$\alpha = 0.323$; 3) $Pr_d = 0.1$, $\alpha = 0.31$; b) $\varepsilon = 2.0$: 1) $Pr_d = 10$, $\alpha = 0.206$; 2) $Pr_d = 1.0$, $\alpha = 0.157$; 3) $Pr_d = 0.1$, $\alpha = 0.126$.

We note that when $\varepsilon = 0.1$ and $Pr_d = 10$ and 0.1 the corresponding velocity profiles differ from Blasius profiles by no more than 2%. The most interesting is the relative friction τ/τ_0 at the plate surface, where τ_0 is the friction for ordinary Blasius flow. The quantity τ/τ_0 is shown in Fig. 4 (curves 1–3 correspond to $Pr_d = 0.1$, 1.0, and 10), from which it is seen that an order-of-magnitude decrease in viscosity is required for an appreciable decrease in resistance, such as by 50%.

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DIAGNOSIS OF THE FUNDAMENTAL TURBULENT
CHARACTERISTICS OF TWO-PHASE FLOWS

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In the experimental investigation of two-phase gas–liquid flows there is today a noticeable shift from the measurement of averaged characteristics (pressure drop, average gas content, and average heat-transfer coefficient) to the detailed study of the turbulent structure of the flow. What is of interest is to determine the local values of gas content, the phase velocities, the frictional stresses at the wall, and pulsation and spectral characteristics.

Among the most detailed investigations in this field we should include [1–3], published during the past few years, which give the results of measurements of local gas content and liquid and gas velocities, as well as the intensity of the velocity pulsations. The work is being done mainly by means of a thermoanemometer, by the electrical-conductivity method and partly by means of optical probes.

For a number of years the Thermophysics Institute of the Siberian Branch of the Academy of Sciences of the USSR has been conducting detailed investigations of the turbulent characteristics of gas–liquid flows. The methods used are based on electrochemical diagnosis, which makes it possible to carry out measurements of the average values and pulsations of the tangential stress at the wall and also to increase the resolving power in the measurement of phase velocities. In this way it is possible to supplement to a considerable degree the information obtained by the methods mentioned above and to obtain a more detailed picture of the flow.

In the present study we describe a method for determining the main characteristics of a gas–liquid flow.

1. Tangential Stress at the Wall. The electrochemical method of determining the tangential stress at the wall [4–6] consists in the following. Two electrodes — a small cathode and an anode — are placed in a stream of electrolyte of a special composition. The cathode serves as a sensor for determining the tangential stress and consists of a small segment of platinum or nickel wire or plate embedded flush with the wall of the channel. The application of voltage to the electrodes starts a rapid electrochemical reaction, which results in polarization of the cathode. For the case of the most widely used electrolyte composition, which consists of a

$10^{-3}N - 10^{-2}$ N solution of potassium ferricyanide and ferrocyanide and a 0.5–2 N solution of sodium hydroxide in distilled water, the reaction takes the form

$$Fe(CN)_6^{3-} + e^- \rightleftarrows Fe(CN)_6^{4-}.$$
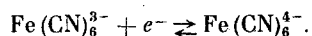
As a result of the reaction, the concentration of $Fe(CN)_6^{3-}$ ions at the cathode becomes equal to zero, and the difference in concentration between the stream and the surface of the cathode gives rise to a process of diffusion of the ferricyanide ions to the cathode. The Na^+ and OH^- ions produced by the dissociation of the sodium hydroxide enter into the solution in much larger quantities than the ions of ferricyanide and ferrocyanide, giving the solution high electrical conductivity and precluding the migration of active ions under the effect of an electric field. The area of the anode is chosen to be several hundred or several thousand times larger than the area of the cathode, and therefore the diffusion of ferrocyanide ions to the anode does not affect the process of current flow. Thus, under the indicated conditions the value of the current in the circuit is determined only by the diffusion of ions to the cathode.

A schematic diagram of the arrangement for measuring the frictional stress is shown in Fig. 1. The cathode 1 embedded in the wall and the anode 2 are in a stream of liquid with velocity profile u(y). A constant voltage is applied to the sensor by means of the voltage source 3, the current is amplified by the dc amplifier 4, and the amplifier output signal 5 is transmitted to the measuring device. At the cathode there is formed a diffusion boundary layer of thickness δ_D, the diffusion equation for which has the form

$$\partial c/\partial t + u\partial c/\partial x + v\partial c/\partial y = D\partial^2 c/\partial y^2, \tag{1.1}$$

where c is the concentration; t is the time; x is the longitudinal coordinate; y is the coordinate perpendicular to the wall; u, v are the components of the liquid velocity in the directions of the x and y axes, respectively; D is the diffusion coefficient of the ferricyanide ions. The concentration of active ions outside the diffusion boundary layer is constant and equal to c_0.

Since the $Fe(CN)_6^{3-}$ ions have low mobility, the Schmidt number for this system is high (of the order of 1500); for this reason, and also because the cathode is small, the thickness of the diffusion layer turns out to be much less than the thickness of the viscous sublayer, and within the limits of the diffusion layer we may assume that the velocity profile is linear:

$$u = y\tau/\mu,$$

where τ is the frictional stress at the wall; μ is the viscosity. If τ does not vary with time, then for the boundary conditions $c = c_0$ for $x = 0$, $c = c_0$ for $y = \infty$, $c = 0$ for $y = 0$, $0 \leq x \leq l$ (l is the dimension of the sensor in the direction of the stream), (1.1) has a stationary solution from which it is possible to determine the diffusion flow to the surface of the electrode.

In criterion form, the connection between the diffusion flow and the tangential stress at the wall has the form [4]

$$kl/D = 0.807(\tau l^2/\mu D)^{1/3}, \tag{1.2}$$

where $k = I/SFc_0$ is the mass transfer coefficient; I is the sensor current; S is the electrode area; F is the Faraday number.

If τ is not constant with respect to time, a recording of the diffusion current of the sensor can be used for determining the instantaneous value of the tangential stress at the wall. Because the active ions have low mobility, in the general case, the inertiality of the sensor current must be taken into consideration in comparison with the variation of the tangential stress. From the solution of Eq. (1.1) for $\tau = \bar{\tau} + \varepsilon \exp(i\omega t)$, where $\bar{\tau}$ is the average value over time of the tangential stress at the wall and ε and ω are the amplitude and
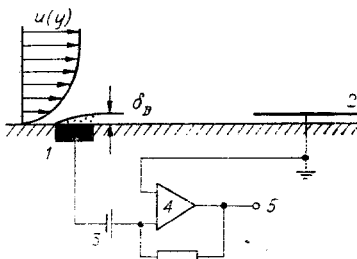

Fig. 1

circular frequency of the friction pulsations, it is possible to determine the sensor function $H(\omega)$, which reflects the amplitude−frequency characteristic of the sensor. The modulus of this function has the form [7]

$$|H(\overline{\omega})|^2 = 1/\sqrt{(9 + 0.54\overline{\omega}^2)^2 + (0.027\overline{\omega}^3)^2},\qquad(1.3)$$

where $\overline{\omega} = \omega(\mu l^2/\tau^2 D)^{1/3}$. Knowing the transfer function, we can use the spectral density of the pulsations of the current S_I in the sensor to reconstruct the spectral density of the pulsations in the friction S_τ at the wall, making use of the relation

$$S_\tau = S_I/|H(\overline{\omega})|^2.$$

This enables us to determine the mean−square value of the intensity of friction pulsations.

The operation of the friction sensor in two−phase flow is analogous to its operation in one−phase flow, since in all flow regimes there exists at the wall a film of liquid sufficient for the development of a diffusion layer. All of the relations given above are therefore applicable to measurement in two−phase flow as well.

To determine τ from Eq. (1.2), we must know the properties of the liquid (viscosity, diffusion coefficient), the dimensions of the sensor, and the concentration of active ions. Since all of these values are known with a certain error, the total error in the measurement may reach 10–15%. Therefore it is advisable to use a relative variant of the method, rewriting (1.2) in the form

$$\tau = AI^3,$$

where A is a coefficient determined in the course of calibration. It is convenient to carry out the calibration when there is a single−phase liquid flowing in the tube, determining the coefficient deflection for a known flow rate by means of the Hagen−Poiseuille formula for a laminar regime or the Blasius formula for a turbulent regime. In this case the error in the measurement of τ is 3–5%.

A transfer function of the form (1.3) is calculated on the assumption that the intensity of the friction pulsations at the wall is much lower than the average value. This condition is frequently violated in two−phase flow. For this reason it is desirable to carry out the measurements in the frequency band in which $H(\omega) \simeq H(0)$ (the quasistationary band). This can be done by using small sensors. The authors have used sensors with dimensions of 20×200 μm. In this case the real spectrum of energy−carrying frequencies in the friction pulsations lies entirely inside the quasistationary band. It is not necessary to take account of the transfer function except when measuring the high−frequency part of the spectrum.

2. Velocity of the Liquid. The only method used nowadays for determining the local velocity of a liquid in two−phase flow is the constant-temperature thermoanemometer method [1, 2]. The sensor used is a thin metal film applied on top of an insulating substrate, usually conical in shape. In [2], e.g., the dimension of the sensor was 0.6 mm. It is impossible to construct a film sensor much smaller than this.

In a number of cases, for example when operating in streams with fine gas bubbles, and also in measurements made near the wall, it is necessary to use much more miniaturized sensors. This is why the authors used an electrochemical method for measuring the velocity.

The principle of operation of an electrochemical velocity sensor is the same as that of the sensor used for measuring tangential stress at the wall. An electrode (cathode) of a determined configuration is introduced into the stream, and an electrochemical reaction takes place on its surface. The process of diffusion of active ions to the surface of the cathode is determined by the velocity of the liquid flow in the immediate vicinity of the sensor.

Figure 2 shows the shapes of electrochemical velocity sensors used by various authors: a) spherical [8], b) conical [9], c) wire thermoanemometer type [5], d) hemispherical [5, 10], e) "frontal−point" type [10, 11]. In two−phase flows, obviously, it is preferable to use the last two types, since their dimensions can be made quite small.
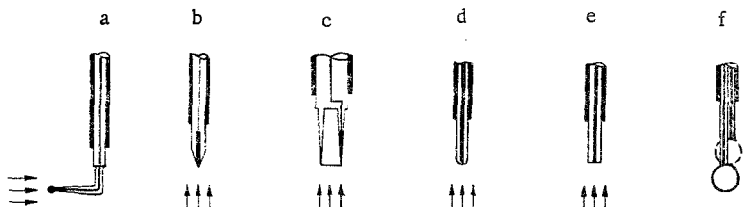

Fig. 2

The solution of the diffusion equation with a known velocity profile near the sensor is obtained from the connection between the stream velocity and the sensor current. In criterion form this relation can be written [5, 12] as

$$Nu_D = B \, Re^{1/2}, \qquad (2.1)$$

where Nu_D and Re are the Nusselt diffusion number and the Reynolds number, determined as follows:

$$Nu_D = Id/FSc_0D, \quad Re = ud/v,$$

where d is the characteristic dimension of the sensor. The coefficient B depends on the shape of the electrode.

Since the dimension for a miniature sensor is difficult to determine precisely, it is desirable not to use the relation (2.1) but instead to construct a function I(u) (where I is the sensor current, u is the stream velocity) in dimensional form for each sensor. In practice, it is desirable in the general case to use the following relation:

$$I = a + bu^{1/2}, \qquad (2.2)$$

where a and b are constants for a given sensor. It should be noted that unlike the analogous formulas for a thermoanemometer, the exponent of the velocity in (2.2) is equal to 0.5 in all cases.

In measuring high-frequency pulsations in velocity, it is important to take account of the amplitude – frequency characteristic of the sensor. Matsuda and Yamada [10] obtained a transfer function for a sensor of the "frontal-point" type,

$$|H(\omega)|^2 = \frac{0.25\left(1 + 0.0576\omega_*^2\right)}{1 + 0.331\omega_*^2 + 0.00249\omega_*^2 Sc^{1/2}},$$

where $\omega_* = \omega d/4k_1 u \, Sc^{1/3}$; Sc is the Schmidt number; the coefficient k_1 depends on the shape of the sensor nose. In particular, for a hemispherical shape $k_1 = 2$. A decrease in the dimension of the sensor is accompanied by an increase in the range of frequencies that can be transmitted without distortion. As in the measurement of the tangential stress at the wall, in determining the velocity in a stream with intense pulsations it is desirable to work in the quasistationary range, where $H(\omega) \simeq H(0) = const.$

In the present study we used velocity sensors of types d and e (Fig. 2). They were constructed by baking a platinum wire with a diameter of 20 μm into a thin glass capillary. The diameter d of the glass envelope on the endface was 30–40 μm. To give the sensor the correct shape, its endface was ground with fine sandpaper. After this the glass capillary was bent at a 90° angle and its other end was glued with epoxy resin into a stainless-steel holder 3 mm in diameter. In operation, the holder served as an anode.

Figure 3 shows the angular characteristics of sensors of two types obtained by rotating them with respect to the direction of the flow (I_0 is the sensor current along the stream, α is the angle between the axis of the sensor and the direction of the stream, 1 is a sensor of type d, and 2 is a sensor of type e). It can be seen that in the "frontal-point" sensor the angular characteristic is not monotonic; there is a rise at a certain angle of rotation, apparently caused by eddies torn away from the sharp edge. For this reason, sensors of this type were not used in the measurement. For a sensor with a hemispherical nose the current is independent of the direction of the flow up to an angle of rotation of 60°. Thus, in estimating the error of the measurements of the average velocity and the intensity of the longitudinal component of the velocity pulsations, the angular characteristic may be considered constant.

The calibration of the velocity sensor was carried out along the axis of a tube with pure liquid flow. The
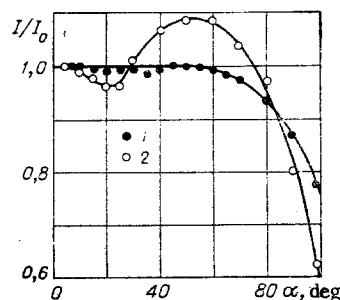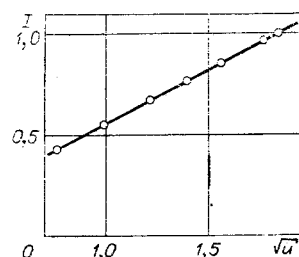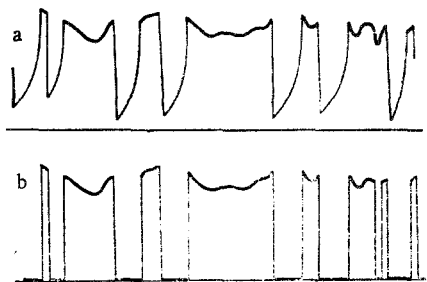

Fig. 3   Fig. 4

Fig. 5

velocity value was determined by means of a Pitot tube. Since along the axis of the tube the intensity of the velocity pulsations is low even in a turbulent regime and since there is no velocity gradient, there was no need for any correction to the Pitot tube readings. The error in the velocity measurement with the tube is no worse than 1%. The calibration function for the electrochemical velocity sensor is shown in Fig. 4; it has the form (2.2), and for u = 3.5 m/sec the first term on the right side of (2.2) does not exceed 5% of the total current.

Now let us consider the operation of a sensor in a two-phase flow. In those cases in which the gaseous phase is discrete, the cathode−electrolyte−anode circuit is closed if the sensor is in the liquid. The sensor current is determined completely by the instantaneous value of the liquid velocity near the sensor. As the sensor enters the gaseous phase, the circuit is broken and the sensor current drops. In practice there is no drop of the current to zero; as the sensor goes from the liquid into the gas, the sensor signal decreases exponentially. Figure 5a shows a typical oscillogram of the current from a sensor in a two-phase flow (the time axis is directed toward the left). It can be seen that the crossing of the interface between the phases is very clearly marked, and this makes it possible to distinguish without difficulty those times when the sensor is in the liquid. Since the dimensions of the sensor are much smaller than those of the gas bubbles, it may be assumed that the sensor does not deform the interface between the phases. Making use of simple electronic equipment, it is possible to shape the signal shown in Fig. 5b: when the sensor is in the liquid, the signal remains unchanged, while when the sensor is in the gas, the signal drops to zero. By appropriate processing of such a signal, we can obtain the characteristics of the liquid phase: the average velocity and the mean-square value of the velocity pulsations.

3. Measurement of the Local Gas Content. The simplest and most widespread method of determining the local gas content is the electrical−conductivity method [13-16]. Two electodes are placed in the stream, one of them having very small dimensions and consisting of a segment of metal wire whose surface is insulated except for a small area on the endface. This electrode is alternately in the liquid and in the gaseous phase. This alternation is accompanied by sharp changes in the electrical resistance between the two electordes, which is the indication that the sensor is in one phase or the other. A voltage is applied between the electrodes, and the current in the circuit is measured. The current has two fixed values: The larger value corresponds to the time when the sensor is in the liquid phase, the smaller value to the time when it is in the gaseous phase.

For the practical realization of this method, it is necessary to take account of the following circumstance, which affects the accuracy of the measurement. In the first place, on the surface of the electrode there may take place electrochemical processes leading to deposition of a solid coating on the surface of the sensor or to erosion of that surface, which results in a change of the sensor properties with time. In the second place, it is necessary to take account of the hydrodynamic process of interaction between the sensor and the phase interface.

In order to reduce the effect of the electrochemical processes, the measurements must be made at low values of voltage between the electrodes, since then the ions present in the solution do not participate in the electrochemical processes on the electrodes. When operating in a liquid whose composition is indicated in the preceding section (necessary for the operation of the electrochemical method), no more than 10-20 mV should be applied between the electrodes, since at higher voltage values the current in the circuit begins to depend on the velocity of the liquid near the electrode. In this case an amplifier must be used for recording the current. The use of a dc voltage source to supply the sensor, reported in numerous studies [13-15], is difficult because it places very severe demands on the measuring equipment. It is more convenient to use as the source a voltage generator with a sinusoidal or rectangular ouput. The frequency of the voltage must be
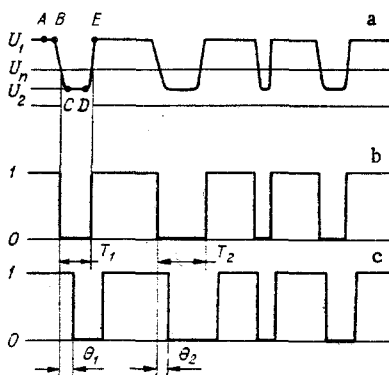
Fig. 6

several times higher than the frequency of the process. In the present study the voltage applied between the electrodes was 1-5 mV, with a frequency of 100-250 kHz. The capacitive reactance of the input cables in this case was several times as high as the ohmic resistance between the electrodes, and at the same time the measuring equipment was very simple.

The hydrodynamic process of interaction between the sensor and a gas bubble is rather complex. The real form of the sensor signal is shown in Fig. 6a, where U is the output voltage of the amplifier, proportional the sensor current.

At time A the liquid–gas boundary would intersect the sensitive element of the sensor if the latter were not there. In actuality, however, the presence of the sensor distorts the phase interface, so that the sensor intersects the interface at time B. A film of liquid remains on the sensor and gradually grows thicker, and its resistance increases. Because the film is present, the leading edge of the signal is not ideal. At time C the film disappears and the sensor is in the gaseous phase. At time D the sensor is again touching the liquid, and for some interval of time DE its current is restored to the value U_1. The trailing edge is considerably steeper than the leading edge. Therefore the above-described effect leads to a decrease of the true length of time the sensor is present in the gaseous phase, and consequently a decrease in the gas-content value. On the other hand, the presence of the sensor leads to some braking of the bubble, which makes an opposite contribution to the measured value of gas content.

A factor of great importance is the choice of the value of the threshold voltage U_t at which there is a "cutoff" of the signal. When U_t has been selected, signal a is shaped into a signal with shape b, which has ideal edges. The local gas-content value φ is determined by the formula

$$\varphi = \Sigma T_i / T, \tag{3.1}$$

where T_i is the length of time the sensor is in the i-th gas bubble; T is the total measurement time. The measurement time T must be fairly large in comparison with T_i.

There are several different recommendations concerning the choice of the U_t value [2, 15]. This question has been most carefully investigated in [2], in which the gas-content value obtained according to (3.1), integrated over the cross section of the tube, was compared with the value of the average gas content determined by the gamma transillumination method. The two values agreed to within 3-5% for a choice of $U_t = (0.5-0.7)(U_1 - U_2) + U_2$. It appears desirable to select U_t closer to the liquid level, but care must be taken to make sure that U_t is below the level of the noise imposed on U_1.

4. Measurement of the Gaseous-Phase Velocity. To measure the velocity of the gaseous phase, a double electrical-conductivity sensor is used [2, 3, 13]. If there are two sensors available, as shown in Fig. 2f, then during operation in a two-phase flow their signals will have the form shown in Fig. 6b, c: The signal from the second sensor is displaced to the right of the first-sensor signal. The times θ characterize the time of passage through the phase interface between the endfaces of the first and second sensors. The velocity of motion of the phase interface (identified with the velocity of motion of the gas bubble) is equal to $u_g = \Delta / \theta$, where Δ is the distance between the electrodes of the double sensor. By suitable averaging, it is possible to obtain the average velocity of the gaseous phase.

The most correct way would be to determine θ as the average time delay between the crossings of the leading and trailing edges of the bubble. However, in practice, for the sake of simplicity, these lines are as-

$$\tau \quad \boxed{1} - \boxed{2} - \begin{matrix} \boxed{4} \\ \boxed{3} \end{matrix}$$

$$u_l \quad \boxed{5} - \boxed{6} - \boxed{7} - \boxed{8}$$

$$\varphi \quad \boxed{9} - \boxed{11} - \boxed{13} - \boxed{15} \quad \boxed{16}$$

$$\begin{matrix} u_g \\ c_b \end{matrix} \quad \boxed{10} - \boxed{12} - \boxed{14}$$
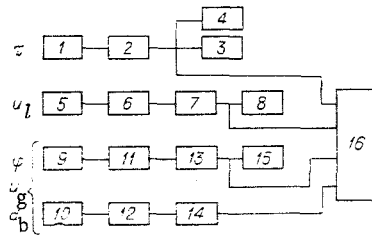
Fig. 7

sumed to be equal, and θ is determined on the basis of one of the two edges, usually the leading edge. It is assumed that the interactions of the phase interface with the first and the second sensors are identical.

Accumulation of the values of U_{gi} corresponding to different bubbles makes it possible to obtain not only the average velocity of the gaseous phase but also the mean-square value of the pulsations and other characteristics.

5. Distribution of Bubbles Along the Dimensions. From the record of the signal obtained from the electrical-conductivity sensor, shown in Fig. 6b, c, it is possible to obtain also the distributions $\sigma(T_i)$ of the time intervals T_i during which the sensor is in the gaseous phase. From this distribution it is possible to determine the distribution function $P(D_i)$ for the bubble diameters. This requires making a number of assumptions: a) All the bubbles are spherical in shape; b) all the bubbles have the same velocity u_g; c) the distribution of the bubbles with respect to the dimensions is independent of the coordinates in some neighborhood of the sensor. The relations connecting the distributions $P(D_i)$ and $\sigma(T_i)$ are given in [2, 3]. Burgess and Calderbank [17] describe a method for determining the dimensions of the bubbles which does not require making the above assumptions. However, in this case the sensor used has five electrodes and dimensions of the order of 3 mm, which limits the possibility of using this method.

6. Measuring Equipment. The block diagram of the measuring equipment used in this study is shown in Fig. 7 (sensors 1 and 5; amplifiers 2, 6, 11, and 12; double sensors 9 and 10; quadratic voltmeter 4; integrators 3 and 8; formers 7, 13, and 14; frequency meter 15; computer 16).

The signal from an electrochemical friction or velocity sensor is amplified with a dc amplifier which has measurement limits from 0.1 to 100 μA (for an input voltage of 0-5 V) and a passband of 0-100 kHz. The voltage source built into the amplifier makes it possible to choose the necessary regime of operation of the sensor. The amplified velocity sensor signal passed through a former, whose output voltage was 0 when the sensor was in the gaseous phase. Digital integrators with an integration time of 100 sec were used for measuring the average value of the voltages. The mean-square voltmeter was used only in the friction-sensor circuit, since its signal was continuous. For small values of pulsation intensity the values of $\bar{\tau}$ and $\bar{u}$ were determined by means of analog equipment. For the determination of the average values of the frictional stress and the liquid velocity $\bar{u}_l$ and the mean-square values of frictional pulsation intensity at high pulsation levels, as well as for measuring the intensity of the velocity pulsations, the signals were processed on the "Ural 14" computer.

A single or double electrical conductivity sensor was used for measuring the characteristics of the gaseous phase. The sensor signal was amplified by means of amplifiers tuned to the frequency of the input voltage. After this the amplified signals were shaped by rectangular pulses (see Fig. 6b), where the voltage threshold value in the formers could be varied. The measurement of the time the sensor remained in the gaseous phase, and consequently of the local gas content, was carried out by means of the frequency meter. To determine the distributions of the velocities and the dimensions d_b of the bubbles, the signal was accumulated and processed on an electronic computer.

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