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Different Self-Oscillation Modes in Flows with a Ventilated Cavity and Their Possible Use in Forming Periodic Pulsed Jets

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Abstract—The problem of the generation of cavitation self-oscillations in a liquid flow in a pipe with two resistances is considered. The first resistance is a cavitator, behind which there is an artificial ventilated cavity, where the mean pressure is greater than the atmospheric pressure, while the liquid and gas outflow into the atmosphere takes place through the second resistance. Investigations show that the self-oscillation frequencies are chiefly determined by the cavity properties and the conditions of the outflow into the atmosphere. The generation of different self-oscillation modes is directly associated with the number of waves formed along the cavity length. It is shown that the pressure pipeline properties and the cavity volume have an effect on the cavitation self-oscillation mode (up to four frequency modes can be observable at the same geometry and hydraulic flow parameters). The question arises of whether the self-oscillations can be used for generating pulsed jets at the outlet. It seems that it is the first mode regime that is most suitable for producing the pulsed jets, since in this case the pressure fluctuations in the cavity are maximum. Using the exponential Voitsekhovskii nozzle the regimes, in which an intermittent jet flow of the liquid is realized at the outlet, are experimentally obtained.

Keywords: jet flows, cavity, negative cavitation number, Rayleigh–Taylor instability, cavitation self-oscillations, pulsing technologies

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Over a period of years liquid flows with the formation of a ventilated gas cavity, where the pressure is greater than the external pressure (cavities with a negative cavitation number), were studied in the Institute of Mechanics of Moscow State University [1]. The cavity is formed by ventilating the area behind obstacles in the hydraulic pipeline (cavitator), the cavity length being limited by the second resistance, through which the liquid and the gas flow out into the atmosphere. At fairly intense ventilation and small volumes of the cavity and the air supply manifolds connected to the cavity self-oscillation regimes with strong pressure fluctuations are generated both in the cavity and in the water supply systems [2]. The experiments were performed on a plane jet setup described in detail in [2]. The water arrives in the setup from a damping tank, where pressure fluctuations are settled down by an air cushion; the air supply into the cavity is controlled by a valve working in the critical regime. For this purpose, a large pressure difference is maintained on it: in the air manifold the pressure is about 60 MPa, while the pressure in the cavity is less than 10 MPa. The measurements were performed under the condition that the pressure difference coefficient on the gas valve is not smaller than 0.7 (necessarily critical regime). Thus, the flow is fluctuating in the water-supply pipe, the plenum chamber of the working section of the setup, and the cavity. The schematic of the plane working section of the setup is presented in Fig. 1. The flow of the liquid and the gas occurs in a 9 mm-wide gap between two transparent thick-walled plates made of Plexiglas. The water supply and gas ventilation are realized normal to the plates: the water flows out of plenum chamber *5* through a D-wide slot *2* between the vertical wall and the horizontal insert with a sharp edge (cavitator *1*). In Fig. 1 a case of steady limiting (critical) jet flow is presented, when the jet flowing out into the atmosphere through the H-wide slot *4* is tangent to the horizontal screen *7*.

One more geometric parameter should be introduced, namely, the cavity length L equal to the sum of the length of the shield *3* overhang and the slot *4* width. As shown earlier in [3], the overhang begins to influence the critical cavitation number, when its length becomes smaller than the thickness of the jet issuing from the plenum chamber (in our case, approximately $D/2$). The value of critical steady pressure coefficient in the cavity, under the condition that the overhang-to-D ratio is greater than 0.5, depends mainly on the ratio H/D. We will also introduce the designations $\overline{p}_k$ and $\overline{p}_0$ for the mean pressures in the cavity

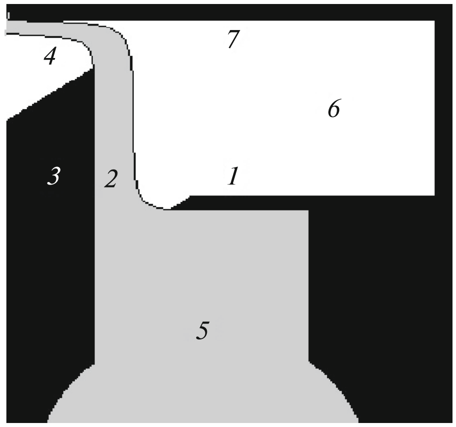

Fig. 1. Schematic of the working section; *1*, plate cavitator; *2*, slot between the cavitator and the shield; *3*, plane shield; *4*, slot between the shield and the screen; *5*, plenum chamber; *6*, gas cavity; and *7*, screen.

and the plenum chamber and p_a for the external (atmospheric) pressure. Then the pressure coefficient $C_d = (\overline{p}_k - p_a)/(\overline{p}_0 - p_a) = P_k/P_0$, the characteristic velocities of the steady liquid outflow into the atmosphere $V_\infty = \sqrt{2P_0/\rho_l}$ and at the cavity boundary $V_k = V_\infty\sqrt{1 - C_d}$, ρ_l is the liquid density, $C_q = Q_g/Q_l$ is the coefficient of gas ventilation into the cavity, where Q_g and Q_l are the volume flow rates of the gas injected into the cavity and the liquid in the jet, and the Strouhal number $\mathrm{Sh} = fD/V_\infty$, where f is the oscillation frequency. We note that the characteristic velocities V_∞, V_k correspond to the steady flow in which the constant pressures in the plenum chamber and the cavity are equal to the time-average values of the actual unsteady flow. The above-noted geometric parameters and the pressure coefficient C_d are sufficient for the theoretical determination of a plane steady flow of ideal fluid, that is, either outflow through slot *4* (Fig. 1) or according to the pattern with a return jetlet, or with jet attachment to the screen (critical regime), or without interaction with the screen (supercritical regime). In the unsteady regime (rigorously speaking, the flow under consideration is always unsteady: the least disturbances associated only with the Rayleigh—Taylor instability of the cavity boundary occur in the near-critical regime) an important role is played by the cavity volume and the supply pipe parameters (the length and the propagation velocity of pressure waves). Investigations showed [2] that in our case the self-oscillation effects are probably due to the interaction between two oscillation systems, namely the fluid dynamics of the ventilated cavity and the hydroacoustics of the pressure pipeline. A similar situation of the generation of strong pressure fluctuations in the pressure water pipeline of a hydraulic aggregate is presented in [4]. Below we will present the examples of the influence of the pressure pipeline parameters and the cavity volume on the oscillation modes. It was experimentally shown [2] that the oscillation modes are related with the number of the waves formed at the cavity boundary. The velocity of the travel of these waves is similar in value with the characteristic liquid velocity at the cavity boundary V_k introduced above. This is in agreement with the existing theoretical solution of [5]. In that study it was shown that in the case of unsteady outflow of a fluid through a slot from a volume containing a fluctuating source waves are generated on the flowing out jet and travel at a velocity equal to the mean fluid outflow velocity.

Associating the oscillation period with the time of the wave passage along the cavity, L in length, and assuming that the wave velocity is V_k we can write for the Strouhal number of the first oscillation mode

$$\mathrm{Sh} = \frac{fD}{V_\infty} = \frac{DV_k}{LV_\infty} = \frac{D\sqrt{1 - C_d}}{L}. \quad (0.1)$$

In the case of excitation of the higher modes the Strouhal number Sh in Eq. (0.1) should be multiplied by the mode number. It should be borne in mind that Eq. (0.1) may be used if the time of the wave travel along the cavity is considerably greater than the time of outflow of a fluid portion through slot *4* (or a nozzle) and if the cavity boundary begins at the cavitator edge (in the process of oscillations the air does not break through into the region ahead of the cavitator). Generally speaking, the oscillation Strouhal numbers must be not greater than those calculated according to Eq. (0.1), since the process period is equal to

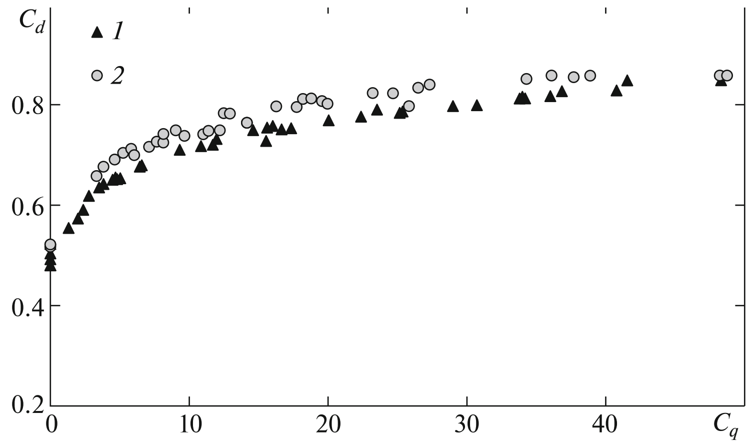

Fig. 2. $C_d(C_q)$ dependence for two cavities of different lengths: *1*, $L/D = 5.3$ and *2*, $L/D = 3.2$ at the same $H/D = 1.2$.

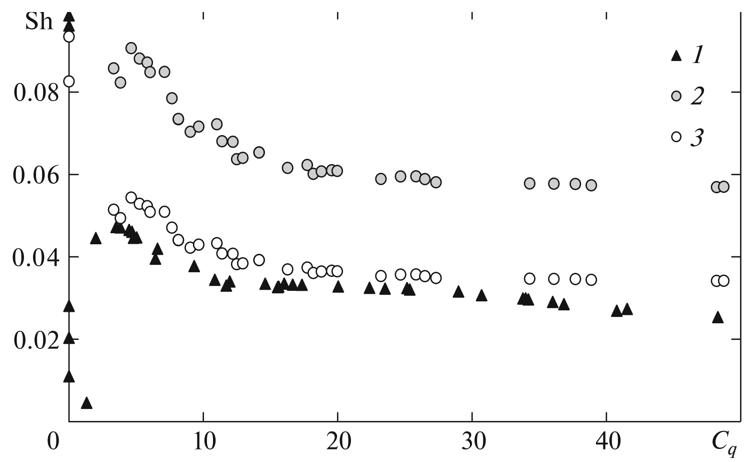

Fig. 3. Sh(C_q) dependence. Recalculation of the cavity length according to Eq. (0.1) at the same $H/D = 1.2$: *1*, $L/D = 5.3$; *2*, $L/D = 3.2$; and *3*, recalculation of the frequency from the shorter to the loger cavity (curve *1*) with the coefficient equal to the cavity length ratio.

the sum of the times of the wave travel along the cavity and the liquid outflow into the atmosphere through the second resistance.

1. CAVITY LENGTH EFFECT ON THE SELF-OSCILLATION FREQUENCY

For the head pressure $P_0 = 3$ MPa we have presented the data for two different cavity lengths $L/D = 5.3$ and 3.2 (Figs. 2 and 3) for the same $H/D = 1.2$. Therefore, for same values of C_d the difference in the entire gas ventilation rate range is about 1% (see Fig. 2). The delivery pipes are made of durite; they are 50 mm in the inside diameter and 342 (the longer cavity) and 1000 mm (the shorter cavity) in length. However, in both cases the first self-oscillation mode was excited. Clearly that with increase in the gas ventilation rate C_d increases, whereas Sh diminishes, in accordance with Eq. (0.1). It can also be seen that for the shorter cavity the frequencies are higher. Curve *3* is obtained by means of recalculating the frequencies for the shorter cavity to the case of the longer (curve *1*) with the coefficient equal to the cavity length ratio (as it follows from Eq. (0.1)). The difference between curves *1* and *3* is about 1%, which indicates that in the example presented above this formula is valid. Thus, the self-oscillation frequency can be varied by changing the spacing between the cavitator and the screen (all other parameters being the same).

It should be noted that the presence of the long overhang of the shield is important: when it is absent, it is the mechanism of the outflow (exhaust) of a portion of the liquid from the slot (or nozzle) that is pre-

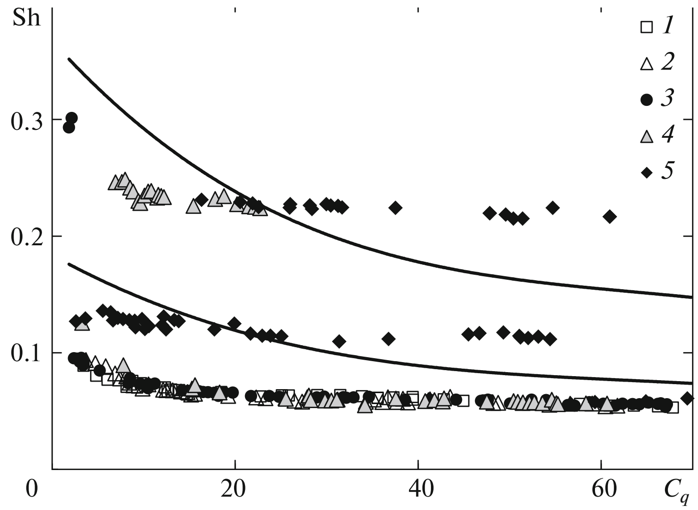

Fig. 4. Sh(C_q) dependence; the effect of the head pipeline parameters; *1*, 590 mm-long steel tube; *2*, in the absence of an insert (only steel deliveries with the total length of 150 mm); and *3* to *5*, durite inserts, 160, 500, and 1000 mm in length.

dominant. For example, the response of these two mechanisms on the pressure rise in the cavity is opposite: while the wave travel velocity decreases, the liquid portion exhaust velocity contrariwise increases. In [1] in the case of jet outflow of a convergent nozzle directly into a channel with decrease in the channel width H the self-oscillation frequency remained H-independent, despite a considerable increase in C_d.

2. GENERATION OF DIFFERENT MODES OF CAVITATION SELF-OSCILLATIONS

The experiments showed that at the same parameter values different oscillation modes can be realized. The previous study [2] presented an example illustrating the effect of the pressure pipe length and its acoustic properties on the appearance of two self-oscillation modes. The experiments were carried out at the mean excess pressure in the plenum chamber P_0 = 2 MPa. The pipes with the inside diameter of 50 mm were used (the wall thickness was 5 mm). The pipe material was either steel (the pressure wave propagation velocity about 1400 m/s) and durite (less than 100 m/s). The dimensions of the plane working section (Fig. 1) were L = 80 mm, H = 30 mm, and D = 25 mm. The numbers in Figs. 4 and 5 denote the results obtained for different insert pipes: *1* relates to the 590 mm-long steel pipe, *2* means the absence of an insert (only steel supply pipes to the flanges with the total length of 150 mm remained), and *3* to *5* are durite inserts, 160, 500, and 1000 mm in length, respectively. The continuous curves in Fig. 4 are plotted from the Strouhal numbers calculated according to Eq. (0.1) (the values of C_d presented in Fig. 5 were used) for the experimental data obtained for the flow with the 1000 mm-long durite insert tube. The data for the second mode are obtained using the coefficient 2 in Eq. (0.1). The data calculated according to the formula are in agreement with the direct measurements of the Strouhal number for this case. At least, it is possible to separate the cases in which different self-oscillation modes are excited.

From the data in Fig. 4 it follows that the low-frequency self-oscillation mode was excited in all experiments with the tested steel pipes, whereas in the case of durite pipes it was excited only when their length was less than 500 mm. For the longer durite pipes the second mode was excited. For the 500 mm-long durite pipe the second mode appears at moderate gas ventilation rates ($C_q \approx 6$), while at $C_q > 23$ the first mode regime occurs (the self-oscillation frequencies coincide with those for the shorter durite and steel pipes). For the 1000 mm-long durite pipe the second mode occurs at $C_q > 20$ and changes over to the first mode at very large ventilation rates. Moreover, in the same range and for the same parameters the first mode can also be excited (this is similar with the hysteresis phenomenon described in [7]). In the range, in which the two regimes can exist, the first mode frequency for the 1000 mm-long durite pipe turned out to be somewhat higher than for the other cases presented, which so far has defied explanation. Below it is shown that the oscillation mode (and not only the amplitude) is also influenced by the cavity volume. We will introduce one more parameter, namely, the cavity area S_k for the plane flow and the area HD as the characteristic quantity for a jet issuing through a slot, H in width; the dimensionless coefficient character-

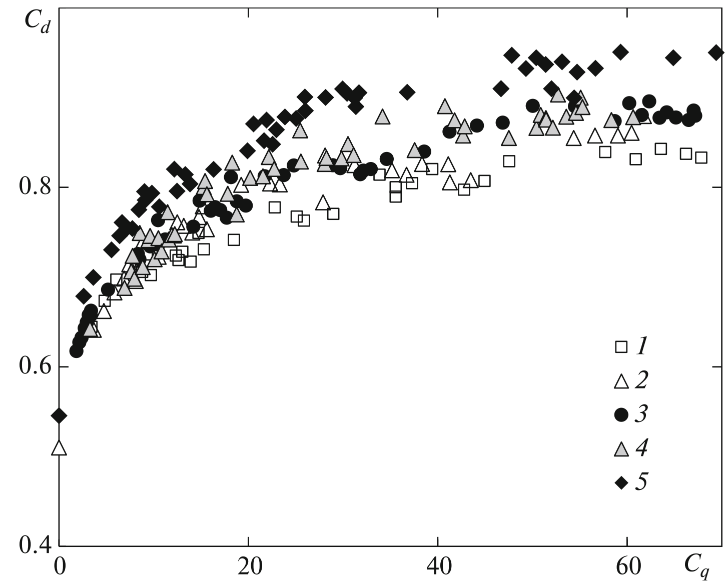

Fig. 5. $C_d(C_q)$ dependence; the effect of the head pipeline parameters; *1*, 590 mm-long steel tube; *2*, in the absence of an insert (only steel deliveries with the total length of 150 mm); and *3* to *5*, durite inserts, 160, 500, and 1000 mm in length.

izing the cavity area $C_k = S_k/HD$. In the example considered above $C_k = 16.14$. In Figs. 6 and 7 we have presented the data analogous to those in Figs. 4 and 5 for the same head pressure $P_0 = 2$ MPa but with an enlarged slot width $H = 54$ mm (the cavity length $L = 104$ mm). In this case, the value of C_k changes ($C_\kappa = 11.66$) and C_d considerably decreases (compare Figs. 5 and 7). Here, the number *1* relates to the experiment with the 1230 mm-long steel insert, $C_k = 11.66$, *2* to the same but with $C_k = 7.69$, and *3* to the experiment with the 1210 mm-long durite insert, $C_\kappa = 11.66$. The continuous curves present the dependences following from Eq. (0.1) for modes *1* to *4*. There is a considerable qualitative difference from the data presented in Fig. 4. Clearly that in the case of the durite delivery pipe (Fig. 6, experiment *3*) only the first mode is stably excited. In the case of the steel pipe (Fig. 6, experiment *1*) the first mode is also excited at comparatively small ventilation rates but with increase in the ventilation intensity ($C_q > 15$) there occurs the change-over to the third mode (under the same conditions the second and even the fourth modes can exist). With decrease in the cavity area using the insert (Fig. 6, experiment *2*) the oscillations in the presence of the same steel pipe change over to the second mode. Earlier [1] it was shown that the cavity volume has an effect on the self-oscillation intensity; now, it turns out that it can also influence the excitation of different frequency modes.

Despite the qualitative difference between the unsteady flow characteristics, the mean flow parameters (Fig. 7) are almost independent of the oscillation mode (the difference is not greater than 6.5%).

The oscillograms of the pressure fluctuations in the plenum chamber (continuous curves in Fig. 8) and in the cavity (dashes) illustrate the self-oscillation structure in the case of excitation of different modes. Here, the excess pressure is by normalized byP_0 and time is divided by the time of the wave travel along the cavity length ($T_w = L/V_k$). The oscillograms are obtained for $P_0 = 3$ MPa and $C_q \approx 20$ and for the fourth mode (Fig. 5d) for $P_0 = 2$ MPa and $C_q \approx 30$. Clearly that the time T_w is very close to the first-mode self-oscillation period (Fig. 8a). The periods of the other modes are similar in value with integer fractions of the first mode. The comparison of the curves obtained on the basis of Eq. (0.1) with the experimental data (Fig. 6) shows their good agreement in the case under consideration. The greatest amplitude of the pressure fluctuations within the cavity is observable, when the first mode is excited. In this case, the pressure fluctuations are equally intense in the cavity and the plenum chamber. Characteristic of the higher modes is a decrease in the oscillation intensity in the cavity and a relative pressure fluctuation buildup in the head manifold (true, for the second mode the regimes with the oscillation predominance in both the plenum chamber and the cavity could be observable). If a task of obtaining the most intense jets flowing out into the atmosphere is set, then the regimes, in which the first mode is excited, seem most suitable. In what follows, precisely this regime will be studied.

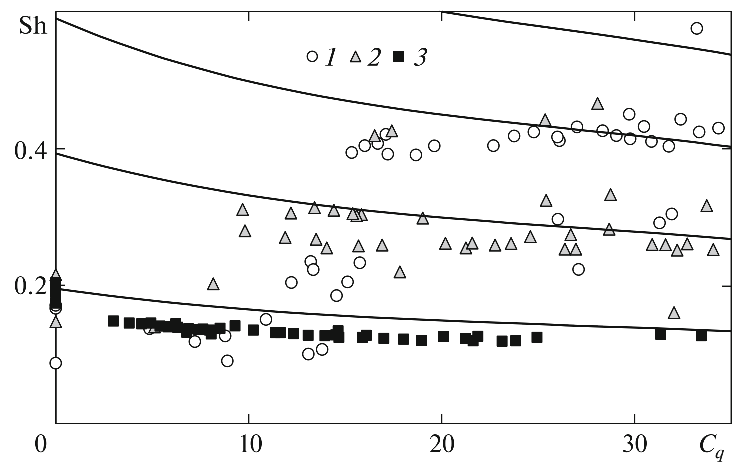

Fig. 6. Generation of different self-oscillation modes under the same hydraulic conditions. Continuous curves correspond to the calculations according to Eq. (0.1); *1*, experiment with the steel 1230 mm insert, $C_k = 11.66$; *2*, same but $C_k = 7.69$; *3*, experiment with the durite 1210 mm insert, $C_k = 11.66$.

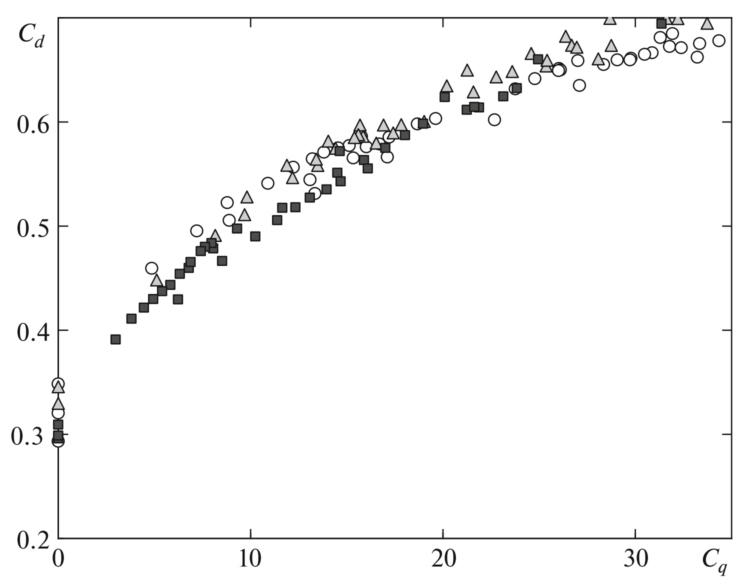

Fig. 7. $C_d(C_q)$ dependences for the same conditions, as in Fig. 6.

3. RELATIONSHIP BETWEEN THE SELF-OSCILLATION FERQENCY AND INTENSITY AND THE EXIT RESISTANCE PARAMETERS

For the working section under consideration (Fig. 1) the process can be subdivided into two stages, namely, the propagation of liquid waves at a velocity V_k from the cavitator to the screen and the outflow of liquid portions into the atmosphere under the action of the excess pressure in the cavity. Obviously that an increase of the maximum velocity of the outflow into the atmosphere requires an enhancement of the pressure fluctuations in the cavity. We investigated the dependences of the pressure fluctuation parameters in the cavity on parameter H (with decrease in H the hydraulic resistance at the exit increases, together with the mean pressure in the cavity), all other geometric factors being the same. In Figs. 9a–9d, we have presented the processed data of the experiments performed at $P_0 = 3$ MPa, $D = 25$ mm, the shield overhang 50 mm, and $H = 76$, 54, 30, and 10 mm (points *1* to *4*, respectively). With increase in H the cavity

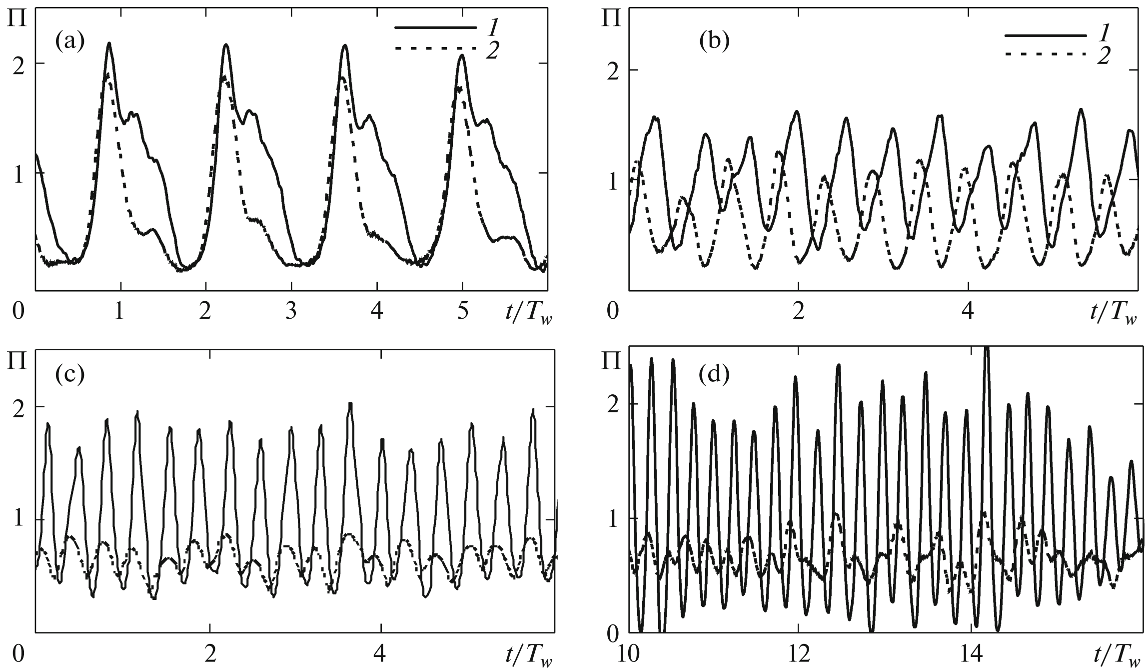

Fig. 8. First to fourth self-oscillation modes (a to d); *1* and *2*, pressure oscillograms in the plenum chamber and the cavity; $\Pi = (p - p_a)/P_0$.

becomes longer but the pressure coefficient C_d also increases; then, from Eq. (0.1) it follows that there is a frequency maximum in the H-dependence (the variation of C_d as a function of H can be theoretically estimated for the steady flow). For this reason, the frequencies corresponding to $H = 76$ and 54 mm almost coincide (see Fig. 9a): actually, these are the maximum frequencies in the H-dependence. With decrease in H the frequency monotonically diminishes. In Fig. 9b the dependences of the ratio of the time of the wave travel along the cavity to the self-oscillation period $\tau = T_w/T$ are plotted. Clearly that this ratio is everywhere smaller than unity. A strong decrease in τ at $H = 10$ is due not so much to a decrease in the velocity V_k at large values of C_d (Fig. 9c) as to an increase in the intensity of the pressure fluctuations in the cavity (Fig. 9d) and, as a consequence, the appearance of the air breakthrough from the cavity into the plenum chamber, which leads to a considerable increase in the effective cavity length. The data in Fig. 9d show that the relative swing of the pressure fluctuations in the cavity $A' = A/P_0$ (A is the observation-time-average difference between the pressure maxima and minima for the observation period) actually increases with a decrease in H, as well as the mean pressure in the cavity. At $H = 10$ mm the pressure fluctuation swing is by a factor of greater than three greater than the mean pressure difference P_0 in the hydraulic system (Fig. 9d); in this case, the fluctuation maximum is achieved at C_q greater than 15. With increase in the ventilation rate the pressure coefficient C_d approaches unity and the air from the cavity starts to arrive in the head manifold. However, from the standpoint of obtaining the greatest velocity of the exhaust of liquid portions outwards this limiting regime seems the most suitable. We note that in the case of outflow through the slot, as shown in Fig. 1, a jet at the exit is not formed; instead, the liquid is intensely spilled.

4. SELF-OSCILLATIONS IN THE CASE OF OUTFLOW THROUGH THE VOITSEKHOVSKII NOZZLE

For the purpose of obtaining a fluctuating jet at the exit into the atmosphere the Voitsekhovskii nozzle was used. In [8] a theory of hydrogun was devised under the assumption that the fluid is ideal and incompressible, its motion is quasi-one-dimensional, and the pressure during the gunshot remains constant. The necessary shape of the nozzle contour was determined and the velocity and pressure distributions in the nozzle were obtained; thus, only the forward part of the water flowing into the nozzle accelerates,

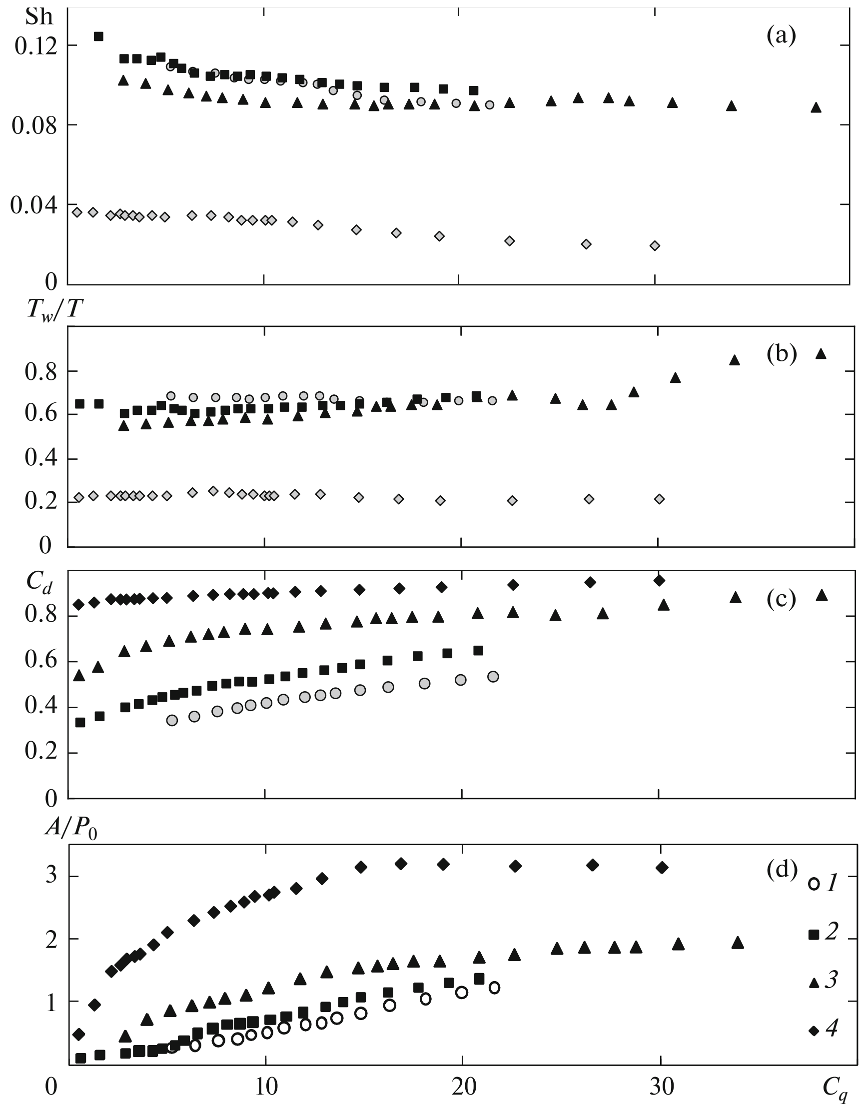

Fig. 9. Dependences of the Strouhal number (a), the ratio of the wave passage time to the self-oscillation period (b), the pressure coefficient (c), and the relative swing of the pressure oscillations (d) on the ventilation coefficient C_q: $H = 76$, 54, 30, and 10 mm (*1* to *4*).

while the main body of the water is decelerated sending its energy to the forward particles of the fluid. Here, the spatial energy redistribution in an unsteady fluid flow manifests itself.

This theory was used in selecting the plane nozzle contour. It was assumed that the mass of water exhausted for one act corresponds to the mass flowing during one period with the initial velocity V_k. It was assumed that the fluid outflow through the slot formed by the cavitator edge and the vertical shield (first resistance) is quasisteady, with the flow rate coefficient equal to 0.611. The same working section as in Fig. 1 was used, namely, one of the nozzle walls is the plane horizontal screen *7* and the curvilinear section of the nozzle is joined with the exit edge of the vertical overhang *3*.

Then the nozzle shape is described as follows:

$$H(x) = H_1 \exp(-bx), \quad b = \frac{0.611(L + H_1)}{DH_1}. \tag{4.1}$$

Here, x is the coordinate measured from the entry section *4* along the horizontal screen, $H(x)$ is the current spacing between the curvilinear nozzle boundary and the screen, and $H_1 = 50$ mm is the entry section of the nozzle. The nozzle length is determined by preassigning the exit section width H_2. The data for

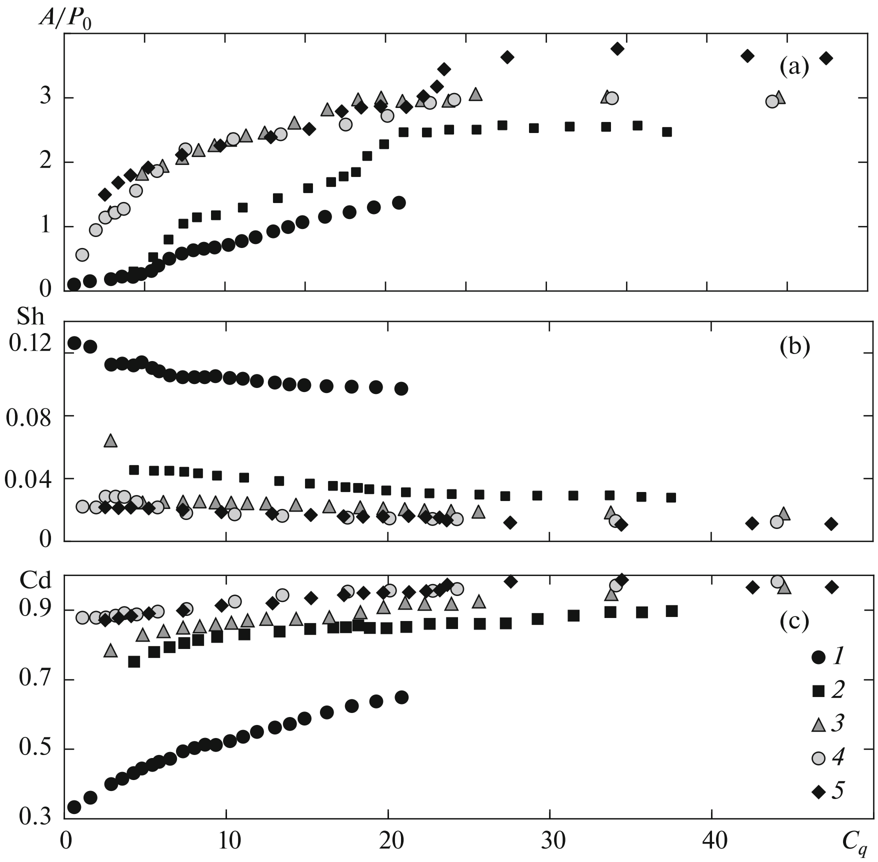

Fig. 10. Dependences of the relative swing of the pressure oscillations (a), the Strouhal number (b), and the pressure coefficient (c) on the ventilation coefficient C_q: H_2 = 20, 10, 5, and 7 mm (*2* to *5*), *1*, outflow through the slot with H = 54 mm.

four values of H_2 are presented in Figs. 10a–10c, at P_0 = 3 MPa. Here, as in the case of the outflow through a slot, the parameter C_d increases with decrease in the width H_2. When H_2 = 5 mm, the mean pressure in the cavity is so close to the mean pressure in the plenum chamber that in the process of fluctuations there occurs a strong air breakthrough from the cavity to the plenum chamber (and even in the head pipe line), which attenuates the fluctuations at even moderate ventilation rates. A maximum amplitude was observable in the case of the exit section width H_2 = 7 mm at the ventilation rates greater than 20 (curve *5* in Fig. 10a). The fluctuation intensity amounts to the same level, as for the 10 mm slot (curve *4* in Fig. 9d). For the sake of comparison the data corresponding to the outflow through the 54 mm slot are also presented (curve *1* in Fig. 10).

Using the high-speed Motion BLITZ videocamera with the speed of 3700 frames per second the picture of the displacement of the forward front of a liquid portion in the Voitsekhovskii nozzle with the exit section width H_2 = 5 mm could be obtained (Fig. 11). The outflow conditions were as follows: the characteristic outflow velocity V_∞ = 10 m/s, C_d = 0.93, C_q = 8, and the frequency f = 8 Hz. The sequence of seven snapshots (with the time step of 27 ms) illustrates the process of the outflow of a successive portion of the liquid from the nozzle. The black at the snapshot bottoms corresponds to the plane contour of the Voitsekhovskii nozzle, while the top is occupied by the plane screen. The forward part of the exhausted liquid portion is marked by the black-and-white curve. The processing of the videograms during several periods shows that the velocity of the forward part of the liquid portion is by a factor of about 3.5 greater than the outflow velocity. This factor makes stronger the impact on the obstacle. Here, the main thing is to organize a periodic exhaust of separate liquid bodies, which upon the interaction with an obstacle can be accompanied by the water hammer phenomenon at a considerably greater pressure. This result raises hopes, the more so that the flow geometry proposed is in no case optimal: when rotating 90° the liquid body first impacts the screen and then is exhausted through the nozzle. In Figs. 12a–12c, the results for two different nozzle orientations are presented. The exit section width is the same (7 mm); in one case the jet rotates 90° (Fig. 12, curves *1*) and in the second case (Fig. 12, curves *2*) the plane screen is placed along

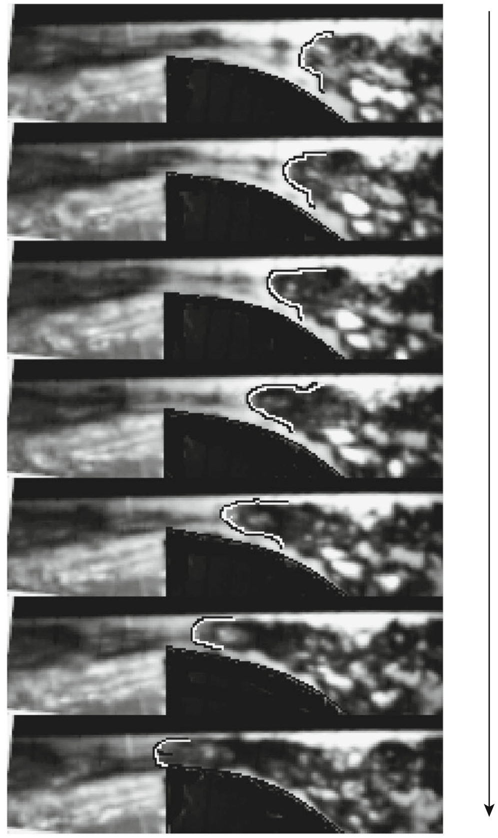

Fig. 11. Videogram of the outflow of a liquid portion through the plane nozzle; $H_2 = 5$ mm and the step between the snapshots is 0.27 ms; t is time.

the jet flow direction (the screen is circumferentially joined with the horizontal boundary of the cavity). The vertical overhang *3* (Fig. 1) is the same but the nozzle is oriented relative to the new screen position. Due to the variation in the cavity boundary, the cavity volume diminished, together with its characteristic length L. Thus, in Figs. 12a–12c, the number *1* marks the data for the nozzle rotated by 90° to the overhang line *3* (Fig. 1), and the number *2* relates to the nozzle oriented parallel to the overhang. In both experiments the mean pressure in the plenum chamber $P_0 = 4$ MPa.

Clearly that the C_d values for the two cases are very close, which indicates the nearness of the exit resistances. The fluctuation amplitudes are somewhat different but similar in value. The difference in the frequencies can be attributed to the variation in the effective cavity length.

SUMMARY

Flows with the formation of a cavity with a negative cavitation number behind a hydraulic resistance (cavitator) are experimentally investigated. The cavity length is limited by the second hydraulic resistance (slot or nozzle). It is found that under the same hydraulic conditions the self-oscillations generated can be different depending on the properties of the delivery pipe and the cavity volume. The oscillation frequency is determined by the properties of cavitation flow, while the head pipeline acoustics and the cavity volume can influence the excitation of different frequency modes.

It is shown that the presence of the exponential Voitsekhovskii nozzle at the exit does not violate the self-oscillatory nature of the flow. The possibility of using the nozzle for forming periodic pulsed jets is demonstrated.

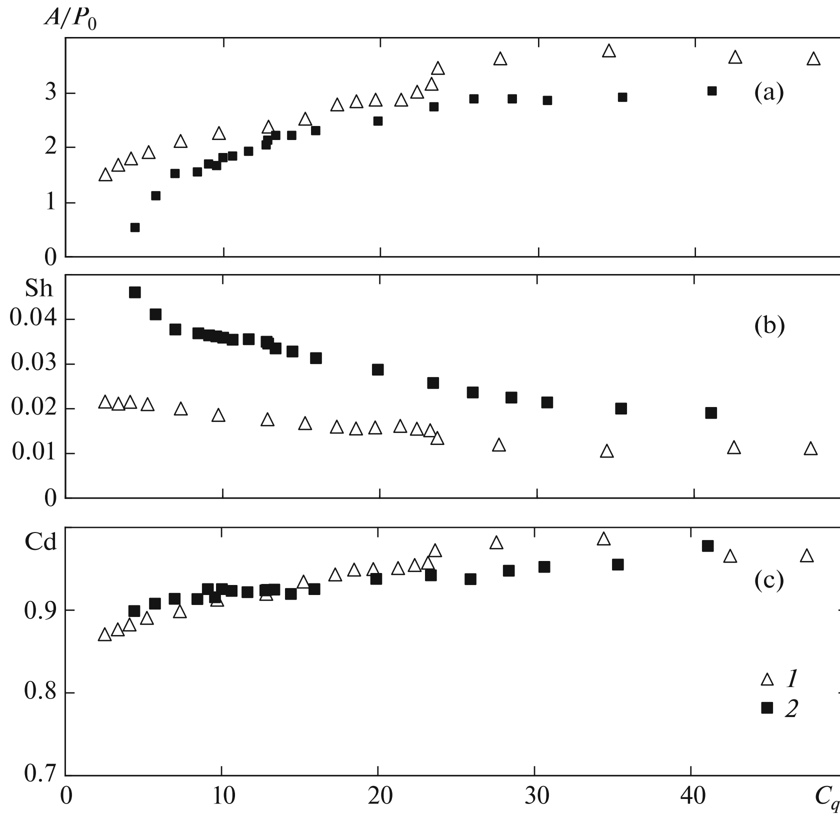

Fig. 12. Dependences of the relative swing of the pressure oscillations (a), the Strouhal number (b), and the pressure coefficient (c) on the ventilation coefficient C_q. Comparison of the hydrodynamic flow parameters for two nozzles with the same $H_2 = 7$ mm but differently orientated; *1*, as in Fig. 1 and *2*, parallel to the overhang line.

DECLARATION OF CONFLICTING INTERESTS

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