Hydraulic spillways using the effect of interacting circulation currents

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Abstract. The paper is devoted to study of hydraulic characteristics of flow energy dissipators on hydraulic spillways. Transfer to high-head structures requires unconventional approaches to studying the phenomena associated with high-velocity flows and development of fundamentally new kinds of currents and flow energy dissipation designs forming new technological solutions in hydraulic engineering. Considered here is flow energy dissipation with the aid of counter-vortex dissipators based on interacting circulation currents. The objective of the paper consists in justification of effectiveness of operation flow energy dissipator discharged by hydraulic spillways. The analysis was based on physical modeling method. The described flow energy dissipation method based on the work of viscous friction forces allows for excess flow energy to be dissipated in a very short portion of the spillway water conveyance system. The results of the analysis made it possible to state that with counter-cortex flow the energy dissipation coefficient can be very high. It is shown that the proposed approach favorably differs from the known methods of energy dissipation. In the conclusions it is noted that: efficiency of flow energy dissipation at the counter-vortex dissipators can reach 90-98% of the operating head at a length of 6-8 diameters of the mixing chamber.
Key words: hydraulic spillways, flow energy dissipators, fluid circulation currents, fluid hydrodynamics, turbulence, viscous friction forces, hydraulic resistance, flow rate and fluid flow velocity.

1. Introduction

Spillway systems are a part of waterworks for various purposes. In the practice of hydraulic engineering and hydropower construction, various designs of spillways and ways of flow energy dissipation are used. There are several basic schemes for spilling water downstream: surface free-flow [1], pressurized [2] or bottom [3].

The flow energy dissipation and surface flow transition at the spillways are carried out in different ways. The main, long and often used scheme consists in application of a stilling basin [4]. The applied scheme consists in throwing the jet from the hydraulic structure towards downstream [5]. In some cases, depending on the water flow velocity, topography, geological features of the spillway foundation, a stepped surface design [6] or in the form of various piers located in a certain order [7] are used. Such a design of the water conductor system of the spillway simultaneously serves a flow energy dissipators stretched lengthwise the entire spillway [8]. Despite the traditional application of these spillway schemes and the flow kinetic energy dissipation, many researchers are currently engaged in improving their designs in the construction of new and reconstruction of existing hydro power systems.

A characteristic feature of operation of conventional schemes of energy dissipation of the discharged water flow is that the energy dissipation occurs mainly due to interaction of the entire flow or its individual jets with special elements of hydraulic structures of the dissipator. Dissipation of the flow energy is mainly takes place due to vortex formation when the flow regime changes in the interfacing device, due to jets impingement, direct hydrodynamic contact with a solid body. The power of the flow, which is extinguished in the downstream of the hydro power facility, can reach very high values. For example, when passing a flood discharge of 62,000 m^3/s through the spillway structures of the Zhiguly hydro power project (Russia) during the flow passes through the spillway, the flow energy of 7×10^6 kW is dissipated which is three times the flow energy used by all the units of this station [9]. During interaction of the flow with the structural elements, significant hydrodynamic time-varying forces can occur, which are transmitted to the entire spillway and other structures of the hydro-engineering complex. Moreover, as a result of the effect of high-velocity flows on the structures, there are manifestations of erosion due to cavitation [10, 11], aeration [12], wave formation [13] and other phenomena. Errors in the design, operation of spillways in non-design modes can lead to serious damage and accidents. The cases are known that are associated with complete failure or destruction of parts of the spillway or the downstream infrastructure [14] One of the latest examples is an accident at the Oroville hydro power plant (USA) [15]

In all the above schemes of flow energy dissipation the water flow interacts with the structural elements of the spillway generating alternating hydrodynamic forces that act on these elements. The higher is the head, the higher are the flow velocities acting on the structures, the more complicated is the flow control and the greater is the excess kinetic energy of the water to be dissipated in the downstream.

Transition to designing the high-head hydro power projects has highlighted that the level of engineering hydraulics in most cases satisfying the requirements of construction of low- and medium-head spillways does not solve the problems arising in engineering the high-head structures and does not guarantee their reliable operation. However, the transition to high-head structures requires unconventional approaches to the study of phenomena associated with high-velocity flows and development of fundamentally new types of currents and designs of flow energy disspators that form new technological solutions in hydro-engineering construction. One of them is the method of flow energy dissipation with the help of counter-vortex dampers, based on phenomena arising from interaction of circulating currents [16-18].

2. Objective

The objective of the researches consists in finding new approaches to solution of an important problem of designing the high-head spillway systems for hydro power projects. This paper gives some provisions and dependences justifying the high hydraulic efficiency of flow energy dissipators using the hydrodynamic effects of viscous interaction of coaxially located and oppositely swirled layers of liquid. Such systems minimize the dynamic impact on the structures allowing the flow kinetic energy to be dissipated by its own internal friction forces.

The objectives of the study are:

- experimental study of the model of high-pressure hydraulic spillway;
- a flow capacity of the spillway, the degree of dissipation of the kinetic energy of the stream;
- determination of the hydraulic resistance of the whole energy dissipator, both local resistance;
- distribution of static and dynamic pressure along the dissipator flow path.

3. Method

The counter-vortex flows have a very complicated structure therefore; practically the only method for solving essentially any problems of the dynamics of such flows is a physical experiment. The counter-vortex flow is a spatial non-uniform flow with interacting, oppositely rotating coaxial layers of liquid or gas coaxially arranged in a cylindrical channel. In contrast to the widespread in nature and technology of longitudinal and circulation-longitudinal currents, the counter-vortex flows do not occur in nature. They are characterized by a complicated form of distribution of velocity components and specific structural parameters. Such artificially created dynamic structures of fluid (or gas) flows are formed due to special organization of the input flows.

Figure 1 shows one of the possible schemes for providing the two-layer counter-vortex flow in a circular cylindrical chamber (tube).

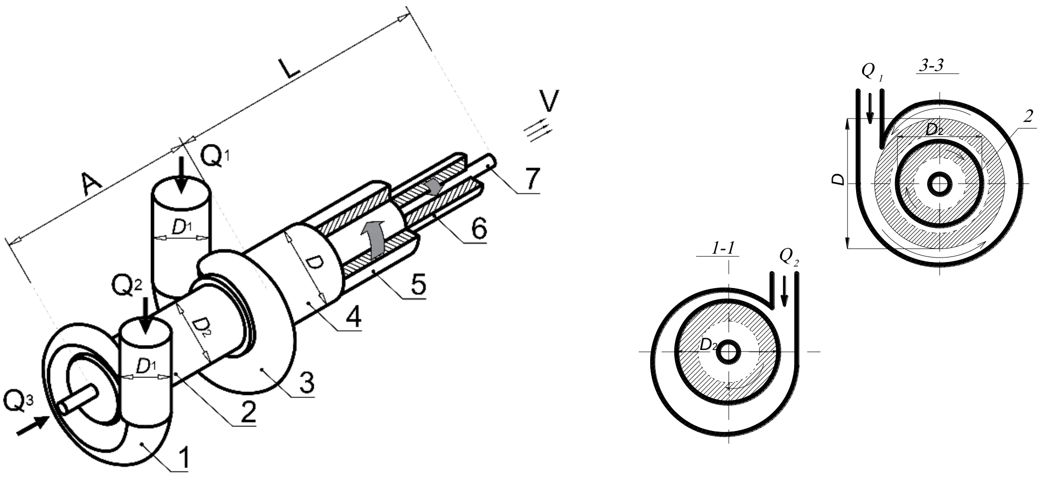

Figure 1. Schematic of the counter-vortex dissipator of the energy of the hydraulic spillway with tangential cylindrical flow swirlers

Zone *A* - supply of water to the energy dissipator and formation of swirled flows prior to their interaction, formation of cavities of rupture with pressure below atmospheric pressure (P_0); zone *L* - region of interaction of flows in the quench chamber. 1 - swirler of internal swirling flow; 2 - swirler of peripheral swirling flow; 3 - external swirling flow; 4- inner swirling flow; 5 - axial flow of water (free jet); 6 - cylindrical blanking chamber. Q_1, Q_2, Q_3 – water flow rate fed to the unit from the pressure of the spillway system

The investigations were carried out on a high-pressure installation, which included the energy dissipation model. The main geometric parameters of the counter-vortex dissipator model and its hydraulic characteristics are given in Table 1

Table 1. Geometric and hydraulic parameters of the model

Geometric parameters of the model					Hydraulic parameters of the model			
D_1 (m)	D (*m*)	D_2 (*m*)	H ($m\ H_2O$)	Q (m^3s^{-1})	Re by R_H	Re_{GR} by R_H	k_e	λ
0.3	0.8	0.66	5-70	0-3	1.5-5.6 10^6	5.64 10^4	0.015	1.58 10^{-2}

During the study, the following values were measured: Q – water flow that passes through the model for different modes, H – operating head, P – pressure on the walls of the flowing part. Calculated: η – coefficient of dissipation of the kinetic energy of the flow, ς – coefficient of hydraulic resistance of the energy dissipator. The errors in these quantities were determined in accordance with the requirements of [19] and are given in Table 2.

Table 2. Mean square errors of measured values × 10^{-2}

Water flow rate, Q	Operating head, H	Pressure, P	m	η
±2.8	±3.6	±1.7	±3.2	±2.9

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4. Results

Modeling of high-head counter-vortex spillway systems is not an easy task. The fact is that in different sections of the flow path in such spillways the flows are significantly different and, therefore, must be modeled in different ways. At the section to the local swirls, there is a classical pressure flow simulated by the Euler criterion. From local swirls to the stilling basin, it is necessary to take into account the specific nature of the circulation currents, whose movement takes place under prevailing effect of the field of centrifugal mass forces. This is the reason for forming the cylindrical cavities called vortex core in the center of swirled flows with the pressure P_0 therein of the atmospheric one with the air supplied to absolute vacuum. Such a fluid motion should be simulated according to the Euler criterion, taking into account the vacuum, and by the Froude criterion, as a flow with a free surface. Since the Euler and Froude criteria are scale compatible, then such simulation is possible. Free flow movement in the flume after the flow energy dissipation pressure chamber should be simulated only by Froude criterion as a classical open flow.

In the described studies, the main task was to determine the discharge and energy dissipation characteristics of the counter-vortex spillways, as well as the hydrostatic and dynamic loads on the elements of the water conductor system. In this case the system of criteria values will take the form

$$Re \geq Re_{GR}, \; Eu = \frac{P_0}{\rho V^2} = idem, \; A_i = \frac{M_i}{2R_G I_i} = idem \tag{1}$$

We consider the condition of self-similarity with respect to Reynolds. On the model studied the Reynolds numbers calculated from the average axial velocities at the exit from the stilling basin made up from Re = $0.4 \cdot 10^5$ to $2.5 \cdot 10^5$. If we use the Levi formula [20], then with roughness of the model walls made of metal equal to $k_Э$ = 0.015 mm and the coefficient of hydraulic resistance along the length λ = 0.0158 we obtain

$$Re_{\text{GR}} = \frac{14R_H}{k_e\sqrt{\lambda}} = \frac{14 \cdot 200}{0.01558} = 1.49 \cdot 10^6.$$

We see that the first condition (1) $Re \geq Re_{GR}$ is generally achieved.

Let us turn to the Euler criterion. As noted above, when simulating a counter-vortex flow, it is necessary to provide relative vacuums in the near-axis flow zone similar to that as in the prototype, that is, the vacuum (P_0) should be a scale-recalculated value with respect to the acting head

$$\frac{P_0}{\rho g H} = \overline{P}_0 = idem. \tag{2}$$

If the velocity of the flow leaving the counter-vortex spillway, as a result is determined by hydraulic losses therein, then it is fair to write down $V = \varphi(2gH)^{0.5}$, where φ velocity coefficient of the flow outgoing from the mixing chamber.

Then, if outflow to the free flow flume on a model or into the free flow tunnel in the prototype occurs by full cross section of the mixing chamber with which the discharge coefficient of the counter-vortex spillway is equal to the outflow velocity coefficient $m = \varphi$, then the modeling conditions by Euler will be written as

$$Eu = \frac{P_0}{\rho V^2} = \frac{P_0}{\rho m^2 2gH} = idem. \tag{3}$$

It immediately follows that the simultaneous observance of conditions (2) and (3) ensures equality of the discharge coefficients of the model and full-scale counter-vortex spillways

$$m = \sqrt{\frac{\overline{P}_0}{2Eu}} = idem. \tag{4}$$

It can be shown that the coefficient of the flow energy dissipation at the counter-vortex spillway-dissipator equal to

$$\eta = 1 - \frac{V^2}{2gH},$$

is similar for both the model and prototype with observance of (2)

$$\eta = 1 - \frac{\dot{P}_0}{2Eu(1+\dot{P}_0)} = idem, \qquad (5)$$

here H – hydrodynamic head [21].

That is, the Euler similarity conditions can be written as equalities (4) and (5). These equalities show that the coefficients of discharge and flow energy dissipation at the counter-vortex spillway do not depend on the Reynolds number and, consequently, are head-scaled (do not depend on it). As will be shown below, this is indeed the case, but only in the self-similarity zone by Reynolds.

Hydrostatic and dynamic loads on the elements of the counter-vortex spillway flow conductor system can also be represented in the form of equal local Euler numbers on the model and in the prototype.

$$Eu = \frac{P}{\rho V^2} = idem, \quad Eu' = \frac{P'}{\rho V^2} = idem \qquad (6)$$

here P and P' hydrostatic pressure and its dynamic (pulsating) component.

Write down

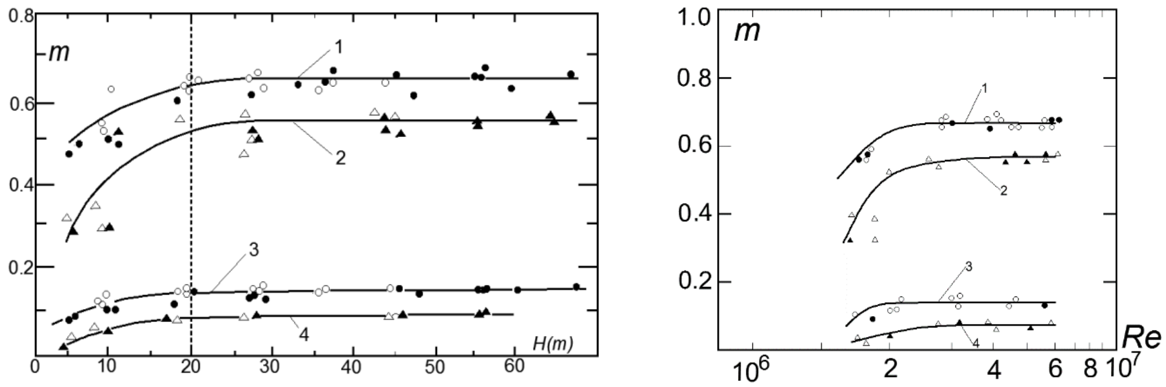
$$Eu = \frac{P}{\rho V^2} = \frac{P}{\rho g H 2m^2} = idem, \quad Eu' = \frac{P'}{\rho g H 2m^2} = idem. \qquad (7)$$

Correctness condition of the hydrodynamic simulation of the counter-vortex flow is observed

$$A_i = \frac{M_i}{2R_{Hi}I_i} = idem,$$

when the geometric similarity of local swirls of peripheral and internal swirled flows is provided for the model and prototypeю. Here: M_i – angular momentum of the peripheral or inner layer of a swirling flow, I_i – longitudinal component of the pulse of the peripheral or inner layer of the stream**.**

To illustrate the correctness of the simulation conditions, Figures 3 and 4 give the data showing self-similarity zones in which, as noted above, the main hydraulic characteristics of the counter-vortex systems do not depend on the Reynolds number (*Re*), and, hence, on the head (*H*). In the figures, the measured values of the discharge coefficients *m* are shown by dots; the solid lines show their design values. The model operation modes are indicated in accordance with Table 1



a) b)

Figure 2. Self-similarity of the flow rate coefficient: a) – by flow rate with $P_0(\rho g H)^{-1}$ = -0.03; b) – by Reynolds with $P_0(\rho g H)^{-1}$ = -0.075. Positions 1, 3 with a central jet (Q_3), – 2.4 without a central jet (Q_3)

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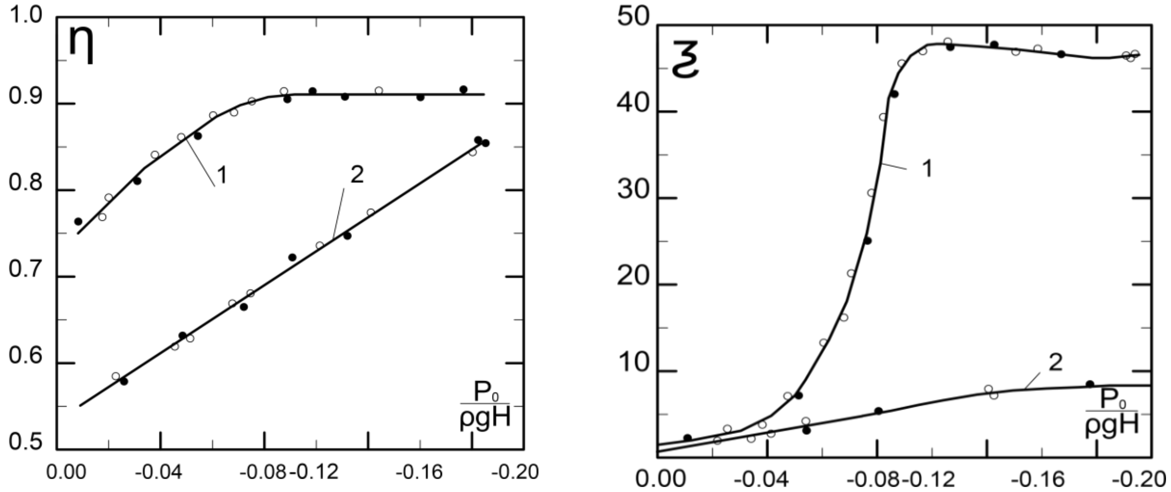
In the illustrations in the modes without an axial flow supply (Figure 2), the relative vacuum in the near-axial zone of the counter-vortex flow is maintained constant at the level $P_0(\rho gH)^{-1}$ = -0.03 (Figure 2,a); in the modes with the supply of the axial flow $P_0(\rho gH)^{-1}$ = -0.075 (Figure 2,b). This depletion caused by the action of centrifugal forces in swirling flows, was regulated on the model by air supply ejected from the atmosphere through air ducts. On the whole, in the experiments, the discharge was varied from zero with atmospheric pressure in the near-axis zone, achieved by vacuum break by full opening of air duct up to $P_0(\rho gH)^{-1}$ = -0.75 (ultimate relative vacuum) with its complete cutoff. It is interesting to note that the ultimate vacuum $P_0(\rho gH)^{-1}$ = -0.75 corresponds exactly to its value in the compressed flow cross-section in a short nozzle with uninterrupted jet flowage to the atmosphere. In the full-scale conditions of high-head spillways with the heads of more than 50 m, the discharge value can reach an absolute vacuum (-98.1 kPa), while the relative vacuum will be from zero to $P_0(\rho gH)^{-1}$ = -0.2. This was taken into account during the studies. Obviously, without air admission to the counter-vortex flow in the prototype, they will work in cavitation conditions.

According to Figures 2, with $P_0(\rho gH)^{-1} < -0.03$, the self-similarity conditions by head and Reynolds are guaranteed to be attained with the values of u $H \geq 20$m and $\geq 2.8\ 10^6$ (the self-similarity zones are cut off by dashed lines). The same result was obtained for other values of the relative vacuum (to $P_0(\rho gH)^{-1}$ = -0.75). This shows that the self-similarity conditions by Reynolds in counter0-vortex flows occur much earlier than by Levy's recommendations for axial flows ($Re_{GR} = 1.49\times10^6$). Undoubtedly, this is the result of a high artificial flow turbulence transition with interaction of coaxial, oppositely-swirled flows, much higher than the natural turbulence of axial currents, determined by Reynolds number. This allows us to conclude that simulation of counter-vortex flows, to some extent, is similar to simulation of such a phenomenon as a hydraulic jump. Just as in the counter-vortex flow the bulk of the kinetic energy of the flow is lost in the hydraulic jump at a short section, due to high flow turbulence and it is known that the hydraulic jump parameters are scaled from the model to the prototype without distortion with Reynolds model numbers more than two times lower than the boundary values [22, 23]. This conclusion seems to be very important to us, since it does not give extrapolation, but direct empirical recommendations for the conditions of physical simulation of counter-vortex flows.

The experiments allow an important conclusion to be drawn that local swirls divided by a wall (item 2 in Figure 1) do not actually have any effect on each other's work Substantial excess pressures are an important factor eliminating the development of cavitation on streamlined surfaces of the water conductor section of the counter-vortex system.

One of the most important questions to be studied experimentally in the process of the hydraulic studies described consisted in determining the energy-dissipation capacity of counter-vortex spillways demonstrating their effectiveness (Figure 3).



a) b)

Figure 3. a) – the energy dissipation factor η; b) – coefficient of hydraulic resistance of the system

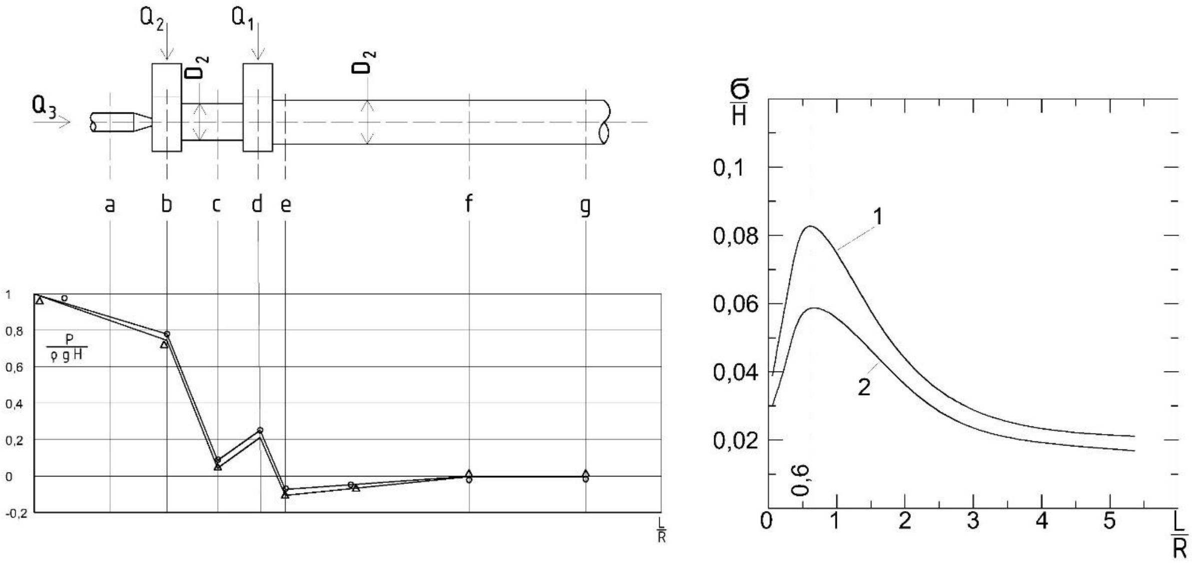
The energy-dissipating capacity was determined by the energy-dissipation coefficient reduced to the head on the model.

The values of the energy dissipation coefficient with the found discharge coefficients and the known geometric parameters of the model were determined by measuring the depth of the flow in the outlet free-flow flume at the exit from the mixing chamber. Such a determination of the energy-dissipation coefficients was possible, since with the studied model operation modes practically axial flow with a sufficiently smooth free surface has been established in the free-flow flume. This indicates that the interacting streams almost completely dissipate each other, and the fact that this process is very intensive, because the mixing chamber with a length of only six of its diameters turned out to be quite sufficient to complete it.

In addition to the energy dissipation factor, the efficiency of the counter-vortex system can also be estimated by a conventional method through the coefficient of hydraulic resistance. The results of the studies show that the effectiveness of energy dissipation with interaction of coaxial oppositely swirled flows is very high. Attention is called to the effect of a sharp increase of energy dissipation with the increase in the relative vacuum $P_0(\rho gH)^{-1}$ in the modes without supply of axial flow to the mixing chamber.

In practice, in pursuit of the goal of the excess energy dissipation of discharged flow, one should strive to reduce the discharges passed through the central waterway, bearing in mind that it has auxiliary functions.

Information about the pressure on the walls of the flow path and its pulsating component is necessary to set the hydrodynamic load in the calculation and design of the structure, as well as to predict the cavitation phenomena. Figure 4 shows the pressure distribution along the length of the dissipator. Figure 4,a shows that there is a vacuum in the interaction zone of the flows in the dissipation chamber at a length of approximately 0.75*L*. Figure 4,b shows the distribution of the pulsation component of pressure along the length of the dissipation chamber. The values of the pulsating component were assigned to the head acting on the model. It can be seen that the pulsations reach a maximum at a distance of approximately 0.6*R* of the quench chamber. Before the chamber and immediately afterwards σH^{-1} value decreases to 0.02, which corresponds to the fluctuation in the conventional longitudinal flow.



a) b)

Figure 4. a) – distribution of relative static pressure along the length of the dissipator flow path; b) – standards of pressure pulsations, referred to the head on the model

5. Conclusion

1. The nature and intensity of the hydrodynamic processes occurring in the counter-vortex devices ensure the effectiveness of their use in a wide range of branches of modern technology, in particular, the damping of excess mechanical energy of water flows in the hydro-engineering spillways.

2. Hydraulic studies of counter-vortex systems with pressure local swirls have shown that the Reynolds self-similarity zone corresponds to $Re \geq 1 \cdot 10^5$. In this zone the main hydraulic parameters are as follows: the discharge coefficient and energy dissipation coefficient do not depend on the Reynolds number and, as a consequence, on the acting head. These results allow the conclusion to be made that the self-similarity conditions by Re for the counter-vortex flow occur earlier than for longitudinal-axial flows. Undoubtedly, this is the result of an artificial turbulence of the flow that occurs when coaxial, oppositely swirled flow layers interact, much higher than the turbulence of natural longitudinal-axial flows.

3. The discharge coefficient m of the studied counter-vortex flow energy dissipation system is in the range from 0.35 without a central jet to 0.75 with the central jet included. The effectiveness of energy dissipation in the interaction of coaxial oppositely swirled flows is very high, reaching a value of 90-98% of the head. The coefficient of energy dissipation increases: a) with vacuum increase in the central zone of the counter-vortex flow at the entrance to the mixing chamber; b) with transition from the operation modes with the central axial jet to the operation modes without central flow. The energy dissipation occurs on a very small portion of the chamber length, which is 6-8 radii.

4. The static pressure in the zone of the dissipation chamber has a negative value. The pressure pulsations on the walls of the energy dissipation chamber reach the maximum values at a distance of $0.67R$ from its beginning. Here the standard of pulsations increases with respect to the initial longitudinal flow approximately 4.5-5 times. Beyond the zone of maximum, the pulsations intensity gradually decreases downstream and to the site $6\text{-}8R$ distant from the beginning of the chamber again returns to the level of the longitudinal flow.

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