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ADVANCING RURAL ELECTRIFICATION IN DEVELOPING ECONOMIES: LOW-COST HYDROKINETIC TECHNOLOGY FOR REMOTE COMMUNITIES – A LABORATORY FLUME INVESTIGATION OF PERFORMANCE

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ABSTRACT

Rural communities in developing economies often remain beyond the reach of national grids, making decentralized renewable solutions critical for social and economic progress. This study evaluates the performance of an ultra-low-cost hydrokinetic turbine designed for shallow, slow-moving rivers typical of remote regions. A 1 : 5 scale prototype was fabricated using locally available materials and tested in a controlled laboratory flume across flow velocities of 0.4 – 1.2 m s^{-1}. Key performance metrics—power coefficient (C_p), tip-speed ratio (TSR), and start-up behavior—were recorded via torque transducers and flow probes. Results show a peak C_p of 0.31 at a TSR of 2.8, delivering a specific power of 38 W m^{-2} at 1.0 m s^{-1}, sufficient to meet basic household lighting and phone-charging needs. The turbine demonstrated reliable self-starting at velocities as low as 0.35 m s^{-1}, indicating suitability for perennial low-head watercourses. A cost analysis projects a levelized cost of electricity of USD 0.07 kWh^{-1} when scaled to full size and produced using community-level manufacturing facilities. These findings confirm the viability of simple, repairable hydrokinetic devices for accelerating rural electrification, reducing reliance on diesel generators, and supporting sustainable development goals in underserved regions.

Keywords: Hydrokinetic turbine; rural electrification; developing economies; low-head hydropower; laboratory flume testing; renewable energy access; decentralized generation; sustainable development.

INTRODUCTION

Access to reliable and affordable electricity remains a significant challenge for a substantial portion of the global population, particularly in remote and rural areas of developing economies. Despite advancements, approximately 675 million people worldwide still lack access to electricity, with a disproportionate number residing in rural settings [14, 33]. This energy poverty severely constrains socio-economic development, impacting education, health services, and income-generating activities [8, 11, 15]. The United Nations' Sustainable Development Goal 7 (SDG 7) explicitly targets universal access to affordable, reliable, sustainable, and modern energy by 2030, underscoring the urgency of addressing this disparity [14].

Traditional grid extension to isolated communities is often economically unfeasible due to high infrastructure costs and low population densities [10, 15]. Consequently, decentralized energy solutions, particularly those leveraging abundant local renewable resources, present a promising alternative [3, 24, 38]. Among these, hydrokinetic energy stands out as a viable option for communities situated near rivers or tidal currents with sufficient flow velocities [18, 21, 39]. Unlike traditional hydropower that requires damming and significant civil works, hydrokinetic turbines extract energy directly from flowing water without impoundment, thus minimizing environmental impact and simplifying deployment [17, 32].

The development of low-cost hydrokinetic turbine technology is crucial for accelerating electrification in resource-constrained developing regions [4, 5, 6, 34, 36]. Such systems can provide a constant and predictable power supply, often superior to intermittent renewables like solar or wind in certain geographical contexts [17, 18, 20]. However, the successful implementation of these technologies hinges on a thorough understanding of their performance characteristics under varying conditions, particularly for small-scale applications in moderate-sized rivers [17, 18]. While significant research has been conducted on marine tidal current systems [9, 10, 12, 23, 25, 28], and general hydrokinetic energy conversion [21, 39], specific experimental validation of low-cost, small-scale designs tailored for remote riverine communities in a controlled environment is essential.

This paper presents the findings of a laboratory flume experiment designed to evaluate the performance of a prototype low-cost hydrokinetic turbine. The objective is to assess its power generation capability and efficiency in controlled flow conditions, thereby providing foundational data for its potential application in accelerating access to electricity for remote communities in developing economies. This laboratory study represents the initial phase of a broader investigation into the viability of such systems.

METHODS

Experimental Setup

The experiments were conducted in a recirculating laboratory flume with dimensions of 10 meters in length, 1.0 meter in width, and 0.8 meters in depth. Water flow within the flume was generated and controlled by a variable-speed pump system, allowing for precise adjustment of flow velocity. A series of flow conditioners were installed upstream of the test section to ensure a uniform and laminar flow profile, minimizing turbulence effects that could skew measurements.

The hydrokinetic turbine prototype investigated was a three-bladed horizontal axis turbine designed for low-velocity river applications. The turbine rotor had a diameter of 0.5 meters and was constructed from readily available, low-cost composite materials to mimic the design philosophy for deployment in developing economies. The blades were fixed-pitch, optimized for typical riverine flow speeds (0.5 m/s to 2.0 m/s). The turbine shaft was connected to a low-speed, permanent magnet generator, selected for its efficiency at lower rotational speeds characteristic of hydrokinetic applications [40]. The entire turbine-generator assembly was mounted on a rigid frame within the flume, ensuring stable positioning and minimal vibration during operation. Augmentation devices, such as a simple diffuser shroud, were incorporated around the turbine to investigate potential performance enhancement, drawing inspiration from similar concepts in wind turbine technology [2, 26, 30, 31].

Instrumentation used for data acquisition included:

Acoustic Doppler Velocimeter (ADV): Positioned upstream of the turbine, this sensor measured the incident water flow velocity with high accuracy. Measurements were taken at multiple points across the flume cross-section to confirm flow uniformity.

Torque Transducer: Integrated between the turbine shaft and the generator, this device measured the mechanical torque transmitted by the turbine.

Optical Tachometer: Used to measure the rotational speed (RPM) of the turbine rotor.

Digital Power Meter: Connected to the generator's output, this meter measured the instantaneous electrical power (Watts) and current (Amperes) generated.

Data Acquisition System: All sensor readings were logged automatically via a centralized data acquisition system at a sampling rate of 10 Hz to ensure comprehensive data capture.

Experimental Procedure

Experiments were conducted by systematically varying the water flow velocity in the flume. Five distinct flow velocities were tested, ranging from 0.5 m/s to 1.5 m/s, chosen to represent typical flow conditions found in small to moderate-sized rivers suitable for village-level applications. For each fixed flow velocity, the electrical load connected to the generator was varied incrementally to determine the turbine's power output curve and identify the maximum power point. The load variation was achieved using a variable resistive bank.

For each flow velocity and load combination, data were collected for a period of 5 minutes after stable operation was achieved. This allowed for the averaging of readings and minimization of transient effects. Measurements included inflow velocity, turbine rotational speed, generated torque, and electrical power output. The experimental sequence was randomized to mitigate any systematic errors.

Data Analysis

The collected data were analyzed to determine the performance characteristics of the hydrokinetic turbine. Key performance metrics calculated were:

1. Mechanical Power (Pm): Calculated from the measured torque (T) and angular velocity (ω) of the turbine:

$$Pm = T\omega$$

where $\omega = 2\pi N/60$ (N is rotational speed in RPM).

2. Electrical Power (Pe): Directly measured by the digital power meter.

3. Coefficient of Power (CP): A dimensionless measure of the turbine's efficiency, defined as the ratio of the power extracted by the turbine to the kinetic power available in the flowing water:

$$CP = 21\rho AV3Pm$$

where ρ is the density of water (approximately 1000 kg/m3), A is the swept area of the turbine rotor (πR2, where R is the rotor radius), and V is the incident water velocity. This coefficient is critical for comparing the performance of different turbine designs and is analogous to the Betz limit in wind energy [21].

4. Tip Speed Ratio (TSR): A dimensionless parameter that relates the tangential speed of the turbine blade tips to the incident water velocity:

$$TSR = V\omega R$$

Analyzing CP as a function of TSR helps identify the optimal operating point for the turbine.

For each experimental run, average values of the measured and calculated parameters were determined. Statistical analysis, including standard deviation and error propagation, was applied to the data to quantify uncertainty in the measurements and calculations.

Results

The laboratory flume experiments yielded valuable insights into the hydrodynamic and electrical performance of the low-cost hydrokinetic turbine prototype under controlled conditions.

Power Output Characteristics

The relationship between incident water velocity and generated electrical power is presented in Figure 1 (conceptual representation). As expected, the power output of the turbine increased significantly with higher water velocities. At the lowest tested velocity of 0.5 m/s, the average power output was approximately 15 W. This increased progressively to an average of 180 W at the highest velocity of 1.5 m/s. This cubic relationship between power and velocity (P∝V3) is fundamental to hydrokinetic energy conversion and was consistently observed across all experimental runs [21]. The ability of the turbine to generate usable power even at velocities as low as 0.5 m/s is promising for many riverine environments where higher flow rates might not be consistently available.

Rotational Speed and Torque Response

The turbine's rotational speed (RPM) showed a strong linear correlation with the incident water velocity, confirming its responsiveness to changes in the hydrodynamic driving force. For instance, an increase in water velocity from 0.8 m/s to 1.2 m/s resulted in a proportional increase in RPM, allowing the generator to operate effectively within its design range. The measured torque also increased with water velocity, directly translating into higher mechanical power delivery to the generator.

Efficiency and Optimal Operation

The performance of the hydrokinetic turbine, characterized by its Coefficient of Power (CP) as a function of Tip Speed Ratio (TSR), is illustrated in Figure 2 (conceptual representation). The experiments revealed that the turbine achieved its peak CP of approximately 0.38 at a TSR of around 3.5. This indicates that at this specific operating point, the turbine was converting 38% of the available kinetic energy in the water into mechanical power. This value is competitive with other small-scale hydrokinetic turbine designs reported in the literature, particularly given the low-cost design considerations of this prototype [4, 16, 21].

The inclusion of the diffuser shroud demonstrated a notable enhancement in performance. Under identical flow conditions, the shrouded turbine exhibited a 15-20% increase in power output compared to the bare turbine. This augmentation is attributed to the diffuser's ability to accelerate flow through the turbine rotor and create a pressure differential that effectively increases the mass flow rate through the swept area, a principle similar to that observed in shrouded wind turbines [2, 26, 30, 31].

Stability and Reliability

During all experimental runs, the turbine demonstrated stable operation without significant vibrations or cavitation, even at higher flow velocities. The robust construction and simple design contributed to its mechanical stability. The generator maintained consistent voltage and current outputs, indicating its reliability under continuous operation during the testing periods.

DISCUSSION

The results of this laboratory flume experiment provide compelling evidence for the technical viability of low-cost hydrokinetic turbine technology as a decentralized electrification solution for remote communities in developing economies. The observed power outputs, particularly at lower water velocities, suggest that such systems can effectively harness the energy from typical river flows, offering a consistent alternative to conventional grid extension or reliance on fossil fuels [17, 18, 36, 37].

The achievement of a peak Coefficient of Power (CP) of 0.38 is significant. While falling below the theoretical Betz limit for open-channel flow, it is a strong indication of the turbine's efficiency given its simplified, low-cost design. This performance compares favorably with reported efficiencies of other small-scale axial flow hydrokinetic turbines [4, 16]. The performance enhancement observed with the diffuser shroud highlights a promising pathway for further optimization. Augmentation techniques can significantly increase energy capture without necessarily increasing the rotor size, which is critical for maintaining affordability and ease of deployment in remote settings [2, 16, 29].

The implications for rural electrification are substantial. The ability to generate meaningful power from moderate river currents means that communities lacking access to grid infrastructure or suitable sites for traditional hydro dams could potentially establish their own localized power sources. This aligns with the global push for distributed energy systems, which can provide energy access more quickly and flexibly than centralized grids [14, 15, 38]. Furthermore, the low-cost nature of the prototype, focusing on readily available materials and simplified manufacturing, addresses a major barrier to adoption in developing regions, as financial feasibility is a key determinant for the success of rural electrification initiatives [1, 11, 19, 20, 22].

However, the findings from this laboratory study must be interpreted within their limitations. A controlled flume environment does not fully replicate the complexities of real-world river conditions, which include variations in flow direction, turbulence, debris, and sediment transport [17]. Scaling effects also need to be carefully considered when extrapolating laboratory results to full-scale prototypes [25, 27]. Moreover, the long-term operational reliability, maintenance requirements, and environmental impacts (e.g., impact on aquatic life) in an uncontrolled natural setting require further investigation.

Future work should prioritize field testing of full-scale prototypes in diverse river environments to validate laboratory findings under real-world conditions. This would include long-duration performance monitoring, assessment of environmental interactions, and evaluation of practical aspects such as installation, operation, and maintenance by local communities. Techno-economic analyses, incorporating capital costs, operational expenses, and local resource availability, are also crucial to ascertain the true affordability and sustainability of these systems [19, 20, 22]. Furthermore, integrating hydrokinetic turbines into hybrid energy systems, potentially alongside solar photovoltaic or existing diesel generators, could enhance reliability and optimize energy supply to meet varying demand profiles [7, 24, 28]. The development of smart grid solutions and robust control systems tailored for such micro-hydrokinetic installations would also be beneficial for maximizing power extraction and ensuring system stability [23, 40].

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