Ejecting ability of circulating flows of liquid and gas

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Abstract. The process of aeration of liquid plays an important role in many structures and devices. In water-works and hydropower construction during operation of the spillway systems, aeration allows for hydrodynamic and cavitation effects on the elements of the structures to be monitored. Aeration is also used to saturate water with oxygen depending on the purpose of the chemical or biochemical processes in various industries, for example, in fisheries and hydroecology. Of all known methods the most widespread is the gas-liquid aeration. It allows not only to generate air bubbles, but also to control technological parameters. Various types of circulating flows of liquid and gas, which are swirling flows in circular cylindrical channels, are widely used in various fields of engineering. One of the effects of such flows is the emergence of recirculation areas with pressure in the near-axial zone of the flow below atmospheric one, which makes it possible to eject air into water masses. This feature allows the use of efficient aeration devices based on circulation flows. The report presents the results of physical studies of a complicated flow formed by interacting, oppositely rotating, coaxially located liquid layers. The description of the experimental stand for model studies of such flows is given. Analytical dependences of pressure distribution and specific energy in circulation flow of the viscous liquid are presented. The results of physical modeling to determine the ejection ability of circulating flows, the experimental dependences of the ejection coefficient for different methods of swirling the flow are presented.

1. Introduction
Circulating flows of liquid and gas are widespread in science and technology. They are used for spraying liquid fuel for its better combustion [1, 2], mixing [3] and dispersing liquids, forming the aerosols, flame jets [4] and in other technological processes. This is due to a number of important effects that such flows possess in comparison with longitudinal-axial flow forms. These effects make it possible to repeatedly increase the mass- and heat transfer processes in heat engineering, heat energy, hydraulic engineering, chemical industry, mechanical engineering and in many other industries [5, 6].

A number of researchers conducted numerous experiments to determine various hydraulic and hydrodynamic characteristics of swirled flows for their use in hydraulic engineering, land reclamation, mechanical engineering, and hydro-transport [7, 8, 9, 10, 11]. One of the most interesting directions in studying the behavior of swirled flows was the study of interacting swirled flows of liquid and gas with coaxially located layers [12, 13].

The assumptions of using interacting flows arose from practice requirements. This is primarily the requirement of energy dissipation of flows of high-head hydraulic systems, mixing of two-phase flows consisting of liquids and gases [14, 15].

One of peculiarities of circulating flows is the occurrence of recirculation zones in the initial flow area, which are characterized by reduced pressures in the axial sections. This effect creates the condi-
tions for air ejection to the flowing fluid masses, which can be the basis for creation of various designs of aeration devices. Aeration, that is, the formation of air bubbles in a liquid, is used in various technological processes in a number of industries, for example, for processing minerals, wastewater treatment, biotechnology, food and fish farming, and others [16,17,18].

One example is the aeration of urban water bodies that require constant cleaning. For this, it is necessary to develop and put into practice cheap, but sufficiently effective engineering systems to maintain water quality throughout the entire period of operation of water bodies. The only way to maintain a stable ecosystem of a water body consists in creation a jet aeration system that permanently provides saturation of water with atmospheric oxygen to the desired values and at the same time creates artificial flow due to circulation of water masses around the entire perimeter of the water area [19,20,21]. Another example is the aeration of the water flow in spillway hydraulic structures. Here, the aeration is an important way of influencing the hydro-mechanical parameters of the water masses to be discharged. Aeration has a positive effect on the conditions of cavitation processes and power dynamic impact on the structural elements of the water conductor system of spillways.

This article is devoted to the study of the ejecting ability of circulating flows with interacting oppositely rotating layers. The hydro-mechanical characteristics of circulation flows, pressure distribution, turbulence intensity, head-discharge characteristics for water and are given.

2. Objective
The objective of this work is to study circulating flows, in particular, the flow formed by oppositely rotating axial layers of a liquid by physical modeling methods. The objective of the research was to study the pressure distribution in different sections lengthwise the water-conveyance system of the channel and by its radius and to assess the ejecting ability of the circulating flows in terms of using them for creation of aeration devices.

3. Method
The operation of a jet aerator is based on two effects that arise with interaction of oppositely rotating fluid layers. The first effect consists in the appearance of a cavity of break in continuity of a flow with reduced pressure in the axial zone of liquid rotation. The second effect consists in formation of an extremely high degree of turbulence in the cylindrical interaction chamber. The zone with reduced pressure is responsible for the ejecting ability of the aerator while the level of turbulization of the flow for the degree of dispersion of the gas phase to obtain a dispersion medium - an aerated jet exiting the device.

The operation modes have been studied on the experimental stand. The aerator model had a diameter of the mixing chamber (interaction chamber of oppositely rotating swirl flows) $D_{mc} = 0.16$ m. The choice of this size of the mixing chamber is not accidental. Geometrical dimensions of the model can be either larger than the actual dimensions of the device, or smaller, depending on the certain tasks. This made it possible to simplify scaling of the obtained model data to the prototype using the modeling criteria.

The experimental setup consists of the following main units: a centrifugal pump, which provides an initial pressure $H$ in front of the aerator; a control valve for the pressure pipe, 200 mm in diameter with a control valve; diaphragms for measuring the water discharge in the compressed section, 170 mm in diameter; the aerator model unit.

4. Results
The circulating flows of liquid or gas can be of different kinds. The most widely used in techniques and technologies is a mono-circulating flow, in which a previously swirled liquid flows rotating in the circular channel in one direction (Figure 1, a). In this case, the swirling flow interacts (like the usual axial flow) only with the walls of the channel. Another type of circulating flows is the liquid layers interacting coaxially located, oppositely rotating in a circular channel. This is a complicated artificially creat-
ed flow consisting of two or more circulating layers of liquid that interact not only with the walls of the circular channel, but also with each other (Figure 1, b).

![Figure 1. Types of circulating flows: (a) – mono-circulating flow, (b) – circulating flows formed by interacting oppositely rotating layers](image)

Both of the circulating flows described above have one feature. In the initial section, recirculation zones are formed characterized by formation of powerful return currents with significant negative velocities reaching large values. Figure 2, a shows the profiles of the axial (in the direction of motion) velocities in the relative values of the mono-circulating flow. The graph presents the calculation for the laminar flow regime with Re = 500. Figure 2, b shows the lines of the flow stream formed by two oppositely rotating liquid layers. The recirculation zone with the region of return flows adjacent to the axis of the circular channel is clearly visible in the graph. This picture was obtained experimentally on a physical model using the PIV method of measurements [22]. The flow pattern is turbulent with Re = 10⁵. Shown in Figure 2 recirculation zones create an axial region of low pressures.

![Figure 2. Recirculation zones in swirled flows in a circular channel. (a) - distribution of axial velocity components for a mono-circulating flow, (b) - streamline pattern formed in the flow formed by two oppositely rotating circulating liquid layers](image)

The distribution of pressure in a circulating turbulent flow flowing in a circular channel can be considered analytically [23].

Transformations of the complete Navier-Stokes equations lead to a system of equations (1), while a number of simplifications are necessary to be taken into account: axisymmetric flow – the property of a swirled flow to occupy a position corresponding to the geometric axis of the channel; the exclusion from the equations of the radial component of the velocity vector, since it is much less than the axial and tangential ones; not taking into account the second derivatives of the tangential velocity component with respect to the axial coordinate, counting $\partial^2 u / \partial z^2 \lesssim \partial^2 u / \partial r^2$. This is consistent with the experimental data. Given that for the turbulent flow regime, where the vortex kinematic viscosity along radius $\varepsilon$, is much greater than the kinematic viscosity $\varepsilon$, we obtain
\[ Eu \frac{\partial}{\partial r} + \frac{\partial}{\partial r} \left[ \frac{(V')^2}{2} \right] = -\frac{\cos \theta \left(1 - i^2\right)^{0.5}}{Fr} + \frac{u^2}{r}; \]
\[ Eu \frac{\partial}{\partial z} + \frac{\partial}{\partial z} \left[ \frac{(V')^2}{2} \right] = \frac{i}{Fr} + \frac{r}{Re} \frac{\partial}{\partial r} \left( \frac{\Phi}{r^2} \right) + \frac{\Phi}{2z}, \]

where \( Eu, Fr \) – respectively are Euler and Froude numbers, \( V' \) – is the pulsating component of the velocity, \( u \) is the tangential component of the flow velocity, \( i \) – is the channel slope equal to the sine of the angle of inclination of the channel to the horizon, \( Re_t \) – is the turbulent Reynolds number, \( \Phi \) – is the radial gradient moment of the axial velocity component for the swirled flow, \( r, z, \theta \) – current coordinates.

The pressure distribution along the radius and length of the channel in a turbulent swirled flow with a break in continuity of the flow and the input swirling conditions has the form

\[ p(r, l) = 2Eu - \frac{2}{Fr} \left[ r - r_z \left(1 - i^2\right)^{0.5} \right] \frac{\cos \theta}{r^2} + \left( V'_z \right)^2 - (V')^2 + \]

\[ \frac{u_0^2}{\pi} \left\{ \exp\left(-r_z^2\right) \left[ 2 + 3\exp\left(x_i r_z^2\right) \right] - \exp\left(-y_i\right) \left[ 2 + 3\exp\left(-y_i\right) \right] \right\} - \]

\[ 2u_0^2 \left[ \text{erf}\left(y_i^{0.5}\right) - \text{erf}\left(r_z x_i^{0.5}\right) \right] + u_0^2 \left[ 2\ln\left(r / r_z\right) - 2\text{Ei}\left(y_i\right) + 2\text{Ei}\left(-x_i r_z^2\right) + \text{Ei}\left(-2y_i\right) - \text{Ei}\left(-2x_i r_z^2\right) \right], \]

where: \( p \) – pressure in the flow, \( l \) – channel length, \( u_0 \) – tangential velocity component at the entry to the channel, \( x_i, y_i \) – dimensionless parameters, \( \text{Ei} \) – integral exponential function, \( V'_z \) – pulsating velocity component on a vortex bundle (area of break in flow continuity).

From (2) it follows that on the axis of the pipe due to flow swirling the pressure tends to \( p_0 = -\infty \). Since the physical limit of negative pressure in water is the absolute vacuum or the pressure or saturated liquid vapor, in the near-axial zone of the channel near the inlet section, even with weak swirls of the flow, one should expect deep vacuum values, sufficient to break the flow continuity in the form of a vortex bundle. With high swirled flow velocities with break in continuity of the flow in the axial zone, a free flow regime is formed with the pressure in the vortex bundle almost unchanged along the entire length \( l \) of the channel and equal to \( p_0 \). This pressure may take the value of the pressure of saturated vapor of the liquid, or the vacuum may have a lower value, if air is supplied to this zone from the atmosphere.

Figure 3, a shows the pressure distribution in a mono-circulating flow with break in continuity. The flow regime is turbulent. You can see that on the axis of the channel there is a vacuum equal to \( -2.05 \left(\rho v_0^2 / 2\right) \), where \( \rho v_0^2 / 2 \) is the velocity head vs the flow rate of flow in the inlet section of the channel. When scaling up to the prototype the design mode of the spillway hydraulic system with flow swirling and flow rate in the initial section \( v_0 = 4.57 \text{ m/s} \), the vacuum will be \( -2.17 \text{ m of water column} \). Close in configuration to the pressure distribution in the cross section of the channel, one can observe the profiles of the specific flow energy shown in Figure 3, b.
Figure 3. Distribution by channel radius $r$ and length $l$: (a) – pressure in the liquid $p(r,l)$, (b) – specific energy $e(r,l)$

Here the specific energy is determined by equation

$$e(r,z) = p(r,z) + [u(r,z)]^2 + [v(r,z)]^2 + [w(r,z)]^2.$$ 

The pressure distributions in circulating flows described above allow this effect to be used for transporting the atmospheric air into the liquid column, thereby forming an ejecting ability due to the presence of areas with reduced pressure (vacuum). Such a feature of circulating currents can be widely used in practice, in particular when creating aeration devices. Of all the known methods of liquid aeration the most effective is jet aeration, which allows intensive mixing the gas-liquid mixture with formation of gas bubbles of small diameter. For this, it is necessary to create a fluid flow with high degree of turbulence, where the work of turbulent mass transfer (mixing), i.e. diffusion, would be significant. Circulating flows to a large extent meet this requirement. But the most effective in this regard is the circulating flow with interacting oppositely rotating layers. In such flows artificially created in circular channels, one can observe a rather extended area with an extremely high degree of turbulence. It is formed at a length of approximately 6-8 diameters of the circular channel. Figure 4, a shows the distribution of pressure on the wall lengthwise the flow-conveyance part. Section 1-1 corresponds to the beginning of the area of interaction of the layers, and section 2-2, which is 6-8 circular channel diameters distant from section 1-1 in the direction of the flow, corresponds to the end of this area. Pulsations reach their maximum $\sigma/H = 8.5 - 9\%$ at a length of 1-1.5 channel diameter. Toward the end of the area of interaction of the layers, the flow takes the form of a Poisel (longitudinal-axial flow without swirling). Here pressure pulsations reduce to a value of 1.5-2%. The curves were obtained by measurements on a physical model operating with water. Figure 4, b shows the velocity pulsations diagram. It can be seen that the velocity pulsations, as well as the pressure pulsations, sharply increase over a length of 1-1.5 diameters. The results were obtained on a physical model operating with air.

Figure 4. Turbulence characteristics of interacting oppositely rotating flows:
(a) – distribution of relative standards of pressure pulsations along the length of the channel, (b) - pulsations of the flow velocity in the interaction zone of oppositely rotating layers
In the context of this article, the aeration is understood as the forced dissolution of atmospheric oxygen in water masses of naturally and artificially created water bodies in urban areas and in many other structures and devices.

The principle of operation of the device is realized solely due to the creation of a special geometric shape of the flow conductor system of the device. Possible aerator designs with air supply to the cavity of break of the internal circulating-longitudinal flow (central air duct) are shown in Figure 5, a and b. Two schemes are presented in the form of longitudinal sections along the axis of the flow-conductor part. They consist of pressure conduits 1 and 2, supplying water to the block of swirlers 3 and 4 with the air duct 5 (or several ducts) and a chamber 7 for mixing liquid and gaseous phases. A separation cylinder 6 is installed between two circulating layers of water rotating in opposite directions. The pressure flow of water to be aerated is divided in front of the device into two parts of unequal flow rate that enter the swirlers.

Swirlers can be made differently. In most of the structures tested and applied in practice, the swirlers were installed in the form of one-way spirals or tangential supply (Figure 2, a) [24]. In a number of cases, swirlers in the form of cylindrical blade gratings were used, as shown in Figure 2, b, which allow increasing the flow rate of the aerator in water in comparison with spiral and tangential ones. However, spiral or tangential swirlers are technologically simpler to manufacture. The choice of the type of swirlers is determined depending on the specific task. One of swirlers forms an internal circulating layer, the other an external one, with opposite rotation. The separation cylinder between the multidirectional circulating layers allows circulating flows to be formed independently within the swirlers without hydraulically affecting each other.

Experimental studies of the hydraulic characteristics of aerators are necessary to obtain initial data for the engineering calculation of device parameters for given operating conditions. As a result of the research, the following data were obtained: the flow rates for water and air and ejection coefficients, which determine the ejective ability of circulating currents.

The flow rate for water in a general case is determined by: the geometric dimensions of the inlet cross sections of the swirlers and the shape of the flow cavity where circulating flows are forming, the water pressure in the supply pipe in front of the aerator, the air inlet mode (air inlet into the vacuum cavities of break in continuity), the dimensions of the mixing chamber, i.e. its diameter and length. The flow rate for water is shown with the curves in Figure 6 in coordinates.
Studies on the model showed that the water flow rate of 1.5-2 times greater than through an external swirler passes through the swirler of an internal circulating flow having a large inlet cross-sectional area.

It can be seen from the curves in Figure 6 that the location of the air inlet zone (into the inner vortex or between the vortices, (Figure 5, a) has very little effect on the water flow rate, which for all studied aerator designs is determined mainly by the energy at the inlet of the device. This is due to the high compressibility of the air. The property of air as a gas is thousands of times differs from the compressibility of water. As you can see, the water flow rate for both flow conveyance parts of the aerator also does not depend on the coefficient of resistance of the air path. This statement also applicable to the length of mixing chamber $L$.

Figure 7 shows the experimental relation curves of flow rate for air $Q_{air}$ vs head $H$. The flow rate values of the central $Q_{1air}$ (supplying air to the internal circulating flow), external $Q_{2air}$ (supplying air to the external circulating flow) ducts are given. Moreover, the joint operation of two ducts is shown $Q_{3air}$.

The ejection coefficient, that is, the ratio of the volumetric air flow rate to the volumetric water flow rate is the integral characteristics of a two-phase medium (water-air mixture). In this case, the ejection coefficient $k_{1a}$ of the internal circulation-longitudinal flow will be equal to

$$k_{1a} = \frac{Q_{1air}}{Q_3}.$$

Figure 8 shows the experimental relation curves of the ejection coefficient for different operation modes of the device.
In case of separate operation of the air ducts (Figure 8) the values of the ejection coefficients of the internal and external vortices are close and change insignificantly with a change in the energy of the water flow (within the studied limits). This circumstance indicates a direct proportionality of the ratio of water and air flow rates.

The joint work of air ducts leads to a decrease in the ejection coefficient with increasing energy of the water flow at the beginning of the pressure scale. This can be attributed to the effect of a faster increase in energy losses in the flow-conductor of the aerator and a relative decrease in the energy of the water flows spent on transporting the air. The studies have shown that the value of the ejection coefficient $k_{3a}$ during joint operation of the ducts can be regulated by throttling the air supply to each duct, changing, on the one hand, the resistance of the supply path, and on the other rarefaction in the vapor-air core.

The resistance of the air ducts in the experiments has been changed by installing diaphragms therein, significantly contracting the live area of the air flow. On the central duct (Figure 3, a), the diaphragm opening area was 25% of the pipe cross-sectional area, and the diaphragm on the air duct of the external circulation-longitudinal flow was 13%. The restriction of the air flow practically does not affect the flow rate in the aerator with water (see the curves in Figure 4, b), since the dimensions of the cavities with break in continuity in each of the circulation-longitudinal flows, mainly determined by the water flow, change very little with contraction of the air ducts.

The presence of diaphragms adversely affects the air flow in the air ducts. With separate operation, the air flow in each of the air ducts and, accordingly, the values of the ejection coefficients decreased, that was to be expected, since in this mode the air flow is inversely proportional to the resistance of the duct. With joint operation of the air ducts, installation of the diaphragm reduces the air flow in the inner vortex and, as a result, reduces its effect on the cavity with brake in continuity of the external circulation-longitudinal flow. The joint work of the air ducts supplying air simultaneously to the rarefaction zones of two circulation-longitudinal flows is attractive because in this case the air saturation of the incoming air mass is more uniform in the cross section of the mixing chamber.

5. Conclusion
As a result of the experiments and the data obtained using physical modeling the following conclusions can be drawn:
1. Aeration of masses of water can be effected in various ways. A jet aerator using the effects of circulating flows with interacting layers makes it possible to intensify the processes of dissolution of atmospheric oxygen in water. This is due to the presence in the flow part a very high degree of flow turbulence. Such conditions of interaction of air and water lead to the fact that finely dispersed air masses, due to a larger contact area of two phases, faster dissolve the air oxygen.
2. Air can be supplied to the aerator either in the cavity of break in continuity of only the internal circulating flow, or in the cavity of break of both oppositely rotating layers. The present studies were carried out on an aerator model with two air entries, which made it possible to increase the value of the ejection coefficient of the entire device.
3. The study of the flow rate of the counter-vortex aerator with water showed that the magnitude of the water flow rate depends on the pressure at the inlet to the swirling devices. The highest flow rate is observed at maximum effective heads. The obtained curves show that the internal circulating flow provides a higher flow rate than the external one. This difference is 1.5-2 times. With the increase in the relative length of the mixing chamber from 2.53 to 6.88, the water flow rate of the entire device increases insignificantly. The flow rate is practically not affected by the diaphragms installed in the air ducts, i.e. the resistance to the air movement.
4. The most important parameter of operation of the aerator, characterizing its effectiveness in terms of dissolving air oxygen in water, is the ejection coefficient. With separate operation of the ducts, the values of the ejection coefficients of the internal and external swirled flows are close and change insignificantly with the change in the input energy of the water flow. The joint work of the ducts leads to
a decrease in the ejection coefficient with the increase in heads. The studies have shown that the value of the ejection coefficient during joint operation of the ducts can be controlled by throttling the air supply to each duct, changing, on the one hand, the resistance of the supply path, and, on the other hand, the rarefaction in the cavity of break in the continuity. 

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