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A METHOD FOR THE ANALYSIS OF HOT-FILM ANEMOMETER SIGNALS IN TWO-PHASE FLOWS

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Abstract—The authors discuss the application of hot-film anemometers in gas–liquid two-phase flow. Having stored the digitized record of the anemometer output signal on magnetic tape, methods are discussed that permit the identification of the vapour-phase using electronic computer programs. Methods are described to identify large vapour slugs and small bubbles. The authors propose an extension of these methods to the treatment of two-phase flows containing both large and small bubbles.

INTRODUCTION

Several authors have reported (for example Delhaye 1968, 1969; Hsu *et al.*, 1963) on the response of hot-film probes in liquid–gas two-phase flow. These studies described the probe behaviour in some detail. Only limited efforts were made to examine two-phase flow characteristics in large scale experimental programs.

Over the last two decades a variety of methods have been proposed to evaluate hot-film anemometer signals obtained during the passage of a two-phase flow. These methods usually treated the anemometer output as an analog signal. The evaluation was carried out using electronic analog devices. The authors propose an entirely different method where the analog signal is converted into a digital equivalent. The processing of the signal from that point on uses numerical rather than analog techniques.

The first requirement in evaluating a two-phase flow with a hot-film probe is the ability to identify the phases on a record of the anemometer signal. A method is described here, where the phases are identified on a digitized version of the anemometer signal using digital programming techniques.

HOT FILM ANEMOMETER RESPONSE TO THE PRESENCE OF A LIQUID–GAS INTERFACE

The hot film probe is an analog device which provides information about the flow field by relating changes in this field, such as turbulent velocity fluctuation, to changes in the heat transfer at the probe surface. These changes in heat transfer affect the power supplied to the probe in order to maintain for example, a constant film temperature on the probe. Detailed discussions of these relationships are given for instance by Resch & Coantic (1969) and Resch (1970).

When the flow-field contains gas–liquid two-phase flow, very sharp variations occur in the anemometer output because the heat-transfer characteristics of the second phase are usually very different. Figure 1 illustrates this behaviour schematically. Abel (1975) observed this type of behaviour during the passage of large vapour slugs in a horizontal slug flow. The signal can be interpreted as follows:

A number of authors (Fuentes 1969, Gardner & Crow 1970, Brooke Benjamin 1968, Haberman & Morton 1954) have shown that in horizontal conduits large vapour bubbles travel at a higher velocity than the surrounding liquid. As the vapour slug approaches, the probe enters a boundary layer near the phase interface where the liquid velocity approaches that of

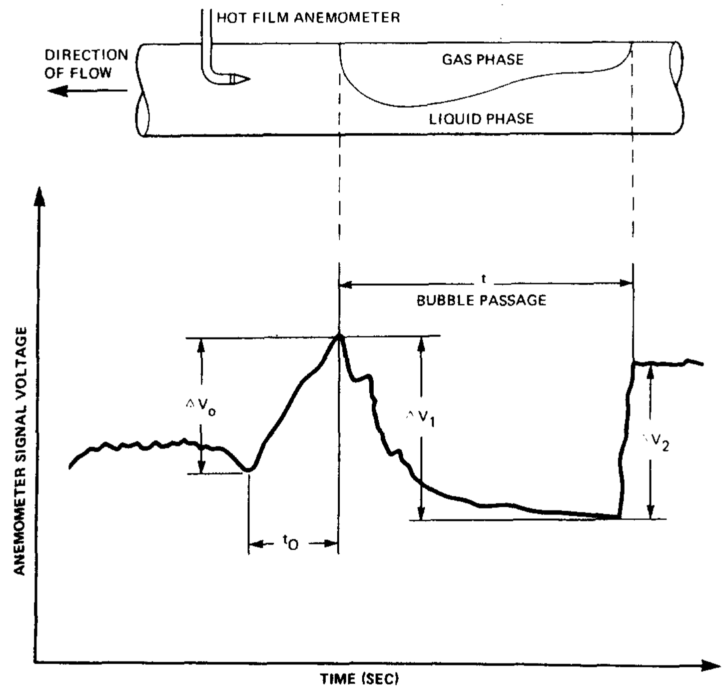


Figure 1. Schematic anemometer signal during bubble passage.

the vapour. This explains the rise in the anemometer output just before the probe pierces the bubble surface.

Delhaye, (1968, 1969) suggests that a thin liquid film which gradually evaporates remains on the probe as it enters the vapour space. The thinning film causes a gradual decrease in the rate of heat transfer. This in turn requires less power to maintain the probe temperature in the constant-temperature mode of operation. The drop in power is reflected in the gradual decrease in the anemometer voltage signal.

When the probe passes through the trailing phase interface, normal heat transfer conditions are rapidly restored as liquid wets the probe. This accounts for the rapid rise in the anemometer signal at the tail of the bubble.

Abel (1975) observed this anemometer signal behaviour during an examination of horizontal slug flow in steam water. Resch (1970) found similar characteristics in an air–water regime in the aerated portion of a hydraulic jump. Both researchers used conical hot-film probes in their studies.

Resch & Leutheusser (1972) and Resch, Leutheusser & Alemu (1974), examined the two phase region of a bubbly-type flow (hydraulic jump). Figure 2 describes the type of anemometer signal obtained in this case. This signal exhibits gradual voltage drops and sharp voltage rises during the passage of a bubble past the probe similar to those observed by Abel. But the characteristic gradual rise in voltage observed with large vapour slugs just before a bubble reaches the probe is missing. This is so because the bubbles in Resch's experiments are much smaller than the slugs in Abel's experiments and move with nearly the same velocity as the surrounding liquid.

ANALYSIS OF THE ANEMOMETER OUTPUT DURING TWO-PHASE FLOW

A large quantity of anemometer records can be handled efficiently, if the analysis can be performed with the help of digital computers. The signal must therefore be available in a form that the computer can manipulate easily. Abel (1975) and Resch & Leutheusser (1972) and Resch, Leutheusser & Alemu (1974) have used an analog-to-digital converter† to convert the

†Remote Analog-to-Digital Data Terminal (RADDT) IBM-3963 with a 12-bit precision.

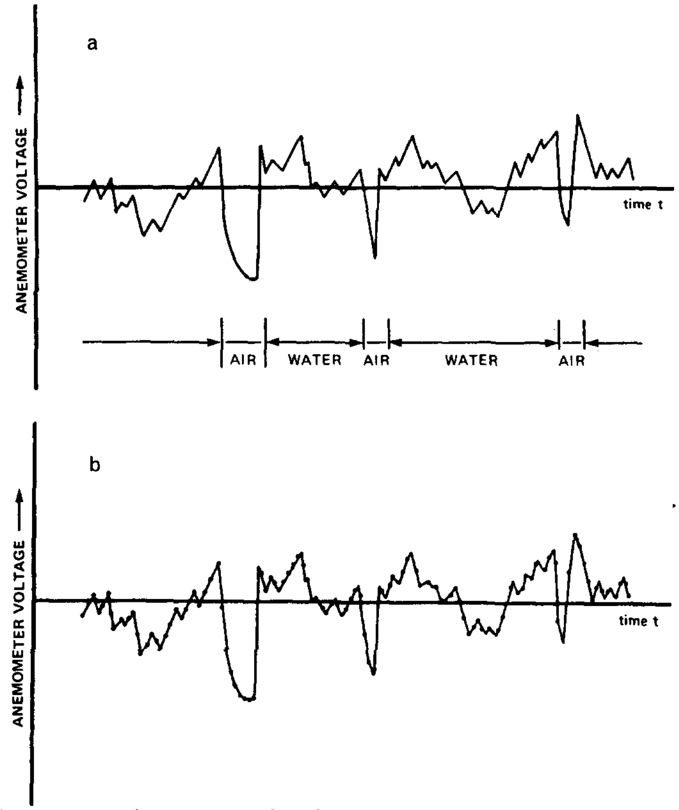


Figure 2. Phase separation: (a) analog signal in bubbly two-phase flow; (b) digitization of signal.

anemometer analog signal into digital form which was then recorded on magnetic tape using a high speed digital computer. The entire operation was done on line.

The total record length recorded and the digitization rate were chosen to provide statistical stability of the record sample as well as sufficient information to carry out analyses of the turbulence characteristics including energy spectra of the continuous liquid phase. Resch & Abel (1975) describe these requirements in detail.

Given such a digital record of the anemometer signal it is necessary to develop programs which allow the computer to detect the bubbles within a particular record. It is therefore necessary to identify the characteristics of the anemometer signal associated with the passage of a bubble in terms that are "understandable" by the computer.

(a) *The case of large bubbles or slugs*

Abel (1975) observed the motion of large vapour slugs in a horizontal conduit of 75 mm i.d. Let the passage time be defined as the time taken for a vapour bubble to move past the anemometer probe. Passage times of individual vapour slugs varied over a significant range. Examining plots of the recorded anemometer signal it became obvious that the voltage drop, which occurs when the bubble first reaches the hot film probe, increases in magnitude with increasing passage time. Similarly, the sharp voltage rise experienced when the bubble leaves the probe, shows an increase in magnitude with increasing passage time. Figure 3 shows some typical results together with a least squares fit through each group of data.

Figure 4 shows a typical portion of the anemometer signal including the passage of a vapour slug. The very distinct behaviour of the anemometer signal during the passage of the vapour slug is obvious. A specially designed subroutine named TPFLO3† takes advantage of this

†Subroutine TPFLO1 was developed by Abel & Resch for a bubble flow using a threshold technique for phase separation (Resch & Leutheusser 1972). Subroutine TPFLO2 was developed by Abel & Resch for a bubble flow using an amplitude filtering technique for phase separation (Resch, Leutheusser & Alemu (1974)).

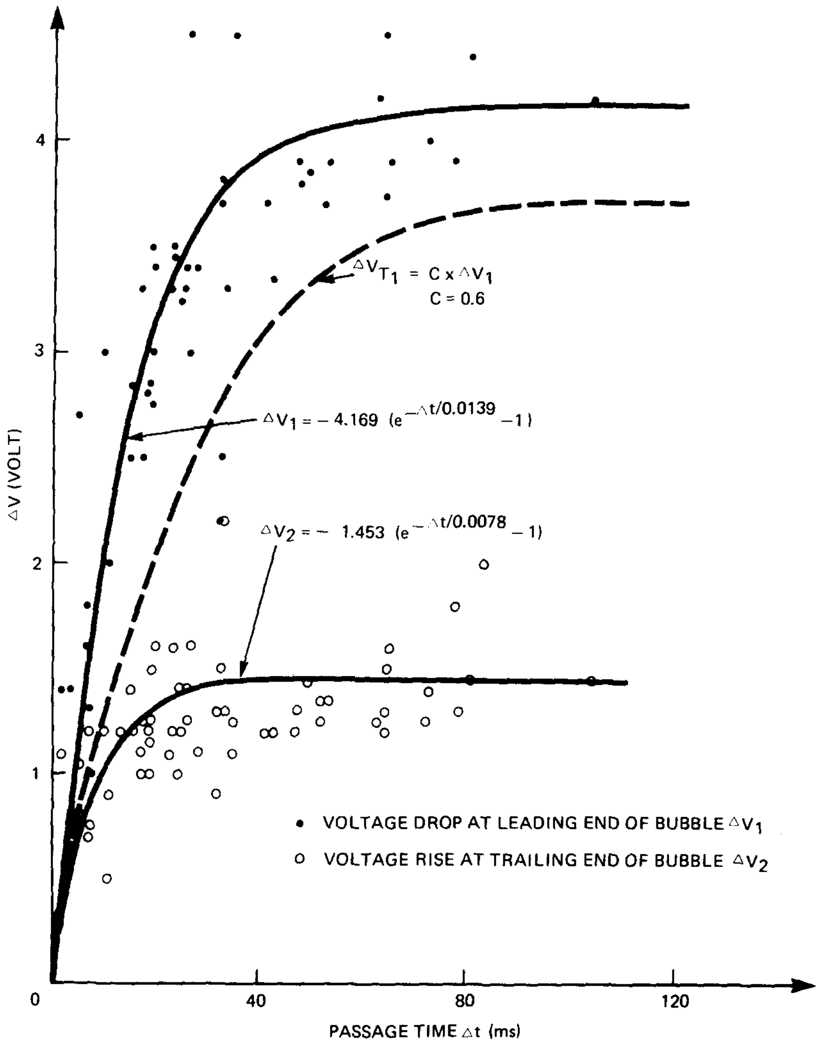


Figure 3. Anemometer signal voltage change during bubble passage.

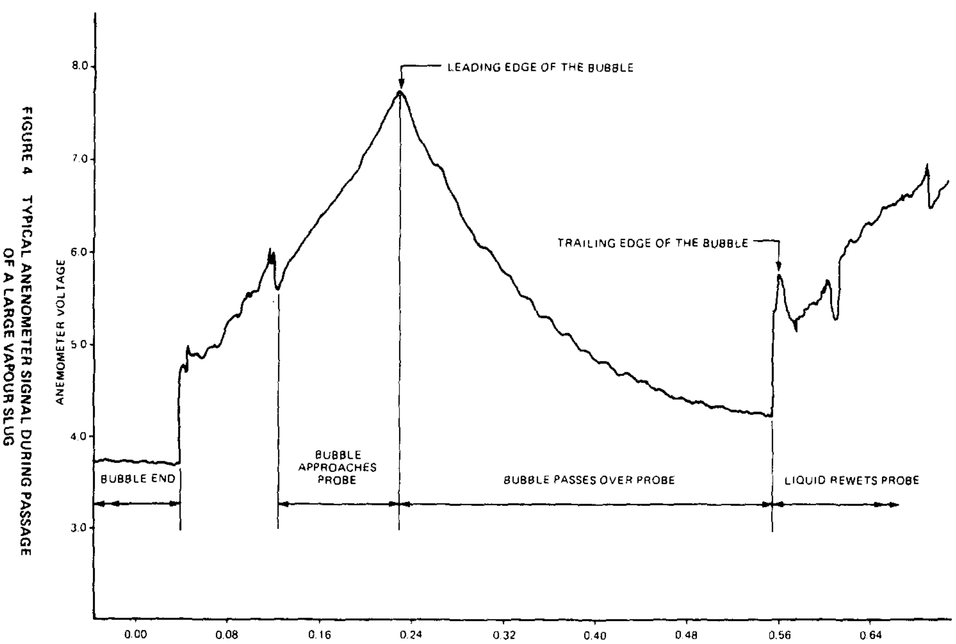


Figure 4. Typical anemometer signal during passage of a large vapour slug.

characteristic response in order to determine the location and the extent of individual vapour slugs within a particular signal record.

The principal task of this subroutine is then to distinguish between normal turbulent fluctuations in the liquid phase and the typical fluctuation due to the passage of a large bubble. The criterion employed to make this distinction is based on the behaviour described in figures 1, 3 and 4.

Each pair of successive voltage decreases and increases is tested against threshold values, which are related to the type of correlation shown in figure 3 for the spacing along the time axis between neighbouring voltage peaks. The method of testing for bubbles by the subroutine along the data record is illustrated in figure 5. If the phase separation criterion used in subroutine TPFLO3 is to be successful the proper choice of these "threshold" values is crucial. If they are set too low, liquid turbulent oscillations will be mistaken for fluctuations due to the passage of vapour bubbles. If they are set too high, some bubbles will not be identified.

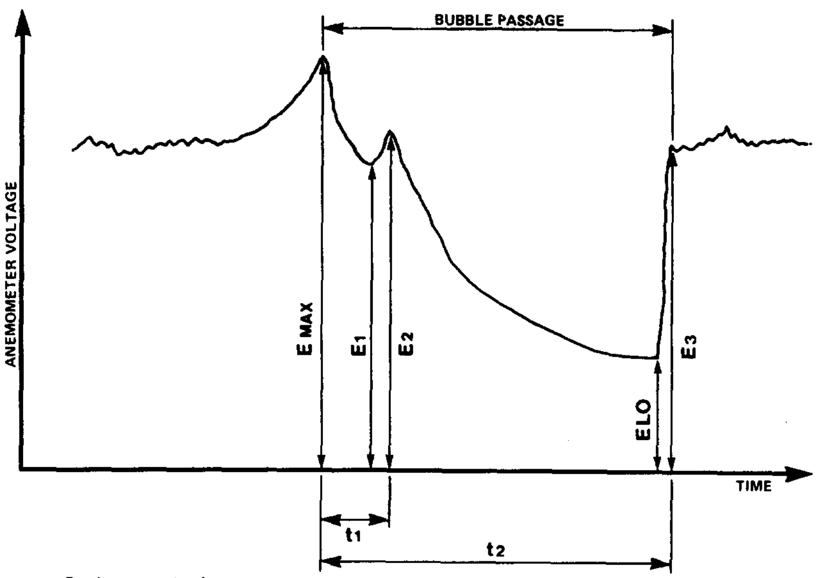
Let a least squares fit through the data of anemometer voltage change due to bubble passage be given in the form:

$$\Delta V = A(e^{-(\Delta t/\tau)} - 1). \qquad [1]$$

A corresponding threshold value V_T would then be obtained by introducing an "attenuation factor" C so that:

$$\Delta V_T = C(\Delta V) \qquad [2]$$

where ΔV, anemometer voltage change; A, correlating coefficient; Δt, bubble passage time; τ, time constant; C, attenuation factor; ΔV_T, threshold value of voltage changes to test the anemometer signal for the presence of a gas phase.



For the passage time t1:

$\Delta V_2 = E_2 - E_1 < \Delta V_{T2}$ (Threshold voltage change corresponding to t1 to recognize a bubble end from Fig. 4)

If $\Delta V_2 < \Delta V_{T2}$ the voltage change does not indicate a bubble end TPFLO3 retains the value and position of EMAX within the data-record

For the passage time t2:

$\Delta V_2 = E_3 - ELO > \Delta V_{T2}$ (Threshold voltage change corresponding to t2 to recognize a bubble end from Fig. 4)

Also:

$\Delta V_1 = EMAX - ELO > \Delta V_{T1}$ (Threshold voltage change corresponding to t2 to recognize a leading bubble end from Fig. 4)

Figure 5. Principle of bubble identification procedure in TPFLO3.

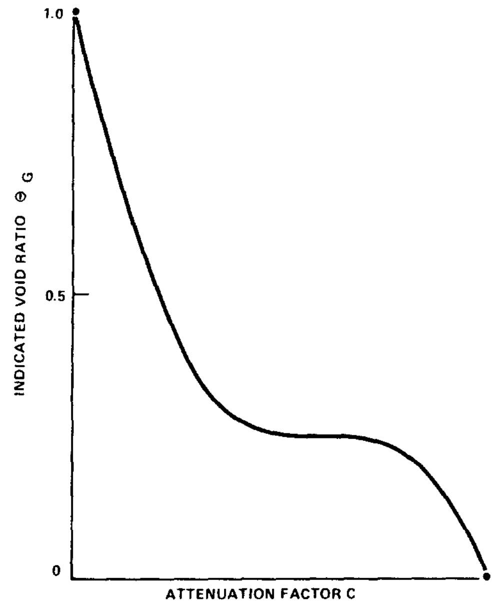


Figure 6. Variation of indicated void ratio with attenuation factor.

The attenuation factor C modifies the least square fit of ΔV to give a lower envelope to the data of the type shown in figure 3. When any actual anemometer voltage change is now compared to the threshold value ΔV_T, the computer can easily identify whether such a fluctuation is due to turbulence ($\Delta V < \Delta V_T$) or due to the passage of a phase-interface ($\Delta V > \Delta V_T$).

This approach can be taken for the voltage changes at both the leading and trailing ends of the bubble using the same attenuation factor.

Thus the choice of the correct threshold values to test anemometer signal oscillations reduces to finding the right attenuation coefficient. Before describing the method to find the correct C-value it is necessary to put one restriction on the use of [1] and [2]. Within any two-phase flow there is usually some minimum passage time t_{min}. Thus [1] and [2] are only valid above a minimum value of the passage time. This minimum value is chosen by visual examination of sample records looking for a minimum passage time.

Given a particular anemometer voltage recording, the proper value of the attenuation factor C is obtained in the following manner. The record is analysed a number of times, using the subroutine TPFLO3. For each run a different attenuation factor is used. Let the vapour time fraction θ_G be defined as the ratio of the time that the probe spends in vapour to the total time in the sample analogous to the so-called "void ratio". Plotting θ_G versus C for the series of C-values a characteristic curve should be obtained of the form shown in figure 6. Such plots were obtained by Resch, Leutheusser & Alemu (1974).

The shape of the curve can be explained as follows: For very small values of C the threshold values ΔV_T for the anemometer voltage change due to the passage of a bubble approach the magnitude of voltage fluctuations due to existing liquid velocity oscillations. Therefore a large proportion of these voltage fluctuations is "mistaken" for voltage changes due to the passage of vapour bubbles: the local vapour time fraction, θ_G, is over-estimated.

As the value of C increases, the value of the threshold voltage ΔV_T increases. It moves out of the range of voltage fluctuations due to liquid velocity oscillations but remains less than those due to the passage of vapour bubbles. When C is in this range the subroutine properly discriminates between portions of the anemometer signal due to the turbulent flow of liquid and those due to the passage of vapour bubbles. This is the reason for the plateau in figure 6.

If the attenuation factor is increased further, the threshold values of ΔV_T become too large.

Some anemometer fluctuations due to the passage of vapour bubbles are treated as though they were due to liquid turbulence. The indicated value of θ_G therefore decreases. In the extreme all voltage fluctuations are interpreted as though they were due to liquid turbulence and θ_G approaches zero.

In a real case the diagram of θ_G vs C is not always as definitive as indicated in figure 6. It is quite possible that the plateau reduces to a single point of inflection as shown in figure 7. Nevertheless, choosing an attenuation factor near this inflection point meets with reasonable success.

In identifying the phase boundaries Abel (1975) has shown very good agreement between a computer based examination of the digitized anemometer record and the visual examination of the same anemometer record reproduced on an X–Y plotter such as the sample shown in figure 4. The authors acknowledge that comparison with and confirmation by means of radiation attenuation techniques would be desirable. Unfortunately the necessary equipment was not available to the authors. They therefore recommend that their method be examined in this context by any researchers with the necessary equipment.

The programming logic used in TPFLO3 warrants some explanation. The program is designed to examine the digital voltage record in blocks. One block at a time is read into central memory and analyzed. The block size depends on the organization of the magnetic tape on which the digitized anemometer signal is recorded. In Abel's (1975) application the block size was 16,000 data. Within each block the subroutine TPFLO3 searches for combinations of voltage decrease ΔV_1 and voltage rise ΔV_2 which exceed their corresponding threshold values. The threshold values are calculated from [1] and [2] where the coefficients A and τ have been

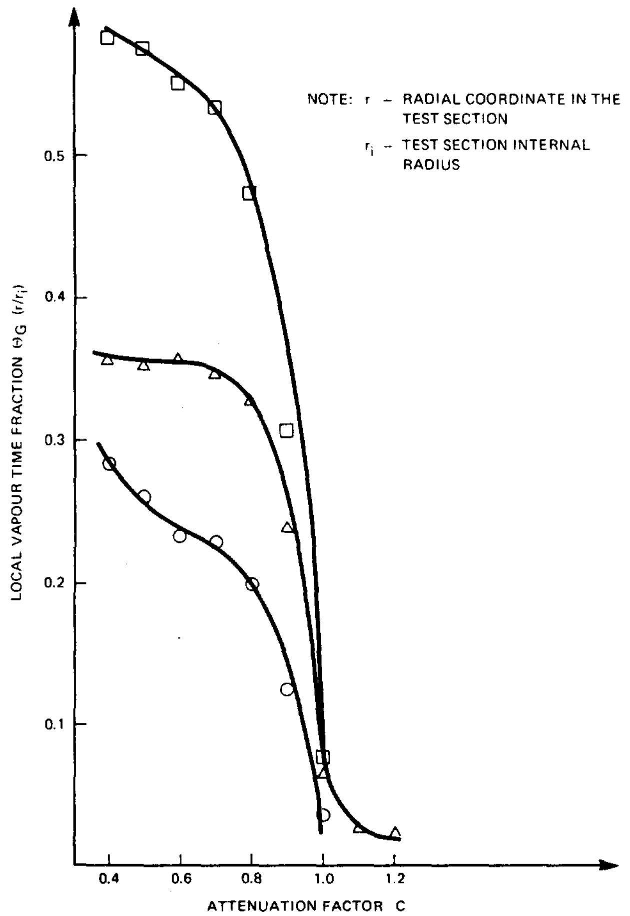


Figure 7. Local vapour time fraction vs attenuation coefficient.

determined beforehand from data of the kind shown in figure 3. If the pair of voltage drop and voltage rise does not exceed the threshold values, the examination moves on to the next pair. If the program identifies a bubble, the location of the beginning and end of the bubble is identified and stored in two arrays of integers corresponding to the array index within the data block of anemometer voltages. When the program has searched through one block, all voltage values recorded during the passage of the liquid phase are converted to equivalent liquid velocities based on the appropriate anemometer calibration. Voltages located between the leading and trailing ends of bubbles are given zero velocity values, arbitrarily.

(b) *The case of small bubbles*

The hot film anemometer signal obtained in a bubbly flow has already been treated numerically by Resch & Leutheusser (1972) and Resch, Leutheusser & Alemu (1974). This signal is illustrated schematically on figure 2 and figure 8a. Comparing figure 8a with figure 1, it is evident that ΔV_0 is very small in the case of small bubbles, while it is very significant in the case of large slug-type bubbles. For the case of small bubbles it is also found that $\Delta V_1 \simeq \Delta V_2 \simeq \Delta V$ which is not the case for large slugs.

Plotting the voltage change ΔV as a function of passage time would lead to a graph as illustrated on figure 8b. Part 1 corresponds to bubbles of type 1. These bubbles are small enough so that the liquid film covering the hot-film probe does not have enough time to

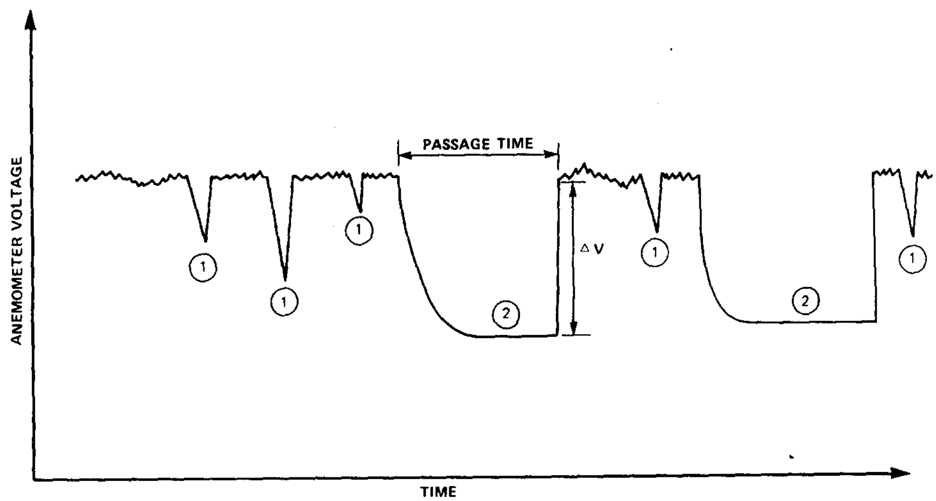


Figure 8a. Schematic anemometer voltage output in a bubble two-phase flow with bubbles of different size.

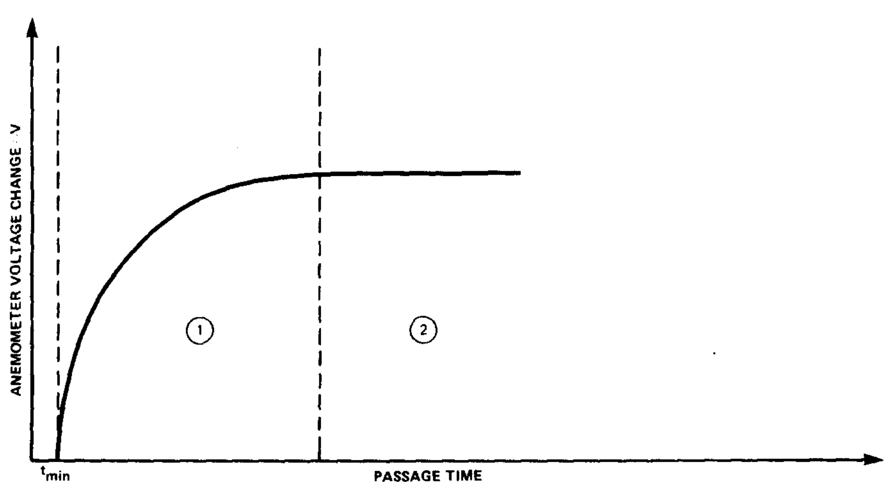


Figure 8b. Change in anemometer voltage output due to passing bubbles as a function of passage time.

evaporate while the probe is in the gas phase before the liquid phase rewets the probe as the trailing end of the bubble passes the probe. Part 2 corresponds to bubbles of type 2 on figure 8a. These bubbles are of sufficient size so that the liquid film deposited on the probe has enough time to evaporate.

Therefore one could easily apply a method identical to that for large slugs to identify small bubbles in a bubbly flow. This would require the determination of an attenuation factor C so that

$$\Delta V_T = C\Delta V$$

where

$$\Delta V = \Delta V_1 \simeq \Delta V_2$$

and where ΔV_1, anemometer voltage change due to bubble arrival at the hot film probe; ΔV_2, anemometer voltage change due to bubble departure from the hot film probe; ΔV_0, anemometer voltage change due to bubble approach near the hot film probe. For a bubbly two-phase flow a different method of bubble identification was used where the absolute anemometer voltage output is compared to a predetermined threshold value as described by Resch, Leutheusser & Alemu (1974). Consequently no data are at present available to be compared to the schematic representation of Fig. 8b.

(c) *The case of two-phase flow where both large and small bubbles are present*

In a slug type two-phase flow it is sometimes possible to find smaller near-spherical bubbles present, particularly near the downstream end of the larger slugs. A general scheme to identify the passage of the gaseous phase by means of a hot film anemometer is proposed here, which would apply to the case of a two-phase flow with a wide spectrum of bubble sizes. This approach is based, as in the two cases discussed previously, on the change in anemometer voltage output with the passage of the gaseous phase as a function of passage time. In combining figure 3 and figure 8b a characteristic anemometer voltage change vs passage time of the type shown on figure 9 would be obtained. This characteristic would incorporate those of the two extreme forms of two-phase flow, small bubbles and large slugs.

CONCLUSION

In order to analyze an anemometer signal of a two-phase flow, recorded in digitized form on magnetic tape, an effective method is required to identify the extent and location of the gaseous phase within the record. A method has been described here which has proven to be successful in the case of large slug-type bubbles. An extension of this method to deal with small bubbles and with two-phase flows containing a wide range of bubble sizes has also been proposed. Unfortunately, this proposed method could not be tested, because the authors did not have suitable two-phase flows available to them.

The authors acknowledge that other techniques such as global attenuation techniques can yield descriptions of a two-phase flow regime more quickly than the methods described here. However, local techniques of the kind proposed here are necessary if information is sought about the local character of a two-phase flow regime. When, for example, turbulence levels of the liquid phase are of interest, only a local measuring technique can be applied.

Using a local probe traverses can be carried out effectively across the flow field. If the analog signal is recorded in digital form using on-line computing facilities, the analysis of the flow can be carried out quite rapidly, even where large quantities of data are involved.

The proposed method concentrates on identifying the boundaries between the liquid and vapour phases within a particular two-phase flow. Its success in this regard has been demon-

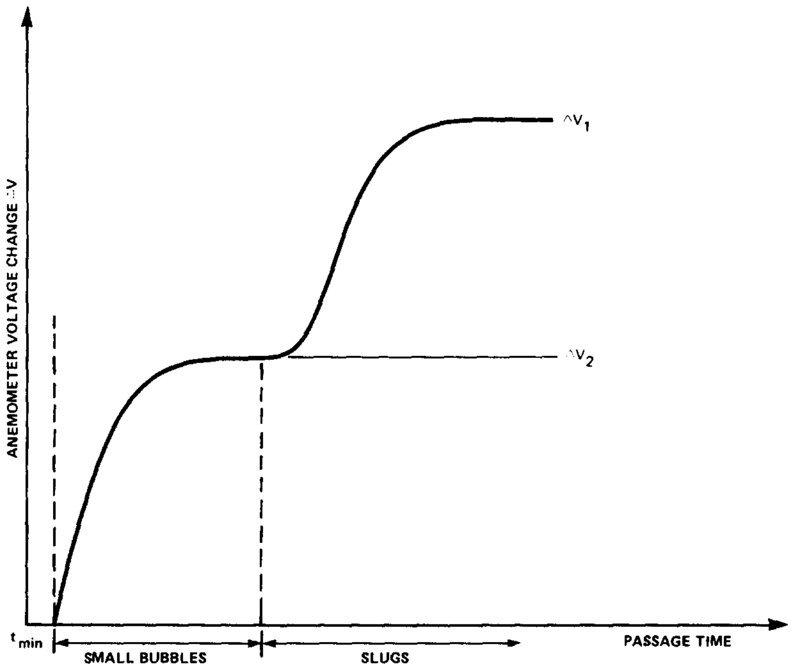


Figure 9. Change in anemometer voltage output due to passing bubbles and slugs as a function of passage time for a two-phase flow with a wide range of bubble sizes.

strated for two vastly different flow-patterns. The authors therefore propose that this method would also prove effective in identifying the phase boundaries for other flow patterns. Further development would be required to extend the capability of the proposed method to identifying the type of flow examined. Since the type of two-phase flow is dependent on such factors as phase velocities and relative volumes of the phases present, such factors would have to be taken into account.

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APPENDIX—LIST OF SYMBOLS

A	correlating coefficient;
C	attenuation factor;
E_1, E_2, E_3,	local values of absolute anemometer;
EMAX, ELO	voltages defined in figure 5;
r	radial coordinate in the test section;
r_i	test section internal radius;
t	time;
t_0	bubble approach time;
t_{min}	minimum bubble passage time;
ΔV	anemometer voltage change;
ΔV_0	anemometer voltage change due to bubble approach near the hot film probe;
ΔV_1	anemometer voltage change due to bubble arrival at the hot film probe;
ΔV_2	anemometer voltage change due to bubble departure from the hot film probe;
ΔV_T	threshold value of voltage change to test the anemometer signal for the presence of a gas phase;
θ_G	local vapour time fraction;
τ	time constant.