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Design Facilities for Air-Lift Fishery and their Effectiveness

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***Abstract*— The withdrawal of a huge amount of water for needs of municipal and agriculture, for industry and energy production significantly affects the reduction of fish stocks and reduce the economic potential of fishery water bodies. To protect aquatic fauna, water diverting structures should be equipped with effective fish protection devices and fish protection structures. At present, a sufficiently large number of various designs of fish protection devices have been developed. However, functioning of many of them cannot be considered as satisfactory. This largely applies to water diverting facilities with a capacity of more than fifteen cubic meters per second, located on the water bodies in South of Russia, where there are rich and unique stocks of valuable commercial fish species. For fish protection structures of large water diverting facilities one of the most difficult is the task to divert the protected fish larva/young fish outside the zone of influence, which is complicated with the speed of a flow in the water intake area. Air-lift pumps conform to the requirements about removing young fish to protect them, because air-lift pumps do not have moving mechanical parts that might be traumatic for the fish. However, the use of air-lift elevators in practice is hampered by the lack of constructive developments and methods for calculating airlifts with a small lifting height, as well as the data about survival of young when these devices are in operation. Constructions used for forced removal of protected fish should ensure the viability of fish at all stages of their movement, with high technical reliability. Options to design an air-lift fish diverter have been proposed to be used in fish-protecting devices such as a floating fish-removal line. The rationale to use the air-lift elevator as a power plant aimed at removal protected young fish from fish protection structures is provided. We reported about some observed damage caused to fish during their contact with fish protection and fish removal constructions. The necessary conditions, which should be met in order to avoid injuring the protected young fish are described; the results of the study on young fish in the airlift fish elevator are introduced.**

Keywords—water-air flow, air-lift elevator, fish protection facility, fish larva.

I. INTRODUCTION

The withdrawal of a huge amount of water for communal and agricultural needs, as well as for needs of industry and energy sectors has a significant impact on reducing fish stocks and reducing the economic potential of water bodies. To protect aquatic fauna, water diverting structures should be equipped with effective fish protection devices and fish protection facilities. Currently, a large number of various designs of fish protection devices have been developed, however, many of them are not met the requirements. This primarily relates to water diverting structures with a capacity of more than 15.0 m3/s. This issue is particularly relevant for water bodies located in the South of Russia, which are rich in unique stocks of valuable commercial fish species. Thus, the presence of water diverting facilities on the Don River with a low efficiency of fish protection leads to the death of more than 5 billion young fish species annually.

II. Materials and Methods

For fish protection structures of large water diverting facilities, one of the most difficult tasks is to divert the protected fish larva outside the zone of influence, which is complicated with the speed of a flow in the water intake area. In this case, forced diversion is used to remove protected fish larva. Facilities to be used for the forced removal of the protected fish should ensure the viability of fish at all stages of their movement, with high technical reliability. Low-pressure water-lifting machines, installations and air-lift elevators are used as power plants.

Air-lift pumps conform to the requirements about removing young fish to protect them, because air-lift pumps do not have moving mechanical parts that might be traumatic for the fish. The introduction of air-lift elevators in practice of fish protection is hampered by the lack of constructive development and methods for calculating air-lifts with a small lifting height and the immersion coefficient that will be close to 1, as well as the data about young fish species survival when such a device are in operation.

The biggest advantages of air-lift pumps are the absence of moving parts, the ability to move solid bodies, and simplicity of a device. Therefore, the task to optimize the hydrodynamic process and the air-lift pump design used for hydrotransporting of protected young fish is very relevant, since it is aimed at solving either the environmental issue.

In air-lift pumps, the fish are lifted by vertical currents of water created by jets and air bubbles due to the work performed during isothermal expansion of air under the action of pressure fall in a lifting pipe. One of the features of the airlift is the change in hydrodynamic parameters (a speed of mixture lifting, mixture density, a volumetric flow speed of gas content, pressure fall due to gravity, friction and acceleration of the air-water flow, pumped volume of the mixture) within the specific flow regimes.

The most significant hydrodynamic parameters of a two-phase flow from the condition of influence on the viability of the fish are the mixture speed, the volumetric gas content and pressure change. Analysis of the literature [1] shows that the safe parameters of the air-water flow are the interaction speed of the flows which is less than 12.5 m/s, the supersaturating of water with oxygen is less than 150 % and the pressure fall is in the range from 0.01 to 0.05 MPa, the speed of discharge is 0.04 MPa/s.

Values of permissible hydrodynamic and required flow parameters were taken into account when developing the design parameters of individual units and the layout of the hydraulic scheme of the air-lift fish elevator for fish protection structure at water diverting facilities in Novocherkasskaya GRES (power plant).

One of the conditions to use the airlift elevators for forced diversion of the protected young fish is to prevent significant local losses in the fish-diverting system.

Studies [2] showed that local pressure losses should not exceed 2m. If this value exceeds local losses, there is an injury towards the protected young fish. In closed pipelines there is a danger of blocking them with floating debris, so the design of the fish diverting facilities must be compact, with a minimum number of turning sectors.

Depending on a design of fish pick-up tray, fish collection basin, hydraulic parameters of a water flow and hydrological conditions of a water source, we propose the several schemes of matching the air-lift elevator and fish protection facility that are presented in figures 1-4.

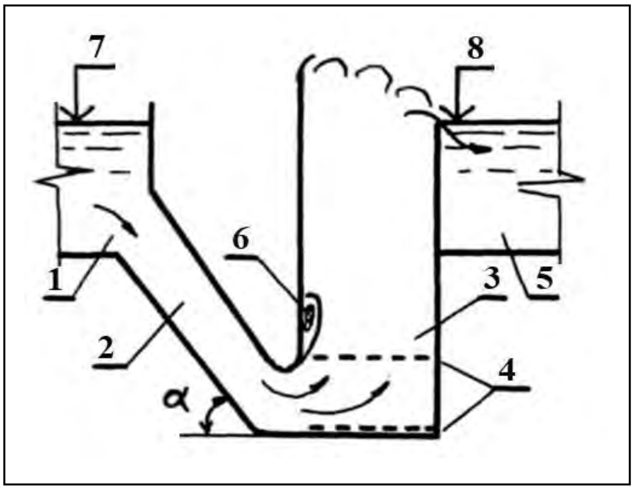

Fig. 1. Constructive scheme of matching an air-lift elevator with a fish removal channel of the fish protection facility through a diaphragm plate: 1 – pick-up tray; 2 – fill line; 3 – lifting shaft; 4 – air jet; 5 – removal line; 6 – eddy zone; 7 – water level in upper pounder; 8 – water level in low pounder

As shown in figures 1 - 4, the main aim at improving the facility in term of construction is to reduce a number of places with possible formation of eddy zones and to reduce the size of them. Eddy zone, on the one hand, increase the losses and, as a consequence, decrease the productivity. On the other hand, they impact the conditions of fish transportation because each eddy zone is a place fish concentration that leads to the young fish death.

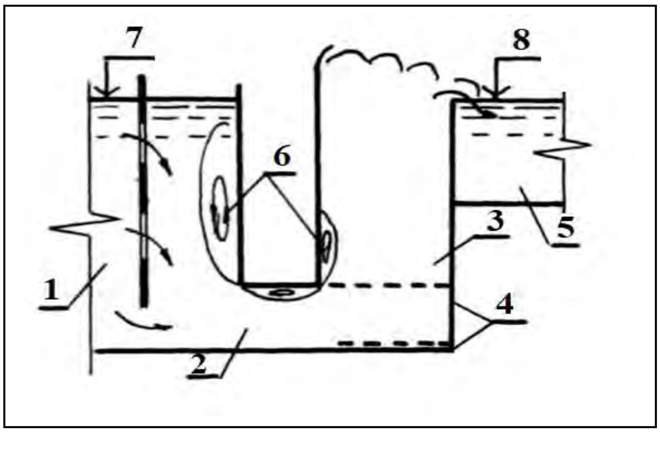

Fig. 2. Constructive scheme of matching an air-lift elevator with a fish removal channel of the fish protection facility through a tower with different species depth: 1 – pick-up tray; 2 – fill line; 3 – lifting shaft; 4 – air jet; 5 – removal line; 6 – eddy zone; 7 – water level in upper pounder; 8 – water level in low pounder

The first two schemes (fig. 1 - 2) can be used in the fish removal channel at the depth enough to provide the required productivity of the air-lift (with sufficient immersion coefficient). However, the presence of a large number of eddy zones requires facilities upgrading in compliance with the implementation conditions, which are not into consideration in the current paper.

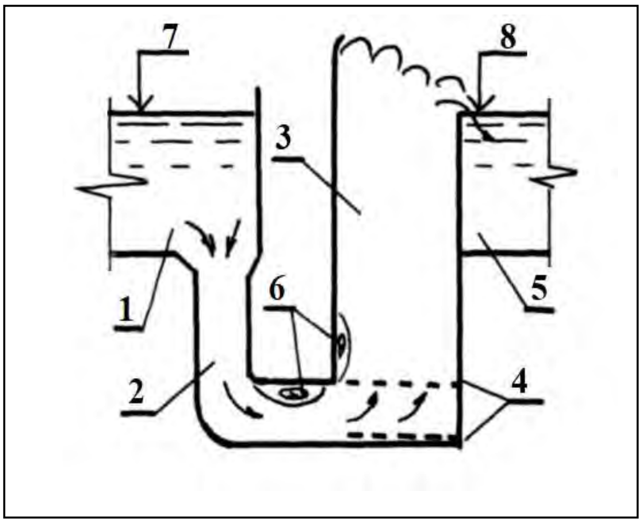

Fig. 3. Constructive scheme of matching an air-lift elevator with a fish removal channel of the fish protection facility through a vertical shaft: 1 – pick-up tray; 2 – fill line; 3 – lifting shaft; 4 – air jet; 5 – removal line; 6 – eddy zone; 7 – water level in upper pounder; 8 – water level in low pounder

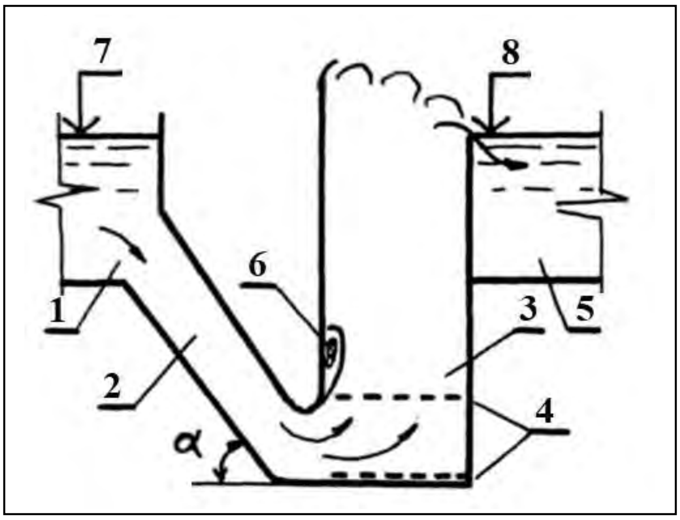

Fig. 4. Constructive scheme of matching an air-lift elevator with a fish removal channel of the fish protection facility through inclined shaft: 1 – pick-up tray; 2 – fill line; 3 – lifting shaft; 4 – air jet; 5 – removal line; 6 – eddy zone; 7 – water level in upper pounder; 8 – water level in low pounder

Implementation of the lifting shaft of matching (fig. 3 and 4) enables to extend the possibilities to use the air-lift elevator as the fish removal channel.

This provides the maximum possible depth for the air jet under the water level and enables to increase the height of the lifting shaft.

Meanwhile the necessity to optimize the particular elements of the facility is underpinned with the following circumstances:

Firstly, when implementing the air-lift elevator with the immersion coefficient that equals or close to 1 and with the aim at minimizing the losses, it is needed to make thoroughly the constructive treatment of all aquiferous elements – horizontal, inclined and knee sectors, their length and the distance between them, cross-sectional shapes of conducting elements and shapes of transition sectors.

Secondly, with the aim to achieve the expected productivity of the airlift, either to ensure high rate of young fish species survival and to create receptive structure for water-air flow, it is needed to find the rationale constructive solution on how to construct the allocation air jet with optimization of its parameters.

Thirdly, we take into account the criteria, as the basic one, towards the evaluation of the air-lift fishery elevator, which is used as a survival tool for young fish species. The evaluation depends not only upon a construction of particular elements but either upon the hydraulic regime; the evaluation and choice of optimal speed characteristics of a flow and the allocation of these speeds along the cross-sections are needed.

And, finally, the air-lift fish diverting facility depends upon a type and composition of fishery protection constructions, the part of which this facility is.

Depending on the hydraulic and height-related conditions in places of fish protection constructions to be installed, it is possible to apply one- or multi-stepped air-lift fish diverting facilities from pick up fish part to water body fish receiver, according to the conditions applied towards hydro-transports used for young fish protection (fig. 5, 6).

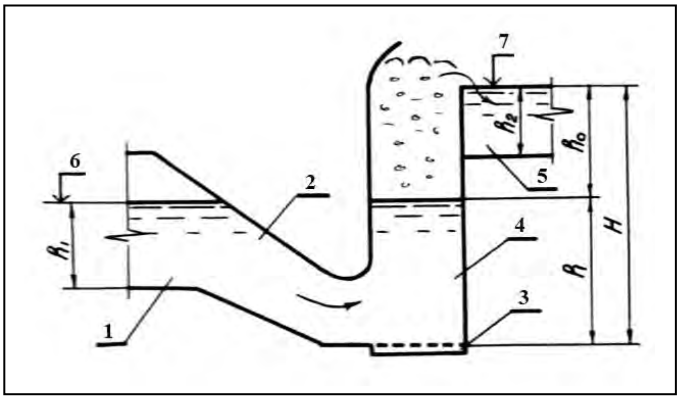

Fig. 5. Implementation of one- or multi-stepped air-lift fish removals: 1 – pick-up tray; 2 – fill line; 3 – lifting shaft; 4 – air jet; 5 – removal line; 6 – eddy zone; 7 – water level in upper pounder; 8 – water level in low pounder

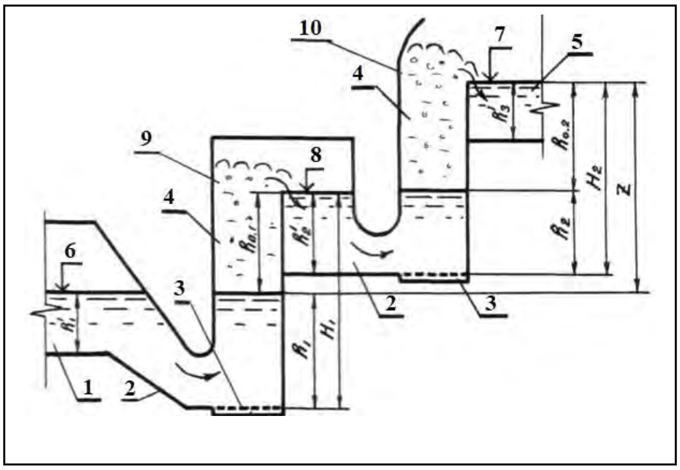

Fig. 6. Scheme of one- or multi-stepped air-lift fish removals with K< 1,0: 1 – pick-up tray; 2 – fill line; 3 – lifting shaft; 4 – air jet; 5 – removal line; 6 – eddy zone; 7 – water level in upper pounder; 8 – water level in low pounder; 9 – first spet; 10 – second step.

One-stepped air-lift fish diversions can have the immersion coefficient for the air jet as K = 1.0 or $K<1.0$, thus, they are classified as one-level and multi-level.

One-level fish diversions are characterized with non-changeable water level in a fish receiver part of a water body. This fish diversion can be used with fish protection facility as a floating fish diverting boom [3].

Multi-level one-stepped air-lift fish diversions are characterized with non-equal water levels in a fish receiver part of a water body. The both options should be designed within allowable limits in relative pressure falls $1> P_{end} / P_{start} \geq 0.4$ [4], either within allowable speed in pressure changing. Multi-level fish diversions based on the air-lift can be applied when the conditions described are not fulfilled.

The study research stated that the water supply with the air-lift increases significantly with the increase of cross-section square of the lifting shaft, with the immersion depth of an air allocation device and with the amount of air to be supplied. However, the immersion depth of an air jet in air-lift-based fish diverting facilities depends on the depth of water source in the location place.

Assumed that the ratio of the air jet immersion depth towards the lifting shaft height is the immersion coefficient ($k=h/H$). According to the data introduced in [5] the maximum productivity of the air-lift elevator can be reached under the conditions when the immersion coefficient is in limits of 0.50 – 0.75, rather than the maximum productivity is reached when the coefficient is 0.667.

It follows from the above that when the immersion depth of the air jet is known, the height (h) of the lifting shaft can be found as (1):

$$H=h/k. \quad (1)$$

Whether with calculated height of the lifting shaft the required limits for pressure falls are provided, this value can be taken to be in use. In case when the conditions described above are not fulfilled, the lifting shaft height is calculated with the allowable range of pressure falls and the immersion depth is defined from the expression (1).

A number of steps in the air-lift fish diversion is defined through dividing a value relating to water level differences (Z) in fish basin and water body by the shaft height.

$$N_C = Z/H.$$

To find the basic parameters of the airlift, the method proposed in [6] can be used as more universal one, and either the method applied in calculation of the air-lift facilities with the lifting coefficient that equals to 1, as proposed in [4].

If there is a forced fish diversion, the survival rate of young fish species should be determined not only due to the contact with a fish protection device, but also due to the survival rate after passing the fish diversion. Therefore, the forced diversion of fish from the fish protection device should ensure the maximum survival rate of young fish, i.e. prevent its injury in the working chambers and while transporting through the facilities' elements [5]. Injuries in the facilities intended for transportation of alive protected fish species occur as a result of mechanical injuries of the fish with facilities' construction elements: when there is a sharp pressure fall in the working chamber of the device; when the airlift fish elevators are in use; and when water is supersaturated with gases, that is called hypersaturation.

The fish lifting in air-lift pumps is performed with water-air mixture, and the process is affected with isometric air expansion when the pressure changes at the level of gas allocation device and in lifting pipe orifice. All these factors exclude using of all moving mechanical parts.

Consequently, the degree of mechanical impact coming from the surface of the airlift flow section can be defined through the speed of the mixture and its hydrodynamic state. The regime according to which the mixture is moving in the lifting pipe can be classified as turbulent, with Reynolds number of more than 2 kilo ($Re>2000$). Under the turbulence regime the thickness of a boundary-layer flow is in inverse relation from Reynolds number, whereas the core of the constant speeds occupies the bigger part of a pipe cross-section and it is changed only when close to walls.

Young fish species are floating near the center of the water body at the distance of 20 mm from the pipe's walls. Against the background that there is a smoother increase in mixture lifting speed, with entering air, the mechanical injury towards the fish in airlift elevator is practically excluded.

The impact of hydrostatic pressure fall on the fish species survival has been studied by a number of authors [7] in a pressure chamber. The research data show that the degree of injury on the fish, particularly, their death, are in the direct relation upon the specific and age composition. Mortality among carp larva with instantaneous picking up from 2.5 atm amounted to 50 %; from 3.0 atm – 70 %. Among the larva of Amur ide the numbers are 28 % and 42 % relatively.

The different speeds in pressure dumping result in different results. When pressure dumping speed is 0.2 атм/s from 2.5 atm the survival rate regarding the carp larva is 100 %. The larva of crucian carp endures the excessive pressure up to 6 atm with the dumping speed that amounts to 0.8 atm/s (without morality). In the experiment the fish length was balancing within 10 – 100 мм. Among sturgeons and Atlantic salmon larva, who have unfilled swim bladders, the morality has not been observed.

The rapid increase and decrease in vacuum (0.01-0.05 MPa) does not adversely affect the fish if its maximum value does not exceed 0.045 MPa. With an increase in vacuum up to 0.06 MPa, alarm is observed among the fish.

The studies researching the hypersaturation effects among young fish revealed that the fish placed in gases oversaturated water after some time, in 4 - 10 min. died. This time depended on the value of overpressure and the time the water was under pressure. The behavior of the fish placed in water oversaturated with gases begins dramatically to change in 0.5-2.0 min. This is expressed in anxiety, in the increase of moving activity, and in the increase of respiratory actions. The body of the fish is covered with small gas bubbles that gradually increase. It results in negative swimming capability.

A sharp decrease in hydrostatic pressure also adversely affects larva. Initially, anxiety is observed in fish species, which is turning into fear, resulting in positive swimming capability and moving activity increase. The fish species often rose to the surface and swam on the side or belly up. They lacked an explexia to a visual excitator. Some cases when young fish died from oxygen supersaturation of water that amounted up to 150 – 200 % have been also noted. As autopsy showed, gas bubbles in fins, gill, mouth and abdominal cavities, hemorrhages in vessels and other tissues were noted in dead fish. Some carp species had a gap in the walls of the swim bladder, eyes bulging. Observed damage in fish can be classified as follows:

- mechanical (worn, minced body parts, lose skin, injuries in scaly skin);
- barometric (swim bladder rupture or its increase, bloodstroke in tissues and organs, eyes bulging, gas bubbles in tissues and etc.);
- hypersaturation (gas bubbles on external parts of a body, in a mouth, in branchia, in fins and blood vessels – that means that water is oversaturated with dissolved gases);
- behavioral (reorientation and allocation fish species in space, changes in fish moving activity, respond to different visual excitators and etc.).

When the airlift is under the operation and with air-in, it is observed the physical water stabilization, in other words, observed the changes of biotopes physical properties, primarily the degree of water saturation with gases (oxygen).

Water saturation with oxygen is occurring in water-air mixture lifting with the help of diffusion. The efficacy of this aeration approach is very low. Intensification of oxygen diffusion from air to water is possible only under pressure in special aeration chambers when air bubbles are fragmented nto tiny particles. These conditions in airlift are possible to establish only in case of significant depth immersions. If we consider that a fish protection device provides the diversion of surface water layers together with the larva, where the oxygen content is 10 – 12 mg/l, then, the increase in its concentration is possible by 0.3, or 5 mg/l. This change in oxygen content in water is not dangerous for fish and does not affect their swimming capability. The possibility for fish to exist in water with a large content of oxygen is provided with two types of hemoglobin in fish blood that have different physical properties. The water activated with this method will be drifted downstream and will lead to aeration of the significant river areas. This will enable the increase in spawning and in number of larva. Consequently, there is no ground to worry about fish death in the airlift that might be caused by gas embolus.

As already noted, one of the conditions to use the air-lift elevators aimed at forced diverting the protected fish species into fish protection facilities is to prevent significant local losses in the fish-breeding system and in the elevator itself. Studies [7] showed that local pressure losses in connecting pipelines caused by the influence of pipeline fittings and shapes (elbows, confused-diffuser junction) should not exceed 2m. Exceeding the specified value of local losses causes a sharp pressure drop that contributes to injury the protected young fish. It is necessary to avoid the long length of connecting pipelines. In closed pipelines, the danger is that they can be blocked with floating rubbish and eel grass, therefore, the design of a pumping device in combination with the connecting lines should be compact, with a minimum number of turning sections [8].

As the analysis showed, the physical process of air and water interaction, as well as the studies addressed the regularities of parameters changes in water-air environment from quantitative air indicators, the nature of the outflow of air stream into water mass, etc. are very complex. When the air-lift elevator is used as a fish diverting facility, the phenomenon under investigation is complicated by the presence of a living object, the viability of which must be preserved. Therefore, when studying the airlift fish diverting facilities the laboratory method was used that consisted of hydraulic and biological parts [9].

In a lifting pipe of the airlift, used for forced diversion of young fish species, the three-component mixture – water, air and fish species – is running. Considering a low fish concentration in a flow, the basic technical features of the facility are identified with the hydrodynamic state of a liquid-gas flow, not only with a number of fish species. However, the flow structure and consequently the airlift productivity depend upon the components ration – water-air mixture and its physical properties, the constructive parameters of a lifting shaft and the pressure [10], providing the fish viability after passing through the facility. The functional ration for the airlift specific discharge Q_g/ Q_f has been found as (2):

$$Q_g/ Q_f = f(\omega_0/H^2, Fr, Re, D/H, We, Eu), \qquad (2)$$

where Q_g, Q_f – air and water discharge correspondingly, m^3/s;

$Fr = Q_f^2/(gH^5)$, $Re = Q_f\rho_f/(\mu_f H)$, $We = Q_f^2\rho_f/\sigma H^3$, $Eu = Q_f^2\rho_f/PH^4$ – Froude, Reynolds, Weber, Euler numbers correspondingly;

g – gravity factor, m/s^2;

H – water pipe height, m;

D – pipe diameter, m;

ρ_f – liquid phase density, kg/m^3;

μ_f – dynamic liquid viscosity, Pa·s;

σ – coefficient of surface tension on the border of phases division, H/m;

ω_0 – jet hole square, m^2.

The connection between non-dimensional units has been found experimentally. Thus, the aim of hydraulic laboratory research is to assess the impact of the following factors on the airlift work [11]:

- Volume concentration of a working agent (air);
- Speed with what air is coming out from the air jet;
- Geometrical parameters of a lifting shaft;
- Nature of movements of water-air environment.

Based on the analysis of literature sources and theme-related projects devoted to design of fish protection devices, an approximate range of changes in non-dimensional units that are in dependence (2) has been established; the experimental facility has been designed [12].

The purpose of biological research was to establish the general conditions under which the fish can be swimming in the shaft of the airlift fish elevator and their viability after passing through it.

The study on how the airlift works was carried in a hydraulic engineering laboratory [13] with installation that resembled a physical geometrically similar model of a fish-diverting facility with the lifting pipe, the height of which was 3.0 m, the diameter is 100 mm and the immersion coefficient of a blender is close to 1, in the mode of maximum productivity. The structure of water-air flow in the lifting pipe (both at inlet and at outlet) is bubble-natured [14].

The total pressure of upward water-air flow in the vertical pipe varies linearly from 0.13 MPa at the blender level up to 0.101 MPa at the upper end of the pipe. Reducing the pressure in the course of the water-air mixture leads to an increase in the volumetric flow rate and true gas content and in the speeds of the flow components [15].

The volumetric discharge of gas content increases from 0.382 at the level of a blender up to 0.443 at the level of outlet from the lifting pipe. True gas content due to phases slipping has the value that equals to 0.317 and 0.376 at the outlet and inlet correspondingly. The density of the water-air mixture due to the volumetric air expansion along the height of the lifting pipe decreases from 617.4 kg/m^3 with the maximum pressure up to 556.4 kg/m^3 in the pipe orifice [16]. The superficial water speed in the lifting pipe has the constant value along the height and it equals to 2.0 m/s. The superficial air speed increases from 1.58 m/s up to 2.01 m/s, and the superficial mixture speed increases form 3.27 m/s up to 3.58 m/s. The true water speed along the lifting pipe height has the value that is less than the superficial mixture speed and it equals to 2.15 m/s at the level of a blender and 2.48 m/s at the pipe outlet. The true air speed exceeds the value of the superficial mixture speed and equals to 3.18 m/s and 4.28 m/s correspondingly. The average mixture speed amounts to 4.1 m/s. The speed of the pressure fall reached 0.035 MPa/s [17].

When the airlift was under operation, the oxygen content in water fluctuated within the limits of 12.1 – 12.8 mg/l. such oxygen content fluctuation in water is not dangerous for the young fish and can not affect their swimming capabilities. The intension of the oxygen diffusion from air is possible only under pressure in the special aeration chambers when air bubbles are fragmented into tiny particles. The similar conditions can not be created for the airlift [18, 19].

The analysis on the changes of the mixture hydrodynamic parameters showed that they do not reach the critical values and can not bring a negative impact on the larva vitality [20].

To verify the conclusions introduced and to identify the functional dependence of the larva injury rate, we conducted some research with this experimental facility. In the experiments there were used the larva of different species and size: В опытах использовалась молодь рыб различного видового и размерного состава: bream, bleak, rudd, ram, buster, carp, silver carp, grass carp. The fish length varied within 12 – 80 mm. The experiments were conducted in 4 – 5 sequence, subject to obtain the stable results within commonly used methodology. As basic the experiments with the larva of bream species were taken. The bream species is characterized with more sensitive response towards any extreme environmental changes and are prone to injuries. A number of species in each experiment was from 5 to 20 [21]. The total number of experiments was 85; in the airlift we launched 470 bream larva species and 458 other species. All observations on the larva state and behavior were conducted immediately after the experiment and during 7 days [22].

III. CONCLUSIONS

Based on studying the hydraulic-biological conditions of forced-type fish diverters, the negative effects on young fish transporting in fish diversions and analyzing the measures on how to increase the larva survival rate when they are diverted from the fish protection devices, we proposed the airlift fish facility with the immersion coefficient that is equal to or close 1 and either the multi-stage scheme for fish diverting facilities. The fish diverting facility is designed to be used with a fish protection device such as a floating fish boom.

The studies did not reveal the negative impact of the air-lift fish elevator on the viability of the larva and confirmed the feasibility to use the air-lift elevator in fish protection constructions with the aim to divert forcibly the protected young fish beyond the zone of water intake constructions that might impact negatively on the larva survival rate.

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