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VELOCITY DISTRIBUTION IN HORIZONTAL SLUG FLOW

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Abstract—An experimental device for measurement of the velocity distribution in a two-phase slug is developed. Velocity profiles both in the film and the liquid slug besides velocity variation along the pipe bottom (at a distance of 1 mm) through the slug front are presented.

1. INTRODUCTION

Two-phase gas–liquid flow is a frequently occurring flow situation in many problem areas of practical importance. In most cases gas–liquid flow in conduits represents a much more complicated flow phenomena than single-phase flow; it may be due to unknown and variable space distribution of gas and liquid, phase change, change in flow regimes, large velocity fluctuations, etc. For a survey of the problem area, the reader is referred to the book by Wallis (1969). A large number of investigations have been performed in the field, most of them experimental. Many investigations have been concerned with measurements of flow regimes, pressure drops and void fraction ratios, Malinovsky (1975); Taitel *et al.* (1978); Spedding *et al.* (1980) and Gregory *et al.* (1978). For slug flow also slug frequencies, slug lengths and translation speed of the slugs have been measured, Dukler & Hubbard (1975); Gregory & Scott (1969) and Haywood & Richardson (1978).

In hydrocarbon production pipe lines where the oil–gas also contains corrosive agencies (H_2O, H_2S and CO_2), slug flow is found to represent severe safety risks, Eriksrud *et al.* (1982). One of the main reasons for carrying out the present study was to examine the relation between flow conditions and damages observed in oil–gas carrying pipe systems. For example it is believed that the large fluctuations in the wall shear stress may remove the protective corrosion products from the pipe wall and thus severe erosion–corrosion attacks may occur. The periodic liquid slugs may further cause vibrations in the pipe system and resonance may occur since often the slug frequency is of the same order of magnitude as the eigenfrequency of the pipe system (typically 1–10 Hz). Also temperature fluctuations on the pipe inner wall may initiate material fatigue cracks which combined with erosion–corrosion and vibrations may propagate through the pipe material. Models developed by Dukler & Hubbard (1975); Taitel & Dukler (1977) and Nicholson *et al.* (1978) make it possible to obtain average liquid velocities both in the slug and the film, pressure drops, length of film, length of slug and slug frequencies if the gas and liquid mass fluxes are known. These models seem to give acceptable results when compared to experimental data. However, the models cannot give the detailed velocity distribution throughout the liquid phase of a slug unit. This information is necessary not only to understand the basic hydrodynamics of slug flow and establish predictive models, but also to understand the relation between damages and flow.

The application of LDV in two-phase flow and especially for slug flow measurements, introduces technical difficulties due to large velocity differences between the fast moving liquid slug and the slowly moving liquid film, dispersed bubbles in the liquid phase and variation of the length of the slugs and the gas pockets separating the slugs. The main problem is to obtain velocity measurements from a well-defined position relative to the front of the slug. It is the objective of the present paper to describe an experimental method for detailed velocity measurements in slug flow. The method combines uses of LDV and optical two-phase probes. The experimental setup is used to measure the velocity distribution throughout a slug-flow unit in a 24 mm inner diameter horizontal tube of atmospheric pressure. The liquid phase is a refractive index matching fluid—a mixture of a mineral oil (Gravex) and kerosene (Shellsol K)—and the gas phase is nitrogen. In addition to the velocity distribution throughout a slug unit, results are also given for slug length, slug frequency and translation speed of the liquid slugs.

2. EXPERIMENTAL FACILITIES

2.1 *Two-phase flow loop*

The flow loop, see figure 1, is made of an acrylic pipe with inner diameter $d = 24$ mm. The liquid flow rate can be read on a rotameter and regulated by two valves, one in series with the flow loop and one in a by-pass line. Nitrogen gas from a gas bottle is injected after the liquid rotameter. The gas flow rate is measured by a rotameter. The gas pressure at the rotameter inlet is measured by a pressure transducer and can be regulated by the manometer valve at the gas bottle. The gas flow rate is regulated by a valve immediately after the rotameter.

The temperature of the liquid is kept constant applying a tap-water cooling system.

The LDV test section is 400 mm long and mounted near the end of the flow-loop. The inlet to the test section is about 20 m (a 10 m long horizontal flexible tube followed by a bend of length 3 m and a 7 m long straight acrylic pipe, figure 1. The LDV-test section has been machined from a rectangular solid piece of acrylic plastic.

It was found necessary to use a liquid with the same index of refraction as the acrylic plastic:

—To obtain a linear relationship between a movement of the transmitting optics and the measurement volume.

—To avoid ambiguity in the relation between Doppler frequency and tracer particle velocity.

—To avoid strong reflections from the pipe walls.

A suitable liquid was found to be a mixture of mineral oil having an index of refraction higher than the acrylic plastic and a kerosene having an index of refraction lower than the acrylic plastic.

Density of the liquid $\rho_L = 800\ \mathrm{kg/m^3}$ and the gas $\rho_G = 1.14\ \mathrm{kg/m^3}$. Kinematic viscosity of the liquid $\nu_L = 15 \cdot 10^{-6}\ \mathrm{m^2/s}$ and the gas $\nu_G = 1{\cdot}57 \cdot 10^{-5}\ \mathrm{m^2/s}$.

2.2 *Method for macroscopic characterization of the slug flow*

Two optical probes were mounted in the top of the pipe at a distance $\Delta 1 = 400$ mm from each other (figure 2a). The probes together with their associated conditioning electronics provide a logical signal indicating whether a liquid- or gaseous phase is present at the probe tip. A high signal (1) indicates gas while a low signal (0) indicates liquid (figure 2b). The probe signals were processed by a Hewlett Packard Structural Dynamics Analyzer, Model 5423A. by performing different kinds of statistical analysis of the signals, various macroscopic parameters of the slug flow could be evaluated.

The slug frequency, $f = 1/T_u$, is found from the autospectra function of one probe signal. From the crosscorrelation of the two probe signals the translation speed, V_T, of the slugs can be found, and by integrating one probe signal the average time liquid and gas is present at the probe tip can be obtained. from this the length of a slug unit (liquid slug + gas pocket), l_u, and the length of the liquid slug, l_s, are found.

To obtain representative statistical values for the parameters mentioned above, measurements were performed till the statistical distribution reached a stable shape. Normally this corresponded to a recording time of about 5 min.

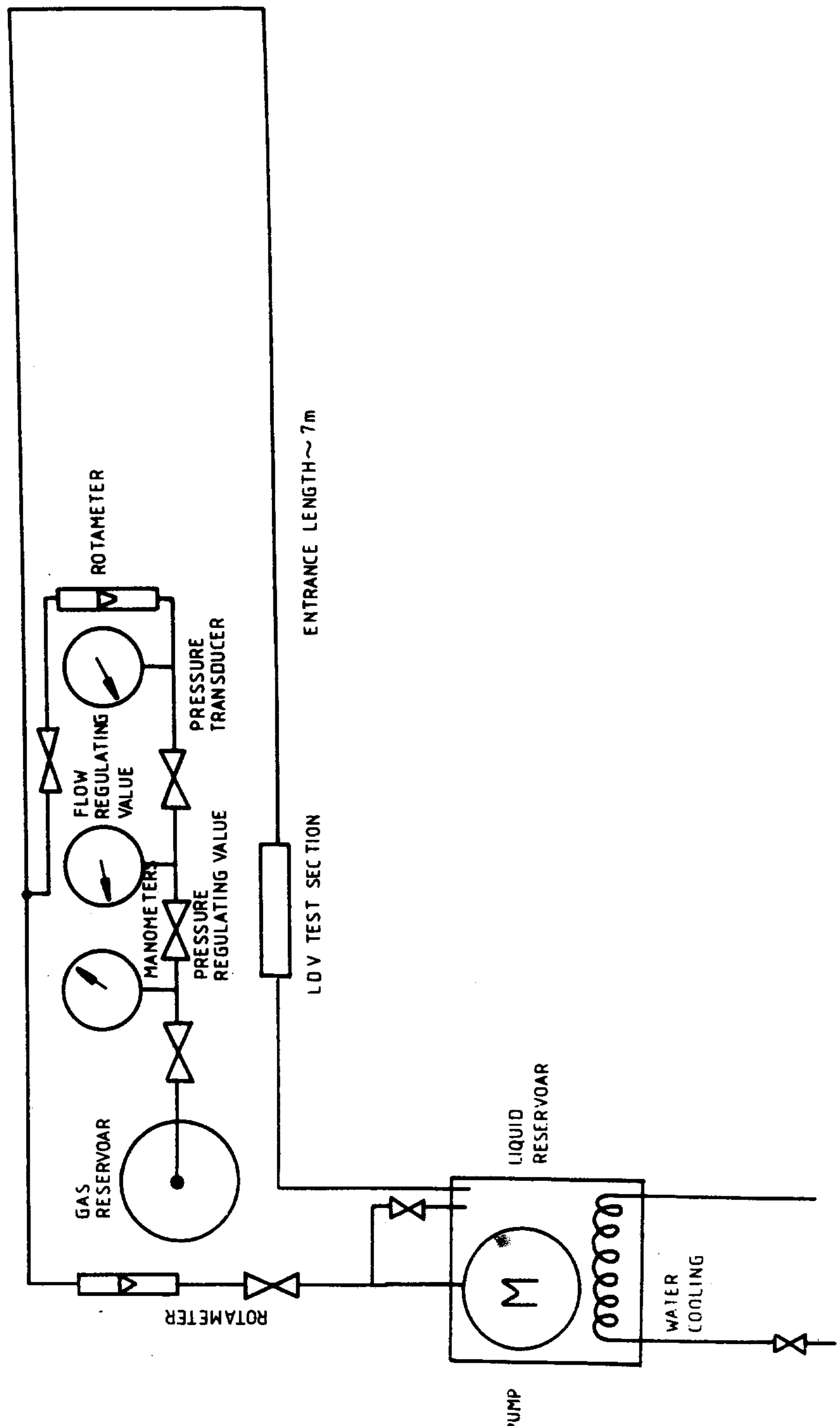

Figure 1. Flow loop.

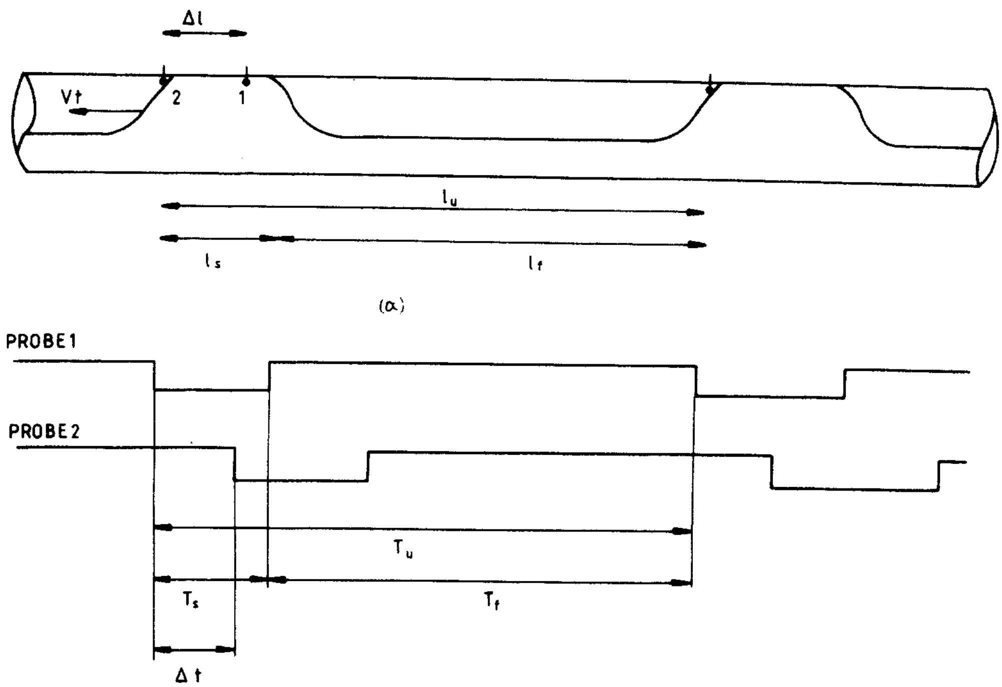

Figure 2. (a) Slug flow with optical probes. (b) Signals from optical probes.

2.3 *LDV-system for conditioned measurements of local velocity distribution in slug flow*

For a description of the LDV-technique in general, the reader is referred to the book by Durst *et al.* (1976) or Drain (1980). Here, only the problems related to LDV-measurements in a slug flow will be discussed. The liquid phase of the slug flow will contain tracer particles as well as gas bubbles. Only the tracer particles can be assumed to follow the liquid flow. Whereas the bubbles spread much light in the backwards direction, the tracer particles scatter most light in the forward direction. Therefore, to obtain information about the liquid velocity, the receiving optics was mounted in the forward scatter mode. This corresponds to the setup used by Ohba (1980) in his two-phase flow experiments.

The basic layout of the LDV-system is shown in figure 3. The processing of the LDV-signals is based on a transient recorder in conjunction with a minicomputer. As the velocity in the measurement volume will vary due to the quasi-periodic nature of the slug flow, it is necessary to relate the LDV-measurements to the actual part of the slug where they are obtained. An optical miniature two-phase probe is used for this purpose.

The filtered LDV-signal is connected to a gate that will open when the probe signal has a negative transition. This corresponds to a change from gas to liquid phase at the probe tip. The gate will then stay open for a preselected time, in this case 10 ms, and any LDV-signals during this time interval will be let through to the storage electronics. To ensure that the negative transition of the probe signal corresponds to the front of a slug, the gate will open if the probe signal has been continuously high during a second preselected time, i.e. 100 ms. Thus, bubbles within the slug triggering the optical probe will not open the gate.

Measurements can thus be performed in any part of the slug relative to the slug front by physically moving the measurement volume relative to the optical probe.

It was found that with increasing gas flow rate, the number of gas bubbles suspended in the liquid phase increased markedly, making the liquid phase more or less opaque. It was difficult to obtain processable LDV-signals under such conditions, especially in the central part of the pipe where the laser light had to pass through the full diameter. The

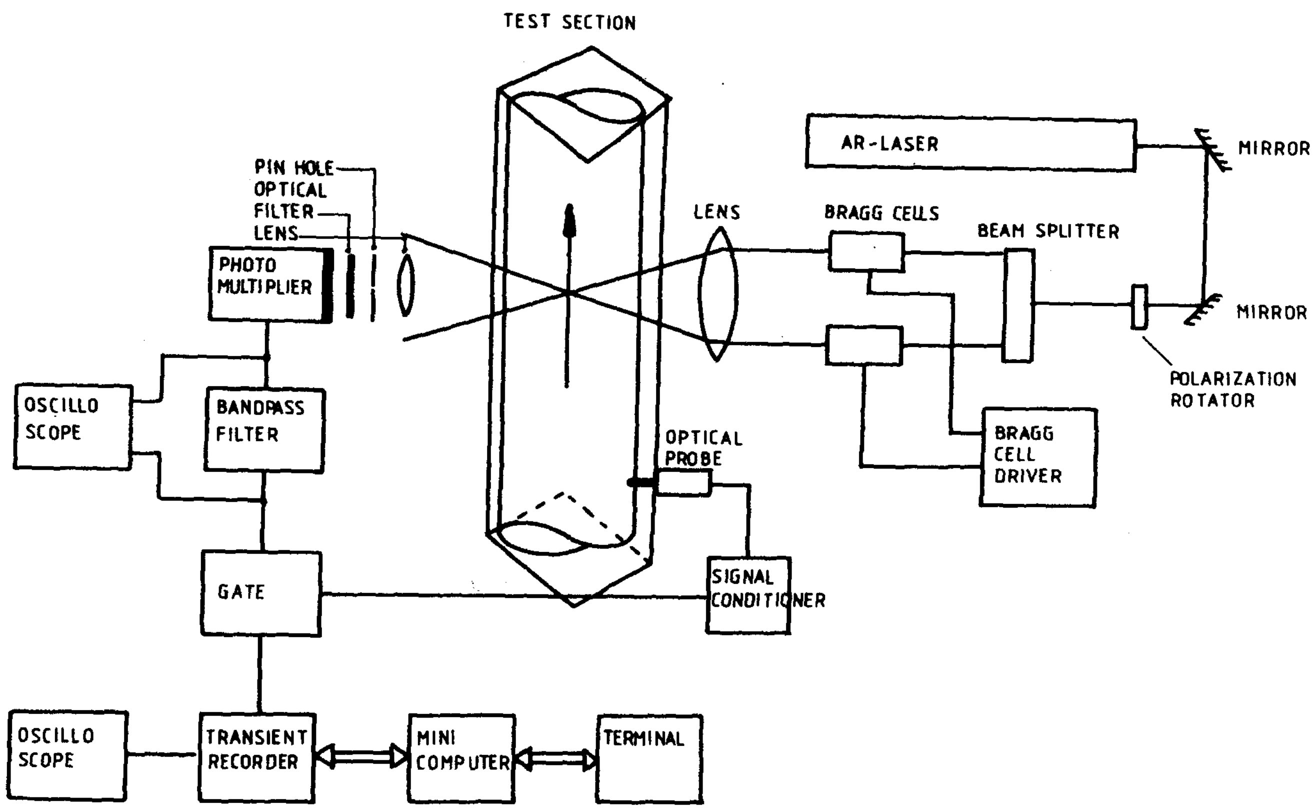

Figure 3. LDV-system.

technique described here is therefore best suited for moderate gas flow rates and for measurements near the pipe walls.

LDV-signals coming through the gate are registrated by a transient recorder, and thereafter transferred to a minicomputer in digital form. A zero-crossing program comprising various signal validation schemes is run on the data and the corresponding signal frequency evaluated. The system is then ready for the next opening of the gate. Due to the time needed for signal transfer and evaluation, only one signal can be handled during the opening time of the gate. When a predetermined number of signals has been evaluated, the mean value and standard deviation of the velocity are computed and displayed together with a histogram showing the velocity distribution.

3. EXPERIMENTAL RESULTS

3.1 *Macroscopic measurements*

Five different flow conditions corresponding to two-phase Reynolds numbers, Re_{TP}, equal 3200, 4800, 6400, 4600 and 6100 were examined. The gas and liquid flow rates for the different conditions are given in table 1. Conditions I–III are characterized by having the same liquid flow rate, $V_L^s = 1.0$ m/s, but different gas flow rates corresponding to $V_G^s = 0.95$, 1.9, 2.8 m/s, respectively. Condition IV has the same gas flow rate as condition II, 1.9 m/s, but somewhat smaller liquid flow rate. 0.9 m/s as compared to 1.0 m/s for condition II. Condition V has the same gas flow rate as condition III, 2.8 m/s, but a liquid flow rate of 0.8 m/s as compared to 1.0 m/s for condition III. The low Reynolds numbers are due to the refractive index matching fluid mixture applied in the experiments ($\nu_L = 15 \cdot 10^{-6}$ m^2/s). However, all conditions are well inside the slug flow regime map, figure 4, Mandhane *et al.* (1974).

Due to the special technique applied for the velocity measurements, the results obtained are characteristic for "an average slug unit". For a given gas and liquid flow rate "an average slug unit" is defined to have an average length of the liquid slugs, an average length of the gas pockets between the liquid slugs and an average translational speed of the slugs. Results for these quantities for the present flow conditions are shown in table 1 together with results for the slug frequencies and the ratio between the translational speed of the slugs, V_T, and the mixture velocity V_m.

$$V_m = V_G^s + V_L^s. \qquad [3.1]$$

3.1.1 *Translational speed.* The results indicate that the translational speed is directly proportional to the mixture velocity. These findings are in accordance with results by Hubbard (1965) and Gregory & Scott (1969). However, for the present conditions the proportionality factor is found to be approx. 1.52 while Hubbard obtained 1.25 and Gregory & Scott 1.35. By applying the formula developed by Dukler & Hubbard (1975) for the present flow conditions the proportionality factor should have been approx. 1.20.

Table 1. Experimental conditions and macroscopic flow characterization

Flow conditions					Results				
Flow	Sign	V_L^s m/s	V_G^s m/s	Re_{TP}	f Hz	V_t m/s	L_u m	L_s m	$V_T/(V_L^s + V_G^s)$
I	□	1.0	0.95	3200	3.5	3.0	0.85	0.37	1.54
II	△	1.0	1.9	4800	3.1	4.4	1.4	0.42	1.52
III	×	1.0	2.8	6300	3.3	5.7	1.8	0.45	1.50
IV	+	0.9	1.9	4600	2.5	4.3	1.7	0.46	1.54
V	▽	0.8	2.8	6000	2.0	5.5	2.8	0.53	1.53

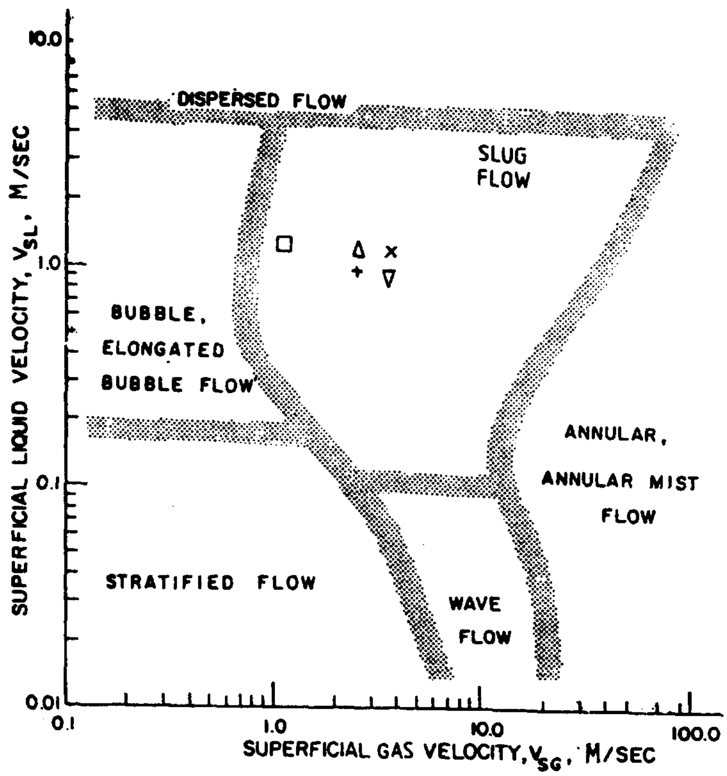

Figure 4. Flow regime map.

One must, however, be aware of that these formulas are developed and tested for Two-phase Reynolds numbers, Re_{TP}, greater than 30,000 while $3000 < Re_{TP} < 6500$ for the present experiments. These low Reynolds numbers seem to give a nearly laminar flow in the film just before pick up.

3.1.2 *Slug frequencies.* The measured slug frequencies for the conditions examined are given in table 1. Changes in the gas flow rate just slightly affects the slug frequency. The results indicate that for a given liquid flow rate, there exists a gas flow rate which gives minimum slug frequency, see condition I–III. This is a well-known result for horizontal slug flow reported by several other authors; Gregory & Scott (1969) and Hubbard (1965). However, while they observed a minimum slug frequency for a translation speed for the slugs about 5–6 m/s, the present result indicates that the minimum slug frequencies are to be found for a translation speed about 4.5 m/s (case I–III). By comparing the results for the slug frequency for condition II and IV and condition III and V it is seen that the slug frequencies decrease with decreasing liquid flow rate. This result is also well known from earlier experiment; Gregory & Scott (1969) and Hubbard (1965).

Taitel & Dukler (1977) have presented a model for determination of the slug frequency during gas–liquid flow in horizontal and near horizontal pipes. They claim that the dimensionless frequency will depend on the following dimensionless groups for horizontal flow:

$$\frac{fd}{V_L^s} = f(X, Z, F_L, F_G)$$

$$X = \left[\frac{(\mathrm{d}p/\mathrm{d}x)_L^s}{(\mathrm{d}p/\mathrm{d}x)_G^s}\right]^{1/2} = \left[\frac{f_L^s \rho_L}{f_G^s \rho_G}\right]^{1/2} \frac{V_L^s}{V_G^s}$$

$$Z/X = [4 f_L^s]^{-1/2}$$

$$F_L = \frac{V_L^s}{2\sqrt{dg}}$$

$$F_G = \frac{V_G^s}{2\sqrt{dg}}\sqrt{\frac{\rho_G}{\rho_L - \rho_G}}.$$

Fanning friction factor for laminar flow

$$f_i^s = \frac{16}{\mathrm{Re}_i^s}, \quad i = G, L$$

and turbulent flow as given by Lockhart–Martinelli

$$f_i^s = \frac{0.046}{(\mathrm{Re}_i^s)^{0.2}}$$

Here transition is assumed at $\mathrm{Re}_i = 2000$.

In this set of equations X is the Lochart–Martinelli parameter, Z represents the ratio of inertial to gas phase pressure drop forces, F_L is the liquid Froud number, F_G is the ratio of gas phase inertial forces to liquid phase gravity forces. $(\mathrm{d}p^s/\mathrm{d}x_L)$ and $(\mathrm{d}p^s/\mathrm{d}x_G)$ represent superficial pressure drop for liquid and gas, respectively. f_G^s and f_G^s are the Fanning friction factors (superficial) for liquid and gas, respectively, g is acceleration due to gravity and d is the pipe diameter.

Flow conditions I–III, table 1, give $F_L = 2.06$ and $Z/X = 5$. This makes a comparison between the graph presented by Taitel & Dukler (1977), (figure 5) and the present experimental results, possible.

Table 2 shows that the present experimental results lie within 15% of the theoretical values. However, Taitel & Dukler themselves found that the model had an accuracy of approx. 25%, which show that the present experimental results is within the expected range.

3.1.3 *Slug length.* As a consequence of variation in the slug frequencies and the translational speed for the slugs, also the total length of a slug unit (length of slug plus length of film) will change. The total length of a slug unit is given by the relation

$$l_u = V_T T_u \qquad [3.2]$$

It is seen by comparing conditions III and V in table 1 that even a small change in the liquid flow rate—from 1 to 0.8 m/s—may cause a large change in the total length of a slug unit—from 1.8 to 2.8 m.

However, it looks like alterings of the flow rates mainly are reflected in the length of the film section, not the liquid slug length, which is almost constant within the present range of flow condition.

Increased gas flow rate increases the length of the film region while increased liquid flow rate reduces it.

Table 2. Comparison between present experimental results and theoretical results, Taitel & Dukler (1977)

Case	F_G	X	Frequency model	Frequency experiments
I	0.074	26.6	3.9	3.5
II	0.148	14.5	3.1	3.1
III	0.218	10.2	2.9	3.3

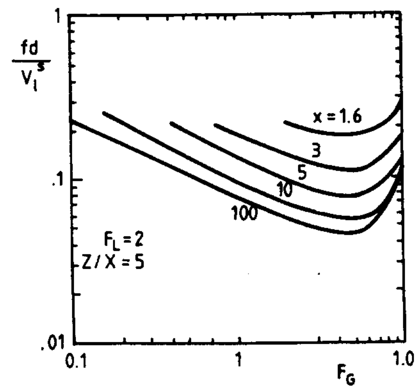

Figure 5. Dimensionless slug frequency (Taitel & Dukler 1977).

3.2 *Velocity measurements*

Due to limitations in experimental setup, time and available funds it was decided to perform velocity measurements only in a vertical plane through the axis of the pipe and in the region plus/minus 400 mm relative to the front of the slug. Velocity profiles in the film 180 mm before the front of the slug and in the slug 40, 150 and 260 mm behind the front of the slug were measured. Also the velocity variation along the bottom of the pipe (at a height of 1 mm) in the region minus 400 mm to plus 400 mm relative to the front of the slug were recorded (see figure 6).

3.2.1 *Velocity variation along the bottom of the pipe*. The velocity variation along the bottom of the pipe—through the slug front—is shown in figure 7. These results demonstrate the characteristic behaviour of a horizontal slug flow; i.e. a liquid film with a low, slowly decreasing velocity followed by a zone with large acceleration in the front of the slug where the liquid is accelerated from film speed just before pick-up to the slug speed. after the maximum velocity has been reached, the velocity shows a slowly decreasing character throughout the rest of the liquid slug. However, by looking into the details, some interesting characteristics for horizontal slug flow can be observed.

For case I–III with mixture velocities 1.95, 2.9 and 3.6 m/s, respectively, the measured pick-up velocity (the lowest velocity in the film) is found to be the same. for case IV and V, however, the pick-up velocity is smaller than for case I–III. Also in the rest of the film region the velocities for case I–III exhibit similar trends, while the velocities for case IV and V are somewhat lower. These results indicate that the pick-up velocity is mainly dependent on the liquid flow rate, even though the velocity in the slug increases strongly with increased gas flow rate (see figure 7).

The length of the zone of acceleration in the front of the slug is seen to increase with increased two-phase Reynolds number; from approx. 120 mm for case I to approx. 240 mm

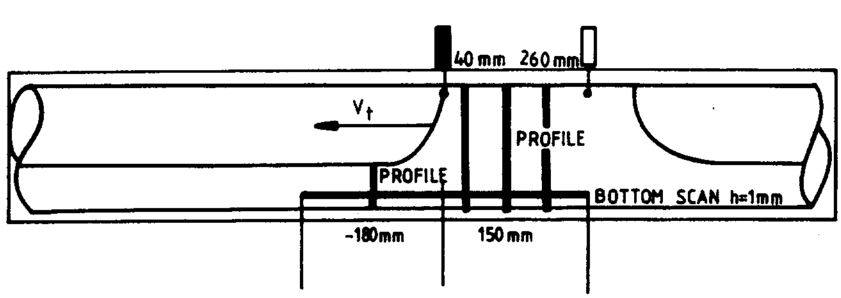

Figure 6. Measuring region.

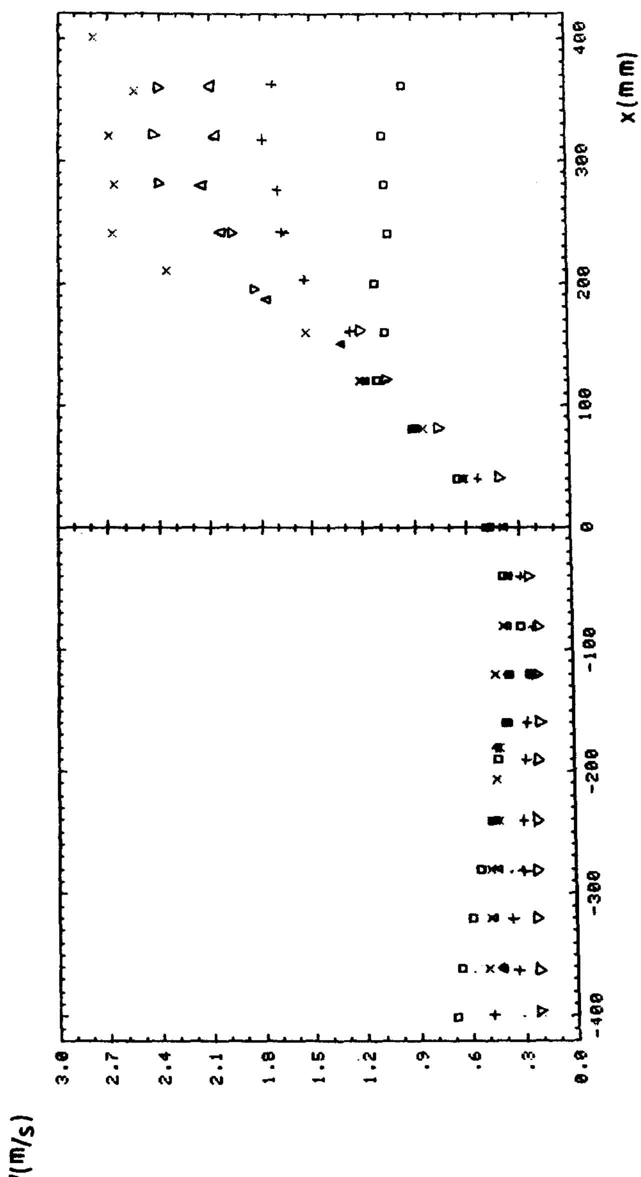

Figure 7. Velocity variation along bottom of pipe.

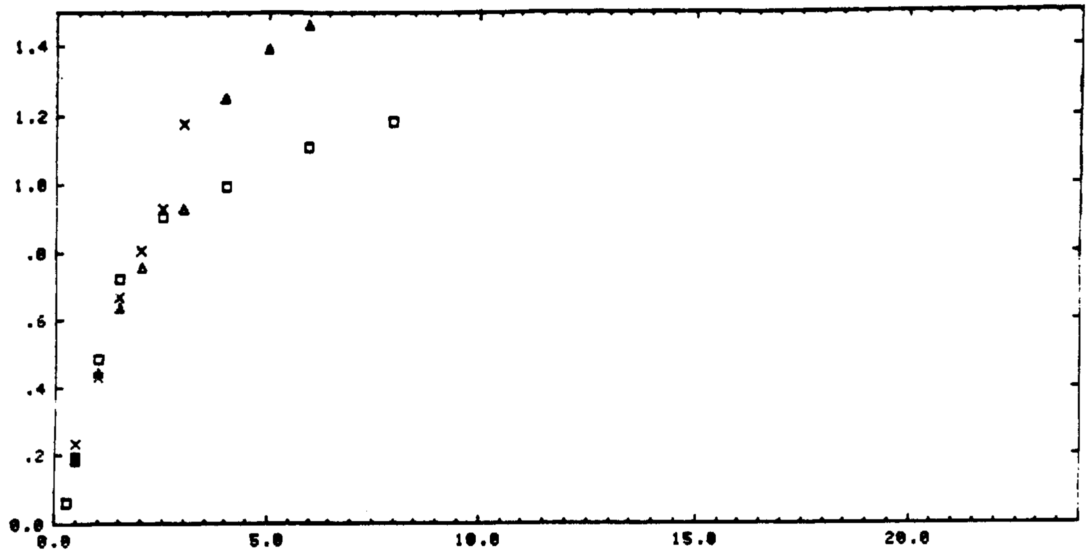

Figure 8. Velocity profile film.

for case III. It is of interest to notice that the liquid for case I–III is accelerated at the same rate until the end of the zone of acceleration for each case. After the maximum speed has been obtained the velocity decreases slowly. However, even at the end or near the end of the slugs the velocity is not much less than its maximum value, figure 7.

3.2.2 *Velocity profile film.* Velocity profiles in the film, figure 8, were measured 180 mm before the front of the slug for case I–III. It was difficult to obtain acceptable signals near the upper "free" surface of the liquid film due to light reflection and slightly wavy surface. The thickness of the film for the different cases was found to be 8, 7 and 6.5 mm for case I–III, respectively. The profiles below a height of 2.5 mm seem to be independent of the gas flow rates. However, above 2.5 mm the velocity is seen to increase with increased gas flow rate. This is probably due to an increased interfacial shear force due to the increased relative velocity between the film and the gas. Within the part of the film we were able to measure only small axial variation of the velocity profiles was found.

3.2.3 *Velocity profiles, slug.* Velocity profiles recorded in the slug 40, 150 and 260 mm upstream the slug front (see figure 5) are shown in figures 9–11, respectively, for case I–III. For the highest gas flow rate the bubbles dissolved in the liquid phase made it diffiicult to obtain an acceptable rate of processable signals in the core of the pipe. velocities in the core were therefore not recorded for case III.

The results presented in figure 9 are measured 40 mm upstream the slug front. This is within the zone of acceleration for all three cases, figure 7. The velocity profiles show an unsymmetrical character with the largest velocities in the upper part of the pipe. Case II and III exhibit a strong shear layer at about 9–10 mm and 6.5–7.5 mm above the bottom of the pipe, respectively. These heights correspond well to the thicknesses of the respective liquid film. The shear layer for case I is not so pronounced as for case II and III.

Figure 9 shows how the slowly moving film is overrunned by the much faster moving liquid slug and how the slowly moving film is accelerated due to the shear forces in the shear layer. The velocity fluctuations in the shear layer are large.

The results displayed in figure 10 are measured 150 mm upstream the slug front. From figure 7 we see that both case II and III are still within the zone of acceleration while case I is just at the point of entering the quasi-steady state. This is also revealed by the degree of symmetry of the profiles in figure 10. In case II and probably also in case III a shear layer can still be seen, while case I has obtained a nearly symmetrical character.

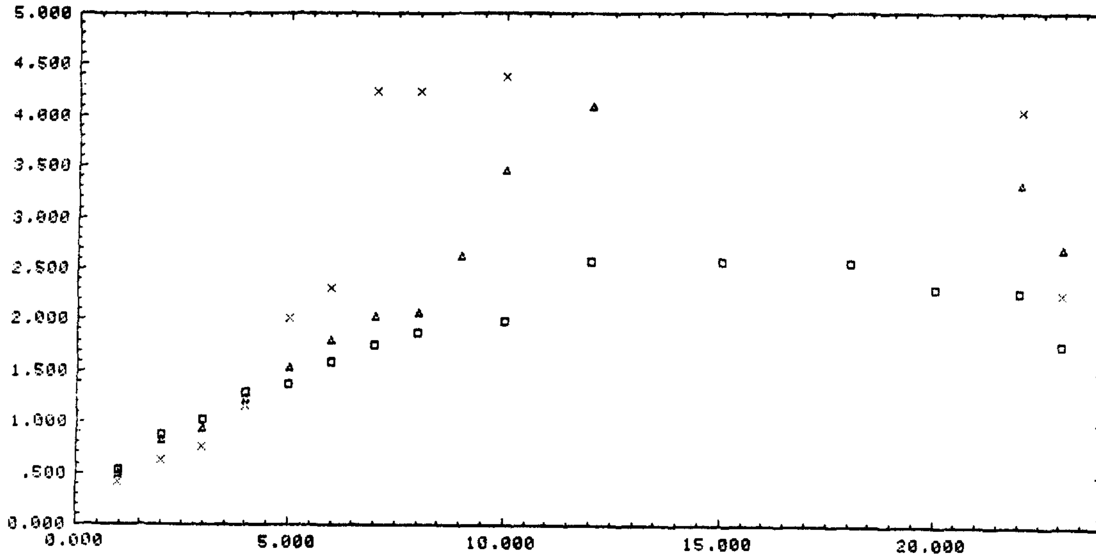

Figure 9. Velocity profiles 40 mm behind front of slug.

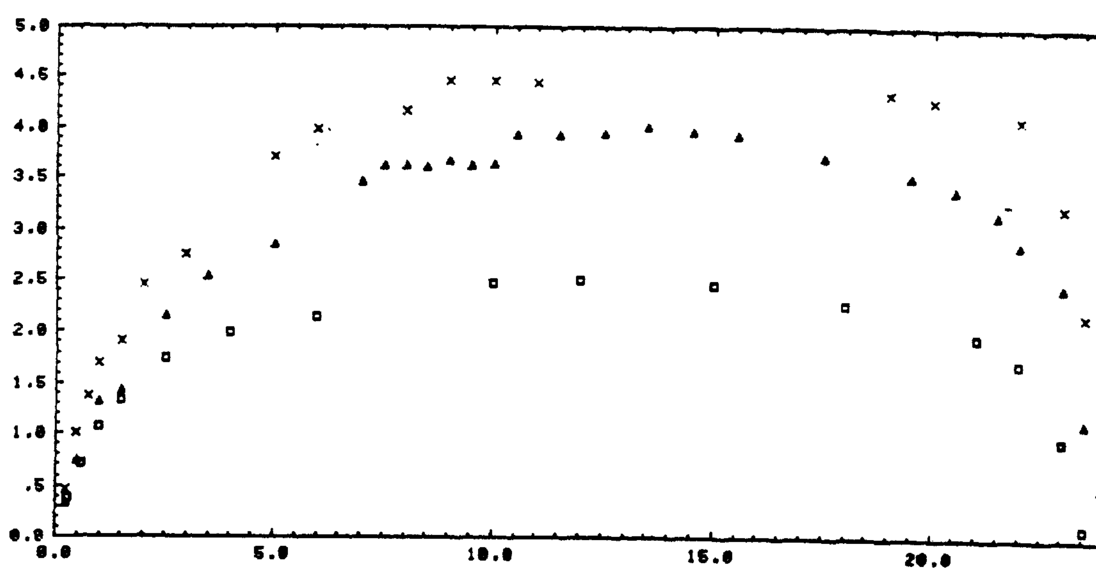

Figure 10. Velocity profile 150 mm behind front of slug.

Figure 7 shows that the position for the recordings displaces in figure 11 is outside the zone of acceleration for all three cases. The profiles now also exhibit a nearly symmetrical character for case I and II, while the profile for case III still has some kind of unsymmetrical shape. The profiles shown in figure 11 have the same character as for fully developed pipe flow. the maximum velocity in the slug, V_{max}, is seen to be somewhat smaller than the translational speed of the slugs, V_T. For case I and II we find that the mixture velocity $V_m \simeq 0.8\ V_{max}$ and $V_m \simeq 0.83\ V_{max}$, respectively. For a fully developed turbulent profile the mean slug velocity $V_s \simeq 0.8\ V_{max}$.

Accordingly, the measurements give that $V_s \simeq V_m$ when the profiles have obtained a fully developed character. This is the same result as obtained by Dukler & Hubbard (1975) from continuity considerations and empirically justified by Nicholson *et al.* (1978).

Figures 12–14 show curve fits to the experimental data for case I–III, respectively. In each figure liquid and gas flow rates are constant. The figures thus show how the velocity

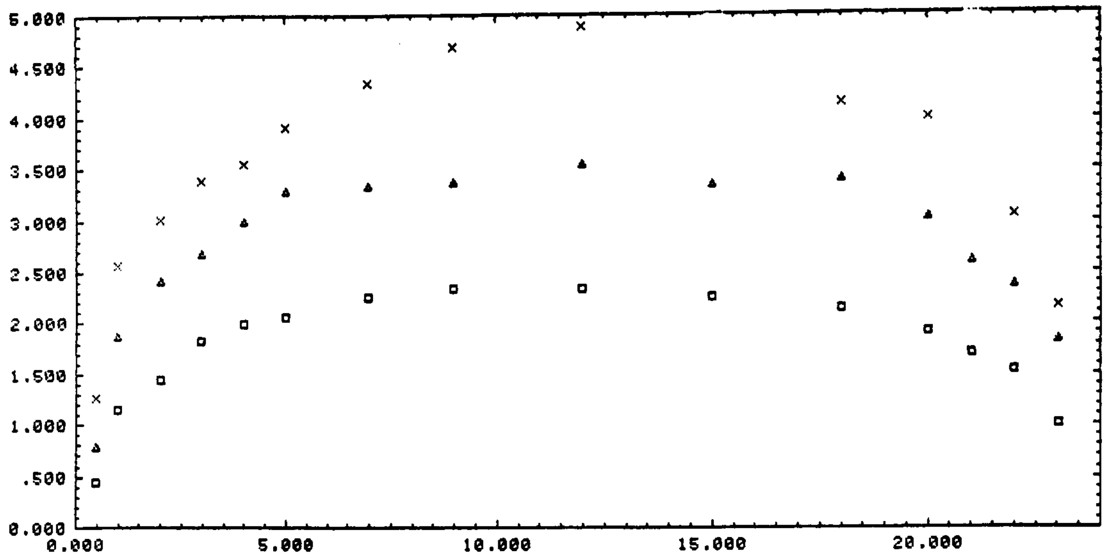

Figure 11. Velocity profile 260 mm behind front of slug.

profiles develop within the slug from an unsymmetric profile with the largest velocities at the top of the pipe near the slug front to a nearly symmetric profile at the slug end. However, by comparing the velocity profiles in figures 12–14 we find that areas defined by the profiles at different locations are not equal. This is probably due to three-dimensional effects in the slug.

Dukler & Hubbard (1975) developed their model for slug flow from pressure time traces and global measurements of film and slug velocities. It is a two-zone model which requires a pick-up of the film in the mixing zone, the existence of a "fully developed pipe flow" region behind the mixing vortex and a process of shedding of the film behind the slug to form the film region. The detailed evolution of the velocity profiles shown in figure 12–14 may give a new and better basis for their model.

5. CONCLUDING REMARKS

A method for macroscopic characterization of slug flow has been developed. It is mainly based on the use of two optical "two-phase" probes and a structural dynamics analyser performing statistical analysis of the probe signals.

A technique for making LDV-measurements in liquid–gas slug flow has been developed. In addition to a laser and a standard aquisition system comprising necessary electronics and a minicomputer it was necessary to design a system for recording data at given position relative to the slug front. The system was based on a commercial available optical "two-phase" probe with a signal conditioner and an "in-house" designed electronic gate. It was found necessary to utilize a transparent tube and a liquid both with the same index of refraction.

This technique was used with success to obtain detailed velocity distributions inside a liquid slug in horizontal flow. Problems arose, however, in regions with high concentrations of gas bubbles. Such regions were the slug front and the slug core at the highest gas flow rates.

The detailed information obtained is in accordance with accepted description of slug flow dynamics derived from visual and macroscopic data.

Some of the major findings of this study were as follows:

The lengths of liquid slugs are relatively constant under the present flow conditions. Increased gas flow rate increases the length of the film region, while increased liquid flow rate reduces it.

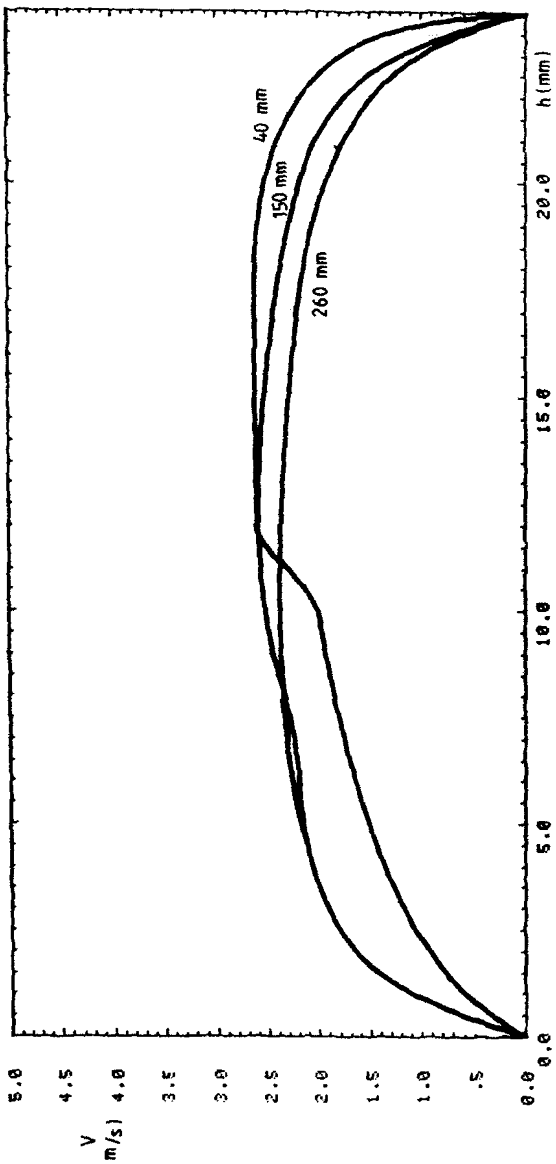

Figure 12. Variation of velocity distribution through liquid slug, case I.

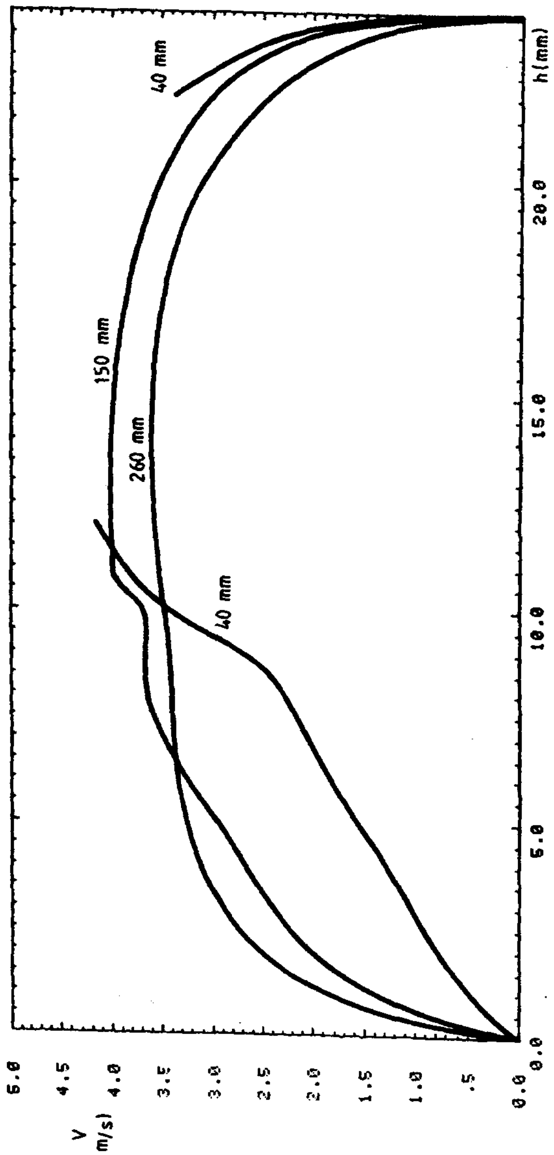

Figure 13. Variation of velocity distribution through liquid slug, case II.

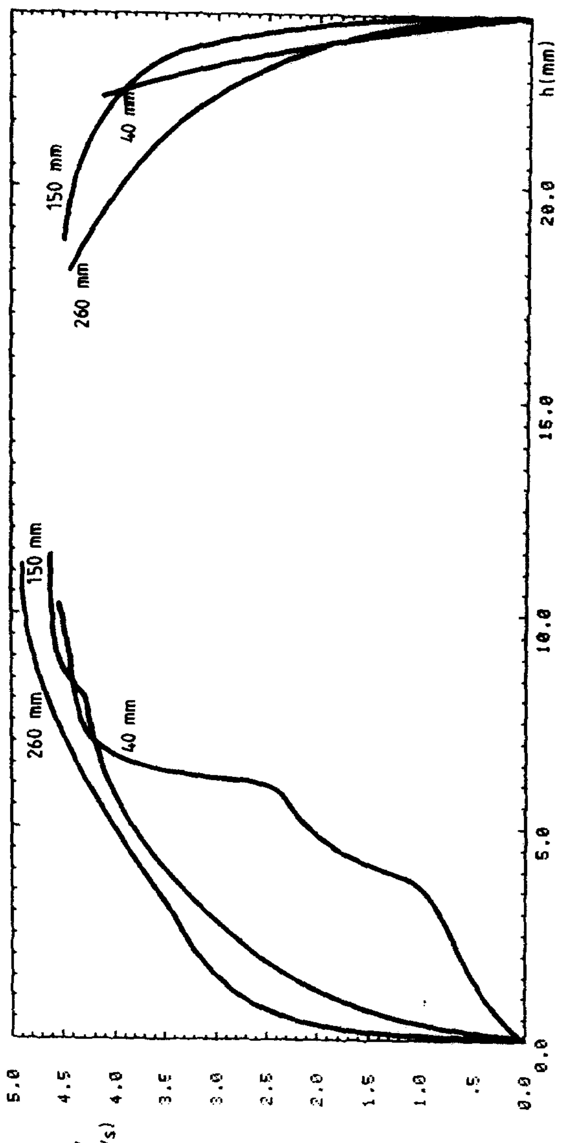

Figure 14. Variation of velocity distribution through liquid slug, case III.

The translational speeds of the liquid slugs are proportional to the mixture velocity, $V_T \simeq 1.52\ V_m$. This result is reported earlier, but with another proportionality constant.

Upstream the slug front the liquid slug tends towards fully developed pipe flow. The mean slug velocity V_s will in this region be equal to the mixture velocity (relative velocity) V_m of the slug flow, $V_s = V_m$. This is reported by others also.

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