The development of the design of an experimental model of a water-turning micro hydroelectric power station

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Abstract. The article discusses the advantages of small hydropower as an alternative energy source that meets modern environmental requirements. The design of high-efficiency micro hydroelectric power station, intended exclusively for slow-moving rivers as an independent source of electric power is proposed. The devices and equipment necessary for the functioning of micro hydroelectric power station are described. Mathematical model is developed, which links speed parameters of water flow with geometrical parameters of turbine. Technical and operational characteristics of MHPS were investigated. To solve the problems, methods of mathematical statistics, functional analysis, linear algebra were used. Simulation and computational experiment were performed using MS Excel and MathCad math packages.

1. Introduction
At present, the environmental situation is increasing the attention of the international community. Integration of economic and environmental approaches is a priority task under consideration by the World Commission on Environment and Development. (WCED). Greening the economy is possible by increasing energy efficiency. The most promising area of alternative energy sources is hydroenergy.

In the last decade, the field of small hydropower has been actively developed, the use of which allows to minimize environmental damage caused by large hydroelectric power plants by changing the physical and chemical characteristics of water, reducing the flow rate, disrupting the functioning of ecosystems, accumulating harmful substances at the bottom of water bodies, etc. One third of electricity based on alternative energy (about 3 billion kWh) in Russia is generated at small hydropower plants. Small hydropower is particularly important for remote, hard-to-reach and isolated energy-deficient areas, as well as for local energy supply to small towns [1,2]. It is urgent to develop a MHPS design that ensures efficient use of water energy of small rivers, ducts, full-water streams for power generation.

2. The experimental model of MHPS
Water-turning MHPS refers to renewable energy sources, namely to water energy of small rivers, ducts, full-water streams [3]. The proposed MHPS is intended for electric power generation for consumers of various nature.

MHPS design includes:

- slow-moving multi-tier magneto-electric generator (SMMG),
- hydraulic turbines,
• water-turning concrete pipe,
• entrance rectangular opening,
• concave bottom of water-turning concrete pipe,
• output opening,
• output pipe,
• diffuser,
• square straight part of rectangular confuser,
• drain concrete tray,
• water latches.

To protect the MHPS structure from large floating objects, a grid with large cells is installed at the entrance to the rectangular confuser.

The water-turning MHPS operates as follows. Water flow at the rate of not less than 0.5 m/s is supplied to rectangular confuser, which increases water flow rate by not less than 2.5 times, and then water flow through water gate valve and rectangular inlet hole is supplied to water-turning concrete pipe. Water flow, which at increased speed enters concrete water-turning pipe, is twisted and organizes vortex movement of water. Vectors of jets of water flow entering the water-turning pipe and twisted water flow will interact with each other at about angles in the range of 60° - 80°, which leads to braking of water flow entering the concrete water-turning pipe. This disadvantage is eliminated by introducing a curved guide into the MHPS structure, which guides the vector of the twisted water flow to the vector of the incoming flow at an angle equal to 10° - 15°, which does not prevent the incoming water flow into the water-turning concrete pipe and simultaneously increases the flow rate of the water in its water-turning movement. Concave bottom provides stability of water funnel of water vortex flow. The flow area of the outlet pipe should be equal to the area of the outlet hole, wherein the outlet hole and the outlet pipe with the diffuser are located tangentially at the bottom of the water-turning concrete pipe, which contributes to an additional increase in the flow rate of water in the whirlpool.

Water flow movement of water, acting on blades of hydrodynamic profile, drives shaft of hydraulic turbine and further through flange this movement is transmitted to flange of shaft of slow-moving magneto-electric generator.

![Figure 1. Layout diagram of the water-turning MHPS design.](image)

Water gate valves installed respectively on rectangular outlet hole of rectangular confuser and at inlet to drain concrete tray serve to control water flow in compliance with seasonal fluctuations of its level. Electric power generated by magneto-electric generator is supplied through charge-discharge controller to battery, where it accumulates [4]. For consumer use, the electric power stored in the battery is fed through the inverter to the public electric network.
3. Mathematical method linking speed parameters of water flow with geometrical parameters of turbine

In the design of water-turning MHPS concentrator (confuser) is used to increase the rate of incoming water flow [5]. Water flow rate $\mu$ passing through the confuser section at equal inlet and outlet pressures is equal to zero, and at pressure increase $\Delta p$ at the inlet water flow rate increases, but to a certain limit, which can be observed on the figure 2. [3]. The effect of the degree of narrowing $n$ of the confuser on the flow rate of water $\mu$ passing through it at constant pressure difference $\Delta p$ reaching a certain value before and behind it ($\Delta p$ - const) is shown in the graph figure 2.

The effect of the degree of narrowing $n$ of the confuser on the flow rate of water $\mu$ passing through it at constant pressure difference $\Delta p$ reaching a certain value before and behind it ($\Delta p$ - const) is shown in the graph figure 3.

$$n = \frac{S_1}{S_2}$$

where $S_1$ – is the area on an entrance, $S_2$ – is the area at the exit.

As can be seen from the graph, at a certain pressure, a certain degree of narrowing of the confuser causes the water flow rate to begin to fall through the confuser. Consequently, it becomes not effective for the confuser to do too much narrowing.

![Figure 2](image1.png)

**Figure 2.** Dependence of water flow on pressure change [3].

![Figure 3](image2.png)

**Figure 3.** Dependence of water flow on pressure change [3].

The confuser has a square cross-section, its input area $S_1$ is $1\times1 = 1$ m$^2$, the output area of $S_2$ is $0.6\times0.6 = 0.36$ m$^2$. The area ratio (degree of confuser narrowing) is 2.5, which is acceptable for conditions of installation of water-turning MHPS on slowly flowing rivers of the midland of Russia. Since the degree of narrowing $n$ is 2.5, an accelerated multiple of the degree of narrowing $n$ of the flow of water will be directed to the water flow tube. At an average flow rate of water entering the confuser of 1 m/s in the water flow tube, the incoming water flow will have a flow rate of about 2.5 m/s, taking into account the efficiency of the confuser of 70%. If the flow rate entering the confuser is $0.5-0.8$ m/s, the flow rate entering the water flow tube will be $1.25-2$ m/s.

The mode of water flow in the confuser and in the water flow pipe is different. Prior to entering the water-turning concrete pipe, the flow of water has a laminar flow pattern after flow pipe, the flow of water becomes turbulent. And it is possible to more accurately characterize the movement of water in the water flow tube by calling it vortex (or whirlpool). In the pipe, the water moves radially, so that the tangential velocity, approaching the axis of rotation, increases to a maximum and then falls to zero at the axis itself. Two flow zones can be distinguished - central and peripheral. In the central part, the axial flow velocity $v$ is significantly higher than the radial velocity $w$. Therefore, the ratio $v1/w1$ can be a characteristic of the degree of flow twist in the central part. The more turns the flow will make when advancing along the jet by one its diameter, the more it is twisted. The value of $Sv = v/w$ is called the flow twist degree in the central part.
In the peripheral region \((r > R)\), the axial velocity component varies in both radius and height of the chamber, therefore it cannot serve as a flow characteristic. A characteristic motion in the peripheral region is a spiral motion in a plane perpendicular to the axis of the chamber.

The whirlwind movement of the fluid was considered by G.L.F. Helmholtz, M.A. Lavrentiev, T. Carman, and others. There are three groups of models describing vortex motion: integral, theoretical with tangential velocity that depends on radius, and models with tangential velocity that depends on both radius and axial coordinate \([2]\).

In this research, it is useful to consider equations of motion and inseparability within a model with a tangential velocity dependent on both radius and axial coordinate. In this case, the equation of motion is the Navier-Stokes equation. If mass forces are neglected, the system is obtained:

\[
\begin{align*}
\frac{u}{r} \frac{\partial u}{\partial r} + \frac{v^2}{r} + w \frac{\partial u}{\partial z} &= -\frac{1}{\rho} \frac{\partial p}{\partial r} + \nu \left[ \frac{1}{r^2} \frac{\partial}{\partial r} \left( r \frac{\partial u}{\partial r} \right) \right] + \frac{\partial^2 u}{\partial z^2}; \\
\frac{\partial v}{\partial r} \frac{r}{r} + uv + w \frac{\partial v}{\partial z} &= \nu \left[ \frac{1}{r^2} \frac{\partial}{\partial r} \left( r \frac{\partial v}{\partial r} \right) \right] + \frac{\partial^2 v}{\partial z^2}; \\
\frac{u}{r} \frac{\partial w}{\partial r} + v \frac{\partial w}{\partial z} &= -\frac{1}{\rho} \frac{\partial p}{\partial z} + \nu \left( \frac{\partial^2 w}{\partial r^2} + \frac{1}{r^2} \frac{\partial}{\partial r} \left( r \frac{\partial w}{\partial r} \right) + \frac{\partial^2 w}{\partial z^2} \right); \\
\frac{1}{r} \frac{\partial (ru)}{\partial r} + \frac{\partial w}{\partial z} &= 0.
\end{align*}
\]

It is necessary to present the equation of turbine rotor movement used in water-turning MHPS:

\[
I_\Sigma \frac{d\omega}{dt} = M_d - M_c \quad (3)
\]

where \(I_\Sigma\) - is a reduced to turbine shaft total moment of inertia of rotating masses; \(M_d\) - is a driving moment, \(M_c\) - is a torque of resistance to shaft movement, \(\omega\) - is a rotation frequency.

A driving moment \(M_d\) it is possible to present:

\[
M_d = \frac{Q \Delta \rho \eta}{\omega} \quad (4)
\]

where \(Q\) – is a water flow rate through the turbine; \(\Delta \rho\) - is a pressure drop at turbine, \(\eta\) - is a turbine efficiency.

Taking into account the presence in the installation of a confuser increasing the speed of the water flow affecting the turbine, it is possible to estimate the power of the proposed MHPS. To do this, you need to know the following indicators for the expected site of the station:

- average bias of the river \(\Delta H\) (m/km);
- average water consumption during the summer period, \(Q\) (m\(^3\)/s);
- average current velocity during the summer period, \(V\) (m/s);
- number of hours per year with open channel, \(H\).

The power of the whole plant at the difference of water levels at the beginning and end of the section of the river \(H\) (m) at the length of the section \(L\) (m) and the average water flow rate \(Q\) (m\(^3\)/s) will be (W):

\[
P = \eta \rho g Q H \quad (5)
\]

where \(\eta\) – is the efficiency factor of hydroelectric unit, \(\rho\) – is the water density (1000), kg/m\(^3\), \(g\) – is the acceleration of gravity (9,81), m/s\(^2\).

4. The research of technical and operational characteristics of water-turning MHPS

In order to evaluate technical and operational characteristics of the water-turning MHPS, it is necessary to carry out a research using test equipment of similar characteristics of the main elements of its structure.
– low-speed magnetoelectric generator and turbine based on conical screw rotor. For research, inverter, accumulators, charge-discharge controller, multimeter are required.

The methodic for investigation of technical and operational characteristics of slow-moving magnetoelectric generator and MHPS turbine on the basis of conical screw rotor is divided into two parts – the development of test bench for slow-moving generator check and the turbine analysis by similarity method.

An experimental sample of a turbine based on a cone-screw rotor is made in a reduced version on a 3D printer - on a scale of 1:5 compared to the original turbine of water-turning MHPS is shown in figure 4.

The methodic for carrying out the research of technical and operational characteristics of a turbine on the basis of a conical screw rotor consists in sequential measurement (determination) of a number of parameters by means of instrumentation. In order to determine the quality of the hydraulic unit, the energy properties are first evaluated and studies are carried out on the basis of them. The purpose of energy research is to determine the performance characteristics of a water-turning micro MHPS with a turbine based on a conical screw rotor. The study of the turbine characteristics will be carried out in an air environment followed by the application of similarity factors. At first it is necessary to consider the effect of wind force on the turbine surface. The wind flow will have a cross section equal to \( f \). The kinetic energy of this flow can be represented by the expression:

\[
\frac{mV^2}{2}
\]

Through the above cross section of wind flow \( f \) flows at speed \( V \) a certain mass of air:

\[
m = \rho \cdot f \cdot V
\]

Thus,

\[
\frac{mV^2}{2} = \frac{\rho \cdot f \cdot V^3}{2}
\]

Let us assume that the surface \( f \) is set perpendicular to the wind flow direction. This surface will inhibit the airflow, which in turn will flow around and produce pressure by force \( P \). Under this force, the surface moves in the direction of the airflow at some speed \( U \). You can define the work as the product of surface velocity and force \( P \):

\[
T = P \cdot U
\]

Figure 4. Turbine experimental sample.

The pressure force of the airflow on the surface is the resistance force of the surface to the airflow:

\[
P = C \cdot \frac{F}{2} \cdot (V - U)^2
\]
Note here that \( C \) is aerodynamic drag factor, \( f \) is a projection of the area of the body on a plane perpendicular to the direction of airflow, i.e. the surface of the midsection of the body.

Then

\[
T = C \cdot f \cdot \frac{\rho}{2} \cdot (V - U)^2 \cdot U
\]

(11)

If we present the ratio of the work developed by the surface moving in the direction of the air flow to the energy of the air flow, the cross-section of which is equal to this surface, we obtain the wind energy utilization factor:

\[
\xi = \frac{C \cdot f \cdot \frac{\rho}{2} \cdot (V - U)^2 \cdot U}{f \cdot \frac{\rho V^3}{2}} = C \cdot (V - U)^2 \cdot \frac{U}{V^3}
\]

(12)

Convert this expression

\[
\xi = C \cdot \left(1 - \frac{U}{V}\right)^2 \cdot \frac{U}{V}
\]

(13)

The wind energy utilization factor depends on the speed of movement of the surface in the direction of the airflow.

Maximum wind energy utilization can be obtained at surface speed:

\[
U = \frac{1}{3} \cdot V
\]

(14)

If a hydrodynamic flow resistance coefficient is used in the calculation of the wind energy utilization coefficient instead of the aerodynamic air drag coefficient, a water flow energy utilization coefficient can be obtained.

Aerodynamic coefficient of wind air resistance is similar to hydrodynamic coefficient of resistance at flow and is calculated by formula:

\[
C = \frac{2F}{\rho V^2 f}
\]

(15)

where \( F \) – Experimentally produced force, N.

A 21 air test of the water-flow MHPS turbine was conducted. At the same time, studies were carried out at typical wind speeds for the middle band of Russia - from 2.5 m/s to 4.5 m/s. Experimentally obtained technical characteristics of turbine depending on wind speed are presented in Table 1.

Aerodynamic drag factor can be calculated using calculated average wind speed and turbine force values. The projection of the turbine area on a plane perpendicular to the direction of the air flow will take 0.225 m\(^2\), as the experimental turbine sample has a height and a diameter of 15 cm.

\[
C = \frac{2F}{\rho V^2 f} = \frac{2 \cdot 8,063,728,411}{1,225 \cdot 3.55^2 \cdot 0.225} = 4,642,913,311
\]

(16)

The obtained wind drag aerodynamic coefficient makes it possible to calculate the wind energy utilization coefficient, the maximum value of which is:

\[
\xi = C \cdot \left(1 - \frac{U}{V}\right)^2 \cdot \frac{U}{V} = 4,642,913,311 \cdot \left(1 - \frac{1}{3} \cdot \frac{3.55}{3.55}\right)^2 \cdot \frac{1}{3} \cdot \frac{3.55}{3.55} = 0.688
\]

(17)

The calculated wind energy utilization factor is similar to the theoretical water flow energy utilization factor [6]. Taking into account the fact that aerodynamic coefficient of wind drag is equal to hydrodynamic coefficient of resistance during flow, it can be concluded that experimentally obtained values of turbine action force will be equal to turbine action force of water-turning MHPS in water medium [7,8].
Table 1. Experimentally obtained technical characteristics of turbine depending on wind speed.

| Tests numbers | Wind speed, m/s | Experimentally received force $F$, N |
|---------------|----------------|-------------------------------------|
| 1             | 2.5            | 3.994581445                         |
| 2             | 2.6            | 4.320539291                         |
| 3             | 2.7            | 4.659279798                         |
| 4             | 2.8            | 5.010802965                         |
| 5             | 2.9            | 5.375108793                         |
| 6             | 3              | 5.752197281                         |
| 7             | 3.1            | 6.14206843                          |
| 8             | 3.2            | 6.54472224                          |
| 9             | 3.3            | 6.96015871                          |
| 10            | 3.4            | 7.388377841                         |
| 11            | 3.5            | 7.829379633                         |
| 12            | 3.6            | 8.283164085                         |
| 13            | 3.7            | 8.749731198                         |
| 14            | 3.8            | 9.229080971                         |
| 15            | 3.9            | 9.721213405                         |
| 16            | 4              | 10.2261285                          |
| 17            | 4.1            | 10.74382626                         |
| 18            | 4.2            | 11.27430667                         |
| 19            | 4.3            | 11.81756975                         |
| 20            | 4.4            | 12.37361549                         |
| 21            | 4.5            | 12.94244388                         |
| Average value | 3.55           | 8.063728411                         |

The low-speed magneto-electric generator shall generate electric power at low rotor rpm within 30 rpm. up to 200 rpm. In order to increase efficiency of slow-moving generator at small dimensions, it is necessary to use trapezoidal spiral-shaped coil made by etching of printed circuit boards and double-sided arrangement of magnets, due to which generator power is increased and minimum moment of stragging is provided (figure 4).

![Diagram of trapezoidal flat coils](image)

**Figure 5.** Diagram of trapezoidal flat coils.

Application of this technical solution allows to increase generator efficiency by 10-15%.
5. Conclusion
As a result of the studies carried out, a highly efficient design of water-turning MHPS was developed, intended exclusively for slow-moving rivers as an autonomous source of electricity. The theoretical studies carried out on the basis of the developed mathematical model allowed to determine the performance characteristics taking into account the relationship between the river flow speed and the main structural parameters of the MHPS. Experimental samples of the main structural elements of the water-turning micro-HPP were produced, which allowed to carry out research of technical and operational characteristics of the proposed structure, using a test bench for generator testing and turbine testing in air. Turbine design on the basis of conical screw rotor allowed to increase water energy utilization coefficient and efficiency of MHPS due to special surface of blades.

The developed design of MHPS is best suited for operation in the middle strip of Russia, using the energy of small rivers, ducts, full-water streams. The low-speed generator provided in the structure will allow to generate electricity for the needs of local objects - country areas, street lighting, objects of the agro-industrial complex, etc.

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