Capture of Air by a Water Stream at Coupling of Sites of a Non-Pressure Collector with a Large Level Difference

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Abstract. The article considers the modeling of aeration of water masses by water jets falling on the surface in order to improve the quality of water from surface water sources. The mechanism of the aeration process is described when a turbulent non-crushed jet falls onto the water surface. Calculated analytical and experimental studies of air entrapment by cylindrical jets falling into the water made at the Department of Hydraulics of MSUCE made it possible to obtain a universal dimensionless dependence, suitable for describing the process of air entrapment in various conditions. The results of experimental verification of this dependence are presented, as well as the results of simulation of air entrainment in specific conditions of the collector chamber when its sections are mated to a large level difference. The results of mathematical simulation of the release of air-gas inclusions from the water flow at the lower part of the collector are presented. The volumetric flow rate of the air-gas mixture in the collector below the collector chamber is identified. Estimated calculation of the parameters of the deaeration of the water flow: the length, time and the rate of ascent of air bubbles, is executed.

1 The justification of the calculated dependences on the identification of air entrapment at large differences and mathematical modeling of the capture of the air-gas mixture in the collector chamber

In the development of engineering measures for improving of the quality of water from surface water sources, improving of the water quality in urban water bodies, improving of the efficiency of the use of settling ponds for cleaning up of contaminated surface runoff and industrial wastewater, an artificial aeration of water masses is used [1], [2]. Aerators, perturbing the surface of the stream, serve as an artificial turbulence promoter of the water mass, therefore, for the known perturbation parameters initiated by the aerator on the free surface, physical modeling of this process must be considered taking into account the hydrodynamic features. The dimensions and power of the aeration devices are different, but the accuracy of their hydro-aerodynamic calculations based mostly on laboratory experimental data is currently insufficient

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in connection with the lack of valid criteria for the similarity of the aeration phenomenon in installations of different scales and the lack of a developed physical modeling technique. Physical modeling of the aeration process is characterized by a complex interaction of forces of different nature and has not been sufficiently studied to the present time, although achievements in the field of mathematical modeling of aeration structures are known [3]. The problems of modeling of the aeration of water by jets falling on its surface have been studied little or not at all, in spite of the high efficiency of this aeration method.

Let us consider in more detail the physical essence of the process of aeration of the water mass by turbulent jets falling on its surface. The performed studies [4] allow illustrating jet aeration as follows. When a turbulent jet flows from the nozzle, perturbations develop on its surface due to the interaction of the jet with the surrounding air under the conditions of the stabilizing role of the surface tension. At some distance from the nozzle, perturbations in the jet develop so much that the forces of surface tension cannot resist them. There is a violation of the compactness of the jet and its disintegration into separate water masses, which are further broken into drops, when they interact with the surface of the water mass, it is aeration in the so-called "drop" mode. When the fractured jet falls on the surface of the liquid, due to the impact of the drops, caverns are formed, and the free surface of the water is locally curved. In these zones, Laplace forces of surface tension and hydrostatic pressure arise, which "slam" the cavern, forming an air bubble. When the following drops fall, the bubbles are fractured and dragged under the surface of the water. The actual process is much more complicated than the described scheme, since turbulent pulsations in the jet spread drops over a certain area, but the above description of the aeration of the water mass when a fragmented jet falls on it, is qualitatively correct and may be taken into account when developing the frameworks of its modeling.

Mathematical modeling of hydro-aerodynamic phenomena becomes possible in the presence of analytical dependencies describing the simulated phenomenon. Until recently, it was believed that the process of capturing air by water flows does not obey the laws of similarity and is an unmodified process [5]. This is explained by the simultaneous action of a sophisticated force complex, which includes the force of gravity, the force of viscosity, the buoyancy force, the inertial forces and the surface tension force. For this reason, many attempts to obtain dependencies describing the process of air capture were unsuccessful. The dependencies irregularly reflected the nature and extent of the influence of these factors, their comparison showed very significant quantitative discrepancies.

The physical picture of air entrainment during the aeration of water masses by jets incident on its surface makes it possible for us to identify the determining parameters and establish on their basis the similarity criteria. It seems obvious that the flow rate of the attracted air will depend on the velocity of the jet V, the diameter of the nozzle d_0, the length of the jet L, the angle of its incidence α, the physical properties of the liquid (viscosity υ, density ρ, surface tension σ), gravity force acceleration g and the nozzle undulation $k_э$. In this case, the functional dependence for the flow rate of the attracted air Q_a may be written in the form of the following functional connection:

$$Q_a = f(V, d_0, L, \upsilon, \rho, \sigma, \alpha, g, k_э) \tag{1}$$

Using the π-theorem this functional dependence may be represented in the form:

$$f(\pi_1, \pi_2, ..., \pi_7) = 0, \tag{2}$$

where π_i are dimensionless complexes.

Using the principles of dimensionality, we represent the dependence for the air flow involved in the water by a falling jet stream with a flow rate Q_j in the form:

$$\frac{Q_a}{Q_j} = f\left(\mathrm{Re}, \mathrm{Fr}, \mathrm{We}, \frac{L}{d_0}, \frac{k_э}{d_0}, \sin\alpha\right), \quad (3)$$

where $\mathrm{Re} = \frac{Vd_0}{\nu}$, $\mathrm{Fr} = \frac{V^2}{gd_0}$, $\mathrm{We} = \frac{\rho V^2 d_0}{\sigma}$.

The results of calculated analytical and experimental studies of air entrapment by cylindrical jets falling into the water performed at the Department of Hydraulics of Moscow State University of Civil Engineering are presented in Fig. 1 [6].

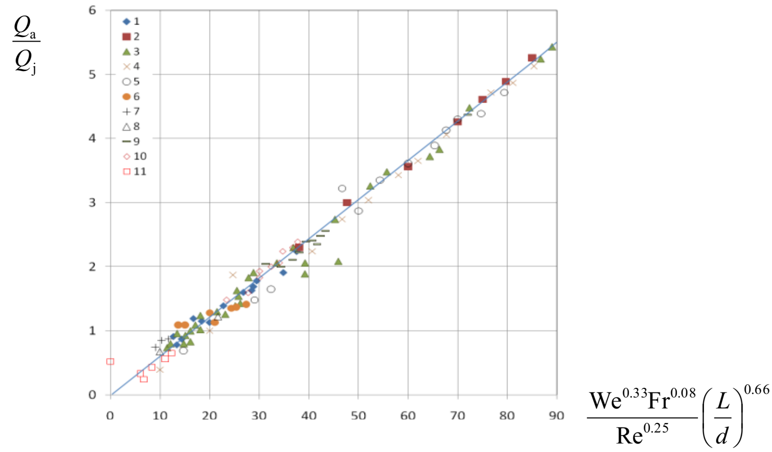

Fig. 1. Generalization of the results of experimental studies on the measurement of volumetric absorption of atmospheric air, 1-11 – groups of experiments with different values of numbers Fr, Re, We, *L/d*.

Experimental data made it possible to obtain a universal dimensionless dependence, suitable for describing the process of air entrapment under various conditions, which has the form:

$$\frac{Q_a}{Q_j} = 0.06\frac{\mathrm{We}^{0.33}\cdot\mathrm{Fr}^{0.08}}{\mathrm{Re}^{0.25}}\left(\frac{L}{d}\right)^{0.66}, \quad (4)$$

where Q_a – volumetric air flow at atmospheric pressure; Q_j – secondary water flow; L – drop height; d – the diameter of the jet in the plane of its contact with the mass of the liquid; $\mathrm{Re} = \frac{Vd}{\nu}$ - the Reynolds criterion, which takes into account the influence of fluid viscosity and inertia forces; V – the velocity of the jet in the plane of its contact with the mass of the liquid; ν - the kinematic viscosity of the liquid; $\mathrm{Fr} = \frac{V^2}{gd}$ - the Froude criterion, taking into account the influence of gravity; $\mathrm{We} = \frac{\rho V^2 d}{\sigma}$ - the Weber criterion, taking into account the influence of surface tension forces, here σ - coefficient of surface tension at the water-air interface.

It should be noted, however, that the experimental verification of this relationship is performed under laboratory conditions with limited water flow and with jets diameters up to 50 mm. For these reasons, the quantitative results of mathematical modeling of air entrapment when the water flow falls into the vertical shaft of the collector chamber should be treated with caution and considered only as estimates. In order to use the dependency (4) for simulating the air intake under specific conditions of the collector chamber, a conversion was performed, taking into account the fact that the height of the drop depends on the water flow rate, and the velocity and transverse dimension of the incident jet in the plane of contact with the level in the vertical shaft of the collector depend on its turn from the height of the drop.

Assuming that, at a significant height of the L-drop, the jet in the plane of its entry under the water level in the collector shaft moves vertically and, assuming the energy losses when falling insignificant, the velocity of the jet in the plane of the water level in the shaft is equal to:

$$V = \sqrt{2gL} \tag{5}$$

Dependence (5) reflects the apparent increase in velocity with an increase in the fall height of the flow. As the velocity of the incident jet increases, the area of its cross section $\omega_э$ decreases:

$$\omega_э = \frac{Q_\mathrm{j}}{\sqrt{2gL}} \tag{6}$$

Assuming in the plane of the jet to the water level in the vertical shaft the circular shape of its cross section, we find the equivalent diameter of the jet in this plane:

$$d_э = \sqrt{\frac{4\omega_э}{\pi}} = \frac{2Q^{0.5}}{\pi^{0.5}(2gL)^{0.25}} \tag{7}$$

Using the relations obtained, we perform the transformations of the above criteria:

$$\mathrm{Re} = \frac{2}{\pi^{0.5}\nu} Q_\mathrm{j}^{0.5}(2gL)^{0.25}, \quad \mathrm{Fr} = \pi^{0.5}(2g)^{0.25}\frac{L^{1.25}}{Q_\mathrm{j}^{0.5}}, \quad \mathrm{We} = \frac{2\rho}{\sigma\pi^{0.5}} Q_\mathrm{j}^{0.5}(2gL)^{0.75} \tag{8}$$

Taking into account the expressions obtained, the complex of dimensionless quantities entering into the dependence (4) is transformed as follows:

$$\frac{\mathrm{We}^{0.33}\mathrm{Fr}^{0.08}}{\mathrm{Re}^{0.25}}\left(\frac{L}{d}\right)^{0.66} = \frac{52.47Q_\mathrm{j}^{0.165}L^{0.248}\cdot 1.11L^{0.1}}{39.41Q_\mathrm{j}^{0.125}L^{0.0625}Q_\mathrm{j}^{0.04}}\frac{L^{0.66}L^{0.165}}{0.66Q_\mathrm{j}^{0.33}} = 2.24\frac{L^{1.11}}{Q_\mathrm{j}^{0.33}} \tag{9}$$

The performed transformations of formula (1) to the form (9) made it possible for us to establish the nature and degree of dependence of the captured air intake Q_a on the water flow Q_j and the drop height L in the following form:

$$Q_\mathrm{a} = 0.134L^{1.11}Q_\mathrm{j}^{0.67} \tag{10}$$

Dependence (10) shows that the consumption of the air captured by the flow increases with the flow rate of water and depends to a large extent on the height of the fall. The dependence also shows that in the real conditions of the collector chamber, the reduction in air intake can be achieved by reducing the height of the fall of the flow.

The obtained dependence (10) was further used in mathematical modeling of the air-capture process when the water flow fell into the vertical shaft of the collector chamber. Since the consumption of the air-gas mixture according to the dependence (10) depends on the water flow and the height of the fall of the water flow into the vertical shaft of the collector chamber, mathematical modeling of this process uses the results of mathematical modeling of the hydraulic regimes and the position of the piezometric line in the collector section. Mathematical modeling data show that the ratio of the average air-gas mixture consumption to the water discharge decreases with an increase in water flow from 1.2 (at $Q_j = 0.1\ Q_p$) to 0.46 (at $Q_j = Q_p$). However, the absolute value of the air flow Q_a increases with increasing water flow (Fig. 2). For calculated conditions, the air flow rate is 4.1 m^3/s at atmospheric pressure. The entrained air currents as they immerse in the liquid reduce their volume under the influence of excessive hydrostatic pressure.

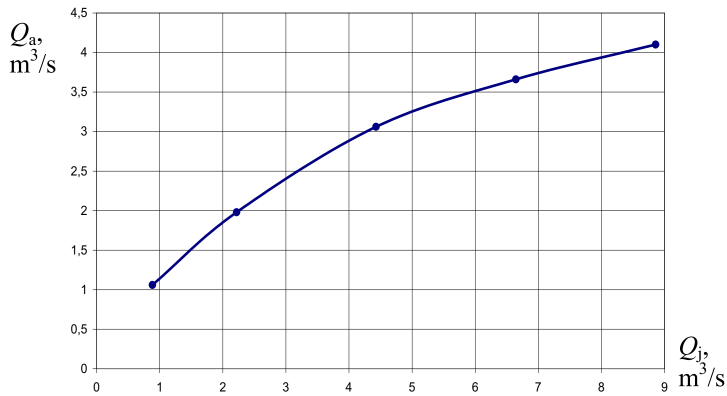

Fig. 2. Schedule of air-gas mixture flow rate change at different water flow rates $Q_a = f(Q_j)$.

Due to the partial decomposition of the water flow during its fall at the drop, the amount of air drawn in can vary (pulsate) with respect to the established average value.

2 Mathematical modeling of the release of air-gas inclusions from the water flow in the lower part of the collector

To substantiate the engineering measures for intercepting the air-gas mixture in the collector section adjacent directly to the collector chamber, it is necessary to establish a distance from the collector chamber, within which air-gas inclusions completely leave the water stream. To determine this distance, it is necessary to have data on the speed of movement of the water and air flow, the proportion of the cross-sectional area occupied by the water and air flow at various water flows, as well as information on the hydraulic size of the air-gas inclusions that characterizes the rate of their ascent.

According to the results of experimental studies [7], large air-gas inclusions are unstable and under the influence of the turbulence of the water flow they are split into spherical bubbles of 4-5 mm in size, which are stable. According to Wallis [8], the ascent rate of such bubbles in the water flow is close to w = 0.25 m/s (Fig. 3). It should be noted that the asymmetry of the turbulent pulsations in the velocity of the water flow affects the bubble uptake. However, at the present time there are no reliable data characterizing the asymmetry of turbulence, therefore, in the mathematical modeling of the ascent process, the effect of vertical turbulent pulsations was not taken into account.

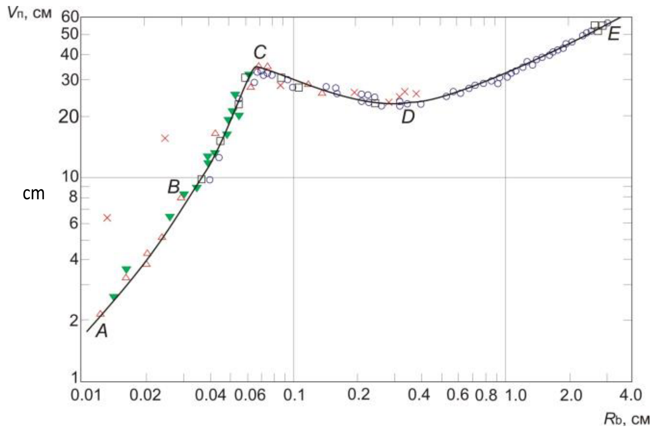

Fig. 3. Limit the rate of rise of air bubbles in water depending on their size, R_b - the equivalent radius.

When the flow from the vertical shaft of the chamber to the collector changes, the air inclusions are uniformly distributed over the cross section of the water flow due to intensive turbulence. The greatest distance corresponding to the exit of air bubbles will be determined by the distance of the bubbles from the lower layers of the water flow. Air inclusions that leave the water stream are collected in the underwater space of the collector. The resulting air mass moves as a result of interaction with the water flow along the collector, with a speed close to the speed of the water flow. The motion of air masses in the underroof space can have a different character depending on the hydraulic characteristics of the flow, as illustrated by the Lockhart-Martinelli diagram [9], [10], [11] obtained on the basis of laboratory experiments. Using it for the conditions of a given collector requires additional research and full-scale research. Analysis of the data of the Research Institute of Power Structures on the motion of air masses in hydraulic tunnels suggests that in the conditions of the collector in the underroof s cm e, the air masses will move in the form of separate volumes occupying a significant portion of the cross section.

To determine the proportion of the cross-section occupied by the air mass, it must be taken into account that the trapped air is in the collector under excessive hydrostatic pressure determined by the level mark in the collector chamber. Excessive hydrostatic pressure compresses the air-gas mixture, which leads to a decrease in its volumetric flow rate. To correct the volume associated with the action of hydrostatic pressure, the equation of state for the isothermal process has been used:

$$pW = const\ , \tag{11}$$

where p – absolute pressure; W – air volume at pressure p.

Taking into account expression (11), we can write in the form:

$$\frac{Q_p}{Q_a} = \frac{p_a}{p}\ , \tag{12}$$

where p_a – atmosphere pressure.

This ratio is used to determine the volumetric flow rate of the air-gas mixture in the collector below the collector chamber. Estimated calculation of the deaeration length of the water flow can be performed taking into account the following relationships. The ascent time of the air bubble, the flow rate, the flow time of the deaeration flow are:

$$t_в = \frac{h}{w},\ V = \frac{q}{h},\ t_д = \frac{L_д h}{q} \tag{13}$$

where h - depth, w – hydraulic size, q – specific water discharge per unit of collector width, m^2/s, $L_д$ – deaeration length, m.

Taking into account (13) we find the condition for complete deaeration of the flow in the form:

$$L_д > \frac{q}{w} \tag{14}$$

For the design conditions, the deaeration length $L_д$ = 16 m. With decreasing water flow, the extent of the deaeration section of the flow decreases. The results of mathematical modeling of the deaeration of the flow at flowrates less than the calculated ones are shown in Fig. 4. This estimated calculation does not reflect the effect of compression of the air-gas mixture under the influence of excessive hydrostatic pressure in the collector.

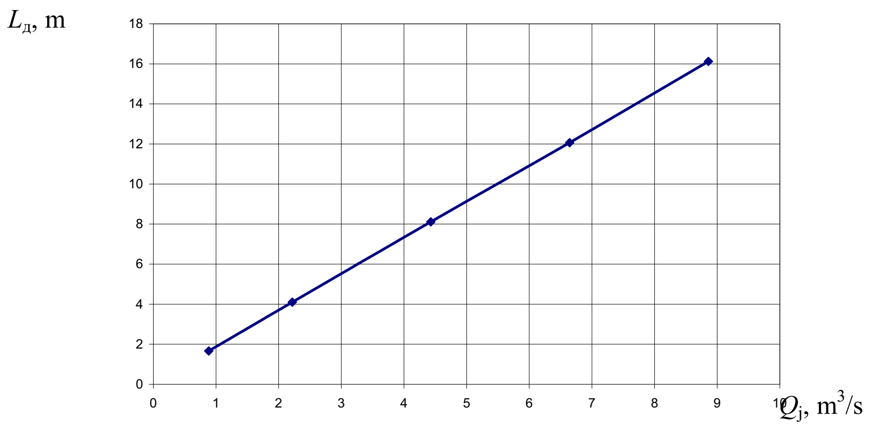

Fig. 4. Graph of changes in the length of the de-aeration flow in relation to the flow rate of water.

Calculation data show that the average volumetric flow rate of the air-gas mixture in the collector under consideration with allowance for compression under the influence of excess hydrostatic pressure at the design flow is close to 2 m^3/s. Thus, through the cross-section of the collector, the total flow of water and air-gas mixture passes. The filling of the collector with an air flow was determined by calculation, taking into account the geometric and hydraulic characteristics of the collector [12]. It should be noted that the maximum length of the deaeration of the flow, set taking into account the compression of the air-gas mixture, is close to that found above on the basis of estimated calculations of the maximum deaeration length.

The obtained data on the length of the deaeration of the water flow determine the location of the formation of the underroof air current and were taken into account in determining the location of the chamber for intercepting and diverting the air-gas mixture in the region directly adjacent to the collector chamber.

References

1. Recommendations for calculating pressure losses along the length of the hydroelectric power lines (VNIIG imeni B. Ye. Vedeneyeva, Leningrad, 1981)

2. *Hydraulic calculations of spillway hydraulic structures. Reference Manual* (Energoatomizdat, Moscow, 1988)
3. G. Schlichting, *The theory of the boundary layer* (Science, Moscow, 1969)
4. *Handbook of hydraulic calculations*. Ed. P. G. Kiselev. (Energia, Moscow, 1972)
5. V. M. Lyatkher, A. M. Prudovsky, *Investigations of open flows on pressure models* (Energia, Moscow, 1971)
6. V. S. Borovkov, Yu. M. Fetisov, *Capture air when the jet interacts with a fluid at rest. Questions of hydraulics and water supply* (Proceedings of the MISI imeni V. V. Kuibyshev, 1980)
7. C. Sow, *Hydrodynamics of multiphase systems* (Mir, Moscow, 1971)
8. G. Wallis, *One-dimensional two-phase flows* (Mir, Moscow, 1972)
9. A. D. Altshul, P.G. Kiselev, *Hydraulics and aerodynamics* (Stroyizdat, Moscow, 1975)
10. Yu. V. Bryanskaya, *Refinement of velocity profile parameters for flows in smooth and rough pipes,* International Journal of Applied Engineering Research, Volume 11, 3 (2016)
11. Yu. M. Fetisov, V. S. Borovkov, O. V. Pavlova, *Methodical bases of physical modeling of artificial aeration of water by falling jets*, Ecology of urbanized territories, 3 (2013)
12. A. M. Kurganov, N. F. Fedorov, *Hydraulic calculations of water supply and sanitation systems. Directory*, (Stroyizdat, Leningrad, 1986)