INCREASING THE EFFICIENCY OF FREE-FLOW MICRO-HYDROELECTRIC POWER STATIONS
(preprint)

G.V. Treshchalov

Abstract: The article provides additional explanations about the previously published materials on the use of the hydrodynamic effect that appears in a free flow of liquid when it accelerates and the flow mode goes through the critical state.

Keywords: energy, power, turbine, free-flow, flow, calm, turbulent, depth, critical, subcritical, supercritical, hydrodynamic, effect, feedback, hydraulics, Reynolds number, Froude number, criteria of hydrodynamic similarity, hydraulic jump

Abstract

Previously, a series of works [1-10] 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" [5] 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 [1-8]:

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

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

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, ρ – 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 [1-4]. 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 [10]. Some other options are descried in [17].

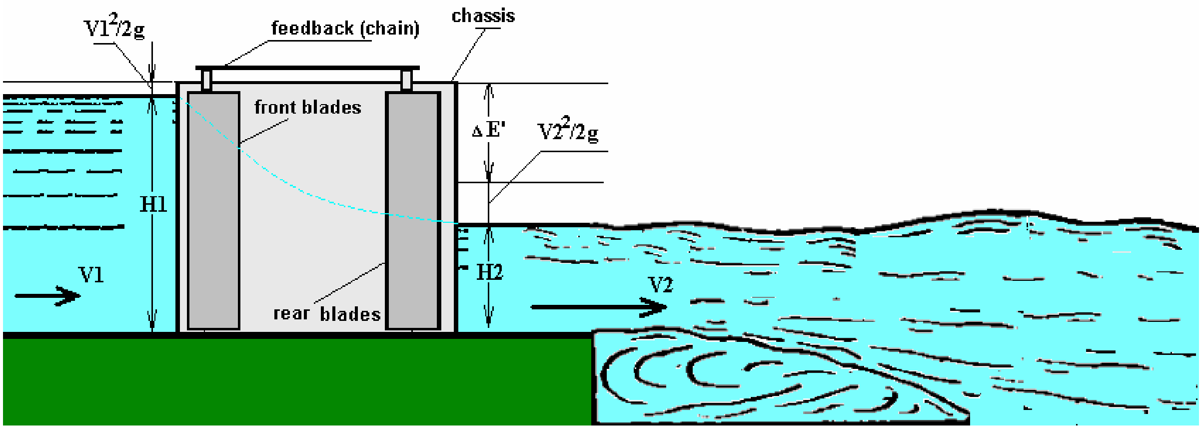

Fig.1. One of the variants of the turbine design

All the calculations in the materials [1-8] 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.
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 50% 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 free-flow turbines, which is equal to no more than 15%.
This is clearly seen in Diagram 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. The diagram shows that this is a barely noticeable part of $\mathbf{V_1^2/2g}$. 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 in a series of articles found in the Cornell University's electronic arXive [11].

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

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

Formula 3 was derived in a way different from that presented in [1-8] (Formula 6 in [11]). 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 [12,13,14]:

$$N = g * \rho * Q * H * \eta \qquad (4)$$

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.

Here is a more complete energy diagram constructed by Formula 1.

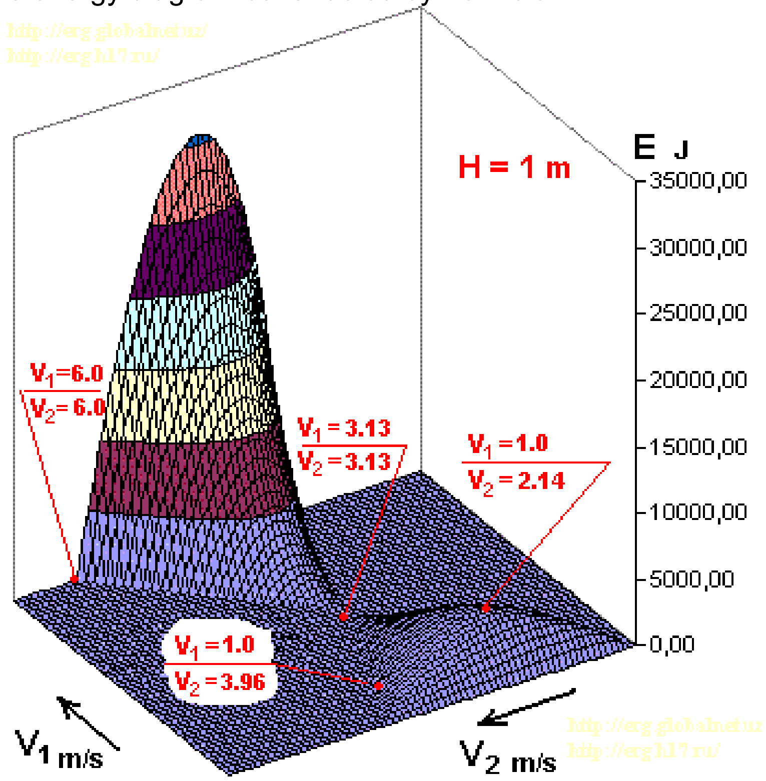

Fig.2. Energy diagram of inlet and outlet flows depending on their velocities, with inlet flow's effective depth of 1m.

This diagram 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.

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.

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 difference between 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).

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.

References

1. G.V.Treshchalov, A highly efficient method for deriving energy from a free-flow liquid on the basis of the specific hydrodynamic effect // Economics and production – **2008. – №2**. – p. 71-77. http://elibrary.ru/item.asp?id=11521752

2. G.V. Treshchalov."Analysis of the possibility for realistic modeling of the working modes of a hydraulic turbine that uses the hydrodynamic effect of power amplification" // Alternative power engineering and ecology. **2012. No 11**. pp 37-40. http://elibrary.ru/item.asp?id=18191851

3. O.Ya.Glovatskiy, Treshchalov G.V. A study of the hydrodynamic effect for extracting energy from a headless flow of liquid // Issues of energy and resource saving. Special issue. **2011**. pp 109-113.

4. G.V.Treshchalov, A.A.Mukolyants, A.A.Djumanov. Application of the specific hydraulic effect in free flow liquid for energy purposes // Proceedings of International Scientific and Practical Conference "Innovation - 2011". Tashkent. **2011** P.152-155.

5. G.V. Treshchalov. A highly efficient method of extracting energy from a headless flow of liquid on the basis of a specific hydrodynamic effect // a collection of materials from the 6th International Research-to-Practice Conference of Irkutsk State Technical University. 2009.

6. G.V. Treshchalov. Application of free-flow hydraulic turbines and possibilities for increasing their energy efficiency // Hydrotechnical construction. **2013, No 9**. pp 36 - 39. http://elibrary.ru/item.asp?id=20413229

7. G.V. Treshchalov. A highly efficient method for deriving energy from a free-flow liquid on the basis of the specific hydrodynamic effect // International Scientific Journal for Alternative Energy and Ecology. ISJAEE. **2010. No 12**. P. 23-29. http://elibrary.ru/item.asp?id=18191852

8. G.V.Treshchalov, R.S. Fedyuk. Energy analysis of Treshchalov's hydrodynamic effect // Vologdin readings: materials from a scientific conference. Vladivostok, 2011. Publ. house DVFU, **2012**. pp 162-164. http://elibrary.ru/item.asp?id=18166093

9. V.I.Lipkin, E.S.Bogombayev. Micro-hydroelectric power stations: user manual // UN Development Programme. Bishkek. **2007**. p 33.

10. N.I. Lenev.Damless hydroelectric power stations of a new generation on the basis of a hydroenergy unit // Alternative power engineering and ecology. **2005. No 3**. pp 76-78.

11. Igor Sokolov. The energy conservation law in hydrodynamics vs the pseudo-law of alternative energy. Comment on "Alternative energy vs pseudoscience" and the papers cited and not cited therein (in Russian) // **arXive**

12. I.I.Agroskin, G.T.Dmitriyev, F.I.Pikalov. Hydraulics // State power-engineering publishing house, **1954.**

13. R.R. Chugayev."Hydraulics" // "Energoizdat" **1982**

14. D.V. Shterenlikht. Hydraulics // Energoatomizdat. **1984.** p 640.

15. L.D.Landau, Y.M. Lifshits. Hydrodynamics. M., Nauka, **1986,** p 736.

16. V.M. Lyatkher, A.M.Prudovskiy Hydraulic modeling // Moscow Energoatomizdat,

17. Treshchalov, G. V. Verfahren Zur Gewinnung Von Energie Aus Der Strцmung Eines Fliessenden Mediums EP2019202 WIPO **WO/2007/131246**