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FLOW PATTERN CHARACTERIZATION IN TWO PHASE FLOW BY ELECTRICAL CONDUCTANCE PROBE

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Abstract—An improved system of conductance probes is used to identify the flow patterns in two phase horizontal, near horizontal and upward flows. The results show that this system is very well suited to distinguish among flow patterns consistent with visual observations.

INTRODUCTION

Flow pattern information in gas liquid flows is usually obtained by visual observation. The designation of flow pattern has not yet been accurately standardized and depends largely upon individual interpretation of visual observations, therefore a variety of classifications exist.

The major difficulty of visual observation, even using high speed photography, is that the picture is often confusing and difficult to interpret, especially when dealing with high velocity flows. In addition, there are systems which are opaque where flow visualization is impossible.

Although considerable experimental work has been performed studying two phase gas liquid flows, not very much was done in the development of an objective device for the flow pattern classification. Jones & Delhaye (1975) reviewed and summarized a variety of measuring techniques used in two phase flow of which only few are used directly for flow pattern characterization. Hus *et al.* (1964), utilized a hot wire anemometry technique for measuring void distribution for vertical flow and used the signal output also for flow pattern characterization. Jones & Zuber (1975) developed an X-ray void measurement system for obtaining statistical measurements in vertical air water flow in a rectangular channel. The probability density function of the void fraction fluctuations was used as a quantitative flow pattern discriminator for bubbly, slug and annular flows. Govier *et al.* (1975), Chaudhry *et al.* (1965) and Isbin *et al.* (1958) tried to relate the flow pattern to the pressure gradient variation. Their results, however, are not systematic. Furthermore, it needs mapping of the pressure gradient with flow conditions, namely the flow pattern can not be detected at one flow condition. Hubbard & Dukler (1966) suggested a method by which the flow pattern can be determined from the spectral distribution of the wall pressure fluctuations. They distinguish, however, only between separated, intermittent and distributed flows. They could not discriminate between stratified and annular flows, or between the dispersed liquid or dispersed gas flow regimes. Choe *et al.* (1976) detected the slug annular transition based on a direct trace of the pressure fluctuations on an oscilloscope.

A conductance probe technique was used by Solomon (1962), and Griffith (1964). They applied this technique using a single conductivity probe. Fiori & Bergles (1966) and Bergles *et al.* (1976) also used a conductivity probe for boiling flows in horizontal tubes. They used a single central probe and were able to detect differences among bubbly, slug and annular flows.

In this work, an improved conductivity probe technique is proposed. Special efforts were made to design the probe system to detect flow pattern differences as dictated by the basic definitions of the flow patterns. As a result a set of probes system is suggested and shown to clearly detect all flow patterns in horizontal, near horizontal and vertical flows.

FLOW PATTERN TERMINOLOGY

The definition of the flow pattern has been directly related to the visual observation of the gas liquid distribution within the pipe flow. However, the flow is quite often chaotic and even a basic classification is subject to non-uniform approach of various observers (not mentioning the difficulty to determine the flow pattern visually once a definition exists).

As a result a variety of classifications exist. For the purpose of identifying the flow using electrical probes, it is important first to define clearly a flow pattern classification. In doing this, we tried to minimize the number of classifications, to stress consistent and accurate definitions and at the same time to use, with minimum modification, acceptable classifications. As a result, the following pattern description is proposed.

For horizontal flow:

Stratified. Liquid flows at the bottom of the pipe with gas at the top. The stratified pattern is subdivided into *stratified smooth* where the liquid surface is smooth and *stratified wavy* where the interface is wavy.

Intermittent. Plugs or slugs of liquid which fill the pipe are separated by gas zones which contain a stratified liquid layer flowing along the bottom of the pipe. The intermittent pattern is sub-divided into *slug* and *elongated bubble* flow patterns. When the flow is calm and the liquid slug is free of gas bubbles the pattern is that of elongated bubble flow. For high flow rate when the liquid is aerated and contain gas bubble the flow is that of slug flow.

Annular. A liquid surrounds a core of high velocity gas which may contain entrained liquid droplets. When the gas flow is relatively low, most of the liquid flows as a film at the bottom of the pipe while aerated, unstable waves are swept around the pipe and wet its periphery. This type of flow pattern is the beginning of annular flow and have been called *wavy annular.*

Dispersed bubble. The gas phase is distributed as discrete bubbles within a continuous liquid phase. Normally the bubble density at the top will be higher than at the bottom of the pipe.

The basic flow patterns for upward flows are:

Bubble flow. Here the gas phase is approximately uniformly distributed in the form of small discrete bubbles in a continuous liquid phase.

Slug flow. Most of the gas is located in large bullet shaped bubbles moving upwards and designated as "Taylor Bubbles". The Taylor Bubbles are separated by slugs of continuous liquid which bridge the pipe and which usually contain small gas bubbles.

Churn flow. The churn flow is somewhat similar to slug flow. It is, however, much more chaotic, frothy and disordered. The bullet shaped Taylor Bubble becomes narrow and its shape is distorted. The liquid bridging is short, very aerated and often breaks, falls down and merges with the slug beneath it therby creating an oscillatory motion of the liquid slug.

Annular flow. Annular flow is characterized by the continuity of the gas phase along the pipe in the core. Liquid phase moves upwards partly as wavy liquid film and partly in the forms of drops entrained in the gas.

EXPERIMENTAL

The experiment is carried out in a water–air system using plexiglass pipe of 2.5 cm dia. A more detailed description of the flow system is given in Barnea *et al.* (1979). The electrical probes were sited in a short test section, 30 cm long, which is flunged into the pipe.

The proposed technique is based on the significantly different electrical conductivity of air and water. Probes were used at different locations for the purpose of accurately determing the pattern. The electrical diagram is shown schematically in figure 1 for the case of horizontal flow. The electrical unit contains a power supply that provides variable d.c. voltage from 0 to 10 V. The variable resistors and the input output connections were integrated in this unit. The output is recorded with a digital oscilloscope with memory and the results could be later copied by a X–Y plotter. The purpose of this circuit is to measure the conductance as a function of time between the probes and a flat large electrode. When the pipe is full of water the electric circuit is closed through the water and a maximum voltage is detected at the output signal. When the pipe is empty of water the circuit is open and the output signal is zero.

The use of direct current somewhat hinder reproducibility as far as the exact value of the

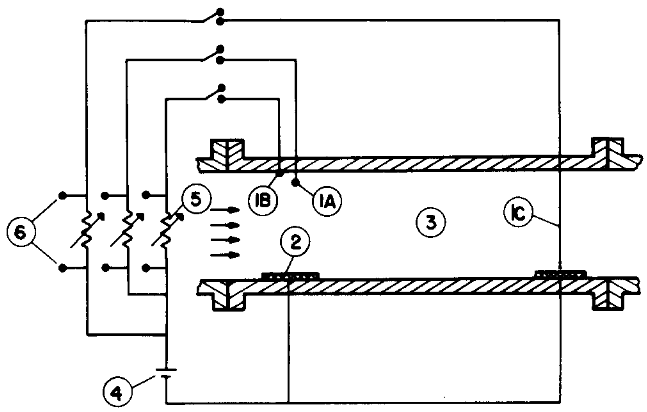

Figure 1. Scheme of probing system. (1A) Probe—Tip electrod, stainless steel wire, 0.25 mm dia., teflon coated, 3 mm down from tube top; (1B) Probe—Tip electrod, stainless steel wire, 0.25 mm dia., teflon coated, flat with tube surface; (1C) Probe—Metal needle, not insulated; (2) Flat copper electrode; (3) Two-phase flow; (4) Voltage supply; (5) Variables resistors; (6) Output signal (to oscilloscope).

output voltage (Brown *et al.* 1978). However, for the purpose of flow pattern identification, the slight variation in the maximum voltage output was irrelevant.

Three probes designated as 1A, 1B and 1C were used at different locations to detect flow pattern in horizontal and slightly inclined pipes. The flat large electrode (2) is located in this case at the bottom of the pipe.

Probe 1A is designed to detect bubbles at about 3 mm below the top of the pipe. Since the probe is quite small it can detect easily even small gas bubbles yielding zero voltage during a bubble passage. The fall, as well as the rise, of the voltage has been found immediate and for bubble flow the voltage fluctuate from zero to maximum.

Probe 1B is flat with the upper part of the wall. It is designed to detect any surface wettness around the inner tube periphery. Even thin liquid films that are present in annular flow or the remaining film after the passage of the liquid slug in intermittent flow causes a voltage output of this probe.

Probe 1C is designed to detect the liquid level under stratified conditions. It is constructed of non insulated needle that is inserted vertically along the pipe diameter and almost reaches (about 3 mm gap) the bottom flat electrode. A change of the liquid level interface is easily detected by this probe.

In this case of vertical upflow, the flow is symmetrical and from this point of view, less complicated. In this case, two probes were sufficient to detect the flow patterns. Probe 1B was used for the same purpose as in the horizontal case. Probe 1A was extended to the center of the pipe to detect bubbles at the tube centerline.

RESULTS

Representative runs for each of the flow regimes are presented in figures 2–14. The method of identifying the flow pattern was based on an oscillograph trace that was obtained continuously on the scope. For convenience the free run could be stopped and the last run could be observed stationary on the scope and/or be transferred to an $X-Y$ plotter.

The oscilloscope traces have been found to yield an accurate and convenient picture of the flow patterns based on their basic definitions and using the detection character of the aforementioned probes.

We may note that we tried to use a spectrum analyzer for possible detection of the flow patterns (Hubbard & Dukler 1966; Jones & Zuber 1975), but the picture obtained was much less informative as compared to the direct output trace.

Flow pattern characterization in horizontal flow

Figures 2(a) and 2(b) show typical traces of elongated bubbles obtained by probes A and B

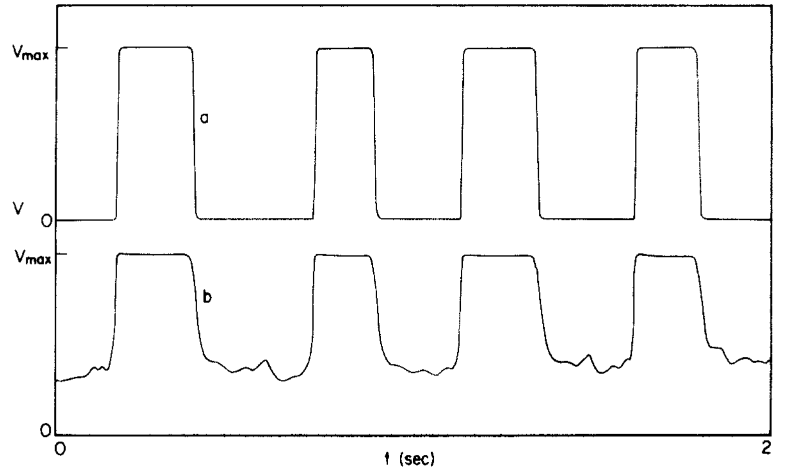

Figure 2. Elongated bubble flow, $u_{Gs} = 0.12$ m/sec, $u_{Ls} = 0.48$ m/sec, horizontal.

respectively. In trace 2(a) the voltage fluctuates intermittently from maximum conductivity, that corresponds to a full liquid bridging, to zero conductivity which corresponds to the gas zone; in trace 2(b) the voltage falls from maximum conductivity to partial conductivity, which shows that the tube surface remains wet during the gas passage. Elongated bubbles were defined as an intermittent flow pattern in which the liquid slug is free of entrained bubbles. This fact is observed very clearly in the output signal.

The traces of figures 3 and 4 correspond to slug flow. In slug flow, adjacent gas zones are separated by a liquid zone which is aerated by gas bubbles. The air bubbles in the liquid slug are indicated by short pulses in the fully conducting slug region. Figures 3 and 4 show two consecutive typical cases for increasing liquid and gas flow rates. Figure 4 shows already quite fast aerated slugs. In slug flow, like in the case of elongated bubble flow, a liquid film covers the whole periphery in between the liquid bridging zones, as shown by the tracing of probe B.

Figure 5 illustrates the type of trace obtained in dispersed bubble flow. The probe is exposed in this case to a continuous conducting liquid phase and to many dispersed bubbles which hit the probes at high frequency and cause a sequence of very crowded pulses. In probe A the pulses are between zero to maximum conductance. The zero conductance is obtained when the probe tip is surrounded by the air bubble during passage. This is possible because of the small size of the probe tip. In probe B the conductance does not fall to zero because the bubbles slide near the tip which is flat with the tube wall and is always wetted by the liquid film at the wall

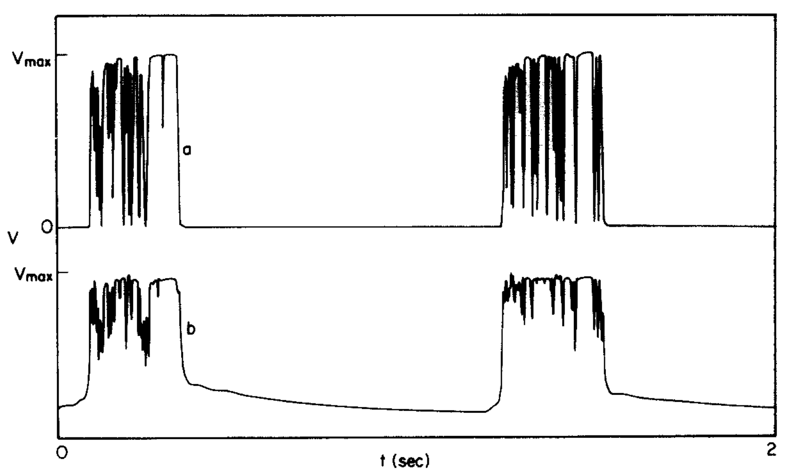

Figure 3. Slug flow, $u_{Gs} = 1.2$ m/sec, $u_{Ls} = 0.48$ m/sec, horizontal.

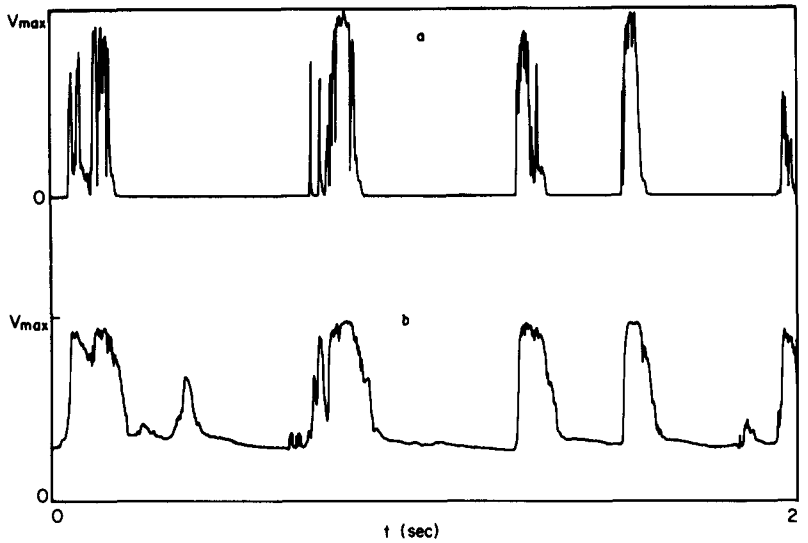

Figure 4. Slug flow, $u_{Gs} = 4.8$ m/sec, $u_{Ls} = 1.2$ m/sec, horizontal.

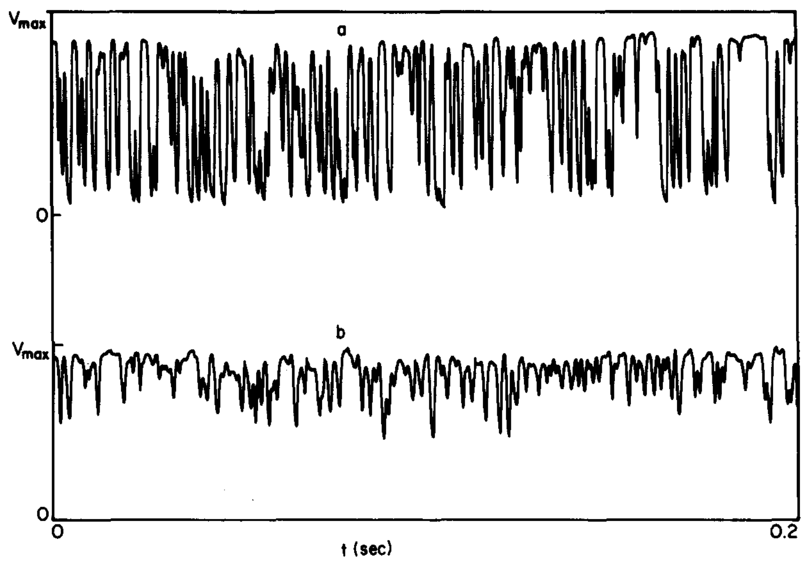

Figure 5. Dispersed bubble flow, $u_{Gs} = 0.19$ m/sec, $u_{Ls} = 3$ m/sec, horizontal.

(as in intermittent flow). Note that contrary to all cases, this case was taken in a faster free run (0.2 sec per picture). This is because of the high frequency of the dispersed bubbles pulsed. However, this has been done only for clearity; the flow pattern itself can just as well be detected by the slow free run, namely 2 sec per picture.

Annular flow is characterized by a gas core while the liquid covers the tube periphery. In this case probe A is completely or almost completely dry while the voltage output of probe B corresponds to the liquid film conductivity around the tube wall. The output of probe B indicates the wavy character of the film. Figure 6 shows a typical trace of annular flow. The film thickness at the top and around the periphery is approximately constant but it fluctuates owing to the wavy interface of the film. The mean output voltage of probe B is proportional to the film thickness. Probe A is completely dry as seen from the zero voltage output. When the gas flow rate decreases the annular film thickness becomes somewhat less uniform and occasional temporary increase in film thickness indicates that the annular flow contains waves that are swept around the pipe periphery. This phenomenon can be observed in figure 7. Figure 7 also

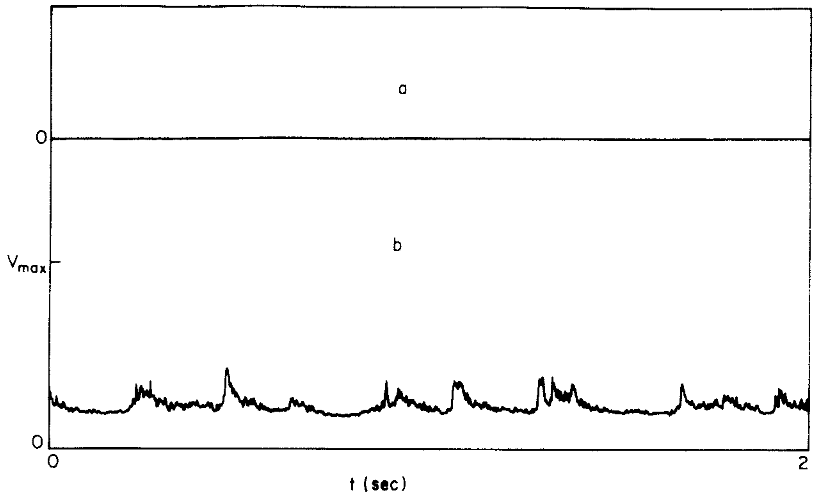

Figure 6. Annular flow, $u_{Gs} = 30$ m/sec, $u_{Ls} = 0.048$ m/sec, horizontal.

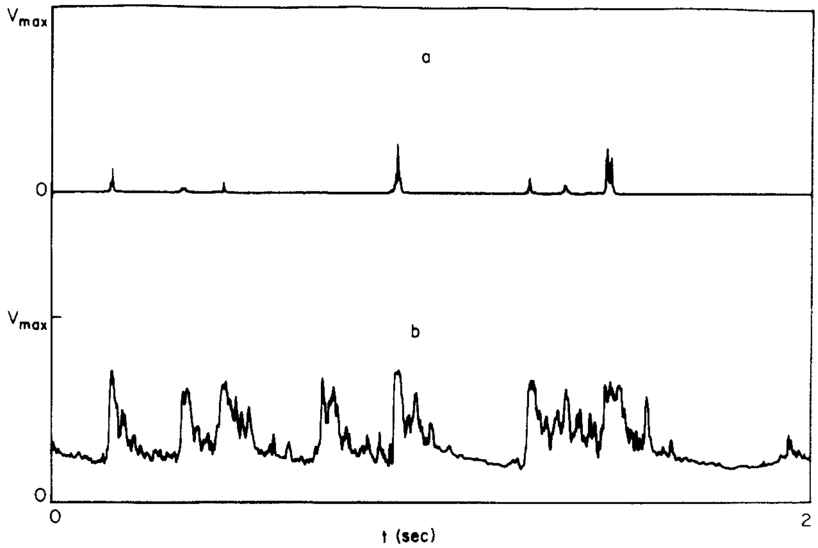

Figure 7. Annular flow, $u_{Gs} = 19$ m/sec, $u_{Ls} = 0.48$ m/sec, horizontal.

shows that when the liquid flow rate increases considerably the waves that are swept around the pipe cause the film thickness to be large enough to activate probe A. Yet the basic character of annular flow remains such that the voltage output of probe A is mostly nil.

Figure 8 is an example of the "wavy annular" flow pattern. This type of flow occurs when the gas flow rate is relatively low, most of the liquid flows as a film at the bottom of the pipe, while aerated unstable waves are swept around the pipe. This wavy annular pattern is on the border of stratified wavy and slug flow. It is close to stratified flow since most of the liquid stays at the bottom of the pipe and only a small amount is swept around to wet the pipe with a thin film. At the same time, it is similar to slug flow since the frothy waves may resemble slugs though they do not establish competent bridging of the air passage. Although generally investigators grouped this flow pattern with slug flow, it was observed by some that this flow pattern is not quite slug flow and for example, Nicholson *et al.* (1977) termed it proto slug. As seen by the oscilloscope trace, it can be easily observed that the liquid lump is indeed swept around the periphery and does not form a competent bridging as evident from the short pulses of probe A, that does not reach a maximum voltage as characteristic of slug flow. The general

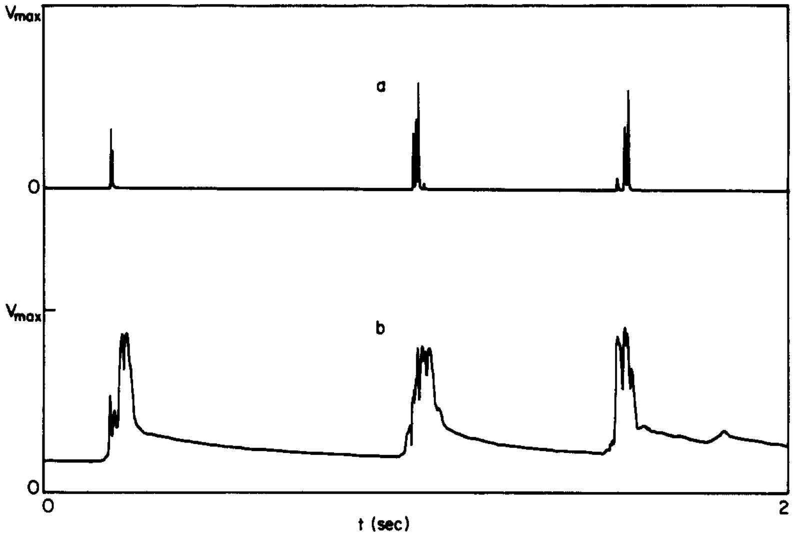

Figure 8. Wavy annular flow, $u_{Gs} = 4.8$ m/sec, $u_{Ls} = 0.3$ m/sec, horizontal.

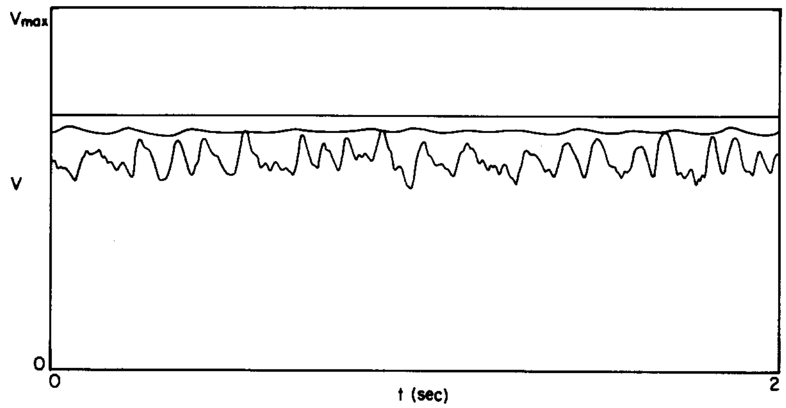

Figure 9. Stratified flow, $u_{Gs} = 1.2$, 3.0 and 4.8 m/sec, $u_{Ls} = 0.048$ m/sec, horizontal.

picture is closely related to annular flow. Probe B shows a continuous film with occasional waves while probe A is mostly dry except for short jumps indicating occasional wetting owing to aerated waves.

The output singal of probes A and B for stratified flow is a zero voltage. To distinguish between stratified smooth and stratified wavy regimes probe C is used. Probe C is a non insulated metal needle which is placed into the tube along the tube diameter while its tip almost touches the large flat electrode. A thicker liquid film in the lower part of the pipe is indicated by a higher voltage output of probe C. A stratified wavy flow is indicated by a wavy shaped signal. Figure 9 shows a sequence of three traces of stratified flow that were taken as the gas flow rate increases gradually from stratified smooth to stratified wavy. The middle trace corresponds to the transition boundary itself.

Flow patterns characterization in vertical upward flow

Figures 10–13 describe the transitions from slug flow through churn to annular at a constant liquid flow rate and increasing gas flow rates. Figure 10(a) shows typical traces for upward slug flow which has essentially the same basic characteristics as for horizontal slug flow. The liquid film in this case covers symmetrically the periphery of a Taylor Bubble in between the liquid slug zones. The film is much thicker than that observed in the upper part of the tube in

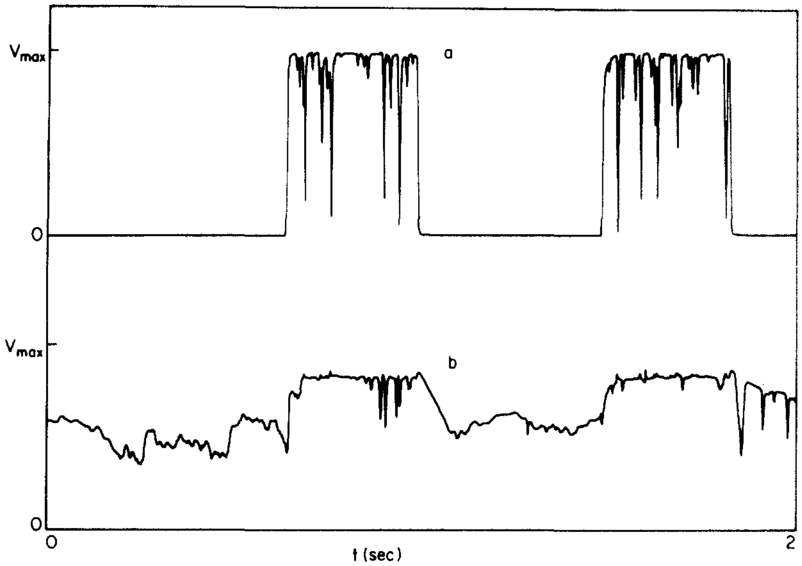

Figure 10. Slug flow, $u_{GS} = 0.3$ m/sec, $u_{LS} = 0.03$ m/sec, vertical upflow.

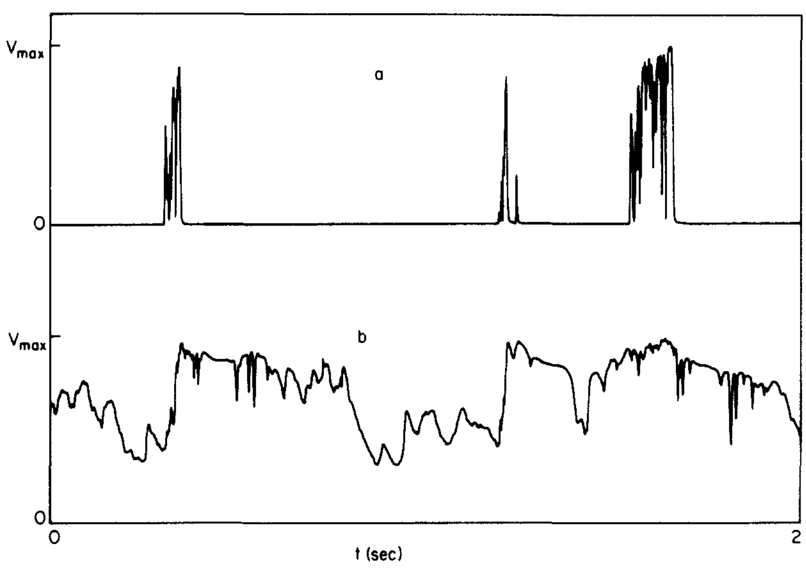

Figure 11. Churn flow, $u_{GS} = 1.9$ m/sec, $u_{LS} = 0.03$ m/sec, vertical upflow.

horizontal slug flow, it is also wavy like and as a result the structure of the slug itself is somewhat less observable by Probe B as in horizontal slug flow (trace b).

Figures 11 and 12, illustrate churn flow near transition to slug and annular flow respectively. Characteristics of churn flow is a quick, short bridging between two successive distorted "Taylor Bubbles" with high gas concentration. Characteristics of the churn flow trace are short pointed at top pulses contrary to the typical "square shaped" trace of slug flow which is approximately "flat" at top. In figure 11, which is very close to slug churn transition boundary two typical churn pulses are observed accompanied by one aerated slug pulse. Figure 12, is near the annular flow boundary. Bridging is very quick and sharp and it disappears in annular flow when gas continuity is restored along the tube.

Figure 13 illustrates a typical trace corresponding to annular flow. Annular flow is designed by a continuous gas core along the pipe with a symmetrical upflow liquid film. Thus, in annular up-flow probe A shows an open circuit indicating no liquid bridging of the flow at all times. Probe B shows the typical wavy like trace corresponding to unstable wavy film interface.

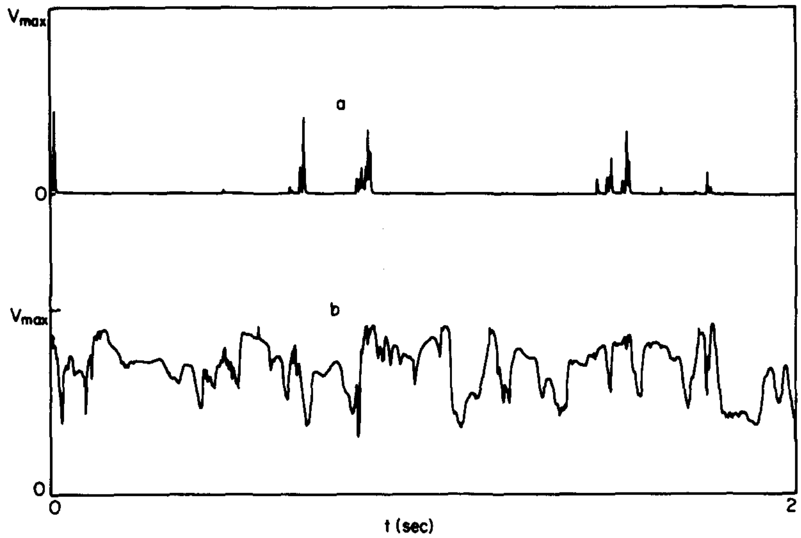

Figure 12. Churn flow, $u_{Gs} = 7.6$ m/sec, $u_{Ls} = 0.03$ m/sec, vertical upflow.

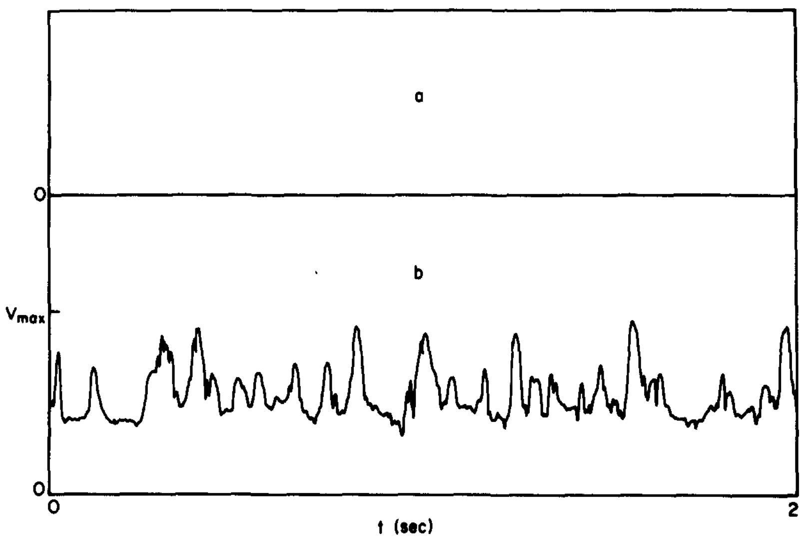

Figure 13. Annular flow, $u_{Gs} = 12$ m/sec, $u_{Ls} = 0.03$ m/sec, vertical upflow.

In figure 14, the type of trace obtained in dispersed bubbles is observed. The continuity of the voltage output of the conducting liquid phase is broken by pulses that are caused by the dispersed bubbles. Similar to the horizontal case the conductance of probe B does not fall to zero. It should be mentioned that in upflow at relatively low gas flow rate, the bubbles tend to concentrate at the tube wall (trace b), and only few bubbles are observed by probe A. As the gas flow rate increases, *increasingly* more bubbles are detected at the center line.

SUMMARY AND CONCLUSIONS

Flow pattern maps for two phase horizontal, near horizontal and vertical upward flow can be easily constructed by using the direct information from the oscillograph trace obtained by a set of conducting probes. The sensitivity of this method was excellent for identifying the individual flow patterns also very close to the transition boundaries. The logic in which the use of this probe system is utilized for the construction of flow pattern map is as follows.

For horizontal and near horizontal flows. Zero voltage output from probes A and B points

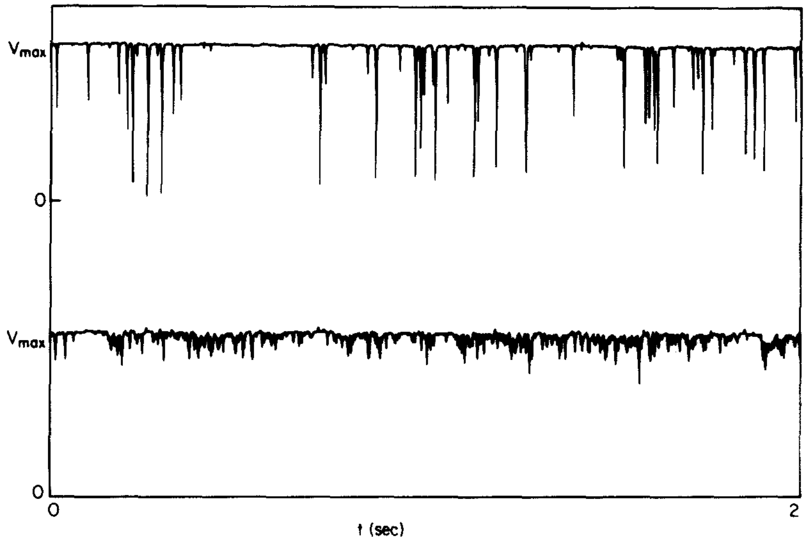

Figure 14. Dispersed bubble flow, $u_{Gs} = 0.3$ m/sec, $u_{Ls} = 1.9$ m/sec, vertical upflow.

out that stratified flow exists. In such case probe C is used to distinguish between stratified smooth and stratified wavy.

A voltage output from probe B while probe A is dry, except possibly for short and infrequent pulses, indicates annular flow. When the output of probe B is wavy type, it indicates "normal" annular flow. When probe B shows large pulses with a tendency to drain and dryout as indicated by the smooth decaying signal after the pulse (as in intermittent flow) the flow is wavy annular.

A voltage output from both probes A and B indicates intermittent or dispersed bubble flow. The exact pattern is detected by probe A alone. Dispersed bubble flow is characterized by uniform high frequency crowded pulses of magnitude zero to maximum voltage. Intermittent flow is characterized by the intermittent rectangular shaped long pulses separated by zero voltage. Slug flow is distinguished from elongated bubble flow when bubbles are detected within the liquid slug zone.

For vertical upflow. Again, the exact flow pattern is detected by probe A alone. Dispersed bubble flow is indicated by short abrupt fall of the output voltage. Typical for both slug and churn flows are the intermittent appearance of slug and gas zones. In churn flow the slug zone is short and the output trace is pointed at the top separated by long zero output of the gas zone, whereas the trace for slug flow has a rectangular characteristic, "flat" at top and normally contains gas bubbles.

In annular flow the output of probe A is zero while probe B output is a wavy signal.

The present method is limited to electrically conducting liquids. The actual results were obtained for water–air systems only and the applicability of this method for non air–water systems remains to be determined.

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