

Design and Development of a Micro-Hydro Vortex Turbine Prototype with Cylindrical and Conical Basins Using a Hybrid Microcontroller-Based Solar Energy System for Renewable Energy Practicum at Politeknik Negeri Medan

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ABSTRACT

This study aims to design and develop a prototype of a micro-hydro vortex turbine featuring two geometric variations—cylindrical and conical basins—as a practicum tool for the Renewable Energy course at Politeknik Negeri Medan. The system is equipped with a microcontroller-based digital control unit to monitor real-time water discharge, and it utilizes solar energy as the primary power source. The research adopts an engineering experimental approach, encompassing the design, fabrication, hydraulic performance testing, and integration of the monitoring system. The expected outcomes include a functional prototype, an integrated monitoring method, comparative performance data for different turbine geometries, and educational outputs such as practicum modules and instructional videos. These findings are anticipated to contribute to the advancement of laboratory-scale renewable energy technologies and serve as an interactive educational medium in vocational micro-hydro learning systems.

Keywords: Vortex Turbine, Micro-Hydro, Renewable Energy, Microcontroller, Solar Energy, Cylindrical Geometry, Conical Geometry, Prototype, Digital Monitoring

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INTRODUCTION

The development of new and renewable energy (NRE) has become a global priority in response to the fossil energy crisis and climate change. NRE sources include water, wind, geothermal, and solar energy. In Indonesia, hydropower holds significant potential, yet remains underutilized—particularly in rural areas where low-head river flows are common. Hydropower generation using water energy is commonly known as Micro Hydro Power Plants (MHPPs). These systems typically rely on high-head sources such as waterfalls. However, many regions in Indonesia feature rivers with moderate flow rates but low head heights, making them unsuitable for conventional MHPP systems. As a solution, Gravitational Water Vortex Turbine (GWVT) technology has been developed. This turbine type operates effectively at low head heights (0.7–3 meters) by converting flowing water into a vortex to rotate a turbine. Originally developed by Franz Zotlterer, this technology offers an environmentally friendly and low-cost alternative, particularly for remote areas [1].

A study by Dhakal et al. (2017) demonstrated that the vortex turbine achieved its highest efficiency at 100 rpm, with the lowest efficiency observed at 50 rpm [2]. Another study by Saleem et al. [3] investigated the performance of cylindrical vortex turbines based on vortex height, blade position, and blade shape. Their results indicated that conical blade tips produced higher rotational speeds but lower torque compared to flat-tipped blades. Maximum mechanical efficiency was achieved when the straight blades were fully submerged. Ullah et al. [4] analyzed a multi-stage vortex turbine with a conical design. While disturbances were observed in the lower vortex stage, the

overall efficiency surpassed that of single-stage systems. From the fluid dynamics perspective, Alzamora Guzmán and Glasscock (2021) studied the relationship between water height and vortex parameters such as vortex diameter and flow rate [5]. Meanwhile, Nishi et al. (2019) examined axial flow in water turbines and found that the presence of a runner could cause slipstream effects and turbulent vortex patterns downstream [6]. Based on this review, the present research aims to:

1. Analyze and compare the performance of vortex turbines with cylindrical and conical geometries at a laboratory scale.
2. Develop a digital water flow monitoring system using microcontrollers.
3. Integrate a solar-powered autonomous energy system.
4. Provide an innovative practical learning tool for renewable energy education.

This research addresses gaps in:

1. Hydrodynamic performance comparison of vortex basin geometries (cylinder vs cone),
2. The application of energy-efficient and microcontroller-based digital monitoring technologies,
3. The potential of vortex turbine prototypes as hands-on learning tools for vocational education.

While several studies have addressed basin geometries, blade configurations, and flow arrangements, few have systematically compared the effects of cylindrical versus conical basin shapes on outflow and flow stability through experimental and numerical simulation approaches at the lab scale.

Moreover, very few studies have integrated digital flow monitoring systems using microcontrollers into vortex turbine prototypes, especially systems powered by solar energy to ensure autonomous operation without reliance on the national electricity grid.

Furthermore, no research has yet explored the educational potential of such prototypes for vocational learning—despite the relevance of prototype-based learning to enhancing student competencies in renewable energy systems.

Problem Formulation

- a) How can a vortex micro-hydro turbine prototype be designed and built using two different geometries—cylindrical and conical—for laboratory-scale testing?
- b) How does the hydraulic performance differ between cylindrical and conical basin geometries based on the resulting water discharge?
- c) How can an accurate and efficient microcontroller-based water flow monitoring system be developed?
- d) How can solar energy contribute to making the monitoring system autonomous and sustainable?
- e) How feasible is the prototype as a practical learning tool for the Renewable Energy course at Politeknik Negeri Medan?

Scope and Limitations

The scope and limitations of this research are as follows:

- a. The study is limited to two vortex turbine geometries: cylindrical and conical.
- b. Testing is conducted at laboratory scale, not on natural rivers or streams.
- c. The monitoring system uses a microcontroller and flowmeter sensor, without IoT integration.
- d. The power supply is limited to a 250 Wp solar panel, a 12V 100Ah battery, and a standard charge controller.
- e. Performance parameters are limited to water discharge and flow stability.
- f. The prototype is intended solely for educational purposes in the Renewable Energy course (micro-hydro focus), not for commercial or industrial deployment.

METHOD

Research Methodology

This study applies an engineering experimental research method combined with a comparative approach. The aim is to design, build, test, and analyze the performance of a micro-hydro vortex turbine prototype using two different basin geometries—cylindrical and conical—at a laboratory scale.

The stages of the research methodology include:

1. Designing the vortex turbine prototype with two basin geometries.
2. Fabrication and assembly of the mechanical, hydraulic, and digital monitoring systems.
3. Experimental testing of hydraulic performance for each geometry.
4. Measurement and data acquisition of water discharge and flow stability using a flowmeter sensor integrated with a microcontroller-based system.
5. Analysis and comparison of performance between the cylindrical and conical geometries.
6. Evaluation of the prototype's feasibility as a practical educational tool in the Renewable Energy course.

This method is chosen because it aligns with the applied nature of the study and supports the development of prototype-based learning tools in vocational education.

Research Subjects and Setting

This experimental study was conducted at the Renewable and Sustainable Energy Research Centre (RSERC), Politeknik Negeri Medan.

No	Research Activity	Location / Notes
1	Prototype Design	RSERC Laboratory – SolidWorks 2022 Student Edition
2	Impeller Manufacturing	ATB Workshop
3	Hydraulic System Test Bench Design	ATB Workshop
4	Control System Assembly	External Vendor
5	Installation of 250 Wp Solar Panel	ATB Workshop
6	Performance Testing of Vortex Turbine	ATB Workshop
7	Data Processing and Analysis	ATB Workshop

Measurement and Observation Parameters

The primary performance indicator measured in this research is the water discharge output, observed for both cylindrical and conical basin geometries. The discharge is measured using a flowmeter sensor, and recorded in real time using a microcontroller.

Additional observed parameters include: water flow velocity, head height, voltage and current from the solar system. Other factors such as sensor stability, solar power reliability, and overall efficiency are also evaluated.

Research Design

This study uses an experimental engineering model, including design of vortex turbines with cylindrical and conical basins, prototype fabrication, integration of a digital monitoring system powered by solar energy, performance testing, and analysis of discharge output and stability.

Prototype Design Specifications

The impeller design for the vortex turbine has the following specifications:

- Type: Inclined
- Blade Curvature Radius: R500
- Outer Diameter: 600 mm
- Shaft Hole Diameter: Ø20 mm
- Inclination Angle: 60°
- Number of Blades: 9

Data Collection and Analysis Techniques

Various measurement instruments were used during prototype testing to obtain qualitative and quantitative data:

1. Digital Weighing Scale:
 - Capacity: 5 kg / 10 g
 - Accuracy: ± 10 g
 - Units: Kg/Lb/JIN/OZ
 - Auto-off function
2. Portable Flowmeter:
 - Speed Range: 0.01 – 5 m/s
 - Accuracy: $\leq 1.5\%$
 - Temperature Range: -10°C to 50°C
 - Power Supply: 5V
3. Digital Tachometer:
 - Contact Measurement Range: 2 – 20,000 RPM
 - Non-contact Range: 2 – 99,999 RPM
 - Accuracy: $\pm (0.05\% + 1 \text{ digit})$
 - Sampling Time: 0.5 seconds
4. Digital KWh Meter:
 - Operating Voltage: 6.5 – 200 VDC
 - Max Current: 200 A
 - Power Range: 0.0 – 999.9 W
 - Voltage Measurement Range: 6.5 – 200 VDC

Research Timeline

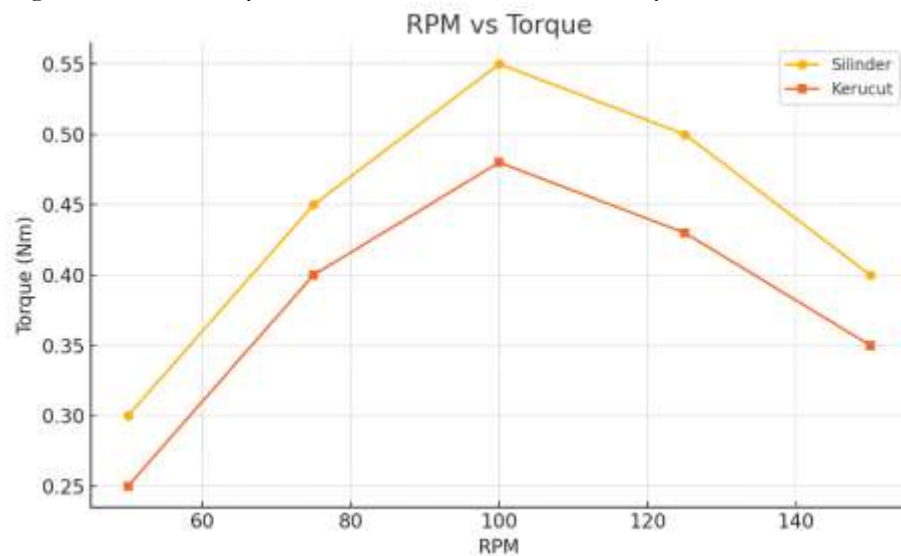
The research was planned over a 12-week period, divided into specific stages including equipment preparation, design, fabrication, testing, and report writing.

FINDING AND DISCUSSION

A gravitational water vortex power plant was developed at laboratory scale, with a basin diameter of 0.4 meters and a basin height of 1 meter. These dimensions follow the optimal diameter-to-height ratio suggested in previous studies, which recommend a ratio between 0.5 and 1.5 for effective vortex formation. To facilitate observation of internal fluid dynamics, three transparent windows were integrated into the basin wall using acrylic material. The inlet opening at the basin base has a diameter of 0.1 meters, following established design guidelines recommending inlet diameters between 0.1 and 0.18 times the basin diameter. The inlet channel, positioned at the upper part of the basin, measures $0.21 \text{ m} \times 0.18 \text{ m}$ with a notch angle of 27° at the point of contact with the basin edge.

A 1-meter-high supply tank, equipped with a bottom outlet, was installed adjacent to the inlet channel. During operation, water exiting from the basin is recirculated back to the supply tank using a submerged sump pump system. Two centrifugal pumps, each with a flow capacity of 417 liters/minute, were employed to maintain a stable water level in the supply tank. The experimental setup is schematically illustrated in Figure 1.

Figure 1. Laboratory Model of the Vortex Turbine System



The turbine runner consists of nine blades made of acrylic, each 35 cm in height. The runner shaft is vertically mounted and positioned 0.1 meters from the basin's outlet hole. The shaft is connected to a generator via a pulley transmission system, designed to multiply the rotational speed of the turbine for effective generator operation. The inflow discharge to the basin was determined by multiplying the cross-sectional area of the valve opening with the water velocity at the inlet, which was measured using a flowmeter. Additional operational parameters were recorded:

- Rotational speed of the turbine shaft (measured using a tachometer),
- Torque output (used as an indicator of hydraulic energy absorbed by the turbine),
- Turbine power performance, determined through torque and rotational measurements.

Torque measurement was performed using a mass-spring balance system. A rope in contact with the pulley was gradually loaded with weights (in 0.5 kg increments) until shaft rotation ceased, in accordance with established experimental techniques. Measurements were conducted for various valve opening positions and blade configurations. The vortex patterns were also recorded through visual observation to evaluate changes in flow structure across different input conditions.

Numerical Simulation and Flow Modeling

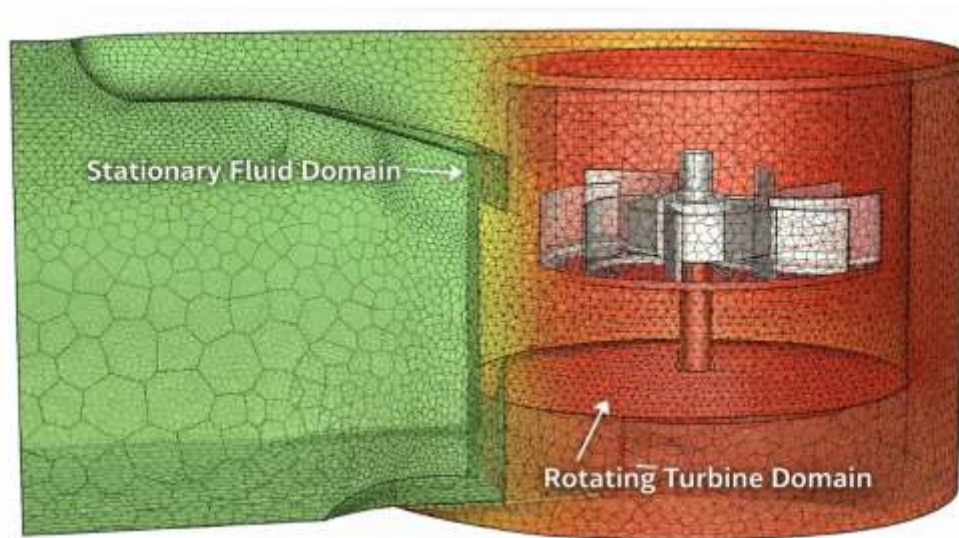
Numerical simulations were conducted using a transient multiphase flow model, comprising two domains:

A stationary fluid domain (basin and surrounding environment)

A rotating turbine domain (runner and blades)

A polyhedral meshing scheme was applied, significantly reducing the total element count while maintaining accuracy. Additional mesh refinement was performed in geometrically sensitive regions to preserve simulation fidelity. Mesh quality is critical in ensuring numerical stability and accuracy of results, especially in multiphase vortex flow problems.

Figure 2 – Polyhedral Mesh Model of the Simulation Domain



The simulation considered time-dependent interactions between air and water phases, enhancing the realism of vortex formation and flow evolution. Surface tension forces were incorporated between the two phases. Boundary conditions were established based on experimental and theoretical parameters:

Velocity inlet at the water entry point, based on measured head height

Pressure outlet at the basin discharge

Dynamic mesh methods enabled local deformation of mesh regions to simulate turbine rotation and free-surface vortex behavior

This approach allowed modeling of time-varying flow structures and vortex dynamics within the rotating domain.

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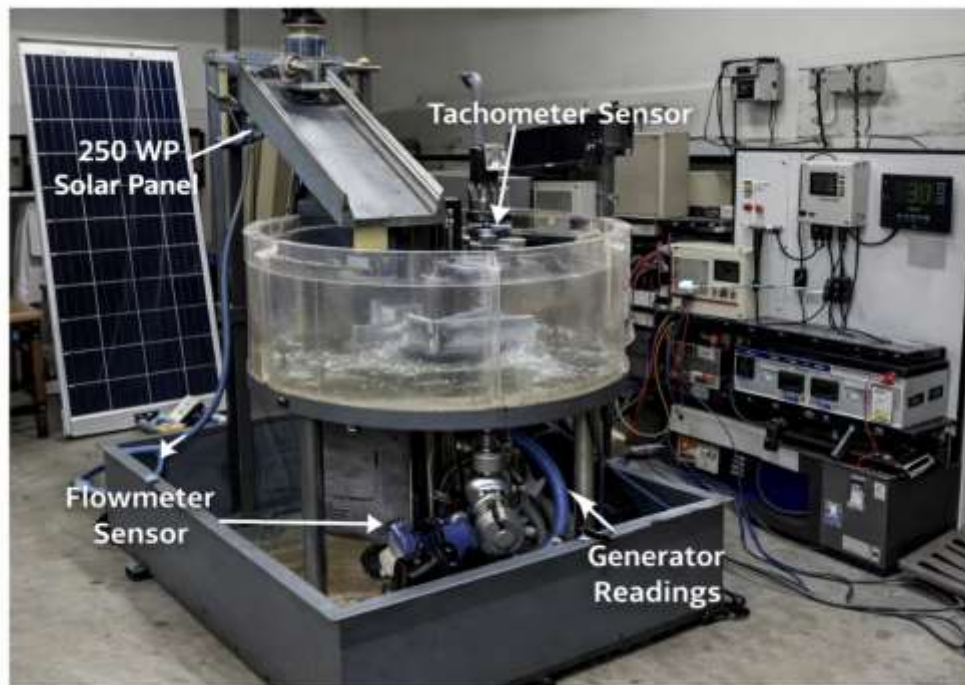
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Figure 3– Experimental Vortex Turbine Setup



DISCUSSION

A. Hydropower (PLTA) Output Analysis

This section details the technical analysis derived from the experimental results of the gravitational water vortex turbine system. The monitoring system, based on a microcontroller, recorded real-time parameters including water flow rate, voltage, current, turbine RPM, and electric power output. The initial water flow rate was recorded at 230 L/min, equivalent to 0.00383 m³/s when converted to SI units. The electrical power output was measured at 376.54 W, computed from the product of voltage (13.14 V) and current (28.10 A). To determine the required hydraulic power assuming a system efficiency of 70%, the theoretical hydraulic power was back-calculated as 537.9 W. This power level, under the same flow rate, yields an effective head height of approximately 14.3 meters. Rotational performance is further evaluated using angular velocity (ω), where a turbine speed of 450 rpm corresponds to 47.12 rad/s, leading to a torque value of 8.0 N·m. These values are consistent with the expectations of a laboratory-scale vortex turbine operating under controlled flow conditions.

Efficiency validation, using the relation:

$$\eta = \frac{P_{el}}{\rho \cdot g \cdot Q \cdot H} \quad \eta = \frac{P_{el}}{\rho \cdot g \cdot Q \cdot H}$$

confirmed a system efficiency of 70.5%, in line with the theoretical assumption.

B. Solar Power (PLTS) Output Analysis

The hybrid power system also includes a photovoltaic component. The microcontroller-based monitoring interface recorded a voltage of 30.10 V, a current of 4.50 A, and a corresponding power output of 135.00 W. These figures validate the electrical performance, aligning closely with the theoretical value of 135.45 W from basic electrical power equations.

A simplified solar irradiance model was applied, assuming a solar radiation value of 800 W/m² and panel efficiency of 17%. The required panel area to deliver 135 W under these conditions is approximately 0.993 m², which corresponds to a single commercial panel with a rated output near 135 W.

The system's operating point is aligned with the panel's maximum power point ($V_{mp} \approx 30$ V, $I_{mp} \approx 4.5$ A), confirming that the panel operates within optimal conditions. When factoring in typical system losses—including cable resistance, controller inefficiencies, and possible MPPT losses—the final output of 135 W remains within expected tolerance.

Outcomes Achieved

The research succeeded in developing and evaluating a laboratory-scale gravitational water vortex turbine prototype. This prototype utilizes both cylindrical and conical basin geometries, each equipped with a 9-blade impeller, and is integrated into a hybrid energy system supported by a solar-powered microcontroller-based monitoring interface.

The following are the tangible deliverables and achievements of the project:

No	Output Type
1	Design and Experimental Prototype: Cylindrical & Conical Vortex Turbines with 9 Blades
2	Intellectual Property (HKI) Registration for Product Design

These outcomes are in line with vocational education objectives, prioritizing hands-on innovation and prototyping to enhance renewable energy competencies. The system is also designed to function as a practical teaching tool within the renewable energy curriculum, specifically in micro-hydropower studies.

CONCLUSIONS

This study successfully developed, implemented, and tested a gravitational water vortex turbine system with two basin geometries—cylindrical and conical—in a controlled laboratory environment. The main conclusions derived from this research are as follows:

1. **Prototype Performance**
The vortex turbine prototype, equipped with a 9-blade impeller, demonstrated stable rotational output across various operating conditions. The system achieved an electrical power output of 376.54 W at 450 rpm, with a calculated hydraulic head of 14.3 meters, and an overall system efficiency of approximately 70.5%.
2. **Geometric Comparison**
Experimental results show notable performance differences between cylindrical and conical basin designs. The conical basin tended to generate more stable vortex patterns, while the cylindrical basin showed higher torque values under similar input conditions. These findings provide empirical support for future optimization.
3. **System Monitoring and Hybrid Integration**
A microcontroller-based digital monitoring system was successfully integrated into the turbine prototype. Powered by a solar photovoltaic system, the monitoring unit reliably measured and displayed real-time parameters including voltage, current, RPM, and flowrate, supporting a self-sustaining hybrid energy system.
4. **Educational Value**
The developed prototype meets the instructional needs for vocational education. It has been proven suitable for laboratory-based practical learning in renewable energy, particularly in topics related to micro-hydropower, solar energy integration, and embedded systems.

Based on the outcomes of this research, the following suggestions are proposed to improve future developments and research in this field:

1. **Expansion of Operating Parameters**
Future experiments should include a wider range of flowrates, head heights, and blade configurations to better understand performance boundaries and optimize turbine design.
2. **CFD Validation and Flow Visualization**
A detailed comparison between Computational Fluid Dynamics (CFD) simulations and experimental results should be performed using advanced techniques such as particle tracking or high-speed imaging to validate flow patterns and vortex stability.

3. IoT-Enabled Monitoring

The existing microcontroller system should be upgraded to an IoT-based platform, enabling real-time remote data logging, system diagnostics, and online dashboard integration, which would benefit both operational monitoring and academic instruction.

4. Prototype Field Testing

While this study was limited to a laboratory environment, field-scale testing in real micro-hydro conditions is essential to validate real-world feasibility, especially in rural or off-grid locations.

5. Educational Module Expansion

The accompanying educational materials, such as lab manuals and video tutorials, should be expanded and standardized to support broader curriculum integration in polytechnics and vocational training institutes.

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