

A correlation that is often used as a closure relation in slug flow models is the empirical relation by Gregory *et al.* (1978). This is based on experiments with oil/air for which the void is much higher than in water/air systems. The semiempirical correlation of Andreussi & Bendiksen (1989) takes into account fluid property effects and is mainly based on water/air experiments. The two correlations are shown in figure 16. At large mixture velocities, the present measurements are lower than the previous data on which the correlation by Andreussi & Bendiksen is based. This is probably due to a better discrimination of developing slugs in the present work.

4.2. Slug length

The slug length is determined from the residence time of a slug at the trigger probes and the slug velocity. As the holdup time trace of a slug has a finite slope at the front and the tail, the measured length of a slug depends on the discrimination level. Figure 17 shows the length vs the superficial mixture velocity.

The extremes of the error bars are the values obtained with two different discrimination levels, 1/3 and 2/3 of the mean voltage signal taken in the central part of the slugs.

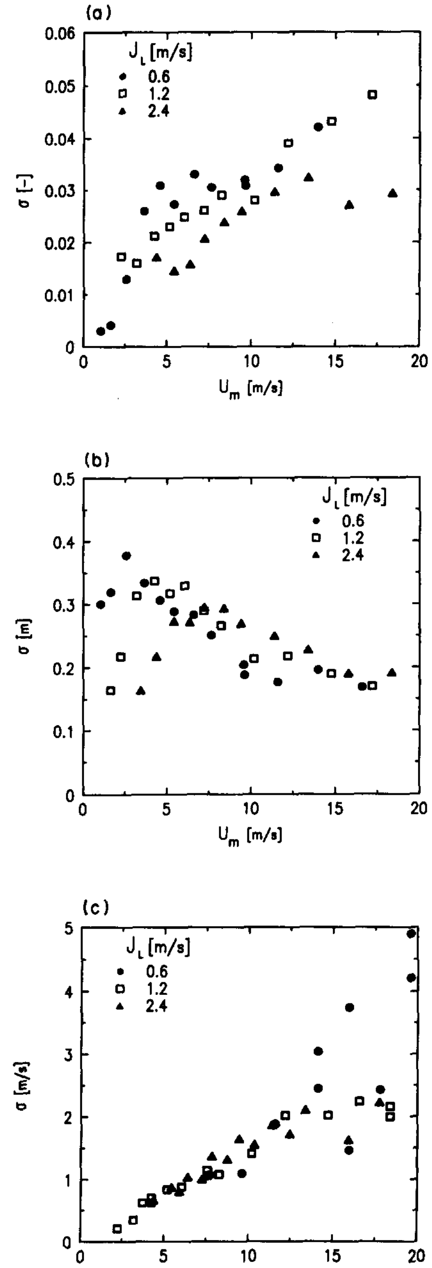

Figure 15. Standard deviations from the mean slug parameter values; $d = 5$ cm. (a) Void fraction in the slug. (b) Slug length. (c) Slug velocity.

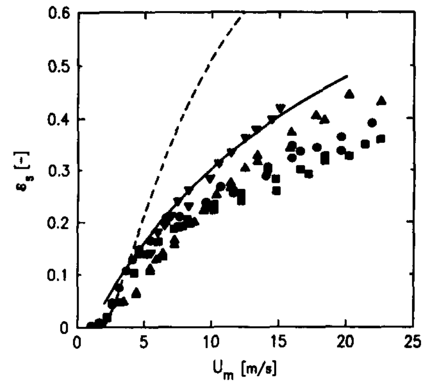

Figure 16. Mean void fraction in the slugs with two correlations: ---, Gregory *et al.* (1978) (air/oil); ——, Andreussi & Bendiksen (1989). $d = 5$ cm, J_L (m/s): ● = 0.6, ■ = 1.2, ▲ = 2.4, ▼ = 3.5.

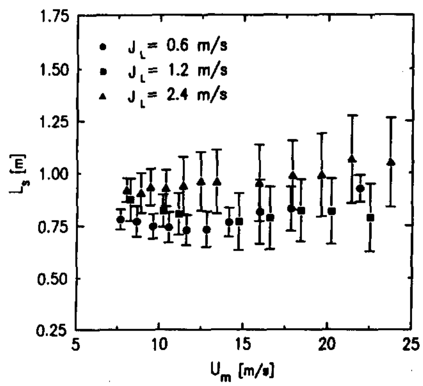

Figure 17. Mean slug length. The error bars represent the values obtained with a trigger level of 1/3 and 2/3 from the mean top value of the slug holdup signals; $d = 5$ cm.

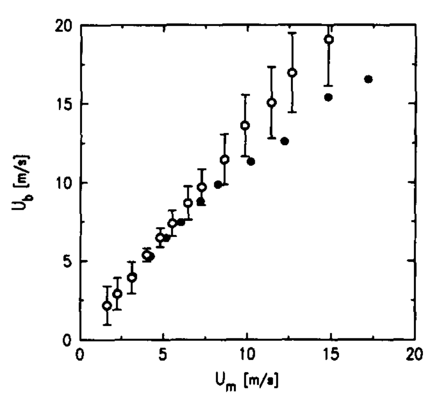

Figure 18. Mean slug bubble velocity; $J_L = 1.2$ m/s, $d = 5$ cm. Open symbols are relative to *in situ* U_m, filed symbols are relative to U_m at standard conditions.

Slug lengths were seen to be quite constant for a large range of velocities. These lengths are:

$$\frac{L_s}{d} = 15 \text{ to } 20, \; 5\,\text{cm i.d.} \quad \text{and} \quad \frac{L_s}{d} = 12 \text{ to } 16, \; 9\,\text{cm i.d.}$$

A fairly constant slug length, in the same range as the present values, has also been reported by other authors (Dukler & Hubbard 1975; Nicholson *et al.* 1978; Ferre 1981; Andreussi & Bendiksen 1989).

4.3. Slug bubble velocity

The relation obtained by Nicklin *et al.* (1962) for the velocity of large bubbles in a stagnant or flowing liquid has been generalized to the bubble velocity in slug flow at all inclinations:

$$U_b = C_0 U_{Ls} + v_0. \qquad [6]$$

The interpretation of [6] is that the bubble moves with a velocity v_0 relative to the centreline velocity of the liquid ahead of the bubble. This gives approx. $C_0 = 1.2$ for turbulent velocity profiles. For high velocities in horizontal flow $v_0 = 0$.

Conservation of volume at all pipe locations in the slug unit gives, for incompressible flow:

$$J_L + J_G = \varepsilon_s U_{Gs} + (1 - \varepsilon_s) U_{Ls}. \qquad [7]$$

The slip ratio between the mean phase velocities in the slug is defined as

$$S = \frac{U_{Gs}}{U_{Ls}}. \qquad [8]$$

From [8] and [9], we obtain

$$U_{Ls} = \frac{U_m}{1 - (S - 1)\varepsilon_s}. \qquad [9]$$

When $S = 1$ or $\varepsilon_s = 0$, the mean phase velocities in the slug are equal to the superficial mixture velocity,

$$U_{Ls} = U_m = J_L + J_G. \qquad [10]$$

In evaluating C_0, U_m usually replaces U_{Ls} in [6].

Figure 18 shows an example of slug bubble velocities for a series of experiments at $J_L = 1.2$ m/s. The ordinate is the mixture velocity at standard conditions, which corresponds to the volumetric flow rate per unit area at the pipe outlet. In order to obtain the mixture velocity at the measuring station, the gas velocities must be computed at the actual pressure.

The pressure along the slug bubble is fairly constant, so that the gas pressure in the bubble is equal to the peak value in the pressure signal taken at the measuring station. The mean superficial gas velocities were computed at the mean pressure relative to a large number of slugs.

The mean bubble velocity is plotted as a function of the local mixture velocity in figures 18 and 19. The error bars show the standard deviations from the mean values.

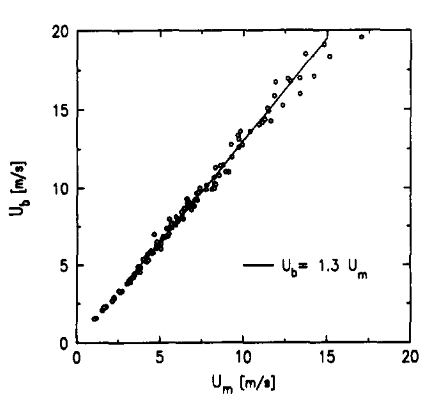

Figure 19. Mean slug bubble velocity vs *in situ* U_m; $d = 5.9$ cm.

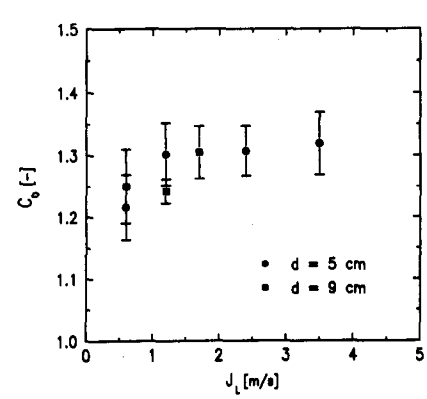

Figure 20. Mean values C_0 in the slug bubble relation [6]. Each point is the mean value for several gas velocities at constant liquid velocity. The error bars are the standard deviations from the mean.

The coefficient C_0 has been computed from these measurements and the measured values of C_0 in each series at constant liquid superficial velocity are given in figure 20.

The data points at low velocities were excluded from the computation of the mean value since accurate measurements of the propagation velocity of single bubbles (Bendiksen 1984) show the presence of a drift velocity in the low velocity range. This is also seen in the data of figure 19.

As other authors also report, C_0 values are somewhat higher than the ratio of the mean to the centreline velocity in turbulent flow [$C_0 = 1.35$ (Gregory & Scott 1969), $C_0 = 1.25$ to 1.28 (Dukler & Hubbard 1975), $C_0 = 1.02$ to 1.3 (Ferre 1981). Possible explanations are:

- The velocity profile at the tail of a slug is modified by the presence of bubbles in the slug. The local mean liquid velocity in front of the slug bubble may then not correspond to the centreline velocity in pure liquid flow at the same Reynolds number.

  Recent bubble velocity measurements in horizontal bubbly flow show appreciable changes in the velocity profiles with respect to the 1/7 power law for turbulent flow (Andreussi *et al.* 1990).
- There may be an appreciable slip between the mean phase velocities in the slug. The velocity ratio S may be different from unity and the liquid velocity in the slug will then differ from the mixture velocity. The experiments reported by Andreussi *et al.* (1990) confirm that in air/water bubbly flow U_L can be larger than U_m. It is then possible that $C_0 > 1.2$ in order to compensate the difference between U_m and U_{Ls}.
- With respect to an observer moving at the translational velocity of a slug there is a net gas flow through the slug body, given by

$$Q = (U_b - U_{Gs})\varepsilon_s. \qquad [11]$$

  A number of small bubbles in the slug may coalesce at the bubble nose and modify the displacement velocity of the bubble boundary.

The discrepancy between the present bubble velocities and the results from single bubble experiments is probably caused by combinations of these effects. In the present experiments, gas expansion effects complicate the determination of the local gas velocity. Therefore, the present results should be confirmed by experiments performed at high pressure.

5. CONCLUSIONS

An instrumentation for slug flow characterization has been developed in order to obtain statistically meaningful data on air/water slug flow for a wide range of gas and liquid superficial velocities. Simultaneous data acquisition and analysis allowed a large number of slugs to be recorded. This has given statistical information and mean values with very good reproducibility.

The main results have been:

Developing slugs

For short pipes or high gas velocities developing slugs were seen to be present in the pipe. These are shorter and more aerated than regular slugs and develop into slugs when travelling down the pipe.

Initial developing length for slug flow

The initial developing length for slug flow has been estimated from the conditions where no developing slugs are observed. This length increases with increasing gas velocity and decreases with increasing liquid velocity.

Statistical distributions

The slug length and in most cases the slug holdup were seen to be lognormally distributed. The slug bubble velocity is normally distributed. At low velocities, slug length and holdup are weakly correlated. No statistical relations between other slug parameters have been observed. The characteristics of one slug do not seem to influence the characteristics of following slugs.

Slug length

The slug length is fairly insensitive to the flow rates. Systematic errors in determining the slug length from holdup time traces can be appreciable at high flow rates.

Slug void fraction

The void fraction in the slugs is much smaller for water/air than for oil/air flow. A liquid flow rate effect is observed for the minimum mixture velocity at the onset of gas entrainment in the slugs. The diameter effect on the void is very weak.

Slug bubble velocity

The measured bubble velocities are somewhat higher than single bubble velocities in pure liquid flow. This may be due to a modification of the liquid velocity profile in the aerated slug compared with single-phase flow, to the slip between the phases in the slug, or to bubble coalescence at the nose of the slug bubble.

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REFERENCES

ANDREUSSI, P. & BENDIKSEN, K. 1989 An investigation of void fraction in liquid slugs for horizontal and inclined gas–liquid pipe flow. *Int. J. Multiphase Flow* **15**, 937–946.

ANDREUSSI, P., DI DONFRANCESCO, A. & MESSIA, M. 1988 An impedance method for the measurement of liquid hold-up in two-phase flow. *Int. J. Muliphase Flow* **14**, 777–787.

ANDREUSSI, P., PINTUS, S., NYDAL, O. J. & SANCHEZ SILVA, F. A. 1990 Measurement of the mean gas velocity in horizontal bubbly flow. Presented at the *ICHMT Semin. on Phase-interface Phenomena in Multiphase Flow*, Dubrovnik.

ANNUNZIATO, M. 1986 Catena di misura con sonde a fibra ottica per il rilievo della frazione di vuoto. ENEA Report NQDM 1TS4B 86093.

BARNEA, D. & BRAUNER, N. 1985 Holdup of the liquid slug in two-phase intermittent flow. *Int. J. Multiphase Flow* **11**, 43–49.

BENDIKSEN, K. H. 1984 An experimental investigation of the motion of the long bubbles in inclined tubes. *Int. J. Multiphase Flow* **10**, 467–483.

BENDIKSEN, K. H. & MALNES, D. 1987 Experimental data on inlet and outlet effects on the transition from stratified to slug flow in horizontal tubes. *Int. J. Multiphase Flow* **13**, 131–137.

BRILL, J. P., SCHMIDT, Z., COBERLY, W. A., HERRING, J. D. & MOORE, D. W. 1981 Analysis of two-phase tests in large-diameter flow lines in Prudhoe Bay Field. *SPE Jl* **1981**, 363–377.

DUKLER, A. E. & HUBBARD, M. G. 1975 A model for gas liquid slug flow in horizontal and near horizontal tubes. *Ind. Engng Chem. Fundam.* **14**, 337–347.

FERNANDES, R. C. 1981 Experimental and theoretical studies of isothermal upward gas–liquid flows in vertical tubes. Ph.D. Thesis, Univ. of Houston, TX.

FERRE, D. 1981 Ecoulments gaz-liquide a poches et a bouchons dans les conduites de section circulaire. These, Inst. National Polytech., Toulouse, France.

GREGORY, G. A. & SCOTT, D. S. 1969 Correlation of liquid slug velocity and frequency in horizontal cocurrent gas–liquid slug flow. *AIChE Jl* **15**, 833–835.

GREGORY, G. A., NICHOLSON, M. K. & AZIZ, K. 1978 Correlation of the liquid volume fraction in the slug for horizontal gas–liquid slug flow. *Int. J. Multiphase Flow* **4,** 33–39.

MALNES, D. 1983 Slug flow in vertical, horizontal and inclined pipes. Report IFE/KR/E-83/002, Inst. for Energy Technology, Kjeller, Norway.

NICHOLSON, M. K., AZIS, K. & GREGORY, G. A. 1978 Intermittent two phase flow in horizontal pipes: predictive models. *Can J. Chem. Engrs* **56.**

NICKLIN, D. J., WILKES, J. O. & DAVIDSON, J. F. 1962 Two-phase flow in vertical tubes. *Trans. Instn. Chem. Engrs* **40,** 61–68.

SAETHER, G., BENDIKSEN, K., MULLER, J. & FROLAND, E. 1990 The fractal statistics of liquid slug lengths. *Int. J. Multiphase Flow* **16,** 1117–1126.

SCOTT, S. L., SHOHAM, O. & BRILL, J. P. 1987 Modelling slug growth in large diameter pipes. In *Proc. 3rd Int. Conf. on Multi-phase Flow*, The Hague, The Netherlands, Paper B2.