Journal of Mines, Metals and Fuels, *73(1): 221-228; 2025. DOI: 10.18311/jmmf/2025/46440*

Print ISSN : 0022-2755

Journal of Mines, Metals and Fuels

Contents available at: *www.informaticsjournals.co.in/index.php/jmmf*

Numerical Simulation of Micro Wind Turbine for Low Speed Applications

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Abstract

The primary objective of this work is to utilize numerical modeling techniques to optimize the performance of a micro wind turbine specifically built for low-speed applications. A meticulous 3D model of the turbine blade was created and examined using Computational Fluid Dynamics (CFD). The methodology involved generating a precise fluid domain, carrying out a thorough meshing process, and completing a grid independent study to assure the accuracy of the solution. The simulations were conducted using several blade radii, specifically 200 mm, 220 mm, 240 mm, and 260 mm, in order to assess their effects on power generation and turbine speed. The results showed that increasing the size of the blade radius had a substantial impact on power generation, with the 260 mm radius achieving the highest power output. The increased efficiency of the turbine in low-speed wind conditions commonly found in metropolitan areas is due to its greater swept area, which allows it to absorb more wind energy. Nevertheless, greater blade radii led to decreased rotational speeds as a consequence of heightened inertia, hence alleviating mechanical strain and diminishing levels of noise and vibration. The 260 mm blade radius is the optimum choice for low-speed wind applications because to its ability to efficiently gather power while minimizing mechanical stress.

Major Findings: *The optimal number of elements for this simulation is around 4,50,000 at which increasing the grid density will no longer yields a more accurate solution. The largest radius, 260 mm, exhibits the highest power generation and lowest rotational speed across all wind speeds.*

Keywords: *Computational Fluid Dynamics (CFD), Micro Wind Turbine, Power Generation, Turbine Speed*

1.0 Introduction

The increasing demand for renewable energy sources has driven significant advancements in wind energy technologies. Micro-Wind Turbines (MWTs) represent a promising solution for renewable energy generation, especially in urban and low wind speed environments[1]. These small-scale turbines provide notable benefits, such as lower costs, simple installation, and the capability to produce energy from lower wind speeds. The power generation through micro-wind turbines promotes sustainable energy practices as it contributes to significant reduction in greenhouse gas emissions with reduced cost of electricity[2]. Micro-wind turbines are suitable for variety of applications like power generation for residential buildings and as a power source for small electric appliances[3]. MWTs are also being explored for their potential to power wireless sensor nodes and other small devices, offering a sustainable and independent power source for remote monitoring systems[4].

The incorporation of modern control systems like electronic braking mechanisms has enhanced safety and reliability of MWTs. These allied systems enhance performance of MWTs by regulating power output and providing emergency braking to prevent damage during high wind speeds scenarios. Advancements in

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manufacturing techniques, such as 3D printing, have facilitated the rapid prototyping and testing of micro-wind turbine blades. This not only improves aerodynamic performance but also reduces production costs significantly[5]. In conclusion, MWTs represent a promising and practical solution for decentralized renewable energy generation.

Recent experimental studies on micro wind turbines have provided valuable insights into their aerodynamic performance, efficiency, and structural dynamics under various conditions. Moussa[6] investigated the power coefficient evolution of a 3-blade HAWT, finding a maximum power coefficient of 0.24 at a tip speed ratio of 5.39 using outdoor experiments and CFD models with SST turbulence and RANS equations, showing good agreement with an error margin of 5%. Akour *et al.*,[7] designed and implemented MWT blades for low wind speed regions using airfoils BW3, A18, and SG6043, optimized with Blade Element Momentum theory and QBlade simulations, finding BW3 blades perform best; validated via 3D-printed prototypes, showing cost-effectiveness and improved energy harnessing. Charabi and Wahab[8] evaluated wind power generation in Northern and Southern Oman using HOMER Pro, finding the DW54 turbine optimal for northern Oman at $0.119/kW and the Hummer H25.0-200 kW turbine best for southern Oman at $0.070/kW, with significant CO_2 emission reductions. Patil[9] designed and analyzed wind amplifying rotor platform modules for Indian wind conditions (annual wind speed ~6.5 m/s), achieving amplification of 1.5 to 1.8 times free stream velocity, using airfoil data from NAL to optimize micro wind turbine twist, thickness, blade profile, and aerodynamic characteristics. Ngala and Shuwa[10] developed a HAWT blade for Nigeria's semi-arid region using 32 years of wind data, modifying a NACA 4412 airfoil via Design Foil Workshop CAD, achieving a lift-to-drag ratio of 124 at an 8° angle of attack; validated by CFD (ANSYS Fluent 6.18) and wind tunnel tests, showing 33% energy extraction at 6 m/s. Aljafari *et al.*,[11] designed a 100W HAMWT for low wind speeds using Blade Element Momentum theory and CREO CAD 3.0, selecting the S9000 airfoil, and comparing ABS and PLA materials in ANSYS 15, finding PLA superior in structural properties and lower deformation. Bourhis *et al.*,[12] analyzed Reynolds number effects on MWTs using wind tunnel tests and particle image velocimetry, finding that higher Reynolds numbers increase power and torque coefficients, optimum tip-speed ratios, and induce wider wake expansion and larger axial velocity defects. Muniandy *et al.*,[13] studied that MWTs designed for low wind speeds (~3 m/s), using an industrial fan and LED lights to demonstrate functionality, finding three turbines produce 0.27 W to light green LEDs and a rechargeable battery discharges 14.4 W for white LEDs.

The use of Computational Fluid Dynamics (CFD) models has become instrumental in optimizing turbine design. These models simulate wind flow and predict performance, enabling engineers to refine designs for maximum efficiency[3]. Castellani *et al.*,[14] investigated the aeroelastic behavior of a 2m rotor diameter HAWT with 3kW power output using experimental wind tunnel tests and the FAST code for numerical simulations, emphasizing the importance of integrated numerical and experimental methods for comprehensive system dynamics characterization. Tabatabaei *et al.*[15] investigated numerical simulation methodologies for an upwind three-bladed wind turbine using transient simulations, structured hexa mesh refined to y+=1, and turbulence models (k-ε, SST, SAS-SST), finding good agreement with experimental data for power coefficient but needing improvement for high TSR wake modeling. Korukcu[16] investigated the aerodynamic performance of a straight-bladed VAWT using URANS equations in ANSYS Fluent 18.2 and the DMST model in MATLAB, finding maximum moment coefficient at 70°-190°-310° azimuthal angles and validating numerical results with experimental data. Kim and Kim[17] conducted a preliminary study for commercializing a 300W horizontal axis small downwind wind turbine. The study analyzed performance at wind speeds from 6m/s to 12m/s, calculating torque and mechanical power at different speeds using 3D CAD design and CFD. Viswanathan *et al.*[18] investigated MWTs with modified S1223 blades featuring leading-edge bumps, using 2D and 3D numerical calculations, showing a 75% increase in energy production compared to standard blades, tailored for urban wind speeds of 0 to 5 m/s in India. Kapen *et al.*[19] evaluated MWT performance in low wind speed cities in West Cameroon using 2D COMSOL Multiphysics CFD simulations, k-ϵ turbulence model, and analyzing five airfoils (A18, BW3, 3R F1B, FX60-100, K3311), finding 3R F1B airfoil most efficient at various attack angles (0°, 10°, 20°, 30°).

Rahmatian *et al*.,[20] studied the impact of an encompassing duct on a micro HAWT's performance, finding that an optimized duct design increases inlet wind speed from 5 m/s to 10.7 m/s and turbine power coefficient from 0.33 to 1.2, using wind simulator experiments and numerical modeling with 52 duct configurations. Tayeb *et al*.,[21] presented a numerical model for a domestic horizontal axis wind turbine with power output between 0.4 kW and 50 kW. The study analyzed efficiency across varying Reynolds numbers, wind speeds, and turbine parameters, detailing streamlines, vectors, and power using CFD to solve 3D Navier-Stokes equations. Recently, Sekar *et al*.,[22] used ANSYS to model and perform FEA on wind turbine blades made of structural steel, epoxy carbon, and aluminum alloy, concluding that epoxy carbon is best suited for windmill blades due to its favorable strength and stability properties.

2.0 Methodology

The numerical simulation of a micro wind turbine for low-speed applications required the completion of various critical stages. The turbine blade design was initially generated using the Design Modeler tool in ANSYS. This tool enabled the creation of a comprehensive 3D model that is crucial for precise CFD simulations. The blade geometry was intricately crafted to ensure optimal performance in low-speed wind circumstances,

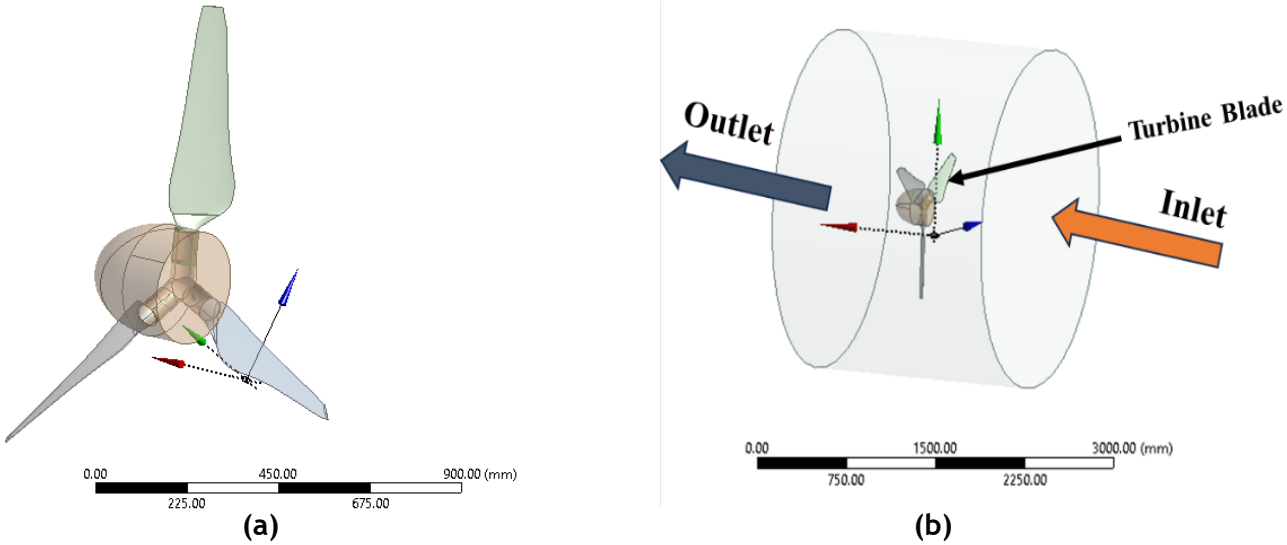


Figure 1. Geometrical model used for the CFD analysis. **(a)** 3D Model of blade design. **(b)** Fluid domain used for CFD analysis.

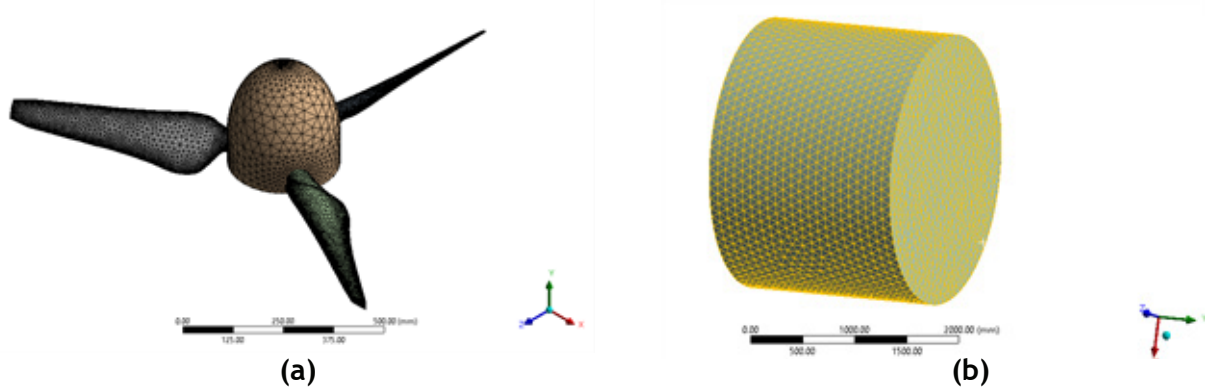


Figure 2. Meshing details of the model used for simulation. **(a)** Meshing of the blade (Coarse at the middle and dense at edges). **(b)** Complete meshing of the domain.

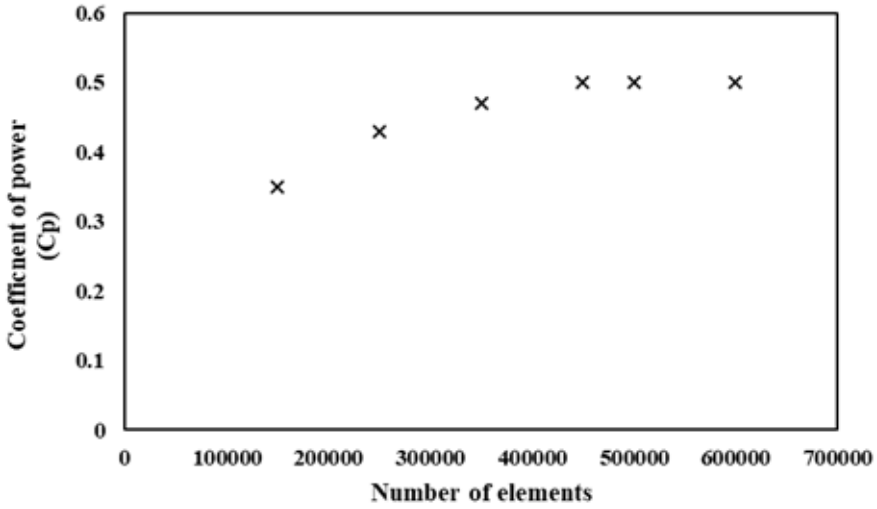


Figure 3. Grid independence test.

Table 1. Boundary conditions used for the numerical analysis

Sr. No.	Named selection	Type of boundary
1	Inlet	Velocity inlet
2	Turbine Wall	Moving wall
3	Domain wall	Stationary wall
4	Outlet	Outflow
5	Type of Solver	Pressure based
6	Algorithm and coupling	SIMPLE algorithm with pressure based coupling
7	Convergence criteria	10^{-5}

commonly found in metropolitan areas or locations with below-average wind speeds. The fluid domain was created to encompass essential boundaries, such as the inlet, outflow, turbine blade, and domain walls, to accurately identify all required boundaries.

After completing the modeling phase, the fluid domain was meshed using the ANSYS Meshing tool. Due to the intricate surfaces and volumes of the blade shape, polyhedral elements were selected for the mesh as they offer versatility in meshing. The blade edges were subjected to a greater mesh density in order to accurately capture boundary layer phenomena, whereas a coarser mesh was employed in the core areas to minimize computing expenses. Emphasizing the importance of mesh quality, we thoroughly examined characteristics such as skewness, orthogonality, and aspect ratio to reduce numerical errors and improve the stability and accuracy of the simulations.

A grid independence study was undertaken to ensure the solution's autonomy from the grid size, with the coefficient of power (Cp) being the parameter of focus as shown in Figure 3. The number of mesh elements was systematically increased from 150,000 to 600,000, and the Cp value was measured for each arrangement. It was noted that the Cp value initially exhibited substantial fluctuations, suggesting that the larger grids were not accurately representing the flow characteristics. Once the number of elements exceeded 450,000, the Cp value

reached a stable point of 0.5. Subsequent increases in grid density had minimal impact on the observed changes. This stabilization signifies that the solution has attained grid independence. Hence, a total of 450,000 elements were considered to be the most suitable for the simulation, striking a favorable equilibrium between computing expense and solution precision.

The CFD simulations were performed using a transient model that used a Moving Reference Frame (MRF) to accurately represent the dynamics of the rotor. After doing a comparison analysis with various models such as k-epsilon and Reynolds-Averaged Navier-Stokes (RANS), the k-ω SST turbulence model was chosen for the simulation. The selection of the k-ω SST model was based on its capacity to precisely forecast flow separation and its resilience in managing intricate aerodynamic flows. The boundary conditions used for the simulations are tabulated in the Table 1 given.

3.0 Results and Discussion

3.1 Power Generation vs. Wind Speed

The results from the numerical simulation examines the relationship between power generation and wind speed for four different PLA material blade radii: 200 mm, 220 mm, 240 mm, and 260 mm as shown in Figure 4. As anticipated, power generation increases with wind speed for all blade radii, consistent with the Betz law, which states that the power available from the wind is proportional to the cube of the wind speed. Each blade radius produces a distinct curve, with larger radii generally yielding higher power output at a given wind speed. The smallest radius, 200 mm, shows the lowest power output across all wind speeds, attributed to its smaller swept area, which limits the amount of kinetic energy captured from the wind. As the blade radius increases to 220 mm, there is a noticeable improvement in power generation, indicating that even a modest increase in blade length significantly enhances energy capture. For the 240 mm radius, the power output is substantially higher than the previous two, demonstrating a more considerable gain in energy capture with increased blade length. The largest radius, 260 mm, exhibits the highest power generation across all wind speeds, underscoring the advantage of maximizing the swept area of the turbine. However, the rate of increase in power output begins to diminish at higher wind speeds for this blade length.

3.2 Turbine Speed vs. Wind Speed

The results focuses on the relationship between turbine speed (rotational speed) and wind speed for the same PLA

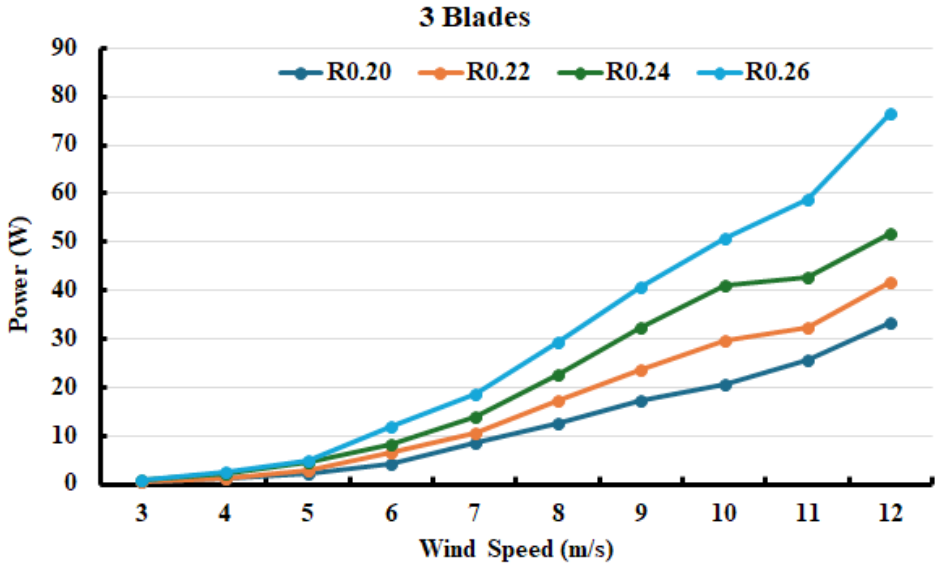


Figure 4. Variation in power generation with respect to wind speed for 3 bladed wind turbine with different blade radius.

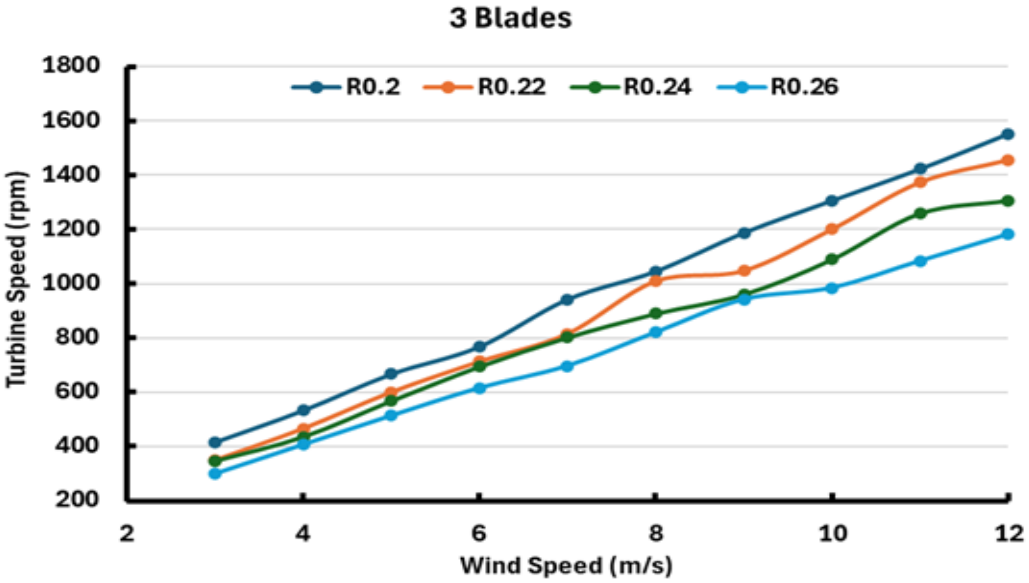


Figure 5. Variation in turbine speed with respect to wind speed for 3 bladed wind turbine with different blade radius.

material blade radii as shown in Figure 5. As expected, turbine speed increases with wind speed for all blade radii, as higher wind speeds exert more force on the blades, causing them to rotate faster. Each blade radius produces a distinct curve, with smaller radii generally resulting in higher rotational speeds at a given wind speed. The 200 mm radius shows the highest rotational speeds across all wind speeds due to the smaller blades having less inertia, allowing them to spin faster in response to wind forces. As the blade radius increases to 220 mm, the rotational speeds are slightly lower compared to the 200 mm radius, indicating that the increased blade length adds more inertia, which moderates the rotational speed. For the 240 mm radius, the rotational speeds are further reduced compared to the 220 mm radius, showing a trend where increasing blade length and, consequently, blade mass and inertia lead to lower rotational speeds. The 260 mm radius exhibits the lowest rotational speeds among the four radii, as the longer blades have significantly higher inertia, dampening their rotational speed despite higher wind forces.

4.0 Conclusion

The objective of this study was to enhance the design and efficiency of a small-scale wind turbine for use in low-speed scenarios by utilizing Computational Fluid Dynamics (CFD) for numerical simulation. The process entailed generating a comprehensive 3D representation of the turbine blade, conducting meshing with the right level of density, carrying out a research to ensure grid independence, and choosing an appropriate solver and boundary conditions to ensure precise simulation. The results yielded significant insights into the influence of blade radius on power generation and turbine speed.

The investigation demonstrated that augmenting the blade radius substantially amplifies power generation as a result of the expanded swept area, which effectively captures a greater amount of wind energy. Out of the evaluated radii, the blade with a radius of 260 mm showed the best power output. This is especially advantageous for places with modest wind speeds, such as urban or suburban areas. Maximizing energy capture and guaranteeing efficient operation in environments with normally lower wind speeds are dependent on this key development.

In contrast, the study discovered that greater blade radii led to reduced rotational speeds as a result of heightened inertia. The blades with a radius of 200 mm exhibited the highest rotational speeds, whilst the blades with a radius of 260 mm had the lowest rotational speeds. The decrease in velocity caused by bigger blades serves to

alleviate mechanical strain, hence diminishing centrifugal forces and improving the durability and lifespan of the turbine components. Decreased speeds additionally contribute to diminished noise and vibration, rendering the turbine more appropriate for installation in noise-sensitive residential locations.

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Nomenclature and Abbreviations

Cp	=	Coefficient of Power
CFD	=	Computational Fluid Dynamics
MMT	=	Micro Wind Turbine
HAWT	=	Horizontal Axis Wind Turbine
SST	=	Shear Stress Transport
RANS	=	Reynolds-Averaged Navier-Stokes
PLA	=	Polylactic Acid
FEA	=	Finite Element Analysis
MRF	=	Moving Reference Frame
TSP	=	Tip Seed Ratio