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An innovative idea: Injection valves for irrigation ducts

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Abstract: More than 4.6 mln ha in the Russian Federation are irrigated. Their culvert hydraulic structures are part of network structures and are the most widespread. After the crisis of the 1990s, proper maintenance of many reclamation systems was impossible due to a lack of funds. This led to the loss of about half of the water taken from irrigation sources in irrigation canals. The planned increase in the technical level of irrigation systems requires the automation of the operation of both the entire system as a whole and separately located culverts. This will avoid significant losses of water supply for irrigation and prevent water shortages with the insufficient discipline of water users. Means of hydraulic automation of water supply are being installed on small irrigation canals in Russia. A water flow regulating valve is proposed, with no mechanical movinparts, and gates are not involved in the control process. The operation of the structure is based on the injection effect, in which excess water entering the downstream with a decrease in water consumption begins to circulate between the outlet section of the transit pipe and the diffuser at the end section of the valve. Using the methods of measuring hydrodynamics and the theory of jet devices, theoretical dependences were obtained, which make it possible to determine the main hydraulic characteristics of the structure. The design form of the flow part of the regulator has been developed and a physical model has been made. In a mirror hydraulic flume, the operation modes of the water outlet were studied with and without regulation. The actual values of hydraulic parameters were obtained, which confirmed the validity of the use of theoretical dependencies. The discrepancy between the theoretical and experimental results is within the experimental error. It has been proven that it is possible to circulate excess water between the downstream and intermediate pools of the regulator.

Keywords: automation, hydraulic engineering, hydraulic structures, hydraulics, irrigation, irrigation canals, valves

INTRODUCTION

According to the current national standard, land irrigation is a reclamation measure carried out by supplying water from a water source to regulate the water regime of soils [Gidenstam *et al.* 2008; Yan *et al.* 2020]. In the total area of reclamated land in the Russian Federation, equal to 11.3 mln ha, 41% falls on irrigated land. According to the Federal Agency for Water Resources (Rus. Federal'noe agentstvo vodnykh resursov), about 7 bln m^3 of water is used per year, or 13% of the annual volume of fresh water intake from sources for the needs of irrigation and agricultural water supply in Russia. According to the data of the Land Reclamation Cadastre of the Russian Federation (Rus. Meliorativnyy kadastr Rossiyskoy Federatsii), the reclamation systems include more than 1.6 mln hydraulic structures. Network hydraulic facilities of irrigation systems, including low-pressure culverts, are the most widespread. The unsatisfactory condition of the hydraulic facilities leads to the fact that up to 50% of the water taken from the irrigation sources is lost in the irrigation canals [Dörre 2020].

The work of Kang and Park [2014] is devoted to the problem of studying the return flow of irrigation water in the cascade of irrigation reservoirs in the Balan watershed (South Korea). Studies have found a possible range of the return flow of irrigation water from 28.0 to 35.0%. Lack of water distribution management often results in irrigated lands located downstream of the canal, lacking water for irrigation of plants [Ali *et al.* 2019; Wu *et al.* 2019]. This problem has arisen in the main irrigation area in the Rio Dulce Basin in Argentina (Proyecto Río Dulce), where overconsumption by the upstream farms leads to a lack of irrigation water for downstream farms over an area of 350,000 ha [Ertsen, van Nooijen 2009].

According to the National Report "O sostoyanii i ispol'zovanii zemel' sel'skokhozyaystvennogo naznacheniya v Rossiyskoy Federatsii v 2018 godu" [FGBNU 2020], more than 2 mln ha of land irrigation systems require their upgrade. Reconstruction and repair of hydraulic culvert structures must consider the use of automated water distribution control, saving water, energy, materials, and labour resources [PARDO-BOSCH, AGUADO 2015; ROMANOVSKAYA *et al.* 2020].

Many domestic and foreign research papers have been devoted to the automation of hydraulic structures [MOHAMMADI *et al.* 2019]. For the rice canals of Rio Grande do Sul (Brazil), an automatic regulating valve has been developed, with the capacity related to the hydraulic pressure above the holes [DO AMARAL *et al.* 2005]. Design tests revealed their advantages over sluice gates and proved a more efficient flow control.

In Russia, main canals with flow rates over 30 $m^3 \cdot s^{-1}$, as a rule, are equipped with electrically operated, integrated automation devices. Small canals with flow rates of 1–10 $m^3 \cdot s^{-1}$, where the use of electricity is economically unfeasible, use hydraulic automation water supply systems. Based on the water distribution control scheme (normalised water distribution or on-demand distribution), the process of regulating the automatic hydraulic action is based on changing a specific parameter: water flow or water level in the canal.

The domestic irrigation pipe outlets on canals are equipped with automatic gates: ring, shield, curtain, conical, step box shields of various modifications [WRIGHT, MARCHESE 2018]. The gates are water operated and can be located at the head or end of the structure. Moving mechanical parts of the gates affects their average service life, no more than 8–10 years [CHANDEL *et al.* 2015]. The development of reliable flow controllers, combined with hydraulic culverts on irrigation canals, is one of the urgent tasks of technical re-equipment of reclamation systems in the Russian Federation.

The main objective of the current study is to development of theoretical relationships for determining the main hydraulic parameters of valves with their subsequent verification according to the data of a physical experiment.

MATERIALS AND METHODS

MATERIALS

Pipe outlets, using the properties of merging streams and hydraulic feedback between the water level downstream of the structure and its capacity to regulate the flow rate, were first proposed in the authors' previous works [KIM, KIM 2012; LEAT, FISHER 1994]. Unlike most existing valves, these structures do not use water-operated gates and mechanical moving parts, which increases the reliability and durability of their operation. The valves are for use on open irrigation canals with a flow rate of up to 2 $m^3 \cdot s^{-1}$ at a depth difference of 0.2 m. The general view of the valve is shown in Figure 1.

The outlet serves to supply a flow rate corresponding to the water consumption in downstream of the structure or to regulate water supply "on-demand". The entrance head of pipe *2* is equipped with gate *1*, which is necessary only for the complete shutdown of the structure. Through pipe *2*, the transit flow enters the downstream. The end section has a diffuser *4* with a sufficiently high expansion ratio. The diffuser is equipped with two dividers to

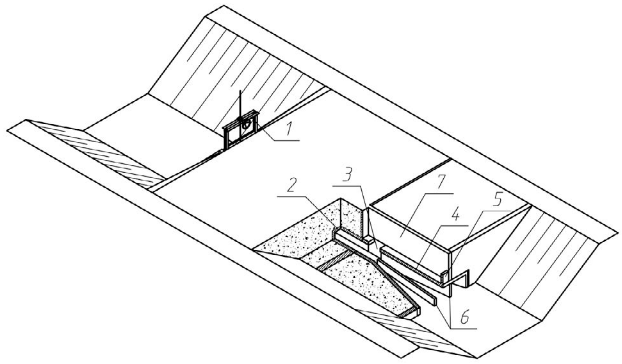

Fig. 1. Pipe valve: *1* = gate-controlled culvert inlet, *2* = pipe, *3* = mixing chamber, *4* = flat diffusor, *5* = weir, *6* = anti-break devices (dividers), *7* = regulating reservoir; source: own elaboration

prevent flow failure within it. At maximum water consumption downstream, the water level in the outlet channel has the lowest mark. The valve has the maximum possible throughput with a decrease in water consumption below the section of the partitioning structure. The water level in the outlet channel increases. The weir *5* is switched on, the threshold of which coincides with the minimum water level in the canal. Excess water from the channel enters the regulating reservoir *7*, which is the space above the diffuser *4*. In the upper wall of the pipe in front of the diffuser, there is an opening through which the flow from the regulating tank enters the mixing chamber *3*, where it is connected to the transit flow. Hydraulic losses caused by flow confluences can reduce the valve's flow rate (flow capacity) by up to 35% of the original value. As a result, a reduced transit discharge enters the downstream, and the discharge formed by the growth of the downstream circulates between the outlet channel and the mixing chamber.

METHODS

To derive theoretical relationships, the basic equations of technical fluid mechanics were used. To verify the obtained equations, a physical experiment was carried out on a modelled facility. The design diagram for the theoretical determination of the hydraulic parameters of the valve is shown in Figure 2.

The mark of the weir edge *6* corresponds to the maximum water consumption below the section of the partitioning structure, at which the water level in the outlet canal ∇WL_3 is minimal. When the canal-powered sprinklers are switched off, the waterhead level ∇WL_1 remains constant, while the water level in the downstream reaches ∇WL_2. The flow rate entering through the weir forms a certain level ∇WL_0 on the diffuser cover. The position of this level is determined by the ratio of the flow delivered by the weir to the flow through the opening in the diffuser cover. During regulation, the throughput of the structure decreases due to the circulation of excess flow.

The hydraulic flow pattern of the valve has been proposed to consider as an injection process. In this case, the transit flow Q_1 is an injecting flow, and the flow Q_0 coming from the intermediate pool is injected, that is, the energy of the transit flow is lifted to the downstream level. The basis for theoretical calculations was the provisions of the theory of water-jet pumps, based on the application of impulses to mixing flows. Some of the first works belong to MUELLER [1964] and VOGEL [1956]. Calculations of jet devices are based on the quasi-one-dimensional theories of REDDY and KAR [1968], SANGER [1968], BOGY and TALKE [1984], GRUPPING

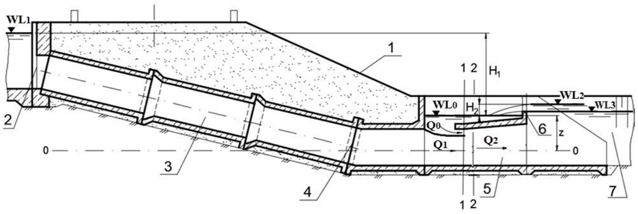

Fig. 2. The hydraulic calculation scheme for a pressure drop-combined valve: *1* = divider, 2 = gate-controlled culvert inlet, 3 = pipe links, 4 = horizontal section joint, 5 = diffuser, 6 = weir edge, 7 = outlet canal, WL_0 = the water level in the intermediate pool, WL_1 = the waterhead level, WL_2 = the water level in the downstream, WL_3 = the water level in the outlet canal, Q_0 = injection flow rate, Q_1 = transit flow rate, Q_2 = summary flow rate, H_1 = the difference in water levels in the waterhead and the control tank, H_2 = the difference in levels in the downstream and the control tank, z = the distance from the pipe axis to the water level in the control tank, 1-1 and 2-2 = sections for calculation; source: own study

et al. [1988], HATZLAVRAMIDIS [1991], YU *et al.* [2006], LONG *et al.* [2009], TRUBETSKOY *et al.* [2015], YAKYMCHUK *et al.* [2020], LONG *et al.* [2021] also studied the characteristics of jet pumps.

The proposed valve was similar to an asymmetric jet pump [MUELLER 1964; SADAT *et al.* 2020], in which the nozzle is formed not by solid-state boundaries but by an interface between flows in the mixing chamber. The flow of liquid in a mixing chamber of the constant area between control sections 1–1 and 2–2 was considered (Fig. 2). The derivation of theoretical dependencies was based on the basic equations of hydromechanics: balances of flow and energy, momentum, Bernoulli equations.

RESULTS AND DISCUSSION

During regulation, the water from the intermediate pool was pumped out by the transit flow, and the summary flow rate Q_2 entered the mixing chamber with area F_2, equal to the transit flow rate Q_1 and the flow rate from the intermediate pool Q_0:

$$Q_2 = Q_1 + Q_0 \tag{1}$$

In section 1-1, flow rate Q_1 occupies area F_1, flow Q_0 occupies area F_0, together, these flows occupy the area of the mixing chamber F_2. This is equivalent to expressing the area of the flow rate Q_0.

$$F_0 = F_2 - F_1 \tag{2}$$

The difference in water levels in the waterhead and the control tank is denoted by H_1, and H_2 denotes the difference in levels in the downstream and the control tank. The distance from the pipe axis to the water level in the control tank is indicated by Z. A diffuser with a resistance coefficient ξ is located behind the mixing chamber.

Equating the second impulse of pressure forces along the flow axis on the liquid in the mixing chamber between sections 1–1 and 2–2 and the second increment in the momentum of this liquid, we got:

$$F_2(P_2 - P_1) = \rho Q_1 v_1 + \rho Q_0 v_0 - \rho Q_2 v_2 \tag{3}$$

where: F_2 = the ara of the chamber, P_1 = pressure in section 1-1, P_2 = pressure in section 2-2 (Fig. 2), Q_2 = the total flow rate, ρ = the density of the water, v_0 = injected flow rate, v_1 = injection flow rate, v_2 = the flow rate at the end of the mixing chamber.

Considering that $F_2 = \frac{Q_2}{v_2}$, $Q_1 = F_1 \cdot v_1$ and $Q_0 = F_0 \cdot v_0$ we got:

$$\frac{P_2 - P_1}{\rho} = v_2\left(\frac{F_1 \cdot v_1^2 + F_0 \cdot v_0^2}{F_1 \cdot v_1 + F_0 \cdot v_0} - v_2\right) \tag{4}$$

If the pressure P_1 at the chamber inlet is the same for both merging flows Q_1 and Q_2 (they are practically parallel and have a small curvature) and there are no losses at the inlet to the mixing chamber, the following relationships are valid:

$$Z = \frac{P_1}{\rho g} + \frac{v_0^2}{2g} \tag{5}$$

$$H_1 + Z = \frac{P_1}{\rho g} + \frac{v_1^2}{2g} \tag{6}$$

where: g = the acceleration of gravity (m·s^{-2}).

The pressure at the mixing chamber outlet in the inlet section of the diffuser according to the Bernoulli equation is:

$$\frac{P_2}{\rho g} = Z + H_2 - (1 - \xi)\frac{v_2^2}{2g} \tag{7}$$

The chamber outlet velocity according to the continuity equation:

$$v_2 = \frac{Q_1 + Q_0}{F_2} = \frac{F_1 v_1 + F_0 v_0}{F_2} \tag{8}$$

After excluding the pressure P_1 and P_2 from Equation (3) and expressing the velocities v_0 and v_2 in terms of v_1, as a result of the joint solution of the equations of the system, the main calculated relationships were obtained to determine the hydraulic characteristics of the injection flow controller. Injecting flow rate:

$$Q_1 = F_1\sqrt{\frac{2gH_1B^2 - 2AC + \sqrt{\left(2AC - 2gH_1B^2\right)^2 + 4C^2\left(B^2 - A^2\right)}}{2(B^2 - A^2)}} \tag{9}$$

$$Q_2 = F_2\,\frac{F_1\vartheta_1 + F_0\sqrt{\vartheta_1^2 - 2gH_1}}{F_2} \tag{10}$$

where: A, B, C = constants associated with the design features of the flow path of the valve:

$$A = \frac{F_1}{F_2} + \frac{F_0}{F_2} - \left(\frac{F_1}{F_2}\right)^2 - \left(\frac{F_0}{F_2}\right)^2 - \frac{1}{2} - \frac{(\xi - 1)}{2}\left[\left(\frac{F_1}{F_2}\right)^2 + \left(\frac{F_0}{F_2}\right)^2\right] \tag{14}$$

$$B = (1 - \xi)\frac{F_1}{F_2}\frac{F_0}{F_2} - 2\frac{F_1}{F_2}\frac{F_0}{F_2} \tag{12}$$

$$C = gH_2 + gH_1\left[2\frac{F_0}{F_2} - 1 - \left(\frac{F_0}{F_2}\right)^2(\xi + 1)\right] \tag{13}$$

To verify the obtained calculated Equations (9) and (10), a physical experiment was performed. The 1:10 scaled model of the valve made of organic glass with an equivalent hydraulic roughness 0.03 mm, was tested in a mirror hydraulic chute.

The water flow through the valve is due to the difference in depth in the section of the blocking structure, therefore, the Froude criterion was the main criterion for hydraulic modelling of turbulent flow characteristics:

$$\mathrm{Fr} = \frac{v^2}{g \cdot h} \tag{14}$$

where: v = the speed, h = the depth in typical sections.

Compliance with the condition of similarity of the hydraulic roughness of the pipes of the full-scale (concrete) and model outlets made it possible to study the operation of the structure in the self-similarity zone. The Reynolds numbers in the experiment were at least 1.3×10^5. The limiting relative total errors (with non-excluded systematic error) with a probability of 95% when measuring the flow rate did not exceed 4%, the pressure did not exceed 1.8%.

Consideration of the initial section of the mixing chamber as a nozzle with a conditionally constant compression ratio F_1/F_2 = 0.86, equal to the ratio of the cross-sectional area occupied by the transit (injecting) flow rate to the area of the mixing chamber, made it possible to compare the theoretical and experimental values of the valve flow rates at different heads (Fig. 3).

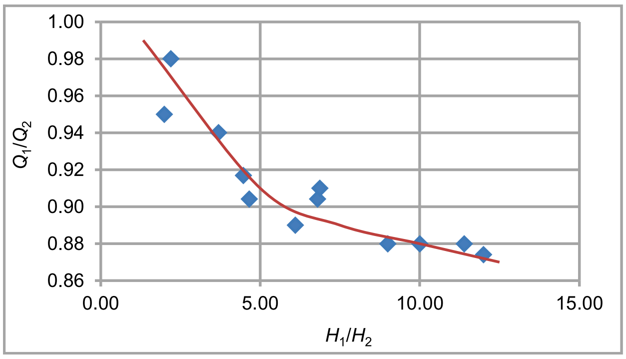

Fig. 3. Theoretical correlation curve and experimental points for a double-divider valve; source: own study

The coincidence of the theoretical curve, constructed based on equations (9) and (10), and the test data of the valve in a mirror hydraulic flume is satisfactory and lies within the experimental error. This proves the legitimacy of the application of methods for calculating hydraulic jet devices to determine the hydraulic characteristics of the flow controllers of the developed design.

The pressure on the structure is equal to $H = H_1 - H_2$, and the pressure ratio above the intermediate pool is always greater than one $H_1/H_2 > 1$. In the total discharge of the outlet, up to 20% of the transit discharge can be taken from the intermediate pool. Ensuring the accuracy of regulation should be carried out by linking the length of the spillway front and the water level in the intermediate pool, to which all heads are tied.

As mentioned earlier the main target of this paper is to development of theoretical relationships for determining the main hydraulic parameters of valves with their subsequent verification according to the data of a physical experiment, in a way equipment such as the sensors, gates and mechanical moving parts for flow control not be used in our suggested flow valve. Our main focus for developing such a study was that it is certainly impossible to equip reclamation systems due to lack of funding. Of course, this is not just a problem for Russia. Many countries, even developed ones, face this problem and prefer to spend relatively less money to rehabilitate their systems. Unlike most existing valves (such as KIM and KIM [2012], LEAT and FISHER [1994]), our suggested structures do not use water-operated gates and mechanical moving parts, which increases the reliability and durability of their operation. According to Figure 3, the results of the mentioned idea indicated the good performance of our proposed method.

CONCLUSIONS

The proposed flow valve does not use gates, sensors and mechanical moving parts for flow control. The operation of the structure is based on the injection effect. Excess flow supplied to the irrigation canal circulates between the tailwater and the mixing chamber, reducing the discharge capacity.

Authors of this paper have developed a method for determining the hydraulic parameters of the valves, which is verified by the data of their hydraulic tests. Calculations can be carried out at a constant compression ratio value, which characterises the fraction of the cross-section of the mixing chamber occupied by the injection flow.

The flow rate, a part of which will be injected into the mixing chamber, and the rest will remain in the over-diffuser space, should come from the tail water through the weir. The control accuracy is related to the ability to maintain the required water level above the diffuser cover.

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