AIR-WATER PARALLEL CHANNELS TRANSIENT FLOW

by

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Paper present results of the experimental and analytical study devoted to the investigation of transient regimes in air-water adiabatic two phase flow in the three parallel hydrodinamically not identical vertical channels. Under specific conditions in the individual channels, it is possible to obtain selfsustainable oscillations of the pressure drop which, due to interechannel interactions lead to unstable flow regimes which are characterised with stable characteristics of the system as a whole and its individual channels. The onset of pressure drop oscillations in three parallel channel two phase flow in time and complex domain is analysed. Using experimentally determined transfer function of the system the criterion's for the determination of the linearity or nonlinearity was defined.

Introduction

Transient two-phase flow represents a complex nonstationary process which is, in the system comprised of parallel channels, related to the thermal and hydrodynamic processes of mutual interactions between channels. Upon introduction of external or internal disturbances in one or more channels, the mechanism of interchannel couplings undergoes a transient process characterized by the redistribution of parameters and depends on the number of channels and their relationship in the system. With respect to the conservation laws, the redistribution of parameters in systems with two parallel channels is unique, while in systems with more parallel channels it contains indeterminacies which represent additional degrees of freedom reflecting the ways the parameters redistribute themselves within the system and being related to the mutual influence of inertial, compressible and dissipative effects. This mutual relationship between the inertial and dissipative effects in compressible medium of non-stationary two-phase flow sets up the emergence of the nonlinear behavior in certain channels as well as it induces unstable oscillations in one or more channels while the whole system may exhibit stable behavior as a whole.

Unstable behavior of two phase mixture which, depending on the system characteristic and working parameters diapason, will appear in oscillation form or selfsustanable flow rate oscillations, pressure, temperature and other parameters. Limits defining appearance of the substantially change in parameters of the system are the characteristic parameters describing respective unstable regimes and represents limits of normal condition of the system and equipment's in which two-phase flow is used as the working fluid. Instabilities are particularly important in the systems with large number of parallel channels which are used in almost all equipment's with two-phase flow.

Investigation of hydrodynamic instability of two-phase flow at its beginning was connected with the investigation of the instability heat transfer fluid in the once through boilers at the beginning of the reties with Ledinegg 1938 and Petrov 1939 [21, 28]. The fundamental classification of the causes and mechanisms of the thermo-hydraulic instability in the channels was given by Boure, Bergles, Tong 1973 [4] while Veziroglu, Lee, Kakac 1977 [31] experimentally investigated basic forms of instabilities in the single diabatic channel. Adiabatic regimes in a single channel has been also investigated by Nassos, Bankoff 1966 [25] with considering propagation of the density disturbance in two-phase air-water mixture. Miyazaki, Fuji, Suita 1971 [24] have performed experimental and analytical study of the pressure wave propagation while Ozawa, Akagawa, Sakaguchi and Suezawa 1980 [26] the pressure drop oscillation.

Hydrodynamic instability of the system with parallel channels have more complex characteristic than the system with a single channel, since all forms of the instability immanent to single channel are present in the multy channels system within the constrains of the multichannel or interchannel instability. With larger number of channels the interchannel instability is more frequent, resulting that the operation of this system is very sensitive [5]. Massini, Possa,Tacconi 1968 [23] have studied instability of two identical parallel channels and Fukuda, Kobori 1978 [9] have determined instability limits for the natural and forced flow in two parallel channels. Crawley, Gouse, Deane 1967 [2] and D'Acy 1967 [2] have investigated instability of three heated channel system. Akagawa *at all* 1971 [1] have focused attention to the Ledinegg instability limits in three long parallel horizontal channels. Dolgov, Sudnicin [8] have determined stability conditions for diabatic four channels system and Komyshyj *at all* 1983 [19], Yarkin, Kulikov, Shvidchenko 1986 [3] determined boundary for the interchannels oscillation's in the system with two and three channels. Oscillation characteristics of the unstable regimes in two and four parallel channels have been considered in work published by Veziroglu, Lee 1971 [30], Lee, Veziroglu, Kakac 1977 [22], Kakac, Veziroglu, Akiuzu, Berkol 1974 [17]. Hydrodynamic characteristics of two phase adiabatic unstable flow of air-water mixture in parallel channelled have been investigated by Ozava, Akagawa, Sakaguchi 1989 [27]. Determination of transfer function and identification of dynamic characteristics of three channels have been considered by V. Jović, L. Jović, N. Afgan, M. Djorović 1972 [10] and V. Jović, L. Jović, N. Afgan 1974 [11].

In this paper are presented results of the experimental and analytical study devoted to the investigation of oscillation regimes of interchannel instability in air-water adiabatic two-phase flow in the three parallel hydrodinamicaly not identical vertical channels. Analysis in time and complex domain has been performed.

The obtained results show that dynamic equilibrium of conservative forces in two-phase system does not assure stable operation of all of its parts, but that in regimes where compressible forces in two-phase regions of the channel are more dominant then the dissipative and inertial ones, unstable pressure drop oscillations occur in one, two or all three parallel channels, while the characteristics of the system as a unit remain stable.

Experimental apparatus

Experimental investigation was performed in the laboratory scale apparatus which represents closed loop circulation with three vertical parallel channels and adiabatic flow of water and two phase air-water mixture. Installation is composed of the main water loop parallel channels, separator, downcomer part and air supply system (Fig. 1). The parallel channels, consisting of vertical and horizontal parts, are located between the single phase collector and the separator which serves as the two phase collector. In horizontal part of the loop is water flow but in the vertical part of the loop, two-phase mixture formed in the mixing chamber is flowing. In order to make it similar to real system the experiments are performed asymmetrical flows rate in the parallel channels. With the aim in horizontal part of the loop were different hydraulic resistance adding required hydrodynamic instability of parallel channels.

Experimental section with the length of 1300 mm was part of the vertical channel with annular cross section with diameters 66/50 mm. Outside tube was made of glass giving possibility for visual observation of the individual flow regimes. For outside

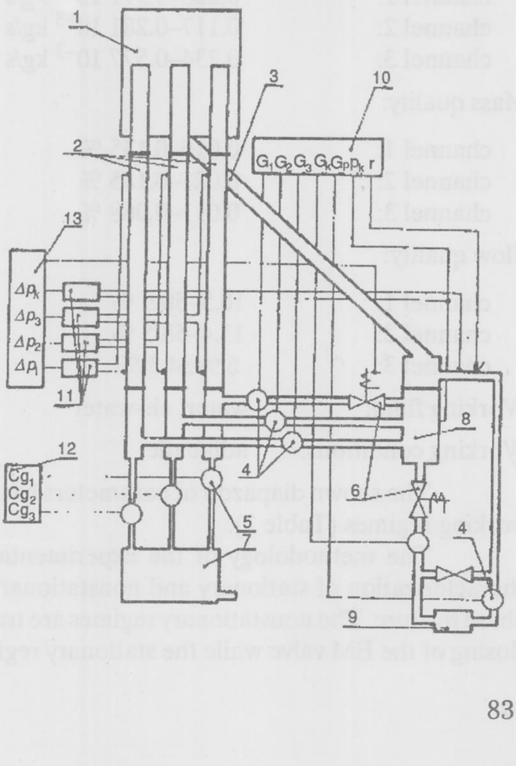

Figure 1. Schematic diagram of the hydrodynamic loop
1 – Liquid-gas collector; 2 – Test section; 3 – Downcomer 4 – Liquid flow meter; 5 – Gas flow meter; 6 – Electromagnetic valves; 7 – Gas tank; 8 – Liquid-phase collector; 9 – Pump; 10 – Digital date acquision system; 11 – Gas flow rate acquision system; 12 – Pressure drop measurement chain; 13 – Instrumental tape recorder

perturbation of the water flow two electromagnetic valves are used. First one was placed in horizontal, single-phase flow part of one of the parallel channels (channel 1 - driving channel), produces interchannel perturbations, and the second one, located in the main part of the loop for induces loop perturbations in the main flow.

Measurement and acquisition of the experimental data was performed with the instruments which ensured sufficient accuracy in stationary regimes and required sensitivity for unsteady regimes. For the sensitivity assessment the dynamic analysis of the phase-amplitude characteristic has been determined for the main elements of the measurement system in conjuction with active and passive filters. Obtained results have shown that the measuring system has sufficiently wide frequency range pass to accommodate respective total signal spectra with minimum error.

Measurements have been obtained for the regimes with parallel and individual channels with single-phase and two-phase flow, within the following diapason of parameters:

Pressure	atmospheric
Temperature	17–37 °C
Water flow rate:	
channel 1:	0.439–1.663 kg/s (channel with the EMV)
channel 2:	0.172–0.538 kg/s
channel 3:	0.845–2.247 kg/s
Air flow rate:	
channel 1:	0.226–0.591 10^{-3} kg/s
channel 2:	0.117–0.281 10^{-3} kg/s
channel 3:	0.234–0.577 10^{-3} kg/s
Mass quality:	
channel 1:	0.016–0.135 %
channel 2:	0.021–0.185 %
channel 3:	0.011–0.068 %
Flow quality:	
channel 1:	10.5–50.9 %
channel 2:	13.4–58.5 %
channel 3:	6.9–34.3 %
Working fluid:	water, air-water
Working conditions:	adiabatic

The shown diapazon of parameters has been realized in four water and three air working regimes (Table 1).

The methodology of the experimental work is related to the hydrodynamic characterization of stationary and nonstationary flow regimes of single phase and two-phase mixture. The nonstationary regimes are transient processes triggered by the sudden closing of the EM valve while the stationary regimes are flow stages before the introduc-

Table 1. Operating regime of the parallel channel system

Water flow rate [kg/s]				
Regime	1	2	3	4
chanel 1	1.59–1.66	1.44–1.52	1.24–1.29	0.77–0.80
chanel 2	0.42–0.45	0.38–0.42	0.33–0.35	0.17–0.22
chanel 3	1.88–1.93	1.73–1.77	1.45–1.48	0.84–0.92
Air flow rate [g/s]				
Regime	A single-phase flow	B two-phase flow "low gas flow"	C two-phase flow "high gas flow"	
chanel 1	0.0	0.266–0.331	0.564–0.582	
chanel 2	0.0	0.117–0.131	0.258–0.284	
chanel 3	0.0	0.255–0.281	0.532–0.574	

tion of perturbations (the initially stationary state) and flow regimes after the completion of the transient regime (the final stationary state). In stationary regimes no distinction between individual and parallel operation of channels was noticed, while in the case of nonstationary operation the difference is considerable.

The static hydrodynamic characteristics of the system do not show decreasing tendencies (negative slope) for either parallel or single channel operation in the initial or the final state (Fig. 2), so since that the characteristics are unique, there are no conditions for the occurrence of the interchannel instability of the Ledinegg type.

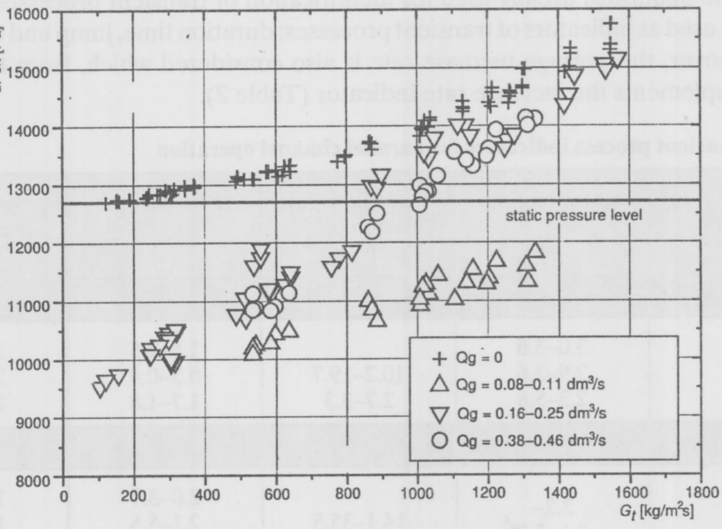

Figure 2. Parallel channel steady state characteristics

Characteristics of transient processes

Introduction of the interchannel disturbance in the form of the local resistance increase alters the condition of parallel relationship, *i.e.* it alters the equality of stress and resistive forces in the parallel channels and the main loop. The occurrence of the mechanical nonequilibrium induces interchannel forces into the system which, in the dynamical process of parameter redistribution, tends to reinstate the parallel relationship between channels at the new level.

The process of parameter redistribution and the transition to the new stationary state takes place under the influence of the propagating pressure disturbance waves and includes balance mechanisms of circulation pump force and the resistive forces in parallel channels and the main loop.

Transient curves represent temporal characteristics whose character is related to the channel position and the operating parameter range. For the driving channel the transient curves have decreasing tendencies, with different decreasing rates depending on the operating regime, while the curves of undisturbed channels and the main channel always increase however with different shapes depending on the regime of each channel. The shape of the curve is determined by the water flow rate change which induces the level change, while the gas flow leads to the occurrence of oscillations being superimposed to the level change. In the regimes of the least water flow rate the transient process has a strong oscillatory character such that the positive slope part does not represent the expansion front but instead the oscillatory increase.

The analysis of the temporal characteristics of the curves is related to the parameter analysis of the factors indicating change of transient processes under the influence of varying parameters which characterize flow regimes of the two-phase flow mixture. The quantities usually used for identification of transient processes in the real domain are used as indicators of transient processes: duration time, jump and the increase time. Moreover, the average increase rate is also considered which, from the physical aspect, complements the increase rate indicator (Table 2).

Table 2. Transient process indicators for parallel channel operation

Channel	Duration time [s]	Water flow rate jump [%]	Increase time [s]	Average increase rate [kPa/s]
Single-phase regime				
1	3.0–3.6		1.5–2.5	1.8–2.5
2	2.9–3.6	10.2–19.7	0.3–0.4	2.7–6.9
3	2.3–5.8	2.7–3.3	1.7–1.8	2.0–5.3
Two-phase flow				
1	3.2–		2.0–3.7	1.6–2.6
2	2.6–5.5	14.1–35.5	2.1–5.5	1.2–6.4
3		1.9–18.6	1.9–2.9	1.9–5.9

Results indicate that the experimental curves of the two-phase flows in the first and the second channel are not in the ±5% of the final stationary flow; that the magnitude of the jump (excess final stationary flow level) lies in the range between 2% and 35% indicating that oscillatory state occurs for regimes with the jump value over 5%; that the increase time (between 10% and 90%) represents the function of water and gas flow rate and that it increases with the increase of the mass and volume flow lying in the range between 0.3 s and 5.5 s. Moreover, that the average increase rate of the output quantity, which is also the function of the mass and volume flow, varies between 1.2 and 6.9 kPa/s and that it is larger in single-phase than in the two-phase flow regimes.

The analysis of the transient process was performed in the complex domain. Based on the experimentally recorded time responses of the pressure decrease on the step disturbance of the water flow rate in the driving channel, the transfer functions, in the order range 1 to 5, were formed for each channel and for the main loop. For the transfer functions of the order 2, 3 and 4 the inverse Laplase transform was performed and the responses of the model were determined. Obtained responses were compared with the experimental ones. The results indicate that the exponential and the periodic function represent the main features of transient curves and that they depend on the working regime, *i. e.* the poles of the transfer function. Exponential character occurs in the case of real poles of the transfer function of the second kind, and that the periodic ones appear for the complex conjugate poles. For the exponential feature the damping factor is greater than 1 while less than 1 for the periodic case. For the damping factor less than 0.4 the curves have distinctive periodic shape, while in the region (0.7–1.0) the curves exhibit wide moderate maximum. For single-phase flows the damping factor varies for the first and the third channels in the range (0.6–2.7) while for the second in (0.3–0.8). For two-phase flows the corresponding ranges are (0.7–1.5) and (0.5–1.2) for the first and the third channel respectively, while (0.2–0.5) corresponds to the stable regime of the second channel. Certain two-phase flow regimes in the second channel have positive real poles resulting in the negative damping coefficients causing the distinctive oscillatory increasing character.

In the process of redistribution of parameters for the single-phase flow, the decrease in the water flow rate decreases the damping of the exponential curves and leads to the transition into the periodic pattern. The decrease of the water flow rate in the two-phase flow leads to the oscillatory phenomena and to the emergence of the nonlinear effects.

Mutual effects among the channels are expressed only during the transient process and are related to the hydrodynamic redistribution of parameters (flow rates, pressure drop, void fraction). The character of the parameter redistribution suggests the mutual relationship between changes in dissipative, compressible and inertial effects in channels. Experimental results indicate that compressibilty effects increase in the process of hydrodynamic parameter redistribution in the driving channel while the dissipative ones decrease.

In the case of the other two channels the situation is the opposite. These changes induce the water and air flow rates change, the flow regimes change, the change of the oscillatory stability conditions and other characteristics of flow regimes. The change in the flow rate alters the mutual relationship between the flow rates of water and air in the channels. While the ratio of the flow rate in the driving and the response channels in the initial stationary state was 40.5 : 11.5 : 48% for water and 41.9 : 18.8 : 39.3% for air, the corresponding ratios for the final stationary state were 24.1 : 14.6 : 61.3% for water and 43.7 : 18.4 : 37.9% for air. The flow regimes in the driving channel change into slug and churn flows while in the other two channels remain in or change into the bubble and dispersed bubble flows (Fig. 3). The oscillation amplitude in the driving channel increases in the driving channel while in the others it decreases. For that reason the oscillatory stability decreases in the driving channel while in the other two parallel channels it increases. It is assumed here that the oscillatory stable regimes are the ones with the oscillating amplitudes within ±5% of the corresponding stationary state, and the oscillatory unstable ones with the amplitudes greater than ±10% [14, 15].

The fluctuation range of these effects is shown in Table 3 expressed through the hydraulic resistance values, mass flow rate and the void fraction in the initial and the final state. (Hydraulic resistance represents the measure of dissipative effects, void fraction is the measure of compressible effects while the time derivative of mass flux represents the measure of inertial effects.)

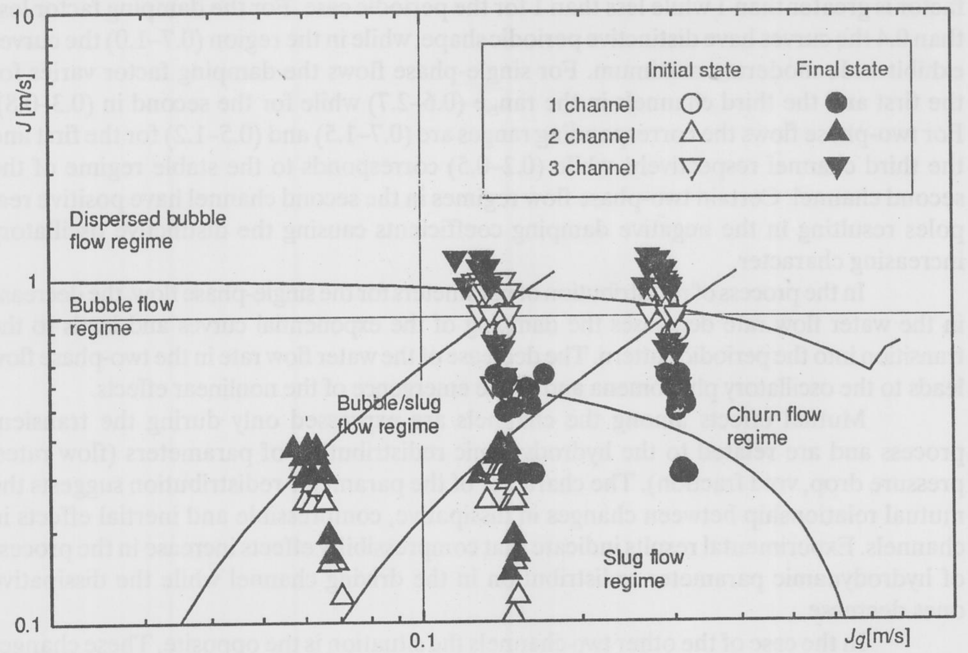

Figure 3. Flow chart map

Table 3. Characteristics of the interchannel redistribution effects for two phase regimes

Parameter	Dimension	Initial stationary state	Final stationary state
Hydraulic resistance	$\frac{kPas^2}{kg^2}$		
1. channel		33–67	137–245
2. channel		431–835	396–650
3. channel		24–47	21–36
Mass flux rate	$\frac{kg/s}{m^2}$		
1. channel		534–1157	303–641
2. channel		104–362	144–375
3. channel		582–1334	755–1568
Void fraction	%		
1. channel		6.6–21.3	10.8–25.3
2. channel		13.7–25.0	11.8–24.3
3. channel		6.8–23.0	5.6–20.1

Oscillatory characteristics

Oscillatory characteristics represent complex periodic variations in time of stationary state parameters arising when compressible forces become dominant over dissipative (frictional) forces in two-phase parts of the parallel channels. In the process of hydrodynamic redistribution of parameters compressible forces increase and the dissipative ones decrease in the driving channel, while in the case of the other two channels the effect is the opposite: the dissipative forces increase while compressible decrease. For that reason the amplitude decreases in the driving channel while the oscillatory instability increases.

The analysis of the oscillatory instability which emerges as the complex periodic variation with large amplitudes, and not as the divergent change of flow parameters, was performed in the complex domain. Methods of phenomenological and statistical analysis were used in the real domain while in the complex domain the Nyquist and Bode methods were used [7, 3].

Phenomenological analysis

Phenomenological analysis is related to the examination of the dependance of two-phase flow characteristics upon the pressure drop oscillation amplitude and to the specification of the oscillations threshold.

The analysis of time response characteristics of parallel channels and the main loop indicates that oscillations of all outlet parameters, especially the pressure drop, occur in all analyzed stationary regimes about the initial or the final stationary value. Depending on the flow regime oscillations parameters have different amplitudes and frequencies. The pressure drop amplitudes are in the range 0.37–93.94% of the corresponding stationary value, while the frequencies range from 0.36 to 3.44 Hz. The largest pressure drop amplitudes occur in the second channel which is the most intensely hydraulically damped in the inlet section (Table 4).

Table 4. Pressure drop oscillations amplitudes in parallel channel flow [%]

	Initial state				Final state			
No.	1 ch	2 ch	3 ch	4 ch	1 ch	2 ch	3 ch	4 ch
Single-flow regimes								
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 regimes								
1B	2.78	38.7	1.13	0.49	12.90	13.4	0.76	0.57
2B	1.66	29.1	3.73	0.50	6.96	16.7	2.24	1.0
3B	1.38	55.6	7.17	0.41	8.94	7.47	4.11	0.56
4B	2.54	81.9	11.90	0.97	23.10	33.3	6.19	0.99
1C	2.09	34.6	3.36	0.43	20.2	19.1	1.40	0.72
2C	2.11	47.7	8.90	0.44	55.9	29.8	2.79	1.11
3C	4.74	47.9	2.01	0.41	32.3	9.89	3.42	0.88
4C	7.13	93.9	27.10	0.93	20.2	37.1	10.1	0.75

Analysis of the relationship between the oscillations amplitude of the flow charactersitics of the two-phase mixture indicates that in the range of geometric and flow parameters under consideration, the domain of oscillatory instability arises for the value of the mass flow rate less than 0.95 kg/s and the void fraction value greater than 11%, while the domain of stationary oscillations is related to the mass flow rate greater than 1.8 kg/s and the void fraction less than 8% (Figs. 4, 5).

The results of the analysis indicate that the regimes of oscillatory instability for the parallel mode operation may occur simultaneously in one, two or all three channels. This feature of the oscillatory instability is related to the relationship between the dissipative and the compressible components of the pressure drop in the channel. Regimes of oscillatory instability, for which compressible forces dominate in two-phase parts of the channel, arise when the total pressure drop in the channel triggers the pressure drop in the single-phase portion of the channel. The two-phase part of the channel is hydrodynamically "free" in which, under the influence of compressible forces, the oscillations of large amplitude are possible.

The factor *BRR* (Break Regime Relation), determining the oscillations threshold, is defined as the relationship between the two-phase and the total pressure drop:

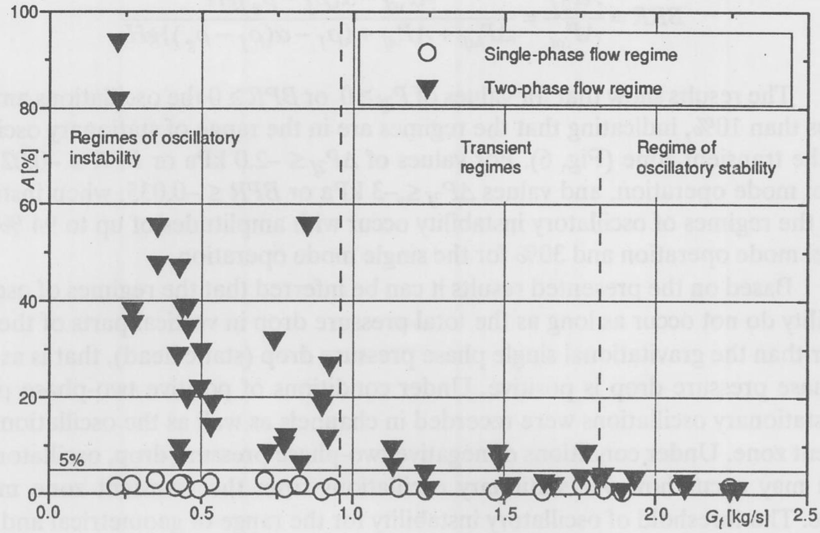

Figure 4. Dependence of oscillations amplitude on the water flow rate

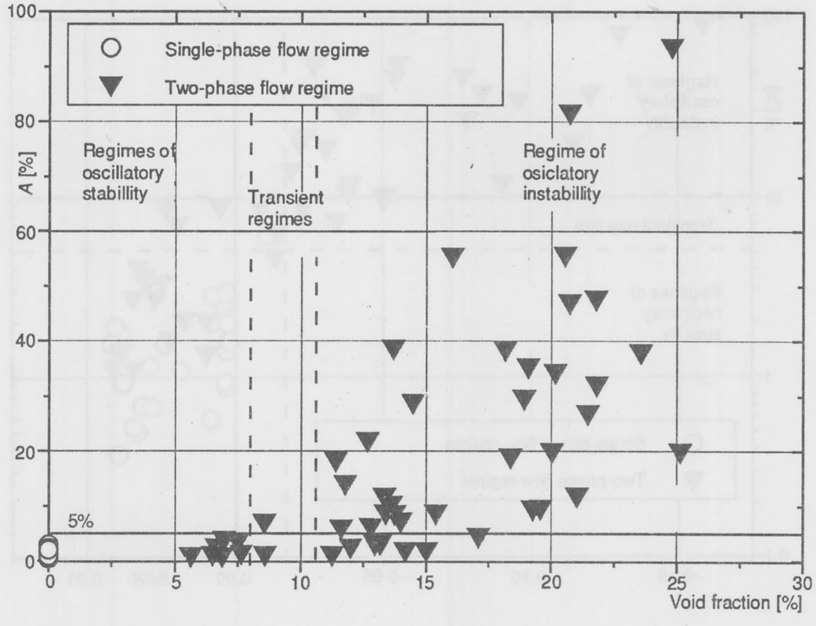

Figure 5. Dependence of oscillations amplitude on void fraction

$$BRR = \frac{\Delta P_{2f}}{\Delta P_{tot}} = \frac{\Delta P_{vtf} - \alpha(\rho_f - \rho_g)gH}{\Delta P_{htf} + \Delta P_{vtf} + \{\rho_f - \alpha(\rho_f - \rho_g)\}gH}$$

The results show that for values of $P_{2f} \geq 0$ or $BPR \geq 0$ the oscillations amplitude are less than 10%, indicating that the regimes are in the range of stationary oscillations or in the transient zone (Fig. 6). For values of $\Delta P_{2f} \leq -2.0$ kPa or $BPR \leq -0.02$ for the parallel mode operation, and values $\Delta P_{2f} \leq -3$ kPa or $BPR \leq -0.035$, when instabilities occur, the regimes of oscillatory instability occur with amplitudes of up to 94 % for the parallel mode operation and 30% for the single mode operation.

Based on the presented results it can be inferred that the regimes of oscillatory instability do not occur as long as the total pressure drop in vertical parts of the loop is greater than the gravitational single phase pressure drop (static head), that is as long as two-phase pressure drop is positive. Under conditions of positive two-phase pressure drop, stationary oscillations were recorded in channels as well as the oscillations of the transient zone. Under conditions of negative two-phase pressure drop, oscillatory instabilities may occur however stationary oscillations from the transient zone may also emerge. The threshold of oscillatory instability for the range of geometrical and regime parameters under consideration occurs for $BPR = -0.02$ for the parallel operating mode and for $BPR = -0.035$ for the single channel operating mode.

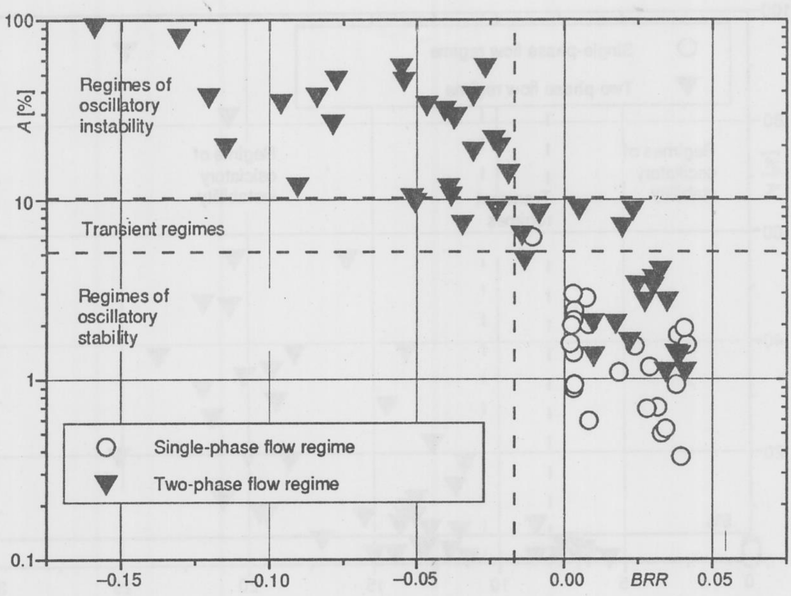

Figure 6. Dependence of oscillations amplitude on the *BRR* factor

Nonlinear and linear characteristics of the transient processes represent important feature of the nonstationary flow of the two-phase mixture. Identification of linearity (or nonlinearity) of the experimental transient processes was performed by comparatively analyzing experimental curves of transient processes and analytical time responses of transfer functions.

The results indicate that the nonlinear character of the transients occurs in those regimes for which both the initial and the final stationary states are oscillatory unstable. This includes all two-phase flow regimes of the second channel and two-phase flow regimes of the first and the third channels with the least water flow rate and the largest air flow rate.

Linear character of the transient process occurs in those regimes for which both stationary states are stable and in regimes for which one stationary state is stable and the other one unstable. Additionally, this includes two-phase flow regimes of the first channel with the stable initial state and the final unstable state, for which a nonlinear transient process would be expected. The reason for occurrence of the linear transient process in the first channel lies in the dominating influence of the driving source over the regime flow parameters on the character of the transient process.

Linear character of the transient process is related to the second order dependence on the damping coefficient, greater or smaller than one. The damping factor less than one have basically single-phase regimes, *i. e.* those regimes for which the factor *BRR* (the ratio of the two-phase part pressure drop to the total pressure drop across the channel) is less than 0.01. Parameters of this kind trigger the oscillatory transient process which represents the outcome of the very small difference between the friction and the compressible force. The other flow regimes have damping factors greater than one and exponential transients of the second kind.

Comparative analysis of transient processes in each of the channels indicate that in all regimes of the parallel operating mode all processes are linear, characterized by the damping factor greater than one in the first and the third channel have, and smaller than one in the second channel. In two-phase flow regimes the second channel is always nonlinear while the transient processes in the first and the third channel are linear with the damping factor basically smaller than one.

Statistical analysis

Determination of statistical features represents an additional useful feature of the experimental results analysis, where the experimental pressure drops in stationary regimes are considered stationary stochastic processes. In this section the dependence of the standard deviation (dispersion) on the liquid velocity, void fraction and the oscillation amplitude is presented.

Standard deviation is defined as:

$$\sigma = \sqrt{\mu_2}$$

where μ_2 – is the static moment of the second kind

$$\mu_2 = \frac{1}{N}\sum_{i=1}^{N} n_i (x_i - x_s)^2$$

where A_i – is random and A_{mean} mean amplitude value.

Analysis shows that dispersion values for all single-phase and two-phase flow regimes in the initial and the final stationary state lie in the range 0.44–1344.59 (Table 5).

Table 5. Standard deviation values for single-phase flow and two-phase flow regimes

State	1. channel	2. channel	3. channel
INITIAL single-phase two-phase	2.8–7.0 4.9–398.1	0.4– 3.2 240.8–1344.6	4.0– 16.5 7.1–187.7
FINAL single-phase two-phase	2.1– 7.6 22.4–282.7	0.9– 3.2 71.6–437.1	9.3–34.4 5.5–70.3

It is also evident that the dispersion varies in the range 0.44–34.37 for single-phase regimes and that it increases with the increase of the flow rate, *i. e.* with the increase of the turbulent pulsations. In two-phase regimes dispersion varies in the range 4.95– 1344.59 and increases with the increase of the void fraction.

Dependence of dispersion on the oscillations amplitude is presented in Fig. 7. For oscillatory stable regimes, when the oscillations amplitude is less than 5%, the dispersion values vary between 0.44–66.87, while regimes of the transient zone extend the values of oscillation amplitude by 20%. Consequently, under considered flow conditions, oscillatory unstable regimes occur for dispersion values greater than 200. Such definition of oscillatory instability facilitates the identification of flow regimes in parallel channels which is important for research on the loop and channels operation under plant operating conditions.

Presented results based on the experimental investigation of oscillatory instability of two-phase flow in parallel channels show that dynamical balance of conservative forces in two-phase flow does not enable stable operation of all its constituent parts, but that for regimes dominated by the compressible forces in the two-phase parts of the loop unstable pressure drop oscillations emerge in one, two or all three parallel channels under stable operating conditions for the system as a whole.

It shoud be stressed the threshold of oscillatory instability is related to the relationship between the total pressure drop and the pressure drop across the two-phase portion of the loop, while the identification of the instability inception is related to the statistical characteristics of pressure drop pulsations in the two-phase part of the loop.

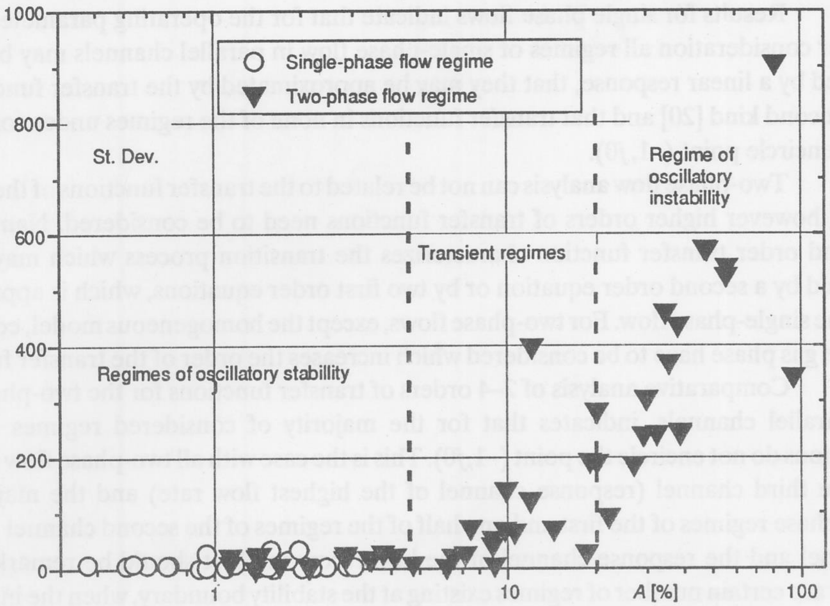

Figure 7. Dependence of dispersion on the oscillations amplitude

Nyquist frequency method

Methodology of the analysis of interchannel hydrodynamic stability in complex domain is based on the transfer functions determined by the methods of parameter identification for experimentally recorded time responses, [13, 7]. Based on numerical values of poles and zeroes of transfer functions from the first to the fifth order, the frequency based relationship between transfer functions (of real and imaginary part, amplitudes and phases) were determined. Twelwe combinations of zeroes and poles from the first to the fifth order were considered. The calculation was performed in the range between 0–50 Hz with variable step size from 0.001, 0.01, and 0.1 Hz.

Since transfer functions contain characteristics of the transient process and consequently certain characteristics of the disturbance propagation in the channel, the Nyquist stability criterion may be applied for the analysis of interchannel stability of two-phase parallel channels [32]. It should be noted however that this analysis was originally developed for linear systems and that it may be applied correctly for regimes which may be approximated by linear response.

Stability analysis based on the Nyquist method includes the examination of the transfer function in the form of $W(j\omega) = \mathrm{Re}(\omega) + Im(\omega)$ and checking whether it encircles the point $(-1, j0)$. Dynamical system is stable if the function $W(j\omega)$ does not encircle this point [20].

Results for single phase flows indicate that for the operating parameters range under consideration all regimes of single-phase flow in parallel channels may be represented by a linear response, that they may be approximated by the transfer functions of the second kind [20] and that transfer functions in none of the regimes under consideration encircle point $(-1, j0)$.

Two-phase flow analysis can not be related to the transfer functions of the second kind, however higher orders of transfer functions need to be considered. Namely, the second order transfer function characterizes the transition process which may be described by a second order equation or by two first order equations, which is appropriate for the single-phase flow. For two-phase flows, except the homogeneous model, equations of the gas phase have to be considered which increases the order of the transfer function.

Comparative analysis of 2–4 orders of transfer functions for the two-phase flow in parallel channels, indicates that for the majority of considered regimes transfer functions do not encircle the point $(-1, j0)$. This is the case with all two-phase flow regimes of the third channel (response channel of the highest flow rate) and the majority of two-phase regimes of the first and one half of the regimes of the second channel (driving channel and the response channel of the lower flow rate). It should be remarked that there are certain number of regimes existing at the stability boundary, when the instability order curve passes very near the point $(-1, j0)$.

Unstable orders of transfer functions occur in regimes of the lower water flow rate. Here the point $(-1, j0)$ may be encircled by curves of one order (3 or 4 order), curves of two orders (3 and 4 order) or curves of three orders (2, 3 and 4 order). The characteristic feature is that multiple unstable orders occur in two-phase flow regimes of the lower water flow rate (Table 6).

Table 6. Characteristics of frequency stability of transfer functions

No.	1 channel	2 channel	3 channel
1B	stable	stable	stable
2B	stable	3, 4 order bond stable	stable
3B	stable	3 order unstable	stable
4B	4 order unstable	3, 4 order unstable	stable 3 order bonder stable
1C	4 order bond stable	3 order unstable	stable
2C	4 order unstable	4 order bond stable	stable
3C	stable	stable	4 order bond stable
4C	stable	2, 3, 4 order unstable	4 order bond stable

Instabilities in all considered orders of transfer functions arise in the regime of the lowest water flow rate and the highest flow rate of the second channel (regime 4C), with the stability threshold at frequencies 0.85 Hz, 1.48 Hz, and 1.96 Hz for the second, the third and the the fourth order of transfer functions respectively (Fig. 8).

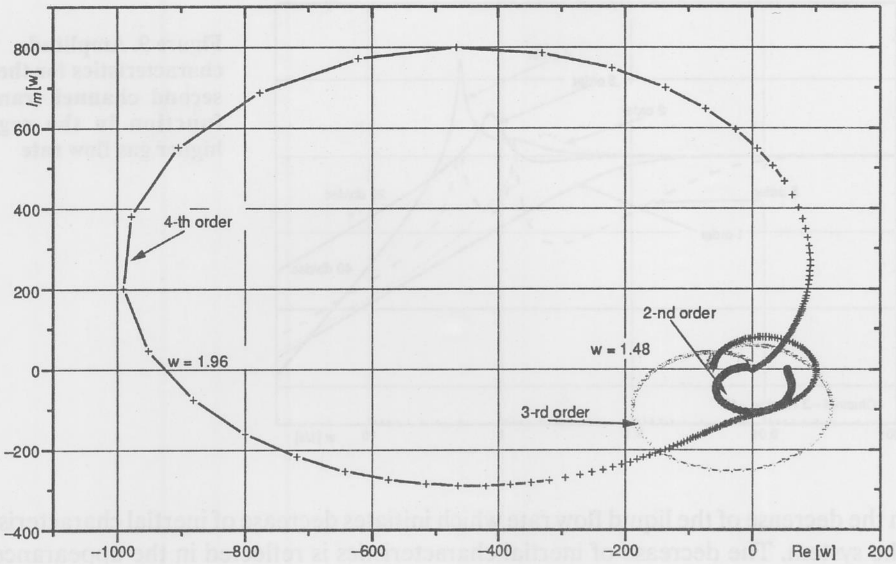

Figure 8. Transfer functions of the unstable regime in the second channel

If it is assumed that the regimes are unstable when all orders of transfer functions encompass point (–1, *j*0); interchannel instability may be recognized only in regimes of the lowest water flow rate and the largest gas flow rate.

Bode characteristic

Bode characteristic represents the amplitude and phase dependence of the transfer function on frequency and characterizes the response of the system to periodic disturbances [3]. It provides the information on band-pass range, characteristics of the system in the band-pass range, eigenfrequencies and resonant frequencies. Here the band-pass range is defined as the frequency for which the amplitude attenuates by 3 db.

Determination of Bode characteristics is based upon the knowledge of transfer functions and is related to the determination of the frequency-amplitude characteristics of the transfer functions.

Analysis results indicate that the band-pass range of single-phase regimes lies between 0.8 and 10.5 Hz, the range being 1.1–1.5 Hz for the driving channel, 1.4–10.5 Hz for the response channel of the lower flow rate and 0.8–2.5 Hz for the response channel of the higher flow rate. It can be noticed that the width of the band-pass range increases

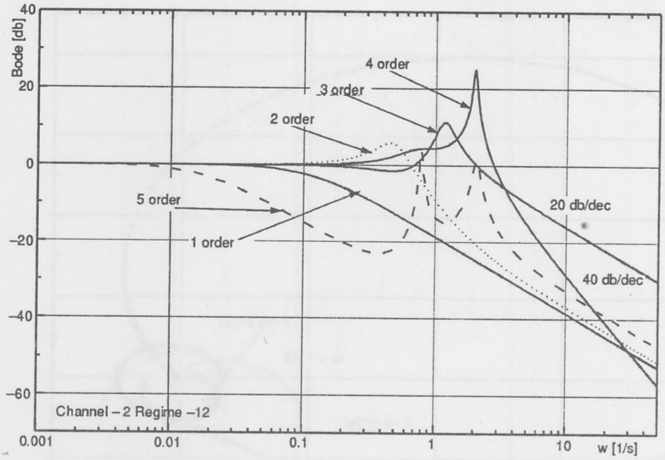

Figure 9. Amplitude characteristics for the second channel transfer function in the regime higher gas flow rate

with the decrease of the liquid flow rate which initiates decrease of inertial characteristics of the system. The decrease of inertial characteristics is reflected in the appearance of peaks both in the band-pass range as well as outside of it. This is clearly noticeable in the case of the second channel, *i. e.* the response channel with the lower flow rate . The peaks appear in the band-pass range 1.4–3 Hz with the maximum of 8–18 db. The decrease rate following the oscillatory region is 20 db/dec, although for some orders the rate is even 40 db/dec. The phase change in the smooth part of the curve takes place only for the first-second function order, while for higher orders the curve has smooth parts only in the band-pass range while outside of it the phase change occurs (–90°, +90°) in single or double combination.

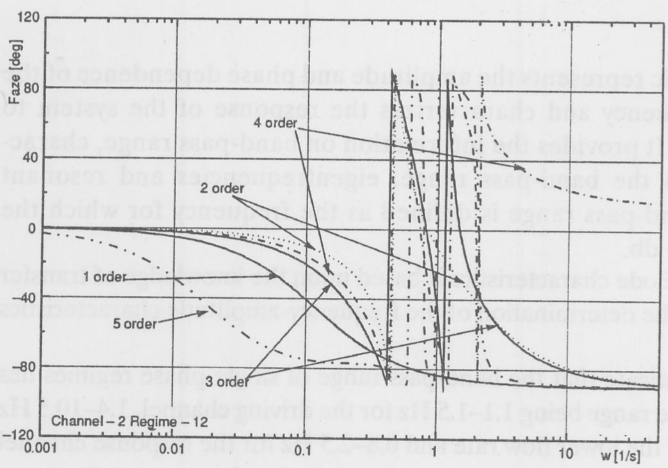

Figure 10. Phase characteristics for the second channel transfer function regime higher gas flow rate

For two-phase flow regimes the decrease of the band-pass range (in the regime of low gas) 0.25–4.9 Hz takes place and also the increase of the pulsation characteristics in the same range. This is particularly relevant for the phase jumps so that the influence of the two phase state may be attributed to the multiple phase changes.

Comparison of results obtained by the generalized Nyquist criterion and the Bode analysis show that in the regime of higher gas flow rate in the second channel, which according to the Nyquist criterion is unstable in all orders, according to the Bode criterion has peaks in 2–5 orders in the band-pass range and multiple phase jumps of these orders in the band-pass range (Figs. 9, 10). This shows that the emergence of irregularity in the amplitude-frequency and phase-frequency characteristics in the band-pass range indicates inception of instability in the physical system under consideration.

Conclusion

Oscillatory instabilities may occur in the system composed of three parallel channels in one, two or all three channels while the other channels and the main loop may exhibit completely stable operation.

The analysis of the oscillatory instability was performed in the real and the complex domain. Methods of phenomenological and statistical analysis were used in the real domain while in the complex domain the Nyquist and Bode methods were used.

Regimes of oscillatory instability occur when compressible forces become dominant over dissipative (frictional) forces in two-phase parts of the parallel channels. In the process of hydrodynamic redistribution of parameters compressible forces increase and the dissipative ones decrease in the driving channel, while in the case of the other two channels the effect is the opposite: the dissipative forces increase while compressible decrease.

Nomenclature

A, A_i [%]	– normalized oscillation amplitude
α	– void fraction
Bode [db]	– amplitude characteristics
BRR	– break regime relation factor
G_t [kg/s, kg/m^{2}s]	– water flow rate
Faze [deg]	– phase characteristics
H [m]	– lengh of experimental channel
Im	– imaginary part of transfer function
J_t [m/s]	– superficial velocity of liquid
J_g [m/s]	– superficial velocity of gas
Re	– real part of transfer function
Δp_{tot} [kPa]	– total pressure drop in the experimental part of the channel
Δp_{1f}	– pressure drop in the single-phase part of the channel
Δp_{2f} [kPa]	– pressure drop in two-phase part of the channel
Δp_{vtf} [kPa]	– friction pressure drop in the horizontal part of the loop

Δp_{htf} – friction pressure drop in the vertical part of the loop
Q_g [dm^3/s] – gas flow rate
St. dev. – standard deviation (dispersion)
w [Hz] – frequency
ρ_l, ρ_g [kg/m^3] – density, liquid, gas

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