Method of calculation of water-diverting structures of low-head hydroelectric power plant for power supply of small power consumers

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Abstract. In recent years and in many countries the economic development of distant regions is increasingly dependent on energy resources. This fact makes the world scientific community pay more attention to the renewable energy sources. Special attention is paid to the solar, wind and small hydropower for electrical consumers who have no possibility to connect to the central power supply lines. In the countries that have water resources the financial support is given to the development of small and micro hydropower stations. The present work presents the results of the research on the improved method of calculation of water-diverting structures of low-head hydroelectric power plant with an installed cross-jet hydro turbine that is actual for the power supply of small power consumers. The presented method can be used for the preliminary analysis of morphometric characteristics of water course as well as the basic parameters of a cross-jet hydro turbine.

1. Introduction

Small hydro power plants are renewable sources of energy, which can be effectively used for the power supply of small power consumers. [1-2]. Micro hydro power plants (MicroHPPs) are one of the first types of HPP in the history of hydraulic power engineering. They were the prototypes of big hydro power plants and often function as models of big hydro turbines. With the active development of the hydraulic power engineering, its main technical decisions started to transmit to small hydraulic power engineering. At the present in the Russian Federation (RF) and many foreign countries the hydro power plants with the capacity of less than 100 kW belong to the category of Micro HPPs [3], while the capacity of one hydraulic unit usually does not exceed 50 kW. The distinction in 100 kW between small and micro hydro power plants is conditional.

In respect to the different natural conditions, it is possible to specify two types of micro HPPs which can realise the potential and kinetic energy of a water course [4]. The examples of the first type are MicroHPPs with classical equipment, river power plants, diversion power plants, hose power plants (a variation of diversion power plants). Micro HPPs of the second type are installed directly in a water course. The examples of these HPPs are the garland HPPs constructed by Blinov B.S. and others, the triplex vertical HPP by Novikov Y.M., rod plane parallel as well as plane lifting by Loginov. M.I. and
Novikov Y.M., membrane, rotary type and capsule hydraulic units which are used abroad. The science is developing and harland HPPs are pushed into the background. Today the world scientific community sees the perspectives of development of low-head MicroHPPs and is involved in the questions of designing of these systems [5-7], but the given technical solutions are more suitable for plain water flows. New technologies on the gravitational swirl of the water flow [8-10] are advanced but studied not enough. They have some disadvantages such as low efficiency of the hydro turbine in comparison with the cross-flow hydro turbine [11], the necessity to construct a forwarding basin with height difference. These circumstances put some restrictions to the usage of low-head Micro HPPs of the said construction. That is why it is necessary to pay attention to the diversion low-head Micro HPPs which are especially effective for mountainous areas. The present research shows an improved method of calculation of water-diverting constructions of a low-head MicroHPPs, which helps to define the morphometrical characteristics of the water course and also the basic parameters of the cross jet hydro turbine.

2. Method of calculation of water-diverting constructions of a low-head micro HPP

For the effective usage of the water course energy the diversion water lines must provide that the necessary amounts of water pass through with the less possible losses for the operation of the MicroHPP. Diversion water lines can be constructed using open-flow or pressure derivation. The water lines made with open-flow concrete flumes and pressure steel pipes are highly effective. Open-flow flumes (figure 1) are placed depending on the local topography: whether aground whether on the support structures.

![Figure 1. Derivation MicroHPP: 1 – open-flow part of the water line (flume); 2 – support structure of the waterline; 3 – connecting union; 4 – the part of the waterline under pressure; 5 – hydro turbine of the Micro HPP.](image)

Such constructions don’t amount to much earthwork which is difficult to perform in a rocky mountainous area. The water lines are made beforehand on a production line basis. The part of the water line under pressure (usually steel pipeline) is installed directly at the descents in front of the MicroHPP, it serves to create the necessary pressure at the hydro turbine. These parts have a relatively small length.

At the construction of the open-flow part the choice of the inclination for the bottom of the line is crucially important as the speed of the water flow depends on it. At small speed of the water flow the water line can silt up or be filled with mud, and in wintertime slush ice and ice sheets can form and jams can occur.

As a rule, silting, slush ice and ice sheets don’t occur at the speed of water as:

$$v_{0y} \geq \left| t^{0.06} \right| \text{ (m/s)},$$

where \( t \) is the calculated minimum ambient air temperature, °C.

On the other hand, at the high speed of the water there are significant head losses and, as a result, the loss of power of the MicroHPP. That is why the speed of the watercourse should be from 1.0 to 1.5
m/s.

The required hydraulic slope of the free-flowing part, m/m, can be calculated by the following formula:

\[ i = \frac{\theta_{sy}^2}{C^2 \times r}, \]  \hspace{1cm} (2)

where \( r \) is a hydraulic radius of the cross section of the free-flowing channel, m; \( C \) is a Chezy's velocity factor.

The hydraulic radius of the cross section of the free-flowing channel, \( m \), can be calculated by the formula:

\[ r = \frac{S_{sy}}{\chi}, \]  \hspace{1cm} (3)

where \( S_{sy} \) is the cross-sectional area of the flow of the free-flowing part, m²; \( \chi \) – wetted perimeter, m.

The cross-sectional area, m², of the flow of the free-flowing part can be calculated by the formula:

\[ S_{sy} = \frac{Q_{cp}}{\theta_{sy}}, \]  \hspace{1cm} (4)

where \( Q_{cp} \) – average annual water flow rate, m³/s.

The length of the wetted surface side (figure 2), m, is calculated by the formula:

\[ a = \sqrt{S_{sy}}. \]  \hspace{1cm} (5)

![Figure 2. Sectional view of the free-flowing part of the water line.](image)

The wetted perimeter, m, is calculated by the formula:

\[ \chi = 3 \times a, \]  \hspace{1cm} (6)

In all the calculations of deviation channels of MicroHPPs, the Chezy's velocity factor is calculated according to the formula of N.N.Pavlovskiy:

\[ C = \frac{1}{m} \times r^{1/6}, \]  \hspace{1cm} (7)

where \( m \) is the roughness factor of concrete flumes.

Head loss, m, at the free-flow part of the water line is calculated by the formula:

\[ \Delta h = i \times l, \]  \hspace{1cm} (8)

\( l \) – the length of the free-flow part, m.

Then at the entrance to the pressure part the water head, m, is:

\[ H = h_i - \Delta h, \]  \hspace{1cm} (9)

where \( h_i \) is the initial velocity head, m.
The inner diameter of the pressure pipe line, \( d_{\text{in}} \), is calculated by the formula:

\[
d_{\text{in}} = \sqrt{\frac{4 \times S_{\text{dy}}}{\pi}},
\]

where \( \pi \) is a mathematical constant.

The average velocity, \( m/s \), of flow in the pressure pipeline is calculated by the formula:

\[
\vartheta_{\text{hy}} = \frac{4 \times Q_{\text{cp}}}{\pi \times d_{\text{in}}^2}.
\]

The length of the pressure part, \( m \), is calculated by the formula:

\[
L = \frac{H}{\cos \alpha},
\]

where \( \alpha \) is the angle of the slope of the pressure tunnel in degrees.

The losses of the heads at the pressure area of the tunnel are calculated by the Darcy-Weisbach formula:

\[
\Delta H = \lambda \times \frac{L}{d_{\text{in}}} \times \frac{\vartheta_{\text{hy}}^2}{2 \times g},
\]

where \( \lambda \) – is a resistance factor of the circular pipe;

\( g \) – gravity acceleration, \( m/s^2 \).

The resistance factor of the circular pipe can be calculated by the formula:

\[
\lambda = 8 \times g \times \left( \frac{4}{d_{\text{in}}} \right)^3 \times \sqrt{f},
\]

where \( f \) is the roughness factor of the iron pipeline.

Then at the entrance to the cross-jet hydro turbine the head of the water, \( m \), will be:

\[
H_r = H - \Delta H.
\]

The outer diameter of the rotor of the cross jet hydro turbine, \( m \), can be calculated by the formula:

\[
d = \sqrt[3]{\frac{Q_{\text{cp}}}{\pi H_r}}
\]

The width of the rotor, \( m \), is calculated by the formula:

\[
b = \frac{Q_{\text{cp}}}{0.42 \times d \times \sqrt{H_r}}.
\]

Let’s calculate the width, \( m \), of the guide blade of the cross-jet hydro turbine:

\[
c = 0.8 \times b.
\]

Let’s calculate the height, \( m \), of the guide blade of the cross-jet hydro turbine:

\[
x = \frac{Q_{\text{cp}}}{0.98 \times c \times \sqrt{2 \times g \times H_r}}.
\]

Shaft speed of the rotor, rot/min, of the cross-jet hydro turbine is calculated by the formula:

\[
n = \frac{30 \times \sqrt{2 \times g \times H_r}}{\pi \times d}.
\]
The shaft energy, kW, of the cross-jet hydro turbine is calculated by the formula:

\[ N = 9.81 \times Q \times H \times \eta, \]

where \( \eta \) is the efficiency coefficient of the cross-jet hydro turbine, \%. Shaft torque, N-m, of the cross-jet hydro turbine is calculated by the formula:

\[ M = \frac{9550 \times N}{n}. \]

3. Results

The present improved method of calculation of water-diverting structures of low head micro hydroelectric power plant was developed with the usage of such computer programs as Matlab Simulink and Microsoft Excel. The length of the free-flow part is 30 metres, the angle of the slope of the pressure tunnel is 60 degrees are used as the input data. After entering the data, the dimensions of the free-flow and pressure area of diversion, head of water at the entrance to the cross-jet hydro turbine, main parameters of the rotor of the hydro turbine, capacity, rate of rotation and the shaft torque of the cross-jet hydro turbine were calculated. Figure 3 demonstrates the dependence of the cross-jet hydro turbine capacity on the water flow at different parameters of the initial velocity head. Figure 4 demonstrates the changes of the rotation of the hydro turbine which depend on the water flow at different parameters of the initial velocity head. As it can be seen from the obtained results the capacity of the hydro turbine is directly proportional to the initial velocity head, the effective usage starts at 2.5–3.0 metres of the initial velocity head. Due to the peculiarities of the construction of the cross-jet hydro turbine the rate of rotation of the rotor remains at the fixed level at different water flows, this fact gives a number of advantages at the year-round usage of MicroHPPs.

![Figure 3](image-url)  
**Figure 3.** Dependence of the cross-jet hydro turbine power on the water flow at different parameters of the initial velocity head: 1 – 1 m, 2 – 3 m, 3 – 6 m, 4 – 9 m, 5 – 11 m.
Figure 4. Changes of the rotation of the hydro turbine which depend on the water flow at different parameters of the initial velocity head: 1 – 1 m, 2 – 3 m, 3 – 6 m, 4 – 9 m, 5 – 11 m.

4. Conclusion
Hydro energetical potential for the usage of the MicroHPPs in the RF is not studied good enough. However, the researches that have been carried out in the scientific and technical literature showed that technical capabilities of the energetical usage of the slopes of numerous small rivers (lowland rivers at to 1.7, and mountainous rivers up to 2 thousand kW) can be used by Micro HPPs. The absence of some methodological information at the present time does not allow to give any recommendations to the application of these or that technological decisions at the construction of the Micro HPPs. The present work presents the results of the research on the improved method of calculation of water-diverting structures of low-head hydroelectric power plant with an installed cross-jet hydro turbine that is actual for the power supply of small power consumers. The presented method can be used for the preliminary analysis of morphometric characteristics of water course as well as the basic parameters of a cross-jet hydro turbine.

The necessity in MicroHPP is great and the conditions of its usage vary a lot – from the objects situated at high altitudes in the mountainous region of ex-Soviet Central Asia to small lowlands river lines in the severe conditions of Yakutia.

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