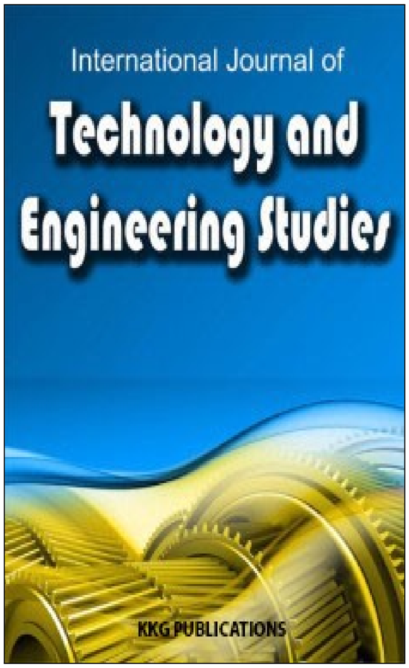

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Published online: 18 June 2016

To cite this article: A. A. Yerzhan and M. B. Koshumbaev, "New design of low-head hydro turbine for small-scale hydropower plant," *International Journal of Technology and Engineering Studies,* vol. 2, no. 3, pp. 87-94, 2016.
DOI: https://dx.doi.org/10.20469/ijtes.2.40005-3

To link to this article: http://kkgpublications.com/wp-content/uploads/2016/2/Volume2/IJTES-40005-3.pdf

International Journal of Technology and Engineering Studies
vol, 2, no. 3, pp. 87-94, 2016
IJTES

NEW DESIGN OF LOW-HEAD HYDRO TURBINE FOR SMALL-SCALE HYDROPOWER PLANT

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Keywords:
Hydro Turbine
Turbulence
Turbulent Flow
Blades

Received: 01 November 2015
Accepted: 22 February 2016
Published: 18 June 2016

Abstract. In this research, the method for calculating vortex flow in a hydro turbine applying theory of turbulent jets, which enables the assessment and analysis of the flow parameters, has been developed. It is theoretical and experimental research that has allowed creating a new hydro turbine design and drawing up the innovation patent application. It has been established that the use of the vortex effect in a hydraulic unit extends the design option and increases the reliability of its operation. This can be achieved when a turbine is made of a cylindrical tube with plates inside it to streamline. Furthermore, the proposed turbine will reform the evaluation and working of the turbine; since the blades have become shorter, it is possible to reduce the length of the turbine that reduces its cost and total weight.

INTRODUCTION

Small-scale hydropower is particularly important for emerging economies, first of all by ensuring the principle of decentralization. Generated electric power is usually transmitted through a low-voltage distribution network to a relatively small number of consumers residing close to the hydropower plant.

Hydropower generation potential of Kazakhstan is estimated at about 170 TW (million MW) per year; at present only 8.7 TW per year, i.e. less than 5% has been generated. This is due to the construction of large hydropower plants on the river Irtysh and Ili River and lack of technical capacity required to connect small-scale and mini hydropower plants to the utility line. Currently, small-scale cascade type hydropower plant construction projects are being developed. In this case, small-scale hydropower plants with the capacity of at least 10 MW are of great importance.

Small-scale hydropower plants can be built on the main channels and pipelines, as well as on the Mountain Rivers at lower costs. In such a case, the construction costs is minimal, since all equipment is a factory fabricated one, and is installed on the selected site with no impact on the environment or on the parameters of water-delivery and water-supply facilities.

The results of literature review and patent search have showed the following existing equipment as turbines of dammed Hydropower Plants (HPP), which convert the energy of water flow into electricity. These turbines have a guide vane and a runner or several runners with blades that are struck by water flow, transmitting their power. Discharged water flows into the reservoir downstream of the dam, while it is moving at a certain speed, still possessing kinetic energy [1].

The closest analogue to the proposed machine is a hydro turbine comprising a casing with a nozzle, a few turbine stages with runners and PTO gearbox [2].

But even this hydro turbine does not allow conversion of kinetic energy of a flowing stream with a high performance coefficient.

The object of the invention [3] is to increase the efficiency of flow kinetic energy conversion into kinetic energy of rotating hydro turbine runners. The specified technical result is achieved because the turbine stage downstream the nozzle is equipped with a screw, and PTO gear with the turbine runner, where all turbine stages are of axial bearing and free fitting option to provide increase in flow rate.

Water through vertical penstocks from the river or waterfall downstream of the nozzle enters the screw of hydro turbine. Due to striking of liquid energy carrier, sequentially and mechanically independently from one another sequentially all turbine stages spin, wherein the torque is removed from the gear wheel and with the increased speed is transmitted to the generator. The present invention makes possible to produce useful energy, in particular electricity, without using dams or

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with them but of minimum height.

At present the problem of environmental security does not allow worsening conditions in which people live near flood zones when constructing hydropower plants. It is because of this factor, many hydropower projects have been either frozen, or if any, have being remained at the design stage for many years. Examples are the construction of the Rogun hydropower plant (Tajikistan), the Katun hydropower station project and construction of hydropower plants on the Abakan River (Russia). To solve this problem, it is proposed to use free flow of rivers, and occupy 1-10% of a moving stream of water, which in turn will not have any impact on the surrounding flora and fauna [4].

Small-scale hydropower plants differ from each other depending on water head. High-head hydropower plants are typical for mountainous areas; and due to the fact that generating the same amount of energy needs smaller flow, they are usually cheaper than other HPP. Small-head hydropower plants are typical for plains; they do not need a penstock. Many factors influence the capital costs associated with the construction of small-scale hydropower plants. However, one of the most important is siting and its “tying up” to HPP. A proper head and flow rate of water are necessary requirements for energy production.

Most hydropower plants need a pipeline feeding water to a turbine. Exception is a screw machine with an open entry. First water must pass through the filter, which traps dirt to avoid contamination and damage of the turbine. The entry is usually located away from the main stream of water to protect the turbine from the direct pressure of water and debris during high-rate flow.

Safety requirements for construction of small-scale hydropower plants are not as high as for large-scale hydropower plants, because even a rupture of a small dam usually does not threaten human lives, and the risk is smaller, respectively, which in turn reduces the capital costs. During the construction of small-scale hydropower plants local materials are commonly used and local population is involved in the process.

The most widely used design is a micro-hydropower plant [5] developed by SEABELL INTERNATIONAL Co., Ltd. (Japan).

Review of literature and patents shows that although there are many design solutions of straight-flow turbines, the available hydro turbine in the form of a tube with attached inside curved blades has no analogues. Taking into account the suggested unique design, it is necessary to develop not only the calculation procedure, but also junction between rotating components and a fixed tube.

Main Part

Numerical analysis of characteristics of hydro turbine guide blades.

When a hydro turbine is under operation, power interaction between a liquid flow and a runner, as well as between a flow and hydro turbine blades, occurs. This interaction appears, when appropriate forces and torques take place. As many researches show, the flow in a straight-flow turbine can be represented as a turbulent vortex flow of fluid in a tube.

Magnitudes of these forces and torques are essential for turbine designs, as if they are unknown, it is impossible to rationally design their main components. In addition to the energy and cavitation parameters they characterize the quality of hydro turbines.

Force and torque values turbine mode of operation, curvature of blades dependences are called power characteristics. Power characteristics of entire turbine operating ranges indicate the magnitude of forces and torques with respect to the pivot axis acting on the blade systems. Spatial flow pattern, number of components and mutual influence of feeding components (spiral chamber, stator columns) and the lack of high-power computers during many years, up until now, have led to the opinion that to determine the amount of force, and especially torque acting on the blades surface, with sufficient accuracy for practical purposes using theoretical method is impossible. The only reliable way to determine power characteristics of a turbine was the experimental study of an object. But its implementation is very labor-intensive, expensive and long. In market conditions it should be replaced by computing method.

The current numerical method of calculating three dimensional velocity flow field in a hydro turbine, computer’s technical parameters and software allows you to abandon traditional methods of determining power characteristics and replace experimental study of an object with numerical simulation.

Another important problem associated with calculating power characteristics of a hydro turbine is to efficiently define blade curvature. The fact is that each guide surface at the same opening a0 is streamlined at different angles of attack. Figure 1 shows the design angles of attack for each of the 32 blades of hydro turbine model with D1 = 460 mm for three-dimensional model.

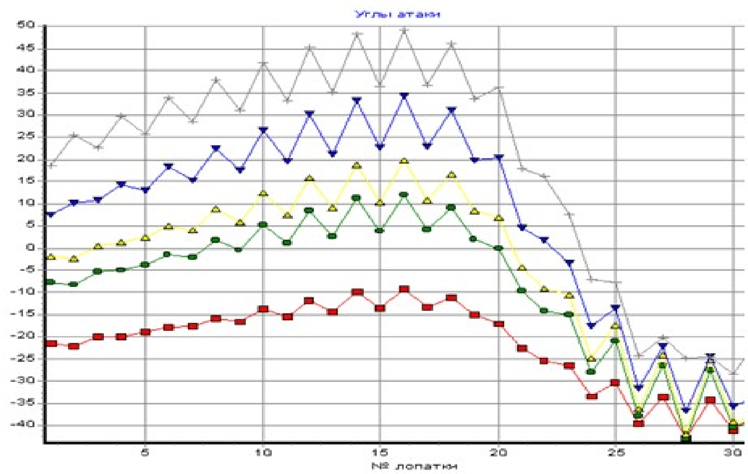

Fig. 1 . Angles of attack on blades for different a_0

Absence of axial symmetry upstream of the guide vane causes the resulting pressure force on each blade, its value and point of application, and therefore the hydraulic torque will be different. The specified streamline blade phenomenon occurs throughout the operating range of the turbine.

Figure 2 shows the results of the distribution of the design torque coefficient with respect to the blade pivot axis for studied model that agree with the experimental results within the margin of error.

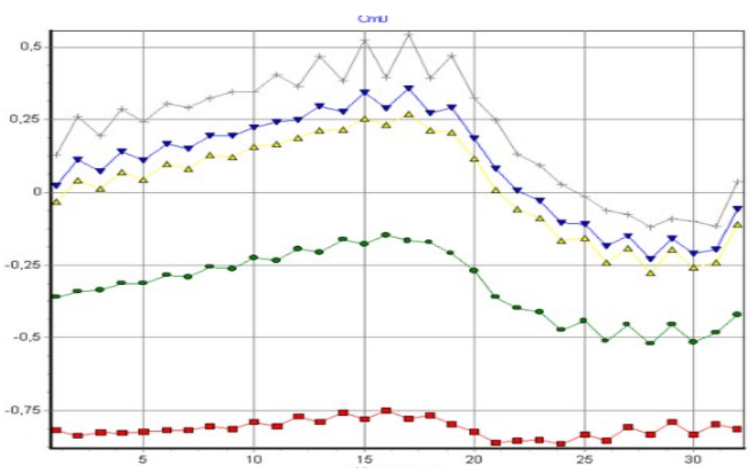

Fig. 2 . Coefficient C_{m0} on blades for different a_0

As regards distribution of power characteristics of drive elements and value of required hydraulic torque (adding frictional torque) to determine traction torque of a servomotor, their value should be constant, and the change from $a_0 = 0$ to a_{0max} should be the same.

To provide reliable operation of the turbine, values of the required torque should not exceed the value of the available traction torque. Otherwise, it is required to increase the available traction torque. If the latter due to any cause is unwanted, what is wanted is to find ways to change the torque characteristics. One of the ways to change the torque characteristic of blades is to change the profile shape, the other - to change the pivot axis or relative eccentricity n0, which characterizes the blade position relative to the pivot axis in the closed position (Figure 3).

$$n_o = \frac{L_1'}{2(L_1' + L_2')} \quad (1)$$

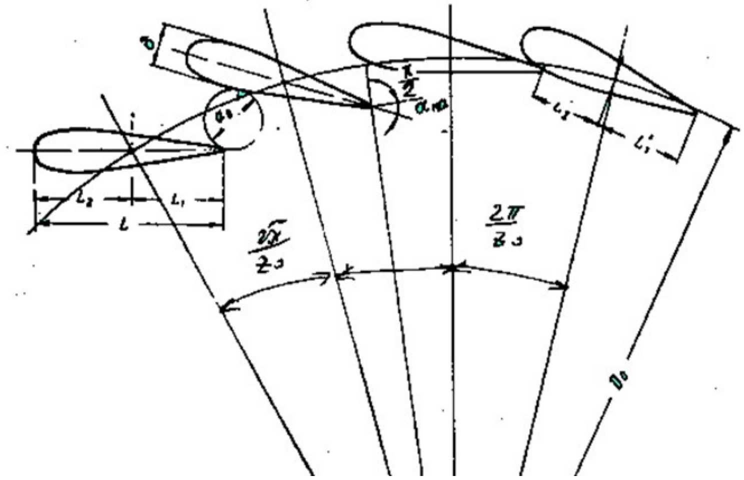

Fig. 3 . Main geometry parameters of radial guide vane xϕ, yϕ

Algorithm for calculating coordinates of the focus of blades profile

It is known [6] that the point against which the hydraulic torque does not depend on the angle of attack, is its focus. Then, if the coordinates of focus are taken as the blade pivot axis, distribution of the torque on blades will be uniform and constant within flow without separation. This result was obtained by S.A. Chaplygin and formulated in such theorem as: fluid pressure forces acting on a profile can be reduced to a lifting force applied in the focus, and to a pair, which torque value is independent of the angle of attack. Let us find the coordinates of the focus xϕ, yϕ. For this purpose let us use a well-known torque formula in mechanics:

$$M\phi = x\phi Y - y\phi X \qquad (2)$$

and torque formula with respect to the leading edge of the profile B (Figure 4)

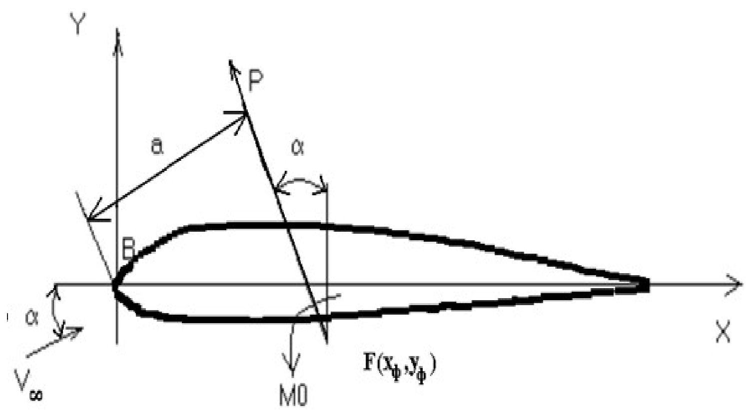

Fig. 4 . Scheme for determining the focus of the profile

$$M_B = M_o + P^*a \qquad (3)$$

In equations (2) and (3) X and Y are the projections of the lifting force P of the profile, which is directed perpendicular to the velocity of the undisturbed flow, V_∞, M_o is the moment of the profile during non-circular streamline with respect to the focus.

If the chord of the profile l coincides with the axis OX, then (3) can be written as follows:

$$P^*a = (x_\phi - x_B)P^*cos\alpha + (y_\phi - y_B)Psin\alpha \qquad (4)$$

Using the expression for the moment in the form

$$M_o = C_m\rho\frac{V_\infty}{2}l^2$$

where C_m is the dimensionless moment coefficient; ρ is the fluid density. Let us write the equation (3) taking into account (4) with respect to the coefficient C_m :

$C_m = \frac{2M_o}{\rho V_\infty l^2} + \frac{2p}{\rho V_\infty l^2}\left[(x_\phi - x_B)cos\alpha + (y_\phi - y_B)sin\alpha\right]$

Taking $\frac{2M_o}{\rho V_\infty l^2} = C_{mo}$ and introducing the dimensionless coefficients of the lifting force C_p force x- C_x and force y- C_y, we rewrite the last equation with respect to the coefficient $C_{mo} : C_{mo}, x_\phi, y_\phi, C_m, C_x, C_y$.

$$C_{m0} = C_{mB} - C_p\left[(x_\phi - x_B)\frac{C_y}{C_p} + (y_\phi - y_B)\frac{C_x}{C_p}\right] \quad (5)$$

The equation (5) has three unknowns C_m0, x_ϕ, y_ϕ. The rest of the values in the equation (5) are defined in the process of solving the problem of the profile streamline. Therefore, to determine the coordinates of the focus of the profile x_ϕ, y_ϕ, it is required to solve the direct problem three times and calculate the coefficients C_m, C_x, C_y with respect to the leading edge. As a result we get the following:

$C_{mo} = C_{m1} - C_{y1}(x_\phi - x_B) - C_{x1}(y_\phi - y_B)$

$C_{mo} = C_{m2} - C_{y2}(x_\phi - x_B) - C_{x2}(y_\phi - y_B)$

$$C_{mo} = C_{m3} - C_{y3}(x_\phi - x_B) - C_{x3}(y_\phi - y_B) \quad (6)$$

Since C_{m0} is a constant value, then (6) can be written as:

$C_{m1} - C_{y1}x_\phi + C_{y1}x_B - C_{x1}Y_B = C_{m2} - C_{y2}x_\phi - C_{y2}x_B - C_{x2}Y_\phi - C_{x2}Y_B$

or

$C_{m1} - C_{m2} = (C_{y1} - C_{y2})x_\phi - (C_{y1} - C_{y2})x_B + (C_{x1} - C_{x2})y_\phi - (C_{x1} - C_{x2})x_\phi$.

Taking into account, that in the resulting expression x_ϕ, y_ϕ are unknown, we rewrite it in respect to the unknowns:

$(C_{y1} - C_{y2})x_\phi + (C_{x1} - C_{x2})y_\phi = (C_{m1} - C_{m2}) + (C_{y1} - C_{y2})x_B + (C_{x1} - C_{x2})y_B$

We obtain the second expression in a similar way (6):

$(C_{y1} - C_{y3})x_\phi + (C_{x1} - C_{x3})y_\phi = (C_{m1} - C_{m3}) + (C_{y1} - C_{y3})x_B + (C_{x1} - C_{x3})y_B$

Denoting

$C_{y1} - C_{y2} = a_1, C_{x1} - C_{x2} = b_1, C_{y1} - C_{y3} = a_2, C_{x1} - C_{x3} = b_2$

$(C_{m1} - C_{m2}) + a_1x_B + b_1y_B = d_1, (C_{m1} - C_{m3}) + a_2x_B = b_2y_B = d_2$

to determine the coordinates of the profile focus, we have the following system of equations:

$$\begin{cases} a_1x_\phi + b_1y_\phi = d_1, \\ a_2x_\phi + b_2y_\phi = d, \end{cases}$$

from which the coordinates of the focus are equal to:

$$x_\phi = \frac{d_1b_2 - d_2b_1}{a_1b_2 - a_2b_1}, y_\phi = \frac{a_1d_2 - a_2d_1}{a_1b_2 - a_2b_1} \quad (7)$$

Using this algorithm for the studied model of the actual turbine, the coordinates of the focus x_ϕ, y_ϕ of the blades profile that are taken as the coordinates of the pivot axis for calculating the torque required to rotate the blade, located on the diameter D_0, have been determined. The obtained results shown in Figure 5 confirm the proposed way of purposeful change of power characteristics of the turbine and can be recommended for practical use.

As simulation shows it is possible to vary input data and find an option of the blade curvature that will minimally disturb the incoming streams [7]. Analysis of the calculated data shows that there is non-uniform loading on the blades. Unfortunately, the mathematical tools are not always able to describe the problem to solve with the accuracy of 3-5%. [8] To improve the quality of calculations boundary data or a specified velocity field, which is generally determined by the experiment, are required.

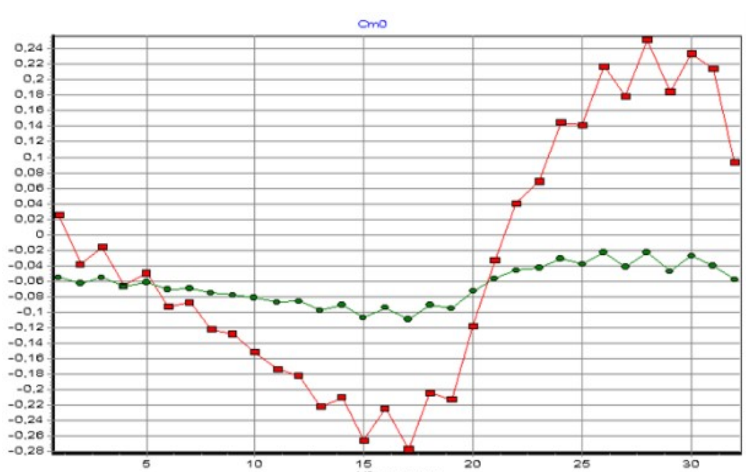

Fig. 5 . Torque coefficient $_{m0}$ on the blades at a_0=32 mm for two options of the pivot axis

The main reason for non-uniform distribution of forces and torques on the curved surfaces is the absence of axial symmetry of the upstream flow.

Using the theoretical result of S.A. Chaplygin on the flow pressure force acting on the profile and a point of its application, it is possible to purposefully change power characteristics of the turbine [9,10].

Thus, symmetrical flow and uniform distribution of loads on the turbine blades can not only improve the calculation methods, but also define the approximation lines of the blade cross section.

Approximate calculation methods give qualitative characteristics, which can be used to determine the basic parameters of the phenomenon under study. With hydro turbine of 20 cm long, the blades were 10 cm in length. Calculated profiles practically coincide with the experimental data.

To develop preliminary drawings of the design of the pilot model of a low-head hydro turbine initial parameters for drawings development have been prepared and worked out.

Simulating various size options of the hydro turbine, the following dimensions have been selected as: the turbine length is 1000 mm, inside diameter of the turbine tube is 150 mm, outside diameter of the turbine tube is 159 mm, the bearing inner diameter is 160 mm, the flange outer diameter is 170 mm, inserts used for the turbine alignment inner diameter is 150 mm and outer diameter is 169 mm, insert length is 300 mm, blade curvature is according to the design data.

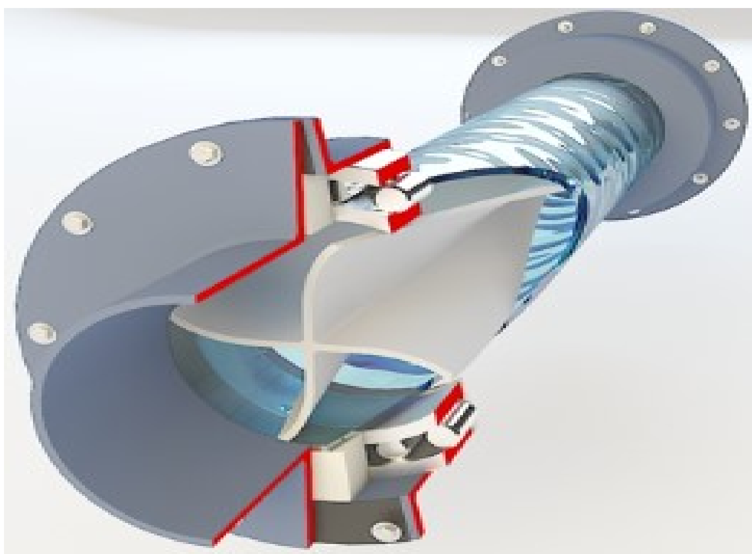

Fig. 6 . 3D picture of low-head hydro turbine

EXPERIMENTAL STUDIES AND TEST RESULTS

Experiments were carried out with experimental model of the hydro turbine. As experimental study has shown the model works in a full range of flow rate variation. It should be noted that the operational state of the experimental model is quite satisfactory that means a well done model and its assembling as part of the experimental installation.

Initial experiments have shown that there are modes in which the rotation of the hydro turbine is not accompanied by jumps in pressure and velocity.

For hydro turbine 100 cm in length speed has been measured depending on the number of blades (Table 1).

TABLE 1
HYDRO TURBINE CHARACTERISTICS DEPENDING ON THE NUMBER OF BLADES

No	Number of blades	Speed
1	4	730
2	8	580
3	12	1200

Reducing the length of the blades and increasing their number, we achieved a stable operation of the hydro turbine and increased its speed up to 1200 rpm. Inlet pressure was normalized and was defined as being zero; it means that the hydro turbine does not show any resistance to the flow.

The results obtained during the study of the hydro turbine model 100 cm long enabled to make the following conclusion: since the blades have become shorter, it is possible to reduce the length of the turbine that reduces its cost and total weight.

When calculations have been completed, drawings have been developed and hydro turbine prototype 20 cm in length has been manufactured, it was provided with the additional gland seal, which incorporated labyrinth seals for water service. The additional seal completely eliminated penetration of water on the bearings.

Laboratory prototype of the hydro turbine 20 cm in length is shown in Figure 7. The new prototype was provided with the increased number of blades up to 18 pieces. More number of blades is physically impossible to be fitted on the inside axel - cylinder. To improve the streamline the blade profile has been changed so, that the angle of stream flow from the blade surface was 50-60^{o} to the surface of the turbine tube.

Fig. 7 . Photo of the prototype of the hydro turbine 20 cm in length

Speed depending on the number of blades (Table 2) at heads 20 m, 40 m and 60 m has been measured for the hydro turbine 20 cm in length.

TABLE 2
HYDRO TURBINE PARAMETERS DEPENDING ON THE NUMBER OF BLADES

No	Number of blades	Head, m	Speed, rpm	Head, m	Speed, rpm	Head, m	Speed, rpm
1	4	20	420	40	640	60	730
2	8	20	520	40	700	60	580
3	12	20	980	40	1200	60	1340
4	18	20	1250	40	1600	60	2020

Theoretical and experimental research has allowed creating a new design of the hydro turbine and drawing up the innovation patent application.

CONCLUSION AND RECOMMENDATIONS

Based on the given equations of fluid mechanics and hydraulics, the method for calculating vortex flow in a hydro turbine applying theory of turbulent jets, which enables the assessment and analysis of the flow parameters, has been developed.

It has been established that the use of vortex effect in a hydraulic unit extends the design option and increases reliability of its operation [11]. This can be achieved when a turbine is made of a cylindrical tube with plates inside it for smooth streamline.

It has been proposed the method for simulation of a vortex flow in a hydro turbine, which differs from the existing ones by the reason that to provide efficiency of the hydro turbine operation, critical and process parameters that affect rotation of the hydro turbine and allow setting the most optimal modes, are identified.

The results obtained during the study of the hydro turbine model 100 cm long gave the opportunity to make the following conclusion: since the blades have become shorter, it is possible to reduce the length of the turbine that reduces its cost and total weight. The additional calculations have shown that the decrease in length of the hydro turbine does not change other parameters. According to the calculations drawings have been developed, and in accordance with them prototype of the hydro turbine 20 cm in length has been manufactured.

Laboratory prototype of the hydro turbine 20 cm in length enabled the increased number of blades up to 18 pieces. More number of blades is physically impossible to be fitted on the inside axel-cylinder.

Theoretical and experimental research has allowed creating a new design of the hydro turbine and drawing up the innovation patent application.

The developed design of the hydro turbine aims to participate in the international exhibition “EXPO-2017” to be held in Astana in 2017.

Declaration of Conflicting Interests

This work has no conflicts of interest.

Acknowledgments

We express our gratitude to the National Agency for Technological Development JSC and Parasat National Scientific and Technological Holding JSC; this article has been prepared as a part of the innovative grant # 376 dated 23.12.2011 and program-oriented funding # 954 dated 31.03.2014.

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— This article does not have any appendix. —