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Hydrokinetic Turbine Blade Design for Enhanced Efficiency in Variable Flow Conditions

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Abstract **-** Hydrokinetic turbines offer a promising solution for harnessing renewable energy from water currents, such as rivers and tidal streams, without the need for large dams or significant infrastructure. This paper focuses on the design and optimization of blade profiles for hydrokinetic turbines to improve their efficiency and performance. Computational fluid dynamics (CFD) simulations were used to conduct a comprehensive analysis of the angle of attack and its impact on blade hydrodynamic performance. Various blade profiles were evaluated to optimize efficiency under different flow conditions, aiming to maximize power output while minimizing cavitation and structural stress. The results demonstrate that optimizing the angle of attack significantly enhances turbine efficiency, improving its viability for large-scale energy production.
The results demonstrate that optimizing the angle of attack can significantly enhance the turbine's efficiency, making it more viable for large-scale energy production. The findings contribute to the ongoing efforts in advancing hydrokinetic technology and provide a framework for future research in optimizing renewable energy systems. At 67.5 degrees, the power output might have been unexpectedly high, surpassing the power output observed at lower angles of attack, 15 and 45 degrees

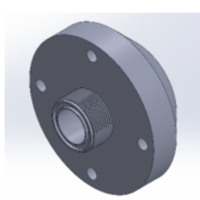
Keywords**:** hydrokinetic, turbine, angle of attack, Blades

1. Introduction

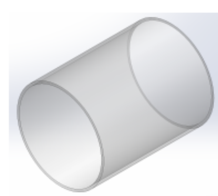
Carbon dioxide is the most significant greenhouse gas due to its naturally high atmospheric concentration and heat-trapping capabilities. CO2 accumulation in the atmosphere has risen exponentially. Pre-industrial revolution, CO2 was at a level of 280 parts per million (ppm), in 2005 CO2 levels were recorded with an increase of over 35% reaching a level of over 379ppm [7]. Transitioning to emphasize low-emission energy generation. For example, nuclear energy, hydroelectric power (HEP), or renewable energy sources, such as wind turbines, and tidal energy. Hydrokinetics is energy generated from moving water currents in rivers, ocean tides, or any other forms of artificial water channels. Technology from the water wheel to horizontal axis turbines has been developed to extract energy for later use. [5] HEP is the most widely used source of energy generation globally, there have been great advances in the development and application of HEP. HEP today aims to have a limited effect on the ecosystem where the system is located. As of 2023, HEP is the leading source of low-carbon energy producer across the globe, which reflects 16% of the world's demanded electricity [1]. Having this weight on global power production provides great insight into reasoning for further research and development towards a broader range of usable applications for HEP and increased turbine design for usage in wildly differing areas where there are specific environmental factors that affect the hydroelectric turbine energy output. This proves to be prevalent due to the changes in rivers and waterways across the globe on a yearly basis along with climate changing factors such as rainfall and watershed due to seasonal changes, and climate change causing irregular rainfall patterns and extreme geological events is believed to be a major factor in fluctuating of HEP production [2]. This type of renewable clean energy has drastically increased in energy production over the past few decades. There are plans in the making to introduce new HEP facilities that are based on river-stream applications that have not previously been used for energy production [3]. The most common reaction turbines are propeller (including Kaplan) and Francis turbines. Propeller turbines generally have 3-6 blades and the water contacts all the blades constantly. Kaplan turbines have adjustable blades and wicket gates for a wider range of operations. Impulse turbines use the velocity of the water to move the runner and discharge at atmospheric pressure. The driving factors behind choosing a specific turbine depend on variables like the height of standing water (head), the flow rate at the site, as well as turbine efficiency, and overall cost [6]. The focus of this report is on turbines' reaction, having the river flow being the primary source of mechanical energy. This negates the need for potential energy from the pressure head available from structures like dams. Hydrokinetic energy as a resultant of the flow allows for a “zero-head” or “in-stream” turbine. Hydrokinetic turbines are a type of reaction turbine and generate electricity from hydrokinetic energy rather than potential energy from head pressure. Turbine blades are essential components responsible for converting hydrokinetic energy into mechanical rotation. Testing turbine blade stakes into consideration the angle of attack in conjunction with the orientation and or number of blades used. There is a direct correlation between the flow rate, angle of attack, turbine rpm, and energy generation, such as having a lower blade angle tends to produce an increased rpm which will result in a higher energy generation [8]. These modifications are made to improve energy generation or turbine efficacy without making other alterations to the turbine assembly. By making slight alterations to the turbine blades during testing it becomes possible to determine the optimal blade geometry for the environmental and geographical factors of the turbine’s location. Two major quantifiable factors that are tested are the turbine rpm and energy output. These factors are tested at a standard flow rate while changing one aspect of the turbine blades at a time, the angle of attack, and then the number of blades. Once the optimal blade geometry is determined, the flow rate is adjusted.

2. Solid Works Model

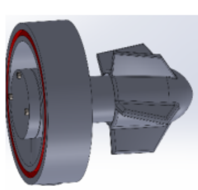
The apparatus is made up of two outer fixtures as shown in Figure 1a, two clear acrylic passage pipes (Fig. 1b), a propeller mount (Fig. 1c) located in the mid-section and the propeller itself. The outer fixtures allow for connection to both the water inlet and outlet of the Gunt HM112 system via a threaded insertion point. Figure 2 shows the Apparatus Assembly. Each passage pipe is then secured to an outer fixture using sealant and an O-ring. The passage pipe has an outer diameter of 80 mm and is with a length of 100 mm. Clear acrylic was used to allow for visual inspection of the flow as well as a view of the propeller. Another set of O-rings and sealant is used to secure both ends to the propeller mount in the middle. The entire structure is then secured using steel rods connected with M10 hex nuts and washers on both ends. The propeller mount is composed of two separate parts, one being the outer cylinder with a 20 mm diameter hole centered on one face and the other being the rotational motion passage. The propeller is then fastened through the mount to a pair of bevel gears arranged at 90 degrees, allowing the rotational motion of the propeller to be taken outside the apparatus and connected to a generator. Connecting the generator in this manner allows for saving time and cost in not having to waterproof the generator itself or spend time creating waterproof housing that would affect the flow of water, in turn reducing the overall system’s efficiency. The Kaplan-style propeller with multiple Angle of Attacks (Figure 3a-3b and 3c) is designed to allow the angle of attack to be change manually throughout testing. The propeller is attached to a 1/8-inch steel shaft that runs through the propeller mount to the first bevel gear. This allows for the motion of the propeller to be translated into the second gear, hence the shaft of the generator. Thus, allowing for a numerical voltage output of the work done by the propeller at the pre-set attack angle.



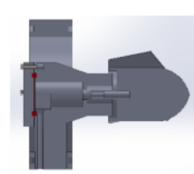
a – *Fluid Table Fixture)*



b – *Passage Pipe)*



c – *Propeller Mount)*



d – *Propeller Mount Cross-Section)*

Fig. 1. The Apparatus Components

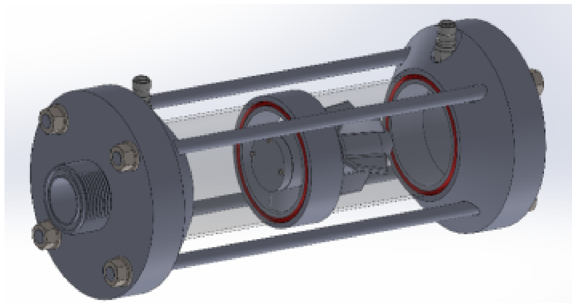


Fig. 2. Apparatus assembly

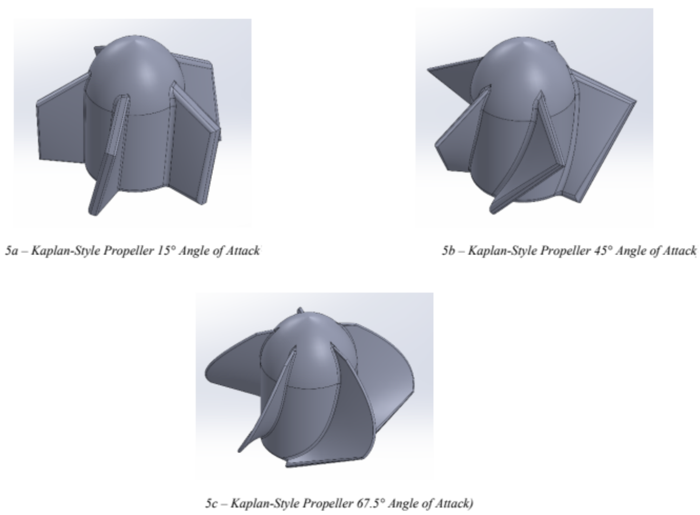


Fig. 3. Kaplan-style Propeller angle of attack, a- 15-degree, b- 45-degrees, c- 67,5-degrees

3. Building Prototype and Testing

The development and execution of the experiment involved a meticulous and detailed process, beginning with the design and manufacturing of the test apparatus. The initial phase of manufacturing involved creating detailed 3D designs for all components of the test apparatus. The apparatus consisted of two fluid table fixtures, two passage pipes, and a propeller mount, which housed the generator. Subsequently, multiple propellers were designed, each with distinct angles of attack, 15 degrees, 45 degrees, and 67.5 degrees. These propellers were designed to maintain the same nominal diameter, ensuring that the only variable between tests is the angle of attack. After finalizing the designs, the components of the apparatus were produced using a fused deposition modeling (FDM) 3D printer, while the propellers were produced using a resin-based stereolithography (SLA) 3D printer. SLA was chosen specifically for the propellers to ensure complete infill, which enhanced the strength of the blades and minimized the risk of deflection. Once manufactured, the components were assembled with a combination of epoxy for sealing when needed and M10 mechanical hardware for structural integrity. The fully assembled apparatus, utilized in subsequent tests, is depicted in Figure 4.

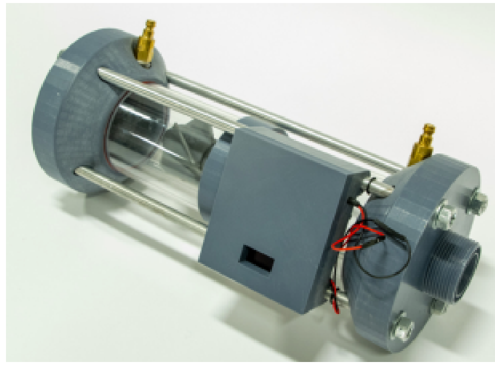


Fig. 4. Physical Apparatus

4. CFD Analysis

Computational fluid dynamics (CFD) simulations are used to conduct a comprehensive analysis of the angle of attack such as 15, 45 and 67.5 degrees and its impact on blade hydrodynamic performance. A mesh with over 2 million cells was used to generate a fine mesh, which is typically used to capture complex flow features and improve the accuracy of the simulation. A visual representation of the mesh is provided in Figure 5. Various flow rates, ranging from 2 to 2.7 m^3/h, were applied as input conditions to the simulation. Convergence of the CFD simulations was achieved, and a representative convergence history is shown in Figure 6.

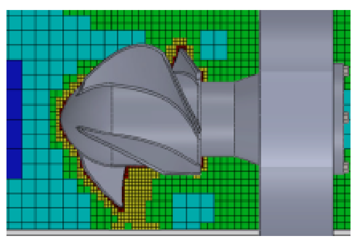


Fig. 5. Sample of the mesh layout

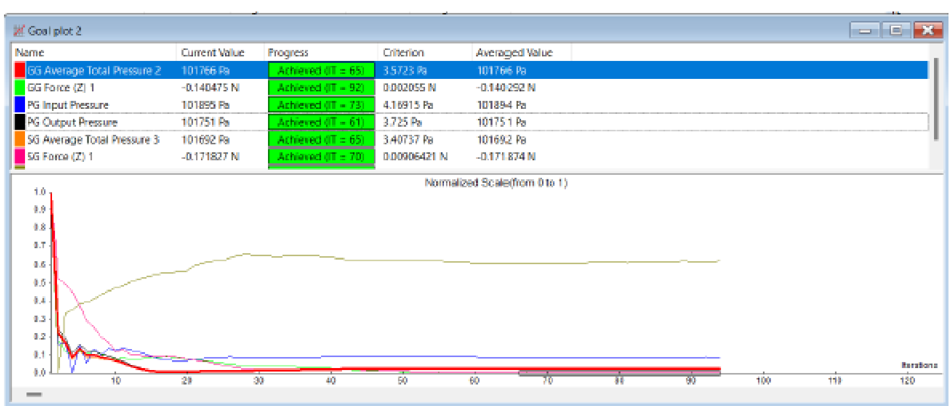


Fig. 6. Convergence of CFD simulation

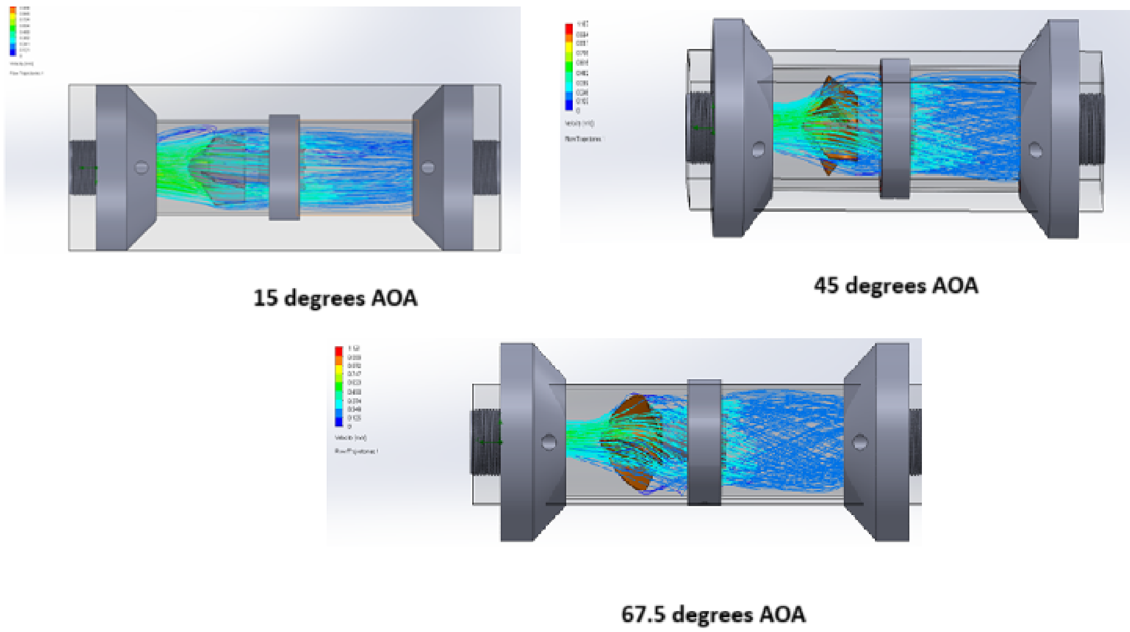


Fig. 7. Velocity flow trajectory at different AOA

4.1. CFD Validation

The study involved extensive CFD iterations to assess the performance of three different propellers with angles of 15 degrees, 45 degrees, and 67.5 degrees. Despite some localized discrepancies, the CFD analysis demonstrated a strong overall correlation with experimental results, validating the robustness of both the experimental design and computational approach. While a few instances showed higher than anticipated percent errors and limited cases where experimental force exceeded CFD predictions, these deviations were infrequent. Throughout the validation process, the percentage error between the experimental data and the CFD results exhibited a range from 0.5% to 15%. The error, particularly at the upper end of the spectrum, highlights specific areas where the current design and experimental methodology require improvement. Figure 8 shows a comparison between experimental results and CFD simulations.

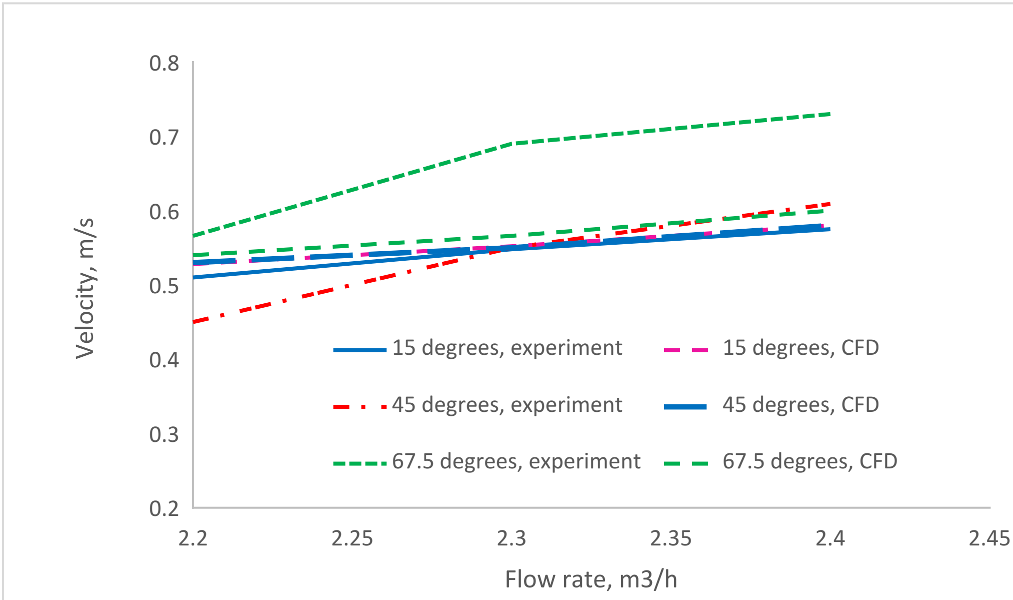


Fig. 8. Comparison of experimental results and CFD simulations

5. Discussion

After conducting eight tests for each of the three propellers, calculations were performed to determine the force (N) along the x-axis (parallel to the flow), the water's velocity (m/s), and the Reynolds number to classify the type of flow as laminar, mixed, or turbulent. The measured and calculated values for all tests are presented in tables 1-3 and Figure 9. The power increases with increasing flow rate at a propeller angle of attack of 67.5 degrees is highly unusual and likely unexpected. It's highly unusual for a hydrokinetic turbine to experience an increase in power at such a high angle of attack (67.5 degrees). It might be due to the complex hydrokinetic turbine systems, interactions between the propeller, the surrounding structure, and the flow field lead to this unexpected phenomenon.

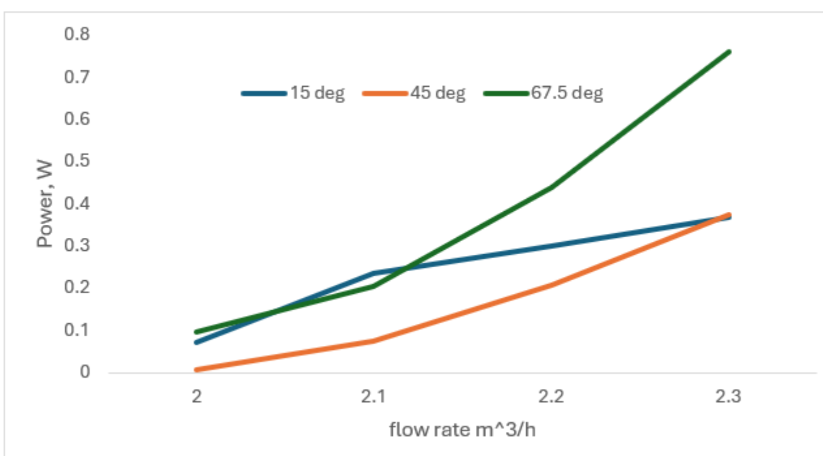


Fig. 9 flow rate vs. power at different angle of attack

Table 1. 15-degrees of angle attack

Input Water Flow Rate (m^3/h)	Delta Pressure (Pa)	Average Voltage Output (mV)	Velocity (m/s)	Reynolds Number	Force (N)
2	50	9.3819	0.316736537	2.76E+04	0.226822990
2.1	110	13.3257	0.469796205	4.09E+04	0.499010577
2.2	130	15.2383	0.51072232	4.45E+04	0.589739773
2.3	150	16.0135	0.548603774	4.78E+04	0.680468969

Table 2. 45-degrees of angle attack

Input Water Flow Rate (m^3/h)	Delta Pressure (Pa)	Average Voltage Output (mV)	Velocity (m/s)	Reynolds Number	Force (N)
2	10.0	10.9256	0.141648885	1.23E+04	0.045364598
2.1	50.0	11.1971	0.316736537	2.76E+04	0.226822990
2.2	100	11.3680	0.447933106	3.90E+04	0.453645979
2.3	150	11.6281	0.548603774	4.78E+04	0.680468969

Table 3. 67.5-degrees of angle attack

Input Water Flow Rate (m^3/h)	Delta Pressure (Pa)	Average Voltage Output (mV)	Velocity (m/s)	Reynolds Number	Force (N)
2	60.0	17.9636	0.346967492	8.00E+00	0.272187588
2.1	100	18.1276	0.447933106	3.90E+04	0.453645979
2.2	160	18.3752	0.566595542	4.94E+04	0.725833567
2.3	240	18.6263	0.693934984	6.05E+04	1.088750350

Conclusion

Throughout the evaluation process of optimizing the angle of attack for hydrokinetic turbine blades, significant insights have been gained, leading to valuable conclusions. However, to enhance the accuracy and reliability of future analyses, several improvements have been planned. Firstly, the design of the propeller mount is slated for enhancement. The upgraded mount will incorporate a gearbox, which will enable the generator to be positioned outside the apparatus. This modification is crucial as it will minimize the risk of water intrusion into the generator, thereby improving the overall efficiency across all tested angles of attack. Secondly, the apparatus itself will be elongated to provide a smoother transition between the input connection and the inner diameter of the passage pipe. This adjustment aims to reduce turbulence and flow separation, leading to more stable and accurate data during testing. This work presents a significant anomaly in hydrokinetic turbine performance. Generally, at a high angle of attack (67.5 degrees), the propeller blades would experience severe stall, leading to a drastic reduction in thrust and power output. At 67.5 degrees, the power output might have been unexpectedly high, surpassing the power output observed at lower angles of attack, 15 and 45 degrees. It might be due to the complex hydrokinetic turbine systems, interactions between the propeller, the surrounding structure, and the flow field lead to this unexpected phenomenon. The experimental and CFD simulations demonstrated results consistent with theoretical predictions. As the angle of attack increased, the force exerted on the blades and the resulting generator rotational speed also increased. The initial hypothesis was validated, demonstrating the significant influence of blade angle of attack on hydrokinetic turbine performance. Peak performance metrics were recorded within the 15–20-degree operational range.

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