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SUBSTANTIATION OF COUNTER-VORTEX SPILLWAY STRUCTURES OF HYDROTECHNICAL FACILITIES

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Розглядаються питання обґрунтування вибору конструктивних рішень гідротехнічних водоскидів, робота яких заснована на ефектах контрвихорових течій. Сформульовано підходи до гідравлічного розрахунку проточної частини водоскидів та визначення їх геометричних розмірів. Наводяться основні конструкції локальних завихрювачів, які формують початкові циркуляційно-поздовжні течії, даються деякі схеми водоскидних систем з такими завихрювачами потоку

Ключові слова: гідротехнічні скидання води, гашення енергії, закручені потоки, вихрові течії, завихрювач, турбулентність

Рассматриваются вопросы обоснования выбора конструктивных решений гидротехнических водосбросов, работа которых основана на эффектах контрвихревых течений. Сформулированы подходы к гидравлическому расчёту проточной части водосбросов и определению их геометрических размеров. Приводятся основные конструкции локальных завихрителей, которые формируют начальные циркуляционно-продольные течения, даются некоторые схемы водосбросных систем с такими завихрителями потока

Ключевые слова: гидротехнические водосбросы, гашение энергии, закрученные потока, вихревые течения, завихритель, турбулентность

1. Introduction

The construction and reconstruction of high-pressure waterworks sets a number of scientific and engineering tasks that require a new approach to their solution. One of them is to design reliable and economical culverts, able to work both in the construction and operational periods, making it possible to combine the spillway and energy flow channels. Damping of the excess energy of idle flows is one of the most important tasks when creating hydraulic spillway systems. The choice of the method for damping the kinetic energy of the flow significantly affects the overall layout of the hydraulic engineering structure.

This task becomes the most urgent in the transition to the construction of high-pressure hydraulic systems, which requires studying the phenomena associated with high-speed water flows, their interaction and the development of fundamentally new designs of spillway structures. The hydraulic sections that are used to solve the problems of transit water flows through such structures have been developed. When designing spillways in high-pressure waterworks, it is necessary to take into account the features of the interaction of high-speed flows with solid boundaries and the air environment. It is essential to take into account the probability of various wave processes, a possible local pressure drop, phenomena of aeration and cavitation and their consequences, as well as peculiarities of energy damping. It is important to ensure ventilation in the case of gravity and partial pressure in closed conduits, as well as take into account other phenomena of hydraulic nature. The resulting hydrodynamic loads under these phenomena are transferred to the building structures, and they must be taken into account in the design, construction and operation of spillway systems.

One of the promising areas for solving these and a number of other problems is the use of swirling water flows in hydrotechnical facilities. The so-called counter-vortex flows of liquid and gas and consideration of the prospects for their practical application have been studied at Moscow State University of Civil Engineering (MGSU, Russia) for several years.

2. Literature review and problem statement

The creation of effective designs of spillway structures for hydrotechnical and hydropower facilities ensures sustainable performance of the entire complex. The design and construction of such systems first and foremost solves the issues of reliability and cost-effectiveness of spillway structures, their throughput, the force effect of the water flow on the structures and elements of the tailrace system, and the choice of the method for damping kinetic energy. In most cases, the energy of the flow dissipates outside the flow channel of the spillway (in the downstream) [1]. There are examples where damping occurs within the flow path through the spillway system [2]. In any case, the high-speed flow affects the elements of the spillway structures. This impact is stronger the higher the pressure on the hydraulic unit.

One of the important issues that ultimately determine the design of the spillway construction is the choice of the method for damping the kinetic energy of the discharged flow. At present, there are several ways to damp the energy of the flow. This is primarily damping of the energy by means of a water well [3, 4]. A widely used method is jet throwing, where the energy of the falling stream is damped in the water massif of the tail water [5, 6]. With relatively small heads, stepped spillways are used [7, 8]. Such a design allows the distribution of energy dissipation along the entire length of the spillway of the dam.

A characteristic feature of these methods of damping kinetic energy is the fact that the dissipation of excess energy occurs as a result of the interaction of a high-speed water flow with a fixed obstacle in the form of structural elements of spillway systems of hydrotechnical facilities or elements of the channel of the lower tail of the hydroelectric complex. In the operation of such spillways, various negative phenomena can occur: alternating flow hydrodynamic forces [9], cavitation [10], and other manifestations. Underestimation of the force impact of the water flow on the structural elements of such systems can lead to their destruction. In this connection, it will suffice to recall a major accident at the Oroville hydroelectric facility in the USA [11].

The negative phenomena noted above urge to look for ways to reduce them by designing optimal structures for the facilities from the point of view of energy damping [12] and, at the same time, by selecting the flow modes for the damped flows. An example is the use of the circulation-longitudinal (swirling) mode of water flow instead of the longitudinal-axial [13, 14].

Thus, proceeding from the aforesaid, it is necessary to create a system that would allow the process of damping (dissipation) of the kinetic energy of the flow into the bulk of the most dumped water, using the forces of internal viscous friction of the fluid. This will minimize the effect of the flow on the structural elements of the spillway. With this method of damping, the above-mentioned negative phenomena can be largely eliminated. In hydropower units, it becomes possible to combine a spillway with a turbine flow path [15].

3. The aim and objectives of the study

The aim of the study is to formulate an approach to determining the main hydraulic parameters and specifying the geometric characteristics of hydraulic spillway systems whose operation is based on the use of counter-vortex flows.

To achieve this goal, the following tasks are set:

– to substantiate, on the basis of physical modelling, the main hydraulic parameters of counter-vortex dampers of the flow energy of spillway systems;

– to suggest, on the basis of the hydraulic flow scheme, an approach to the choice of the geometric characteristics of the energy damper;

– to offer a method for hydraulic calculation of the counter-vortex damper of energy of spillway systems.

4. Materials and methods of research

Nowadays, there are three ways to model the flow of liquid and gas: analytical, a mathematical method using numerical techniques, and physical modelling. Counter-vortex flows have a very complex structure; therefore, practically the only method for solving essentially any problem of the dynamics of such flows is a physical experiment. Thus, the results of model tests are used to determine the basic hydraulic parameters that are necessary to form a schematic diagram of spillway systems with counter-vortex dampers.

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 longitudinal and circulation-longitudinal flows, which are widely common in nature and technology, counter-vortex flows do not occur in nature. They are characterized by a complex form of distribution of velocity components and specific structural parameters. Such artificially created dynamic structures of fluid (or gas) flows are formed due to a special organization of initial flows.

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

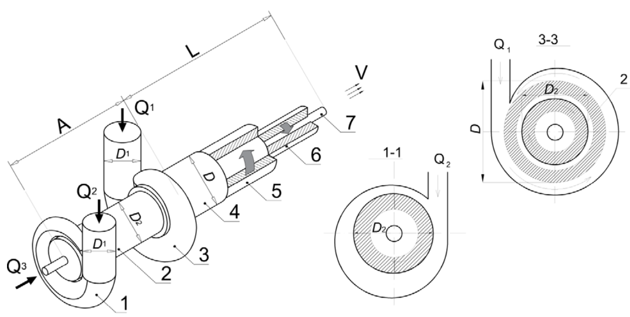

Fig. 1. The diagram of a counter-vortex damper of energy of a hydraulic spillway with tangential cylindrical flow swirlers. The *A* zone entails supply of water to the energy damper and formation of swirled flows prior to their interaction, as well as formation of cavities of rupture with pressure below atmospheric (P_0); the *B* zone is the area of the flows' interaction in the damping chamber. 1 is the swirler of the internal swirling flow; 2 is the swirler of the peripheral swirling flow; 3 is the external swirling flow; 4 is the internal swirling flow; 5 is the axial flow of water (free jet); 6 is the cylindrical damping chamber. Q_1, Q_2, and Q_3 are the water flows to the device from the spillway pressure system

Physical simulation of counter-vortex flows has been carried out on various models, differing in geometric dimensions, effective head, and passing flow. In this article, we present one of the models on which the work of the counter-vortex energy damper was studied. The tests were carried out in an experimental setup that included the energy damper model. The design of the model is shown in Fig. 2, 3.

The model was tested in two modes: 1 – with the head H up to 5.5 mH_2O and the flow rate Q up to 80 l/s; 2 – with the head H up to 8.0 mH_2O and the flow rate Q up to 110 l/s.

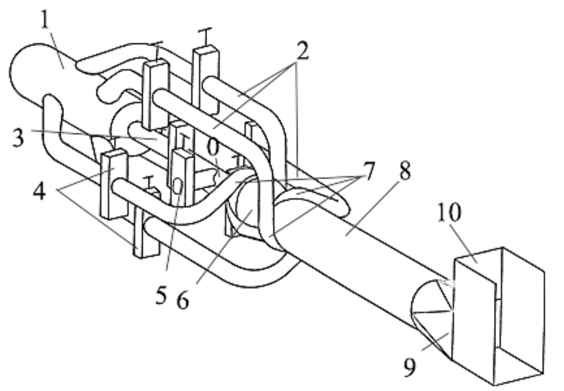

Fig. 2. The model of the counter-vortex damper. Axonometry

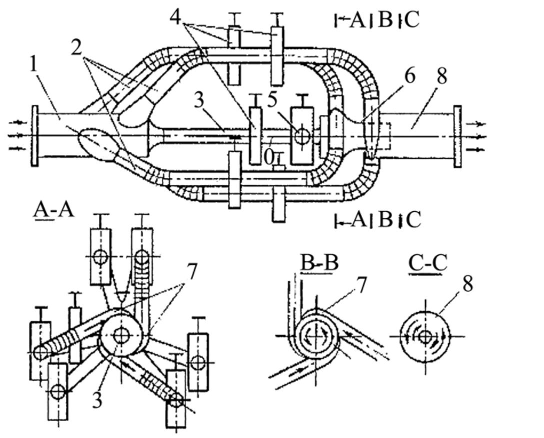

Fig. 3. The model of the counter-vortex damper. Sections: 1 is the water supply conduit (diameter 150 mm), 2 is the tangential water conduits (diameter 50 mm, length 1,400 mm), 3 is the central water conduit (diameter 50 mm, length 1,000 mm), 4 is the gates (diameter 50 mm), 5 is the air duct (diameter 50 mm), 6 is the fairing (diameter 107 mm), 7 is the local swirlers of a tangential type with spiral chambers, 8 is the mixing chamber (diameter 150 mm, length 900 mm), 9 is the transition element with a diameter of 150 mm on a rectangle of 118×150 mm, and 10 is the rectangular discharge chute

During the research, the following values were measured: Q as the water flow passing through the model in different modes, H as the head, P as the pressure on the walls of the flowing part. We calculated η as the coefficient of damping of the kinetic energy of the flow and ς as the coefficient of hydraulic resistance of the energy damper. The errors of these quantities were determined in accordance with the requirements of [16].

In different modes of the model, the number of working channels of the peripheral (n_1) and internal (n_2) swirlers was different. The mode of the model operation determined by the number of fully open channels was denoted by a number where the first digit was equal to the number of open waterways of the peripheral swirling flow, the second was of the number of the internal flow conduits, and the third designated the mode of operation of the central conduit. For example, record 231 meant the opening of two waterways of the peripheral flow $n_1=2$ three waterways of the internal swirling flow $n_2=3$ and the central water conduit; 330 meant the opening of three waterways of the peripheral flow and three waterways of the internal flow ($n_1=n_2=3$), but the central water conduit was closed.

Since the non-pressure axial flow in the discharge chute (the tunnel in full-scale conditions) is an important condition for a reliable operation of spillways, in the process of research the main attention was paid to the "symmetric" operating conditions of the peripheral and internal local swirlers (331, 221, 111, 330, 220, and 110) and modes close to them (131, 231, 121, 130, 230, and 120). In these modes, the flow at the outlet from the mixing chamber had a small residual swirl. Table 1 shows the values of the geometric characteristics:

$$A=\frac{RR_0}{nR_T^2},$$

peripheral (1) and internal (2) local swirlers, correlated with the operating modes of the model studied.

Table 1

The geometric characteristics of the peripheral (1) and internal (2) local swirlers

Mode		n_1	n_2	A_1	A_2
without a central jet	with a central jet				
330	331	3	3	3.28	2.3397
230	231	2	3	4.92	2.3397
130	131	1	3	9.84	2.3397
220	221	2	2	4.92	3.5096
120	121	1	2	9.84	3.5096
110	111	1	1	9.84	7.0192

Here R and R_0 are the radii of the outlet water conduit and the effective radius for the tangential and tubeless swirlers, R_T is the radius of the tangential channel of the circular cross-section.

5. Results of studying the hydraulic parameters of the counter-vortex damper

The flow capacity of the counter-vortex damper. The flow through the spillway system with the counter-vortex energy damper was determined by the formula

$$Q=m\pi R^2\sqrt{2gH_0},$$

where m is the flow coefficient.

Fig. 4 shows the experimentally obtained dependence of the flow coefficient m on the head and the Reynolds number

The graphs of Fig. 4 show that in modes without an axial flow the vacuum in the near-vortex area of the counter-vortex flow was maintained constant at the level of $P_0/\rho gH=-0.02$; in modes with the supply of an axial flow, it was $P_0/\rho gH=-0.08$. This depletion, caused by the action in the swirling flows of centrifugal forces, was regulated in the model by the supply of air ejected from the atmosphere through the air duct (5 in Fig. 3). In general, in the experiments, the discharge was varied from zero at atmospheric pressure in the near-axis zone, which was achieved by vacuum detachment by the complete opening of the air duct, to $P_0/\rho gH=-0.75$ (a limiting relative vacuum) with its complete disconnection. It is noteworthy that the limiting vacuum of $P_0/\rho gH=-0.75$ corresponds exactly to its value in a compressed flow cross-section in a short nozzle with an uninterrupted jet flow of liquid into the atmosphere. In full-scale conditions of high-pressure spillways at pressures 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 $P_0/\rho gH=-0.2$. This was taken into account during the research. Obviously, without air purging of counter-vortex spillways in full-scale conditions, they will operate in cavitation modes.

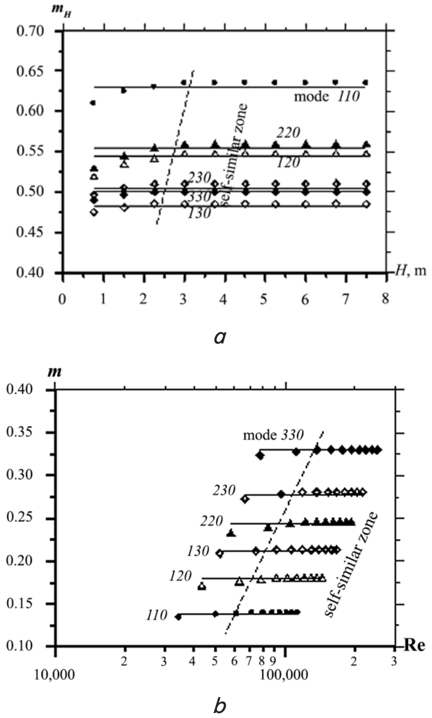

Fig. 4. Self-similarity of the flow coefficient by the head: *a* — according to the Reynolds number; *b* — in modes without the supply of a central water flow at a relative vacuum in the near-axis zone of the flow $P_0/\rho gH=-0.02$. P_0 is the pressure in the axial (tourniquet) cavity of the counter-vortex flow. It is below atmospheric pressure

According to the graphs of Fig. 4, the self-similarity conditions for the head pressure and the Reynolds number are guaranteed to be attained for values of and $\mathrm{Re}\geq 1.25\cdot 10^5$ (the self-similarity zones are cut off by the dashed lines).

In general, it can be seen that the tested counter-vortex spillway is characterized by the same throughput as traditional spillways with flat or segmented gates operating in unopened modes. In traditional spillways, this value of the flow coefficient m is determined by the compression of the flow leaving the gate.

Energy damping. One of the most important issues for the experimental research in the process of the described hydraulic tests was the determination of the energy-damping capacity of counter-vortex spillways to reflect their effectiveness. The amount of the mechanical energy of the flow characterizes the efficiency of the counter-vortex damper, showing the energy of the interacting layers of the liquid used.

The energy-damping capacity was determined by the energy-damping factor, reduced to the general head in the model:

$$\eta = 1-\frac{V^2}{2gH} = 1-\frac{Q^2}{(bh)^2\,2gH} = 1-m^2\left(\frac{nS_T}{bh}\right)^2.$$

It should be noted that the determination of the efficiency of energy damping through a general head in the counter-vortex system is more appropriate than its determination through the head that is effective in local swirlers, since the real hydraulic losses in the counter-vortex system constitute

$$\Delta h_{w\Sigma} = H-\frac{V^2}{2g} = H\eta.$$

The values of the energy damping coefficients with the found flow coefficients and the known geometric parameters of the model (n, S_T, R and b) were determined from measurements of the depth of the flow h with the help of a scintillation scale installed in a discharge non-pressure chute at the outlet of the mixing chamber. These are simple and reliable measurements, much simpler and more reliable than measuring the flow velocities by a hydrodynamic probe with subsequent integration over the cross-section and averaging over the flow.

Fig. 5 shows the experimental plots of the dependence of the coefficient of damping the energy of the flow η on the relative vacuum in the near-axis flow zone.

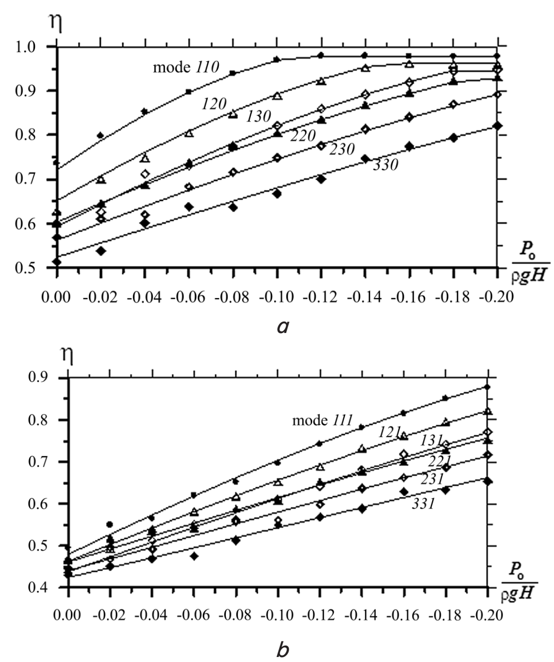

Fig. 5. Energy damping and hydraulic resistance coefficients of the counter-vortex spillway model as a function of the relative vacuum $P_0/\rho gH$ in the modes: *a* — without supplying the axial flow to the mixing chamber, *b* — with the axial flow to the mixing chamber

Fig. 6 shows the experimental dependences of the coefficient of resistance of the entire damping system on the relative vacuum in the near-axis flow zone.

In accordance with the hydraulic circuit of the counter-vortex flow, the energy damper includes three basic elements of the structure. These are the local swirler of the outer layer of the flow, the local swirler of the inner layer of the flow, and the cylindrical chamber in which the oppositely rotating layers of the liquid interact with each other. Particular attention is paid to the design and geometric characteristics of local swirlers.

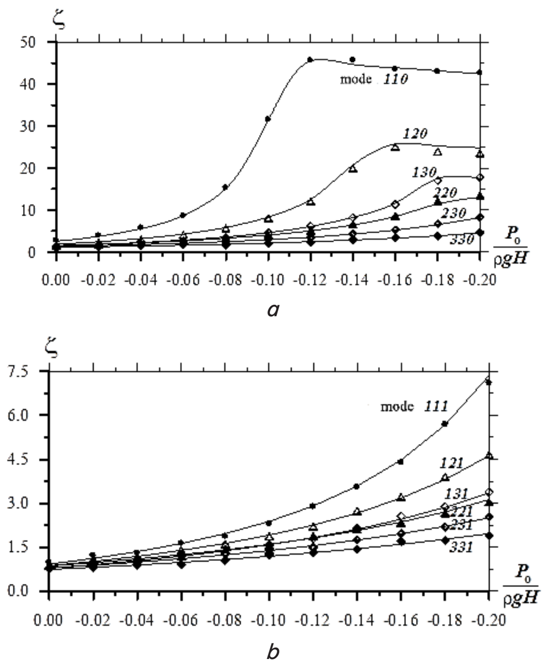

Fig. 6. Coefficients of hydraulic resistance of the counter-vortex spillway model as a function of the relative vacuum $P_0/\rho gH$ in the modes: *a* — without supplying the axial flow to the mixing chamber, *b* — with the axial flow to the mixing chamber

To form the initial swirling flows, which in the active zone of interaction of the oppositely swirled layers of the liquid create the counter-vortex flow, the following designs of local swirlers are mainly used. They are shown in Fig. 7–9 [17–20].

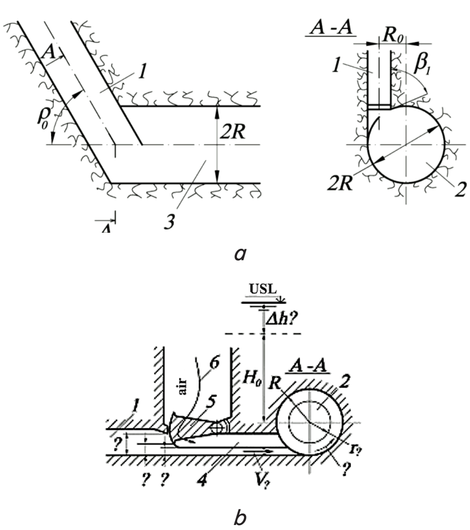

Fig. 7. The designs of tangential local swirlers: *a* — head pressure, *b* — non-pressure

The features of the water flows formed by these swirlers are the following:

– a significant unevenness of the flow along the section of the outgoing cylindrical channel, up to the occurrence of a spiral flow in it, and a part of the perimeter of the channel remains free of liquid. The possibility of formation of a non-pressure flow in the area from the flow regulator (shutter, gate) to the swirl of the flow (Fig. 7);

– a more uniform (homogeneous [21]) swirl along the perimeter that the flow of water acquires in the tangential cylindrical swirler (Fig. 8);

– the blade swirler is an ideal hydraulic design, providing a completely uniform swirl of the flow along the perimeter of the cylindrical channel with minimal hydraulic resistance. The choice of the swirler design is determined by the specific layout scheme (Fig. 9).

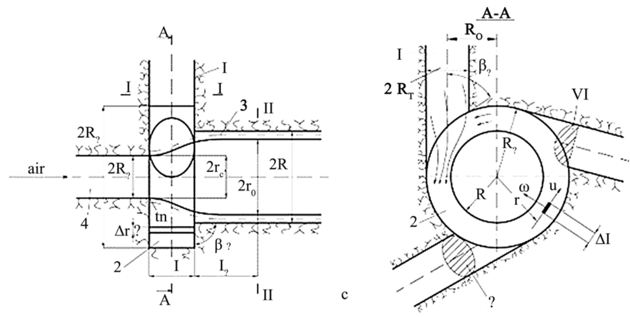

Fig. 8. The design of a cylindrical local swirler

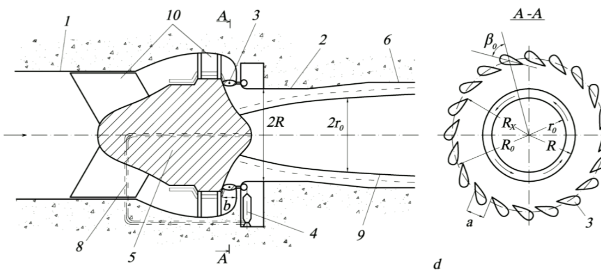

Fig. 9. The design of a bladed local swirler

When assigning geometric characteristics to a local swirler, it is necessary to calculate its hydraulic resistance and throughput, that is, the flow rate Q for a given head H, the radius R_0 of the vortex bundle in the "critical section", and the pressure P on the walls of the channel. The kinematic flow characteristics are the axial velocity components, the tangential velocity components u_x and u_θ, the swirl angle α, and the energy E. The distance from the swirl bend to the "critical section" is determined, which, together with the length of the swirl bend itself, constitutes the total longitudinal dimension of the local swirler.

The loss of the specific energy of the water flow in the local swirler consists of such losses: hydraulic friction in the vortex chamber (ΔE_B) and the swirling flow around the edge of the vortex chamber and the outlet channel (ΔE_K).

The losses of the first type (for hydraulic friction) are determined by the work done by the force $\Delta F_\theta = \Delta F u_\theta / V$ in the section of a length $dl_\theta = u_\theta dr/ur$ and by the force $\Delta F = \Delta F u_r / V$ in the section of $dlr = dr$. Here V is the average velocity of the flow.

The losses of the second type (for the swirling flow around the edge of the vortex chamber and the outlet channel) are determined by the Weisbach formula for local resistances.

The throughput of the local swirler, the structure of the formula of which is analogous to the expression of the flow, determined when flowing out of the holes and nozzles, is found by the expression

$$Q = m_L \pi R^2 \sqrt{2gH},$$

where m_L is the flow coefficient, R is the radius of the swirl chamber, and H is the effective head.

The analytical expression for the flow coefficient of the local swirler is determined as follows

$$m_L = \frac{1}{\sqrt{\frac{1+\varsigma_K}{s_0^2}+\frac{A_0^2}{1-s_0}+\varsigma_B}}, \tag{1}$$

where A_0 is the geometric characteristic of the local swirler, s_0 is the relative area of the live section of the swirling flow, ς_K is the coefficient of the hydraulic edge resistance at the end wall of the vortex chamber and the outflow channel, and ς_B is the coefficient of hydraulic resistance of the vortex chamber.

The relative area s_0 can be determined from the formula

$$s_0 = 1-\frac{r_0^2}{R_0^2},$$

where r_0 is the radius of the axial vortex bundle (steam-air core) of the swirling flow.

Formula (1) contains two unknowns – m_L and s_0. A fairly accurate solution can be obtained using the principle of a maximum flow (the Bélanger principle), in accordance with which the annular cross-sectional area of the swirling flow takes a value corresponding to the maximum flow at a given head.

Below is a simplified scheme for the hydraulic calculation of a counter-vortex spillway structure for various types of swirlers and design solutions for a water discharge system (an open type or an underground tunnel).

The effectiveness of counter-vortex hydraulic spillways is determined by the fraction of the initial mechanical energy of the liquid flow, which is damped within the active zone of interaction of the oppositely swirled layers of liquid. If at the inlet to the spillway the flow has mechanical energy corresponding to the hydrodynamic head

$$E_1 = \rho g H,$$

and at the exit from the core it has kinetic energy equal to

$$E_2 = \rho\frac{V^2}{2},$$

then the efficiency can be determined by the energy damping factor

$$\eta = 1-\frac{E_2}{\rho g H} = 1-\frac{V^2}{2gH},$$

where H is the hydrodynamic head and V is the velocity of the axial flow at the exit from the interaction zone of the oppositely rotating layers of liquid in the damping chamber. The velocity V is averaging, that is, it is determined by the expression

$$V = \frac{Q}{F},$$

where Q is the total water flow through the spillway and F is the cross-sectional area of the interaction chamber of the opposite swirling flow layers.

The efficiency of energy damping can also be determined by the traditional method in hydraulics through the coefficient of hydraulic resistance

$$\varsigma = \frac{2g\Delta h_{w\Sigma}}{V^2},$$

where $\Delta h_{w\Sigma}$ is the total hydraulic losses in the counter-vortex system:

$$\Delta h_{w\Sigma} = H-\frac{V^2}{2g} = H\left(1-\frac{V^2}{2gH}\right) = H\eta.$$

The higher these coefficients, the more effectively the counter-vortex system ensures the damping of the energy of the spillway flow. They are related by a simple dependence:

$$\varsigma = \frac{\eta}{1-\eta} \text{ or } \eta = \frac{\varsigma}{1+\varsigma}.$$

In hydraulic spillways, as a rule, there is no provision for the supply of gas or air to the zone of interaction of the flows. However, in order to suppress the large-scale dynamics associated with the bundle instability of the flow arising in the degeneration of the original vortex layers, a centring unscrewed jet is directed to the paraxial region of the mixing chamber. Calculation of counter-vortex spillways begins with determining this velocity. It is either specified in accordance with

$$V = \sqrt{(1-\eta)2gH} = \sqrt{\frac{2gH}{1+\varsigma}},$$

or determined by technological requirements. In other cases, this speed can be assigned in the range of V=10–20 m/s under the condition of cavitation stability of concrete vaults of spillway tunnels.

The radius of the damping chamber R_1 is determined from the assigned velocity V.

$$R_1 = \sqrt{\frac{Q}{\pi V}} = \sqrt{\frac{Q_0+Q_1+Q_2}{\pi V}}. \tag{2}$$

In formula (2), the notation means the following: Q_0 is the flow rate of the centring unswirled jet, Q_1 is the flow rate of the external swirled layer of the total flow, Q_2 is the flow rate of the inner, oppositely swirling, general flow layer.

Then for a given flow rate Q and head H, setting that R=R_1 and the ratio k_J=R_J/R_1, the value of the effective flow coefficient m_0 is calculated as follows:

$$m_0 = \left(\frac{Q}{\pi R_1^2\sqrt{2gH}}-\varphi_0 k_C^2\right)\sqrt{1+\varsigma_K}.$$

Here R_J is the radius of the centring unswirled jet and 0 is the speed coefficient.

With the calculated value of m_0, we find $ln(m_2)$ and, taking that k=R_2/R_1, determine the corresponding value of $ln(A_2)$. A_2 is the geometric characteristic of the local swirler of the inner layer of the flow.

From the determined value of $ln(A_2)$, $ln(A_1)$ is found and the geometric characteristics of the outer A_1 and inner A_2 of local swirlers are calculated:

$$A_1 = \exp\left[\ln\left(A_1\right)\right],$$

$$A_2 = \exp\left[\ln\left(A_2\right)\right].$$

According to the calculated A_1 and A_2, the type and dimensions of the swirlers are selected.

The length of the path for complete damping of the original circulation opposite to the rotating layers (in fractions of the radius R_1) is determined by the formula

$$\frac{l_{ICh}}{R_1} = \frac{240(1-k)}{\sqrt{4\left[A_1\left(1-\sqrt{1-s_1}\right)+A_2\left(1-\sqrt{1-s_2}\right)\right]^2+\left(\frac{m_1 s_2 - m_2 s_1}{m_1 s_2 + m_2 s_1}\right)}}. \quad (3)$$

In expression (3), l_{ICh} is the length of the interaction chamber of oppositely swirled layers of liquid, s_1 and s_2 are the areas of the annular flows in the local swirlers of the outer and inner flow layers, respectively; m_1 and m_2 are the flow coefficients of the external and internal local swirlers.

6. Discussion of the results of the hydraulic calculations

The resulting values of the throughput capacity of the counter-vortex spillway are characterized by the same throughput as traditional spillways with flat or segmented gates operating in unopened modes. In traditional spillways, the value of the flow coefficient m is determined by the compression of the flow leaving the gate. In the counter-vortex spillway, there is no compression of the flow, but the same values of the flow coefficient are explained by the operation of tangential conduits under conditions of substantial backwater pressure, determined by the centrifugal pressure from the swirling of the flow emerging from them.

We will explain. If the flow coefficient when flowing out from a flat or segmental gate in a conventional spillway is equal to

$$m = \frac{Q}{S\sqrt{2gH}} = \varphi\delta,$$

where S is the area of the culvert while φ and δ are the coefficients of the flow velocity and jet compression, then at $\varphi=0.97$ and $\delta=0.82$, we obtain $m=0.8$.

In the counter-vortex spillway, all water lines (positions 2 and 3 in Figs. 2, 3) operate in the whole cross-section, with $\delta=1$; however, the pressure affecting the water conduits is determined not by the pressure on the counter-vortex spillway as a whole head H, but by the difference between the hydrodynamic head in the supply conduit (position 1 in Fig. 2, 3) and the pressure P on the lower side, i. e.,

$$H_D = \frac{P_W}{\rho g} + \frac{\alpha}{2g}\left(\frac{Q}{S_W}\right)^2 - \frac{P}{\rho g}.$$

This pressure is observed in the central water conduit. In tangential waterways, the pressure P is determined by the centrifugal pressure from the downstream swirling:

$$P = P_T = P_0 + \int \rho \frac{u_\theta^2}{r} \mathrm{d}r,$$

and the effective head will be equal to

$$H_{\mathrm{Pr}} = H_0 - \frac{1}{g}\int \frac{u_\theta^2}{r} \mathrm{d}r.$$

This head is significantly lower than the head H on the counter-vortex system. Thus, the centrifugal pressure from the bottom of the tangential conduits due to the swirling of the flow leads to a decrease in their throughput and the throughput of the counter-vortex system as a whole.

The damping of energy in the counter-vortex damper occurs within a rather short length of the cylindrical damping chamber with a diameter of $2R$. The experiments that were carried out on the model of the spillway system and are presented in the article have shown that the complete degeneration of the initial circulation of swirled water layers occurs at a relative length l_{RJ}/R of 6.

Such a determination of the energy damping coefficients was possible in view of the fact that in the mode of operation of the model studied, a practically axial flow with a sufficiently smooth free surface was established in the gravity free chute. This indicates that the interacting flows practically completely damp each other's swirl, and this process is very intense because a mixing chamber of only six diameters in length was sufficient to complete it.

The experimental tests have shown that, in general, tangential water conduits operate under conditions of substantial backwater pressure, especially at the swirler of the internal swirling flow (Fig. 7), reaching 60–80 % of the head in the counter-vortex spillway. With an increase in the number of tangential conduits running, which is accompanied by an increase in consumption, the head is growing. Substantial pressures are an important factor preventing the development of cavitation on streamlined surfaces of the head section of the flow channel of the counter-vortex system.

Attention is called to the effect of a sharp increase in the damping of energy with an increase in the relative vacuum $P_0/\rho gH$ in modes without the supply of an axial flow to the mixing chamber (Fig. 6). It is especially noticeable in the graphs of the coefficient of hydraulic resistance ς. This effect is related to the regulation of the vacuum $P_0/\rho gH$ by the air supply through the air duct (5 in Fig. 2, 3). The lower the flow rate of incoming air, the deeper the vacuum. The intake of a significant air flow that detaches the deep vacuum reduces the efficiency of energy damping, which is manifested by an increase in the longitudinal velocities of the flow leaving the chamber. At the same time, the liquid flow occupies a part of the cross-section of the mixing chamber, and the other part of it is followed by air ejected from the atmosphere. In this case, the "classical" law of conservation of impulses is manifested, according to which the vacuum at the beginning of the mixing chamber has an impeding effect on the downward flow. The deeper the vacuum, the stronger this effect, the more significant the slowdown of the flow, the more considerable the cross-sectional area of the mixing chamber it occupies. Finally, there is a moment at which the vacuum is sufficient so that the slowdown of the flow results in its filling of the cross-section of the mixing chamber. The moment of the transition of the mixing chamber to full cross-section operation is characterized by a low air flow rate, present in the liquid in the form of a shroud of small bubbles, and the maximum efficiency of damping the energy of the water flow. A further increase in the vacuum leads to a slight decrease in the energy damping, which is explained by the monotonic increase in the capacity of the counter-vortex system with increasing $P_0/\rho gH$, and, consequently, the flow velocities and the head velocity of the outgoing flow increase.

Thus, in systems with the supply of an axial jet in the centre of the counter-vortex flow in the initial section of the mixing chamber, there will be an extremely deep vacuum, which may be sufficient to slow the longitudinal velocities of the outgoing flow and the work of the mixing chamber by the whole cross-section, i.e., in the pressure mode. In practice, in pursuit of the goal of damping the excess energy of the spillway flow, it is better to reduce the flow through the central waterway, bearing in mind that it has auxiliary functions.

Considering the operation of local swirlers of counter-vortex systems, it should be noted that the motion of fluid through a local swirler is analogous to the motion of a longitudinal (axial) open flow through a weir with a wide threshold. Such an assertion is justified, since in both cases (with the longitudinal motion of the flow and the circulation-longitudinal flow in the pipe), similar hydraulic phenomena appear. This sets the mode for the maximum flow. With a decrease in the length of the outflow channel and the length of the weir threshold, the flow rate is increased. For completeness of the analogy, it is noteworthy that there are long longitudinal waves of small amplitude on the free surface of the stream – in the air-steam core [22]. When the outlet channel is below the liquid level, the capacity of the local swirler starts to change only with certain critical values of flooding. The same phenomena also occur in weirs with a wide threshold.

The annular swirling flow with a rupture cavity in the centre (with an axial vortex bundle) is a non-pressure flow moving in the predominant field of mass centrifugal forces. This circumstance leads to the fact that the capacity of a local swirl is determined by its geometric shape and linear dimensions. Up to a certain point, its throughput does not depend on the hydraulic resistance of the underlying path.

The counter-vortex spillway helps damp the excess energy completely at the expense of intrinsic internal viscosity forces of the flow within a relatively short section of the flow path of the damping chamber.

It is of interest to compare the efficiency of damping the energy of the water flow in the counter-vortex spillway and in other types of dampers, for example in a damper with a sudden expansion of the flow in a pressurized water chamber. Such a damper is used at Mica hydropower plant (Canada). Its efficiency can be estimated by the coefficient of hydraulic resistance calculated according to the Borda formula

$$\varsigma = \left(\frac{S_2}{S_1} - 1\right)^2,$$

where S_1 and S_2 constitute the whole cross-sectional area of the water passages blocked by the gates (the compressed cross-sectional area) and the cross-sectional area of the pressure chamber (the wide section).

With respect to the counter-vortex spillway, these cross-sections are equal to

$$S_1 = nS_T = n\pi R_T^2 \text{ and } S_2 = \pi R^2,$$

where n is the total number of working conduits (positions 2 and 3 in Figs. 2 and 3); S_T is the cross-sectional area of one water conduit (tangential or central); R_T and R are the radii of the conduits and mixing chambers.

Then the Borda formula takes the form

$$\varsigma = \left(\frac{R^2}{nR_T^2} - 1\right)^2.$$

In the model studied, the radii of the water conduit and the mixing chamber were R_T mm and R=75 mm; the number of working conduits varied depending on the operating mode of the model.

The results of the comparative calculation are summarized in Table 2.

Table 2

Hydraulic resistance according to the patterns of the sudden expansion and the counter-vortex damper

Mode of the model operation	n	Coefficient of hydraulic resistance ς	
		Sudden expansion (Mica HPP)	Counter-vortex damper
330	6	0.25	up to 4.61
230	5	0.64	up to 8.26
130	4	1.56	up to 17.80
220	4	1.56	up to 13.53
120	3	4.00	up to 25.06
110	2	12.25	up to 45.68
331	7	0.08	up to 1.89
231	6	0.25	up to 2.54
131	5	0.64	up to 3.38
221	5	0.64	up to 3.04
121	4	1.56	up to 4.66
111	3	4.00	up to 7.11

Table 2 shows that the counter-vortex method of damping the energy of the transit flow has a much higher efficiency in comparison with the sudden expansion. Moreover, the difference between the effectiveness of the counter-vortex damper and the Borda damper is all the more noticeable, the larger the ratio S_2/S_1. In addition, effective operation of the counter-vortex damper does not require a flooding of the outlet section of the mixing chamber, whereas the Mica hydroelectric pressure booster chamber must necessarily have a concrete bottom baffle wall equipped with culverts with additional gates.

As already mentioned above, the counter-vortex flow is a very complex artificially created flow with parameters very different from the parameters of traditional and, therefore, more deeply studied longitudinal-axial and circular-longitudinal (swirling) flows. In this respect, it is of interest, including practical, to study further the properties of counter-vortex flows, in particular in the zone of interaction of oppositely rotating coaxially located layers of liquid. Certain possibilities are opened here when carrying out physical modelling by modern contactless methods for measuring the flow parameters: PIV and LDA methods.

7. Conclusion

1. The physical modelling of counter-vortex systems with pressured local swirls has shown that the Reynolds self-similarity zone corresponds to $Re \geq 1 \cdot 10^5$. In this zone, the main hydraulic parameters – the coefficients of energy consump-

tion and damping – do not depend on the Reynolds number and, as a consequence, on the effective head. These results allow us to conclude that the self-similarity conditions for Re for counter-vortex flows occur earlier than for longitudinal-axial flows. Undoubtedly, this is the result of an artificial turbulence of the flow that occurs during the interaction of coaxial oppositely swirled flows, much higher than the turbulence of natural longitudinal-axial flows.

The flow coefficient *m* of the investigated counter-vortex damping system is in the range from 0.35 without a central jet to 0.75 with the central jet included. The efficiency of energy damping in the interaction of coaxial oppositely swirled flows is very high, reaching a value of 90–98 % of the head. The coefficient of damping increases in the following cases: (a) with an increase in the vacuum in the central zone of the counter-vortex flow at the entrance to the mixing chamber; (b) when changing from the operation modes with the central axial jet to operating modes without a central flow. Damping occurs within a very small portion of the length of the chamber, which is 6–8 radii.

2. To organize a counter-vortex flow, it is primarily necessary to swirl two flows in opposite directions with the help of local swirlers. In this case, the work of each local swirler can be viewed from the hydraulic point of view as independent of each other. Therefore, hydraulic calculation of each swirler can be done autonomously, regardless of the work of the other. Schematic diagrams of local swirlers and some analytical expressions that can help determine their geometric parameters are proposed.

3. The simplified method of hydraulic calculation of a spillway system with a counter-vortex damper of the flow energy allows determining a number of basic parameters necessary to create a specific device with given initial conditions – the effective head and the spillway flow rate.

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