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OSCILLATORY REGIME IN LIQUID JET VEIL SEPARATING GAS AREAS WITH DIFFERENT PRESSURE

I. I. KOZLOV, S. A. OCHERETYANY, V. V. PROKOF'EV

Institute of mechanics of the Moscow State University, Rusia,
119899 Moscow, prosp. of Michurin, № 1,
prokof@imec.msu.ru

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In G. V. Logvinovich's monograph "Hydrodynamics of currents with free borders" [1] (in russian) the general properties of flows of liquid with free boundaries are considered. To them treat as a current with formation of cavities on streamline bodies, and jet flows with the boundaries dividing liquid and gas. Questions of behavior of the non-stationary free borders, raised and studied in [1], are actual still and inspire many authors on new researches. Below one of such researches – a problem of creation of the air cushion by means of a jet veil is presented. Presented results of experimental studies for self-oscillating modes of fluid jet discharging in a plane channel with an air cushion. Investigated effect on the flow from the air cavity volume and thickness, width of the channel in a wide range of magnitude of jet rate and amount of gas discharge. Oscillatory flow regimes were realized under constant water pressure in the pressure tank and a constant mass flow rate of the blower to the air cushion. It was found that the previously studied low-frequency mode exists in a certain range of values of gas flow rate to the cavity, with the range depending on the cavity volume. It is shown that in some cases this mode is replaced by a high-frequency oscillatory regime with low amplitude, and in transitional range of air flow-rate both modes are simultaneously presented (there is an intermittency). Video recording of high-frequency regime has shown that unlike in the low-frequency regime there is no direct interaction between the outflowing jet with the channel wall. We found that in both modes the oscillation characteristics of the flow (frequency, amplitude) are independent of the thickness of the cushion (the channel width). However, the regime change event significantly depends on the thickness of the cushion.

KEY WORDS: cavitation, jet, self-oscillations, Rayleigh-Taylor's instability, high-speed video

В монографії Г. В. Логвіновича "Гидродинамика течений со свободными границами" [1] розглянуті загальні властивості течії рідини з вільними границями, до яких можна віднести як течії з утворенням порожнини (каверни) на тілі, що обтікається, так і струйні течії з границями, які розділяють рідину та газ. Питання з поведінкою і росповсюдженням нестаціонарних вільних границь, що поставлені й розглянуті в [1], актуальні на сьогодні, спонукають і дають наснагу багатьом авторам до нових досліджень. В розглянутому нижче маємо одне з таких досліджень, а саме – задачу створення повітряної подушки завдяки струйній завісі. Задача досліджувалась експериментально на плоскій установці, де струї рідини витікають у плоский канал з наявністю піддува повітря в заглушену його частину. Досліджувались виникнення нестаціонарних автоколивальних режимів, їхня залежність від параметрів течії. Виявлено, що в деякому діапазоні кількості піддува газу в каверну маємо низькочастотний режим коливать. Із збільшенням піддуву такий стан течії змінюється на інший з більш високою частотою та більш низькою амплітудою, причому наявні в перехідному діапазоні піддува і одночасно співіснують обидва режима течії. Швидкісне відео демонструє, що на відміну від низькочастотного режиму при високочастотному нема беспосереднього дотика витікаючої струї з стінкою каналу. Виявлено, що в обох режимах автоколивань характеристики коливань (частота, амплітуда) не залежать від товщини подушки (ширини каналу). Але момент зміни режимів течії суттєво залежить від товщини подушки.

КЛЮЧОВІ СЛОВА: кавітація, струмінь, автоколивання, нестійкість Релея-Тейлора, швидкісна відеозйомка

В монографии Г. В. Логвиновича "Гидродинамика течений со свободными границами" [1] рассмотрены общие свойства течений жидкости со свободными границами, к которым относятся как течения с образованием каверн на обтекаемых телах, так и струйные течения с границами, разделяющими жидкость и газ. Вопросы поведения нестационарных свободных границ, поставленные и изученные в [1], актуальны до сих пор и вдохновляют многих авторов на новые исследования. Ниже представлено одно из таких исследований – задача создания воздушной подушки с помощью струйной завесы. Задача исследовалась экспериментально на плоской струйной установке, где струи жидкости истекали в плоский канал, с поддувом воздуха в заглушенную его часть. Исследовалось возникновение нестационарных – автоколебательных режимов, их зависимость от параметров течения. Обнаружено, что в некотором диапазоне величин поддува газа в каверну имеет место низкочастотный режим. С ростом поддува этот режим течения сменяется другим, с более высокой частотой и более низкой амплитудой, причем имеется область поддувов, где одновременно существуют оба режима (имеет место перемежаемость). Скоростная видеосъемка показала, что в отличие от низкочастотного режима при высокочастотном нет непосредственного взаимодействия истекающей струи со стенкой канала. Обнаружено, что в обоих режимах характеристики колебаний не зависят от толщины подушки (от ширины канала). Однако граница смены режимов существенно зависит от толщины подушки.

КЛЮЧЕВЫЕ СЛОВА: кавитация, струя, автоколебания, неустойчивость Рэлея-Тейлора, скоростная видеосъемка

INTRODUCTION

The Institute of Mechanics, MSU conducted experimental studies of transverse fluid jet discharging in a plane channel with ventilated cavity at pressure higher than external. In this setup, we model a flow with formation of artificial cavity with a negative cavitation number, which is characterized by the presence of a concave, unstable in Rayleigh-Taylor sense, boundary. We have previously noted [2] that in addition to the supercritical jet unsteadiness associated with the development of the Rayleigh-Taylor waves [3], the flow may develop substantially unsteady self-oscillating form. For oscillatory modes plane (2D) experimental facility is a good way to model the problem of a high pressure chamber (air bag) bounded by jet curtain as shown in FIG. 1.

1. EXPERIMENTAL SETUP

In this experiment, half of FIG. 1 flow was investigated taking advantage of the symmetry. The experimental setup has 2 transparent side walls (with a gap of 5 or 9 mm). FIG. 2 shows a general view of the working area of the machine, and on FIG. 3 we show a photo of the flow obtained through the transparent side wall. Unlike scheme FIG. 1 on experiment (FIG. 3) the stream is directed up. It has no strong impact on a current as far as acceleration of particles of liquid is much more than gravity acceleration g (that is Froude's numbers are great - for example, at small difference of pressure P_0=0. 02 MPa and maximum channel width in expermental H= 70 mm centrifugal acceleration is equal to 51).

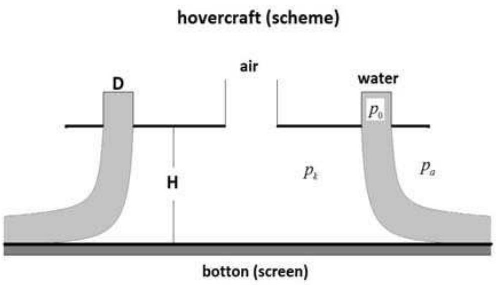

Fig. 1. Scheme to create an air cushion bounded by liquid jet curtains

The stream of water flows out of the nozzle straight up, on the right there is a cavity with high air pressure, on the left there is an outflow of liquid and gas into the atmosphere. On FIG. 3 we show a near-critical flow regime, when the oscillations are absent.

The solid lines represent the theoretical boundary of the jet. On jet's right boundary waves (Rayleigh-Taylor structures) are formed, which are responsible for discharge of air from the cavity [3].

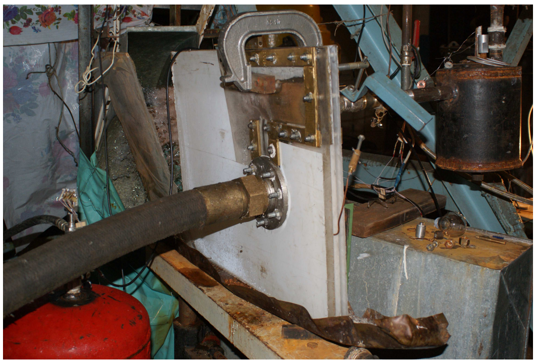

Fig. 2. General view of the working area of the setup

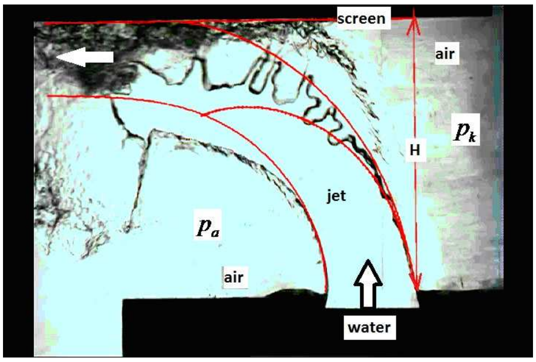

Fig. 3. Flow photo through the transparent side wall

2. TERMINOLOGY

Below is list of variables we will be using for the rest of the article:

$P_k = p_k - p_a$, $P_0 = p_0 - p_a (p_k, p_0, p_a$ – average pressure in the cavity, the pressure of the water flow and atmospheric pressure, respectively),

A – Average range of pressure fluctuations in the cavity for the measurement period

D, H – the width of the nozzle and the channel width,

f – the frequency of oscillation,

h – the gap between the plates (9 mm),

$V_\infty = \sqrt{2P_o/\rho}$ characteristic velocity of the jet,

Q_g – volumetric flow rate of gas in the cavity of the blower,

Q_l – the average flow rate of water,

$C_d = P_k/P_0$ – the coefficient of the pressure in the cavity (factor of base pressure),

$C_q = Q_g/Q_l$ – factor of carry-over of gas (or blowed air),

$St = fD/V_\infty$ – the Strouhal number,

Ω_k – the volume of the cavity,

$C_k = \Omega_k/DHh$ – the relative volume of the cavity,

$K_p = Q_l/(DhV_\infty)$– flow rate coefficient.

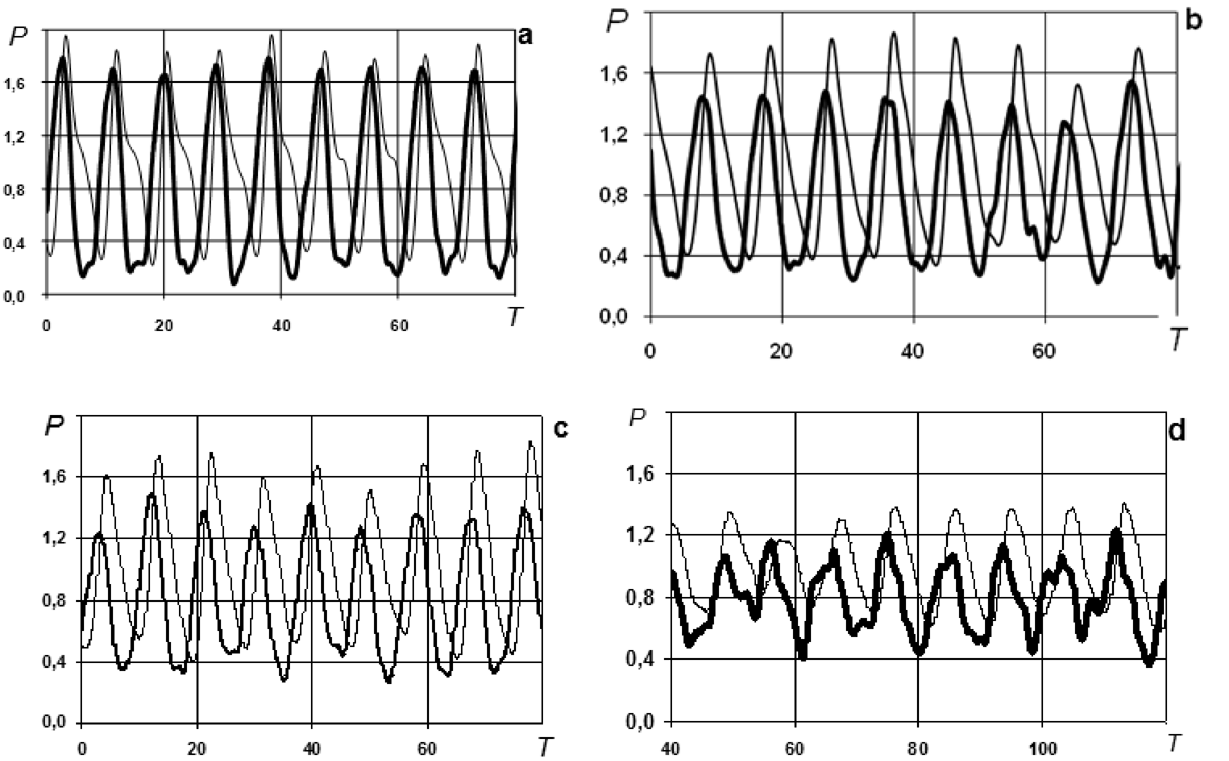

Fig. 5. Oscillograms of dimensionless pressure in the cavity (thick line) and in the settling chamber at $C_q = 14$ for the coefficients of the cavity C_k = 36.6, 60.5, 74.8, 83.6 (a, b, c, d, respectively)

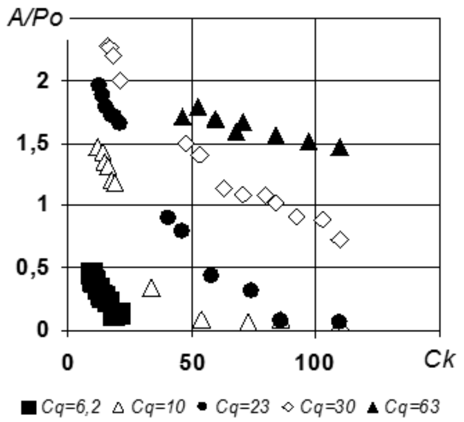

Fig. 4. Dependance of pressure pulsations intensity on the relative volume of the cavity

3. RESULTS AND DISCUSSION

For FIG. 3 flow configuration (we consider only liquid jet discharging perpendicular to the screen), the coefficient of gas discharge at the critical mode approximately equals to 1 (see [4]). A further increase in pressure in the cavity (increase C_d) leads to rapid growth of air injection (C_q). In the theoretical solution at the supercritical C_q the jet ceases to interact with the screen. Practically, one more mechanism of entrainment of gas emerges: gas flow along the screen. With the increase of blowing of air at some point the flow becomes unsteady – self-oscillatory. It was found that the threshold at which oscillations start to develop, is heavily dependent on the volume of the cavity. Therefore, in the experiment it was important to eliminate the influence of the air supply system volume, this was achieved by means of a tap installed at the entrance to the working area with the flow at the tap in critical mode (locked tap). This ensured the constancy of air mass flow to the cavity. In the oscillatory regime the pressure fluctuations occur not only in the cavity, but also in the water line feed. The water pressure of the feed was stabilized by an air cushion in a special container, which was connected to the working area by 50 mm reinforced 1m long tube. Thus, for all experiments the water supply zone (tube, pre-chamber and nozzle on FIG. 2), in which the unsteady fluid motion takes place, was fixed. The flow rate of air and water were measured in the stationary conditions. As an indicator of the water jet momentum the time-averaged pressure p_0 in the pre-chamber was used. Also time-averaged pressure in the cavity p_k was used to characterize the flow.

We also introduce a volume factor of the cavity C_k – i.e. the ratio of the volume of the cavity Ω_k to the characteristic volume DHh associated with the outflowing jet. FIG. 4 shows the intensity A/P_0 of the pressure fluctuations in the cavity depending on the coefficient of the cavity volume C_k at constant blowing ratio C_q. We see quite a strong decrease in the intensity fluctuations with increase in volume of the cavity, and the slope of the curve becomes smaller with growth of C_q. The threshold value of C_k depends strongly on the gas intake rate. Or, conversely, the threshold of C_q increases with C_k. For example, when C_k= 20, auto-oscillatory motion occurs at $C_q > 6$; for C_k= 40, critical C_q= 10, and for $C_k = 80$ oscillations occur at $C_q > 23$. FIG. 5 shows the variation of dimensionless pressure $(p - p_a)/P_0$ (in the cavity and the pre-chamber) by the dimensionless time $T = tV_\infty/D$ with the growth of the cavity at same $C_q \approx 14$ and average P_0= 0.02 MPa. It is seen that the pressure oscillations in the cavity (thick lines) are accompanied by no-less intense pressure oscillations in the settling chamber. With growing volume of the cavity is not only the pressure oscillations in the cavity drop, but also the phase shift between the pulsations in the cavern and the settling chamber increases. In the case of FIG. 5, *d*. pressure fluctuations in the cavity are ahead by about two units of pressure pulsation in the settling chamber (with the pulsation period approximately equal to 10 dimensionless units).

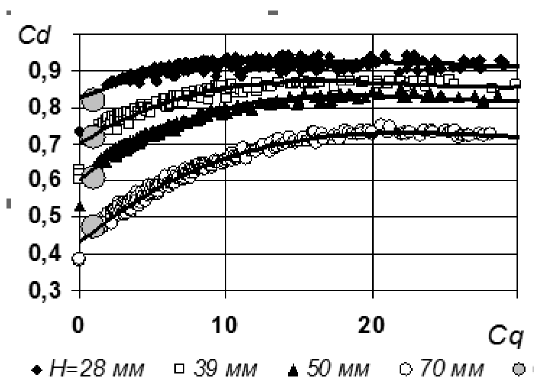

Fig. 6. Graph of pressure coefficient of blowing air

Below we present results of experimental studies for a series of experiments conducted in a relatively small volume of the cavity ($C_k \approx 5$, in this case the transition to self-oscillating mode occurs at $C_q \approx 2$) for different values of the thickness of the cushion H.

FIG. 6 and 7 show dependence of the cavity pressure and the water flow rate on rate of air blowing into the cavity at four channel widths (thickness of the air cushion). Average excess head P_0 pressure varies from 0.02 to 0.07 MPa – some scatter of points is associated with the existing scale effect. It can be seen that the coefficient of blowing rather strongly depends on the thickness of the air cushion. Without blowing air (C_q= 0) in a water-filled cavity has high pressure, which increases with decreasing H. If with the constant parameters we replace water with air in the jets then the cushion air pressure will remain the same – but required air flow rate is 1.000 times greater than water. Large black circles on the graph show the theoretical values of the critical values C_d^*. In [4] it was shown that in the test configuration (turning the water jet at 90^0) the coefficient of blowing $C_q \approx 1$ and pressure ratio increases approximately linearly from zero to a critical blowing. FIG. 6 graphs for presented range of flow rate (supercritical blowing) are well approximated by polynomials (for H = 28 mm – 4-th order polynomials, for other values – third). For all the values of cushion thickness when the critical value C_d^* is reached, the pressure ratio is increased by the same amount of about 0.1 [4], while in supercritical conditions, the greater the thickness of the cushion the more efficient is the supercritical blowing. So at H =70 mm pressure can be increased by 90%, and at H= 28 mm, only by 27%. Moreover, the maximum pressure in the cushion for all cases is achieved with $C_q \approx 20$, and then pressure ratio is slightly reduced (in FIG. 6 not shown).

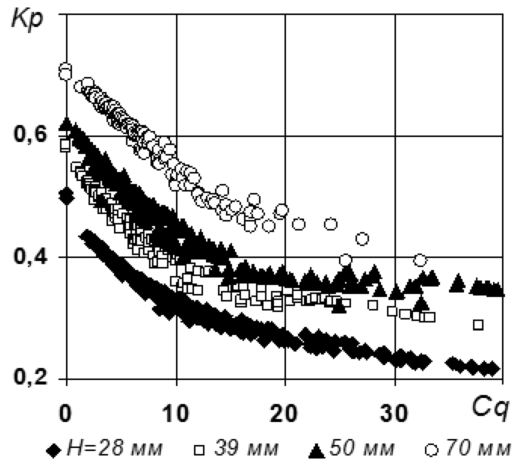

Fig. 7. Graph of flow rate of the blowing air

FIG. 7 shows that actual flow rate of air blowing to the cavity is not growing as much as the value of C_q due to the drop of water flow as the pressure in the cavity increases. FIG. 7 points represent same C_q as in FIG 6. It is seen that, in spite of a slight decrease in the average pressure in the cavity at $C_q > 20$, the

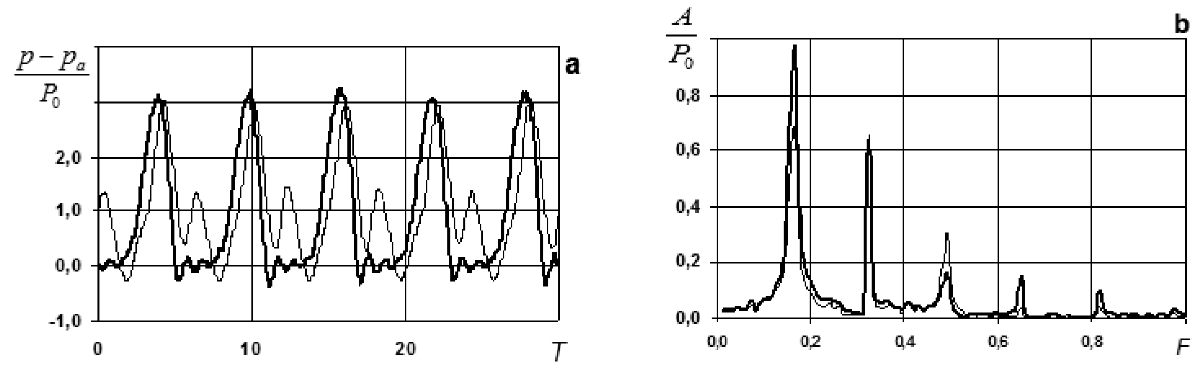

Fig. 8. Oscillograms and spectrum of the cavity pressure (thick line) and pressure in the settling chamber at P_0 = 0.01 MPa, C_q =15.6

water flow rate at fixed average head pressure continues to decrease with increasing blowing. This can not be explained in terms of the concept of stationary jet flow.

Let's turn to the study of pulsation characteristics for oscillatory flow regimes. FIG. 5 shows oscillograms for oscillatory flow regime (observed oscillations of the jet near the steady state - see illustrations in [2]).

In the problem under consideration there is a strong influence of the size effect on the fluctuating characteristics. FIG. 8, *a*. shows similar to FIG. 5 waveforms with similar coefficient of blowing, but at smaller rate of discharge, here there is another - surge (intermittent [4]) regime of flow.

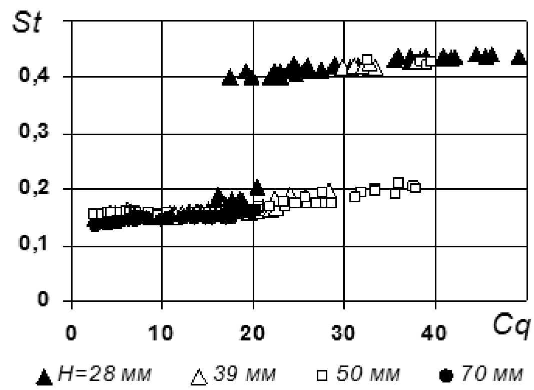

Fig. 9. Strouhal number dependence on the coefficient of gas flow rate into the cavity at P_0= 0.02 MPa and various H

FIG. 8, *b*. shows a spectrum of the waveforms. Here F is the frequency. Following of oscillograms to evolution of the flow was studied in details in [2]. The spectrum of pressure fluctuations in the cavity (solid line) is very close to spectrum of the ramp - so, despite the presence of harmonics, it is a single-frequency regime. Pressure oscillations in the pre-chamber in surge mode are quite different from oscillations in the cavity. In the stage of "purging"of the channel and the discharge of the jet into "Empty"channel (the pressure in the cushion close to the atmospheric pressure) a second hump of pressure is observed in the pre-chamber. As a result, the first harmonic of the signal spectrum decreases and (in some cases it is even less than the second).

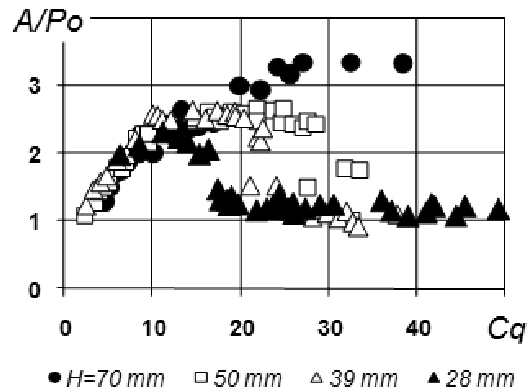

Fig. 10. Dependence of relative magnitude of pressure fluctuations in the cavity on the coefficient of flow rate of gas blown into the cavity at P_0 = 0.02 MPa and various H

FIG. 9 and FIG. 10 shows Strouhal number ($St = fD/V_\infty$) and relative magnitude of pressure fluctuations in the cavity (A/P_0) of the blowing ratio in the cavity with the same medium head (P_0= 0.02 MPa) and different thicknesses of the air cushion.

FIG. 9 shows that with increasing blowing for some of its rate there is an abrupt change in the frequency of pressure fluctuations in the cavity (note that Strouhal number is determined by the leading frequency in the spectrum). The transition to this hi-

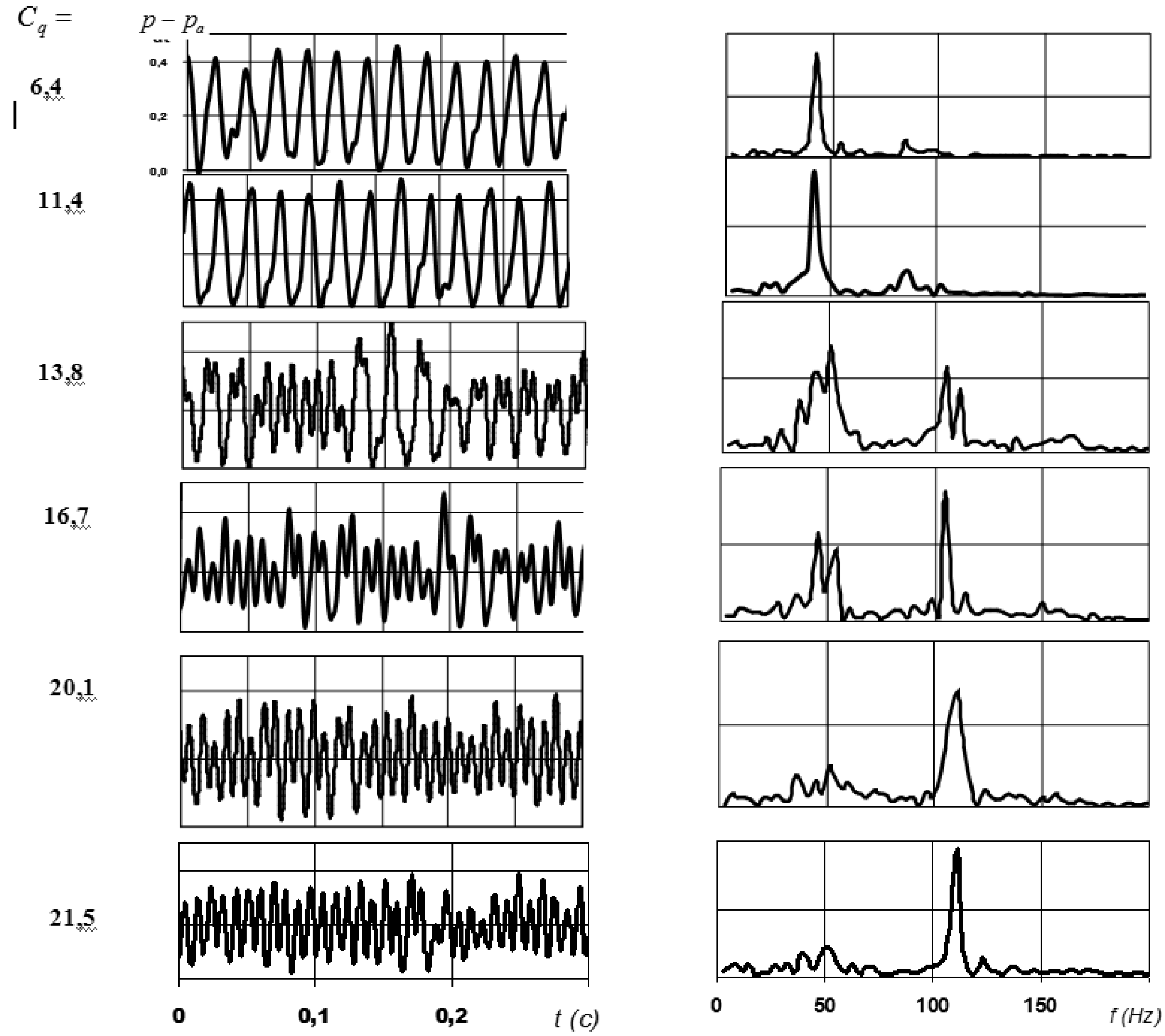

Fig. 11. Waveforms of pressure fluctuations in the cavity and their spectrum show the process of regime change in the oscillations at P_0= 0.02 MPa, H = 28 mm

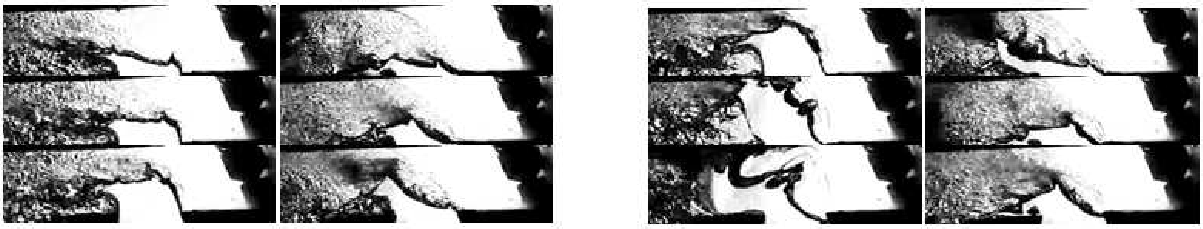

Fig. 12. Snapshots of surges mode (left, C_q =20.1) and high-frequency mode (right, C_q =41.8 for P_0= 0.01 MPa, H = 25.6 mm, D = 25 mm, pitch 0.003 s frames)

gh frequency is different from the transition from the "sine wave"to the surge mode where frequency and amplitude are continuous. We can see that in both modes (low and high frequency), Strouhal number is independent of the cushion thickness and approximately linearly increases with increasing of blowing ratio. The thickness of the cushion depends significantly on the transition from low to high frequency regime.

This is well illustrated by the data on FIG.

10. It shows that average peak-time drops significantly during transition to the high-frequency mode. Intensity of the vibration increases significantly with the increase in low-frequency mode and does not depend on the thickness of pads and practically does not change depending on the blowing in the high mode, the range of variation in this case is approximately equal. Thus variations (in the intensity and frequency) in the studied range do not depend on the thickness of the cushion with the exception of the transition modes.

It is seen that the transition is not abrupt but it takes a whole range of change in blowing ratios (about 10 to 20 – as seen in FIG. 10). The spectrum shows that in this area two modes co-exist (there is an intermittency). In addition, it appears that as the blowing increases the sinusoidal mode is not always progressing to surge. For example, the data of FIG. 11 show that with increasing pressure the sinusoidal mode transitions to a different regime, bypassing surge mode.

FIG. 12 shows a transition to a different mode from the surge mode (under lower water pressure – P_0= 0.01 MPa). The left sequence of frames shows only part of the period of low-frequency pulsations – flow from the nozzle, the interaction with the screen, and early discharge gas liquid plug. Right plot shows sequence of frames flow at the same pressure of the jet, but with a much larger blowing factor. Typically discharging jet ceases to interact directly with the screen – the jet only interacts with the gas flow. As shown in FIG. 10, changes of the frequency and intensity of the pressure fluctuations dramatically decreases in the gas chamber, in this regard, there is no periodic separation of the flow of liquid from the nozzle edge which is common for surge regime.

FIG. 13 and 14 show effect of the discharge rate (scale effect) on the characteristics of pressure fluctuations in the cavity at constant geometry of the boundaries. Thus the scale effect on the relative intensity of fluctuations is particularly high.

The lower the velocity of discharge (or the average pressure P_0), the higher is the relative amplitude. At $P_0 = 0.01$ MPa value A/P_0 reaches 3.7, and $P_0 = 0.07$ MPa only 1.1. Additionally, the more is the pressure P_0 the earlier (in terms of C_q) the transition to high-frequency oscillation mode takes place. But in high-frequency mode, the scale effect is not presented, as in FIG. 10 swings in pressure variations in this mode is approximately equalP_0 .

If the transition to surge, intermittent regime is possible at sufficiently high relative amplitude of the pressure oscillations, then with increasing pressure conditions for this transition disappear.

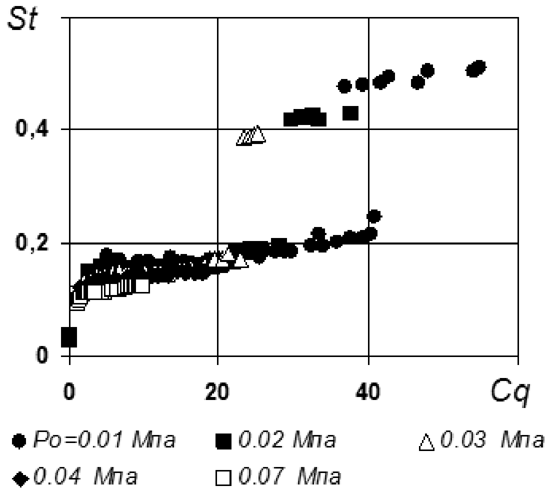

Fig. 13. Dependence of Strouhal number on the coefficient of blowing at $H = 39$ mm and different speeds of the liquid flow

So, it was found that, at other fixed parameters with increase of the relative cavity volume the "threshold"for the transition to self-oscillating C_{q1} mode increases. On the other hand, for a fixed volume of the cavity there is a quantity C_{q2} (depending also on P_0), when coefficients of blowing above that there would be a reorganization of vibrations and discharging jet would not interact with the screen.

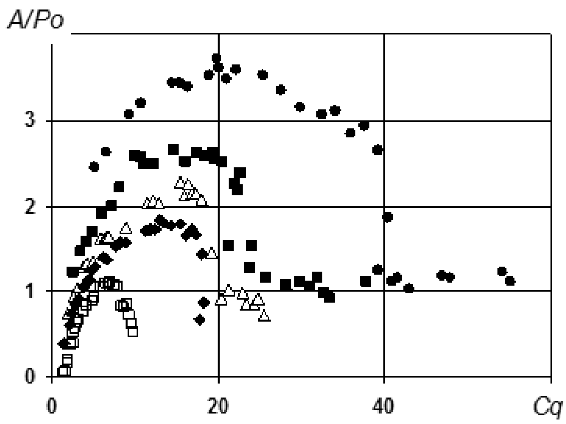

Fig. 14. Dependence of coefficient of blowing at $H = 39$ mm and different speeds of the liquid flow

Thus, low-frequency oscillations occur in the range $C_{q1} < C_q < C_{q2}$, for example if with increase in C_k $C_{q1} = C_{q2}$condition is achieved, this $C_k$limits at the top the range of existence for the oscillations.

FIG. 15 shows experimental data for the dependence of the flow rate of water through the nozzle $K_p$on the pressure coefficient of the cavity

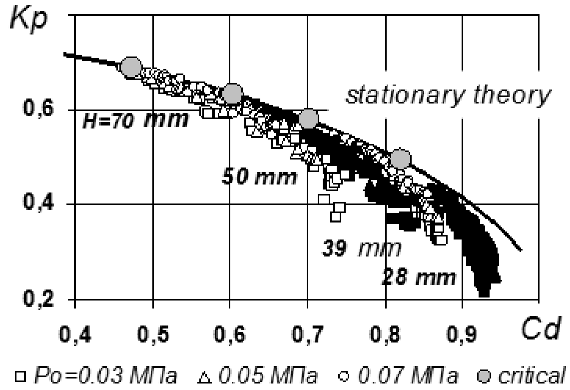

Fig. 15. Dependence of jet flow rate factor on pressure factor in the cavity at $C_k \approx 5$

C_d at different cushion thicknesses $H$and average pressuresP_0. Solid line is theoretical curve for the steady plane flow of an ideal fluid. At $C_d = 0$ flow coefficient is less than 1, because the water nozzle has a constriction as covered in the theoretical calculations. Large gray circle marks the limit - the critical point for the flow of the jet with the accession to the screen for all four values of cushion thickness. Points corresponding to three different rates of discharge of FIG. 15 are shown in symbols of different shapes. Transparent and opaque symbols alternate for successive values of H. We see that at supercritical flow the discharge coefficient is less than calculated by steady-state theory (as presented in FIG. 15, up to 2 times). In [4] it was shown that in the subcritical flow regime the average flow characteristics are well described by the ideal liquid steady theory. Hence, there is a strong influence of significantly unsteadiness of the flow on average parameters. At fixed C_d the rate of fluid flow from the nozzle depends on the thickness of the cushion and the pressure of water.

CONCLUSION

When creating a jet veil with high-pressure cavity (air cushion) in supercritical air flow rate the auto-oscillatory modes of jet flow are observed. In this regime the liquid jet directly interacts with the screen (note, the theoretical steady stream in supercritical mode does not interact with the screen). It was found that the range of blowing coefficients where this regime exists is strongly dependent on volume of the cavity. With a slight overpressure in the cavity (about 0.01 MPa, these are the values common for the hovercrafts) with increasing air blowing the auto-oscillating mode turns into surge (intermittent) flow regime. Despite the fact that average pressure in the air cushion depends on its thickness, the characteristics of vibration (frequency and intensity) in the studied range do not depend on the cushion thickness. There is only dependence of transition point to high-frequency regime on this parameter. The relative intensity of pressure pulses in the cavity noticeably depends on velocity of the jet (scale effect), and in the region high-frequency mode the scale effect is not observed and amplitude of the pressure pulsation in the cavity is approximately equal P_0.

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