

Electrodiffusional diagnostics of gas–liquid flows: techniques and instrumentation*

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Application of the electrodiffusional method to gas–liquid flow studies is described. Problems connected with the use of small-size probes, gas–liquid interphase detection and multichannel measurements are discussed. A brief description of the electronic equipment is given and some results of gas–liquid flow measurements are presented.

Notation

A, a, b calibration coefficients
 D diffusion coefficient
 I probe current
 K mass transfer coefficient
 l, h probe dimensions

S velocity gradient at the wall
 u, U liquid velocity, superficial liquid velocity
 x, y longitudinal and transverse coordinates
 Z dimensionless velocity gradient
 τ_w wall shear stress

1. Introduction

An electrodiffusional (or electrochemical) method was first used for wall shear stress measurements in liquid flows by Hanratty *et al.* [1, 2]. At present this technique is widely applied for various hydrodynamics measurements. One of the fields in which the electrochemical method is effective is the study of gas–liquid flows. Mass transfer measurements in gas–liquid flows were performed by Chouikhi *et al.* [3, 4]. It seems that one of the first successful attempts to use this technique to study hydrodynamics of gas–liquid flow was made in the Institute of Thermophysics, Novosibirsk [5]. Development and application of the electrochemical method for two-phase flows also took place in other laboratories [6, 7]. Usually a wall shear stress or mass-transfer probe [2, 8], embedded into the wall, operates in a gas–liquid flow in the same manner as in a single-phase flow. If the wall is wettable a liquid film exists in all flow regimes thus making the wall probe signal continuous. Some additional problems arise when a velocity probe is used in a gas–liquid flow [9, 10]. Nevertheless, the use of different types of probes allows full information on the hydrodynamic structure of the flow to be obtained. The electrochemical method has some obvious advantages compared to hot-film or laser Doppler techniques for gas–liquid flow measurements.

2. Electrochemical probes

Two-phase flows usually have high turbulence intensities and wide fluctuation spectra and the problem of the probe frequency response is an important factor. The simplest way of avoiding this problem is to use

very small probes which operate, in most cases, in a quasi-steady mode. The size cannot be reduced below a certain limit because a very small probe loses its sensitivity to hydrodynamic parameters. Therefore, it is necessary to choose an appropriately sized probe for measurements. Figure 1 shows the calibration of rectangular wall shear stress probes of different sizes. The probes were tested in a channel of 10 mm \times 100 mm cross section. Line 1 shows the well-known relationship [2]

$$KI/D = 0.807 (S^2/D)^{1/3} \quad (1)$$

It can be seen that the deviation from the Leveque solution (1) starts from $Z < 50$ to 100, where $Z = S^2/D$. It agrees with the prediction of [11, 12]. If $Z < 100$ the probe loses its sensitivity but measurements are still possible with some precautions. The smallest probe tested had a size l of 0.02 mm. A well known result for small probes (l less than 50 μm) is that their calibration does not obey Equation 1. The exponent on the right hand side of Equation 1 becomes less than 1/3; this means that the sensitivity of the probe decreases slightly. Nevertheless, many experiments with very small probes ($l = 20$ to 30 μm) have shown that reliable measurements are possible if a relative version of the method is used. A calibration equation for the probe is used which, in dimensional form, is:

$$\tau_w = AI^n \quad (2)$$

the constants A and n being obtained for a particular probe from a single-phase flow calibration. Usually $n = 3.3$ to 3.6 for small probes. All the experiments are performed in the sequence calibration – measurement – recalibration. If the difference between the

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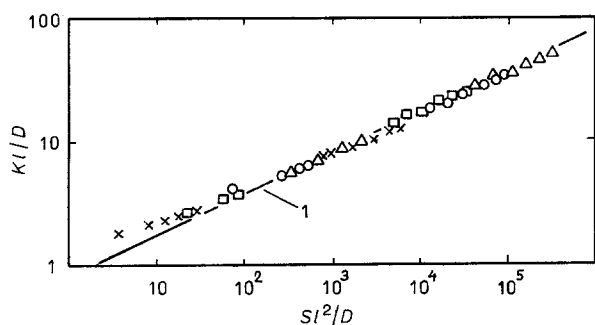


Fig. 1. Calibration of rectangular wall shear stress probes. (l, h): Δ (0.154, 0.71); \circ (0.086, 1.22); \square (0.051, 0.60); \times (0.020, 0.20).

first and the second calibrations is more than about 1–1.5% (in current) the measurement is considered as unreliable. A number of experiments made in the laboratory showed very high long-time stability of the probes, which was improved in highly turbulent flows. Different types of electrodiffusional velocity probes have been suggested elsewhere. In most of experiments it is expedient to use a “blunt-nose” type probe [9]. This is very simple to manufacture and can be made of very small size and has good performance both in single-phase and gas-liquid flows. The calibration equation of the probe has the following form:

$$I = a + bu^{1/2} \quad (3)$$

where a and b can be obtained from a single-phase calibration. The smallest diameter of probe used was 30 to 40 μm . The sensitive element is small in both transverse directions which is important for the study of gas-liquid flows with small bubble sizes.

3. Electronic equipment

The current from the local electrochemical probe is usually in the range 0.5 to 10 μA . Therefore for all the measurements a typical d.c. amplifier circuit was used (Fig. 2). This consists of two stages. The first operational amplifier A1 is a current amplifier, its gain is determined by the resistor R1. The probe voltage is adjusted by the potentiometer R2. The output voltage of A1 is then biased by this constant voltage. In order to compensate it a second operational amplifier A2 is used which suppresses the in-phase signal and the rate of suppression is adjusted by the potentiometer R8. Zero suppression of the whole circuit is made by R3. The total gain of the two-stage amplifier is varied by R1. Usually a set of feedback resistors is connected to

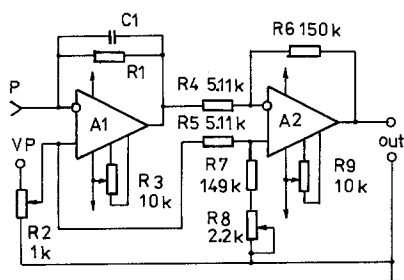


Fig. 2. Current amplifier for electrochemical probes.

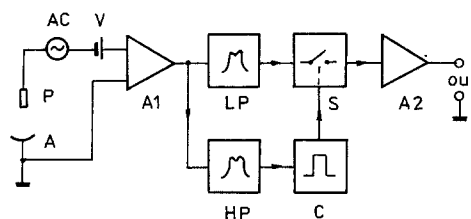


Fig. 3. Circuit for velocity measurements in gas-liquid flow.

the circuit instead of R1 to provide a wide range of measuring current variation.

If the velocity probe is placed in the gas-liquid flow it is alternatively either in liquid or in gas. When the probe is in the liquid its readings are related to the values of the instantaneous liquid velocity. When the probe enters the gas phase the electric circuit is disconnected and a sharp decrease in the current occurs (Fig. 4a). The current does not drop to zero due to the discharge of the double layer through the input resistance of the amplifier. Therefore a problem arises how to separate “liquid” and “gas” levels in the probe signal.

No simple criterion for this separation can be used. A special electronic device has been developed for this purpose. This combines two modes of probe operation, an electrochemical mode which is sensitive to the liquid velocity and a conductivity mode sensitive to the phase present at the electrode. The simultaneous operation in both modes is made by frequency separation of the signals. The conductivity mode is realized at high frequencies of 100 to 500 kHz. The electric circuit for this device is shown in Fig. 3. Two voltage sources are connected in series to the probe. A d.c. supply, V , provides the probe overvoltage necessary to put the probe in the limiting diffusion current regime. An a.c. high frequency supply, AC , adds a high frequency component to the probe current. The value of the latter depends only on the liquid or gas phase on the probe electrode. The current is amplified by a fast d.c. amplifier, A1, the output signal of which is divided into two channels by filters LP and HP.

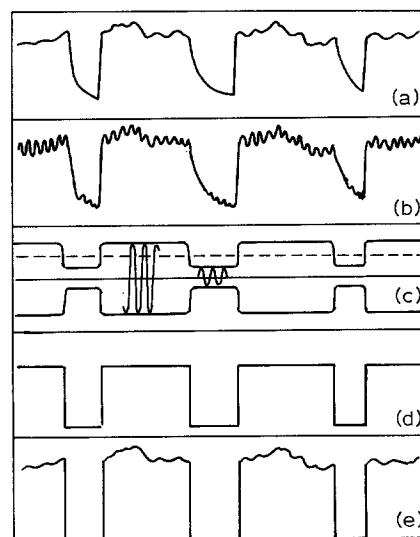


Fig. 4. Voltage diagrams.

A high-frequency component of the signal is then demodulated and processed by a signal conditioner C. This signal controls the electronic switch, S, which passes the low-frequency signal to an output amplifier, A2, only at times corresponding to the liquid phase. When gas is present on the probe, the output signal of the circuit is zero.

Figure 4 shows schematically electric signals in different nodes of the circuit: at the output of the fast amplifier (b), after low-pass (a) and high-pass (c) filters, after the demodulator (d) and the resulting signal (e). Note that the signal of the low-pass filter is just the original probe current amplified by a d.c. amplifier (without high-frequency addition). The output signal of the circuit is well-suited for analog or digital processing. The circuit shown in Fig. 3 only illustrates the principle of operation of the device. For practical purposes it is not convenient because it comprises a fast d.c. amplifier whose bandwidth should be at least 1 MHz. It is much better to use another version of this device.

A high-frequency unit is located separately near the probe. This is necessary in order to reduce the capacity of the connecting cable, which behaves as a shunting resistor at high frequency (h.f.). This unit has two transformers, a preliminary h.f. amplifier and a low-pass filter. The main unit performs the remaining processing of the signal and produces a "phase" signal which controls the gate. It is very important that the principle of phase detection described can be applied to any electrochemical velocity probe. The operation of the probe in the limiting diffusion current mode is not disturbed. If velocity measurements are not needed the d.c. voltage source should be excluded. In this case the well-known conductivity probe for local void fraction measurements is obtained.

To increase the accuracy of void fraction measurements it is necessary to set the triggering level. The "liquid" and "gas" levels were recorded automatically in the circuit described. It is possible to set a predetermined triggering level between these two levels which is indicated in the display panel of the apparatus.

4. Multichannel measurements

The combination of wall shear stress and velocity probes described above permits complex measurements in various types of gas-liquid flows to be performed. It is more effective to use several probes to obtain a set of hydrodynamic characteristics of the flow. The electrodiffusional method also has the simplicity of primary electronics. This makes it possible to use a multichannel version of the method involving simultaneous recording of the signals of a number of electrochemical probes. A diagram of the multichannel unit is shown in Fig. 5.

It consists of 8 identical current amplifiers A1-A8, each of them similar to Fig. 2. The output voltage of amplifiers is fed to sampling-storage circuits S1-S8. Their application is necessary to provide the synchronous sampling of all the signals. The circuits are trig-

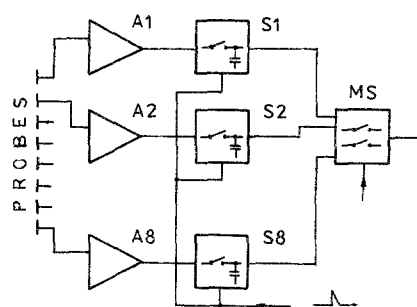


Fig. 5. Circuit for multichannel measurements.

gered by a pulse defining the moment at which the sampling is performed. Then the values of all voltages are stored in an analog form for the time necessary for their digitizing by an A-D transformer. The signals are successively fed to the transformer by an 8-channel switch, MS. If necessary, several units of this type may be used simultaneously to provide multichannel measurements. The application of circuits shown in Fig. 5 is useful, for example, for correlation measurements when simultaneous recording of all channels is of importance.

5. Application

The use of the technique described permitted extensive measurements of the characteristics of gas-liquid flows in different flow regimes to be made. It was shown, for example, that in an upward bubbly flow in a vertical pipe the distribution of wall shear stress and liquid velocity is in many cases not axisymmetric. Multichannel measurements allowed study of the detail of the structure of this asymmetric flow.

Characteristics of an upward slug flow in a vertical pipe were investigated using a special technique for data processing. A set of three probes operating simultaneously was used. The first velocity probe placed on the pipe axis indicated whether a liquid plug or a gas slug was present at the given moment in the pipe cross section. The second velocity probe was traversed from the wall to the pipe axis to measure the liquid velocity profile. Finally, the third probe was used to determine the instantaneous wall shear stress. A "sandwich" probe was used [8] which was capable of measuring both the value and the direction of the wall shear stress. Results of measurements were averaged over an ensemble of 50 liquid plugs and gas slugs.

Figure 6a shows the liquid velocity profiles along the liquid plug, x is the distance from the slug bottom. A strong profile deformation as compared to a single-phase profile (solid lines) can be observed just after the slug which is explained by the action of a toroidal vortex emerging at the front of a liquid plug. The wall shear stress distribution along the liquid plug and the gas slug is shown in Fig. 6b. There is a significant decrease of the wall shear stress when moving along the slug, negative values are possible which means that at some times the liquid near the wall moves in the opposite direction (downward).

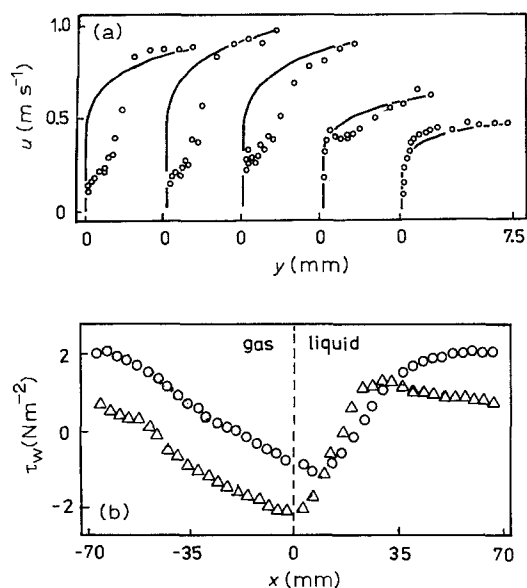


Fig. 6. (a) Liquid velocity profile, $U = 0.3 \text{ m s}^{-1}$; and (b) wall shear stress in a slug flow, (\circ) $U = 0.6 \text{ m s}^{-1}$ and (Δ) $U = 0.3 \text{ m s}^{-1}$.

6. Conclusions

Application of the electrodiffusional method to gas-liquid flow studies is very effective. Both wall shear stress and velocity probes of small size can be used for measurements. Special electronic equipment is designed to provide a reliable method for interphase detection. A multichannel version of the method seems to be useful in the flows which do not have sufficient stability in time. A set of hydrodynamic characteristics of

the flow can be measured such as local void fraction, wall shear stress, liquid velocity, intensities and spectra of shear stress and velocity fluctuations along with space-time correlations. It is clear that the further development of the method will provide new facilities for two-phase flow studies.

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