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NOZZLE REACTIVE HYDROTURBINE WITH GUIDE DEVICE

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Abstract: *The article presents the principle of operation of a jet turbine with a nozzle based on the "Segner" wheel and studies its shortcomings. In order to eliminate the identified shortcomings, a guide device was developed, which is installed inside the hydraulic turbine impeller. Using the Bernoulli equations and the Zhukovsky theory, the energy parameters of a microhydroelectric power station with a developed divertor device and the water flow rate in a hydroturbine are determined. The energy parameters calculated on the basis of theoretical results are analyzed, and it is found that the efficiency of a hydroturbine increases by 10-20% depending on the water pressure. This describes the guide device and the technical solution for its placement.*

Keywords: *Segner, micro hydro power plant, hydropower, hydro turbine, jet turbine, micro hydro power plant, guiding device.*

INTRODUCTION. At the beginning of the 18th century, the water wheel could only work with low water pressure in lowland rivers. Although medium-pressure (10-30 m) and high-pressure (more than 25-30 m) water sources have large reserves of hydraulic energy, it was not technically possible to use them by installing a water wheel. Until the 1740s, the only way to use the energy of such water currents was to create a hydraulic engine that operates efficiently at high pressures, which was fundamentally different from a water wheel [3].

Water wheels rotate under the weight of water or as a result of the impact of water on the blades in it, but the idea of the possibility of using the reactive force created by the pressure of the water column on the blades in the area of hydraulic motors was inspired by the work of Daniel Bernoulli "Hydrodynamics", published in 1738 [4]. In this work, Bernoulli summarized a number of his studies in hydraulics and hydrodynamics and created an equation establishing the relationship between pressure and velocity at each point in the flow of an incompressible fluid.

A reactive impeller based on Bernoulli's theory was first built in 1745 by the English mechanic D. Barker, then used in 1747-1750. During this period, the Hungarian physicist, who worked at the University of Göttingen, A. Segner, created a device that was a prototype of a jet hydraulic motor, called the “Segner wheel” [5]. First, he created a cylindrical hydraulic motor with two discharge pipes, and then with four discharge pipes [6]. Segner tried to use it as a suitable engine to turn a millstone. However, insufficient understanding of the nature of the physical processes occurring in such an engine did not allow the scientist to rationally improve it.

In 1750-1754, in his first lecture at the Berlin Academy of Sciences, L. Euler analyzed the processes in the Segner wheel and showed the great practical possibilities of the Segner jet engine, its advantages over other hydraulic machines. In his later lectures, he pointed out that the low efficiency was due to energy losses when water entered and exited the wheel, and outlined the theory of a hydraulic jet engine.

The stationary part is a guiding device, and the directional flow of water from it enters the lower rotating wheel, mounted on the shaft of the rotating impeller, and the water leaves from there through 20 curved tubes. This design was a transitional design from the original form of the Segner wheel to the hydraulic turbine (Fig. 1).

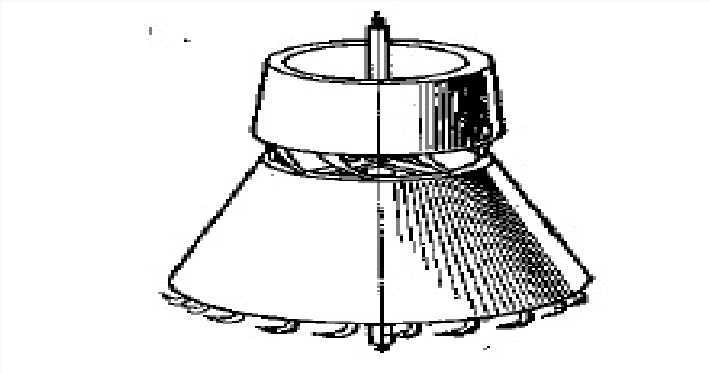

Fig 1. Euler hydraulic turbine.

Despite the complete scientific and technical basis of the hydroturbine project proposed by Euler in the 18th century, it did not find practical application for economic reasons. Over time, in the 40s of the 20th century, in Euler's native Switzerland, the operating model of the turbine was improved, i.e. completed with additional elements that prevent the vessel from swaying when water comes out. This turbine operated at a speed of n = 180 rpm with the highest efficiency at that time (71.2%). Thus, the speed of rotation of the Euler turbine was ten times the speed of rotation of the wheels used in the 18th century.

The discoveries and laws of Faraday in the field of electromagnetism formed the basis of the theory of a device that converts mechanical energy into electrical energy [5]. Based on this theory and discovery in 1832, Hippolyte Pixie made the first "dynamo" an electric generator. Since this period, work on the creation of new generations of electric generators and engines, as well as hydraulic turbines, has been rapidly developing. To date, jet turbines have been developed operating at various pressures, but sufficient solutions have not been found for low-pressure types.

For example, a jet turbine in [6] uses two upper and lower disks in its design, which causes double mechanical friction in the housing and causes inconvenience during its repair and maintenance due to the complexity of the design. Water in the upper disk located between the channels formed by the primary blades and windows, does not flow through the horizontal windows of the blades to the lower disk, creates local resistance to the rotation of the impeller, therefore, reduces the reactive power. The same shortcomings are observed in [7-9].

The components of a micro HPP in [10] are a reservoir, an electric generator, a turbine rotation shaft, an impeller, guide blades fixed to the bottom of the impeller, a fixed outer casing of the hydroturbine stator, a stator, a nozzle with a cone-shaped confuser nozzle, a rotating cylinder, and stator blades.

MATERIAL AND METHODS. The water flow consumes the rotating cylinder of the impeller through the vertical channel of the hydroturbine from the underwater channel. The water flow is directed to the thickness of the wall attached to the nozzle through the window of the working cylinder located in the horizontal plane. In this case, the guide vanes rotate together with the rotating wheel. The nozzle is also located in the same horizontal plane as the guide vanes. The water in the impeller is directed to the nozzle by means of vanes. The flow of water, reflected from the inner wall of the nozzle, creates a reactive force relative to the wall of the nozzle in the direction opposite to its direction. The water leaving the nozzle strikes perpendicular to the stator blades located in the stator, and the downward flow of water is directed to the outlet channel. As a result of the rotation of the guide vane, the water in the supply cylinder rotates around the impeller shaft due to the force generated in the direction perpendicular to the radius of the cylinder.

This circular movement of water occurs due to the speed of displacement of the impeller. Since the absolute speed of the water flow is directed vertically downwards, and the displacement speed of the impeller is perpendicular to it, the relative speed of the water flow is directed at an angle with the vertical direction relative to the base of the cylinder. As a result, the force of the vertical pressure of the water column decreases, resulting in a loss of energy and pressure.

The water flow from the center of the working cylinder along its radius is directed almost perpendicular to the outlet wall of the nozzle, as a result of which the water flow acting on the nozzle again tends to move towards the center of the working cylinder. When exposed to jets of water entering and reflected in the nozzle, the speed of the water leaving the nozzle is significantly reduced, which again leads to a decrease in the reactive force, as well as to the corresponding losses in kinetic energy and head. As a result, the efficiency of the hydro turbine decreases.

Usually, the rotation of the blade of the guide device provides the necessary change in the water flow through the turbine and the best direction of the water flow in the nozzles of the impeller, which increases the efficiency of the turbine [11].

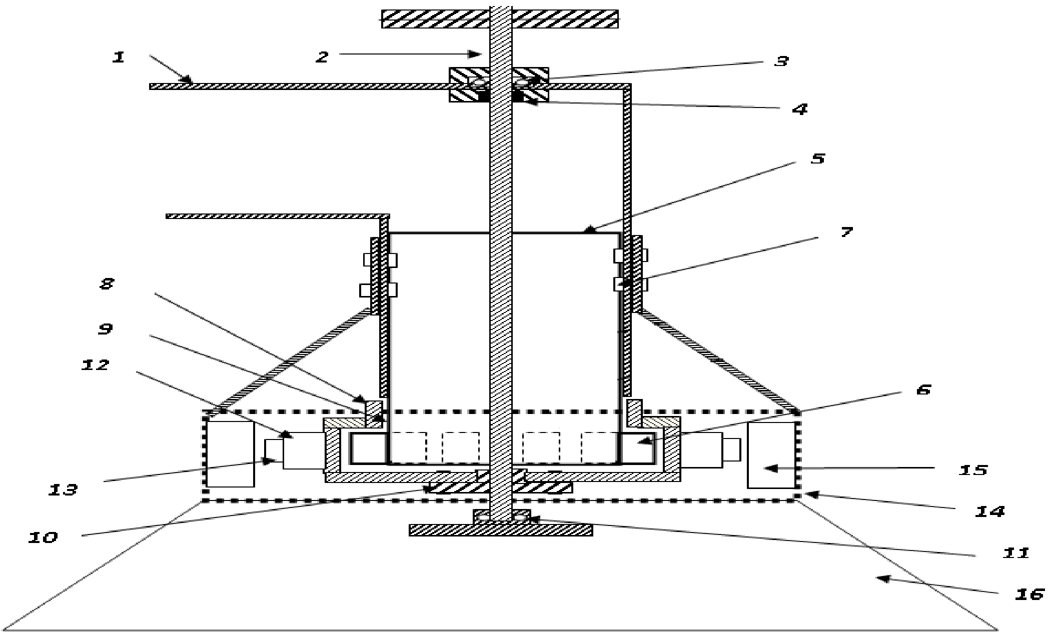

Fig 2. General scheme of a nozzle micro hydroelectric power station with an internal guide device: 1 - supply pipe; 2-shaft; 3- bearing; 4-gland; 5-cylinder feed inner guide device; 6 - guide blades; 7- place and bolts for fastening the guide device to the supply pipe; 8-cylinder hydraulic turbine impeller; 9-rubber seal; 10- cylindrical base connecting the impeller cylinder with the shaft; 11-plate support base; 12-nozzle; 13 outlet channel nozzle; 14-stator; 15 water return wings of the stator; 16-outdoor diffuser.

To eliminate these shortcomings, the guide vanes on the base of the cylinder were removed. In order to eliminate the above disadvantages and increase the efficiency of a micro hydroelectric power plant for a hydro turbine, an additional internal guide device was developed. Below is a general scheme of the developed micro hydroelectric power station with an internal guide device (Fig. 2).

The flow of water from the pressure tank 1 enters through the inlet channel 5 to the inlet cylinder of the guiding device. Then, the water leaves the special windows in the lower part, and rotates under the action of the guide vane 6 and enters the inlet 12 of the nozzle fixed on the cylinder of the impeller 8. The water flow, hitting the inner wall at the nozzle inlet and acting on the inner walls with an active force, moves towards the outlet channel 13 of the diffuser located at the end of the nozzle.

A jet of water, leaving the nozzle at high speed, acts on the nozzle with a force impulse acting in the direction opposite to its direction. This impulse force creates a reactive force on the nozzle, and the impeller of the water turbine rotates in the opposite direction to the direction of the water outlet. The jet of water from the nozzle 14 hits the surface of the blades 15, vertically mounted on the stator, and descends vertically, after which it leaves the outlet channel through the outer diffuser 16. The rotational movement of the impeller is transmitted to the generator through a pulley attached to the shaft in it.

On fig. 3 shows a general schematic view of the design of the guide device. In the guide device, water flows vertically from the supply cylinder 1. Let υ_2 be the average value of the speed of the water flow entering the channels 5 formed by curved blades 4 fixed between the annular disks 2 and 3. When the water flow is distributed from a vertical position through the channels, it turns in the horizontal direction. When turning through 90^0, there is an energy loss h_{90} corresponding to the turn of the flow, as well as a loss of pressure due to friction.

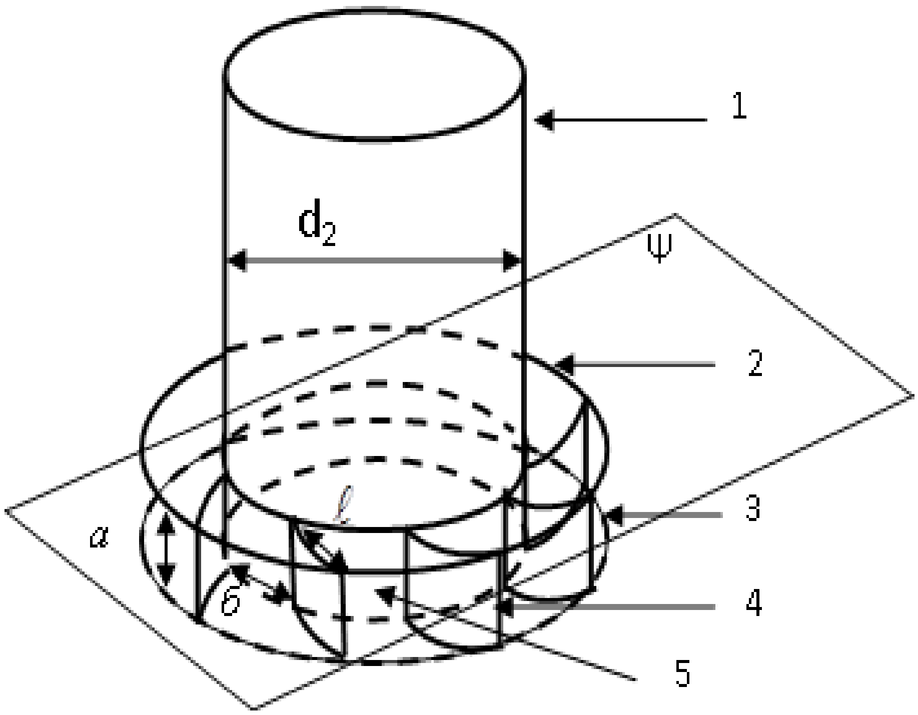

Fig 3. General schematic view of the design of the guide device.

However, due to the short length of the blades in the guide device, the energy losses in them can be neglected. In order not to lose energy due to excessive expansion during the transition from the feed cylinder through the channels to the nozzle, the cross section of the feed cylinder with a diameter d_2 must be equal to the sum of the entrance surfaces to the channels. If the channels are located periodically, symmetrically along the periphery of the cylinder, and all their parameters are considered the same:

$$\frac{\pi d_2^2}{4} = a(\pi d_2 - kb), \qquad a = \frac{\pi d_2^2}{4\pi d_2 - 4kb} \tag{1}$$

where, k is the number of blades; b is the sum of the thickness of the shovel and the length of the arc blocked to secure it (Fig. 3). It can be seen that an increase in the value of b leads to an increase in the vertical height of the blades.

To determine the rate of water exit from the channels of the guiding device, we consider the horizontal spread of the blade ring, taken in a horizontal section, to the plane of the sheet, at which, if we consider the number of blades to be very large, a grid is formed consisting of parallel blade systems. Therefore, to study the flow of water through a grid consisting of a blade profile, we create a grid by moving one blade profile of the guide device parallel to the same distance (Fig. 4). We call this distance the grid spacing.

We direct the *x*-axis along the width of the grid profile. The value is considered as the grating $\tau e^{i\beta}$ period by the angle β formed with the *x*-axis (lattice displacement) of the direction in which the grating profile should be shifted by τ steps in order to obtain an adjacent profile.

RESULTS AND DISCUSSION. Let us consider a potential flow around the grid from the left side of the grid with a flow velocity υ_2 and a direction at an angle α_1 to the *x* axis. Let the direction of the flow of water flowing out of the lattice make an angle α_2 with the *x*-axis, and let its velocity be equal to υ_3. Since the events in each grid profile are periodic, it is natural that the flow through the grid is periodic. In this case:

$$\omega(z + \tau e^{i\beta}) = \omega(z) \tag{2}$$

If we separate two streamlines near the front and rear ends of the profile, starting from infinity to the right and left, the streamlines around each profile formed by the parallel movement of the profiles will be congruent. For the shape we are considering, we use conformal transformations to transfer the circulation and other quantities in it from the space of a complex shape to a circular shape [12,13].

To do this, by introducing an auxiliary plane z and performing conformal replacements of the outer part of the profile grids on a multilayer Riemann surface in the plane of a system of concentric circles of unit radius, the corresponding equations for the complex potential field were solved. In this case, the considered guide vane was considered as a flat plate with a small radius of curvature. Assuming the flow velocity equal to unity, the complex flow potential ω_1 was chosen as follows:

$$\omega_1 = z \tag{3}$$

The parameters for determining the flow in the ζ plane, corresponding to the circulationless flow, are chosen so that, as a result, Γ=0. Then for the complex potential we get the following:

$$z = f(\zeta) = -\frac{\tau}{2\pi i}\left[e^{i\beta}\ln\frac{\zeta-\varepsilon}{\zeta+\varepsilon} - e^{-\beta t}\ln\frac{\zeta-\frac{1}{\varepsilon}}{\zeta+\frac{1}{\varepsilon}}\right] \tag{4}$$

In order for the grating dimensions to be unambiguous in the z plane, the blade width ℓ and the period must be specified; for this, it is necessary to determine the relationship between the parameter ε and the plate thickness. It fits to the front end $\zeta = \tau e^{i(k_0+\pi)}$ and back edge $\zeta = \tau e^{ik_0}$ of the plate.

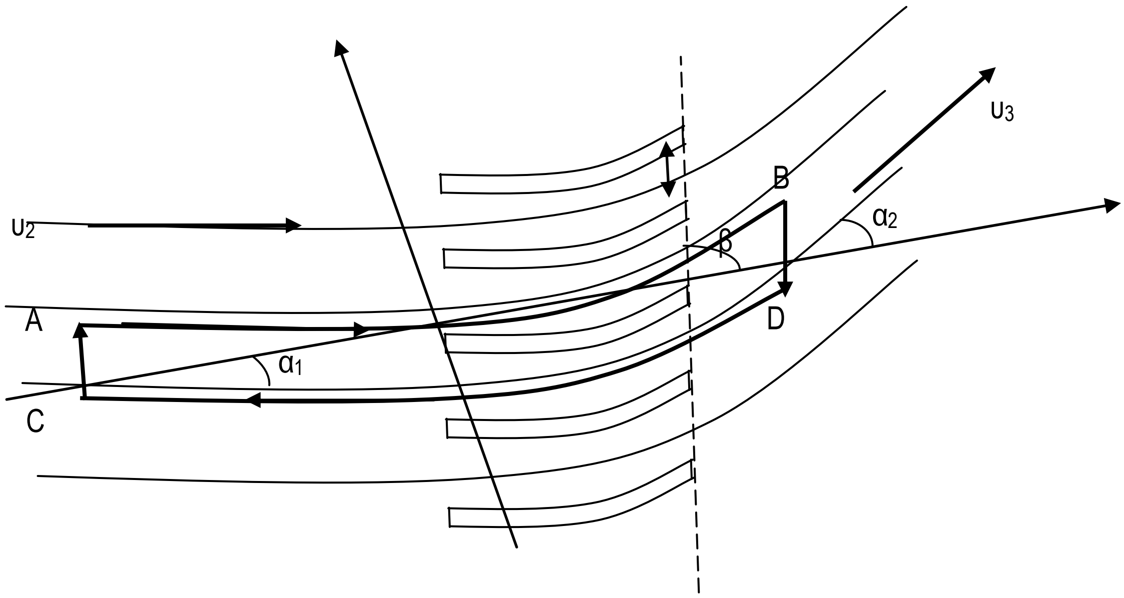

Fig 3. Water flowing through the spade fence

Therefore, the plate thickness is determined as follows [14]:

$$l = f(e^{ik_0}) - f(-e^{ik_0}) \tag{5}$$

Substituting the corresponding values in (5), using (4):

$$\begin{aligned} l &= -\frac{\tau}{\pi i}\left[e^{i\beta}\ln\frac{e^{ik_0}-\varepsilon}{e^{ik_0}+\varepsilon} - e^{-i\beta}\ln\frac{e^{-ik_0}-\varepsilon}{e^{-ik_0}+\varepsilon}\right] = \\ &= \frac{\tau}{\pi i}\left[\sin\beta\ln\frac{1+2\varepsilon\cos k_0+\varepsilon^2}{1-2\varepsilon\cos k_0+\varepsilon^2} - 2\cos\beta arctg\frac{2\varepsilon\sin k_0}{1-\varepsilon^2}\right] \end{aligned} \tag{6}$$

now if we find ℓ from (6):

$$l = \frac{\tau}{\pi}\left[\sin\beta\ln\frac{\sqrt{1+2\varepsilon^2\cos 2\beta+\varepsilon^4}+2\varepsilon\sin\beta}{\sqrt{1-2\varepsilon^2\cos 2\beta+\varepsilon^4}-2\varepsilon\sin\beta} + 2\cos\beta\cdot arctg\frac{2\varepsilon\sin\beta}{\sqrt{1-2\varepsilon^2\cos 2\beta+\varepsilon^4}}\right] \tag{7}$$

From (7) ε can be expressed in terms of β, t. Formulas (5), (7) completely determine the function that gives a conformal reflection inside the circle |z|=1 of the lattice blades.

When choosing the parameter ε, we pay attention to the fact that it characterizes the geometric properties of the flow through the grid. It is determined by formula (7). To determine the parameters A, k1, k2, we use the magnitude and direction of the speed at infinity at the front end of the blade and the limited speed at the rear end of the blade, as a result:

$$\upsilon_2 \sin\alpha_1 = -\frac{A}{A_0}\frac{(1-\varepsilon^2)\cos\frac{k_2-k_0}{2}}{1-2\varepsilon\cos k_0+\varepsilon^2} \tag{8}$$

Solving equations (8), finding A and k_2 and calculating the circulation, we get:

$$\Gamma = -4\frac{\varepsilon\tau\sqrt{1-2\varepsilon^2\cos 2\beta+\varepsilon^4}(1+\varepsilon^2-2\varepsilon\cos k_0)}{(1-\varepsilon^2)(1-\varepsilon^4)}\upsilon_2\sin\alpha_1 . \tag{9}$$

The limit as ε tends to zero gives circulation in the grating profile:

$$(\Gamma)_{\varepsilon=0} = -\pi l\upsilon_2\sin\alpha_1 \tag{10}$$

If the complex velocity of water after passing through the lattice , at z=+ε, then:

$$\upsilon_3 e^{-i\alpha_2}-\upsilon_2 e^{-i\alpha_1} = -\frac{iA}{A_0}e^{-i\frac{k_2-k}{2}}\left(\frac{\varepsilon-e^{ik_2}}{\varepsilon+e^{ik_0}}-\frac{\varepsilon+e^{ik_2}}{\varepsilon-e^{ik_0}}\right) = 4i\frac{A}{A_0}e^{ik_0}\varepsilon\frac{\cos\frac{k_2-k_0}{2}}{\varepsilon^2-e^{2ik_0}} \tag{11}$$

We have the following expression for the water flow rate after leaving the grate, that is, after the guide blades:

$$\frac{\Gamma}{\tau}e^{-i\beta} = \upsilon_3 e^{-i\alpha_2}-\upsilon_2 e^{-i\alpha_1} \tag{12}$$

$$\upsilon_3 = \frac{\Gamma}{\tau}e^{i(\alpha_2-\beta)}+\upsilon_2 e^{i(\alpha_2-\alpha_1)} \tag{13}$$

The drag coefficient for pressure loss when the water flow turns from the horizontal direction by 90° to the vertical direction was taken equal to ξ_1=1.25 [15], for the interval from the inlet to the turbine to the blade of the guide device, the Bernoulli equation was solved.

In the flow of water entering the hydraulic turbine, the flow is compressed due to the speed of movement of particles in the peripheral parts towards the center of the flow. The cross section of the watercourse will be less than the cross section of the inlet pipe. To take this situation into account, we introduce the compression ratio ε=F_d/F, then we can use the following formula to calculate the water flow:

$$Q = \frac{\varepsilon\varphi\pi d_1^2}{4}\sqrt{2gH_0} \quad Q = \varepsilon\varphi\left(\frac{\pi d_1^2}{4}\right)\sqrt{2gH_0} \quad \mu=\varepsilon\phi \tag{14}$$

When calculating the average speed υ1 in the feed cylinder of the hydraulic turbine, taking into account the energy losses at the water inlet, ϕ was corrected and determined as follows [16]:

$$\upsilon_1 = \varphi\sqrt{2g(H_0-z_1)}, \qquad \phi=0,93; \tag{15}$$

For the average flow rate of water entering the blades of the guide device, the following result was obtained:

$$\upsilon_2 = \sqrt{\frac{\frac{\upsilon_1^2}{g}\left[\frac{d_1^2}{\gamma d_2^2}\left(1-\frac{d_1^2}{d_2^2}\right)+\frac{\alpha_1}{2}\right]-\sum h_{1i}+z_1-z_2}{\alpha_2}\cdot 2g} \quad (16)$$

where, d_1 and d_2 are the corresponding pipe diameters; Q water flow. The velocity of water leaving the nozzle is equal to υ_4 if the Cariolis coefficient is equal to $\alpha_1 = \alpha_2 = \alpha_3 = \alpha_4 = 2$ for all pipes [18]. We get the following result for the speed of the water jet from the nozzle:

$$\upsilon_4 = \upsilon_3\sqrt{\frac{4S_3}{N\pi d_4^2}\left(\frac{4S_3}{\pi d_4^2}-1\right)+1-\frac{1}{2}\left(\frac{0{,}25\lambda}{2}\frac{1}{2}\left(1-\frac{\pi d_4^2}{4S_3}\right)+\left(1-\frac{4S_3}{\pi d_4^2}\right)^2\right)}; \quad (17)$$

We calculate the reactive force by determining the change in the momentum of the water jet acting on the nozzle in one second. Accordingly, let the impulses of the amount of water entering and exiting the nozzle be equal to K_3 and K_4, respectively, at which we consider the direction of rotation of the impeller as a positive direction, then:

$K_3 = \upsilon_3 \cdot m_0$; $K_4 = \upsilon_4 \cdot m_0$; $m_0 = \rho\upsilon_3 S_3 = \rho\upsilon_4 S_4$; $\vec{F} = \vec{K}3 - \vec{K}4$ If we use formula (14):

$$F = \cdot m_0 \cdot \left(\upsilon_3 \cos\beta - (-\upsilon_4)\right) = \rho S_3 \upsilon_3^2 (\cos\beta + \frac{\upsilon_4}{\upsilon_3})$$

$$F = \rho S_3 \upsilon_3^2 \left(\cos\beta + \sqrt{\frac{S_3}{NS_4}\left(1-\frac{S_3}{S_4}\right)+1-\frac{1}{2}\left(\xi_{S6}+\xi_2\right)}\right); \quad (18)$$

This design force is the force generated by a single nozzle and is determined by multiplying the total reactive force by the number of nozzles. For the projection of the moment of force per unit time in the vertical direction Oz, the following formula was obtained [16]:

$$M_z = -N\pi\rho r_c^3 \upsilon_4 \left(\upsilon_4 - \omega_z r_c\right); \quad (19)$$

Theoretical calculations were carried out using the analytical expressions considered above. The change in the dimensions and efficiency of a hydroturbine in response to a change in water pressure at a constant water flow has been studied. Table 1. shows changes in the diameter of the hydroturbine supply pipeline and the efficiency of the hydroturbine at five different water flow rates for each pressure when the static water pressure changes from 1.5 to 6 m in 0.5 m increments.

It can be seen from the table that with a constant increase in water flow, the efficiency of a hydroturbine increases with an increase in the pressure of water corresponding to each water flow, and with an increase in the amount of water flow, the efficiency of a hydroturbine decreases. This situation can be explained by the fact that the speed of the hydroturbine decreases due to an increase in the moment of inertia. Also, with an increase in water pressure, the dimensions of the hydraulic turbine become smaller, which leads to an increase in the moment of inertia of the hydraulic turbine, and the efficiency increases by increasing the rotational speed of the impeller.

Table 1

Changing the size and efficiency of a hydroturbine depending on the water level H at a constant water flow.

№	H, m	Q_1=0,2 m^3/s		Q_1=0,4 m^3/s		Q_1=0,6 m^3/s		Q_1=0,8 m^3/s		Q_1=1 m^3/s	
		d_1, m	η(g), %	d_1, m	η(g), %	d_1, m	η(g), %	d_1, m	η(g), %	d_1, m	η(g), %
1	1,5	0,244	79,4	0,345	72,7	0,422	69,1	0,487	66,7	0,545	64,8
2	2	0,227	86,2	0,321	79,3	0,393	75,9	0,454	73,6	0,507	71,8
3	2,5	0,215	88,4	0,303	81,5	0,372	78,2	0,429	76,0	0,480	74,4
4	3	0,205	90,1	0,290	83,1	0,355	79,8	0,410	77,7	0,458	76,1
5	3,5	0,197	91,4	0,279	84,3	0,342	81,0	0,394	78,9	0,441	77,4
6	4	0,191	92,5	0,270	85,3	0,330	82,0	0,381	79,9	0,427	78,4
7	4,5	0,185	93,5	0,262	86,1	0,321	82,8	0,370	80,7	0,414	79,3
8	5	0,180	94,4	0,255	86,9	0,312	83,5	0,361	81,4	0,403	79,9
9	5,5	0,176	95,2	0,249	87,5	0,305	84,1	0,352	82,0	0,394	80,5
10	6	0,172	95,9	0,244	88,1	0,299	84,6	0,345	82,5	0,385	81,0

CONCLUSION. In places where water consumption is limited, changing the size of the hydro turbine in accordance with the pressure of the water will increase its efficiency. When using the developed guide device in a hydraulic turbine with a nozzle, the following results are observed:

-the rotation of the water column in the supply pipeline of the existing hydraulic turbine nozzle together with the hydraulic turbine impeller is excluded;

-there was an increase in the absolute velocity of the flow of water entering the nozzle. This caused an increase in the reactive power of the hydroturbine.

-due to the elimination of the influence of the mass of water inside the impeller of the hydraulic turbine, its moment of inertia is reduced.

-since a decrease in the moment of inertia leads to an increase in the rotational speed of the impeller, the efficiency of the hydraulic turbine increases by 10-20%.

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EFFICIENCY OF A NOZZLE JET HYDROTURBINE WITH INTERNAL DIRECTION DEVICE

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Abstract: *The article analyzes the efficiency of existing jet turbines. The nozzle jet turbine, which works effectively in low-pressure water sources, has also been improved by installing an internal guide device. The results of tests of the developed experimental model of a hydroturbine are analyzed. During the experiment, it was found that the efficiency and speed of the hydroturbine are 16-25% higher than the prototype, depending on the water pressure.*