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Analysis of the efficiency of a counter-rotary hydraulic unit with a jet hydro turbine based on a Segner wheel

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Abstract. In the field of hydropower, which is one of the sources of renewable energy, there are many places where water pressure of 2-5 meters can be created in water sources. However, hydraulic turbines operating on such sources are not widely used due to insufficient efficiency. This paper describes a counter-rotor hydraulic unit developed by installing an additional active impeller to a reaction hydraulic turbine based on a Segner wheel. Based on experimental results and theoretical analysis, the energy efficiency of a counter-rotor hydraulic unit was studied. As a result of research, it was found that the efficiency of a counter-rotor hydraulic unit varies between 87.2-93.5% at a water pressure of 2-5 meters.

1. Introduction

It is known that today, providing the economy and manufacturing sector with uninterrupted electricity has become one of the world's problems. One way to overcome these problems is the efficient use of renewable energy sources. If we focus on the field of hydropower, which is one of the renewable energy sources, then there is almost no space left for the construction of large hydroelectric power stations, although there is space for the construction of small hydroelectric power stations, but they are also limited for environmental reasons. But there are water sources that can create 2-5 m of pressure, they can also be created artificially.

Hydroturbines that operate efficiently at such low pressures have not yet been sufficiently researched and developed. The biggest problem with low-pressure hydraulic turbines is the very low rotation speed of the impellers. A large amount of energy is lost when the rotational motion of the impeller is transferred to the generator. The high cost of electric generators operating at low rotation speeds does not allow the use of such low-frequency hydraulic turbines on a large scale. Therefore, in order to increase the coefficient of water energy use, counter-rotor hydraulic units were created in the works [1, 2, 3, 4]. These hydraulic units are equipped with two successive impellers located in one vertical pipe, and the water entering the first impeller from the first guide vane rotates it, and through the following guide vanes enters the second impeller and causes it to rotate. In this case, two impellers rotate in opposite directions, the rotational motion of one of them is transmitted to the generator rotor, and the rotational motion of the other is transmitted to the generator stator. The impeller shafts are located coaxially. In this case, due to resistance in the second impeller, an upward pressure is created in the water flow, as a result of which both impellers operate with low efficiency. When the water pressure is 2-10 m, the hydraulic unit does not work at all or works with very low efficiency. In [5, 6], a nozzle jet hydraulic turbine based on a Segner wheel was developed; the stream of water emerging from the nozzle of this hydraulic turbine comes out at a very high speed and hits the stator of the device with its blades. The kinetic energy of this outflowing water flow is not used. By replacing the stator of this device with an active water wheel, a counter-rotary hydraulic unit was developed, which has a reactive and active impeller, which work effectively in low-pressure watercourses [7, 8].

2. Methodology

A horizontal section of the impellers of a counter-rotor hydraulic unit based on a nozzle hydraulic turbine is shown in Fig. 1. Water with pressure H is supplied via a pressure pipe to the impeller of a jet hydraulic turbine through a guide

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vane. When the water flow moves in the guide device, the absolute speed increases due to uniform compression between the walls of the cone and the inner side of the cylinder wall of the guide device [10, 11]. Due to the action of the cone, there will be a smooth rotation of the flow from the vertical direction to the horizontal plane through the rectangular hole.

With the help of guide impellers, the water flow is directed to the inlet section of the nozzle, formed from the arc MN. After entering the nozzle, the water flow interacts with the internal walls of the nozzle, and it can be considered that the center of pressure of the water flow on the nozzle wall is located at point A. After interacting with the internal walls of the nozzle, the water flow leaves the nozzle with a relative speed vj, giving impulse to the worker wheel (Fig. 1). A jet of water coming out of the nozzle at high speed hits the inner surface of the blades of the active impeller at a short distance. In this case, the blades are located in the same horizontal plane as the nozzle. A number of water jets equal to the number of nozzles hits the blades of the active impeller. As a result, under the action of paired forces, torques are created that force the active impeller to rotate in the opposite direction relative to the reactive impeller.

The reactive force acting on the nozzles was calculated by changing the momentum of the water jet acting on point A of the nozzle in one second. Using the difference in momentum of the water flow entering and exiting the nozzle, the following result was obtained:

$$F_r = \rho S_3 \upsilon_3^2 \left(\cos\beta + \sqrt{\frac{S_3}{S_6}\left(\frac{S_3}{S_6} - 1\right) + 1 - \frac{1}{2}(\xi_{SK} + \xi_{90})}; \right) \tag{1}$$

When calculating the efficiency of a jet hydraulic turbine, we consider the linear speed ur of the impeller to be equal to half the absolute speed ϑa of the outgoing water flow, that is: $u_r = 0.5\vartheta_a$.

For the absolute speed of water υa at exit from the nozzle, the following formula was obtained:

$$\vartheta_a = \vartheta_3 \sqrt{\frac{4S_3}{\pi d_6^2}\left(\frac{4S_3}{\pi d_6^2} - 1\right) + 1 - \frac{1}{2}\left(\frac{0{,}25\lambda}{2}\frac{1}{2}\left(1 - \frac{\pi d_6^2}{4S_3}\right) + \left(1 - \frac{4S_3}{\pi d_6^2}\right)^2\right)}; \tag{2}$$

where,

$$\vartheta_3 = \frac{-\pi\ell\vartheta_2 \sin\alpha_1}{\tau} + \vartheta_2 e^{i(\alpha_2 - \alpha_1)}.$$

Here ϑ_3- is the speed of water at the entrance to the nozzle; ϑ_2 – water speed at the exit from the guide vane; S_3, d_6 – respectively, the nozzle inlet surface and the diameter of the nozzle outlet; α_1 and α_2 are the angles of water inlet and outlet in the guide vane; ℓ and τ are the length and pitch of the blade, respectively.

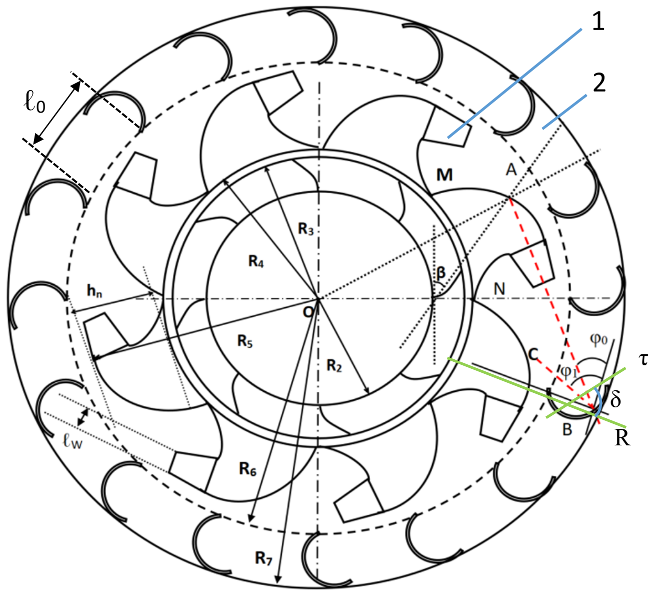


Fig. 1. General view of a horizontal section of the impellers of a counter-rotor hydraulic unit. 1-nozzle jet impeller; 2-active impeller

In the above hydraulic turbine, with a water pressure of 2 meters, the speed of the water jet emerging from the nozzle is 5.9 m/s. In the counter-rotor hydraulic unit where water exits the nozzle, the linear speed of the reactive impeller is $u_r = 0.5\vartheta_a$ m/s, the mass of water with kinetic energy corresponding to the speed $v_j = 0.5\vartheta_a$ m/s is exposed to continuous impacts on the blades of the active impeller. The stream of water emerging from the nozzle hits the blades of the active wheel at an angle φ_0 relative to the direction perpendicular to the radial, at the farthest distance, this angle decreases to φ_1 as the blades approach the nozzle. For convenience of calculations, we will assume that the water flow returning from the blades forms an angle φ_1.
The central axis of flowing water flowing in direction AB falls on point B at an angle φ_0. At this point, the tangent τ, transferred to the inner surface of the blade, makes an angle δ with the radial direction R. At this point, the angle between the normal n and the axis of the water flow is very small, its value is defined as $\delta - \varphi_0$. Consequently, the force of the water flow on the blades of the active impeller perpendicular to the radial direction can be calculated from the change in the momentum of the water flow:

$$F_w dt = m\left[\left(v_j - u_a\right)\cos\varphi_0 + \vartheta_2 \cos\varphi_1\right] \quad (3)$$

If the water flow velocity ϑ_2 after interaction with the impeller is equal to its value upon impact and is directed at an angle φ_1 relative to the perpendicular, then:

$$F_w dt = m(v_j - u_a)(\cos\varphi_0 + \cos\varphi_1) = 0{,}5Nq\rho dt \cdot v_j(\cos\varphi_0 + \cos\varphi_1)$$

$$F_w = 0{,}5Nq\rho \cdot v_j(\cos\varphi_0 + \cos\varphi_1) \quad (4)$$

The total force moment created on the active wheel:

$$M = 0{,}5NR_w q\rho \cdot v_j(\cos\varphi_0 + \cos\varphi_1) \quad (5)$$

Here u_a is the linear speed of the active wheel; N is the number of nozzles; ρ-density of water; q-water flow in one nozzle. If the number of impellers is n=16, then the angle between the two impellers will be $\alpha = 360^0 : n = 22{,}5^0$ (Fig. 2). Then we can say that $\varphi_1 = \alpha$, $\varphi_1 = 2\alpha$, $\text{Cos}22{,}5^0 = 0.9382$, $\text{Cos}45^0 = 0.7604$.
Using the Zhukovsky-Mitchel theory (1963. Part II) for the outflow of water from a nozzle, the jet equation was obtained and the jet width at infinity was determined, i.e. upon impact with the blades of the active impeller [9, 12]:

$$\ell_w = \ell_n - \frac{q}{2\chi L v_j} \int_{-\chi}^{0} \sin\theta ctg \frac{\pi\theta}{2\chi} d\theta \quad (6)$$

The speed of the water jet striking the blades of the active wheel is equal to v_j emerging from the j-nozzle in the reference frame associated with the ground, i.e., it is equal to the vector sum of the linear speed along the circle ut of the point of the jet impeller at a distance R_5 with a relative speed ϑ_a.

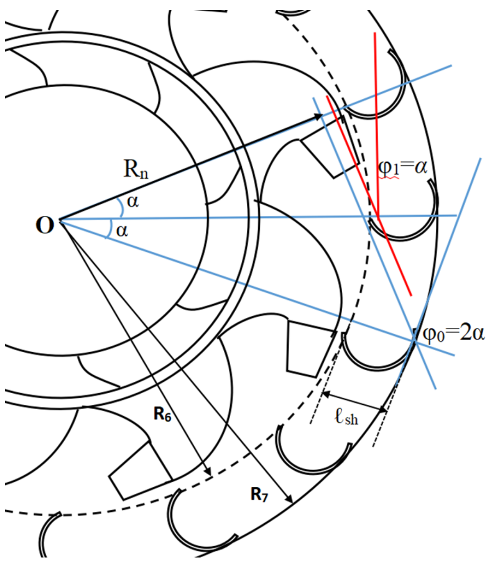


Fig. 2. Angle between the two impellers

The speed of the water jet striking the blades of the active wheel is equal to v_j emerging from the j-nozzle in the reference frame associated with the ground, i.e., it is equal to the vector sum of the linear speed along the circle ut of the point of the jet impeller at a distance R_5 with a relative speed ϑ_a. Since the direction of water exiting the nozzle is perpendicular to the radial direction, the angle between the vectors is 180^0, in this case the sum of the vectors is equal to the following algebraic difference:

$$v_j = \vartheta_a - u_r \tag{7}$$

It is known from the scientific literature that the efficiency of a hydraulic turbine is highest when the linear speed of the point of contact of the impeller with the water flow is equal to half thespeed of the water flow acting on it. For the absolute speed at impact on the blades v_j:

$$v_j = 0{,}5\vartheta_a\left[1 + \frac{1}{\chi}\int_0^{\chi}\sin\theta \operatorname{ctg}\frac{\pi\theta}{2\chi}d\theta\right] \tag{8}$$

$$q = 2L\ell_n\vartheta_a$$

where, ℓ_n is the width of the jet at exit from the nozzle; ℓ_w is the width of the jet at impact; L-nozzle height; χ is the angle of convergence of the nozzle.

A jet of water of width ℓ_w hits the active water wheel with a speed v_j, and the active wheel rotates with an angular speed ω_w. The linear speed of rotation of a water wheel with optimal parameters is equal to half the speed of the water jet acting on it [7]. Then the radius of the active impeller:

$$R_w = \sqrt{0{,}5\cdot(R_6^2 + R_7^2)} \tag{9}$$

$$\omega_w = 0{,}5\frac{v_j}{R_w} \tag{10}$$

Power generated in the active impeller:

$$P_{out} = F\cdot u_a = \frac{1}{4}Nq\rho v_j^2(\cos\varphi_0 + \cos\varphi_1) \tag{11}$$

Water flow power acting on the blades (t=1sec):

$$P_{in} = \frac{mv_j^2}{2t} = 0{,}5\cdot Nq\rho v_j^2 \tag{12}$$

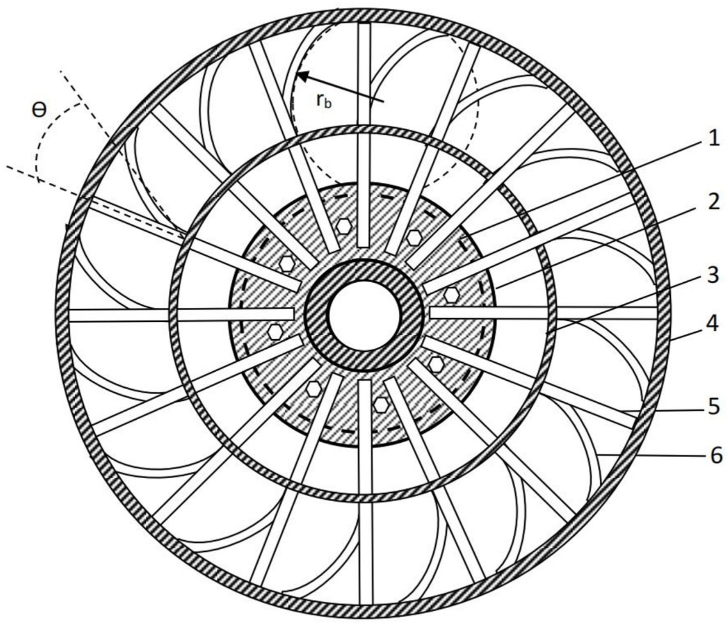


Fig. 3. General diagram of the active impeller, bottom view

Efficiency of the active impeller based on the energy of water leaving the nozzle, without taking into account energy losses due to friction in mechanical parts, splashing of the water flow when the blades intersect:

$$\eta_w = \frac{P_{out}}{P_{in}} \cdot 100\% = 0{,}5 \cdot (\cos\varphi_0 + \cos\varphi_1) \cdot 100\% = 84{,}93\% \quad (13)$$

From theoretical calculations and available literature, it has been established that 3-5% of energy can be lost due to friction in bearings. If additional speed multipliers are used, another 10% energy loss is observed. So, in general, with a loss of 14-15% of energy, the efficiency of the active impeller is 70%.

The cyclic frequency of an active impeller depends on its size, and an increase in the moment of inertia created by the impeller relative to its shaft leads to a decrease in frequency. Therefore, the structural size and structure of the impeller are of great importance for efficiency. Below is a general diagram of the bottom view of the active impeller (Fig. 3).

The active impeller consists of a central disk with a trunnion 1 and a large disk 2, which are connected to each other using bolts, the large disk 2 is equipped with support rods 5 in the radial direction, to which the inner and outer rings 3, 4 are attached to fasten the blade 6.

To ensure that the active wheel rotates at a given frequency, the moment of inertia can be adjusted by changing the size and number of support rods, as well as changing the size and mass of the inner and outer rings and the central disk.

3. Results and Discussion

Based on the above theoretical analysis, the results of calculations carried out to determine the efficiency of the anti-rotor hydraulic unit and its changes depending on the water pressure are presented in Table 1.

At the same time, the water pressure changed in increments of 0.5 m in the range of 1.5-6 m. The table shows that when the water pressure changes from 1.5 m to 6 m, the efficiency of the jet hydraulic turbine changes from 68,5% to 71,3 %. The efficiency of the active wheel varies from 19.1% to 22.29% when calculated in relation to the total energy of the water. The overall efficiency of the anti-rotor hydraulic unit increased from 87,19% to 93,59%.

Figures 4, 5 show the dependence of the efficiency created by reactive and active impellers on water pressure. Using these graphs, it is possible to determine the contribution of each impeller to the efficiency of the hydraulic unit at various pressures at a flow rate of Q=0.2m3/s.

Table 1. Results of theoretical calculation of energy parameters of a counter-rotor hydraulic unit.

№	ϑ_a, m/s	P_r W	P_a, W	E_{tot}, J	η_R, %	η_a, %	$Cos\varphi_1$	$Cos\varphi_2$	η_{kr}, %
1	5.54	2002.70	563.44	2943	68.05	19.15	0.71	0.92	87.19
2	6.46	2725.17	851.89	3924	69.45	21.71	0.71	0.92	91.16
3	7.26	3435.41	1073.92	4905	70.04	21.89	0.71	0.92	91.93
4	7.97	4144.75	1295.66	5886	70.42	22.01	0.71	0.92	92.43
5	8.63	4853.51	1517.22	6867	70.68	22.09	0.71	0.92	92.77
6	9.23	5561.88	1738.66	7848	70.87	22.15	0.71	0.92	93.02
7	9.80	6269.99	1960.01	8829	71.02	22.20	0.71	0.92	93.22
8	10.34	6977.90	2181.31	9810	71.13	22.24	0.71	0.92	93.37
9	10.85	7685.66	2402.55	10791	71.22	22.26	0.71	0.92	93.49
10	11.34	8393.31	2623.77	11772	71.30	22.29	0.71	0.92	93.59

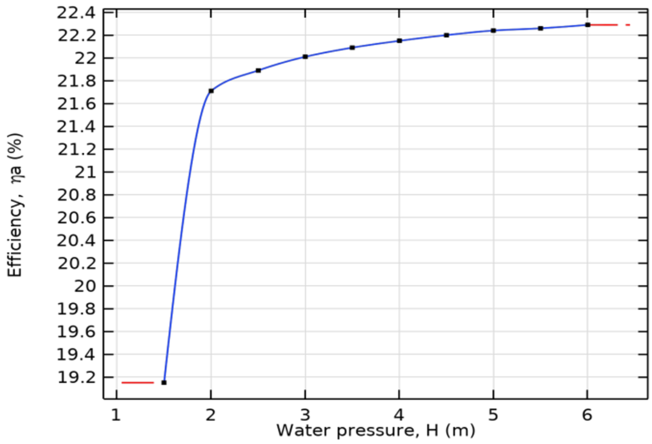


Fig. 4. Efficiency of a jet hydraulic turbine at various water pressures

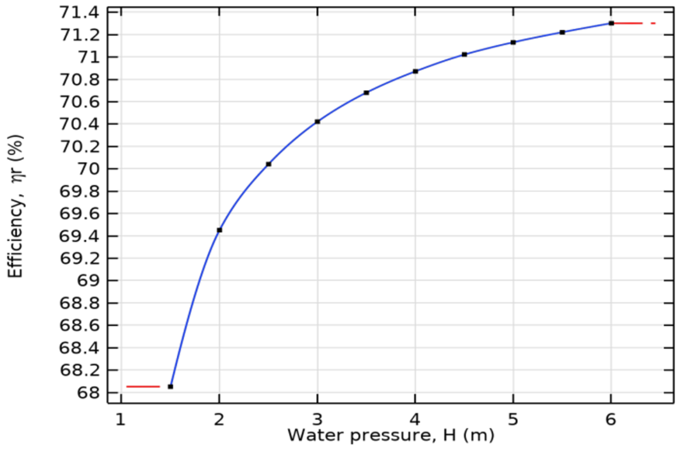
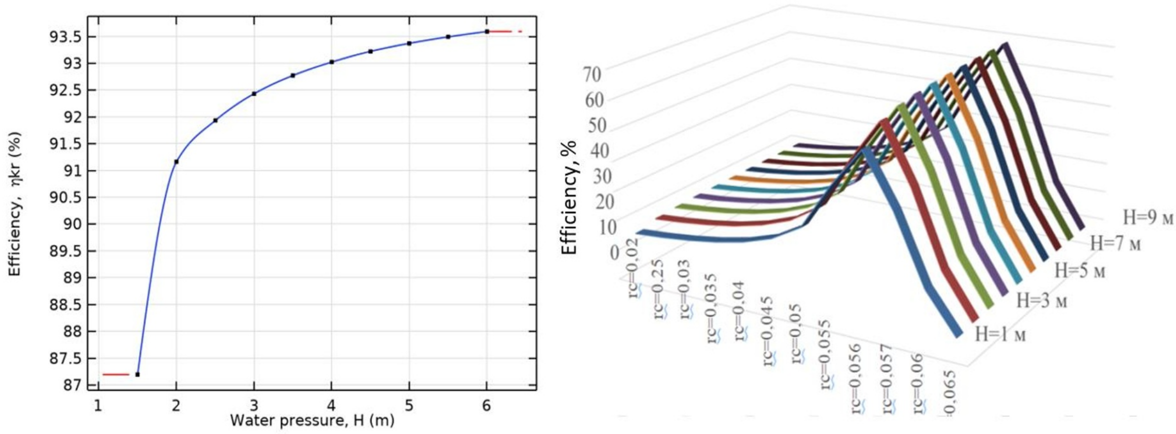


Fig. 5. Efficiency of an active hydraulic turbine at various water pressures



a *b*

Fig. 6. Variation of counter-rotor hydroaggregate: a) efficiency depending on water pressure, b)jet hydroturbine efficiency with respect to nozzle outlet radius

The efficiency of a counter-rotor hydraulic turbine is equal to the sum of the efficiency of two hydraulic generators. This value changes very quickly depending on many design parameters of the jet turbine. Of great importance is the angle of the blades of the internal guide device relative to the radial direction, as well as the ratio of the inlet and outlet surfaces of the nozzle. Figure 6(a) shows the results when the linear speed of the active and reaction wheels is assumed to be equal to half the absolute speed of the water flow. But the reaction impeller has a slightly higher linear speed. This speed can be adjusted by changing the ratio of the inlet and outlet surfaces of the nozzle.

It is interesting to note that the efficiency of a hydraulic turbine is highest only at one value of the water exit surface from the nozzle of a jet hydraulic turbine. This change in efficiency increases with water pressure up to 6-7 meters. At higher pressures the change in efficiency is very small. For example, from Figure 6(b), it can be seen that with a pressure of 1.5 meters and water flow Q=0,2m^3/s in the presence of 8 nozzles, the efficiency of the impeller is 67,8% with the nozzle exit radius r_n=0.56 mm.

4. Conclusion

The efficiency of hydraulic turbines or water wheels operating at a water pressure of 2-5 meters is low, since energy losses on additional mechanical elements and mechanisms with increasing rotation speed, transmitted from the impeller to the generator, constitute a significant part of the total energy. This situation reduces the efficiency of the hydraulic turbine.

In a counter-rotor hydraulic unit, if the movement of the reactive impeller shaft is transmitted to the generator rotor, and the active impeller is transmitted to the generator stator, additional accelerating devices and mechanisms are reduced, and in generators operating at low rotation speeds, they can not be used at all. In addition, one incoming flow to the hydraulic unit is used twice. Accordingly, the energy of the water is fully utilized and operates efficiently at low pressure. Chunki bu agregatda reactive va active ishchi gildiraklar bir-biriga boglanmagan va halakit bermai alohida hydroturbinalar singari ishlaydi. If for some reason one of the impellers stops moving, the remaining second one will continue to work. And the active wheel is placed open, it is convenient to assemble the complex, perform various operational services, and the operating mode can be monitored visually.

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