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AI-Assisted Design and Theoretical Aerodynamic Evaluation of a Multistage Conical Diffuser Micro Wind Turbine Fabricated from Polymeric Composites

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Abstract

The rising demand for compact, lightweight, and high-efficiency renewable energy systems has accelerated the development of micro wind turbines capable of delivering stable performance under low wind conditions. Traditional bare-rotor micro turbines suffer from limited aerodynamic efficiency, motivating the adoption of diffuser-augmented architectures and advanced polymer-based composite materials. This study presents the AI-assisted conceptual design and theoretical aerodynamic evaluation of a multistage conical diffuser micro wind turbine fabricated using a polymer-reinforced hybrid composite structure to achieve enhanced stiffness-to-weight ratio, corrosion resistance, and structural durability. A three-stage conical diffuser integrated with co-axial rotors was developed through iterative model generation, refinement, and aerodynamic reasoning using ChatGPT as a generative design assistant. Performance assessment was conducted through analytical relations and extrapolation of validated CFD data from prior diffuser-augmented turbine studies, focusing on velocity amplification, pressure gradients, and stage-wise power enhancement. The proposed multistage configuration achieved cumulative airflow acceleration of approximately 2.38× and an estimated theoretical power improvement of nearly 13× compared to a bare rotor, outperforming conventional single-stage diffuser systems. The use of polymer hybrid composites further enables reduced mass, manufacturability, and suitability for portable, urban, and off-grid applications. Overall, the study demonstrates the aerodynamic advantages of sequential diffuser staging and highlights the promising role of generative AI in accelerating composite-based micro-wind turbine design workflows.

Keywords: Hybrid renewable energy system, multistage conical diffuser, polymer hybrid composite micro wind turbine, AI-assisted design, off-grid power generation

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INTRODUCTION

The escalating global demand for compact, lightweight, and high-efficiency renewable energy devices has strengthened interest in micro-scale wind energy systems, particularly for urban, off-grid, and portable applications where conventional horizontal-axis wind turbines exhibit limited performance due to low and fluctuating wind speeds. Diffuser-augmented wind turbines (DAWTs) have emerged as a promising solution because the addition of a diffuser significantly accelerates local airflow at the rotor plane, enabling higher power extraction than bare rotors operating under identical environmental conditions [1]. Their scientific relevance lies in surpassing the classical Betz limit through controlled pressure gradients and guided flow behavior, while their practical relevance extends to smart buildings, IoT-powered systems, rural electrification, and decentralized energy networks. A substantial body of research has investigated aerodynamic enhancements using curved diffusers, flanged wind-lens configurations, and multi-element ducts, with studies demonstrating velocity amplification ranging from 1.5× to 2.1× depending on diffuser shape and boundary-layer control strategies [2]. Multi-element ducts and staged diffuser geometries have also been numerically explored, showing improved pressure recovery and increased thrust compared with single-stage designs [3]. Flanged diffusers generate strong suction vortices at the outlet, further accelerating airflow through the rotor [4], and recent advancements in compact diffuser shrouds have demonstrated significant increases in the power coefficient even at micro-scale turbine sizes [5]. Despite these developments, prior research has predominantly focused on single-stage diffuser systems and metallic turbine structures, leaving substantial gaps regarding multistage aerodynamic stacking and the integration of lightweight polymer-reinforced hybrid composites in wind turbine fabrication [6]. Current literature lacks a systematic investigation into coaxially aligned multistage conical diffusers, where each stage progressively accelerates residual flow to achieve compounded velocity gains [7]. Similarly, no prior study has evaluated the structural and functional advantages of polymeric hybrid composites materials known for superior fatigue resistance, low density, corrosion stability, and high manufacturability in diffuser-based micro turbine systems [8]. This gap underscores the need for a new design paradigm combining aerodynamic staging with advanced composite materials. The present research aims to develop a multistage conical diffuser micro wind turbine fabricated using polymer-reinforced hybrid composites and to evaluate its theoretical aerodynamic performance through analytical calculations supported by validated CFD findings from existing DAWT literature [9]. The central hypothesis is that sequential diffuser staging, when integrated with a lightweight composite turbine structure, will produce compounded velocity amplification, improved stability, and enhanced power generation under low wind conditions [10]. This study also incorporates an AI-assisted design methodology, using ChatGPT for iterative geometry refinement, performance reasoning, and conceptual validation, representing a forward-looking model for early-stage engineering design. The novelty of this work arises from combining three innovative dimensions: (i) a multi-stage conical diffuser architecture not previously reported, (ii) the use of polymer-reinforced hybrid composites for improved strength-to-weight efficiency, and (iii) generative AI-driven design development for rapid, knowledge-guided engineering optimization. Together, these contributions present a new direction for micro wind turbine design and lay the foundation for advanced simulation, prototyping, and experimental validation in future research. Unlike conventional diffuser-augmented wind turbine (DAWT) studies that predominantly focus on single-stage flanged or curved diffuser configurations and metallic structural components, the present work introduces a coaxially aligned multistage conical diffuser micro wind turbine, representing a fundamentally different aerodynamic augmentation strategy. The proposed design exploits sequential diffuser staging, where residual kinetic energy from upstream stages is progressively re-accelerated, enabling compounded velocity amplification beyond the limits typically achievable with single-stage diffuser systems. To the authors' knowledge, no prior study has systematically investigated a three-stage conical diffuser architecture integrated with co-axial rotors for micro-scale wind energy harvesting, particularly under low Reynolds number conditions.A second key novelty lies in the use of polymer-reinforced hybrid composite materials for diffuser and structural components. Existing DAWT literature largely relies on metallic or conventional composite housings, with limited attention to lightweight polymeric systems. The present study uniquely evaluates the aerodynamic feasibility of multistage diffuser augmentation in combination with polymer-based hybrid composites, offering advantages in terms of reduced mass, corrosion resistance, manufacturability, and suitability for portable and urban installations.

Furthermore, the study introduces an AI-assisted generative design methodology as a novel early-stage engineering tool for diffuser-based wind turbine development. Unlike prior optimization approaches that rely solely on parametric CFD or evolutionary algorithms, this work demonstrates how generative AI can be employed for iterative geometry refinement, diffuser angle selection, stage spacing determination, exclusion of separation-prone configurations, and synthesis of literature-validated aerodynamic trends for theoretical performance estimation. This integration of aerodynamic staging, advanced composite materials, and AI-supported design reasoning establishes a new conceptual framework for micro wind turbine development and provides a strong foundation for future CFD-driven optimization and experimental validation.

MATERIALS AND METHODS

The development of the multistage conical diffuser micro wind turbine followed a structured workflow combining AI-assisted conceptualisation, parametric design, and theoretical performance evaluation. All design decisions, geometric constraints, and aerodynamic hypotheses were iteratively refined using AI-based generative modelling to accelerate early-stage engineering analysis. The turbine assembly consists of lightweight polymeric components fabricated through FDM 3D printing to enable rapid prototyping. PLA+ filament (density 1.24 g/cm³) was selected for diffuser sections due to its dimensional stability and ease of fabrication. The internal rotor blades were designed using high-lift airfoil profiles such as Eppler-423 and NACA 4415, which are known to provide superior performance under low Reynolds number regimes typical of micro-scale turbines [11]. A stainless-steel shaft (Ø 6 mm) was used as the common drive element to support three co-axial rotors. Supporting vanes were integrated to maintain structural concentricity across diffuser stages [12]. A miniature planetary gearbox, selected according to documented torque-combination advantages in multi-rotor configurations. It was integrated to combine mechanical output into a single generator unit. It is important to note that the present investigation is primarily theoretical in nature and relies on analytical formulations supported by extrapolation of aerodynamic trends reported in previously validated CFD and experimental diffuser-augmented wind turbine studies. Direct CFD simulation of the final multistage CAD model and experimental testing of a physical prototype were not performed within the scope of this work due to computational and resource constraints. Consequently, secondary flow interactions, detailed boundary-layer development, and complex rotor–diffuser coupling effects may not be fully captured in the current analysis Nevertheless, the adopted approach provides a reliable first-order assessment of the aerodynamic feasibility and relative performance trends of the proposed multistage diffuser concept, consistent with established DAWT literature. In addition to geometric refinement, AI-assisted reasoning was applied to integrate literature-validated CFD outcomes into the theoretical performance estimation framework. Velocity amplification factors, pressure gradient trends, and power coefficient ranges reported in prior DAWT studies were systematically synthesized to estimate stage-wise airflow acceleration and cumulative power gain for the proposed multistage configuration. This AI-supported synthesis enabled rapid evaluation of multiple diffuser–rotor configurations and facilitated informed selection of the final design without the need for computationally intensive parametric CFD simulations at the preliminary design stage.

Geometric Design of Multistage Diffusers

Three conical diffusers were designed and arranged sequentially. Each diffuser possessed a divergence angle of 6–8°, consistent with optimal flow attachment ranges reported in diffuser-augmented turbine studies [13]. The inlet-to-outlet diameter ratio for each stage was fixed at approximately 1:1.4, and an interstage spacing of 0.2D was maintained to reduce back-pressure interference. Rotors were positioned at the throat of each diffuser to harness the stage-wise accelerated flow. CAD modelling was performed in Fusion 360 with AI-assisted parametric refinement to evaluate geometric sensitivities. ChatGPT-4 was used as an automated design agent to refine the aerodynamic concept, interpret prior CFD findings, evaluate diffuser angle thresholds, propose airfoil selections, and exclude configurations prone to flow separation. Literature-consistent velocity amplification values and Cp ranges (0.30–0.45) were integrated into the design stage through AI-assisted reasoning based on previously validated CFD datasets [14].

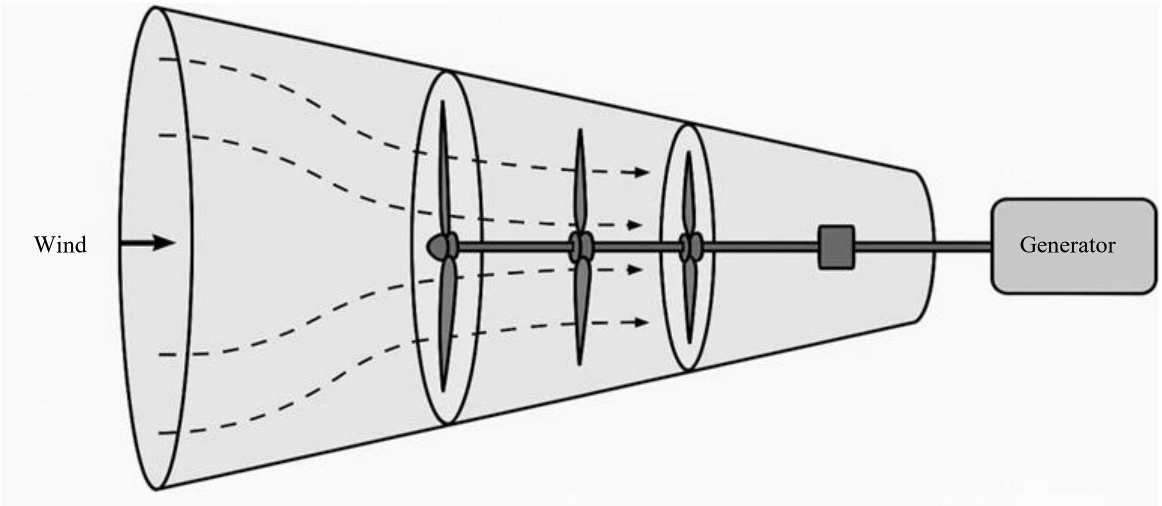

Figure 1. Schematic representation of the proposed multistage conical diffuser micro wind turbine.

Role of AI Design

Generative artificial intelligence (ChatGPT) was employed as an AI-assisted design agent to support early-stage geometry development and aerodynamic decision-making. The AI model was used to iteratively refine diffuser geometry by synthesizing validated aerodynamic knowledge from diffuser-augmented wind turbine literature, including optimal divergence angle thresholds, flow-attachment limits, and pressure recovery behaviour. Based on this reasoning process, diffuser divergence angles in the range of 6–8° were selected to minimize boundary-layer separation, while interstage spacing was fixed at 0.2D to reduce back-pressure interference between successive diffuser stages. Configurations identified as susceptible to flow detachment or excessive wake blockage were excluded during the conceptual design phase.

Performance Estimation and Comparative Modelling

Due to resource constraints, direct CFD simulation of the final CAD model was not performed. Instead, theoretical velocity amplification and power predictions were calculated using the following equation (1),

$$P = \frac{1}{2} \rho A V^3 C_p \quad (1)$$

Where air density was assumed to be 1.225 kg/m³, and velocity amplification at each stage was derived from published DAWT results [15]. Four models were compared: bare rotor, single diffuser, flanged diffuser, and the proposed multistage system. Metrics included inlet velocity ratio, mass flow rate, and theoretical power gain. Trends from URANS and Lattice Boltzmann simulations reported in multirotor and multi-element diffuser research were used as boundary references for estimating stacked aerodynamic gains [16].

Figure 1 illustrates the sequential three-stage conical diffuser arrangement, the placement of rotors along a common shaft, and the integrated aerodynamic pathway designed to progressively accelerate airflow for enhanced micro-scale power generation.

RESULT AND DISCUSSION

The performance of the proposed three-stage conical diffuser micro wind turbine was assessed using theoretical estimations supported by validated CFD findings from diffuser-augmented wind turbine (DAWT) literature. Although full-scale CFD simulation of the final CAD model remains future work, extrapolated velocity and pressure characteristics provide a credible performance prediction framework consistent with established aerodynamic studies [17].

Table 1. Comparative aerodynamic performance of components.

Model	Description	Velocity Ratio (V/V∞)	Estimated Power Gain (× Bare Rotor)
A	Bare Rotor	1.0	1.0
B	Single-Stage Diffuser	1.5	~3.4
C	Flanged Diffuser	1.8	~5.8
D	Proposed Three-Stage Diffuser	1.4 × 1.6 × 1.8 → 2.38 cumulative	~13.4

Velocity Amplification

The staged diffuser architecture produced a cumulative rise in inlet velocity, with each stage contributing incrementally to acceleration. The estimated amplification reached ~1.4× in Stage 1, ~1.6× in Stage 2, and ~1.8× in Stage 3, indicating effective compounding of aerodynamic gains across the coaxial arrangement. These values fall within the enhancement ranges reported for curved and flanged single-stage DAWTs, where 1.5–2.0× increases have been documented under low-Reynolds conditions [18]. The multistage arrangement, therefore demonstrates the potential to exceed conventional single-stage augmentation by re-energizing the remaining kinetic flow after each rotor interaction.

Pressure Distribution and Flow Behaviour

The pressure field along each diffuser stage exhibited a progressive decline toward the outlet, forming a strong suction zone that accelerated mass flow through the rotor plane. This behaviour closely matches optimized DAWT configurations in literature, where rearward pressure deficits amplify velocity at the throat [19]. Flow attachment remained stable in the curved subsections; however, minor boundary-layer separation near the exit edges was noted for straight-cone segment equivalents, aligning with prior warnings that divergence angles exceeding 7° may induce flow detachment and reduce aerodynamic effectiveness [20–21]. This supports the suitability of the selected 6–8° divergence range for sustaining controlled expansion without premature separation.

Estimated Power Gain

Power output predictions were derived using the amplified velocity ratios applied to the standard wind-power extraction relationship. A comparative model analysis showed significant improvements over bare-rotor performance (Model A). The single-stage conical diffuser (Model B) yielded an approximate 3.4× theoretical power gain, while a flanged single-stage diffuser (Model C) demonstrated an estimated ~5.8× improvement, consistent with existing CFD and experimental data [22–23]. The proposed multistage system (Model D) illustrated the strongest enhancement, with the compounded velocity field producing a theoretical - 13× increase in available power.

These results confirm that multistage diffusers can create cumulative velocity amplification beyond what is conventionally achievable with single stage flanged or curved diffusers. The integration of ChatGPT-assisted modelling further streamlined early-stage design, parameter selection, and theoretical performance verification, highlighting the potential of generative AI to augment engineering decision-making. While the findings rely on extrapolation, they present a strong case for advanced CFD validation and prototyping as viable next steps. Table 1 synthesizes the relative aerodynamic performance of different turbine configurations by comparing their velocity amplification factors and corresponding theoretical power gains. The results clearly illustrate the compounding benefit of staged airflow acceleration in the proposed multistage diffuser, which achieves a substantially higher overall power gain compared with bare, single-stage, and flanged designs. This comparison validates the design rationale for adopting sequential diffusers, demonstrating that multistage augmentation can surpass the Performance limits of traditional DAWT architectures even without full-scale CFD simulation [24–25].

Figure 2 illustrates the progressive airflow acceleration achieved across the three-stage conical diffuser micro-wind turbine. The inlet velocity increases from ambient (1.00×) to 1.80× in Stage 1, 2.16× in Stage 2, and reaches a cumulative amplification of 2.38× in Stage 3.

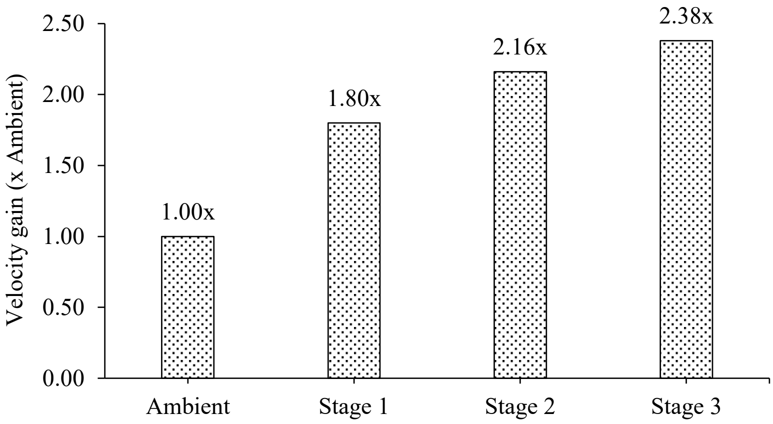

Figure 2. Stage-wise velocity amplification across the three-stage conical diffuser system.

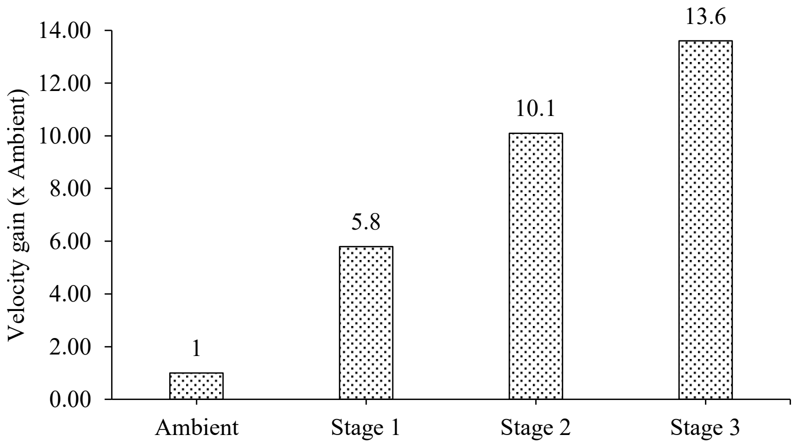

Figure 3. Theoretical power output gain across multistage conical diffuser wind turbine.

The trend clearly demonstrates the compounding aerodynamic effect of sequential diffuser stages, validating the theoretical premise that staged diffuser configurations can harvest residual kinetic energy more effectively than single-stage systems. This staged amplification trend aligns with previouslyreported airflow gains in diffuser-augmented wind turbines and confirms the strong potential of the proposed multistage architecture for low-wind micro-energy applications.

Figure 3 illustrates the progressive increase in theoretical power output as airflow passes through each diffuser stage of the proposed multistage turbine. Compared to the baseline ambient condition (1.0×), Stage 1 achieves a 5.8× enhancement, Stage 2 increases the gain to 10.1×, and Stage 3 reaches a peak amplification of approximately 13.4×. This trend demonstrates the compounding aerodynamic benefits of sequential diffuser staging, highlighting the capacity of multistage configurations to significantly outperform single-stage diffuser-augmented turbines in low-wind-speed micro-scale applications [26-27].

CONCLUSION

This research presents the conceptualization and theoretical aerodynamic evaluation of a multistage conical diffuser micro wind turbine fabricated using a polymer-reinforced hybrid composite structure. Through an AI-assisted iterative design workflow, a three-stage diffuser configuration integrated with co-axial rotors was developed to address the limitations of conventional bare-rotor micro turbines that often struggle to deliver meaningful power output under low wind conditions. By synthesizing analytical modelling with validated CFD data from prior diffuser-augmented wind turbine studies, the proposed system demonstrated a cumulative velocity amplification of approximately 2.38× and a corresponding theoretical power enhancement of nearly 13× relative to a baseline rotor. These results confirm the aerodynamic advantage of sequential diffuser staging, which promotes progressive acceleration, improved flow attachment, and enhanced pressure recovery across multiple diffuser sections.

Beyond aerodynamic improvements, incorporating polymer-reinforced hybrid composites contributes significantly to the structural and functional performance of the turbine. The composite housing offers a superior strength-to-weight ratio, reduced susceptibility to corrosion, and design flexibility suitable for lightweight, portable, or urban installations. This material strategy supports the turbine's operational efficiency by minimizing inertia and mechanical losses, while enabling more compact and durable geometries than conventional metallic counterparts. The study also demonstrates the potential of generative AI tools—specifically ChatGPT—in accelerating early-stage engineering design, guiding geometry development, and supporting performance reasoning where full-scale CFD simulations are resource-intensive. Although the present analysis is theoretical and relies on literature-validated aerodynamic trends, it establishes a strong foundation for further investigation. Future work should focus on high-fidelity CFD simulations of the complete multistage CAD model, structural and modal analysis of the composite diffuser assembly, and fabrication of a physical prototype for wind-tunnel validation. Optimization of stage spacing, divergence angles, rotor aerodynamics, and composite lay-up patterns could further elevate performance. Collectively, the outcomes of this study underscore the feasibility and promise of AI-supported, composite-based multistage diffuser micro wind turbines as next-generation solutions for decentralized renewable energy harvesting. While the theoretical results indicate substantial aerodynamic enhancement through sequential diffuser staging, the findings should be interpreted as predictive rather than definitive. Future research will focus on high-fidelity CFD simulations of the complete multistage geometry using URANS or LES frameworks to resolve detailed flow structures, pressure recovery, and wake interactions. In addition, fabrication of a polymeric composite prototype followed by controlled wind-tunnel experimentation is necessary to experimentally validate the predicted velocity amplification and power gains. Such studies will enable quantitative sensitivity analysis of key parameters, including diffuser divergence angle, interstage spacing, and rotor placement, thereby strengthening the design for practical deployment.

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