



Design Optimization of a 3D-Printed Cross-Flow Turbine for Pico-Hydro Systems Using Computational Fluid Dynamics (CFD) Analysis

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Abstract. Access to electricity in rural areas with low-head water resources remains a challenge due to the limited availability of efficient and affordable pico-hydropower technologies. Cross-flow turbines are well suited for low-head applications; however, their complex geometry often increases manufacturing cost and limits widespread implementation. This study presents the design optimization of a modular 3D-printed cross-flow turbine using Computational Fluid Dynamics (CFD) coupled with additive manufacturing. Three runner configurations with 9, 11, and 13 blades were evaluated under identical operating conditions using the SST $k-\omega$ turbulence model and a Multiple Reference Frame (MRF) approach. The numerical results showed that increasing the blade number improved the flow distribution inside the runner, leading to higher hydraulic performance. The 13-blade configuration produced the highest torque of 0.702 N·m, shaft power of 36.78 W, and hydraulic efficiency of 60.7%, outperforming the 9- and 11-blade designs. Based on the CFD optimization results, the optimum runner was successfully fabricated using fused deposition modeling (FDM), demonstrating the feasibility of rapidly manufacturing complex turbine geometries with high dimensional accuracy. The proposed integration of CFD-based design optimization and additive manufacturing provides an efficient and cost-effective approach for developing modular cross-flow turbines suitable for low-head pico-hydropower applications.

Keywords: Cross-flow turbine, Pico-hydropower, Computational Fluid Dynamics, Additive Manufacturing, 3D Printing Design Optimization.

1 Introduction

Reliable and sustainable electricity access in remote rural areas remains a significant challenge in achieving national energy security and energy independence, in line with Indonesia's long-term national development agenda (Peraturan Presiden Republik Indonesia, 2025). Limited electricity grid infrastructure and challenging geographical conditions have prevented many rural communities from obtaining adequate access to electricity (Karamov et al., 2022; Shi et al., 2024), despite Indonesia's abundant

renewable energy resources, particularly hydropower. With an estimated hydropower potential of approximately 75 GW and thousands of rivers distributed across the country (Haryani, 2016; Hasan et al., 2012; Siyaranamual et al., 2020; Trisasiwi et al., 2017), small-scale hydropower systems, particularly pico-hydropower (<5 kW), offer considerable potential to support sustainable, environmentally friendly, and community-based rural electrification (Haidar et al., 2012; Irlan Malik et al., 2024; Mamat et al., 2025; Williams & Simpson, 2009).

The turbine is the primary component of a pico-hydropower system, responsible for converting the hydraulic energy of flowing water into mechanical energy (Trisasiwi et al., 2017). Among the various turbine types, the cross-flow turbine is widely adopted because of its simple construction, ease of maintenance, and reliable operation under low-head and low-flow conditions (Acharya et al., 2015; Lapisa et al., 2023; Tirono, 2012). However, conventional cross-flow turbine designs continue to face several limitations, including suboptimal hydraulic efficiency, relatively high manufacturing costs, and limited design flexibility to accommodate site-specific hydraulic conditions (Gonabadi et al., 2024). Recent advances in Computational Fluid Dynamics (CFD) have enabled systematic design optimization through detailed flow analysis, while additive manufacturing (3D printing) has created new opportunities for fabricating turbine components with complex geometries in a faster, more flexible, and cost-effective manner (Ma, 2025; Managi et al., 2025; Yusanto et al., 2023).

Based on these challenges, this study aims to develop a cross-flow turbine for pico-hydropower applications by integrating Computational Fluid Dynamics (CFD) and additive manufacturing technologies. The proposed methodology includes turbine modeling using Computer-Aided Design (CAD), optimization of key design parameters through CFD simulations, fabrication of prototype components using 3D printing technology, and preliminary laboratory-scale performance testing. The novelty of this study lies in the integration of CAD, CFD, and additive manufacturing into a unified design framework for cross-flow turbine development, with the objective of improving not only hydraulic performance but also manufacturability, modularity, and the potential for cost-effective replication in rural electrification applications (Acharya et al., 2015; Anand et al., 2021; Boschetto et al., 2022; Fujisawa et al., 2025; Gonabadi et al., 2024; Mehr et al., 2021; Ranjan et al., 2019; Roschli et al., 2023).

2 Methodology

This study employs an experimental research approach combined with an engineering design methodology. The engineering design approach is applied to develop a cross-flow turbine that meets the specified hydraulic head conditions and is subsequently optimized through Computational Fluid Dynamics (CFD) simulations. The research methodology consists of several sequential stages, including a comprehensive literature review, design parameter calculations, cross-flow turbine design using Computer-Aided Design (CAD), numerical simulations based on Computational Fluid Dynamics (CFD), and prototype fabrication using additive manufacturing (3D printing) to produce the turbine runner. A detailed explanation of the methodology is presented in the subsections below.

2.1. Turbine Design

The preliminary stage of this study involved designing a cross-flow turbine using Computer-Aided Design (CAD) software. Design parameters such as blade angle, rotor diameter, number of blades, and nozzle geometry were determined based on literature review and site flow conditions suitable for pico-hydro applications.

Table 1. Fluid Flow Calculation Parameters

No	Parameters	Equations	Result
1	Flow Velocity	$v = \frac{s}{t}$	$0,190 \frac{m}{s}$
2	Cross-sectional area	$A = PxL$	$0,0810 m^2$
3	Flow rate	$Q = v \times A$	$0,001543 m^3/s$

After determining the initial design parameters of the turbine, the dimensions of key components such as the runner blades and the volute casing can be calculated. These dimensions form the basis for the geometric configuration of the cross-flow turbine to be constructed, ensuring compatibility with the available head and flow rate in the pico-hydro system (Trisasiwi et al., 2002).

Table 2. Turbine Design Calculation Parameters

No	Parameters	Equations	Result
1	Relative flow velocity	$v = C * \sqrt{2gH}$	$4,872 m/s$
2	Tangential velocity	$u = 0,48 * v$	$2,338 m/s$
3	Runner Outside Diameter	$D_0 = \frac{u \times 60}{\pi \times n}$	$0,178 m$
4	Jet thickness	$S_0 = 0,17 \times D_0$	$0,0155 m$
5	Blade spacing	$t = \frac{s}{\sin \beta}$	$0,053 m$
6	Turbine thickness	$L = \frac{Q}{S_0 * K_c * \sqrt{2gH}}$	$0,005 m$
8	Blade arc length	$a = 0,17 \times D_0$	$0,030 m$
9	Runner Inner diameter	$D_i = D_0 - (2 * a)$	$0,117 m$

Following the calculation of above, the runner blades can be accurately generated using Computer-Aided Design (CAD) software.

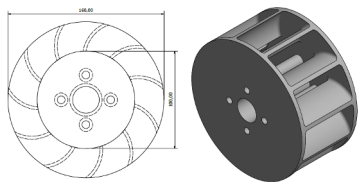


Figure 1. Sectional view and isometric view of runner blade

2.2. CFD Simulation

Computational Fluid Dynamics (CFD) simulations were performed to evaluate the hydraulic performance of the proposed cross-flow turbine and to determine the optimum design configuration. The design optimization was carried out by varying the number of turbine blades while maintaining identical operating conditions for all CFD simulations. The rotational speed was fixed at 500 rpm, while the geometric parameter investigated in this study was the number of turbine blades. All other numerical parameters, including the inlet velocity, turbulence model, computational domain, and mesh configuration, were kept constant throughout the simulations. The simulations were conducted using CFD software based on the Viscous SST $k-\omega$ turbulence model. The numerical setup, including the computational domain, mesh configuration, boundary conditions, solver settings, and convergence criteria, is summarized in Table 3.

Table 3. Simulation Setting Parameters

Parameters	Detail
Mesh Type	Mesh Type: Unstructured Element Size (m): 0.002
Numerical Model	Model Type: Viscous SST $k-\omega$ Solver: Pressure based Time: Steady Gravity (m/s): 9.81 Turbulence Model: SST $k-\omega$
Material	Material type: Water Liquid Rotary domain: Frame motion Rotational axis origin: X axis Axis direction: Z axis Rotational velocity (rad): 500(constant) Rotating Frame Method: Moving Reference Frame (MRF)
Boundary Condition	Velocity Magnitude (m/s): 0.0015 Velocity specification method: magnitude, normal to boundary Turbulence intensity: 2% Viscosity ration: 10

A maximum of 100 iterations was specified for each simulation, and convergence was assessed based on the residual values. The simulations were terminated when the residuals decreased below 10^{-5} or when the maximum number of iterations was reached.

Computational Domain. The computational domain consisted of a three-dimensional model comprising an inlet channel, turbine casing, rotating domain containing the turbine runner, stationary fluid domain, and outlet channel. The rotating domain was assigned to the turbine runner, while the surrounding fluid remained stationary throughout the simulation.

Mesh Generation. The computational domain was discretized using an unstructured mesh to accurately capture the complex geometry of the cross-flow turbine blades and the surrounding flow field. A global element size of 0.002 m was employed throughout the computational domain. Mesh refinement was automatically applied around the turbine blades and the rotating region to improve the prediction of velocity gradients and pressure distribution while maintaining a reasonable computational cost. The final mesh consisted of 347,396 elements and 387,800 nodes, which provided sufficient spatial resolution for the numerical simulations. The generated mesh is in Figure 2 showing the detail and mesh generated.

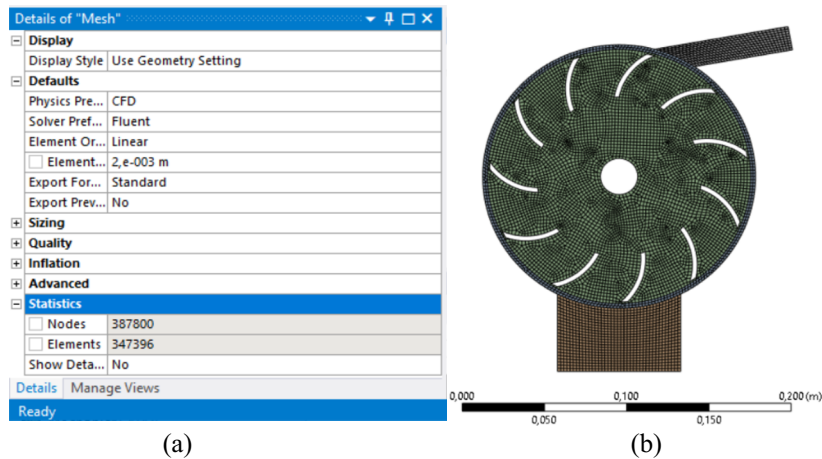


Figure 2. (a). Mesh setup in CFD program, (b). Mesh generated elements in cross flow turbine

Boundary Conditions. The computational domain was defined by assigning appropriate boundary conditions to represent the operating conditions of the cross-flow turbine. The numerical model consisted of four main regions, namely the inlet, outlet, rotating domain, and stationary fluid domain. The inlet boundary was specified as a velocity inlet, where a uniform water velocity of 0.0015 m s^{-1} was imposed based on the experimental operating conditions. The flow direction was set normal to the inlet

surface with a turbulence intensity of 2% and a viscosity ratio of 10. The outlet boundary was defined as a pressure outlet with atmospheric pressure (0 Pa gauge), allowing the fluid to exit the computational domain without imposing a prescribed outlet velocity. The turbine runner was enclosed within a rotating domain, which was treated using the Moving Reference Frame (MRF) approach. The rotational motion was defined about the X-axis.

3 Result and Discussion

3.1 Result

The simulations were performed under identical operating conditions at a constant rotational speed of 500 rpm, allowing the effect of blade number on the internal flow characteristics to be evaluated. The velocity contours shown in figure 3, indicate that the flow pattern inside the turbine is generally similar for all three blade configurations. The highest flow velocities are observed near the outer region of the runner and around the blade passages, whereas the lowest velocities occur near the shaft region and the outlet channel. This behavior indicates that the incoming flow accelerates as it interacts with the turbine blades before gradually losing momentum after transferring energy to the runner.

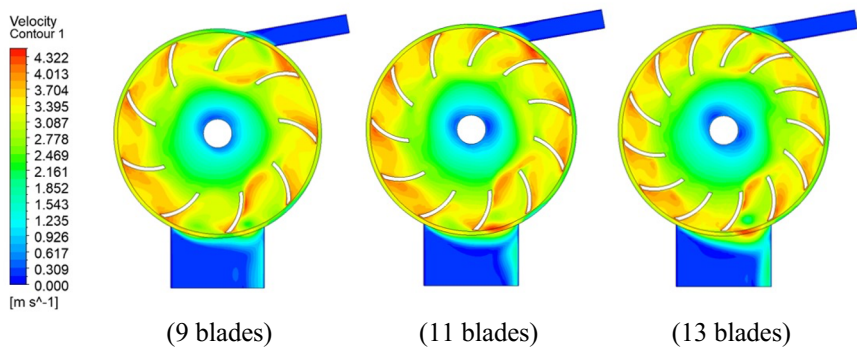


Figure 3. Velocity contour inside the turbine runners blade with 9, 11, and 13 blades

The velocity vectors show that the incoming flow enters the runner through the inlet passage and follows the blade curvature before exiting through the outlet region. In all configurations, the vectors indicate a smooth rotational flow around the turbine axis, confirming that the Moving Reference Frame (MRF) approach successfully captures the interaction between the rotating runner and the surrounding fluid.

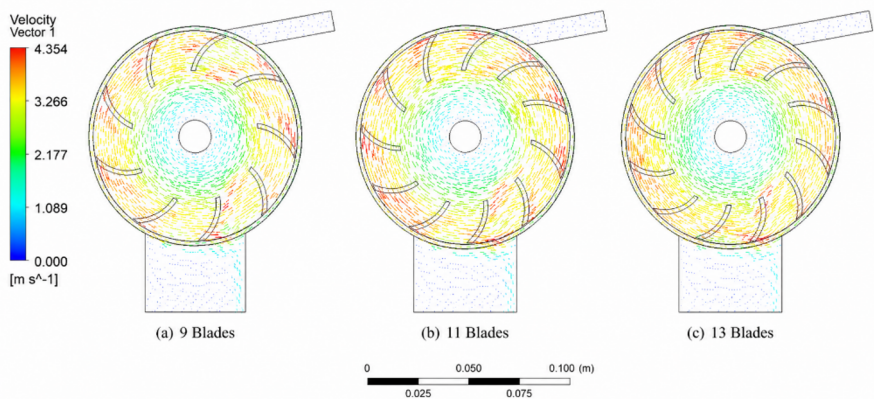


Figure 4. Velocity vector inside the turbine runners blade with 9, 11, and 13 blades

Increasing the number of blades modifies the distribution of the flow within the runner. The 9-blade configuration exhibits relatively wider flow passages, allowing the water to pass between adjacent blades with less obstruction. In contrast, the 11-blade and 13-blade configurations produce narrower blade passages, resulting in a more uniform velocity distribution around the runner circumference. The increased blade number also enlarges the blade–fluid interaction area, which may enhance energy extraction, although excessive blade density may increase hydraulic losses due to stronger flow interference between adjacent blades. Overall, the velocity vector distributions indicate that increasing the blade number modifies the internal flow structure and the interaction between the water and the turbine runner.

3.2 Discussion

The CFD simulations demonstrate that the number of runner blades significantly influences the internal flow characteristics and hydraulic performance of the cross-flow turbine. As shown by the velocity contour and velocity vector distributions, increasing the blade number from 9 to 13 results in a more uniform flow pattern around the runner circumference. The additional blades reduce the spacing between adjacent blades, allowing the incoming water jet to interact with a larger blade surface area. Consequently, the transfer of hydraulic energy to the runner becomes more effective, leading to higher torque generation.

Table 4. Torque and power from CFD simulation

No	Runner Blades	Torque (N.m)	Angular velocity (rad/s)	Power (W) $P = T\omega$
			$\omega = \frac{2\pi N}{60}$	
1	9	0.567	52.36	29.67
2	11	0.646	52.36	33.82
3	13	0.702	52.36	36.78

The CFD simulation predicts the hydrodynamic moment acting on the turbine runner. The resulting torque was extracted from the rotating domain using the moment report function. As the number of blades increased, the predicted torque increased from 0.567 N·m for the 9-blade runner to 0.702 N·m for the 13-blade runner, indicating a more effective transfer of hydraulic energy from the fluid to the runner. Since all simulations were performed at a constant rotational speed of 500 rpm the angular velocity become 52.36 rad/s. The corresponding hydraulic efficiency also improved from 49.0% to 55.9% and reached 60.7% for the 13-blade configuration. These results indicate that increasing the blade number enhances the energy extraction capability under the investigated operating conditions. Based on the CFD optimization results, the turbine runner with 13 blades was selected for prototype fabrication because it produced the highest torque, output power, and hydraulic efficiency among the investigated configurations. The optimized geometry was then manufactured using fused deposition modeling (FDM) additive manufacturing, as shown in Figure 5.

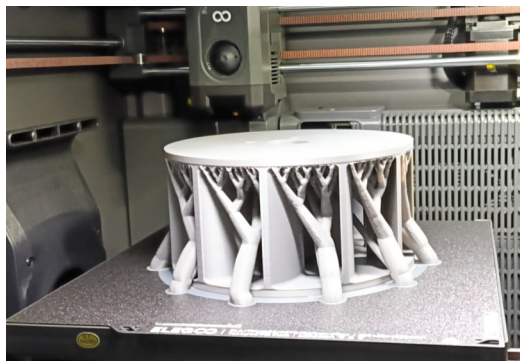


Figure 5. FDM Print Result of 13 blades runner turbine

4 Conclusion

This study investigated the effect of blade number on the hydraulic performance of a 3D-printed cross-flow turbine using Computational Fluid Dynamics (CFD). Three runner configurations (9, 11, and 13 blades) were evaluated under identical operating conditions. The simulation results showed that increasing the blade number improved the flow distribution within the runner, resulting in higher torque, shaft power, and turbine efficiency. Among the investigated designs, the 13-blade runner achieved the best performance, producing a torque of 0.702 N·m, a shaft power of 36.78 W, and a hydraulic efficiency of 60.7%. The optimized runner was successfully fabricated using Fused Deposition Modeling (FDM), demonstrating that additive manufacturing provides a practical and cost-effective approach for rapid prototyping of pico-hydro turbine components. These findings indicate that combining CFD-based design optimization with 3D printing offers an efficient methodology for developing high-performance cross-flow turbines.

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