STRUCTURE OF PRESSURE PULSATIONS IN A HORIZONTAL GAS – LIQUID STREAM

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UDC 532.529

The interface between liquid and gas in a two-phase stream, constantly varying in space, leads to the fact that the local values of the velocities of the phases, the pressure, the gas content, and other characteristics have a significant dependence on the spatial variables and time. In this connection it is very important to investigate the statistical structure of a two-phase stream both in space and in time. An important part of such investigations is the study of the spatial and temporal correlations of pressure pulsations. The correlation and spectral functions allow one to determine the frequency of velocity pulsations and to estimate the connection between pulsations at different times in different pipe cross sections, from which one can determine the scales of turbulent disturbances in a gas–liquid stream, which carry a large part of the energy of the pulsating motion.

Measurements of the pulsating pressure in a gas–liquid stream [1] showed that the amplitude and frequency of pressure pulsations vary with variation of the stream velocity and gas content and depend on the mode of flow of the mixture. In [2] an attempt was made to create a method of classification of modes of flow of two-phase mixtures on the basis of the spectral density distribution of wall pressure pulsations. Measurement of the propagation rate and intensity of pressure pulsations in an ascending bubble stream of Freon-12 was the subject of [3]. In [4] oscillograms of pressure pulsations in a vertical ascending air–water stream were used to calculate such statistical characteristics as the spatial correlations, spectral distribution, and intensity of pressure pulsations. The authors propose to represent the pulsation component of the pressure in the form of a "local" component, the spatial correlation function of which rapidly approaches zero, and a "structural" component with a spatial correlation function having an almost periodic character.

The behavior of the statistical characteristics of pressure pulsations in horizontal pipes is of particular interest. The point is that a horizontal two-phase stream, in contrast to a vertical one, is asymmetric relative to the pipe axis, considerably longer plug lengths occur here, and a layered flow structure can exist for which a nonlinear connnection between the true and the flow-rate gas content is characteristic.

Since a two-phase stream can be treated as a statistically steady process [4, 5], the start of the measurements can be chosen arbitrarily, with the condition that the measurement time is long enough (considerably longer than the characteristic period of the pulsations). By using the property of ergodicity one can measure such characteristics as the intensity of pressure pulsations in a given cross section, $\langle p'(L)\rangle$, and the space–time, spatial, and autocorrelation coefficients $R(L, \tau)$, $R(L)$, and $R(\tau)$.

The measurement of these characteristics in a horizontal pipe was carried out on an experimental installation for which a schematic diagram is shown in Fig. 1. Air from a compressor and water from the water main were supplied through valves 14 to a mixer 12, built in the form of an ordinary tee. Particular attention was paid to the organization of the exit of the mixture from the experimental section 13. The construction of the exit was chosen so as to eliminate pressure pulsations caused by hydraulic shocks upon the exit of the mixture from the experimental section into the separator 16. After passing through the experimental section the mixture drained freely into the separator, mounted directly on the working section. The chosen scheme also made it possible to avoid pulsations due to the rotation of the pump and to various bends at the entrance to and exit from the experimental section. Such pulsations were noted in [3]; the spectra of pressure pulsations obtained there had maxima at frequencies corresponding to the pump rotation frequency and multiples of it.

Rotameters 10 of the RS-3A and RS-3 type for air and of the RS-5 and RS-7 type for water were used to measure the flow rates of the components of the mixture. The experimental section 6 m long was built of pipes with an inner diameter of 15.2 mm. The pressure detectors 1 were located along the length of the pipe at intervals of 0.05, 0.05, 0.1, 0.15, 0.3, and 0.4 m. The first detector along the direction of flow was at a distance of 2.7 m from the pipe entrance. Membrane strain gauges, whose sensitivity was 2 mm of water column per millimeter of scale of the oscillograph 8, were used as the pressure sensors. A counterpressure was applied

Moscow. Translated from Zhurnal Prikladnoi Mekhaniki i Tekhnicheskoi Fiziki, No. 2, pp. 92-99, March-April, 1980. Original article submitted March 20, 1979.

0021-8944/80/2102-0233$07.50

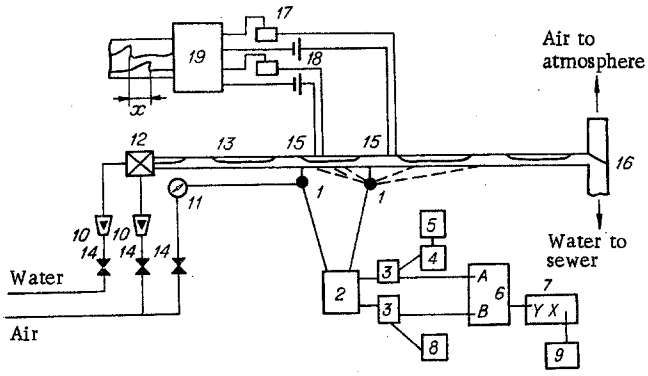

Fig. 1

to the sensor membranes, the amount of which was selected with a manometer 11 so that the sensors operated on the linear section of the characteristic curve. The signals from the pressure sensors were amplified by strain stations 2 of type TA-9.

A set of apparatus of the Disa Electronics Company was used to measure the statistical characteristics of the pressure pulsations. The signal from a strain station was fed to a matching unit 3 (unit 55D25), permitting variation of the signal level; from the matching unit the signal was fed to unit 4, measuring the rms deviation of the signal from its mean value. In the zone of low and moderate gas content ($\beta < 0.7$), where the pulsation periods are short, the rms deviation was measured in an averaging interval of 3 sec, while in the zone of high gas content ($\beta > 0.7$) it was measured with averaging over 10 sec, since the pulsation periods are considerably longer here.

Signals of equal amplitude from two detectors were fed through matching units to the input of a correlator 6 (unit 55D75) to measure the correlation functions. The coarse regulation of the levels was performed at the strain stations while the fine regulation was performed on the matching units and the correlator. The signal from the correlator output was fed to the Y input of a recorder 7. The signal from a time-delay unit 9 (unit 55D75 + 55VO1) was fed to the X input of the recorder. In all the tests the integration time was 10 sec and the maximum time shift of the correlation functions was 100 msec.

The intensity of the pressure pulsations was measured at Froude numbers Fr of the mixture of 0.4, 1, 2, 4, 8, 10, 16, and 20 and the flow-rate gas content was varied from zero to one with an interval of 0.05 for each Fr. The tests results are presented in Fig. 2.

At a fixed Froude number the intensity of the pressure pulsations first grows with an increase in the flow-rate gas content, reaching a maximum at $\beta = 0.7$–0.9, and then falls sharply. This is evidently connected with a change in the mode of flow of the mixture. At $\beta > 0.9$ the succession frequency of liquid connectors decreases and the flow becomes stratified. To determine the boundaries of the transition from plug to stratified flow we used test functions on the true gas content obtained by the cutoff method [6]. The transition to stratified flow is characterized by disruption of the linear dependence between the flow-rate and true gas content and was determined from the location of the bend in the curve of $\varphi = \varphi(\beta)$. The maximum intensity of the

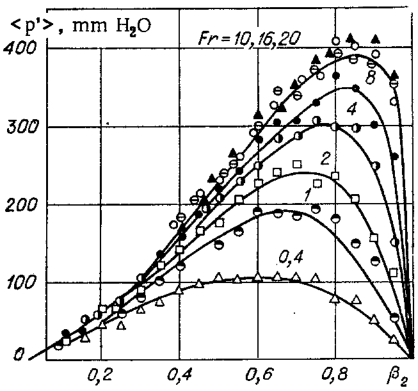

Fig. 2

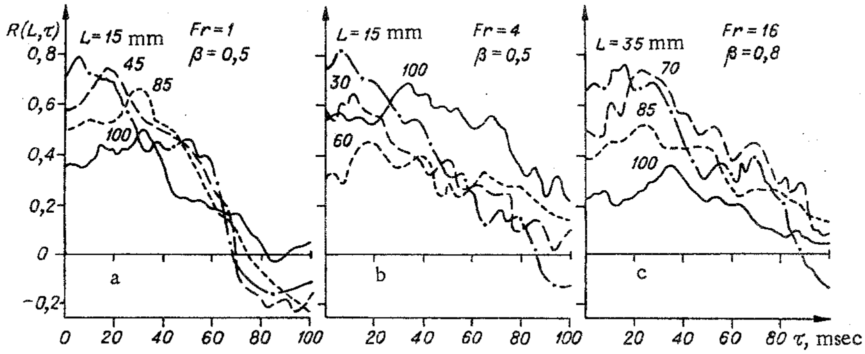

Fig. 3

pressure pulsations occurs in the region of plug flow adjacent to the boundary separating plug and stratified structures. Such flow is characterized by long lengths and low succession frequencies of the gas–liquid plugs.

With an increase in the velocity of the mixture (the Froude number) the pulsation intensity grows, the curves of $\langle p' \rangle = f(\beta)$ become steeper, and the maxima shift into the zone of higher gas content. Self-similarity of the intensity of pressure pulsations relative to the Froude number of the mixture sets in at values of $Fr \approx 10$. In this connection it is also interesting to note the self-similarity of the true gas content relative to the Froude number at $Fr > 4$, observed by many authors [6].

The intensity of pressure pulsations in plug flow is connected with such characteristics as the velocity of the liquid plugs and their length. The velocity c of the liquid plugs was measured with two electric probes 15 placed in the stream. The probes were made of electrically insulated copper wire 0.5 mm in diameter. The uninsulated ends were inserted into the stream at a distance of 1-1.5 mm from the upper generatrix of the pipe; the working liquid served as the return electrode. A constant voltage was applied to the electrodes from a galvanic element 18 of type 165U, which was regulated by potentiometers 17. The current in the circuits of the electric probes was recorded on an N-700 loop oscillograph 19. The passage of a liquid plug was determined from the sharp rise in current. The velocity $c = WL/x$ of a plug could be calculated from oscillograms of the recording of currents from two electric probes located at a distance L from each other (x is the distance on the tape between pulses in the circuits of the electric probes upon the passage of one and the same plug and W is the tape winding speed). The length of a liquid plug was calculated from the equation $l_l = cy/W$ (y is the distance on the tape where a sharp rise in current is observed).

The distance between the electric probes was varied from 0.15 m when measuring the velocity and length of short plugs ($\beta = 0.3$–0.4) to 1 m when the plugs had a long length ($\beta = 0.85$–0.9). In all tests where a plug flow structure occurred the plug velocity proved to be close to the true gas velocity averaged over a cross section. In [7] a similar result was obtained by measuring the velocity of gas projectiles in a vertical pipe, with the electrodes being placed at the pipe axis.

In the region of transition from plug flow to stratified flow with a wavy phase interface the plug velocity proved to be less than the gas velocity in almost all the tests. This is explained by the fact that considerable "slippage" of gas above the wave surface occurs in such a form of flow.

A study of the spatial and temporal correlations of the pressure pulsations provides valuable information about the flow structure of a two-phase mixture. Space–time correlations of pressure pulsations in the experimental section are presented in Fig. 3 for three values of the Froude numbers with $\beta = 0.5$. On the recordings obtained the abscissa of each point corresponds to the time shift τ while the ordinate corresponds to the correlation coefficient $R(L, \tau)$, the value of which is averaged over a time of 10 sec. It was established in the tests that at small values of the mixture velocity the curves of $R(L, \tau)$ have clearly defined maxima for all distances between sensors. This permits a rather simple determination of the optimum delay time for different sensor positions. Here it is interesting to note that the temporal radii of these functions grow with an increase in the Froude number, while the absolute values of the maximum correlation coefficients decrease with an increase in Fr.

The propagation rate of the pressure pulsations was determined from the location of the maxima of the space–time correlations through the equation

$$w_p = L/\tau_{max}, \tag{1}$$

where τ_{max} is the time shift for which $R(L, \tau)$ reaches the maximum value; L is the distance between sensors.

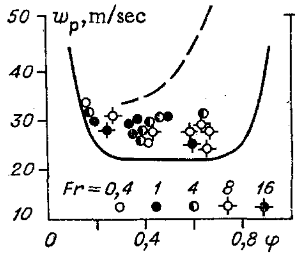

Fig. 4

The propagation rate of the pressure pulsations calculated from Eq. (1) (Fig. 4) proved to be higher than the speed of sound for isothermal flow of the mixture, obtained theoretically and measured in [6, 8] (solid line), for all Froude numbers and values of the gas content.

The speed of sound in a vertical air–water stream was measured in [9] and it was concluded that the propagation of sound signals takes place through the core of the stream and the speed of sound depends to a considerable extent on the distribution of the phases over the cross section of the pipe. A comparison of our test data with the results of [8, 9] is presented in Fig. 4. The considerable disagreement with the data of [9] (dashed line) can be explained by the fact that in our tests the measurements were made with a plug flow structure of the mixture, while in [9] they were made with a dispersed-annular structure, when the distribution of the phases is less uniform and therefore sound waves propagated faster than in plug flow.

In [8] the speed of sound was determined with low-inertia membrane manometers as the propagation rate of an elastic wave generated as a result of the instantaneous stopping of the flow. In the process the stream structure was disrupted, the profile of local concentration became more uniform, and sound waves propagated slower than in our tests.

Typical spatial correlation functions R(L) of the pressure pulsations for Fr = 1, 4, and 8 are presented in Fig. 5. The quantity R(L) was determined from the correlator readings at a zero time delay. In these tests the averaging time was 10 or 30 sec. The coefficients R(L) decrease with an increase in distance. In the general case the functions R(L) do not become equal to zero but gradually approach some value R_{sys} or oscillate about it. The data obtained confirm the tests of [5], where it was established that the time-variable component of the static pressure consists of two elements p'_{sys} and p'_{loc}. It is assumed that the component p'_{sys} acts over the entire length of the pipe and is probably due to the general level of pressure pulsations at the given values of Fr and β. The quantity p'_{loc} is manifested in a cross section of the pipe and is caused by local departures of the pressure from the average pulsation level.

It must be noted that all the spatial correlation functions obtained are characterized by several peaks with maximum values of R(L). It is seen that the curves for $\beta = 0.1$ have a larger number of peaks than for other values of the flow-rate gas content. This is explained by the fact that when $\beta = 0.1$ the lengths of the liquid plugs are small and there are as many of them distributed over the distance of the maximum shift of the sensors as there are peaks on the curve of R(L). A decrease in the absolute value of R(L) with an increase in the stream velocity was also noted in the tests. It must also be noted that the values of R(L) decrease sharply with an increase in the flow-rate gas content, when the plug flow degenerates and a transition to a stratified structure is observed.

In order to obtain a recording of the autocorrelation function of the pressure pulsations, the signal from one sensor was fed to the inputs of both channels A and B of the correlator. The autocorrelation coefficient has the property of approaching zero with an increase in the delay time τ.

With Fr = const the temporal radius of the autocorrelation functions increases with an increase in the flow-rate gas content. The amplitude of the periodic component of the pressure pulsations in the region of large time shifts grows simultaneously.

The measurements made of the correlation functions of the pressure pulsations allow us to determine the outer scales of the turbulence of gas–liquid plug flow.

By definition, the outer or integral scale

$$\Lambda = \int_0^\infty R(L)\,dL \tag{2}$$

of the turbulence characterizes the largest disturbances in the stream.

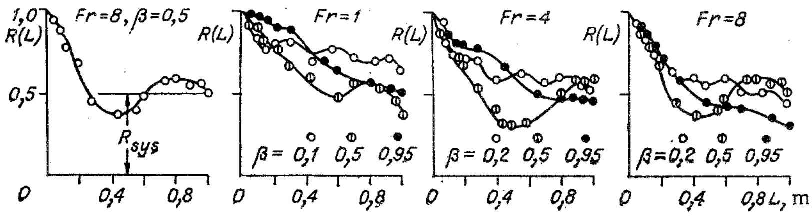

Fig. 5

However, a calculation by Eq. (2) gives infinitely large values of Λ, since with an increase in the distance between the sensors the spatial correlations approach some value R_{sys}, not equal to zero in general (see Fig. 5).

The values of Λ were calculated from the equation

$$\Lambda = \int_0^\infty [R(L) - R_{sys}]\,dL. \tag{3}$$

On the other hand, the outer scale of the turbulence can be found by integration of the autocorrelation function

$$\Lambda = w_p \int_0^\infty R(\tau)\,d\tau, \tag{4}$$

where w_p is determined from Eq. (1).

The method of graphic integration was used to calculate the integrals in Eqs. (3) and (4); the results of the calculations are presented in Fig. 6: 1) Fr = 10; 2) Fr = 4; 3) Fr = 16, calculation by (3); 4) Fr = 1; 5) Fr = 4; 6) Fr = 16, calculation by (4); 7, 8) from data of [4].

Calculations by Eqs. (3) and (4) give approximately the same results. The values of the integral scales Λ calculated from the results of the measurements of [4] and from Eq. (3) are in satisfactory agreement with our data.

In Fig. 6 the outer scales of turbulence are compared with the measured values of the lengths l_l of liquid plugs (solid lines). The comparison shows that the integral or outer scales of turbulence of a gas–liquid stream (the sizes of the largest disturbances) are on the order of the length of a liquid plug.

An analysis of the results obtained allows us to establish the existence of an interrelationship in the laws of variation of the integral scales Λ of turbulence of a gas–liquid stream, the lengths l_l of the liquid plugs, the intensity of the pressure pulsations, and the true gas content φ on the determining criteria of a two-phase stream (the Froude number and the flow-rate gas content).

First of all, we must mention the self-similarity of these quantities with respect to the Froude number of the mixture, setting in at about the same values of Fr ≈ 4-10.

From the physical point of view this can be explained by the fact that with an increase in the Froude number, inertial forces play an ever larger role in comparison with gravitational forces and finally far exceed them when Fr > 10 [5]. From this time gravitational forces have almost no effect on the flow structure (on the shape of the interface), and this leads to stabilization of the turbulence scales of a gas–liquid stream.

The quantities Λ, l_l, and $\langle p' \rangle$ reach their maximum values in the zone of transition to stratified flow of the mixture (see Fig. 6) and then decrease sharply.

The investigation conducted allows us to give a qualitative description of the mechanism of pressure pulsations in a gas–liquid stream. A pulsation in concentration developing due to the instability of the interface generates a pressure pulsation, which propagates in the stream with the speed of sound. The experiment shows that the scales of the energy-bearing pulsations are considerably greater than the scales of the turbulence of a one-phase stream [10] and are close in value to the length of the liquid part of a plug.

Thus, one can speak with complete justification of the existence of two types of pulsations on the hydrodynamic quantities in two-phase streams: fine-scale pulsations, analogous to those of a one-phase stream, and large-scale pulsations, due to pulsations of concentration, having scales close to the length of the liquid part of a plug (the characteristic size of an inhomogeneity of the stream).

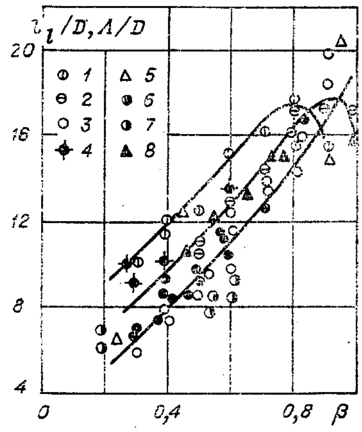

Fig. 6

The characteristics of pressure pulsations essentially depend on the structure of the gas–liquid plugs. In our tests the plug flow was characterized by a sharp phase interface and an almost periodic succession of liquid and gas plugs, which is inherent to pipes of small diameters. Because of this the values of R_{sys} were higher for the same Froude numbers and values of the gas content than those obtained in [4] for less stable gas-saturated plugs characteristic of pipes with a diameter of more than 30 mm.

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