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EXPERIMENTAL OPTIMIZATION OF DESIGN AND ENERGY PARAMETERS OF A GARLAND-TURBINE MOBILE MICRO HYDROPOWER PLANT FOR FREE-FLOWING WATER

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Abstract. The study experimentally evaluates the effects of free-stream velocity, turbine length, number of blades, and number of hydro turbines in a garland on the energy performance of a mobile micro-hydropower plant. A floating physical prototype was tested under laboratory and field conditions at flow velocities of 1.0–3.0 m/s, while rotational speed, current, voltage, power, and torque were recorded. A Hartley design was applied with $b = 1\text{--}2$ m, $\vartheta = 2\text{--}3$ m/s, and $z = 6\text{--}12$; model adequacy was assessed using Cochran's, Student's, and Fisher's criteria. Increasing the flow velocity from 1 to 3 m/s raised the output power from 15.2 to 340.5 W and the rotational speed from 40 to 129 rpm. The relationship $P = 12.93 \cdot \vartheta^{2.884}$ was obtained with $R^2 = 0.981$. In the multi-turbine tests, the maximum power was achieved with four turbines arranged in a single garland. The multifactor model identified $b = 1.7$ m, $\vartheta = 2.9$ m/s, and $z = 12$ as a rational combination, corresponding to a calculated power output of 345.1 W at an efficiency of 24%. The maximum experimentally measured efficiency reached 36.2% at a turbine length of 1.5 m and a flow velocity of 1.5 m/s. The results can support the selection of design and energy parameters for mobile micro-hydropower plants intended for autonomous consumers in mountainous and foothill areas.

Keywords: micro-hydropower plant; garland turbine; hydrokinetic energy; free stream; experiment; optimization; output power.

Annotatsiya. Tadqiqotning maqsadi erkin oqim tezligi, turbina uzunligi, parraklar soni hamda girlyandadagi gidroturbinalar sonining mobil mikroGES energetik ko'rsatkichlariga ta'sirini tajribaviy aniqlashdan iborat. Suzuvchi fizik namuna laboratoriya va dala sharoitlarida 1,0–3,0 m/s oqim tezliklarida sinovdan o'tkazilib, aylanish chastotasi, tok kuchi, kuchlanish, quvvat va burovchi moment qiymatlari qayd etildi. Optimallashtirishda Hartley rejasi qo'llanildi: $b = 1\text{--}2$ m, $\vartheta = 2\text{--}3$ m/s va $z = 6\text{--}12$; modelning adekvatligi Koxren, Styudent va Fisher mezonlari asosida tekshirildi. Oqim tezligi 1 dan 3 m/s gacha oshirilganda quvvat 15,2 dan 340,5 W gacha, aylanish chastotasi esa 40 dan 129 ayl/min gacha ortdi. $P = 12.93 \cdot \vartheta^{2.884}$ bog'lanishi $R^2 = 0.981$ qiymat bilan olindi. Ko'p turbinali tajribalarda maksimal quvvat bir girlyandada to'rtta turbina qo'llanganda kuzatildi. Ko'p omilli model $b = 1.7$ m, $\vartheta = 2.9$ m/s va $z = 12$ kombinatsiyasini maqbul deb belgiladi; bunda hisobiy quvvat 345,1 W, FIK esa 24% ni tashkil etdi. Eng yuqori tajribaviy FIK 36,2% bo'lib, turbina uzunligi 1,5 m va oqim tezligi 1,5 m/s bo'lganda qayd etildi. Olingan natijalar tog'li va tog'oldi hududlaridagi avtonom iste'molchilar uchun mobil mikroGESlarning konstruktiv va energetik parametrlarini tanlashda qo'llanilishi mumkin.

Kalit so'zlar: mikroGES; girlyandali turbina; gidrokinetik energiya; erkin oqim; tajriba; optimallashtirish; chiqish quvvati.

Аннотация. Цель исследования заключается в экспериментальном определении влияния скорости свободного потока, длины турбины, числа лопастей и количества гидротурбин в гирлянде на энергетические показатели мобильной микроГЭС. Испытания плавающего физического образца проводились в лабораторных и натуральных

условиях при скоростях потока 1,0–3,0 м/с с регистрацией частоты вращения, силы тока, напряжения, мощности и крутящего момента. Для оптимизации использован план Хартли с факторами $b = 1\text{--}2$ м, $\vartheta = 2\text{--}3$ м/с и $z = 6\text{--}12$; адекватность модели оценивалась по критериям Кохрена, Стьюдента и Фишера. При увеличении скорости потока от 1 до 3 м/с мощность возросла с 15,2 до 340,5 Вт, а частота вращения — с 40 до 129 об/мин. Получена зависимость $P = 12,93 \cdot \vartheta^{2,884}$ при $R^2 = 0,981$. В многотурбинных испытаниях максимальная мощность достигалась при использовании четырёх турбин в одной гирлянде. Многофакторная модель определила рациональное сочетание $b = 1,7$ м, $\vartheta = 2,9$ м/с и $z = 12$, соответствующее расчётной мощности 345,1 Вт при КПД 24%. Максимальный экспериментально измеренный КПД составил 36,2% при длине турбины 1,5 м и скорости потока 1,5 м/с. Полученные результаты могут быть использованы при выборе конструктивных и энергетических параметров мобильных микроГЭС для автономных потребителей в горных и предгорных районах.

Ключевые слова: микроГЭС; гирляндная турбина; гидрокинетическая энергия; свободный поток; эксперимент; оптимизация; выходная мощность.

INTRODUCTION

The utilization of the kinetic energy of natural and artificial watercourses is a promising direction in distributed renewable energy. Hydrokinetic systems can operate without dams or substantial head differences; however, their efficiency depends on flow velocity and depth, rotor geometry, blade number, and the degree of submergence [1, 2]. For low-power autonomous consumers, it is particularly important to obtain the required output with minimal structural complexity and maintenance. Mobile systems are of practical interest for mountainous and foothill areas of Uzbekistan because they can use the free flow of small rivers and streams and can be relocated without the construction of pressure structures [3]. Their design should also remain operational under seasonal changes in water availability.

The aim of this study is to experimentally justify and optimize the design and energy parameters of a mobile garland-turbine micro hydropower plant, with particular emphasis on rational values of turbine length, blade number, flow velocity, and the number of turbines in a single garland.

LITERATURE REVIEW

Field investigations confirm the need for experimental verification of calculated hydrokinetic designs. Chica et al. [4] and Stanilov et al. [5] reported a high sensitivity of hydrokinetic turbine energy performance to local flow conditions. Reddy and Bhosale [6] showed that the number of blades substantially affects the power coefficient and wake structure. Studies of floating water wheels [7] likewise demonstrate the importance of working-element geometry and interaction among the elements of a hydroenergy system. Optimization studies of free-stream water wheels confirm the need for the coordinated selection of geometric and hydraulic parameters [8]. Experimental and numerical work by Ferraiuolo et al. [9] and Küppers et al. [10] further evaluates how channel-flow conditions and turbine configuration influence hydrokinetic performance.

The reviewed studies address important individual effects, while the developed garland-type mobile micro hydropower plant requires the joint selection of turbine length, blade number, free-stream velocity, and the number of turbines in one garland. This combined design problem defines the research gap addressed by the present experimental and multifactor optimization study.

RESEARCH METHODOLOGY

The research object was a floating garland-type micro hydropower plant with polymer working elements (Figure 1). The turbines were mounted in bearing supports and drove a 500 W three-phase permanent-magnet synchronous generator through pulleys and a belt transmission. The transmission provided an approximately tenfold increase in rotational speed at the generator shaft.

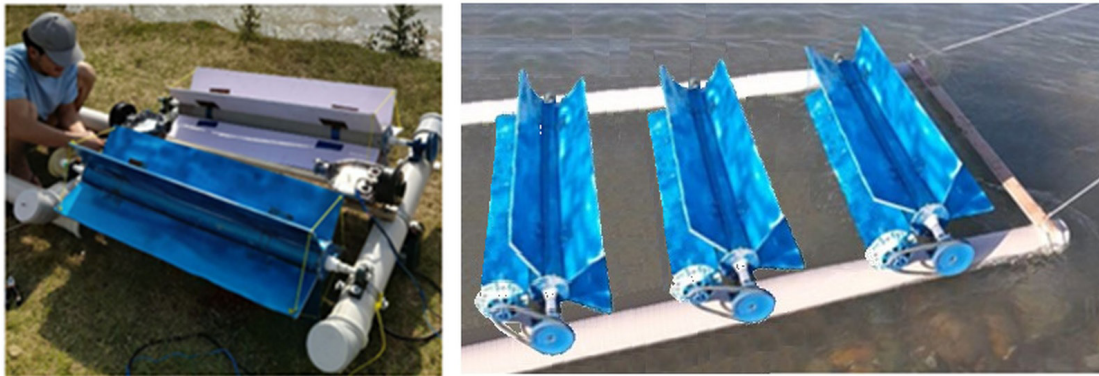


Figure 1. Experimental prototype of the floating garland-type micro hydropower plant

The main design parameters of the developed physical model are presented in Table 1.

Table 1

Main design parameters of the physical model

No.	Parameter	Range / value
1	Outer turbine diameter	400 mm
2	Inner diameter	100 mm
3	Blade height	150–300 mm
4	Turbine length	1000–2000 mm
5	Blade thickness	4 mm
6	Number of blades	6–12
7	Pulley diameter	100 mm

Tests were carried out in the laboratory and on a natural watercourse of the Pop Specialized State Forestry Enterprise in Namangan Region. The measured variables were flow velocity, rotational speed, current, voltage, power, and torque. The instruments included an AT-Laser tachometer, an ISP-1M meter, a hydrometric current meter, a dynamometer, and a K50 kit; the reported electrical measurement error was 0.5%.

Available hydrokinetic power and energy efficiency were determined using the following expressions:

$$P_k = 0.5\rho A\vartheta^3 \quad (1)$$

where ρ is water density, A is the active area of interaction between the flow and the blades, ϑ is flow velocity, and P_e is the electrical output power.

$$\eta = (P_e / P_k) \times 100\% \quad (2)$$

For multifactor optimization, the Hartley design was applied with the following factors: turbine length $b = 1\text{--}2$ m, flow velocity $\vartheta = 2\text{--}3$ m/s, and blade number $z = 6\text{--}12$. The selected levels and variation intervals are given in Table 2. Repeatability was checked using the Cochran criterion, coefficient significance using the Student criterion, and model adequacy using the Fisher criterion at $q = 0.05$. The field dependence of power on velocity was approximated by the function $P = a \cdot \vartheta^n$.

Table 2

Factor levels for the multifactor experiment

Level	b, m	ϑ , m/s	z, pcs.
Central	1.5	2.5	9
Variation interval	0.5	0.5	3
Lower	1.0	2.0	6
Upper	2.0	3.0	12

ANALYSIS AND RESULTS

As the flow velocity increased from 1.0 to 3.0 m/s, the rotational speed rose from 40 to 129 rpm, the current from 4.0 to 22.7 A, the voltage from 3.8 to 15.0 V, and the output power from 15.2 to 340.5 W. These measurements confirm the dominant influence of flow velocity on the energy regime of the installation. The experimental values are summarized in Table 3.

Table 3

Experimental energy parameters of the garland-type micro hydropower plant

ϑ , m/s	n , rpm	I , A	U , V	P , W
1.0	40	4.0	3.8	15.2
1.5	63	6.8	5.0	34.0
2.0	84	10.0	8.5	85.0
2.5	110	16.0	12.0	192.0
3.0	129	22.7	15.0	340.5

Approximation of the experimental data produced the following dependence:

$$P = 12.93 \cdot \vartheta^{2.884} \quad (3)$$

The exponent 2.884 is close to the theoretical cubic dependence of hydrokinetic power on flow velocity, while $R^2 = 0.981$ indicates a good fit to the experimental data. The comparison between the experimental points and the approximating relationship is presented in Figure 2.

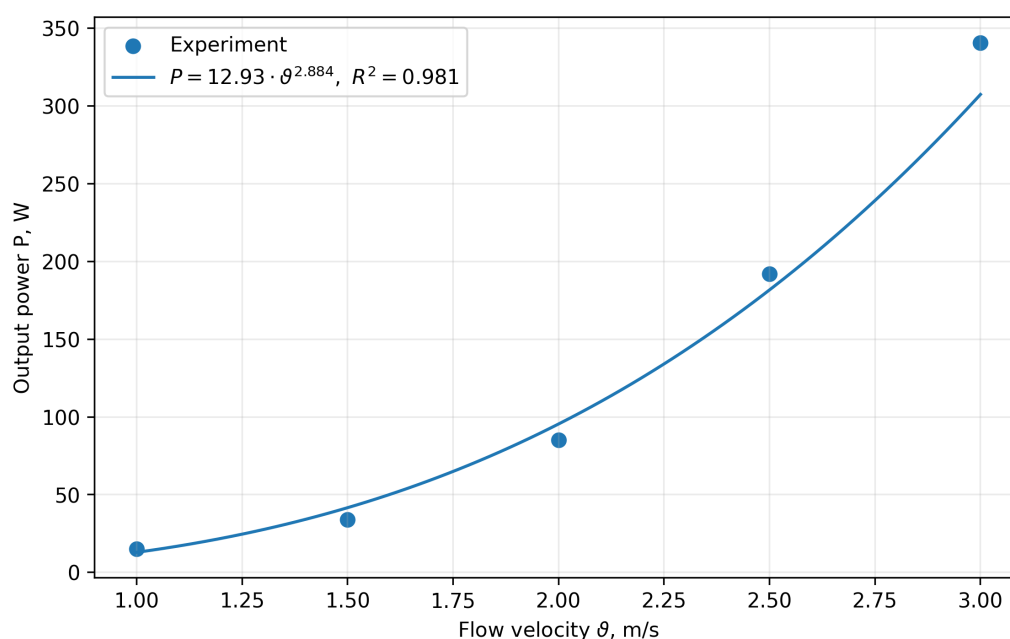


Figure 2. Output power of the garland-type micro hydropower plant versus free-stream velocity

The rotational speed changed almost linearly according to $n = 45 \cdot \vartheta - 4.8$, with $R^2 = 0.998$. Increasing the number of blades also increased the torque: at $\vartheta = 3$ m/s, the measured torque values were 84, 92, and 112 N·m for $z = 6, 9$, and 12 , respectively. Thus, the 12-blade turbine produced approximately 33.3% more torque than the 6-blade turbine. The dependence of torque on blade number and flow velocity is shown in Figure 3.

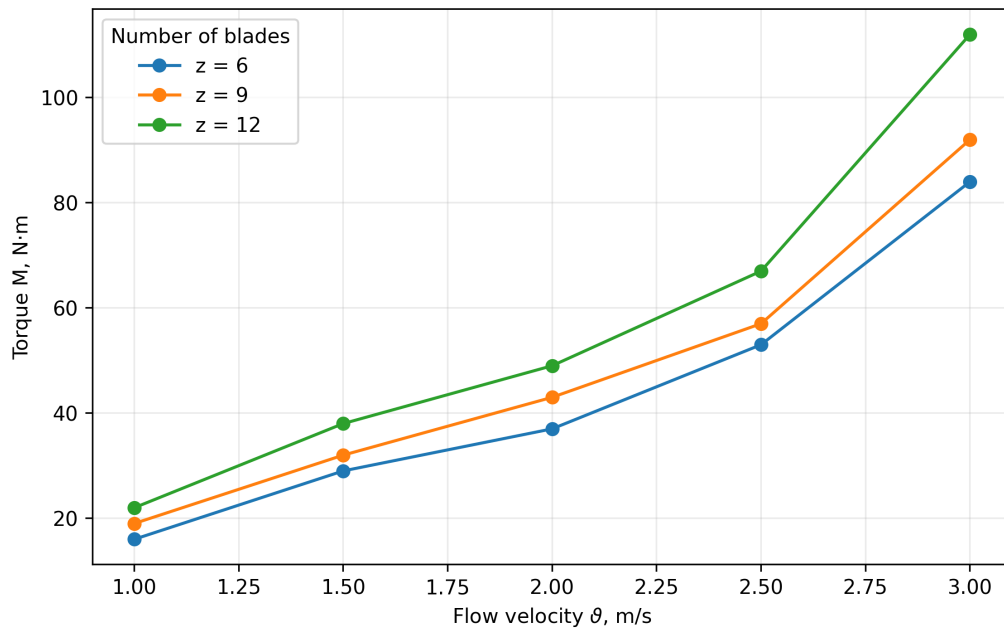


Figure 3. Effect of blade number and flow velocity on torque

When the number of turbines was increased sequentially, the power rose up to $N = 4$ and then decreased. For $b = 1.5$ m at $\theta = 2$ m/s, the power increased from 240 W at $N = 1$ to 960 W at $N = 4$ and then decreased to 920 and 895 W at $N = 5$ and 6, respectively. The same maximum at $N = 4$ was observed for the other turbine lengths shown in Figure 4, indicating hydrodynamic interaction between adjacent working wheels.

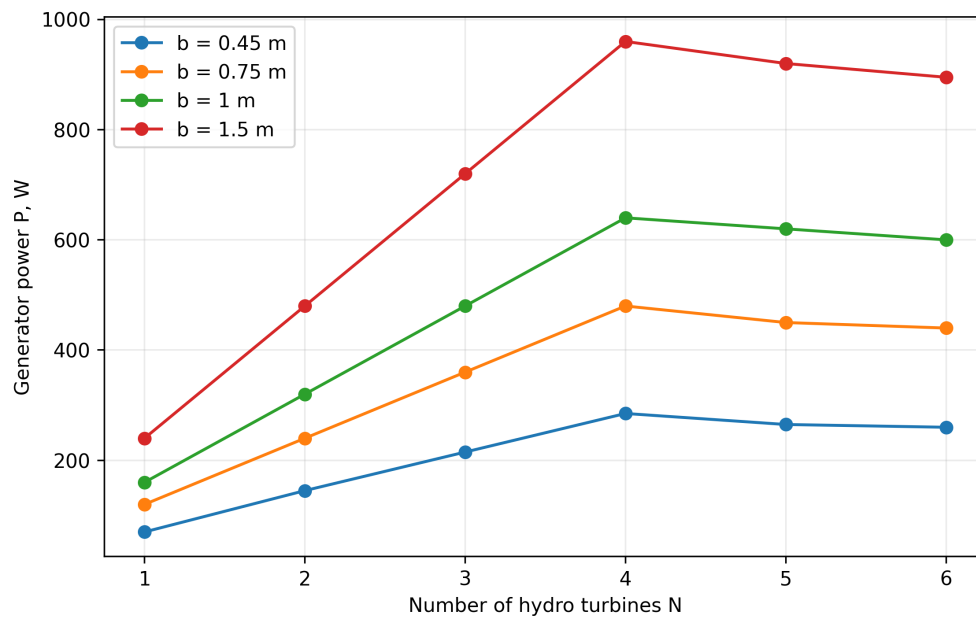


Figure 4. Generator power versus the number of hydro turbines in one garland

The maximum experimental efficiency of 36.2% was obtained at $b = 1.5$ m and $\theta = 1.5$ m/s. As the velocity increased further, the absolute power continued to rise, whereas the relative efficiency decreased. Therefore, the operating regime should be selected according to the required power and the actual flow velocity.

The Hartley design yielded the following quadratic multifactor model of output power:

$$P = 483.258b - 181.9222\theta + 2.1752z - 21.56b\theta + 2.50bz + 0.86\theta z - 132.916b^2 + 60.4164\theta^2 - 0.081z^2 - 61.9424 \quad (4)$$

The model is applicable within $1 \leq b \leq 2$ m, $2 \leq \vartheta \leq 3$ m/s, and $6 \leq z \leq 12$. Model verification yielded $F = 1.3447 < F_{crit} = 3.44$, confirming the adequacy of the model under the stated test conditions. The optimization calculation identified $b = 1.7$ m, $\vartheta = 2.9$ m/s, and $z = 12$; the calculated output power was 345.1 W at an efficiency of 24%. The observed trends are consistent with the cited hydrokinetic studies, which emphasize the sensitivity of system performance to flow velocity and working-element geometry.

For practical selection, the installation can be matched to the actual watercourse velocity and depth, and its expected output can then be evaluated using model (4). For the investigated arrangement, increasing the number of turbines beyond four in a single garland is not advisable; further scaling is better achieved by using separate parallel modules.

CONCLUSION AND RECOMMENDATIONS

The experimental study showed that the energy performance of the mobile garland-type micro hydropower plant is governed primarily by flow velocity, turbine length, and blade number. Increasing the flow velocity from 1 to 3 m/s raised the output power from 15.2 to 340.5 W. The investigated multifactor domain was $b = 1\text{--}2$ m, $\vartheta = 2\text{--}3$ m/s, and $z = 6\text{--}12$. According to the multifactor model, the combination $b = 1.7$ m, $\vartheta = 2.9$ m/s, and $z = 12$ provides a calculated output of 345.1 W at an efficiency of 24%. The highest measured efficiency was 36.2% at $b = 1.5$ m and $\vartheta = 1.5$ m/s. Increasing the number of turbines raised the total power up to four working wheels, whereas additional turbines reduced the output because of mutual hydrodynamic interaction.

For engineering applications, the design should be selected based on the measured site velocity and depth rather than on turbine geometry alone. A single garland should be limited to four turbines under the tested configuration, and a higher installed capacity should be achieved through separate parallel modules. The derived relationships and multifactor model can be used in the preliminary design of mobile autonomous micro hydropower plants for low-power agricultural, forestry, mountainous, and foothill consumers. Further work should verify the model over a wider range of natural flow regimes and operating conditions.

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