Cavitation in swirling flows of hydraulic spillways

Genrikh Orekhov[1],[*]

[1]Moscow State University of Civil Engineering, 129337, Moscow, Yaroslavskoye shosse, 26. Russia

Abstract. During operation of high-head hydraulic spillway systems, cavitation phenomena often occur, leading to destruction of structural elements of their flow conductor portions. The article is devoted to the study of erosion due to cavitation in the circulation flows of eddy hydraulic spillways, including those equipped with counter-vortex flow energy dissipators**.** Cavitation destructive effects depend on many factors: intensity consisting in the rate of decrease in the volume or mass of a cavitating body per unit of time, the stage of cavitation, geometric configuration of the streamlined body, the content of air in water, the flow rate, the type of material. The objective of the study consisted in determination of cavitation impacts in circulating (swirling) water flows. The studies were conducted by a method of physical modeling using high-head research installations. Distribution of amplitudes of pulses of shock cavitation impact is obtained according to the frequency of their occurrence depending on the flow velocity, the swirl angle, the height of the cavitating drop wall and the stage of cavitation. The impact energy depending on the stage of cavitation and the flow rate is given for different operating modes of the counter-vortex flow energy dissipators of a hydraulic spillway. In the conclusions, it is noted that cavitation impacts in the circulation flows occur mainly inside the flow, which is a fundamental difference from similar processes in axial flows.

1 Introduction

Reliability and long-term operation of spillway systems of hydraulic structures is one of the main conditions for ensuring the safe operation of waterworks. They are used both during construction and operation periods. The type, composition and layout of the spillway system in the hydraulic facilities depend on the design flow rate, the difference in the levels of the pools, the purpose and type of the hydro system, the topographic and geological conditions of the site and the operation requirements. Considering the hydraulic, structural and layout features, there are several basic schemes for discharging water downstream: surface free-flow, pressure submerged or bottom, open and closed, integrated with a dam and shore spillways [1]. For flow transition from the upper pool to the tail water a dissipator of the kinetic energy of the discharged flow is required. In practice the most commonly applied are stilling basins [2, 3], flow energy dissipation by jet throwing from hydraulic

---

[*] Corresponding author: orehov_genrih@mail.ru

structures towards the tail water area [4, 5]. In some cases, depending on water flow velocity, topography, geological features of the spillway foundation, a stepped surface spillway design is applied or that in the form of various piers located in a certain order [6]. Such designs of the flow conductor system of the spillway serves at the same time a flow energy dissipator at the entire length of the spillway [7].

In interaction of the flow with structural elements significant hydrodynamic loads arise transmitted to the structural elements of the spillway and, in some cases, to other structures of the hydropower complex. Moreover, as a result of the attack of high-velocity flows on the structures, cavitation manifestation and associated cavitation erosion can be observed [8, 9, 10, 11].

Cavitation occurs when the pressure in the flow decreases to a certain critical value in which the continuity of the flow is disturbed as a result of the formation of caverns filled with saturated vapors. Cavitation can be of general nature, that is, develops in the areas of the flow conductor system of a spillway with reduced head. Such a situation may occur at the end of a pressure outlet or, for example, on the inner surface of the wall of the flow conductor on its turn. It can be local when even with a gauge pressure (more than atmospheric) in this area, a local hydrodynamic pressure drop occurs behind the irregularities of streamlined surfaces – protrusions, cracks, technological grooves [12, 13, 14]. Cavitation bubbles carried by the flow to the area where the pressure is higher than the pressure of saturated vapors disappear (slam, dissolve). Cavitation changes the nature of fluid movement, causes additional energy loss, vibration, noise and erosion of material at solid boundaries. [15].

Cavitation manifestations depend on the nature of the flow. In circulation-longitudinal currents [16] the emergence and development of cavitation processes differs from those in ordinary longitudinal-axial flows (without swirling). This is due to pressure distribution pattern cross-wise these flows. This article presents some results of studies of cavitation phenomena in circulation-longitudinal currents occurring in hydraulic structures

2 Objective

The aim of the research is to study cavitation phenomena in circulation-longitudinal (swirled) axisymmetric flows that can be used when operating various spillway systems, including those with the use of counter-vortex flow energy dissipators. Circulating currents are characterized by pressure gradients in the cross section of the flow and with high peripheral velocities by the presence of a vacuum in the axial zone up to its absolute value. Under these conditions, it is important to know how the cavitation areas are spreading in the volume of the flowing fluid and how cavitation affects the material of the walls of the flow conductor system.

The objectives of the study are as follows:

- experimental model studies of pressure distribution in longitudinal- transverse currents;

- determination of the dependence of the erosion activity of the cavitation zone on the flow velocity, swirl angle, cavitation stage and the size of cavitation initiator (height of obstacles);

- experimental assessment of the cavitation attack on the walls of the flow conductor of the counter-vortex flow energy dissipator.

3 Method

Circulating-longitudinal currents in most cases belong to the group of spatial currents that are located in the prevailing field of centrifugal mass forces. Analyzing this type of fluid motion, gravitational forces, as a rule, can be neglected, with the circumferential (tangential) velocities determining the structure of the flow characteristics. The circulation-longitudinal flows have transverse and longitudinal pressure gradients, which in some cases lead to break in continuity of the flow in the axial zone and the formation of a vortex core. These factors fundamentally distinguish the circulation-longitudinal currents from conventional longitudinal-axial flows [17]. The noted physical features of the circulation-longitudinal currents compared to longitudinal-axial flows are reflected in the complication of the processes occurring in them. Therefore, at present, an effective way to solve essentially any problem of dynamics of such flows is a physical experiment. This statement is fully applicable to the study of cavitation phenomena occurring in circulation-longitudinal currents.

The studies of the cavitation phenomena have been carried out on the physical model. Fig. 1 a and b show an experimental installation and location of the sensors in measuring sections of the model.
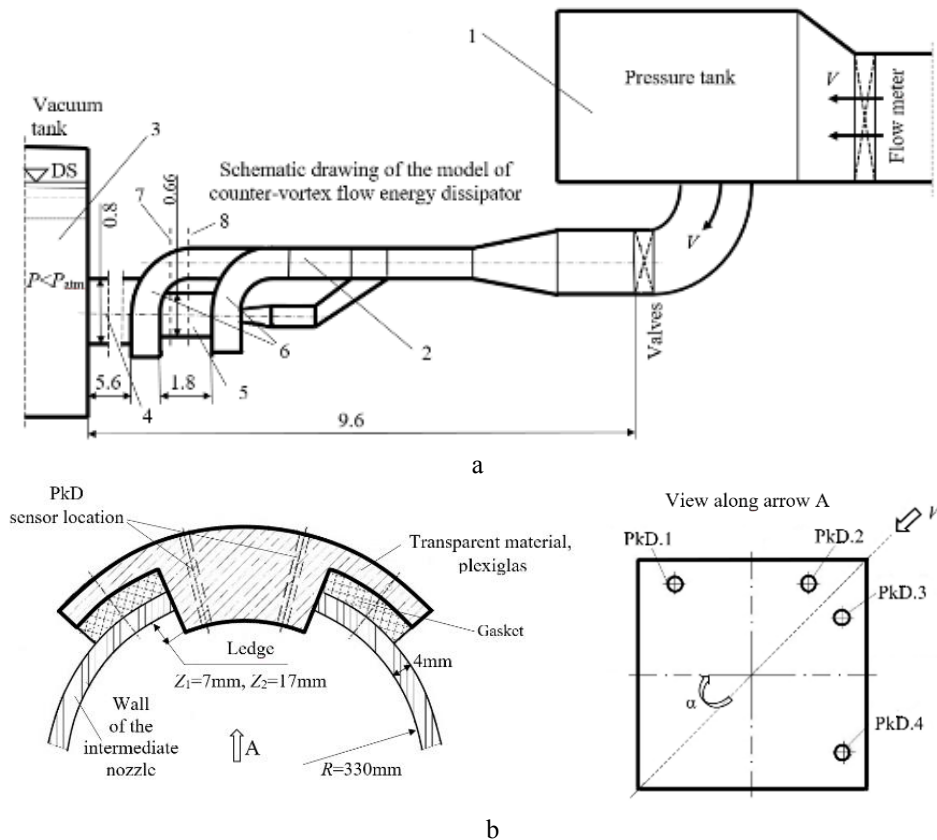
Fig. 1. Experimental installation and model for conducting cavitation studies: a – schematic drawing of experimental installation, b – schematic location of the sensors in measuring sections of the model.

The experimental installation for carrying out a complex of cavitation studies on a model of the counter-vortex flow energy dissipator included a pressure tank 1 (Fig. 1, a) to create an operating head for model 2 and a vacuum tank 3 of the lower pool. The vacuum tank 3 provides a pressure below atmospheric to obtain the necessary cavitation mode in the circulation-longitudinal flow. The geometrical and hydraulic characteristics of the model are as follows: the model length is 9.6 m, the diameter of flow energy dissipation chamber 4 is 0.8 m, its length is 5.6 m, the diameter of the intermediate nozzle 5 is 0.66 m, its length is 1.8 m. Local swirlers 6 are made in the form of spiral chambers with an enveloping angle of 345 degrees. The maximum operating head on the model H is 20 m, the maximum flow rate Q is up to 6.5 m$^{3/s}$. The pressure on the walls of the flow conductor of the flow energy dissipator was measured by instruments located in two sections 7 and 8, shown in Fig. 1, a. The instruments in the measuring sections were located around circumferentially the cylindrical surface of the intermediate pipe 5 of the dissipator where a longitudinal-circulation flow was formed. The pressure values obtained in each of measuring sections 7 and 8 have been averaged by the readings of several instruments.

4 Results

As a result of the carried out studies there have been obtained the non-normalized densities of distribution of probabilities of the amplitudes of pulses of shock cavitation impacts for various operation modes of the.counter-vortex dissipator model studied. The curves shown in Figures 2 and 3 serve as an example of such a distribution. On these curves: N is the number of pulses of shock cavitation impacts; P is the pressure in kPa on the sensitive element PkD; U is the voltage corresponding to the pressure of the pulse in volts; Q - water discharge; u_θ is the azimuthal (tangential) component of the full velocity M of the circulation-longitudinal flow, $u_\theta = M/\cos\alpha$; K_{cr} is a critical value, at which cavitation occurs, equal to 1. The coefficient of cavitation was determined by formula

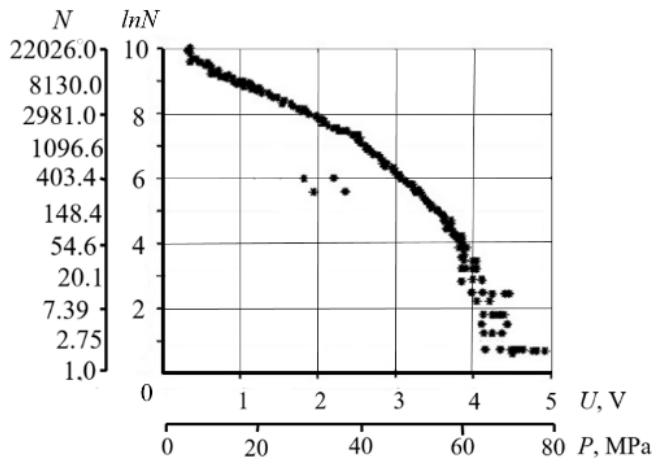$$K = \frac{p - p_{sat}}{0.5\rho M^2},$$ (1)

where: p is the absolute pressure at the measured point, p_{sat} is the pressure of saturated water vapor at a temperature of 20º C, M is the total vector of the flow velocity at the measured point, ρ – is the density of water.
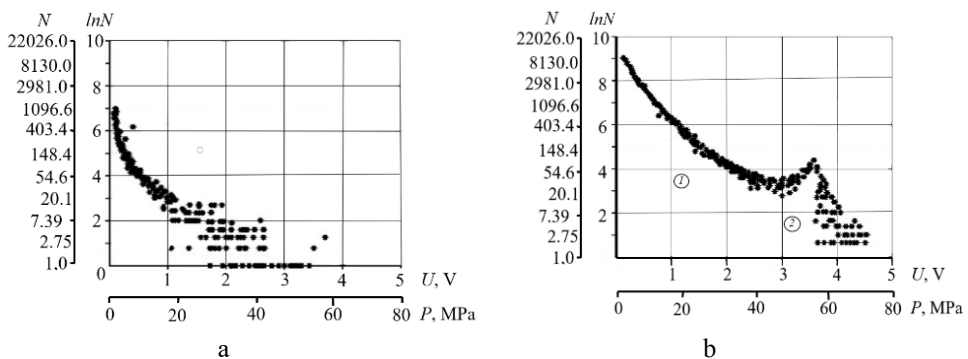
Fig. 2. Distribution of amplitudes of the light pulses of the shock cavitation attacks by frequency of occurrence. The time of process recording 50.2 s: a – pick-up PкD.4, $Q = 5$ m^3/s, $Z_2 = 17$ mm, $u_\theta =$

8.6 m/s, $\alpha = 45^0$, $K/K_{cr} = 0.883$, b – pick-up РкD.2, $Q = 6$ m^3/s, $Z_1 = 7$ mm, $u_\theta = 11.44$ m/s, $\alpha = 45^0$, $K/K_{cr} = 0.703$.

Fig. 3. Distribution of amplitudes of the light pulses of the shock cavitation attacks by fre-quency of occurrence. The time of process recording 50.2 s. Pick-up РкD.1, $Q = 6$ m^3/s; $u_\theta = 13.3$ m/s, $K/K_{cr} = 0.505$.

For different cavitation modes recorded by relative cavitation coefficient K/K_{cr} erosion activity was recorded by the integral energy values of shock attack of cavitation bubbles E_P and the intensity of light flashes of these bubbles. The latter value is directly proportional to the mechanical energy of the bubble [18, 19].

The total energy of cavitation shock or light pulses obtained on the analyzer as the integral sum of the products of amplitudes of pulses by their number and identified with the value of the integral was adopted as the energy characteristics of cavitation aggressiveness.

$$J = \int\limits_{\lambda_{min}}^{\lambda_{max}} J_\lambda d\lambda \quad [\frac{W}{m^2}], \tag{2}$$

where: λ_{min} – the lower limit of pulse attack determined by the instrument sensitivity, λ_{max} – the upper limit set by the absence of the realization of the event on the length of realization of the experimental recording of the process in time 50.2 s.

Let us analyze the forces acting on a cavitation bubble in the circulation-longitudinal flow. In conventional longitudinal-axial flows there is mainly a flat picture of the flow separation zone on the drop wall streamlining. This is due to the fact that the inertial forces here are much more than gravitational ones. The cavitation bubble practically does not float along the length of the cavitation flume and. therefore, in all cavitation modes it is located in the area occupied by the flume. This circumstance leads to the fact that cavitation actively affects the wall material of the flow conductor portion. For longitudinal-axial currents, the values of the energy intensity of the attack of cavitation bubbles and the intensity of the light flux recorded by the sensors for one and the same cavitation mode are proportional to each other.

In the circulation-longitudinal (swirling) flows, a different flow pattern is observed - spatial. The values of the aforementioned energies are no longer proportional here due to the fact that the solid angle recorded by the analyzer (photo-electronic multiplier) makes it possible to obtain the total electromagnetic energy of the entire cavitation flume, while the

PkD sensors register only a part of the impact energy falling on the solid flow boundary. Obtaining both values of energy in such flows is methodologically particularly important, since with a high aggressiveness of the cavitation mode and with its "gentle" impact on the wall we will receive evidence in favor of structures with circulation longitudinal (swirled) flows. The cavitation flume in this case is already directed at an angle to the axis of the conduit in the conical helix trajectory.

The reason for this is that the pushing (Archimedean) force $F_\downarrow$ generated in the field of centrifugal forces becomes significant here. Due to the action of this force, the bubble starts floating up moving to the axis of the circulation-longitudinal flow (Fig. 4). The arrow at $F_\downarrow$ force is directed downwards, since the bubble moves in the water column (floating up) to the axis of the flow conductor, since the pressure forming in the flow axial zone is below the atmospheric one (vacuum).

The values of the force and bubble floating up rate with the assumption that the bubble is spherical in shape (this shape remains intact in bubbles no larger than 0.1 mm [20]. With turbulent nature of fluid motion a bubble that emerges at a rate of $W_\downarrow$ having traveled a path equal to the length of the cavitation flame l, transmits to the fluid mass $m = \pi R_{bub}^2 l \rho$ kinetic energy

$$C = -\frac{mW_\downarrow^2}{2} = -\frac{\pi R_{bub}^2 l \rho W_\downarrow^2}{2}. \tag{3}$$

This energy is spent for vortex generati0n in the flow and turns to heat. With a uniform movement of the bubble, its buoyant force $F_\downarrow$ and braking force (hydrodynamic resistance force) $F_\uparrow$ will be equal to each other:

$$m\frac{dW_\uparrow}{dt} = F_\uparrow = F_\downarrow = -\frac{Z}{l} = \frac{4}{3}\pi R_{bub}^3 \rho j = \frac{\pi R_{bub}^2 \rho W_\downarrow^2}{2}, \tag{4}$$

where j –centrifugal force acceleration in a cylindrical flow conductor with radius R, bearing in mind that a drop wall of Z. height horizontally located in the flow conductor is the source of cavitation. Then
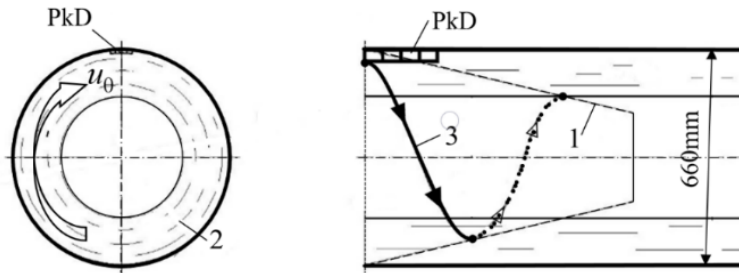
$$j = u_\theta^2 / (R - Z). \tag{5}$$

Let us determine the bubble floating up rate $W_\downarrow$ in circulation-longitudinal (swirled)

$$W_\downarrow = u_\theta \sqrt{\frac{8R_{bub}}{3(R-Z)}}, \tag{6}$$

and longitudinal-axial flows.

$$W_\downarrow = \sqrt{\frac{8R_{bub}g}{3}} \tag{7}$$

Fig. 4. Schematic drawing of cavitation bubble floating up trajectory in the circulation-longitudinal (swirling) flow: 1 – imaginary cone on whose helix the trajectory of a cavitation bubble is located, 2 – a rotating annular layer of water of the circulation-longitudinal flow, 3 – trajectory of the cavitation bubble.

For a cavitation bubble $R_{bub} = 10^{-4}$ m in a conduit of radius $R = 1$ m with an azimuthal (tangential) flow velocity $u_\theta = 30$ m / s the bubble floating up rate in the circulation-longitudinal (swirled) flow will be 1.4 m / s, and in the longitudinal-axial - 0.05 m / s.

The above calculation shows that the floating up rate of the bubble in the circulation-longitudinal (swirling) flow:

- more than an order of magnitude higher than in the conventional longitudinal-axial flow;

- directly proportional to the azimuthal (tangential) component of the total flow velocity;

- increases with increasing size of the bubble moving from the wall of the flow conductor towards the centrally located axial zone.

For example, the distance of a bubble from the wall for previously selected values of u_θ $W_\downarrow$ and R_{bub} at the end of the cavitation flume of $l = 0.15$ m in a circulation-longitudinal (swirling) flow will be about 0.01 m. The similar value for the axial flow is an order less. This circumstance drastically changes the pattern of erosional impact on the wall. First, the wall ceases to affect the bubble. It collapses now spherically symmetrically. Secondly, the amplitude of the shock wave front maximum in the event of such a collapse decreases exponentially with distance from the bubble. For example, if the amplitude maximum is observed at a distance of radius R_{bub} from the collapsed bubble, then at a distance of 4 R_{bub} the amplitude of the shock wave front is already more than an order of magnitude smaller.

Let us analyze the probable causes of the presence of peaks on the graph of distribution of shock pulses for aggressive cavitation modes (Fig. 2, b). The right short distribution (1) features a small number of impacts N – from 1 to 20 with large amplitudes. The other, left (2) starts with smaller amplitudes with a significantly larger number of impacts N – from 70 to 8000. With regard to the nature of the numerous experimental amplitude-frequency distributions for various cavitation modes the value of bubble floating up rates, the exponential law of attenuation of shock waves and the kinematics of bubble movement, we can assume that the distribution (1) arises from single bubbles collapsed directly on the wall, that is, those failed to float up and get away from the wall.

The left distribution of shock pulses (2) in Fig. 2, b is the amplitude-frequency characteristics of the main mass of bubbles of the entire cavitation flume. These bubbles floated up to the flow axis, i.e., moved away from the wall. When the bubbles collapses in the stream, their shock pulse attenuating exponentially, reaches the wall significantly weakened. The energy intensity of such a distribution (the area of the sub integrated curve zone (2)) is significantly less than that for the distribution in zone (1). The result of this

impact of weakened impulses will be the "gentle" nature of destruction of the wall material. This is a feature of circulation-longitudinal (swirling) flows.

Considered was the impact energy of single cavitation bubbles versus:

- stages of cavitation $E_P = f\left(K / K_{cr}\right)$;

- flow velocities $E_P = f\left(V\right)$;

- location of the area of low pressure under study;
- height of cavitation cause Z.

According to the results of the calculations, the relationships between the energy of the shock pulses Ep and the stage of cavitation are plotted, shown in Fig. 5.
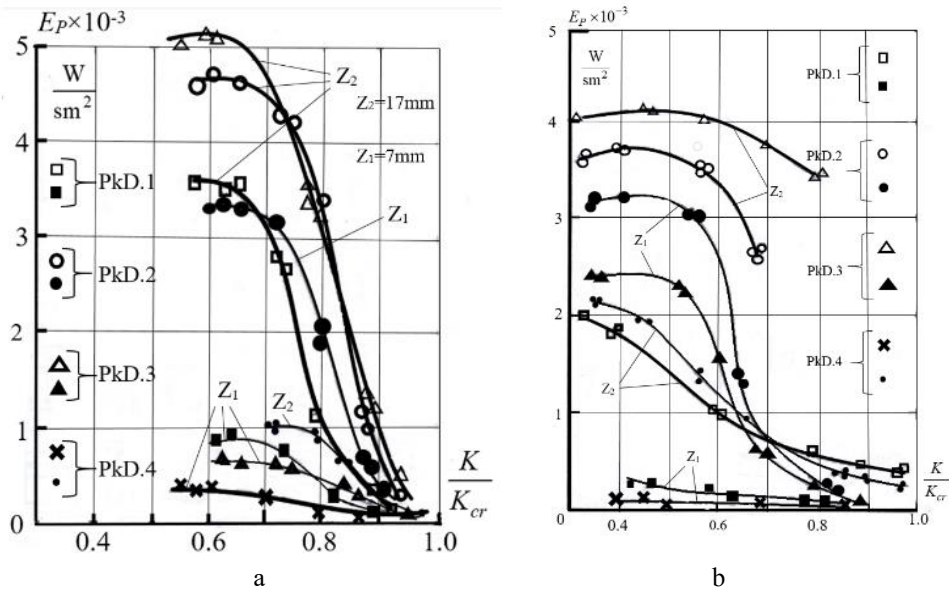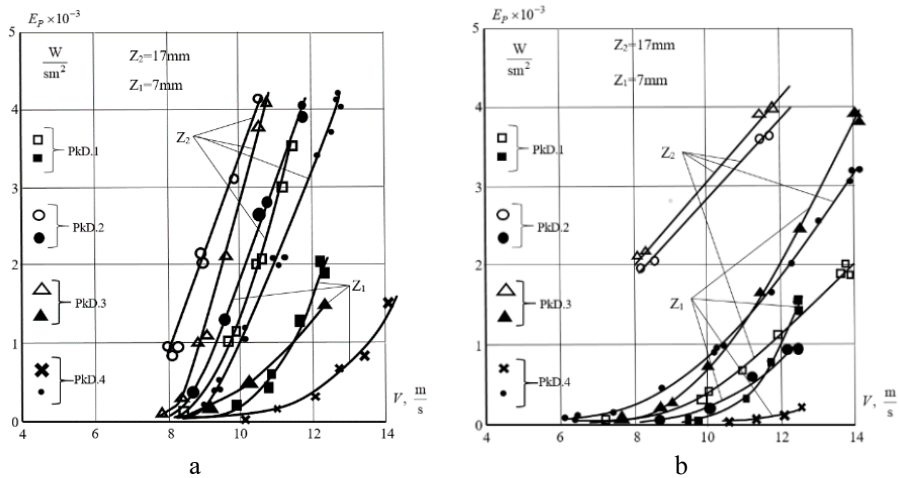

Fig. 5. Shock impact energy and stage of cavitation relation curves in the modes: a – without air supply to the axial zone of the circulation-longitudinal flow, b – with air supply.

The following are the parameters here: the height of the drop wall initiating cavitation and availability of air supply to the axial flow zone. The position of the sensor with respect to the cavitation flume is also taken into account. The pattern of relation curves of Ep values vs stage of cavitation shows that with parameter K / K_{cr} from 1 towards zero, the Ep value first increases, reaching its maximum with $K / K_{cr} = 0.59$, then decreases. This indicates the advancement from the onset of cavitation (K / K_{cr} close to 1) to super cavitation when the shock impact decreases and disappears completely. At the same time, the amplitudes of shock impacts and light radiation decrease insignificantly.

Supply of air to the axial zone of the circulation-longitudinal flow did not significantly affect the erosion activity of the cavitation zone (Fig. 5, a and b).

Fig. 6 shows the relation curves of the energy of the shock cavitation impacts and the total flow velocity vector; the parameters are the same as for those described in Fig. 5 relation curves.

Fig. 6. The dependence of the energy of shock cavitation impacts of the flow velocity in the modes: a - without air supply to the axial zone of the circulation-longitudinal stream, b - with air supply.

As to dependence *of Ep* on the flow velocity, noteworthy is the following here. It is currently known [21] (for longitudinal-axial currents) that the intensity of cavitation damage depends on the flow velocity of the fluid streamlining the cavitation source. This dependence is expressed by exponential function:

$$J = kV^n, \tag{8}$$

where k –is a proportionality factor, n – a positive number, unequal among a number of researchers. The exponent ranges from 2 to 8. The calculations showed that for the conditions of the experiment presented in the article the exponent varies from 4.8 to 5.3, that is, it fits into the specified range. In the graphs of fig. 6, a and b, it can be seen that the supply of air to the axial flow zone does not have a significant effect on the energy of the shock impacts and as a result, on the erosional activity of the cavitation attack.

5 Conclusions

The conducted studies have shown that:

- the pattern of cavitation impacts occurring in in circulation-longitudinal (swirled) flows significantly differs from the cavitation manifestations in conventional longitudinal-axial flows due to the more complicated spatial flow patter;

- analysis of the flow kinematics in the circulation-longitudinal (swirling) flows shows that the bubbles arising in the cavitation flame are much faster carried away by the swirling flow. The bubble movement velocity towards the axial zone of the flow featuring reduced pressure is much higher than in the conventional longitudinal-axial. This suggests that the cavitating bubble as quickly as possible leaves the wall of the flow conductor and collapses already in the flow stratum. This pattern of the cavitation flame results in a "gentle" erosive attack of cavitation on the wall material;

- the cavitating bubble movement velocity in the circulation-longitudinal flow is directly proportional to the azimuthal (tangential) component of the total flow velocity of the swirling flow;

- the cavitating bubble movement velocity towards the centrally located axial zone increases with the increase in its size.

References

1. M. Mahzari, A. Schleiss, Dam. Eng. **20(4)**, 307-327 (2010)

2. A. Gurjev, N. Khanov, N. Volgin, Scientific practical j. of environmental management **4**, 48-53 (2015)

3. G. Sudolskiy, Power Techn. and Engin **8**, 32-40 (2016)

4. J.-h. Wu, L. Yao, F. Ma, W.-w. Wu, J. of Hydrodynamics, Ser. B **26**, 86-93 (2014)

5. F. Ma, Z. Xu, J.-h. Wu, J. of Hydrodynamics, Ser. B **27**, 907-912 (2015)

6. J. Toro, F. Bombardelli, J. Paik, I. Meireles, A. Amador, Environmental Fluid Mechanics **16(6)**, 1195-1221 (2016)

7. A. Parsaie, A. Haghiabi, M. Saneie, H Torabi, J. of Hydraulic Eng. **22(3)**, 281-292 (2016)

8. E. Kermani, G. Barani, M. Ghaeini-Hessaroeyeh, World Applied Sciences J. **21(1)**, 73–78 (2013)

9. H. Chen, B. Ni, W. Hu, Y. Xue, Shock and Vibration **2018**, 8456925 (2018)

10. B. Jiang, W. Yang, Z. Hui, J. of Hydroelectric Eng. **28**, 71–74 (2009)

11. S. Mirbagheri, M. Mansouri, International J. of Eng. Transactions **18**, 18-26 (2005)

12. R. Knepp, Dzh. Deili, F. Khemmit, *Cavitation* (Mir Publ., Moscow, 1974)

13. I. Pirsol, *Cavitation* (Mir Publ., Moscow, 1975)

14. V. Lyatkher, *Turbulence in hydraulic structyures* (Energiya Publ., Moscow, 1976)

15. W. Wan, B. Liu, A. Raza, Shock and Vibration **2018**, 1817307 (2018)

16. A. Zuykov, International J. for Computational Civil and Struktural Eng. **8(2)**, 82-96 (2012)

17. A. Zuikov, *Hydrodynamics of circulation flows* (MGSU Publ., Moscow, 2010)

18. U. Mezon, *Physical acoustics* (Mir Publ., Moscow, 1966)

19. G. Vorobyev, A. Efimov, Russian J. of Physical Chemistry **1**, 108-122 (1988)

20. C. Brennen**,** *Cavitation and Bubble Dynamics* **(**Oxford University Press, Oxford, 1995)

21. S. Slisskiy, *Hydraulic analysis of high-head hydraulic structures* (Energiya Publ., Moscow, 1986)