INCREASING THE EFFICIENCY OF FREE-FLOW MICRO-HYDROPOWER STATIONS

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Research paper

Abstract.

This article presents a comprehensive analytical investigation into the performance and efficiency of free flow hydro power turbines. The study delves into the intricate dynamics of water flow, turbine design, and operational parameters to evaluate the overall effectiveness of hydro power generation. The applicability of the calculation formulas is obtained as a result of the previous research and correctness of applying the upper limit of power for hydraulic turbines in open-channel-flow, similar to the Betz limit for wind turbines, is analyzed.

The limits of manifestation of the hydrodynamic effect are determined that appears in a free flow of liquid when it accelerates and the flow mode goes through the critical state and its applicability for generating energy by free-flow hydraulic turbines are determined.

The purpose of this article is to summarize, analyze and provide additional explanations to previously published materials on the interpretation of experimental data from tests of a free-flow hydraulic turbine of a special design.

Through the use of advanced analytical models and computational fluid dynamics (CFD) simulations, the authors explore the complex interactions between water flow and turbine components, shedding light on the factors influencing free flow turbine efficiency and output. The findings offer valuable insights for optimizing turbine design and operational strategies, with implications for enhancing the overall performance of hydroelectric power generation systems. This article serves as a crucial resource for researchers, engineers, and stakeholders involved in the sustainable development and management of hydroelectric power plants.

Keywords: hydraulic turbine, free-flow, depth, supercritical, Froude number, hydraulic jump

INTRODUCTION

Previously, a series of works Treshhalov (2008), Treshchalov (2012), Vidali et al (2016), Pelz (2011) Lenev (2005), Sokolov (2014) have been published that touch upon matters of hydrodynamics, specifically, hydrodynamic effects that appear during the functioning of free-flow turbines. These materials describe very specific peculiarities in the behavior of free-flowing liquids during the functioning of free-flow turbines of special design. In addition, issue No 9-2013 of the journal "Hydrotechnical construction" Treshhalov (2013) has an article describing the advantages of such turbines and some options for their use.

You may recall that calculation formulas for the total power output of a free-flow turbine - (1) and (2) - were derived analytically in the materials Treshchalov (2012), Treshhalov (2008):

$$E = \rho * L * H_1 * V_1 * [(g * H_1 * (1 - V_1 / V_2) + (V_1^2 - V_2^2) / 2]$$
(1)

$$E = \rho * L * (H_1^2 * V_1 * g + H_1 * \frac{V_1^3}{2} - \frac{3}{2} * \sqrt[3]{(H_1 * V_1)^5 * g^2})$$
(2)

In these formulas, E – the energy taken by the turbine from the flow at a unit of time, L –linear width of the turbine across flow, H_1 – effective depth of flow at the entry to the turbine, V_1 –flow speed at turbine inlet, V_2 – outlet flow speed, P – water density, g – acceleration of gravity force.

These formulas have been developed without regard to a specific turbine design, which was emphasized repeatedly in the materials Treshhalov (2008), Treshchalov (2012), Treshchalov. (2010). Therefore, it is possible to create hydro turbines of various designs on the bases of these hydrodynamic patters.

One of the variants of a free-flow hydro turbine design is shown in Figure 1 Lenev (2005). Some other options are descried in Treshchalov (2007).

Fig.1. One of the variants of the turbine design Lenev (2005)



METHODS AND MATERIAL

Calculating the performance of gravity hydraulic turbines is a critical aspect of hydropower engineering. Lipkin et al. (2007). These turbines use the kinetic energy of flowing water to produce mechanical energy, which is then converted into electrical energy using a generator. Turbine efficiency and performance depend on various factors, including turbine design, water flow characteristics, and operating conditions. In this text, we will review a method for calculating the performance of gravity turbines as reviewed by Pankaj et al (2023).

The performance of a gravity hydraulic turbine is usually described by its efficiency, which is the ratio of the actual power output to the theoretical power input. The theoretical power input can be calculated based on the water flow and the head, which is the difference in height between the water source and the turbine.

After calculating the theoretical power input, the actual power output of the turbine can be determined by measuring the electrical power produced by the generator. Turbine efficiency is then determined by the ratio of the actual power output to the theoretical power input, expressed as a percentage.

Turbine efficiency is affected by various factors, including turbine blade design, friction and turbulence losses, and mechanical losses in the generator. Improving turbine efficiency involves optimizing its design and minimizing energy losses in the system.

Apart from efficiency, other performance parameters such as specific speed, flow coefficient and cavitation index are also important to evaluate the performance of gravity hydraulic turbines. Specific speed is a dimensionless parameter that characterizes the shape and speed of the turbine, while the flow coefficient relates the flow rate to the size of the turbine. The cavitation index indicates the likelihood of cavitation occurring in the turbine, which can reduce its efficiency and lead to damage to the blades.

In conclusion, calculating the performance of free-flow hydraulic turbines involves determining the theoretical power input based on water flow and head, measuring the actual power output, and calculating the turbine efficiency.

By optimizing the design and minimizing energy losses, the efficiency and productivity of hydraulic turbines can be increased Cacciali et al. (2023) for sustainable hydroelectricity production.

DATA ANALYSIS AND MODELLING

All calculations, analysis and modelling in the previously materials are based on continuity equation (law of conservation of mass) and Bernoulli's equation (Bernoulli integral) - the law of conservation of mechanical energy for free liquid flow. Modeling methods were also applied according to Ljather et al. (1984). Let us calculate the power output of the turbine in watts according to the formula (1) (Table 1) for different rates of velocity and the effective depth of the input stream per one meter across the flow and analyze the power characteristics of turbines that use this effect.

Depth (m)	0.3	0.6	0.9	1.2	1.5	1.8
flow velocity (m/s)						
0.3	144	672	1619	2998	4820	7090
0.6	167	930	2400	4624	7629	11436
0.9	128	934	2637	5329	9064	13883
1.2	66	779	2494	5357	9460	14864
1.5	14	542	2098	4897	9068	14703
1.8	0	291	1563	4108	8102	13670

Table 1. Turbine output power (in watts), depending on the depth and speed of the input stream.

From Table 1 it can be seen that the output flow speed of the stream equals 1.8 m/s and the depth equals 0.3 m, the state of the incoming flow is critical, as can be easily seen by inserting the data into the critical depth of flow formula. As seen from the Table 1, the additional turbine output in this mode goes to zero. The table 1 also

shows that increasing the effective depth of the downstream turbine capacity increases in a non-linear manner and has an extreme point

The criteria of hydrodynamic similarity are used during modelling of hydraulic phenomena, of which the main ones are the Reynolds number and the Froude number, which should be the same for both the real object and the model.

However, as is shown in Chugaev (1982), it is impossible to achieve a complete hydrodynamic similarity between the model and the actual object because the similarity coefficients turn out to be different when both similarity criteria are implemented and the similarity conditions are incompatible with one another. Therefore, one of the criteria – the one that is less important for a specific model - is ignored during modeling. Therefore, we will ignore it in this modelling, and the Froude number will be the main one during the modelling.

In our case, the main parameters of the flows were the states of flow, namely – the subcritical flow at the entry to the device and the critical state at the exit. These parameters are strictly subordinated to the Froude number, which is precisely what determines the state of flow. The Reynolds number was not so important in all of the mathematical calculations shown in the previous articles. We will remind you that what is called the Froude number is the following expression that characterizes the state of a free-flow stream.

$$Fr = \frac{V^2}{g * H}$$

Where: H - flow modeling depth, V - flow velocity, g - acceleration of gravity If Fr = 1 the flow will be in the critical state, if Fr < 1 - it will be in a subcritical state, and if Fr > 1 - the flow will be in a supercritical state.

Let's make (Table 2) keeping the Froude number constant, we will calculate the energy generated by the turbine in accordance with formula (1) for various values of the inflowing stream's velocity and effective depth for one linear meter across the flow.

inflowing stream depth (m)	1.0	0.7	0.5	0.3
inflowing stream velocity (m/s)	1.0	0.8	0.7	0.55
Froude number for inflowing stream	0.102	0.102	0.102	0.102
critical depth (m)	0.467	0.317	0.232	0.141
critical flow velocity (m/s)	2.14	1.76	1.51	1.17
Froude number for critical flow	1	1	1	1
energy generated by turbine per second (J)	3430	1407	606	169

RESULTS

It should be noted that in low-speed water flows with the Froude number significantly less than 1 (one), the potential energy component of flow dominates and significantly exceeds its kinetic energy component, which is clearly seen in the diagram (Fig. 1). That is, the potential head (elevation head) in such flows is much greater than the velocity (dynamic) head.

The Bernoulli integral is one of the expressions of the law of conservation of energy in fluid dynamics, and, according to it, simple calculations of turbine power efficiency (capacity factor) related to the total inlet flow power show that it does not exceed 60-70% under all circumstances.

By simple substitution of values in the calculation formulas (in particular, in the Bernoulli equation), we obtain that the water flow with a depth of 1 m and a flow velocity of 1 m/s has a total power of 10.3 kW (0.5 kW - kinetic component and 9.8 kW - potential component). The maximum power output of the micro HPP turbine at such flow parameters is no more than 3.4 kW according to formulas (2) and (3) and, therefore, the turbine's power efficiency (capacity factor) is 33%. Despite this, it compares favorably with this parameter's values for traditional (hydrokinetics) free-flow turbines, which is equal to no more than 15%.

This is clearly seen in Figure 1. Conventional free-flow turbines can only obtain a fraction of kinetic energy from water flow. More precisely, in the best case considering the Betz limit, they can harness no more than 59% of this energy. Although the applicability of this limit for hydraulic turbines remains controversial to this day and discussions on this issue continue Pelz (2011), Gorban et al (2001). The Figure 1 shows that this is a barely noticeable part of $V_1^2/2g$. However, turbines of the new design can obtain power equal to **deltaE** under these conditions.

An interesting interpretation of the abovementioned formulas was derived later by another author and published Sokolov (2014) in a series of articles found in the Cornell University's electronic arXiv.

$$E = \rho^* L^* V_1^* g^* H_1^2 (1 + \frac{Fr}{2} - \frac{3}{2} \sqrt[3]{Fr})$$
(3)

In this formula, **Fr**- represents the Froude number of turbine inlet flow.

Formula 3 was derived in a way different from that presented in Treshhalov (2008) (Formula 6 in Sokolov (2014). The only difference is that some summands in Formula 2 are represented in Formula 3 using the Froude number.

It should be noted that Formulas 2 and 3 are universal for calculating the power of any type of hydroturbines with flow optimization in the downstream (at turbine outlet) - pressure or free-flow turbines and at any Froude number of the incoming flow less or greater than 1. All the formulas available in hydropower engineering for calculating the optimal output power of any hydropower turbines can ultimately be derived from them.

Specifically, there is a well-known formula for calculating the power of pressure hydraulic turbines given in any textbook on hydraulics or hydropower Shterenliht et al (1984):

$$\mathbf{N} = \mathbf{g}^* \boldsymbol{\rho}^* \mathbf{Q}^* \mathbf{H}^* \boldsymbol{\eta} \tag{4}$$

In this formula, N – is a turbine's capacity, Q – full water discharge of the turbine, H– gross head on the turbine, ρ – water density, g – acceleration of gravity, and η –the turbine's overall power efficiency.

This formula can be easily derived from Formula 3 given that the Froude number in the upstream section of pressure HPPs is very small and can be neglected. Then, the term in brackets in Formula 3 becomes equal to one and, given that the product of L*V*H in this case is the total discharge Q passing through the cross-section of the HPP, we derive Formula 4 from Formula 3.

Let's consider a more complete energy diagram constructed according to formula 1 (Fig. 2)

This diagram on Fig. 2 shows more clearly what exactly the hydrodynamic effect of power amplification looks like. It shows a pronounced power peak at a point defined by the inlet/outlet velocities of 1.0/2.14. In this condition, the turbine produces a maximum power of 3.4 kW, as mentioned above, at a total flow power of 10.3 kW. It should be noted that the total power of the velocity (dynamic) head in this case is only 500 W. An optimal mode appears at point 1.0/2.14 in terms of speed and flow depth at the exit and all the parameters of the outcoming flow are equal to the critical ones - the critical depth and speed.

Fig.2. Energy diagram of inlet and outlet flows depending on their velocities,



with inlet flow's effective depth of 1m.

If the speed at the outlet is increased or decreased, then the turbine moves out of its optimal mode and the turbine's power becomes equal to zero at boundary points. These are the turbine's idle modes.

This turbine has two idle modes – at point 1.0/3.96 and at point 1.0/1.0 (this point cannot be seen as it is beyond the diagram's peak).

At point 1.0/1.0, the turbine is in the most trivial mode, which only shows that the turbine inlet flow does not change its parameters and the energy differencebetween inlet and outlet flows is equal to zero and, therefore, the turbine works in the idle mode.

However, point 1.0/3.96 shows that the inlet flow energy and the outlet flow energy at the so-called "conjugate depths" when potential head that is missing in the output flow relative to the inlet flow is compensated by the dominating dynamic head. But, at the same time, the turbine does not take away energy from the flow; it only transfers the flow from the subcritical state to the supercritical state, while preserving the flow's full power, which is equal to the inlet flow's power.

Point 3.13/3.13 is one of the "critical" points – it is a point of division of the modes.

At this point, in addition to the critical state at both the inlet and output flows, the flow hereafter shifts to another quality, becoming more kinetic - to supercritical state. After this point, the hydrodynamic effect of power amplification cannot appear at any combination of speeds and depths – it appears only when the inlet flow is in the subcritical state (for a rectangular cross section flow, the Froude's number is less than 1).

DISCUSSION

The method of calculating the performance of free-flow hydraulic turbines is a complex and multifaceted process that involves various engineering principles and considerations. While the approach described in the previous response provides a fundamental understanding of the calculation process, it's important to acknowledge that there are additional factors and complexities that should be considered in a critical discussion.

1. Fluid Dynamics and Turbine Design: The calculation of turbine performance involves a deep understanding of fluid dynamics, including the behavior of water flow, pressure differentials, and energy conversion within the turbine. The design of the turbine blades, the shape of the turbine, and the efficiency of the hydraulic passages are critical factors that influence the overall performance. A critical discussion should delve into the intricacies of these design elements and their impact on performance calculations.

2. Losses and Efficiency: The method described focuses on the theoretical power input and actual power output to determine efficiency. However, it's important to recognize that there are inherent losses within the turbine system, including hydraulic losses, mechanical losses, and electrical losses. A critical discussion should address how these losses are accounted for and how they affect the overall efficiency of the turbine.

3. Cavitation and Turbine Performance: Cavitation, which occurs when rapid changes in pressure cause vapor bubbles to form and collapse within the turbine, can significantly impact its performance and longevity. A critical discussion should explore how cavitation is accounted for in performance calculations and how it affects the longterm operation of the turbine.

4. Real-World Variability: The method described assumes ideal conditions, but real-world scenarios often involve variability in water flow, head, and environmental factors. A critical discussion should address how these variations are accounted for in performance calculations and how they impact the reliability and predictability of turbine performance.

5. Environmental Considerations: In addition to performance calculations, a critical discussion should also consider environmental impacts such as fish passage, sediment transport, and ecological effects of damming rivers for hydroelectric projects. These considerations are essential for a comprehensive understanding of the implications of hydraulic turbine installations.

6. Advancements in Turbine Technology: With ongoing advancements in materials science, computational fluid dynamics, and turbine design, a critical discussion should also explore how these advancements are influencing the methods used to calculate and optimize the performance of free-flow hydraulic turbines.

7. It should be noted that the materials Treshhalov (2008), Treshchalov (2012), Treshhalov (2013) do not yet reflect a very interesting aspect, which is the purpose of our further research. Specifically, it is a detailed study of the role of hydraulic jump behind a turbine and energy dissipation in it. The need for such research is also highlighted in Sokolov (2014). Of particular interest is the fact that this type of hydraulic jump, which is reviewed in our materials, has not yet been studied in detail either theoretically or experimentally. Here, the matter concerns the regularities of the hydraulic jump obtained from the equation of the quantity of motion in a flow in which there is no active device like a turbine Chugaev (1982). However, a turbine changes flow conditions, and the parameters of the occurrence of such eddy rollers no longer correspond to the conditions under which the calculation formulas were obtained. In this case, using these formulas to calculate the hydraulic jump that occurs after a turbine no longer reflects a full picture of processes. Therefore, in this case, the

traditional formulas are inapplicable for its calculation and require corrections. Studies in this direction are very promising Landau et al (1986).

In summary, while the basic method for calculating free-flow hydraulic turbine performance provides a foundational understanding, a critical discussion should encompass a broader range of factors such as fluid dynamics, losses, real-world variability, environmental considerations, technological advancements, and their collective impact on performance calculations and turbine operation.

CONCLUSIONS

During these researches, unique formulas were derived that have not yet been found in any scientific sources. The importance of these formulas is demonstrated in this article.

Diagrams constructed using these formulas show the presence of effects in the flow of water, which for many decades eluded the attention of experimenters due to the difficulty of measuring them in a liquid flow. The patterns of these effects in the fluid flow have been identified and we can optimize all the parameters on which they depend.

Based on these scientific researches, it is possible to create various designs of hydraulic turbines, which, judging by calculations, will have significantly increased energy efficiency compared to existing analogues.

Note:

Formulas (1), (2) and (3), as well as the diagram in Fig. 2, are true for rectangular cross section flows, for which the Froude's number is equal to 1.

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