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Modeling of design parameters of a screw turbine for a microhydro power plant

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Abstract. Microhydroelectric power plants with screw turbines operating on low-pressure watercourses represent a new form of small-scale hydropower. Modeling of the design parameters of a micro-hydroelectric power station with two parallel screw turbines operating in low-pressure water flows, and the optimal values were determined. The purpose of the conducted scientific research is the screw turbine outer diameter (D_o), inner diameter (D_i), total length of the screw (L), the number of blades (N), the angle of inclination of the screw (β), the length of one revolution of the blade (S), the height (H) of the pressure generator is to increase the efficiency of the impact on the number of revolutions, torque and mechanical power based on the correct selection of optimal options.

1. Introduction

It is well known that some of the drawbacks of large hydroelectric power plants, such as a significant proportion of capital costs per unit of generated power, are eliminated when a decentralized supply of electricity is implemented in small and micro hydroelectric power plants in conjunction with their advantages. Such hydroelectric power plants also contribute to the development of the region and are especially important for developing economies because they have little environmental impact and can be entirely developed using local labor, resources, building materials, and so on. A comparatively small number of customers who are close enough to the hydroelectric power plant receive the generated electricity. Thus, energy production using small hydroelectric power plants is one of the most effective areas for the development of alternative energy sources.

Comparing modern hydropower to other alternative energy sources, it is the most cost-effective and environmentally benign method of producing electricity. With regard to useful work coefficient, small hydropower is a more dependable and efficient resource in this direction. Small and micro hydroelectric power plants enable the preservation of the surrounding natural environment and scenery both during construction and operation. In contrast to large dam hydropower plants, micro and tiny hydropower plants do not negatively affect the environment [1, 2]. Effective use of micro hydropower plants, which are alternative energy sources for agriculture, light industry and other electricity consumers, contributes positively to the introduction and development of new innovative technologies. Micro hydropower plants with screw turbines may not be a global solution to supply electricity to electricity consumers, but they offer a renewable energy source with economic and environmental benefits[1, 2]. From practical work on its development, research on upgrading the Archimedes screw turbine is taken into consideration [1]. In this regard, the development of hydraulic turbines is a significant issue for the industry's further growth. Screw turbines are an excellent option for situations where other types of turbines cannot be used since they require less maintenance and are easier to operate mechanically than other types of turbines [3, 4]. Archimedean screw hydraulic turbines generate power not due to the upward movement of the fluid, but due to the torque created by the downward movement of the fluid [1, 3, 5, 6]. It is advised that these turbines be built in locations with water flow rates of up to m3/s and water flow pressures of up to 10 m due to their 60–80% efficiency while running in low-pressure water flows [1, 7].

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2. Methods

When calculating and selecting turbines, the main parameters are the pressure creation height H, power P and efficiency factor η. The pressure generation height of the turbine is calculated using the following formula [8]:

$$H = H_{st} + \frac{\alpha_1 \cdot v_1^2}{2 \cdot g} - \frac{\alpha_2 \cdot v_2^2}{2 \cdot g} - h_q \tag{1}$$

where $H_{st} = Z_1 - Z_2$ - difference between water supply and intake levels;

$v_1, \ v_2$ - these are the flow rates at the inlet and outlet of the system;
h_q - pressure losses at the water inlet, in the pipes where the turbine is located, and in external resistances;
g – acceleration of gravity.

The power of water flow is calculated using the following formula:

$$N_c = \frac{\gamma \cdot Q \cdot H_c}{1000} \tag{2}$$

where Q – water consumption; H_c – the pressure of the stream; γ – specific weight [8].

$$H_c = H_{st} + \frac{\alpha_1 \cdot v_1^2}{2 \cdot g} - \frac{\alpha_2 . v_2^2}{2 \cdot g} \tag{3}$$

The power generated by the turbine shaft is calculated using the following formula:

$$N_T = \frac{\gamma \cdot Q \cdot H_c}{1000} \cdot \eta_T \tag{4}$$

where η_T full-time efficiency of the turbine wheel [8].

The efficiency coefficient of the turbine η_T depends on the water consumption Q. If the useful pressure H decreases, the turbine's power efficiency changes imperceptibly [1, 3, 4, 9]. If the water consumption Q is lower than the minimum, the turbine will not work. When the water consumption is Q and the water consumption is Q_A

$$q = \frac{Q - Q_{min}}{Q_\Delta} \tag{5}$$

through the following empirical equations, the power factor of the turbine η_T is as follows [9]:

$$\eta_T = \begin{cases} 0 & uchun \ Q \le Q_{min} \\ \frac{q}{a_1 + a_2 \cdot q + a_3 \cdot q^2} & uchun \ Q_{min} < Q < Q_A \\ \eta_{T\,N} & uchun \ Q_A \le Q \end{cases} \tag{6}$$

When the power factor of the turbine is expressed by the mechanical power supplied to the turbine:

$$P_{mex} = \eta_T \cdot P_{chiq} \tag{7}$$

where P_{mex} – mechanical power of the turbine; P_{chiq} – turbine output power.

Micro hydropower plants with Archimedes screw turbines are also used in low-pressure water flows or in places where the pressure generating height is almost zero. Screw turbines use the kinetic and potential energies of the fluid, and this energy is converted into mechanical work in the process of turning the screw and generating torque. A generator attached to the screws converts the generated mechanical energy into electrical energy. In screw turbines, the outer diameter (D_o), inner diameter (D_o), the total length of the screw (L), the number of blades (N), the angle of inclination of the screw (β), the length of one revolution of the blade (S), the pressure generating height (H) and water consumption (Q) based on the selection of optimal variants of these parameters, an increase in efficiency and mechanical power is achieved [1, 3, 4, 10-16]. Minimum water level hitting the turbine Z_{min}, maximum water level i.e. complete submergence of the fins (without overflow) Z_{max} and the optimal actual water level required to rotate the fins is determined by Z_{wl} (Fig. 1) and dimensionless (relative) water filling height (f) can be seen from the following formulas:

$$Z_{min} = -\frac{D_o}{2} \cdot Cos(\beta) - \frac{S}{2} \cdot Sin(\beta) \tag{8}$$

$$Z_{max} = \frac{D_i}{2} \cdot Cos(\beta) - S \cdot Sin(\beta) \tag{9}$$

By introducing the fill factor f as the relative level, the actual water level can be determined as:

$$\mathrm{Z_{wl}} = \mathrm{Z_{min}} + \frac{\mathrm{Z_{wl}} - \mathrm{Z_{min}}}{\mathrm{Z_{max}} - \mathrm{Z_{min}}}(\mathrm{Z_{max}} - \mathrm{Z_{min}}) = \mathrm{Z_{min}} + \mathrm{f}(\mathrm{Z_{max}} - \mathrm{Z_{min}}) \tag{10}$$

If the dimensionless (relative) height of water filling in the formula (10) is f=0, then $Z_{wl}= Z_{min}$, f=1 $Z_{wl}= Z_{max}$, f>1 is the level of water immersion exceeds 100%, causing water to overflow from the top of the central cylinder, causing water wastage and reduced turbine speed.

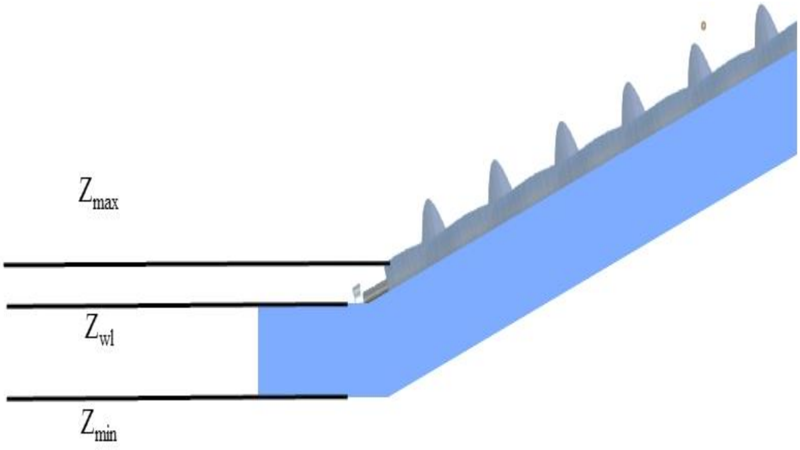

Fig. 1. Cases of water hitting the wings

The volume of water hitting the blades (dV) can be determined parallel to the "w" axis connecting the adjacent points of the upper and lower planes of the blade. In this case, θ - angular position is taken between 0 and 2p, and r - radial position is taken between $D_i/2$ and $D_o/2$ [1, 10, 14], and the total volume of water hitting the filter can be determined as follows:

$$\mathrm{dV} = \begin{cases} 0 & \mathrm{Z_l} > \mathrm{Z_{wl}} \ \text{va} \ \mathrm{Z_{wl}} < \mathrm{Z_2} \\ \frac{\mathrm{Z_{wl}} - \mathrm{Z_1}}{\mathrm{Z_2} - \mathrm{Z_1}} \frac{\mathrm{S}}{\mathrm{N}} \, \mathrm{r\,dr\,d\theta} & \mathrm{Z_1} \le \mathrm{Z_2} \ \text{va} \ \mathrm{Z_{wl}} \le \mathrm{Z_2} \\ \frac{\mathrm{S}}{\mathrm{N}} \, \mathrm{r\,dr\,d\theta} & \mathrm{Z_l} < \mathrm{Z_{wl}} \ \text{va} \ \mathrm{Z_{wl}} > \mathrm{Z_2} \end{cases} \tag{11}$$

$$\mathrm{V} = \int_{\mathrm{r}=\frac{\mathrm{D_i}}{2}}^{\mathrm{r}=\frac{\mathrm{D_o}}{2}} \int_{\theta=0}^{\theta=2\pi} \mathrm{dV} \tag{12}$$

After finding the volume of water hitting the screw blades, we can find the moment of force generated by the impact of water pressure on the spiral planes of the screw. Taking into account the static conditions of the lower (Z_1) and upper (Z_2) water inlet levels on the plane surface of the propeller blade, the hydrostatic pressure (p) at any point of the plane surfaces is determined by the following expression:

$$p_1 = \begin{cases} \rho\, g\, (Z_{wl} - Z_1) & Z_1 < Z_{wl} \\ 0 & Z_1 \ge Z_{wl} \end{cases} \tag{13}$$

$$p_2 = \begin{cases} \rho\, g\, (Z_{wl} - Z_2) & Z_2 < Z_{wl} \\ 0 & Z_2 \ge Z_{wl} \end{cases} \tag{14}$$

The difference between the pressures on the blade's upstream and downstream surfaces is known as the net pressure on the propeller plane surfaces. Thus, the total moment over all submerged surfaces may be computed as follows if p1 and p2 are regarded as the pressure on each side of the plane surface. This will also yield the net moment (dT) on each element area of the screw's plane surface as well as the total moment on a single blade (T):

$$\mathrm{dT} = (\mathrm{p_1} - \mathrm{p_2}) \frac{\mathrm{S}\,\theta}{2\,\pi} \, \mathrm{r\,dr\,d\theta} \tag{15}$$

$$\mathrm{T} = \int_{\mathrm{r}=\frac{\mathrm{D_i}}{2}}^{\mathrm{r}=\frac{\mathrm{D_o}}{2}} \int_{\theta=0}^{\theta=2\,\pi} \mathrm{dT} \tag{16}$$

The total moment due to hydrostatic pressure for the entire length of the screw depends on the total number of blades and can be calculated as [1, 3, 14]:

$$T_{\text{total}} = T\left(\frac{NL}{S}\right) \tag{17}$$

where N- is the number of blades; L- the total length of the screw; S- the length of one revolution of the blade; T- torque.

3. Results

The computations that were achieved were derived from the examination of the literature that has been done thus far. These calculations are based on a mathematical model that was created using data from several books, periodicals, and articles about hydraulic machines [1, 2, 4-6, 9-11, 15]. Additionally, a small screw hydro turbine model was created.

A small model of a screw turbine micro-hydroelectric power plant operating in low-pressure water flows was developed by comparing the parameters that play a key role in its high efficiency. Preliminary comparison results were carried out on the number of blades spirally welded to the turbine shaft, the parameters affecting the change in torque and power were compared at values of the height of the pressure generator from H=0.1 to 1 m.

When checking the number of blades in relation to the angle of inclination, the length of the screw is 1 m, 2 m and 2.5 m, and the number of blades of the screw is N=1, N=3, N=5. When the angle of inclination is up to 300, it is 1 blade screw, we can see that the efficiency f the turbine is high (Figure 3).

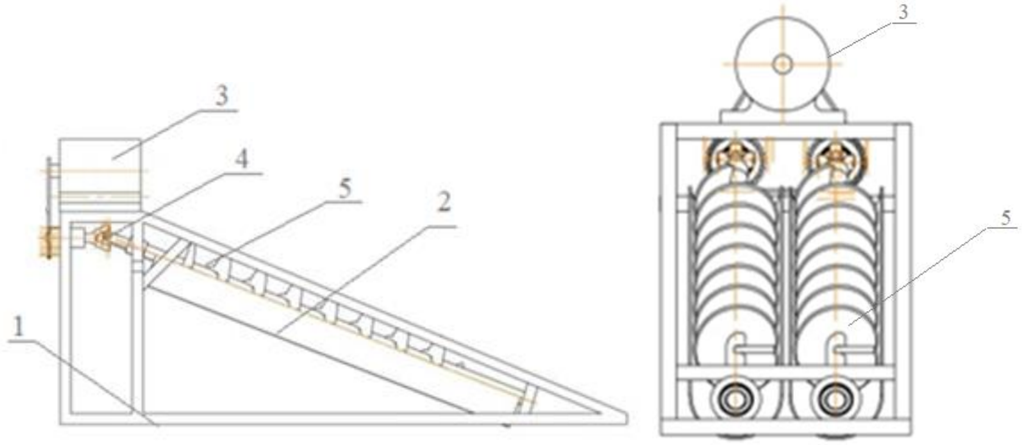

Fig. 2. Microhydroelectric power plant with two parallel screw turbines: 1-device base, 2- turbine tray, 3 - generator, 4 - turbine and pulley connecting part adjusting shaft, 5 - screw

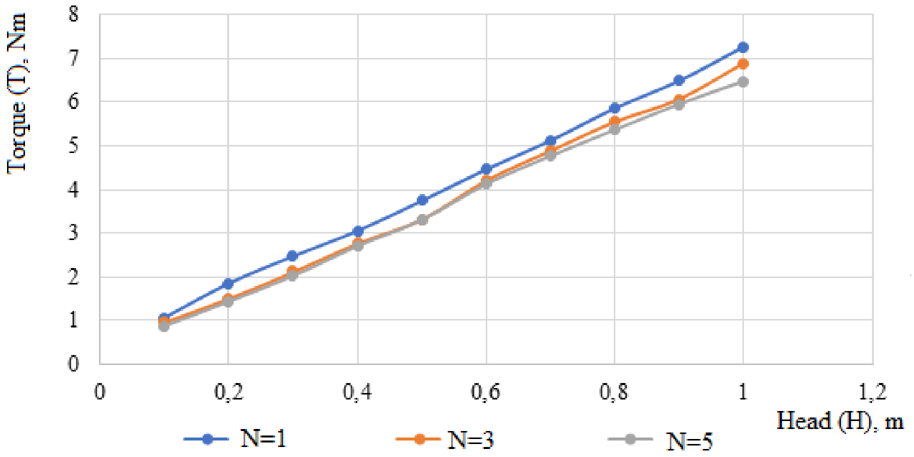

Fig. 3. A graph of the change in torque when the number of blades changes

The primary objective of the study was to create a tiny, easily installable model of a small hydroelectric power station with two parallel Archimedean screw turbines. Based on mathematical modeling of these losses, power losses typical of Archimedean screw turbines were examined and taken into consideration. A tiny model of an Archimedean screw micro hydroelectric power station with a straightforward engineering design was created and tested in a lab using the suggested model as a basis.

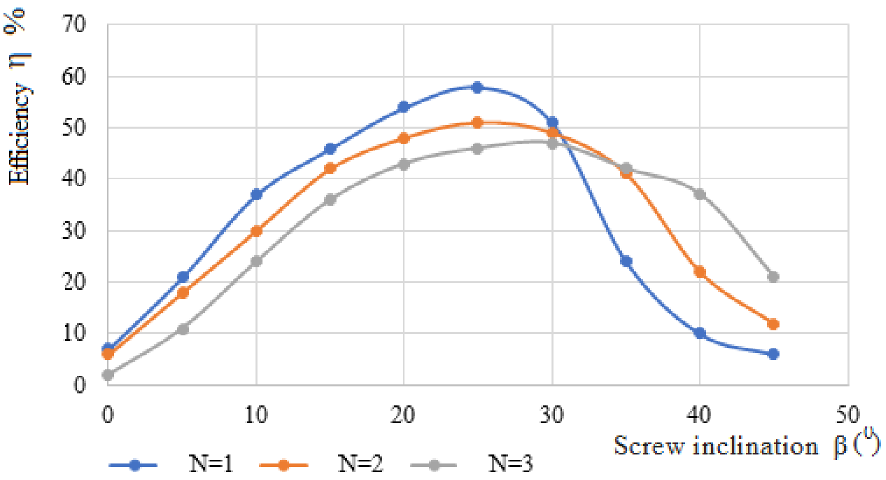

Fig. 4. Variation of the useful work coefficient under the change of the number of blades and the angle of inclination

Table 1. Geometric dimensions of the Archimedean screw turbine

Name	Parameter	Parameter unit	Result
Outer radius	R_o	m	0.0575
Inner radius	R_i	m	0.0287
Radius ratio	δ	m	0.499
Screw length	L	m	0.98
Head	H	m	0.4
Screw inclination	β	(^{0})	24
Number of flights	N		1
Screw pitch	S	m	0.101
The gap between the trough and screw	G_w	m	0.002
Total screw Torque	T	Nm	6.89
Power	P	W	85.3

4. Conclusion

In this work, the model of structural parameters affecting the increase in efficiency of the screw turbine was studied. The influence of the lower ($Z1$) and upper ($Z2$) water entry levels on the plane surface of the propeller blade on the hydrostatic pressure (p) at any point of the plane surfaces, taking into account the static conditions, was studied. Archimedean screw turbines with different parameters were studied and the optimal values were confirmed by comparing the design parameters that increase the efficiency of the screw turbine. As a result, in order to increase the mechanical power, a small model was developed, which was connected by transmission of two parallel turbines to one generator.

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