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STUDIES OF INSTABILITY OF TWO-PHASE FLOWS IN PARALLEL CHANNELS

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Experiments were carried out to determine boundaries of unsteady-state flows of a two-phase water-air mixture in three parallel vertical channels. It is shown that under certain conditions of parallel operation of individual channels self-sustained fluctuations of the pressure drop can appear and that interchannel interations can lead to unstable two-phase flow regimes with stable hydrodynamic characteristics of the individual channels and the whole system. It is shown that these fluctuations are caused by nonlinear characteristics of the two-phase flow.

Introduction. The behavior of a two-phase mixture is a complicated dynamic phenomenon which, depending on the characteristics of the device and the range of operating parameters, manifests itself as damped or self-sustained fluctuations of the flow rate, pressure, temperature, and other parameters. The boundaries within which the system parameters change substantially characterize the appearance of unstable flow regimes, which determines the boundary of normal operating conditions of devices and equipment in which a two-phase flow is used as a working body. Instability is especially important in systems with a large number of parallel channels, which are found in almost all apparatus producing or using two-phase mixtures.

Research on the hydrodynamic instability of two-phase flows was started to solve the problem of stability of a flow of a heat-transfer agent in straight-through boilers in the 1930s [14, 22]. The causes and mechanisms of thermohydrodynamic instability in channels were classified in [3], and in [26] experimental studies were carried out to investigate the main forms of instability in single channels with adiabatic flow of the heat-transfer agent. Adiabatic flows in single channels have been studied by several authors. For example, Nassos and Bankoff [18] investigated the propagation of density disturbances in a two-phase water-air mixture. Miyazaki, Fujii, and Suita [17] studied experimentally and analytically the propagation of pressure waves, and Ozawa, Akagawa, Sakaguchi, and Suezawa [20], fluctuations of the pressure drop.

In a system of parallel channels hydrodynamic instability is much more complicated than it is in a system of single channels, since all kinds of instability occurring in single channels appear in multi-channel systems as well, but with instability common to all channels or interchannel instability. With a large number of parallel channels interchannel instability is exhibited more often and its consequences for the operation of the apparatus can be very important [23]. Masini, Possa, and Tacconi [16] studied the instability in two identical parallel channels, and Fakuda and Kobori [6] determined the boundary of the instability in the case of pressure and natural flows in two parallel channels. Crawley, Gouse, and Deane [4] and D'Arcy [2] investigated the instability in a system of three parallel heated channels, and Akagawa et al. [1], the Ledinegg instability in three long parallel horizontal channels. Dolgov and Sudnitsyn [5] determined the conditions of stability of adiabatic flows in three parallel channels, and Komyshnyi et al. [13] and Yarkin, Kulikov, and Shvidchenko [27] sought the boundaries of interchannel fluctuations in an experimental setup with two and three parallel channels. The fluctuation characteristics of unstable flows in two and four parallel channels are considered in [11, 15, 25]. The characteristics of unstable flows of adiabatic two-phase water-air mixtures in two parallel channels were investigated by Ozawa, Akagawa, and Sakaguchi [21], and transfer functions were determined and the dynamic characteristics of three parallel channels were identified by V. Jovič, L. Jovič, Afgan, and Djorovič [7, 8].

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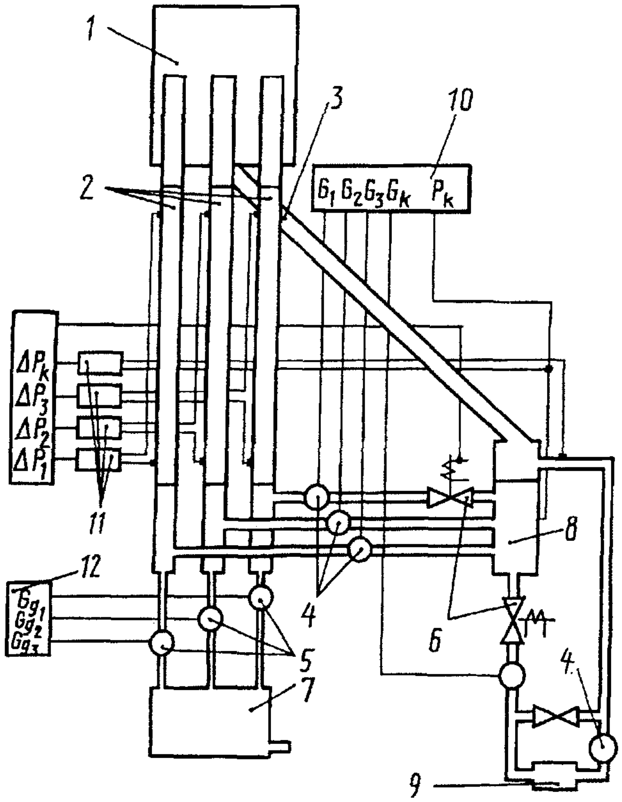

Fig. 1. Schematic drawing of the experimental setup: 1) separator; 2) experimental sections; 3) delivery section; 4) liquid flow meters; 5) gas flow meters; 6) electromagnetic valve (EMV); 7) tank with air; 8) single-phase collector; 9) pump; 10) data recording system; 11) pressure drop measuring scheme; 12) analog data recording system (indices 1, 2, 3, numbers of channels; k, main loop).

This article contains results of experimental and analytical studies of interchannel fluctuation instability in an adiabatic flow of a two-phase water-air mixture in a sysem of three parallel hydrodynamically identical channels. The obtained results show that dynamic equilibrium of conservative forces in the two-phase system does not ensure stable operation of all its parts and that with flow regimes in which in two-phase sections of the channels compressibility forces exceed dissipation and inertia forces, unstable fluctuations of the pressure drop appear in one or all three parallel channels with stable characteristics of the whole system.

Experimental Setup. Experimental studies were carried out in a laboratory setup consisting of a closed circulating loop with three parallel vertical channels and an adiabatic water flow and a two-phase water-air mixture. The setup consists of the main water loop, parallel channels, a separator, a delivery section, and an air supply system (Fig. 1). The parallel channels contain horizontal and vertical sections and are located between a single-phase collector and the separator operating as a two-phase collector. Water flows in the horizontal sections, and the two-phase water-air mixture produced in the mixers flows in the vertical channels. The conditions were made close to real by conducting the experiments with a nonsymmetric distribution of the flow rate in the parallel channels. For this purpose, the horizontal sections of the channels had different hydraulic resistances, which provided the required hydrodynamic identity of the parallel channels.

Experimental sections 1300 mm in length are a part of the vertical channels with a circular cross-section of 66 × 50 mm. The outside walls of the experimental sections are made of glass, which allowed direct observation of the flow in the cross-section. Two electromagnetic valves (EMV) were installed to introduce external disturbance into the system: the first was mounted in the horizontal single-phase part of a parallel channel and used for the introduction of interchannel disturbances into the system and the other was located in the main loop to induce disturbances common to all channels.

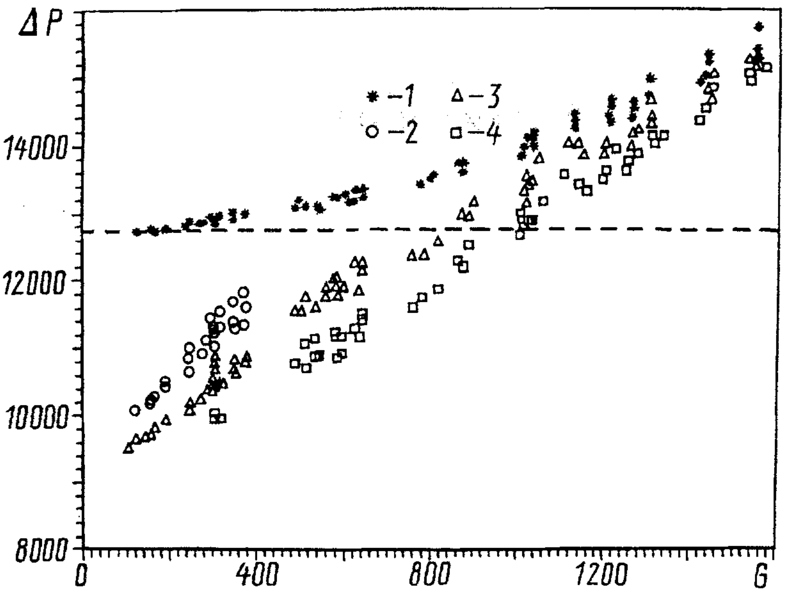

Fig. 2. Stable hydraulic characteristic of the channels: line) gravity pressure level; experimental conditions for air flow rate; 1) $Q_g = 0$; 2) 0.08–0.11; 3) 0.16–0.25; 4) 0.38–0.46 dm^2/sec. G, kg/(m^2·sec); ΔP, Pa.

Experimental data were measured and recorded by instruments providing accuracy in steady-state regimes and reproducibility of measurements in unsteady-state regimes. For estimation of the reproducibility we carried out a dynamic analysis of the amplitude-phase characteristics of the main components of the measuring system, primarily, active and passive filters. The obtained results showed that the assembled measuring system haa a sufficiently wide transmission band and provided reproduction of the full frequency spectrum of the measuring signals with minimal error.

The measurements were carried out for single and parallel channels with a flow of single-phase or two-phase fluid in the following ranges of parameters:

Pressure	atmospheric
Temperature	17–37°C
Water flow rate (kg/sec)	
channel 1	0.439–1.663 (EMV channel)
channel 2	0.172–0.538
channel 3	0.845–2.247
Air flow rate (g/sec)	
channel 1	0.226–0.591
channel 2	0.117–0.281
channel 3	0.234–0.577
Working fluid	water, water-air
Operating conditions	adiabatic

The experimental procedure consisted in determination of the hydrodynamic characteristics of steady and unsteady flows of a single-phase liquid or a two-phase mixture. It should be noted that unsteady flows were transient processes appearing in the channels when the EMV was closed very quickly in the channel with disturbances, and steady were the flows before the introduction of disturbances (initial steady state) and flows after completion of the transient process (final steady state). In steady states there are no differences between individual channels in the case of single or parallel operation, whereas in an unsteady state these differences are quite noticeable.

Steady-state adiabatic flows of a single-phase fluid and averaged parameters of two-phase flow were investigated to determine the hydraulic characteristics of the channels, cubic gas contents, flow regimes, friction coefficients, two-phase factors, etc., necessary for hydrodynamic identification of unsteady flow regimes.

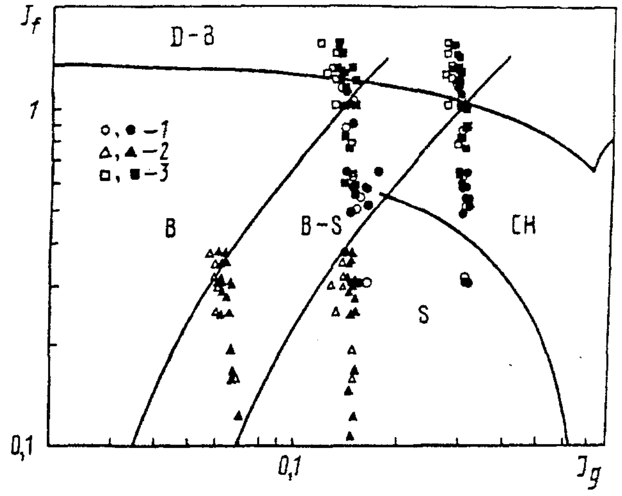

Fig. 3. Two-phase flow regimes in parallel channels; operating conditions of the channels: 1) channel 1; 2) channel 2; 3) channel 3; open points) parallel operation of the channels; filled points) single operation of the channels; flow regimes: B) bubble flow, B-S) bubble-slug flow; S) slug flow; CH) foaming flow, D-B) disperse-bubble flow. J_f, J_g, m/sec.

In the considered flows with single and parallel operation of the channels the steady-state hydrodynamic characteristics of the channels and curves of pressure drops versus fluid flow rates have no regions with a negative slope in the initial and final steady states (Fig. 2).

TABLE 1. Pressure Drop Fluctuation Amplitudes in the Case of Parallel Operation of Channels

Regime	Initial state				Final state			
	channel 1	channel 2	channel 3	main loop	channel 1	channel 2	channel 3	main loop
One-phase flows								
1A	0,50	0,69	0,37	0,71	0,59	0,87	0,59	0,60
2A	0,70	1,40	1,77	0,35	2,01	0,94	1,93	0,48
3A	0,69	2,98	0,53	0,39	2,82	2,14	0,94	0,89
4A	1,09	1,58	1,52	0,40	2,18	1,89	1,17	0,96
Two-phase flows								
1B	2,78	38,86	1,13	0,49	12,95	13,42	0,76	0,57
2B	1,66	29,06	3,73	0,50	6,96	16,66	2,24	1,00
3B	1,38	55,63	7,17	0,41	8,94	7,47	4,11	0,56
4B	2,54	81,92	11,93	0,97	23,13	33,30	6,19	0,99
1C	2,09	34,61	3,36	0,43	20,17	19,10	1,40	0,72
2C	2,11	47,18	8,90	0,44	55,92	29,78	2,79	1,11
3C	4,74	47,86	2,01	0,41	32,26	9,89	3,42	0,88
4C	7,13	93,94	27,07	0,93	20,15	37,15	10,76	0,75

The two-phase flows were studied using the chart of regimes by Kolessediss and Dukler [12], who determined the boundary-value relations between the flow regimes for the considered geometry of a vertical circular channel and experimental range of parameters of a two-phase flow in the channels. The results show that the two-phase flow regimes in the channels are represented in all regions of the chart, and every channel has its dominant part (see Fig. 3). For channel 1, the transition region between bubble and slug flows (about 42%) is dominant; for channel 2, the region of stable slug flow (about 50%) dominates; and for channel 3, the region of disperse bubble flow (about 56%) is dominant.

The results of the experimental studies of unsteady flows are the time characteristics of the pressure drop in the channels and the main loop, which is the system's response to a disturbance of the water flow rate: in the

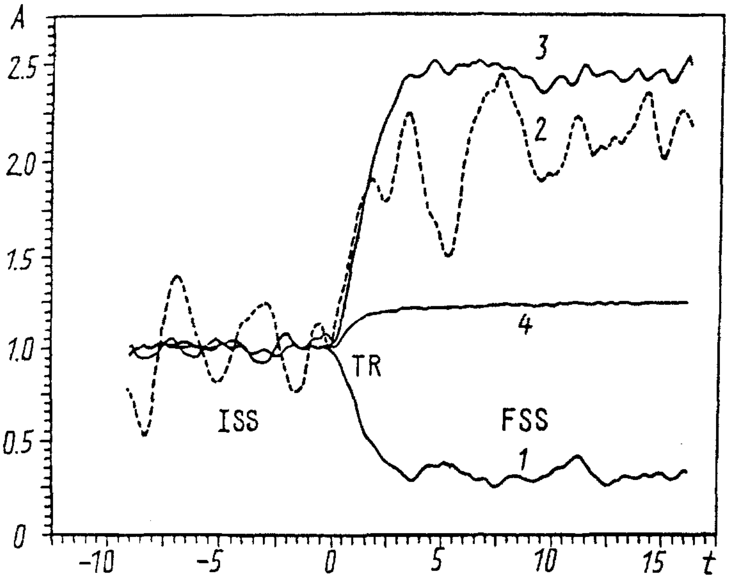

Fig. 4. Time characteristics of parallel channels: 1) channel 1; 2) channel 2; 3) channel 3; 4) main loop; ISS) initial steady state; TR) transient process, FSS) final steady state. *t*, sec.

TABLE 2. Operation Regimes of Parallel Channels and Main Loop

Regime	Water flow rate (kg/sec)				Air flow rate (g/sec)			
	channel 1	channel 2	channel 3	main loop	channel 1	channel 2	channel 3	main loop
One-phase flows								
1A	1,59–1,66	0,42–0,45	1,88–1,93	3,89–4,04	0,0	0,0	0,0	0,0
2A	1,44–1,52	0,38–0,42	1,73–1,77	3,55–3,71	0,0	0,0	0,0	0,0
3A	1,24–1,29	0,33–0,35	1,45–1,48	3,02–3,12	0,0	0,0	0,0	0,0
4A	0,77–0,80	0,17–0,22	0,84–0,92	1,78–1,94	0,0	0,0	0,0	0,0
Two-phase flows								
1B	1,59–1,66	0,42–0,45	1,88–1,93	3,89–4,04	0,266–0,331	0,117–0,131	0,255–0,281	0,0
2B	1,44–1,52	0,38–0,42	1,73–1,77	3,55–3,71	0,266–0,331	0,117–0,131	0,255–0,281	0,0
3B	1,24–1,29	0,33–0,35	1,45–1,48	3,02–3,12	0,266–0,331	0,117–0,131	0,255–0,281	0,0
4B	0,77–0,80	0,17–0,22	0,84–0,92	1,78–1,94	0,266–0,331	0,117–0,131	0,255–0,281	0,0
1C	1,59–1,66	0,42–0,45	1,88–1,93	3,89–4,04	0,564–0,582	0,258–0,284	0,532–0,574	0,0
2C	1,44–1,52	0,38–0,42	1,73–1,77	3,55–3,71	0,564–0,582	0,258–0,284	0,532–0,574	0,0
3C	1,24–1,29	0,33–0,35	1,45–1,48	3,02–3,12	0,564–0,582	0,258–0,284	0,532–0,574	0,0
4C	0,77–0,80	0,17–0,22	0,84–0,92	1,78–1,94	0,564–0,582	0,258–0,284	0,532–0,574	0,0

case of parallel operation, of the flow rate of one of the parallel channels (the channel in which disturbances arise) and in the case of single operation, of the flow rate of the channel considered. In the case of parallel operation, a negative disturbance was introduced into the channel with disturbances, and in the case of single operation, a disturbance was introduced, whose absolute value and sign corresponded to the disturbance introduced in the case of parallel operation. The behavior of the time characteristics normalized on the initial steady state can be described as follows: the time characteristic of channel 1 (the channel with disturbances) drops, and that of the other channels and the main loop rises. Analysis has shown that inertia and dissipative forces that change the achieved level have the greatest effect on the form of the characteristics; in the transient process and in the final steady state the level of fluctuations depends on the compressibility of the two-phase mixture. An increase in the air flow rate and a decrease in the water flow rate result in a lower level of fluctuations.

Fluctuation Characteristics. Analysis of the time characteristics in the parallel channels and the main loop shows that in all steady-state regimes considered, the experimental data on the output physical quantities fluctuate about the initial or final states. The fluctuation amplitudes and frequencies depend on the flow parameters. The pressure-drop fluctuation amplitudes range from 0.37 to 93.3% of the corresponding steady state (Table 1), and the fluctuation frequencies range from 0.36 to 3.44 Hz. The largest pressure drop fluctuation amplitudes appear in channel 2, which has the highest hydraulic losses in the inlet section.

Since a steady state sets in when the curves of the transient processes differ by ±15% from those of the final steady state and instability is exhibited as complicated periodic variations with large amplitudes, from the view point of the fluctuation behavior, single and parallel operating regimes can be divided into (a) hydrodynamically stable regimes with amplitudes of up to ±15% of the corresponding steady state; (b) transition-zone regimes with amplitudes of ±5 to ±10%; and (c) regimes of fluctuation instability with amplitudes exceeding ±10% of the corresponding steady state.

In Fig. 4 one can see time characteristics that clearly illustrate the transient process, the initial and final steady state, and the level of fluctuations, stable and unstable. Table 1 contains pressure drop fluctuation amplitudes in the case of parallel operation of the channels, and Table 2 presents characteristics of one operating regimes of the parallel channels and the main loop.

Analysis of Table 1 shows that in the ranges of parameters considered all single-phase regimes, including flows in the main loop, and about 47% of the two-phase flows occur in the region of stable fluctuations; about 38% of the two-phase flows occur in the region of unstable fluctuations; and about 15% of the two-phase flows occurs in the transition zone. In the range of stable fluctuations most of the flows occurred in channels with a high water flow rate, namely, in channels 1 and 3 (about 62 and 59%, respectively), and in channel 2 with a lower water flow rate there were about 9% of the regimes; in the transition zone most of the regimes occurred in channel 3 (about 25%), in channel 1 there were about 9% and in channel 2, about 6%; in the region of unstable fluctuations an absolute majority of regimes (about 84%) occurred in channel 2 with a high gas content. It should be noted that in channel 1 there was about 28% of regimes and in channel 2, about 15%.

In the case of parallel operation of the channels, regimes of unstable fluctuations can appear simultaneously in one, two, or three channels. Simultaneous fluctuation instability was recorded in three channels in one regime, in two channels in six regimes, and in one channel in three regimes. It is evident that regimes of fluctuation instability occur in one steady state or in both. In one steady state they are exhibited in regimes of the final steady state in channel 1 (the channel with disturbances), and in both states they appear in almost all two-phase flows in channel 2 (Table 1).

Nonlinearity of Characteristics. Linearity or nonlinearity of the characteristics is an important feature of transient processes, which is still studied inadequately, especially for unsteady flows of a two-phase mixture in parallel channels. With this in view, in the present work a study was carried out to investigate the time characteristics of experimental transient processes as regards linearity or nonlinearity, and conditions were found that allow identification of the behavior of the system as linear or nonlinear.

Linearity or nonlinearity of the time characteristics of experimental transient processes was determined by comparison of experimental curves with transfer functions of the channels obtained analytically with the following procedure [9]:

1. In the case of parallel and single operation of the channels, on the basis of experimental curves of the transient processes, the transfer functions of every channel and the main loop were determined by the method of parametric power identification in the range of from the first to fifth powers upon the introduction of a sudden change in the flow rate in the channel with disturbances.

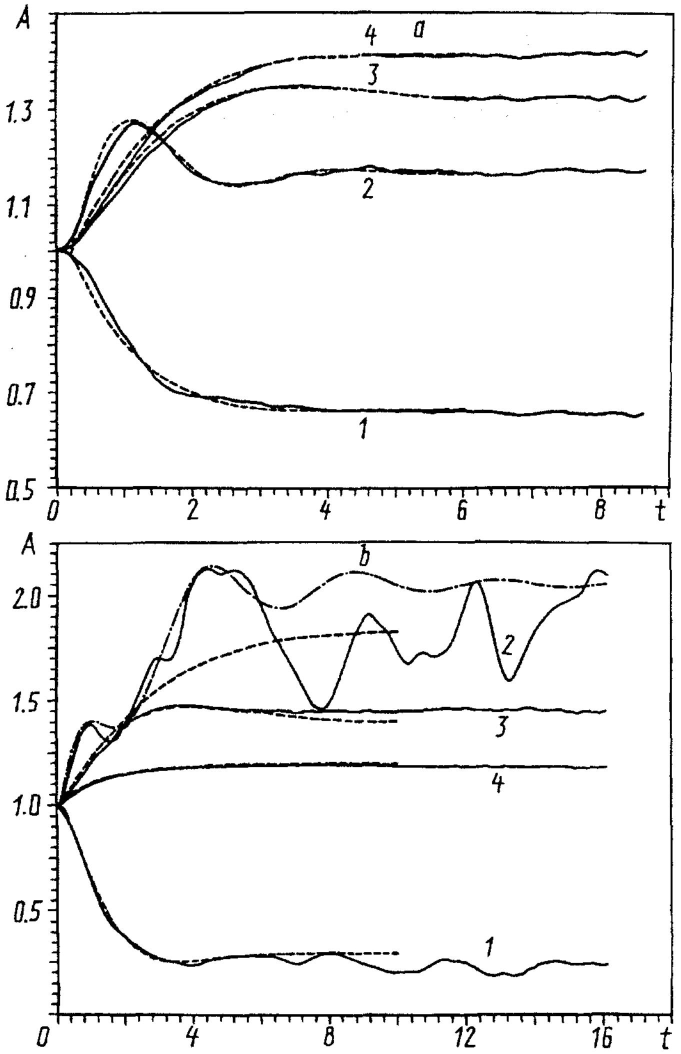

Fig. 5. Comparison of time and model characteristics in two-phase flow (2A) (a) and in two-phase flow (1C) (b): 1) channel 1; 2) channel 2; 3) channel 3; 4) main loop; a: solid curves) experiment; dashed curves) model; b: solid curves) experiment; dashed curves) model, second power characteristic; dotted-dashed curves) model, third power characteristic.

2. For the transfer functions of the second and third powers, an inverse Laplace transformation was carried out and the time characteristics of the model were determined; the second and third powers of the transfer functions were chosen from an analysis of the experimental time functions by the method of nonlinear smoothing.

3. Time functions of the models were analyzed together with the experimental time functions of the channels; since the transfer functions and their time characteristics only occur in the case of linear systems, an experimental curve of the transient process in the channels was identified as linear if it could be represented by the appropriate time function of the model with a small error.

The studies showed that the behavior of the transient process depends on the fluctuation stability of the steady states as follows: transient processes are nonlinear in regimes in which both steady states are characterized by fluctuation instability; transient processes are linear in regimes in which both the initial and final steady states are characterized by fluctuation stability or in which one steady state is characterized by fluctuation stability and the other, by fluctuation instability.

In our experiments all two-phase flows in channel 2 and two-phase flow 4C in the third channel are nonlinear: single-phase flows in all channels, two-phase flows in channel 1 with stable initial and unstable final steady states, and flows in channel 3, except 4C, are linear (Tables 1 and 2).

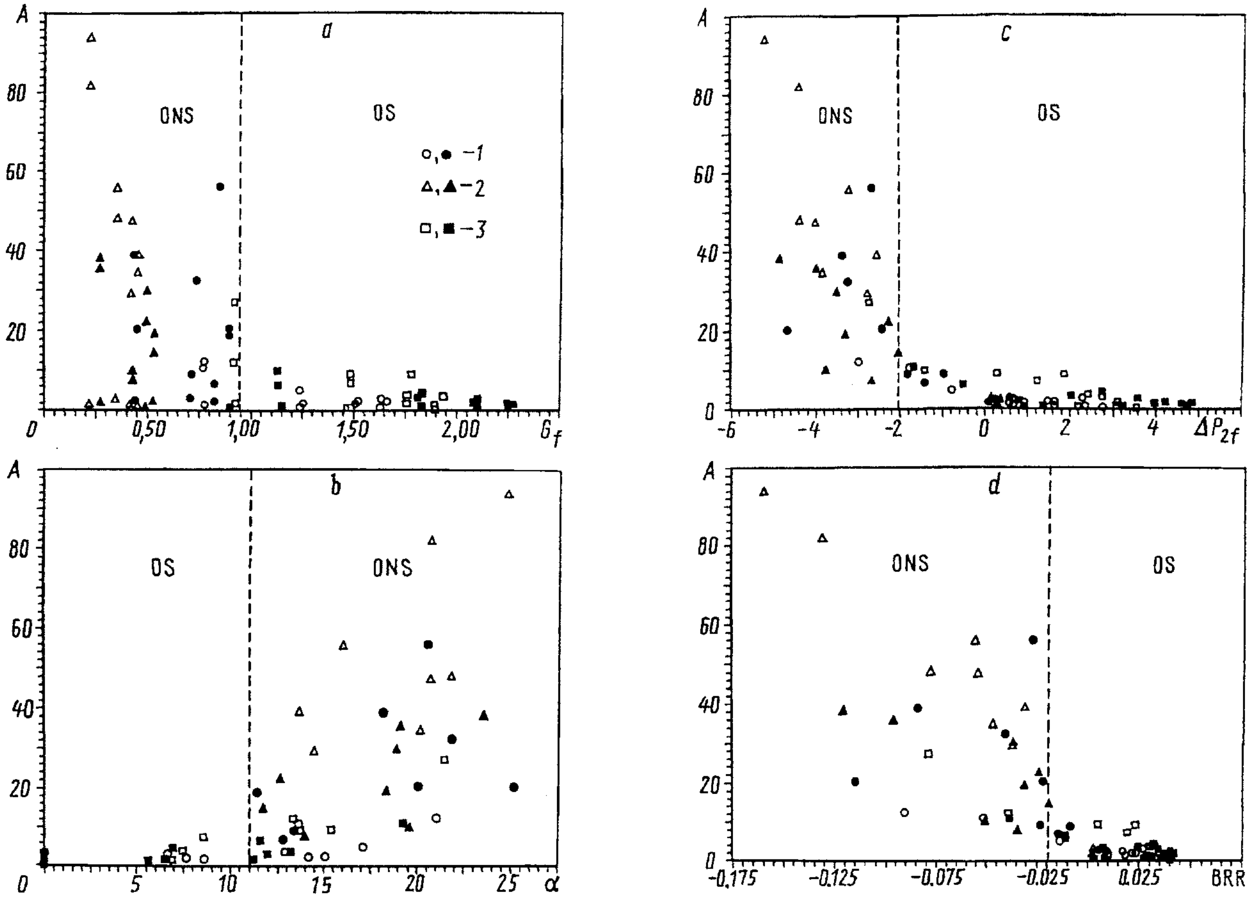

Fig. 6. Plot of the fluctuation amplitude versus the water flow rate (a), gas content (b), two-phase pressure drop (c), and *BRR* factor (d); steady-state conditions: 1) channel 1; 2) channel 2; 3) channel 3; open points) initial state; filled points) final state; OS) stable fluctuation regime and transient regime, ONS) unstable fluctuation regimes. G_f, kg/sec; α, %; ΔP_{2f}, kPa.

In Fig. 5 one can see examples of experimental time characteristics and time functions of the model with parallel operation of the channel for linear and nonlinear flows in the system.

Threshold of Fluctuations. Analysis of the fluctuation amplitude as a function of the characteristics of the flow of a two-phase mixture shows the existence of a threshold of fluctuations. In the range of geometrical and regime parameters of parallel channels considered, the region of fluctuation instability appears at a mass flow rate lower than 0.95 kg/sec and a cubic gas content of the phases higher than 11%, and the region of stable fluctuations appears at a mass flow rate higher than 1.8 kg/sec and a cubic gas content lower than 8% (Figs 6a and 6b). Analysis of the fluctuation amplitude as a function of pressure in a single-phase collector (see Fig. 1) shows that there is no distinct relation between them, therefore, throughout the whole channel the pressure drop does not "feel" the appearance of pressure-drop fluctuations in the two-phase part of one or several channels.

For analysis of the fluctuation behavior of a two-phase mixture in parallel channels, a few computer programs have been developed and analysis of experimental results has been caried out in the real and complex regions [9]. For steady-state phenomenological analysis of the experimental results use was made of the equation of motion of a two-phase mixture in a parallel channel. The equation was written in the form:

$$\Delta P_{\text{tot}} = \Delta P_{1\text{f}} + \Delta P_{2\text{f}} \,. \tag{1}$$

In the single-phase part of the channel the pressure drop is

$$\Delta P_{1\text{f}} = \Delta P_{\text{htr}} + \rho_{\text{f}} g H \,, \tag{2}$$

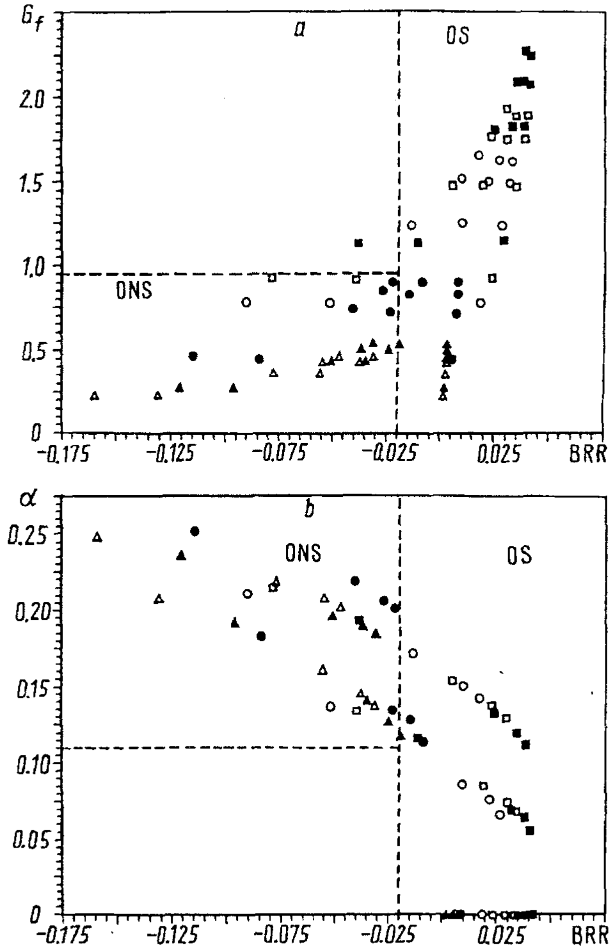

Fig. 7. Plot of the *BRR* factor versus the water mass flow rate (a) and the gas content (b). The same notation as in Fig. 6.

In the two-phase part it is

$$\Delta P_{2\text{f}} = \Delta P_{\text{vtr}} - \alpha\,(\rho_\text{f} - \rho_\text{g})\,gH\,. \tag{3}$$

Analysis of these expressions has shown that in the single-phase part of the channel the pressure drop $\Delta P_{1\text{f}}$ is always positive, and in the two-phase part $\Delta P_{2\text{f}}$ can be more or less than zero, or zero.

For flow regimes in which $\Delta P_{2\text{f}} > 0$, i.e., when the dissipative component of the pressure drop is larger than the compressibility component, both the single-phase and two-phase parts of the pressure drop participate in satisfaction of the condition of parallelism; in the case of $\Delta P_{2\text{f}} = 0$, when the dissipation and compressibility components are equal, ΔP_{tot} depends only on the single-phase part of the pressure drop so that satisfaction of the condition of parallelism is independent of the two-phase pressure drop in the channel. Thereby the two-phase part of the channel becomes "independent" of the system, and then fluctuations can appear in it that are not "felt" by the system as a whole or characterize the flow regime in the two-phase part of the channel.

For regimes in which $\Delta P_{2\text{f}} < 0$, i.e., when compression forces prevail, in the two-phase part of the channel the pressure drop is negative, and, in order that the condition of parallelism be satisfied, the single-phase part "compensates" for the lacking part of the pressure drop. In the two-phase part of the channel fluctuations of large amplitudes can appear under the action of the compression forces.

In Fig. 6c fluctuation amplitudes are plotted versus the pressure drop in the two-phase part of the channel, and in Fig. 6d, versus the *BRR* factor, which is defined as the ratio of the two-phase to the total pressure drops:

$$BRR = \frac{\Delta P_{2f}}{\Delta P_{\text{tot}}}\,. \tag{4}$$

Experimental results show that for $\Delta P_{2f} \geq 0$ or for $BRR \geq 0$, the fluctuation amplitudes are always smaller than 10% of the steady state, and consequently, the regimes are in the region of stable fluctuations or in the transition zone. For $\Delta P_{2f} \leq -2.0$ kPa or $BRR \leq -0.02$ in the case parallel operation of the channels, and for $\Delta P_{2f} \leq -3$ kPa or $BRR \leq -0.035$ in the case of single operation of the channels, regimes of fluctuation instability are observed in which the fluctuation amplitudes can reach 94% of the steady state in the case of parallel operation and 30% in the case of single operation of the channels.

From the present results a conclusion can be made that regimes of fluctuation instability do not appear in the channels as long as the total pressure drop of the vertical two-phase parts is larger than the single-phase gravity pressure drop (2), i.e., as long as the two-phase pressure drop is positive. With a positive two-phase pressure drop stable fluctuations of the transition zone are observed in the channels. With a negative two-phase pressure drop in the channels there occur not only regimes of fluctuation instability but also states of stable fluctuations of the transition zone (Figs. 6c and 6d). For the range of parameters considered, the threshold of fluctuation instability occurs at $\Delta P_{2f} = -2.0$ kPa (accordingly, $BRR = -0.02$) in the case of parallel operation of the channels and at $\Delta P_{2f} = -3$ kPa (accordingly, $BRR = -0.35$) in the case of single operation of the channels.

The boundaries of the region of fluctuation stability are determined from the dependence of the *BRR* factor on the regime parameters. The two-phase flow regimes are characterized by stable fluctuations if the water flow rate in the channels is higher than 1.80 kg/sec and the cubic gas content is lower than 0.11. In the case of parallel operation the fluctuations are unstable at a water flow rate lower than 0.95 kg/sec and a cubic gas content higher than 0.175. The ranges of a water flow rate of 0.95–1.80 kg/sec and a cubic gas content of 0.11–0.175 are a transition zone (Fig. 7).

Thus, the present experimental studies have shown that in the system of three parallel channels fluctuation instability is observed in one, two, or three channels, while the behavior of the other channels and the main loop remains stable; that regimes of fluctuation instability occur when the compression forces exceed the dissipation and inertia forces in the two-phase parts of the parallel channels; and that linearity (nonlinearity) of the transient processes in an unsteady flow of a two-phase mixture depends on the proportion of the dissipative and compressive forces in the two-phase flow. Regimes with steady states (initial and final) characterized by fluctuation instabilities are nonlinear, and regimes with one or both steady states characterized by fluctuation stability are linear.

A large number of technological systems in which a two-phase mixture is a working body operate in a parallel-channel configuration. The results of the present studies provide identification of the instability regions and, thereby, the possibility of choosing operating parameters that prevent fluctuation instability in the channels.

NOTATION

A, fluctuation amplitude normalized on the steady state; α, cubic gas content, %; BRR, ratio of pressure drops; G, mass flow rate; H, length of channel; J, dimensionless velocity; Q, volume flow rate; t, dimensionless time; ΔP_{tot}, total pressure drop; ΔP_{htr}, friction pressure drop in horizontal sections of channel; P_{vtr}, friction pressure drop in vertical sections of channel; ΔP_{1f}, pressure drop in single-phase sections of channel; ΔP_{2f}, pressure drop in two-phase sections of channel; ρ, density. Subscripts: f, water; g, gas, air.

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