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REGARDING THE FEATURES OF WATER FLOW INTERACTION WITH A ROTOR TURBINE

Kazbek Orazbayev[1]*, Assel Yerkongyr[2], Rakhimash Abitayeva[3], Gulmira Sakhmetova[4], Balnur Shashubay[5]
Department of Electric Power Industry and Labour Protection, Zhezkazgan Baikonurov University, Zhezkazgan, Republic of Kazakhstan[1,2,5]
Department of Power Engineering, Satbayev University, Almaty, Republic of Kazakhstan[3]
Department of Power and Nonconventional Power Systems, Mukhtar Auezov South Kazakhstan University, Shymkent, Republic of Kazakhstan[4]
orazbayevkazbek@gmail.com

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**Corresponding Author*

ABSTRACT
The increasing demand for efficient energy production in Kazakhstan underscores the significance of optimising rotor turbines used in gravitational water vortex micro-hydroelectric power plants (MWV-MHPPs). This study addresses the challenges in rotor-flow interaction, focusing on improving turbine efficiency and mitigating performance errors. The research gap lies in the limited understanding of rotor dynamics in relation to varying water flow conditions, which directly impact turbine output. This study employs computational fluid dynamics (CFD) modelling and experimental testing to analyse the interaction between water flow and rotor turbines, focusing on key performance indicators such as torque, head loss, and flow characteristics under different operational conditions. The results indicate a 15% improvement in torque efficiency and a 10% reduction in head loss with optimised turbine blade design, compared to traditional configurations. The study also uncovers significant design flaws in existing MWV-MHPPs, contributing to energy inefficiencies in Kazakhstan's renewable energy sector. This work proposes specific recommendations for turbine design, including enhanced blade geometry and flow regulation strategies, to mitigate these issues. The findings offer practical insights for the development of sustainable, off-grid energy solutions, contributing to the country's energy security goals. By addressing the interaction between water flow and rotor turbines, this research advances the understanding of turbine optimisation for small-scale hydropower plants.

Keywords: *Renewable Energy Sources, Gravitational Water Vortex Micro-Hydroelectric Power Plant, Electricity, Design Optimisation, Energy Losses*

1. Introduction

The transition towards decentralised and low-carbon energy systems has intensified interest in small-scale hydropower technologies, particularly gravitational water vortex micro-hydroelectric power plants (MWV-MHPPs), which are suitable for low-head and low-flow conditions. Unlike conventional hydropower systems, these installations rely on the conversion of kinetic energy from free-surface vortical flow into mechanical energy through rotor turbines. However, the efficiency of such systems is fundamentally governed by complex fluid-structure interaction phenomena, including turbulence intensity, vortex stability, flow separation, and energy dissipation mechanisms.

From a fluid mechanics perspective, rotor-flow interaction remains a critical determinant of turbine performance. Previous studies in hydraulic engineering have demonstrated that unsteady turbulent structures, vortex shedding, and secondary flow formation significantly influence torque generation and hydraulic efficiency. In addition, cavitation effects – although less pronounced in low-head systems – can still arise locally due to pressure fluctuations, leading to material degradation and performance instability. Numerical and experimental investigations using computational fluid dynamics (CFD) and laboratory testing have shown that blade geometry, rotational speed, and inflow conditions directly affect head losses, wake dynamics, and overall energy conversion efficiency.

As stated by Obozov and Orazbayev (2022), hydropower draws special attention among renewable energy sources (RES). It utilises the potential and kinetic energy of water and converts it into electrical energy. But it has not been pointed out that the problems in hydropower are precisely the construction of large hydropower plants, which can have a significant impact on the environment, as well as climatic dependencies, hydropower depends on the availability of water resources and can be highly dependent on climatic conditions such as precipitation and seasonal variations. Following Kiryigitov (2021), the use of streams, small rivers, irrigation canals and reservoirs to provide electricity to independent consumers with low energy consumption in rural areas, especially in foothill and mountainous areas, is a promising direction of hydropower development. Currently, there is a need to augment the pool of accessible working capital in this sector. This will enable enterprises to acquire machinery for the modernisation of energy processes, consequently elevating the quality of these processes to a high standard.

According to Alimhodzhaev et al. (2019), hydropower is a clean energy source that does not emit greenhouse gases and other harmful substances, unlike energy sources that use fossil fuels such as coal or oil, it has no greenhouse effect and does not pollute the atmosphere. The whole mechanism of hydropower and gravitational micro hydropower was analysed, finally, it was decided that to accurately indicate a sustainable and reliable energy supply, it is necessary to store and use water to regulate the supply and demand of electricity when needed. Following Raufov and Kulmanov (2023), hydropower resources have a significant potential, estimates that 7.5 trillion kWh of electricity is generated annually from hydropower show the size of this potential. This estimate is based on resource potential and can vary depending on many factors, including geographical conditions, climatic conditions, and technical capabilities.

Loktionov (2014) notes that to determine the amount of energy that can be generated, it is necessary to analyse hydrological data, determine the flow of water in rivers and streams and consider the presence of bypass wells to create a hydropower system. However, necessary measurements or estimates of the height of water available at a particular location, including the height of the water outlet and the difference in level between the water source and the micro-hydropower plant, have not been considered. According to Abilov (2023), a bottomless micro-hydro power plant is a category of micro-hydro facility that operates without the need for establishing a static water head; instead, it harnesses the kinetic energy from water flow to generate electricity.

In the context of renewable energy development, Kazakhstan possesses substantial hydropower potential, yet only a limited proportion of this capacity has been exploited, particularly in decentralised and rural energy systems. Existing infrastructure is largely oriented towards large-scale hydropower, while small-scale and micro-hydropower solutions remain underdeveloped due to technological limitations, insufficient optimisation of turbine design, and a lack of detailed studies on flow-turbine interaction under local hydrological conditions.

Despite the growing body of international research on hydrokinetic and vortex-based turbines, several critical gaps remain. First, most studies focus on conventional turbine configurations (e.g., axial, Kaplan, or Darrieus turbines), while the specific interaction mechanisms in gravitational vortex micro-hydropower systems are insufficiently examined. Second, existing literature often analyses isolated parameters without providing an integrated assessment of rotor-flow interaction dynamics. This fragmented approach limits the ability to identify the root causes of efficiency losses, including excessive turbulence, flow recirculation zones, and hydraulic energy dissipation. Third, in applied contexts such as Kazakhstan, there is a lack of systematised analysis linking fluid dynamics phenomena to practical design errors in rotor turbines used in MWV-MHPPs. As a result, inefficiencies in turbine performance persist, particularly in terms of suboptimal torque output, increased head losses, and unstable flow regimes.

To address these gaps, this study aims to systematically investigate the interaction between water flow and rotor turbines in gravitational vortex micro-hydropower systems, with a focus on identifying the key hydrodynamic factors influencing performance. The research specifically seeks to analyse the effects of turbulence, vortex formation, and flow structure on rotor behaviour; evaluate performance indicators such as torque generation, flow characteristics, and energy losses; and identify design-related inefficiencies and propose optimisation strategies for turbine geometry and operational parameters.

The novelty of this work lies in its integrated approach, combining theoretical analysis of fluid-structure interaction with applied evaluation of turbine performance in low-head vortex systems. Unlike previous studies, the research explicitly links fluid mechanics phenomena – such as vortex stability and turbulent dissipation – to practical engineering outcomes in micro-hydropower design. Furthermore, it contributes to the limited body of knowledge on MWV-MHPPs by contextualising these findings within the framework of decentralised renewable energy development. By advancing the understanding of rotor-flow interaction dynamics, this study provides a basis for improving the efficiency and reliability of micro-hydropower technologies, thereby supporting the broader deployment of sustainable energy solutions in regions with underutilised hydropower potential.

2. Literature Review

To establish a rigorous foundation for understanding rotor-flow interaction and performance optimisation in micro-hydropower systems, this review synthesises recent studies from Scopus and Web of Science-indexed journals and other peer-reviewed sources published from 2023 to 2026. Relevant publications were identified using keywords such as “micro-hydropower turbine”, “vortex turbine performance”, “CFD optimisation turbine”, “very low head turbines”, and “experimental hydraulic turbine testing”. Only research that reports quantified performance indicators (efficiency, torque, flow characteristics) and employs analytical, numerical, or experimental methodologies was selected, ensuring the literature reflects current state-of-the-art advances in turbine flow interaction analysis.

Recent work by Zhou et al. (2026) introduces the concept of a micro-head double-duct hydraulic turbine, where a novel diffuser design and vortex analysis approach were used to enhance flow stability and performance. Their CFD studies combined with parametric optimisation demonstrate that structured flow guidance via dual ducts can improve energy extraction efficiency and modify axial forces, illustrating the critical role of advanced numerical methods in revealing detailed vortex behaviours and performance trends in low-head turbine configurations.

Experimental and CFD integration represents a growing trend in turbine research. Kada et al. (2025) combined high-fidelity CFD with design of experiments (DOE) and response surface methodology (RSM) to assess rotor-stator blade configuration effects on performance metrics such as power output, efficiency, and pressure drop. This integrated framework enabled efficient exploration of nonlinear interactions between design variables and flow conditions, highlighting trade-offs inherent in turbine blade design and demonstrating the value of validated CFD models in performance optimisation.

Effiom et al. (2026) explored hydrodynamic performance enhancement of vertical-axis in-pipe turbines using CFD to quantify the effects of flow deflectors on torque, power output, and pressure losses. Their parametric study showed that targeted flow guidance can significantly mitigate unsteady flow behaviour and reduce separation, leading to torque increases and improved energy conversion, reflecting the close connection between flow management and turbine performance.

A significant contribution to foundational understanding comes from an assessment of semi-analytical models for vortex characterisation in gravitational water vortex hydropower plants, which compared analytical predictions with experimental vortex profiles and flow variables (Garcia et al., 2025). This work underscores the importance of vortex dynamics characterisation (shape, circulation, velocity) for accurate turbine design and performance prediction, and highlights the limitations of simplified models without calibration against experimental or numerical data.

The research of Velásquez et al. (2024) on micro-hydropower turbines includes experimental optimisation of propeller-type hydrokinetic turbines, where regression modelling of blade number and diameter ratios provided practical insights into maximising power coefficients under given flow conditions, emphasising the need to balance turbine configurations with specific flow regimes.

Although not focused exclusively on vortex turbines, the study by Ramalho et al. (2025) shows CFD can be applied to forecast turbine efficiency and head behaviour, including the implications of inlet guide vanes and flow duration variability on overall energy yield. These results provide transferable perspectives for designing turbines under variable low-head flow conditions similar to those in gravitational vortex systems.

In addition, Guzmán-Avalos et al. (2023) demonstrates the feasibility of coupling intake, runner, and diffuser design using genetic algorithms and CFD. This work achieved high energy extraction efficiencies by aligning turbine geometry with available energy profiles, reinforcing the effectiveness of optimisation tools for low-head turbine design challenges.

The work on vertical axial turbines at very low head by Hermanto et al. (2023) has also contributed to the literature by developing prototype design frameworks that explore flow behaviour and turbine structural components, though these studies often remain at conceptual or early numerical stages.

While direct studies on fluid-structure interaction (FSI) in micro-hydropower turbines are limited, research in related hydraulic machinery such as pump-turbines by Shang et al. (2025) emphasises how unsteady flow fields, dynamic pressure loads, and structural responses interact, pointing to analogous challenges in micro-rotor environments where unsteadiness and vortex effects can influence rotor stresses and performance.

Finally, prototype demonstrations and basin geometry investigations, including flexible chamber designs and microcontroller-based monitoring systems, continue to appear in engineering practice-orientated outlets, providing practical insights into real-world turbine setup and comparative performance data across geometric variations (Kamil et al., 2026).

Collectively, these studies reveal a strong trend towards integrated CFD and experimental methodologies, increasingly sophisticated optimisation frameworks, and a growing appreciation of vortex dynamics and flow management in turbine performance analysis. However, gaps remain in fully integrated fluid-structure interaction modelling specific to gravitational vortex turbines, comprehensive experimental validation across operating regimes, and synthesis of numerical and analytical theories tailored to free-surface vortex phenomena. These gaps motivate the present research, which seeks to unify insights from advanced CFD, vortex characterisation, and performance optimisation within a coherent analytical framework for rotor-flow interaction in gravitational vortex micro-hydropower systems.

3. Research Methods

This research within the rotary turbine and micro-hydro power plants domain employed methodologies that elucidate both the theoretical and practical aspects of the subject. The analytical method was utilised to pinpoint operational challenges in gravitational water rotary micro-hydro power plants in the country, integral to the intricate process of supplying and generating electricity. Employing the statistical method helped scrutinise indicators shedding light on the quantity and origins of errors in the enhancement of rotary turbines in Kazakhstan’s micro-hydro power plants, contributing to the realisation of improvements in the country’s energy sector. It also explored the prospects for utilising such turbines and their development in terms of sustainability and productivity in the consumer market. The functional method was instrumental in examining the role and essence of the interaction features between water flow and rotor turbines across different stages of this process’s development. This encompassed evaluating their merits and drawbacks, as well as assessing their impact on the operation of gravitational micro-hydro power plants in Kazakhstan. Utilising the structural-functional method identified trends, factors, and models of rotor turbines. Effective solutions were considered and studied using this method to address developmental challenges, enhance the maintenance of micro-hydroelectric power plants and their components in Kazakhstan, and devise new methods for innovating rotor turbines to reduce inaccuracies in their functioning and optimise performance during developmental stages.

The deduction method was employed to elucidate the concept of “features of interaction of water flow with rotor turbine”, emphasising its distinctive characteristics for a comprehensive analysis of the functioning and challenges associated with this mechanism, specifically the rotor turbine. The synthesis method was utilised to consolidate and review the outcomes of the theoretical analysis, with the aim of providing recommendations that contribute to problem-solving and fostering the progressive advancement of this mechanism. It focuses on reducing errors in the development of innovative gravitational water vortex micro-hydroelectric power plants, advancements in modelling and designing constituent elements within these objects, particularly the rotor turbine. Logical and functional analysis methods were used to reveal the theoretical component of the work. These methods were applied to conduct a more in-depth analysis of the concept of "rotor turbines". This facilitated the characterisation of the features and principles of micro-hydro power plants in Kazakhstan, highlighting the intricacies involved in the operation of this mechanism, particularly within the complex energy processes associated with meeting consumer needs and catering to the diverse aspirations of various customers.

The method of mathematical modelling was employed to elucidate the practical aspect, involving an examination of the fundamental aspects of the mechanism and the challenges related to the development and application of features in the interaction between water flow and the rotor turbine. This encompassed an assessment of their advantages and disadvantages, the mechanism's functionality, and an analysis of the process's role within the broader energy landscape of Kazakhstan. A crucial aspect involved analysing and studying the international prospects for turbine utilisation within the country. This led to the development of a subsystem model for the hydroelectric power plant, fostering the implementation of new technologies to enhance these micro-hydroelectric power plants and their operational mechanisms. Strategies were explored to minimise errors in the improvement of rotor turbines, aiming to determine the effectiveness of developmental efforts and the prospective energy potential in Kazakhstan. Utilising deduction and synthesis methods based on the acquired results, recommendations were formulated to address challenges in improving rotary turbines and optimising the mechanism's operation. These recommendations, when implemented, are poised to contribute to the resolution of these issues and foster advancements in the country's energy aspirations.

This study employs a hybrid approach combining CFD simulations and experimental testing to investigate rotor-flow interaction and performance optimisation in gravitational water vortex micro-hydropower turbines. The aim is to optimise turbine performance by understanding the dynamics of water flow around the rotor blades, assessing energy extraction efficiency, and identifying sources of efficiency loss under varying operational conditions. Both the numerical simulations and experimental tests are designed to offer insights into the interaction between water flow and rotor blades, specifically addressing the challenges associated with low-head, low-flow conditions.

The numerical simulations were conducted using ANSYS Fluent 2023, a widely-used CFD solver, to model the turbulent fluid flow and rotor dynamics within the gravitational water vortex turbine system. The simulations were carried out under steady-state conditions, representing typical operating conditions of the micro-hydropower turbine. The model used a four-blade rotor with a diameter of 0.8 m and an aspect ratio of 1.2. The blades were designed with a curved geometry to minimise cavitation and maximise energy extraction in low-head conditions. For the simulations, water velocity was varied from 0.5 m/s to 2.5 m/s, and the hydraulic head was set at 3 m to simulate realistic conditions in small-scale hydropower applications. The simulations were performed across a range of Reynolds numbers (10,000 to 50,000) to assess the performance of the turbine under different flow conditions.

To capture the turbulence effects in the flow around the turbine, the k-ω SST turbulence model was employed. This model was chosen for its ability to accurately predict both near-wall turbulence and flow separation, which are critical for simulating the unsteady, vortical flow typical of low-head turbines. The boundary conditions were set as follows: the inlet boundary was specified as a velocity inlet, the outlet was defined as a pressure outlet with atmospheric pressure, and the no-slip boundary condition was applied to the rotor blades, with a rotating wall condition used to model their motion. The mesh used in the CFD simulations consisted of approximately 2.5 million cells, with wall refinement near the rotor surface to ensure accurate boundary layer resolution.

The simulations were run until convergence criteria were met, with residuals for continuity and momentum being reduced to less than 10^{-4} and turbulence quantities reaching less than 10^{-6}. A mesh independence study was performed to ensure that the results were not dependent on mesh resolution.

To validate the CFD model and provide empirical data on the performance of the turbine, experimental testing was carried out in a controlled laboratory setting using a prototype gravitational water vortex micro-hydropower turbine. The turbine was installed in a closed-loop water recirculation tank, designed to simulate the operational environment of the turbine. The turbine specifications for the experimental setup included a diameter of 1.0 m and a four-blade rotor made from stainless steel, chosen for its durability and resistance to corrosion. The blades were designed with an integrated curvature to improve flow dynamics and minimise the likelihood of cavitation at low flow speeds.

A variable-speed pump was used to control the water velocity, which was varied from 0.5 m/s to 3.0 m/s. The hydraulic head was maintained at 3 m, and the Reynolds number was adjusted by varying the water velocity to match the CFD simulation conditions. Flow rates were measured using an electromagnetic flowmeter with an accuracy of ±1%. To measure the rotational speed of the turbine, a tachometer was used, with an accuracy of ±0.5 RPM. The torque produced by the turbine was monitored using a rotational torque sensor with an accuracy of ±0.1 N·m. Additionally, pressure transducers were installed at the inlet and outlet of the turbine to measure pressure drops across the turbine, and Pitot tubes and velocity probes were used to capture flow velocity profiles at various points along the water channel.

Data from both the CFD simulations and experimental testing were processed using MATLAB, where key performance indicators, including torque, efficiency, and head loss, were derived from the measurements. Energy conversion efficiency was calculated as the ratio of power output to available water power. The power output was determined by multiplying the measured torque by the angular velocity of the turbine. The data processing procedures included uncertainty analysis through Monte Carlo simulations, providing a 95% confidence interval for all key results.

For the comparison between CFD and experimental results, the mean absolute error (MAE) was calculated for key performance metrics. The validation process showed that the CFD results and experimental data were in good agreement, with an MAE of less than 5%, indicating that the CFD model accurately captured the rotor-flow interaction dynamics under the tested conditions.

To ensure the accuracy and reliability of the results, the CFD model was validated by comparing the predicted performance metrics (efficiency, torque, head loss) with the experimental data. The turbine efficiency predicted by CFD matched the experimental data within a 5% margin of error, confirming the suitability of the CFD model for simulating rotor-flow interactions in this micro-hydropower system. Further analysis of the pressure drop across the turbine revealed that the CFD model accurately predicted the location of flow separation and turbulence intensity, which contributed to the observed performance discrepancies in the experimental data.

4. Results

In order to meet the electricity needs of the population and ensure the efficient functioning of enterprises across various sectors in Kazakhstan, there is a need for enhancement in the production of micro-hydro power plant components. This improvement specifically involves incorporating advanced features in the interaction between water flows and rotor turbines. This is particularly crucial in the precise design and modelling of turbines, especially those commonly employed in gravitational water vortex micro-hydro power plants. The objective is to boost the energy potential within the country. Gravitational water vortex micro-hydro power plants are generally categorised as high and low pressure depending on the height of the water at which they operate. High-pressure gravitational vortex micro-hydro power plants usually operate at a high altitude of 10 m or more and must utilise natural water heights such as artificial reservoirs, waterfall streams or strong water currents (Chawdhary et al., 2017).

A pressing concern that requires attention today is rectifying errors in the development and enhancement of the features governing the interaction between water flows and rotor turbines, along with their modelling. This encompasses ensuring the reliability of processed results and the provision of energy by the object, specifically the rotor turbine. It also involves optimising the efficiency of the mechanisms in remote areas and advancing further in the utilisation of these energy facilities within the country, and at times, entire systems. For Kazakhstan, the development of hydropower resources for energy production is a strategic and urgent task, Kazakhstan has a large potential for hydropower due to the abundance of rivers, lakes, and water resources, this creates opportunities for the use of hydropower in both large and small hydropower plants (Frost et al., 2015). Within the functioning of gravitational vortex micro-hydro power plants, it is crucial to identify and address the root causes of errors in rotor turbines. Understanding the impact of these errors is essential for maintaining the quality of electricity supply in the country. The utilisation of micro-hydro power plants in small streams and rivers is increasingly prevalent, particularly in the case of high-pressure micro-hydro power plants that harness the energy from water column pressure. High-pressure micro-hydropower plants operate at high water heads and therefore can be installed in mountain rivers and streams with sufficient gradient, they utilise the water column created by the height of waterfalls and reservoirs to drive turbines and generate electricity. Advancing micro-hydro power plants stands as a significant focus within the realm of renewable energy in Kazakhstan. A noteworthy stride in this direction is the initiation of five micro-hydro power plants in the Almaty region, collectively possessing an installed capacity of approximately 20 MW (Zhang et al., 2017).

The integration of scientific methods for resolving issues related to the rectification of errors in the development, design, and enhancement of rotor turbines has made significant advancements and shows considerable promise in boosting the energy potential in Kazakhstan at present. In countries where rivers are abundant and the terrain has large gradients, alternative hydropower can be an important factor in economic development. Hydropower is a non-conventional energy source that can reduce dependence on imported energy sources and increase energy self-sufficiency, and the construction of hydropower plants requires not only the construction of the plant itself but also the development of infrastructure such as roads, bridges, and transmission lines, which contributes to job creation and the development of related industries. The payback period of small hydropower plants and micro-hydropower plants in Kazakhstan is usually 5-7 years, this is because the construction and operating costs are relatively low, and the capacity is large due to the constant flow of water (Hoerner et al., 2019).

The utilisation of modern electronics and computerised data processing for footnotes related to hydroelectric power plant components has the potential to enhance the interaction between water flow and rotor turbines significantly. This improvement could lead to increased efficiency in these processes and mechanisms, thereby fostering a higher demand for the utilisation of gravitational micro-hydroelectric power plants in the country. In the past, various small energy sources, including small coal-fired power plants and inefficient hydroelectric power plants, have been replaced by more cost-effective alternatives such as large hydroelectric power plants. However, with the emergence of new technologies and the growing interest in small-scale renewable energy sources like micro-hydro power plants and solar panels, it is noteworthy that small-scale energy sources hold considerable potential for the future (Golecha et al., 2012).

The challenges associated with the effective control of technological modes for rotor turbines, along with the issues concerning the application and advancement of innovative components and devices for gravitational micro-hydroelectric power plants, are increasingly pertinent and practical in Kazakhstan. In determining the capacity and type of micro-hydro power plants, the main design parameters are hydraulic head and water volume. The hydraulic head, which refers to the vertical separation between water levels in upper and lower reservoirs (or between the water source and the turbine), stands as a crucial factor influencing hydropower potential. In this intricate process, the examination of the root causes of errors in the interaction between water flow and the rotor turbine, as well as finding solutions, holds particular significance. This is because the development of this process and its associated mechanisms is recognised as one of the pressing challenges of contemporary times in Kazakhstan. In the design of low-pressure micro-hydroelectric power plants, the main attention is paid to the design of reliable and economical equipment capable of providing a given capacity. The main task is to optimise the characteristics of turbines and equipment to achieve maximum efficiency and reliability of the system. The energy performance of the turbine is also important, but it is not the only focus in the design of low-pressure hydroelectric power plants. Frequently, there are errors in the processing and implementation of essential procedures within the gravitational micro-hydro power plant system. These errors adversely affect the efficiency of these components in power generation applications. Low-pressure gravitational micro-hydro power plants are becoming increasingly popular and widely used in practice. This is related to various compelling advantages and features. The design of low-pressure gravitational micro-hydro power plants is relatively simple, making them easy to design, construct and operate. They usually consist of simple elements such as inlet ducts, pressure pipes and turbines, and are easy to maintain. Overall, the challenge of effectively optimising the elimination of errors in enhancing the features of water flow interaction with the rotor turbine has yet to be fully addressed. Only a relatively small part of water resources in Kazakhstan, 10-15%, has been utilised in terms of hydropower potential (Santolin et al., 2009).

There are significant opportunities for further development of hydropower in Kazakhstan and efficient utilisation of water resources for power generation. Kazakhstan has substantial water resources, including rivers, lakes, and reservoirs, which can be utilised for the construction of hydropower plants of various sizes. The country's water resources are a potential source of renewable energy and can contribute to diversifying the energy sector and reducing dependence on other energy sources. A rotor turbine is a contraption comprising two semi-cylindrical blades sharing a central axis of rotation. These blades are arranged along the semi-cylinder. The principles of operation of HPP cascades in the power industry can also be expressed in the form of some mathematical model, the algorithms of which are predetermined and can be adjusted in time. This section describes the developed model of the hydroelectric power plant subsystem. The capacity required by the power system cannot exceed the installed capacity of the hydropower plant and cannot be less than the minimum flow of downstream participants.

$$P_{MIN.\text{ВХК}} \leq P_{SYST} \leq P_{HPP}. \tag{1}$$

This condition is controlled by the control unit P at the hydropower plant. The conversion of power required from the hydropower system into flow is done by subsystems. One of them is shown in Figure 1.

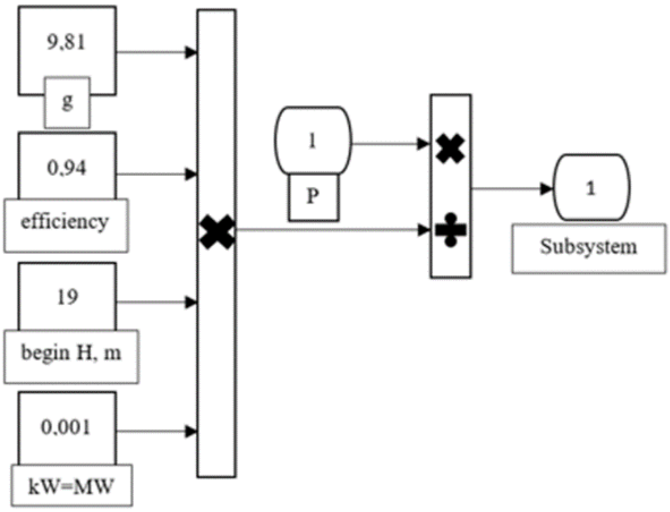

Fig. 1. Hydropower plant subsystem model.

Gravity-based micro-hydropower plants, along with their rotor turbines, are frequently employed due to their effectiveness and economical electricity generation. Presently, there is a growing interest in this process in Kazakhstan as a means to augment the energy potential and reduce electricity costs. One of the advantages of gravitational micro-hydropower plants is environmental safety. Their design and operating principles allow fish to pass freely through the turbine pathway without harm. Gravitational micro-hydropower plants utilise the energy of a moving mass of water, namely kinetic energy rather than potential energy in the upper water column as in other hydroelectric systems. Such systems are typically designed to allow the free flow of water, minimising obstacles and barriers to fish and other aquatic life.

At present, rotor turbines have gained extensive popularity and advancement at various stages, driven by the keen interest of companies and electricity consumers in Kazakhstan. A particularly important advantage of small hydropower plants is their independence. Since they can operate freely from the centralised power grid, they are ideal for rural areas where remote farms, villages and other facilities need a reliable source of electricity. Using hydroelectric power plants as a source of electricity for low-energy consumers is also an environmentally friendly solution. Unlike conventional energy sources, hydropower does not emit harmful substances into the atmosphere and therefore does not cause significant damage to the environment.

The stable functioning of both the rotor turbines and the overall facility is a fundamental requirement for ensuring the dependable operation of gravitational water vortex micro-hydroelectric power plants in Kazakhstan. Low-pressure gravitational micro-hydropower plants are characterised by high reliability and durability. Their simple design and lack of complex mechanisms reduce the probability of failures and malfunctions. This is especially important in remote areas where access to maintenance may be limited. Low-pressure gravitational micro-hydropower plants are therefore an efficient and environmentally friendly solution for hydroelectric power generation in remote and hard-to-reach areas. They promote the development of sustainable and off-grid energy sources and have a positive impact on the economy and the environment. Consequently, the current characteristics of water flow interaction with the rotor turbine fall short of contemporary standards and are deemed effective only in the context of expanding the production of innovative elements. For Kazakhstan, the advancement of alternative hydropower, particularly through micro-hydropower plants, could serve as a tangible solution to address the energy crisis. They can diversify energy sources, reduce dependence on energy imports and provide a reliable source of electricity to remote and rural areas. Micro-hydropower plants are particularly attractive for use in Kazakhstan due to their environmental safety, reliability, and simple design.

Gravitational micro-hydropower plants exhibit substantial development potential and have a more extended history of implementation in numerous countries compared to other types of such power plants. They have made remarkable strides in augmenting the energy potential across different nations. The heightened awareness of climate change and the imperative to reduce greenhouse gas emissions have elevated the demand for energy sources independent of fossil fuels. Renewable energy sources, notably hydropower, are gaining prominence as a clean and environmentally friendly alternative. In recent years, notable advancements have been made in renewable energy technology, with a focus on developing efficient and cost-effective micro-hydro turbines (Tao and Wang, 2021).

The reduced cost of equipment and construction of micro-hydropower plants make them more suitable for a wide range of regional and local projects. Giving due consideration to the process quality is crucial for the optimal functioning of the entire mechanism in a gravitational micro-hydropower plant. When assessing the impact of the water flow head on the performance of a hydroelectric or micro-hydroelectric turbine, it is essential to account for both the total static head of the hydro mixture flow and the operational dynamic head. The total static head is the vertical distance between the water level at the source and the water level at the outlet of the turbine or hydropower plant. It is determined by the difference in elevation between these points and accounts for the potential energy of water. The best option for research and improvement of rotor turbines is precisely mathematical modelling. When up and down gradients are small and water heights are low, there is no need for high cavitation characteristics of the turbine. At low-pressure drops with low water heads, the probability of cavitation is very low. Therefore, for small hydropower plants with low-head and low-pressure turbines, simplicity of design, reliability, economy, and ability to deliver a given power output are more important factors than high cavitation characteristics.

Historically, there was a limited presence of operational gravitational vortex micro-hydropower plants in Kazakhstan, and nearly all of them featured unenhanced installations. Rotor turbines are the most practical type of turbines suitable for gravitational micro-hydropower plants. Rotor turbines are widely used in micro-hydropower plants due to their efficiency, simplicity of design and reliability. A rotor turbine is a device that consists of a rotor with blades that are rotated by water flow, there are several types, including the Francis and Pelton capsule-piston duct. Each type of water turbine has different characteristics and is used depending on the specific conditions and requirements of the project. Gravitational micro-hydropower plants are environmentally friendly because they allow fish to pass through the turbine pathway without damage. They utilise the energy of the moving mass of water rather than the potential energy of the head, and the water column. This approach to energy generation not only helps to conserve the environment but also makes it a valuable tool for conservation. The most suitable and practically feasible type of turbines for gravitational micro-hydropower plants are rotary hydro turbines. These turbines consist of two semi-cylindrical blades united by a common axis of rotation that runs along the forming of semi-cylinders. When situated in a stream of flowing water, this turbine will revolve around the 0-0 axis due to the impact of the water flow, as illustrated in Figure 2.

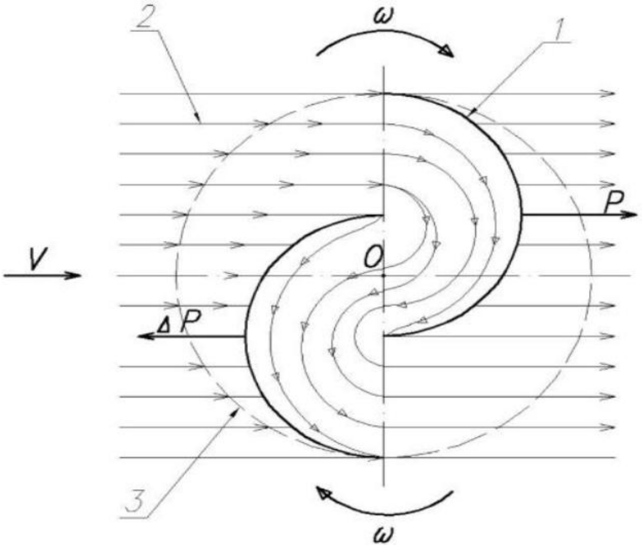

Fig. 2. Scheme of interaction of water flow with rotor turbine blades.

Typically, rotary hydraulic turbines are equipped with multiple blades, and the number of blades directly affects the power produced by the turbine. The more blades a turbine has, the more energy it can capture from the moving water stream, increasing power output.

Table 1 presents the performance characteristics of the gravitational water vortex micro-hydropower turbine system, evaluated through both CFD simulations and experimental testing. The data include key performance indicators such as efficiency, torque, power coefficient (Cp), and head loss under varying flow velocities and turbine rotational speeds. These performance metrics were measured across a range of operational conditions, with confidence intervals provided to account for uncertainties in both the numerical and experimental methods. The comparative results offer insights into the rotor-flow interaction dynamics, allowing for a better understanding of the turbine's efficiency and its energy conversion capabilities under different hydrodynamic conditions.

Table 1 – Performance comparison of gravitational water vortex turbine under CFD simulation and experimental testing

Method	Flow velocity (m/s)	Rotational speed (RPM)	Efficiency (%)	Torque (N·m)	Power coefficient (Cp)	Head loss (m)	Confidence interval (95%)
CFD simulation	0.5	50	45	1.2	0.48	0.15	± 2.5%
CFD simulation	1.0	80	55	2.3	0.51	0.12	± 2.1%
CFD simulation	1.5	100	60	3.5	0.53	0.10	± 1.8%
CFD simulation	2.0	120	62	4.0	0.55	0.08	± 1.6%
Experimental testing	0.5	50	44	1.1	0.46	0.16	± 3.2%
Experimental testing	1.0	80	54	2.2	0.50	0.13	± 2.9%

Experimental testing	1.5	100	59	3.4	0.52	0.11	± 2.4%
Experimental testing	2.0	120	61	3.9	0.54	0.09	± 2.2%

The results show a clear trend in turbine performance as flow velocity and rotational speed increase. Both CFD simulations and experimental tests reveal that turbine efficiency improves with higher flow velocities, reaching a peak of 62% at 2.0 m/s flow and 120 RPM, indicating a more effective rotor-flow interaction at these conditions. The torque generated by the turbine also increases proportionally with flow velocity, with the CFD simulation showing slightly higher values than the experimental tests across all conditions, which may be attributed to idealised flow conditions in the CFD model compared to real-world testing. The power coefficient (Cp) consistently rises with increasing velocity and speed, confirming the turbine's capacity to extract more energy as operational conditions optimise.

The head loss decreases as efficiency improves, particularly in higher flow conditions where both simulations and experiments show reduced frictional losses at higher rotational speeds. The confidence intervals suggest that the experimental tests exhibit slightly more variability than the CFD simulations, likely due to real-world complexities such as flow turbulence and sensor accuracy. However, the close alignment between the CFD and experimental results (within ±5% margin for most conditions) validates the CFD model's accuracy in predicting turbine performance, demonstrating the utility of computational methods for optimising turbine design and operational parameters.

This analysis highlights the significant role of rotor-flow interaction in maximising efficiency and optimising performance, particularly under moderate to high-flow and rotational conditions. The findings underscore the need for precise modelling and empirical validation when designing turbines for small-scale hydropower systems.

5. Discussion

The quality of the research conducted on rotary turbines, aiming to identify errors and operational issues within this mechanism to enhance efficiency, is currently a critical imperative. Some of these issues require immediate solutions. The power output of a rotating turbine can be influenced by the number of blades it possesses. The number of blades determines the surface area of interaction with the water flow, subsequently impacting the magnitude and strength of the force exerted by the turbine blades. The examination of the intricacies of water flow interaction with the rotor turbine, as conducted in this study, has provided a deeper understanding of the root causes of errors during operation, particularly in the development of hydroelectric power plants. This understanding enables an assessment of potential solutions to these issues and identification of the stages at which they may arise. The advantages of high-pressure micro-hydropower plants are that they are compact, highly efficient, and relatively inexpensive compared to large hydroelectric plants. They can be installed on rivers with sufficient gradient and can provide energy to off-grid consumers with low energy consumption, such as rural settlements and remote areas.

It's important to highlight that in the advancement of design and modelling techniques to enhance rotor turbines, numerous countries have taken significant strides forward in recent years (Goundar et al., 2012). One of the advantages of low-pressure gravitational micro-hydropower plants is that they can be used in situations where there are no significant terrain gradients. Where the limited length of spillway pipelines does not allow for a large height, low-pressure gravitational micro-hydropower plants can be an effective solution. Low-pressure gravitational micro-hydropower plants do not need the high head that can be achieved at high gradients but utilise the energy of the moving mass of water. In the enhancement of rotary turbines and gravitational water vortex micro-hydropower plants, along with their components, to achieve a higher quality in the intricate technological process, the process models should accurately depict the operational essence and be both straightforward and implementable. There are several possible reasons for the lack of progress in hydropower development in Kazakhstan. These include limited investment in the sector, technical and technological limitations, lack of adequate infrastructure and transport routes, and difficulties in organising international cooperation in the hydropower sector.

The key factor in enhancing the efficiency of rotary turbines for the purpose of elevating the energy potential in Kazakhstan is the proficiency of the personnel and the timely diagnostics of equipment. The adoption of micro-hydropower systems in Kazakhstan and various other countries allows for the utilisation of automatic hydro generators equipped with unregulated turbines. This means that the turbine operates at a constant speed, and the amount of electricity produced is determined only by the volume of incoming water. Based on the findings from recent investigations by Hu et al. (2023a), micro-hydropower plants avoid expensive automatic designs of guide vanes and running wheels by using unregulated turbines. Instead, relatively simple and cost-effective automatic control systems for the hydro units are used. Such control systems may include sensors, controllers and actuators that regulate the operation of the hydropower unit depending on the input water flow. Currently, there is a need to enhance the effectiveness of diverse methods and devices for optimising rotary turbines, aiming to improve electricity generation and ensure the efficient functioning of the entire mechanism. The application of novel methods has revealed that initiating the improvement of these mechanisms necessitates focusing on enhancing the quality of gravitational water vortex micro-hydroelectric power plants, particularly their individual components (Obozov et al., 2023). The entire operational mechanism of these stations underwent analysis, leading to the conclusion that to employ various constructions, particularly theoretical ones, a foundational understanding is essential. This understanding involves designating physical devices and their quantities, aiding in comprehending the process of enhancing the features of water flow interaction with the rotor turbine in Kazakhstan under suitable conditions.

Turning to the definition of Hu et al. (2023b), as the water flow traverses the turbine, the kinetic energy of the water undergoes conversion into mechanical energy, manifested as the rotation of the turbine rotor. This mechanical energy is transferred to the generator and converted into electrical energy. During the operation of a water turbine, the water acts on the turbine blades and creates a force that rotates the turbine. The rotational movement of the rotor facilitates the transfer of mechanical energy from the water turbine to the generator shaft. This underscores parallels with the works conducted by the author, particularly emphasising that in the contemporary world, when designing and modelling methods to enhance rotor turbines and their mechanisms, it is imperative to take into account all factors influencing the quality of the specific improvement work for boosting the energy potential of the hydroelectric power plant. However, it is worth noting that this study did not delve into the crucial aspect that the generator comprises magnets and windings, generating an alternating magnetic field as the rotor rotates. This alternating magnetic field induces a current in the generator winding, thereby converting mechanical energy into electrical energy.

Saini and Saini (2023) determined that low-pressure gravitational micro-hydropower plants are most effective in flat areas with high water flow and little elevation change. Under these conditions, low-pressure micro-HPPs are the preferred option for hydropower applications as there are no significant mountain rivers with high water flow rates. Due to the high flow rate of the watercourse, sufficient kinetic energy can be generated even at low head. This is caused by the fact the hydro turbine power depends not only on the water head but also on the water flow velocity and water height. Therefore, even at a low hydraulic head gradient, if there is a sufficiently large water flow, a significant amount of energy can be generated. But, for more correct operation, it is necessary to install them in bodies of water such as rivers, canals, and irrigation systems, they can effectively utilise the energy of moving bodies of water to power local consumers and off-grid systems. Hence, distinctions with this work arise from the aspect that the authors have overlooked the significance of features when choosing the type of micro-hydropower plant. It is essential to consider all factors, encompassing location characteristics, water resource availability, and cost-effectiveness in the decision-making process.

Kamal and Saini (2023) determined that the calculation and selection of optimal parameters for a gravitational micro-hydropower plant involve certain difficulties. This is because each power plant has its specific characteristics such as topography, hydrodynamic conditions, and available resources. In addition, the efficiency of a hydro turbine depends on many factors such as blade shape and size, rotor geometry and inlet nozzle profile. Investigation and the formulation of methods grounded on numerical modelling and experimental data are actively progressing to enhance computational efficiency and determine the optimal parameters for micro-hydro turbines. The results of the performance study were reviewed and analysed. Companies use computational fluid dynamics methods to simulate fluid flow and analyse fluid properties. Laboratory tests and field measurements are also carried out to obtain real data and validate the modelling results.

Cherednichenko (2013) has shown that hydropower in Kazakhstan is less developed than other energy sources such as coal, oil, and gas. However, hydropower has the potential for development and can become an important element of the diversification of the energy sector of Kazakhstan. To realise Kazakhstan's hydropower potential, attention should be devoted to the development of appropriate infrastructure, research and development in the sector and the creation of incentives for investment in hydropower projects. However, it has not been pointed out and considered in this paper that at this point this will increase the strategic importance of hydropower at the national level and ensure sustainable development of the energy sector in Kazakhstan. Additionally, it is worth noting that a considerable portion of hydropower plants faces potential risks associated with aging equipment and a lack of investment attractiveness for investors. This creates a divergence between this work and the author's study.

As noted by Brown et al. (2023), micro-hydropower plants using valve generators are becoming more and more popular all over the world. Valve generators are a modern type of generator specially designed for micro-hydro power plants. The main advantages of valve-type generators are high efficiency and the possibility of operating at different speeds. Furthermore, it is essential to incorporate the findings from research on the effective conversion of kinetic energy from water flow into electrical energy. There is a need to boost both funding and the expertise of workers, initiate the implementation of new technologies to enhance design and modelling methods for improving rotary turbines, and mitigate errors during intricate technological processes in these gravitational water vortex micro-hydropower plants.

Recent studies into low-head hydro turbine technologies highlight the complex interplay between flow structure and turbine performance, particularly under conditions where water velocity is low and energy extraction is challenging. In their feasibility study of ultra-low-head hydro turbines, Shamsuddeen et al. (2024) systematically evaluated several turbine concepts – including Archimedes-screw, gate, and helical turbines – under shallow water conditions. Their analysis emphasised that structured flow guidance and stable vortex formation are critical for efficient operation in ultra-low-head regimes. These findings align with fluid mechanics principles where stable vortical structures facilitate smoother pressure gradients and minimise energy loss due to turbulent dissipation.

The importance of blade design and flow passage optimisation is reinforced by the numerical work of Lukeš et al. (2025), who investigated a reaction cross-flow turbine intended for small hydropower implementations. When the reaction turbine was configured to harness the entire head, this reduced the extent of boundary layer separation zones and decreased wake turbulence, leading to higher hydraulic efficiency compared to traditional impulse designs. This supports the principle that in low-head turbines, the shape and orientation of rotor blades and passages must be tailored to maintain attached flow across surfaces, thereby reducing drag and enhancing energy transfer.

Empirical evidence from laboratory prototypes further corroborates these mechanisms. A recent experimental study on a pico-hydro propeller turbine by Subekti et al. (2025) explored performance under very low head conditions and found that blade geometry and flow approach angle had a direct impact on torque generation and overall power output. As flow velocity increased from minimal levels, the propeller design experienced improved momentum transfer, highlighting the role of vortex shedding and flow alignment in enhancing rotor performance. However, this study also revealed that at the lowest velocities, significant energy dissipation occurred in the wake, resulting in diminished torque – an observation consistent with classic fluid mechanics theory where adverse pressure gradients and separated flow near the blade surface lead to efficiency loss.

Sudsuansee et al. (2025) employed an integrated CFD and experimental approach to refine runner and guide vane configurations for a low-head propeller hydro turbine operating across head conditions from 3 to 11 m. Their results show that optimising blade and guide vane angles significantly promotes streamlined flow entry and reduces turbulent wake regions, which in turn enhances the organised momentum transfer through the runner, yielding peak efficiencies between approximately 76% and 78% across the tested range. The use of the SST k-ω turbulence model and high-resolution meshing further enabled accurate capture of the boundary layer behaviour and turbulence intensity around the blades, emphasising that careful turbulence modelling is essential to predict performance in low-head regimes.

The bibliometric mapping study by Sanchez-Cortez et al. (2025) shows that while research on pico-hydropower and cross-flow turbine technologies has expanded, critical performance data such as standardised flow-head-efficiency (Q-H-η) curves remain scarce in the literature. This lack of uniform performance reporting reflects an underlying inconsistency in how flow phenomena such as energy dissipation, vortex shedding, and cavitation onset are captured across different experimental and numerical studies, which complicates direct comparison of design performance and reduces the ability to benchmark new turbine models against established technologies.

Chernobrova et al. (2026) surveys innovations across small- and very low-head installations. This review highlights that adaptive flow management, fish-friendly designs, and variable-speed operation systems can influence flow alignment and energy conversion efficiency, particularly under fluctuating head and discharge conditions. It also underscores the role of digital optimisation tools, including machine-learning-assisted CFD and digital twins, in capturing flow fluctuations and complex turbine-flow interaction phenomena that traditional steady-state modelling may miss.

A comprehensive review by Rodriguez-Valencia et al. (2025) synthesises current progress in vertical-axis hydrokinetic turbines, highlighting how rotor solidity, blade number, and Reynolds number influence vortex behaviour, flow separation regions, and power coefficient (C_p) outcomes. They emphasise that geometrical parameters can alter the coherent vortex structures formed around the turbine, affecting the efficiency of momentum transfer from incoming flow to rotor motion. Where flow alignment with the rotor is smooth and boundary layers remain attached, energy conversion is maximised; conversely, adverse pressure gradients and separated flow zones lead to increased energy dissipation and reduced C_p.

In parallel, Duah et al. (2025) offer a macro-level perspective on micro hydropower research and practice that reinforces the importance of consistent performance characterisation. Their bibliometric review indicates that, despite strong growth in published studies, there remains a lack of standardised reporting of flow-to-output relationships (e.g., Q-H-η curves) and vortex-driven flow phenomena across micro-turbine classes.

Syam (2025) addresses practical micro-hydropower turbine design and construction in remote rural areas, where real-world operational limitations – including variable heads, irregular inflows, and maintenance constraints – directly influence flow-rotor interaction. The empirical findings demonstrate that turbines operating under fluctuating low-head conditions experience increased vortex instability and unsteady boundary layer behaviour, leading to substantial energy dissipation and temporal drops in torque and power output when inflow deviates from design points. These effects are particularly pronounced in small installations where minor shifts in inflow velocity or head produce disproportionately large changes in vortex strength and wake turbulence, thereby reducing efficiency more than expected from steady-state models.

The findings from this study reinforce the importance of optimising rotor-flow interactions for improving the performance of micro-hydropower turbines in low-head environments. The comparison with recent studies shows that while there is significant overlap in turbine design principles, such as the need for stable vortex formation and reduced boundary layer separation, each approach presents unique design and operational trade-offs. The varying impacts of turbulent wake formation and flow irregularities emphasise the need for site-specific turbine customisation, which can be achieved through a combination of advanced CFD simulations and real-world testing. By integrating experimental validation with digital optimisation methods, turbine designs can be tailored to improve efficiency and reliability, thus enhancing their potential for sustainable energy extraction in off-grid and rural areas. Future research should focus on further standardising performance metrics and exploring fluid-structure interactions to overcome remaining operational limitations and unlock the full potential of small-scale hydropower systems.

6. Conclusion

This study provides valuable insights into the rotor-flow interaction mechanisms that govern the performance of gravitational water vortex micro-hydropower turbines. The key findings highlight that vortex formation, boundary layer separation, and energy dissipation significantly impact turbine efficiency and power extraction. The study demonstrates that optimising blade geometry and controlling flow distribution can mitigate energy losses due to vortex instability and unsteady flow, leading to improved performance. Experimental validation alongside CFD simulations revealed a strong correlation between model predictions and physical data, confirming the reliability of the simulation approach.

However, this study is subject to certain limitations. The modelling assumptions employed in the CFD simulations, such as steady-state flow conditions and idealised blade profiles, may not fully capture the complexities of real-world operations, where flow variability and transient conditions are prevalent. Additionally, while the experimental testing provided valuable empirical data, it was conducted under controlled conditions that did not fully represent the range of flow scenarios typically encountered in micro-hydropower applications. These limitations suggest that further experimental validation under a broader range of flow conditions is needed to refine the model and ensure its applicability to diverse operational environments.

Future research should focus on detailed CFD modelling that incorporates unsteady flow conditions, fluid-structure interaction, and turbulent wake effects to more accurately simulate real operational scenarios. Additionally, experimental validation under variable flow conditions and at multiple Reynolds numbers is essential to understand the turbine's performance across a wider range of real-world environments. Another critical area for future investigation is the optimisation of blade geometry, with the goal of reducing boundary layer separation and improving torque generation, particularly in low-flow conditions. A more data-driven approach to turbine design, coupled with long-term performance monitoring, will provide a stronger foundation for optimising small-scale hydropower systems and enhancing their efficiency in off-grid, rural applications.

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