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An Increase in the Energy Efficiency of Vortex Micro HPP with a Flexible Outlet Siphon by Self-Adjustment of Flows in the Pressure Chamber

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Abstract. The article aims to increase the energy efficiency of the vortex micro-power plant, which would be achieved due to its compatibility with the terrain. In particular, the inlet channel connected to the water intake of the pressure chamber and the water collector placed in the upper pool by transverse joints, and the flexible siphon connected by vertical and horizontal joints to the diffuser of the same chamber with a telescopic end. The boundary conditions were selected with parameters such as the water flow acceleration according to the river bed's slope angle and the inclination angle of the upstream channel near the vertical pressure cone chamber. The level difference between the upper and lower pools was adjusted. Inside the pressure chamber, the inclined guides of the small wings were hinged to its wall and were adjusted by ballasts. The reactive forces generated by the upward reflection of the incoming flow from the surfaces on the inclined small guide wings of the pressure chamber were a factor in curbing the said flow (compensating for the insufficient volume flow) and ensuring the continuity of the water supply to the turbine in shallow water. The mentioned circumstances allowed for improving the synchronization of incoming and outgoing flows. As a result of the above improvements, an increase in the energy efficiency (i.e., annual electricity generation) of 15–20 % was achieved.

Keywords: low head turbine, energy efficiency, ascending channel, small guide wings, inflow, outflow.

1 Introduction

Water resources (rivers, lakes, reservoirs, glaciers, underground waters, and swamps) rank first among the natural resources of Georgia. The total number of rivers (about 300) is distinguished by their energy value, whose annual total potential power is equivalent to 15 GW, and the average annual energy is equivalent to $5 \cdot 10^{10}$ kW·h.

Because the rivers are seasonal, these resources are being redistributed by constructing power plants with balancing reservoirs. However, the construction of such plants is facing resistance from an environmental standpoint, so the emphasis is currently on the construction of hydropower plants (HPPs) with small reservoirs [1].

Recently, a particular interest has been aroused in generating electricity from small rivers using vortex micro-power plants. We examine numerically the evolution of a perturbed vortex in a periodic box. The vortex turbine is an environmentally friendly way to consume energy from rivers and channels with a low height difference, as a standalone project or a cluster of turbines will power entire regions. A single turbine can generate constant energy in the 15–70 kW·h range. Turbulent's program is working with a growing network of global partners to ensure optimal local support and availability for user technology. Whether they want to install a single turbine or have projects aiming to electrify entire regions, local partners of the given program are looking to assess the user's project and find the best solution for them. They are also looking for qualified companies to expand their global franchise network. According to [2], "turbulent technology will cause a real revolution in terms of providing clean energy in remote parts of the world", and "turbulent tackles a social issue like renewable energy from an international vision and a self-developed innovative product".

According to [2], the following statements can also be formulated: clean energy from rivers or canals was never viable before (power communities and villages with 50–500 households); generation 100–500 MW·h per year per turbine; scalable up to several MW by installing multiple or cascading units; short total implementation time; fast delivery; easy transport on a small truck; accessible civil works and installation in a couple of days; more accessible permits for individual use as there are no adverse environmental or social impacts; a reliable and constant energy source (unlike intermittent energy sources like wind or solar); energy possible 365 days a year.

2 Literature Review

In general, a vortex micro HPP, including the AquaZoom vortex micro-HPP, contains a basin with a tangential flow guide and a vertical chamber connected to it with a reactive hydro turbine placed in its lower part, with a siphon hermetically connected to the diffuser; water volume flow of about 1 m^3/s; optimal pressure of 1–2 m, and clearance around the area of 5 m [3].

The maximum efficiency derived is around 30 %, while commercial companies have claimed efficiencies of around 50 % with output power in a range of 0.5–20 kW. Therefore, this paper aims to determine the shortcomings of the previous works for developing the vortex power plant technology based on the mentioned circumstances and to develop recommendations for further research [4].

The primary aim of the paper [5] is to determine and prove the possibility of using a gravitational vortex turbine for free-flowing drainage water. The article presents an idea of a power plant, where aeration of drainage water is an added advantage in a vortex flow. Such a power plant is a new idea that combines hydraulics, environmental engineering, and mechanical engineering.

Low-head micro HPPs are gaining interest as traditional turbines, such as the Kaplan and Pelton turbines, are typically limited to heads greater than 3m. Gravitational vortex hydropower (GVHP) is one such low-head hydropower solution. GVHP uses the energy available in a vortex flow, enabling hydropower generation at heads as low as 0.7 m. A vertical axis turbine is placed in the center of a vortex flow and rotates with the flow, thus generating mechanical energy. The article [6] describes a parametric experimental investigation of the operating conditions of GVHP.

The power capacity and facility are two criteria required to classify HPPs. The first consists of five components: dammed reservoir, river flow, pumped storage, flow technology, and new technology gravity vortex. The second criterion - the river (its energy) is classified according to the power scale: large, small, micro, and pico hydropower. The paper focuses on micro-hydropower, particularly gravity vorticity, and provides an overview of flow and power regarding free surface vorticity and applied turbine systems [7].

The design of a micro HPP focuses on the gravitational creation of a water vortex stream, a novel hydropower engineering technique. The water enters a wide, straight inlet through a vertical conical tube, creating a vortex that exits at the shallow basin's center floor. The vortex's dynamic force drives the turbine rather than the vertical pressure [8].

In the article [9], a state-of-the-art review is undertaken on vortex hydropower technology, the underlying hydraulic principles of such devices, and an overview of research and technologies. In article [10], pilot testing of a gravitational water vortex (GWV) HPP was done to evaluate its applicability in a real-world scenario and validate the results from the lab-scale model. A scaled-up model with a capacity of 1 kW was designed for the evaluation purpose. The pilot testing shows an overall plant efficiency of 49 %, validating the lab-based studies conducted beforehand.

The article [9] summarizes the nature of the previous studies. The fundamentals of the vortex dynamics involved and the quantitative analysis of the performance of GWV HPP systems are also described. The turbulence and multiphase models used in leading numerical simulation studies have been reviewed. As a case study, the implementation of a GWV HPP system is presented. Based on the review of previous studies regarding GWV HPP systems, the significant issues and challenges are summarized, and some key topics are recommended for future research on the performance of GWV HPP systems.

To increase the initial speed of the water entering the cylindrical basin, the flow fields inside the basin in the 0–90° range of the inlet channel twist angle were numerically simulated using the ANSYS Fluent software [11]. There is no lack of interest in the micro-hydroelectric power plant, which generates electricity from the accessible waterfall, and the portable micro HPP because these issues are discussed in this article.

In the patent [12], a portable micro-HPP with a silt-conducting channel to be installed in a small area is considered, the entrance of which is self-regulated by a valve and is closed by a lock when the water level is minimal. When the water level rises, the entrance to the channel closed by the lock is opened by raising the valve, and the accumulated silt is carried by the water flow to the lower pool, allowing the hydro units' uninterrupted operation.

The well-known vortex micro-hydroelectric power plants [9, 10] contain upper and lower open channels at different levels. The vertical turbine placed between them is operated by water falling from the upper pool level to the exit hole of the turbine. Still, the level difference from the said hole to the lower pool level is not used, while in the Georgian transfer HPP, this issue is solved. Still, it works only on confluence, and the river's kinetic energy is not used (it is not of vortex type).

Since then, some GWV HPP studies have focused on design variation in the vortex chamber and the runner [9, 11]. Numerous studies were conducted to change only the design of the vortex chamber and the impeller.

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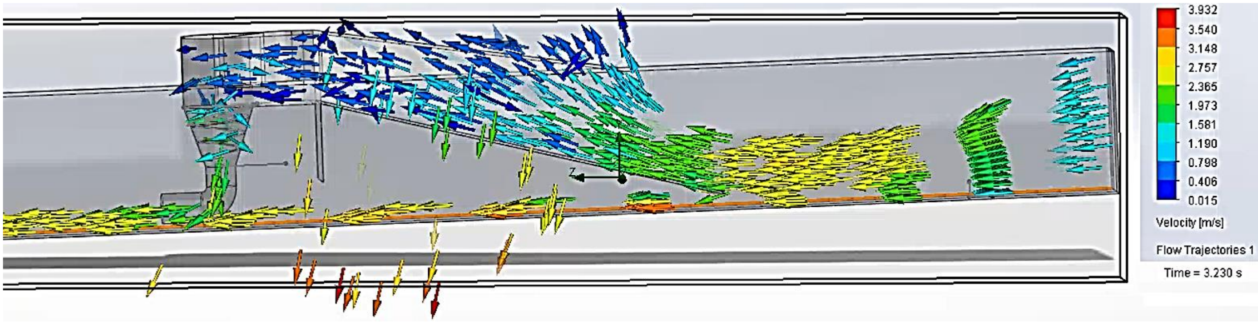
In different works [13, 14], the authors have tested a micro HPP in the upper part of the vertical conical chamber in which the spiral flow guides are placed, and the reactive hydro turbine is placed in the lower part of this chamber; a water-receiving ascending channel is hermetically connected to the conical diffuser with a transverse joint, while a siphon outgoing channel with a telescopic end is connected to the diffuser of the pressure chamber by vertical-horizontal joints [15].

The study [16] allowed CFD simulations considering actual hydrodynamic parameters (Figure 1).



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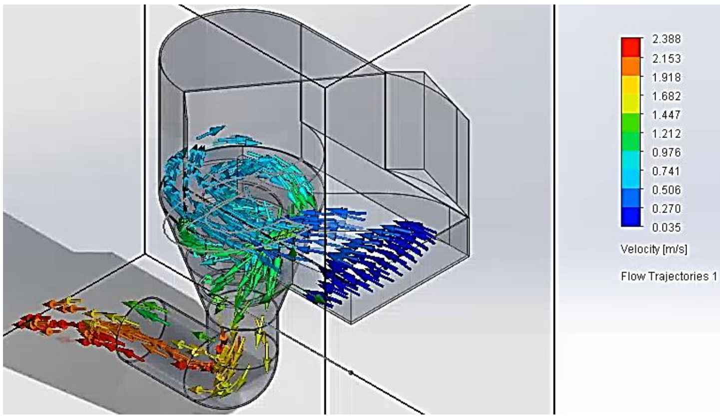

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Figure 1 – CFD simulations considering actual hydrodynamic parameters [16]: a – inlet channel; b – pressure chamber.

The main aim of the article is to reflect an increase in the energy efficiency of the vortex micro-power plant, for which the following objectives should be reached:

1) solving the problem of its compatibility with the terrain;

2) compensating the variable water supply using inclined guide small wings, hinged to its wall and adjustable with ballasts.

3 Research Methodology

3.1 The traditional approach

According to the traditional approach [16], an increase in energy efficiency would be achieved by using the closed lower channel in the suction mode and by matching the parameters, particularly the cross-sectional areas S_1 and S_2 of the upper and lower channels and the outlet and inlet sections of the diffuser concerning the velocities v_1 and v_2 of the water inlet and wing flows, respectively.

In this case, the continuity equation is as follows [16]:

$$S_1 v_1 = S_2 v_2, \tag{1}$$

from which the area S_2 is determined:

$$S_2 = S_1 \frac{v_1}{v_2}, \tag{2}$$

where the velocity v_2 is evaluated as follows:

$$v_2 = v_1 + \Delta v. \tag{3}$$

It includes the velocity change Δv, the value of which can be obtained from the energy conservation law for the process of transferring the potential energy to the kinetic one:

$$mgh = \frac{m \Delta v^2}{2}, \tag{4}$$

where m – mass, kg; $g = 9.81$ m/s^2 – gravity acceleration; h – height, m.

Therefore, the velocity change is as follows:

$$\Delta v = \sqrt{2gh}. \tag{5}$$

Due to expression (3), the continuity equation (1) can be rewritten:

$$S_1 v_1 = S_2 (v_1 + \Delta v), \tag{6}$$

from which, after using equation (5), the expression (2) can also be rewritten:

$$S_2 = S_1 \frac{v_1}{v_1 + \sqrt{2gh}}. \quad (7)$$

This allows for evaluating the height:

$$h = \frac{v_1^2}{2g}\left(\frac{S_1}{S_2} - 1\right)^2. \quad (8)$$

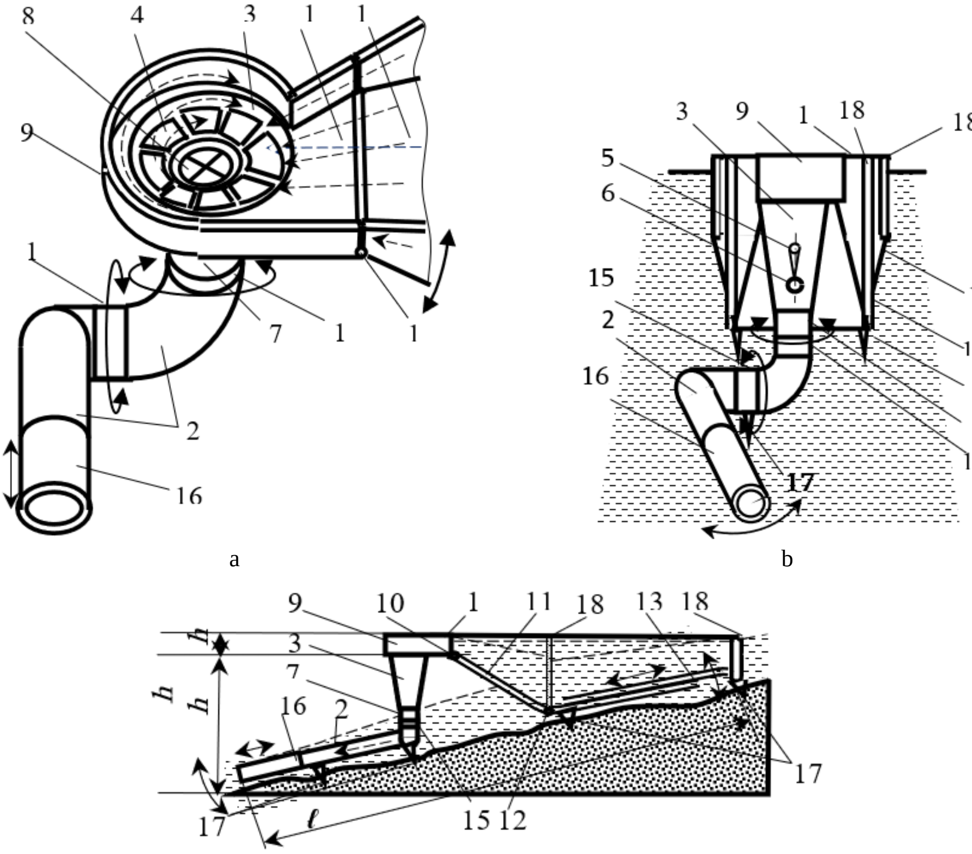
This value corresponds to the flow rate v_1 of the water entering the turbine in the confuser's cross-section S_1 and is required to ensure the velocity of the flow passing through the diffuser's cross-section S_2.

3.2 A new HPP design

A new vortex micro hydro power plant has been developed (Figure 2). It contains a vertical pressure chamber 3 between the open upper inlet 1 and lower (outlet) tube-siphon channels 2. In the upper conical part, small flow–directing wings 4 are placed, the inclination of which is regulated by ballasts 6 connected to them in an articulated manner 5. A reactive hydro turbine 8 is placed in the lower cylindrical pressure chamber 3. The inlet channel 1, located near the diffuser 9, is connected to the water-receiving ascending channel 11 with a horizontal joint 10, which is also connected by horizontal joint 12 to the telescopic water collector 13, located in the upper pool.

The connection of collector 13 to the above-mentioned ascending channel is made by the example of the connection of the water outlet to the narrow-threshold spillway [17]. The outlet (pipe-siphon) channel 2 is hermetically connected to the diffuser 9 or the lower cylindrical part 7 of the pressure chamber 3. It, in turn, is connected to the pressure chamber 3 by vertical 14 and horizontal joints 15. Around them, the possibility of turning the outlet (pipe-siphon) channel 2 allows compatibility with the river bed under difficult terrain conditions.

Channel 2 has a telescopic end 16 at the outlet to the lower pool, through which, by changing the length of channel 2, it can be turned around to the horizontal joint 15. The pressure changes due to the change in the slope, which enables the water supplied to the turbine to match the river's flow.



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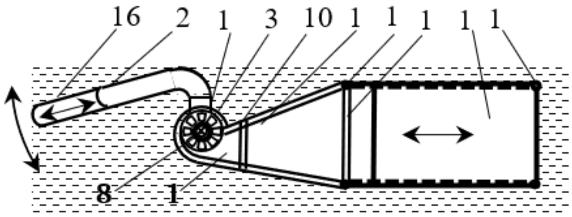

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Figure 2 – General (a), front (b), side (c), and top (d) views of a portable vortex HPP: 1 – inlet channel; 2 – outlet channel; 3 – pressure chamber; 4 – small guide wing; 5 – wing joint; 6 – ballast; 7 – chamber's cylindrical part; 8 – turbine; 9 – diffuser; 10 – horizontal joint; 11 – ascending channel; 12 – horizontal joint; 13 – telescopic water collector; 14 – vertical joint; 15 – horizontal joint; 16 – telescopic end; 17 – wedge, 18 – vertical support; h – pressure head; h_1 – ascending channel height; h_2 – slope height; l – slope length under the portable micro HPP (the dashed lines indicate the directions of water flows; the straight lines indicate the directions of the telescopic connections)

Vortex micro HPP's pressure chamber is presented in Figure 3.

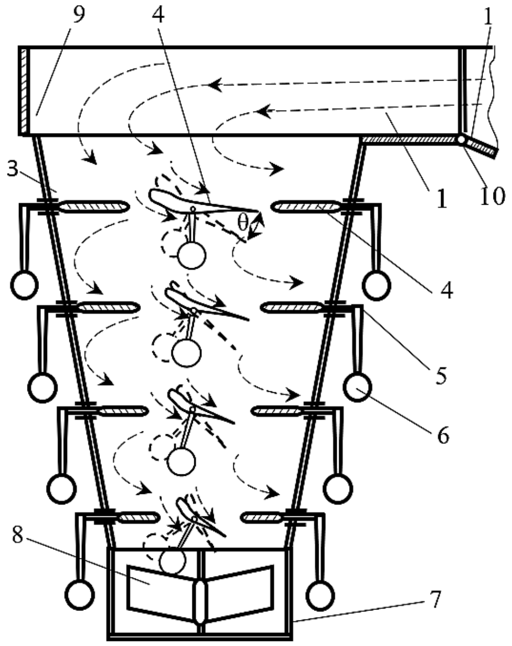

Figure 3 – Vortex micro HPP's pressure chamber (the dashed arrows indicate the direction of the water flows on wings inclined with angle θ)

The flow of water eccentrically delivered from the inlet channel 1 on the periphery of the confusor 8 circulates in pressure chamber 3 and goes towards turbine 8. Currently, the pressure force F_y on the wings 4 guiding the incoming flow in the chamber turns their profile around the radial (same horizontal) axis 5 at an angle θ. In contrast, wing 4 guides the incoming flow, and as a result of reflection from wing 4 guiding the incoming flow in the upper direction, the pressure force Fy causes the retention of the drop of the flow, thus slowing down its downward movement. It compensates for the poor volume flow, which, without operational intervention, ensures the continuity of the water supply to the turbine in shallow water.

The characteristics and equilibrium conditions of the guide wing 4 are subject to the calculation.

4 Results

The proposed approach is based on both geometrical and physical dependencies. For this purpose, wing flow characteristics and equilibrium conditions of the vortex micro HPP's guide wing are presented in Figure 4.

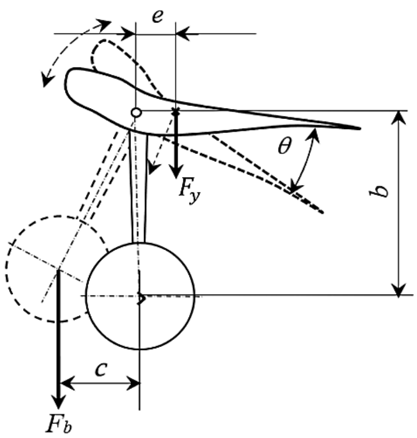

Figure 4 – Wing flow characteristics and equilibrium conditions of the vortex micro HPP's guide wing

The main physical equation for the pressure force is as follows:

$$F_y = C_y \frac{\rho_w V_{rel}^2}{2} S \cdot cos(\alpha), \quad (9)$$

where F_y – pressure force, N; ρ – air density, kg/m^3; C_y – guide wing lift force coefficient; S – the area of the wing, m^2; v_{rel} – relative wing flow velocity, m/s:

$$v_{rel} = \sqrt{v_w^2 + v_b^2}, \quad (10)$$

where v_w – the downward (vertical) component of the falling flow rate in the chamber, m/s; v_b – the horizontal component of the circulating flow rate as the chamber's linear velocity:

$$v_b = \omega r, \quad (11)$$

where ω – circulation frequency, rad/s; r – radius of the pressure chamber, m.

The inclination of the wing's profile (chord) towards the horizontal plane is determined from the equilibrium of the static moments, N·m:

$$F_y e = F_b c, \tag{12}$$

where F_b – ballast weight, N; e – the side from the joint of the guiding wing to the contact point of the pressure force acting on it, m; c – horizontal projection of the ballast's inclination, m (Figure 4):

$$c = bsin(\theta), \tag{13}$$

where b – the length of the ballast's holding lever as the distance from the ballast to the wing joint, m.

Therefore, equation (5) takes the following form:

$$F_y e = F_b bsin(\theta), \tag{14}$$

from which the angle θ can be evaluated:

$$\theta = arcsin\left(\frac{e}{b} \cdot \frac{F_y}{F_b}\right). \tag{15}$$

5 Discussion

With the parametric compatibility of the vortex micro PPH with the terrain and the volumetric flow of the river, in particular, with the synchronization of the incoming and outgoing flows, an increase in energy efficiency is achieved.

Process simulation was carried out considering hydrodynamic parameters, particularly for producing small-scale working models on a 3D printer from biodegradable material, which will have a minimal environmental impact.

An animation simulation was conducted to determine the specifics of creating a water vortex. The boundary conditions of the computational fluid dynamics models were selected with parameters such as the river bed slope's angle, the water flow's acceleration in the bed, and then its deceleration in the ascending channel near the vertical pressure cone chamber.

The animated simulation, which was carried out with parameters such as the acceleration of the water flow according to the slope angle α of the river bed, the inclination angle β of the upstream channel, and its damming up-deceleration on the springboard (in the upstream channel), showed the possibility of installing a vortex micro HPP directly in the river bed by placing the springboard (artificial upstream channel) in front of the turbine siphon (artificial upstream channel).

In particular, the level difference between the upper and lower reservoirs is increased through the artificial upstream channel (springboard) and outgoing siphon (closed) channel used at the entrance of the micro-power plant.

6 Conclusions

Increasing the energy efficiency of the vortex micro-power plant would be achieved due to its kinematic compatibility with the terrain with three degrees of freedom and by its hydrodynamic compatibility with a volume flow of the river; in particular, the level difference between the upper and lower pools is regulated by: on the one hand, an ascending channel rigidly connected to the water intake of the pressure chamber and the water collector in the upper pool, and on the other hand, a siphon flexibly connected to the diffuser of the same chamber with vertical and horizontal joints, which has a telescopic end in the lower pool. Also, the reactive forces generated by the upward reflection of the incoming flow from the surfaces on the inclined small guide wings of the pressure chamber is a factor for curbing the said flow (compensating for the insufficient volume flow) and ensures the continuity of the water supply to the turbine in shallow water. The mentioned circumstances improve the synchronization of incoming and outgoing flows. As a result of the above improvements, an increase in efficiency (annual electricity generation) of 15–20 % is achieved.

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References

1. Wang, X., Lu, Y., Chen, C., Yi, X., Cui, H. (2024). Total-factor energy efficiency of ten major global energy-consuming countries. *Journal of Environmental Sciences*, Vol. 137, pp. 41–52. https://doi.org/10.1016/j.jes.2023.02.031
2. Quaranta, E., Bahreini, A., Riasi, A., Revelli, R. (2022). The very low head turbine for hydropower generation in existing hydraulic infrastructures: State of the art and future challenges. *Sustainable Energy Technologies and Assessments*, Vol. 51, 101924. https://doi.org/10.1016/j.seta.2021.101924
3. Rahman, M.M., Hong, T.H., Tamiri, F.T., Wan Khairul Muzammil, A.R. (2017). A review on the development of gravitational water vortex power plant as alternative renewable energy resources. *IOP Conference Series: Materials Science and Engineering*, Vol. 217(2017), 012007. https://doi.org/10.1088/1757-899X/217/1/012007
4. Anjali Mohanan, M. (2016). Generation with simultaneous aeration using a gravity vortex turbine. *International Journal of Scientific & Engineering Research*, Vol. 7(2), pp. 19–24.
5. Yaakob, O., Ahmed, Y.M., Elbatran, A.A., Shabara, H. (2014). A review on micro hydro gravitational vortex power and turbine systems. *Jurnal Teknologi*, Vol. 69(7), pp. 1–7. https://doi.org/10.11113/jt.v69.3259
6. Power, C., McNabola, A., Coughlan, P. (2016). A parametric experimental investigation of the operating conditions of gravitational vortex hydropower (GVHP). *Journal of Clean Energy Technologies*, Vol. 4(2), pp. 112–119. https://doi.org/10.7763/JOCET.2016.V4.263

7. Gupta, A., Prakash, A., Singh, G.K., Tripathi, H. (2021). Design of a micro hydro power plant based on the vortex flow of water. *International Journal of Advanced Research in Science Communication and Technology*, Vol. 5(1), 1149. https://doi.org/10.48175/IJARSCT-1149
8. Timilsina, A.B., Mulligan, S., Bajracharya, T.R. (2018). Water vortex hydropower technology: a state-of-the-art review of developmental trends. *Clean Technologies and Environmental Policy*, Vol. 20, pp. 1737–1760. https://doi.org/10.1007/s10098-018-1589-0
9. Sapkota, A., Gautam, A., Timilsina, A.B., Dhakal, S., Shakya, S.R. (2021). Development of a 1 kW gravitational water vortex hydropower plant prototype. *In: 8th International Junior Researcher and Engineer Workshop on Hydraulic Structures*, pp. 1–10. https://doi.org/10.26077/1517-74d7
10. Maika, N., Lin, W., Khatamifar, M. (2023). A review of gravitational water vortex hydro turbine systems for hydropower generation. Energies, Vol. 16(14), 5394. https://doi.org/10.3390/en16145394
11. Mamadjanov, A.B., Zakhidov, R.A., Rakhmatov, A., Sharipov, F. (2022). Improving the gravity-vortex micro-hydroelectric power station efficiency by ensuring an acceptable value of the water inlet canal's twist angle. *IOP Conference Series: Earth and Environmental Science*, Vol. 1142(2023), 012015. https://iopscience.iop.org/article/10.1088/1755-1315/1142/1/012015
12. Gelutashvili, A., Gabrichidze, I., Tevzadze, N. (2000). A portable micro HPP. Patent of Georgia, No. GE P 2000 2151 B.
13. Zivzivadze, O., Zivzivadze, B., Geguchadze, A., Dzadzamia, D., Kuparadze, A., Sulakvelidze, N. (2023). Synchronization of inlet and outlet flows for a vortex micro HPP. *In: Proceedings of XIV International Annual Scientific Conference of the Georgian Mechanical Union*, pp. 39.
14. Zivzivadze, O., Zivzivadze, B., Geguchadze, A., Dzadzamia, D., Kuparadze, A., Sulakvelidze, N. (2023). A variable-geometry portable vortex micro HPP. *In: Proceedings of VII Georgian-Polish Scientific-Technical Conference "Transport Bridge Europe-Asia"*, pp. 109–114.
15. Zivzivadze, O.V., Geguchadze, A.C., Zivzivadze, B.L., Dzadzamia, D.B., Kuparadze, A.G., Sulakvelidze, N.I. (2024). Portable vortex micro-HPP with variable parameters. *In: Current State of Science and Technologies and Development Prospects during the Fourth Industrial Revolution*, pp. 180–182. Azerbaijan University of Technology, Ganja, Azerbaijan. https://atu.edu.az/storage/konfrans/2981717799770.pdf
16. Zivzivadze, O., Zivzivadze, B., Geguchadze, A., Dzadzamia, D., Kuparadze, A., Sulakvelidze, N. (2023). A variable-geometry portable vortex micro HPP with a reactive water-intake. In: IV International Scientific Technical Conference "Energy Modern Problems and Their Solutions", pp. 49–53.
17. Noselidze, G. (2022). Preliminary results of an experimental study of the connection of a wide-threshold culvert with a spillway structure. *Works of GTU*, Vol. 2(524). https://doi.org/10.36073/1512-0996-2022-2-119-126