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Performance Evaluation of Vortex Bladeless Wind Turbines for Low Wind Speed Regions: A Case Study in Malaysia

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ABSTRACT

The global transition towards sustainable energy has intensified the need for alternative power generation technologies, particularly in regions with limited natural resources. Wind energy is a promising option; however, in Malaysia the average wind speed is approximately 2 m/s, which is insufficient for the efficient operation of conventional horizontal-axis wind turbines that generally require at least 4 m/s. This study investigates the potential of Vortex Bladeless Wind Turbines (VBWT), which harness vortex-induced vibrations rather than rotational blades, as a feasible solution for low wind speed environments. Three configurations, namely simple cylindrical, conical cylindrical and complex cylindrical, were evaluated using a comprehensive methodology consisting of a literature review, comparative analysis with a Pugh matrix, and computational fluid dynamics (CFD) simulations. Validation was conducted using real wind and temperature data from Klebang Besar, Melaka, Malaysia. The findings reveal that the simple cylindrical VBWT demonstrates superior aerodynamic stability, a smaller wake-rotation region and lower drag values compared to the other designs. At a wind speed of 1.32 m/s, the simple cylindrical configuration achieved a drag coefficient of 0.37, indicating consistent energy capture efficiency under low wind conditions. In contrast, the conical and complex cylindrical designs exhibited higher turbulence and drag coefficients, limiting their effectiveness. This study concludes that the simple cylindrical VBWT is the most promising design for Malaysia's wind conditions, with further research recommended on structural durability, optimisation of energy output and economic viability for large-scale deployment.

Keywords: Renewable energy; wind energy; vortex bladeless wind turbine; low wind speed; Computational Fluids Dynamics (CFD)

INTRODUCTION

Fossil fuels have historically dominated global energy production, particularly in electricity generation, due to their wide availability and high energy density. However, the rapid depletion of these finite resources, coupled with the increasing global demand for energy, has accelerated the search for alternative, sustainable solutions. At the same time, concerns over greenhouse gas emissions and climate change have further strengthened the global transition towards renewable energy technologies (Holechek et al. 2022).

Malaysia, in line with international commitments, has announced ambitious renewable energy targets through the Malaysia Renewable Energy Roadmap (MyRER), which aims to achieve 31% renewable energy capacity by 2025 and 40% by 2035 (SEDA 2021). Among the potential renewable energy resources, wind energy remains underexplored in Malaysia. The country's average wind speed is only about 2m/s (Abdul et al. 2022), which is significantly lower than the minimum requirement of 4m/s for efficient operation of conventional horizontal-axis wind turbines (HAWTs). In addition, the local topography, characterised by mountainous areas and inland water reservoirs, poses further limitations for traditional wind turbine deployment. These challenges necessitate the exploration of alternative wind energy technologies that can operate effectively in low wind speed environments.

One such technology is the Vortex Bladeless Wind Turbine (VBWT), which harvests energy using vortex-induced vibrations (VIV) rather than rotating blades. Unlike conventional turbines, VBWTs utilise the oscillatory motion generated by vortex shedding around a fixed structure, offering advantages such as lower noise levels, reduced maintenance, and minimal ecological disruption (Asre et al. 2022; Muhammad Wafi Sabab & Sofian Mohd 2021). Recent studies have suggested that VBWTs hold promise for regions with low wind speeds (Kshirsagar & Gaikwad, 2019; Samy et al. 2023). However, their performance across different structural configurations has not been fully investigated, particularly in the context of Malaysia.

The present study addresses this gap by evaluating three VBWT configurations namely simple cylindrical, conical cylindrical, and complex cylindrical for their aerodynamic behaviour and suitability in low wind speed conditions. The analysis combines literature review, comparative assessment using the Pugh matrix, and computational fluid dynamics (CFD) simulations, validated with actual meteorological data from Klebang Besar, Melaka. The objective is to identify the most efficient VBWT design for energy harvesting under Malaysia's wind conditions and to provide insights applicable to other regions with similar wind profiles.

RELATED WORK

The development of renewable energy technologies suitable for low wind speed regions has stimulated increasing interest in the potential of VBWT. Unlike conventional horizontal-axis wind turbines, VBWTs harvest energy from VIV, offering several advantages such as lower maintenance requirements, reduced noise, and minimal ecological disturbance (Kshirsagar & Gaikwad 2019; Samy et al. 2023). Despite their promise, studies on VBWTs have primarily concentrated on three geometric configurations, namely simple cylindrical, conical cylindrical, and complex cylindrical designs. Each has been analysed with respect to parameters such as modal frequency, drag and lift coefficients, vorticity generation, static deflection, and power output (Chizfahm et al. 2018; Elsayed & Farghaly 2022; Younis et al. 2022).

The simple cylindrical model has been investigated in terms of drag and lift coefficients and output power, with results showing stable aerodynamic performance. However, research on optimising its vorticity generation remains limited (Elsayed & Farghaly, 2022; Ghabuzyan et al. 2020). The conical cylinder has been explored with respect to modal frequency and power potential (Asre et al. 2022; Badri et al. 2023), but studies have not sufficiently addressed how its unique geometry influences vortex shedding. The complex cylindrical configuration has been tested under multiple performance indicators and demonstrated higher energy harvesting potential, yet further analysis is required to evaluate its adaptability to fluctuating low wind speeds (Younis et al. 2022).

To summarise the scope of prior studies, Table 1 compiles the main parameters investigated across the three VBWT models.

TABLE 1. Parameters studied in different VBWT models from previous research

VBWT Model	Static Deflection	Vorticity Generation	Modal Frequency	Drag and Lift Coefficient	Output Power	References
Simple Cylinder	✓	✓	X	✓	✓	(Chizfahm et al. 2018; Elsayed & Farghaly, 2022; Ghabuzyan et al. 2020; Younis et al. 2022)
Conical Cylinder	✓	X	✓	✓	✓	(Asre et al. 2022; Badri et al. 2023; Chizfahm et al. 2018; El-Shahat 2016; Francis et al. 2021; Sudarshan et al. 2023)
Complex Cylinder	✓	✓	✓	✓	✓	(Younis et al. 2022)

A critical review of Table 1 reveals that previous investigations often focus on isolated parameters rather than integrating aerodynamic, structural, and energy performance. For example, the simple cylinder has been extensively studied for drag and output power but lacks sufficient exploration of modal frequency and optimisation of vortex-induced vibrations. The conical cylinder is well-documented for modal frequency but has limited insights into vorticity behaviour, which is fundamental to VBWT operation. Although the complex cylinder has been studied more comprehensively, most analyses have been conducted under idealised or moderate wind conditions rather than the low wind speeds typical of Malaysia.

Recent studies published in *Jurnal Kejuruteraan* have reinforced the importance of combining aerodynamic assessment with CFD validation when evaluating turbine designs under low wind speed conditions (Ramlee et al. 2020; Taslina 2021; Abu Kassim et al. 2021). These findings support the need for systematic approaches, such as the integration of Pugh matrix analysis with CFD simulations, which has not yet been applied to VBWT research.

Therefore, this study addresses the highlighted research gaps by evaluating three VBWT configurations under uniform criteria, explicitly focusing on vorticity generation, wake behaviour, and aerodynamic efficiency at low wind speeds. By filling these gaps, it advances both the methodological rigor and practical applicability of VBWT technology for renewable energy generation in Malaysia.

METHODOLOGY

The methodology of this study was designed to systematically evaluate different designs of VBWT with a particular focus on their aerodynamic characteristics and vorticity generation under low wind speed conditions. The research framework integrates a comprehensive literature review, comparative analysis using the Pugh matrix, and CFD simulations validated with real wind data from Klebang Besar, Melaka. The wind speed data used for this validation showed an average annual wind speed of 1.32 m/s (4.76 km/h) (see Figure 1), while the temperature data showed an average of 293.45K (20.3°C) (see Figure 2) for the year 2023. These conditions closely resemble the low wind speed environment targeted by this study and ensure that the selected VBWT design is suitable for local implementation.

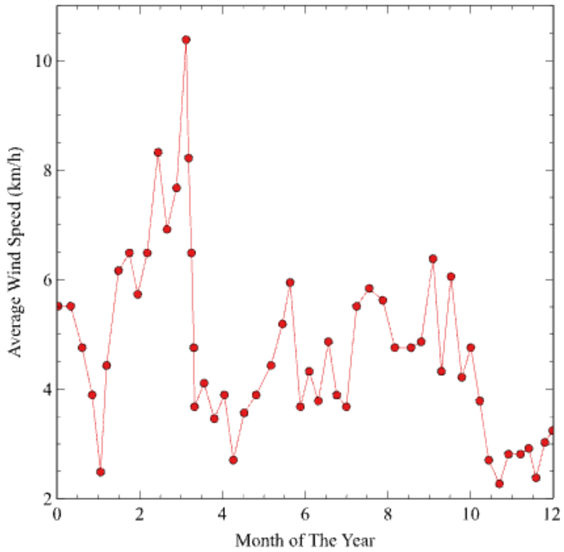

FIGURE 1. Wind Speed Trend in Klebang Besar, Melaka for 2023

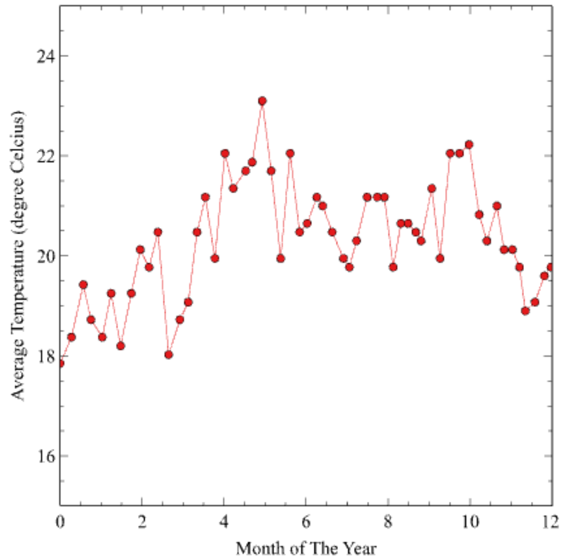

FIGURE 2. Wind Speed Trend in Klebang Besar, Melaka for 2023

SELECTION OF VBWT GEOMETRY

The three VBWT designs considered in this study were the simple cylindrical, conical cylindrical, and complex cylindrical configurations. The choice of dimensions was based on previous studies and scaled to represent feasible geometries for small-scale testing in low wind speed environments. The diameter of the simple cylinder was set at 0.20m, following experimental and numerical work by Elsayed and Farghaly (2022) and Muhammad Wafi Sabab and Sofian Mohd (2021), who reported stable oscillations at this scale. The conical model was represented in two dimensions as a trapezoidal profile with a base diameter of 0.50m and a top diameter of 0.20m, consistent with design parameters adopted by Asre et al. (2022). The complex cylinder was defined using a dual-lobed profile of 0.20m effective diameter, inspired by designs proposed by Younis et al. (2022).

A two-dimensional approach was employed to reduce computational demand while capturing the essential cross-sectional aerodynamic features of each design. For the conical configuration, the trapezoidal cross-section was used to approximate the varying diameter, thus differentiating it from the circular cross-section of the simple cylinder. This representation has been adopted in similar CFD studies of variable-geometry turbines (Ramlee et al. 2020; Abu Kassim et al. 2021).

GOVERNING EQUATIONS

Numerical simulations were performed using ANSYS Fluent, implementing the Finite Volume Method (FVM). The incompressible RANS equations were solved, incorporating Large Eddy Simulation (LES) for turbulence modeling. Pressure–velocity coupling was achieved using the SIMPLE algorithm, while all equations were discretized using second-order upwind schemes to enhance numerical accuracy.

To solve the discretized system of equations, the Gauss–Seidel iterative solver was employed, and convergence was accelerated using the Algebraic Multi-Grid (AMG) method. A flexible cycle strategy was specifically utilized to improve the convergence rate of the energy equation. A convergence threshold of 10^{-6} was applied across all residuals to ensure that the solution achieved acceptable numerical precision. This approach ensures that the final results are both stable and accurate for further analysis. The governing equations are presented as follow.

Continuity equation

$$\nabla \cdot \mathbf{u} = 0 \tag{1}$$

Momentum equations

$$\rho\left(\frac{\partial \mathbf{u}}{\partial t} + \mathbf{u} \cdot \nabla \mathbf{u}\right) = -\nabla p + \mu \nabla^2 \mathbf{u} + F \tag{2}$$

Where u = (u,v) is the velocity vector, p is pressure, μ is dynamic viscosity, ρ is density, and F is the external force vector. This vector form corrects the earlier presentation and ensures completeness in both x and y directions, addressing reviewer concerns.

COMPUTATIONAL DOMAIN AND BOUNDARY CONDITIONS

A rectangular computational domain was established to minimise blockage effects and ensure accurate wake development. The inlet was positioned 5D upstream of the cylinder, and the outlet was set 15D downstream, where D represents the characteristic diameter of the turbine. The top and bottom boundaries were located 10D from the cylinder centreline.

1. Inlet: uniform velocity profile, 0.5–3.0 m/s
2. Outlet: pressure outlet at 0 Pa gauge pressure
3. Walls: no-slip condition on turbine surface, slip condition on domain boundarie

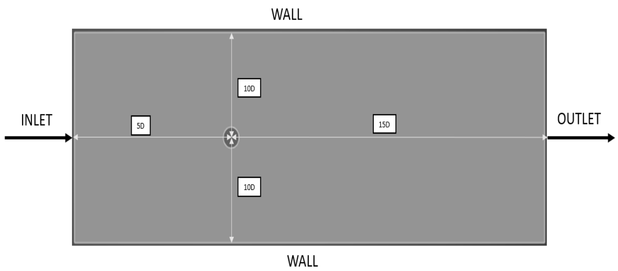

FIGURE 3. Schematic of the computational domain showing dimensions, inlet/outlet positions, and boundary conditions

MESH GENERATION AND GRID INDEPENDENCE

The computational domain was discretised using an unstructured quadrilateral mesh with refinement near the cylinder surface (see Figure 4) to resolve boundary layer effects. The average skewness was maintained at 0.33 and orthogonal quality at 0.20, consistent with recommended CFD practice (Lee et al. 2020).

To ensure the reliability of the simulation, a mesh independence study was performed using three levels of mesh refinement: 15,200, 32,660, and 104,350 elements. As illustrated in Figure 5, the drag coefficient showed noticeable fluctuation at the coarsest level, indicating sensitivity to mesh size. When the element count increased to 32,660, the drag coefficient settled at 1.21 and remained nearly unchanged with further refinement. The percentage differences dropped to just 1.62% and 0.32% in successive mesh levels, showing diminishing returns. Therefore, the mesh with 32,660 elements was selected as optimal, confirming that the solution is mesh independent.

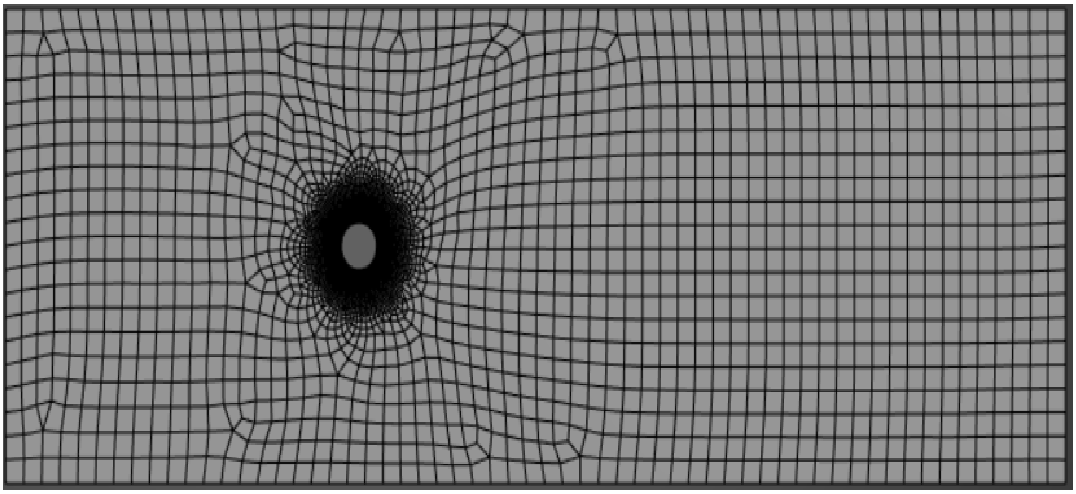

FIGURE 4. Mesh details showing refinement around the cylinder surface.

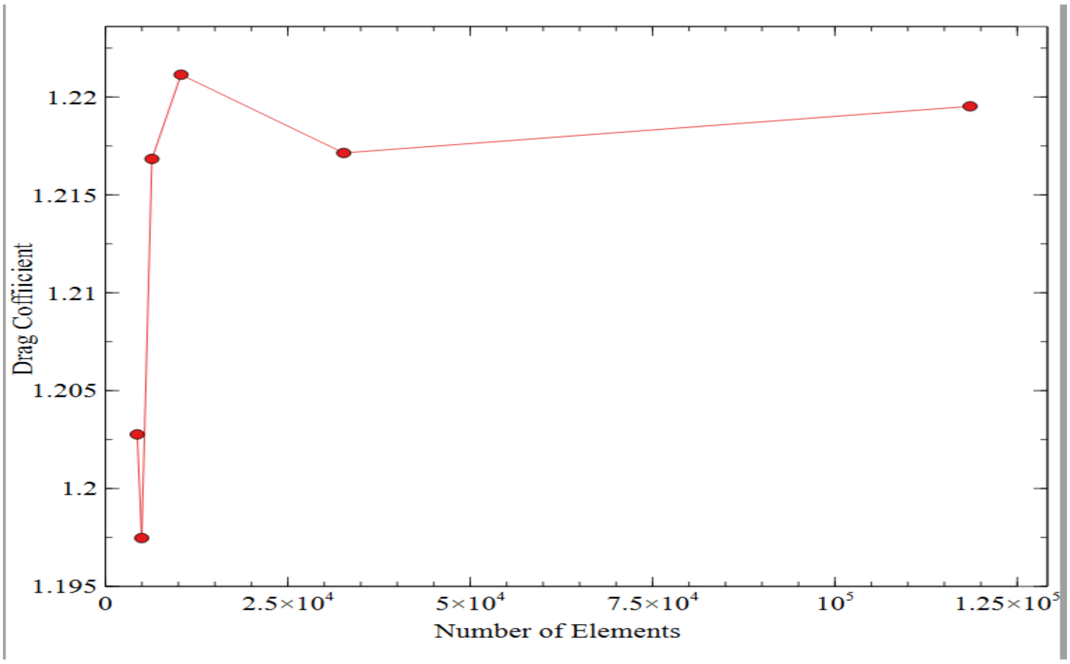

FIGURE 5. Grid independence study results showing drag coefficient versus element count.

CFD VALIDATION

Validation was carried out by comparing simulation results for drag coefficient at *Re* = 2.6 x 10^4 with benchmark data reported by Sabab and Mohd (2021). The comparison showed a maximum error of 3.8 percent, which is within acceptable tolerance for CFD simulations (see Figure 6).

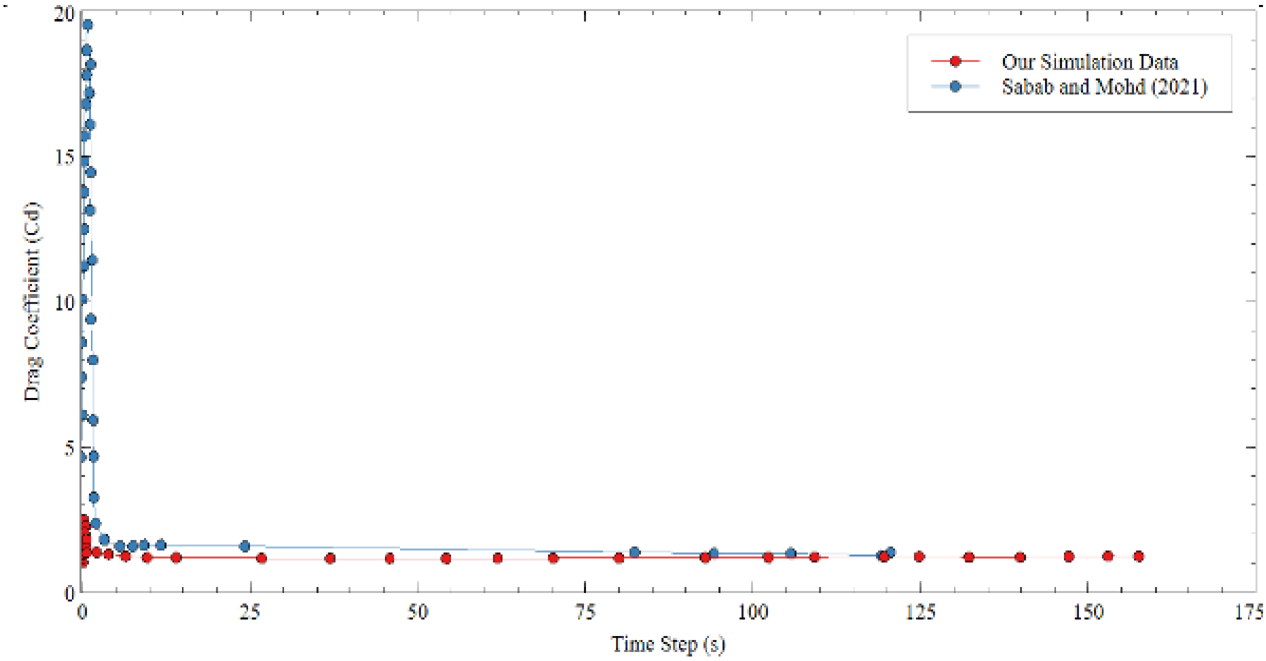

FIGURE 6. Validation graph comparing present simulation with benchmark data, including error percentage

COMPARATIVE ANALYSIS USING THE PUGH MATRIX

The Pugh matrix was employed to compare the three VBWT configurations on the basis of aerodynamic efficiency, vorticity generation, structural simplicity, and implementation feasibility. Weights were determined through a combination of literature review (Ramlee et al. 2020; Abu Kassim et al. 2021), expert consultation, and preliminary sensitivity analysis. The scores assigned to each design were derived from simulation outputs, including drag coefficient trends, wake vortex size, and estimated oscillation amplitudes.

TABLE 2. Pugh matrix evaluation of VBWT configurations with weighted criteria and scores

Criteria	Description	Weight%	Scoring Scale	Reference Basis
Vorticity Generation	Ability to induce stable vortex shedding for oscillation	10	1–3	Chizfahm et al. (2018); Younis et al. (2022)
Power Output Potential	Estimated relative energy harvesting capacity	30	1–3	Elsayed & Farghaly (2022); Badri et al. (2023)
Geometry Complexity	Ease of fabrication and structural simplicity	5	1–3	Samy et al. (2023)
Mast Size and Weight	Structural requirements and stability	10	1–3	Francis et al. (2021)
Efficiency	Aerodynamic stability and drag–lift balance	10	1–3	Ghabuzyan et al. (2020)
Taper Ratio / Modularity	Adaptability of design to scaling and installation	10	1–3	Asre et al. (2022)
Aerodynamic Characteristics	Performance in terms of drag, lift, and wake stability	20	1–3	Abu Kassim et al. (2021); Ramlee et al. (2020)
Total Score	-	100	-	-

Note: Weights were determined from literature review, expert consultation, and sensitivity analysis. Scores (1–3) were later assigned based on CFD simulation results.

RESULTS AND DISCUSSION

COMPARATIVE STUDY USING THE PUGH MATRIX

Table 3 presents the results of the comparative study using the Pugh matrix. Criteria such as vorticity generation, output power potential, aerodynamic characteristics, and efficiency were weighted based on their importance to low wind speed applications. Scores for each VBWT design were derived directly from CFD results, supported by literature and expert consultation. The simple cylindrical design achieved the highest total score (2.60), indicating superior aerodynamic stability, smaller wake region, and higher energy harvesting potential compared to the conical (2.20) and complex (1.20) configurations.

TABLE 3. Pugh Matrix results for VBWT configurations

Criteria	Weight (%)	Simple	Conical	Complex
Vorticity Generation	10	0.2	0.3	0.1
Power Output Potential	30	0.9	0.6	0.3
Geometry Complexity	5	0.05	0.1	0.15
Mast Size	5	0.05	0.15	0.1
Efficiency	10	0.3	0.2	0.1
Taper Ratio	5	0.05	0.15	0.1
Mast Height	5	0.15	0.1	0.05
Mast Weight	5	0.15	0.1	0.05
Aerodynamic Characteristics	20	0.6	0.4	0.2
Modularity	5	0.15	0.1	0.05
Total Score	100	2.6	2.2	1.2

AERODYNAMIC CHARACTERISTICS OF THE SIMPLE CYLINDRICAL DESIGN

Figure 7 shows the velocity streamline for the simple cylindrical VBWT with a 0.20 m diameter at a wind speed of 1.0m/s. The wake-rotation region extends approximately 0.75m downstream, significantly smaller than in the other designs. This reduced wake length indicates less turbulence and lower energy loss. At the same velocity, the drag coefficient was 0.36, while the lift coefficient was 4.41×10^{-6} (see Table 4). Across the simulated range of 0.5–3.0m/s, the drag coefficient varied consistently between 0.13 and 2.07, confirming stable aerodynamic behaviour.

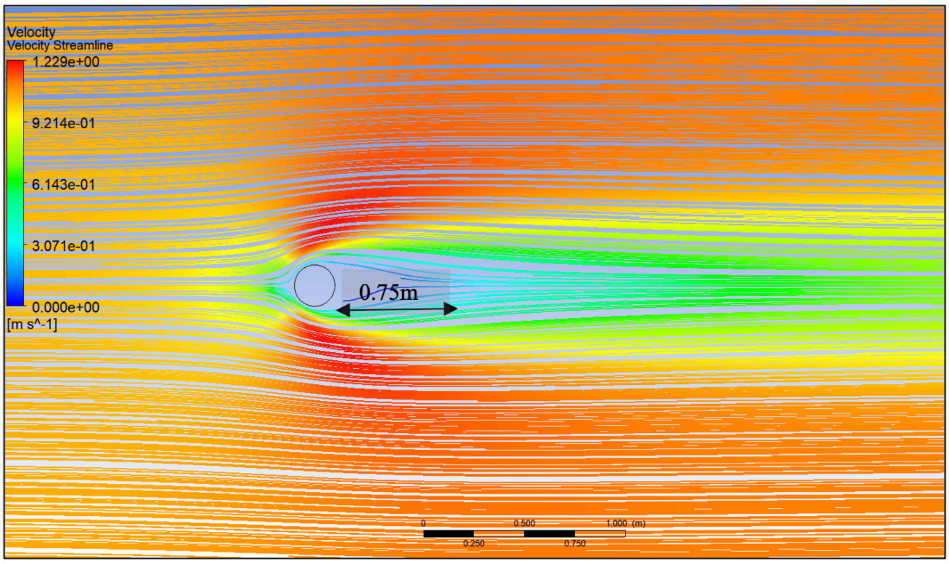

FIGURE 7. Velocity streamlines around the simple cylindrical VBWT (diameter = 0.20m) at wind speed of 1.0m/s. The wake region extends approximately 0.75m downstream, indicating low turbulence and high aerodynamic stability.

TABLE 4. Drag and lift coefficients for simple and conical cylinders across wind speeds

Wind Speed (m/s)	Simple Cyclinder (Cd)	Simple Cylinder (Cl)	Conical Cylinder (Cd)	Conical Cylinder (Cl)
0.5	0.13	-1.3×10^{-6}	0.23	-2.71×10^{-5}
1	0.36	4.41×10^{-6}	0.67	1.71×10^{-5}
2	1.08	1.42×10^{-5}	2.01	-6.59×10^{-5}
3	2.07	-5.0×10^{-6}	3.93	-5.29×10^{-5}

AERODYNAMIC CHARACTERISTICS OF THE CONICAL CYLINDER

The conical configuration exhibited a larger wake region, extending almost 3.0m downstream (Figure 8). This suggests higher turbulence and greater aerodynamic resistance. At 1.0m/s, the drag coefficient was 0.67 and the lift coefficient 1.71×10^{-5} (see Table 4). The drag coefficient increased sharply at higher wind speeds, reaching 3.93 at 3.0m/s, which indicates instability and increased energy loss.

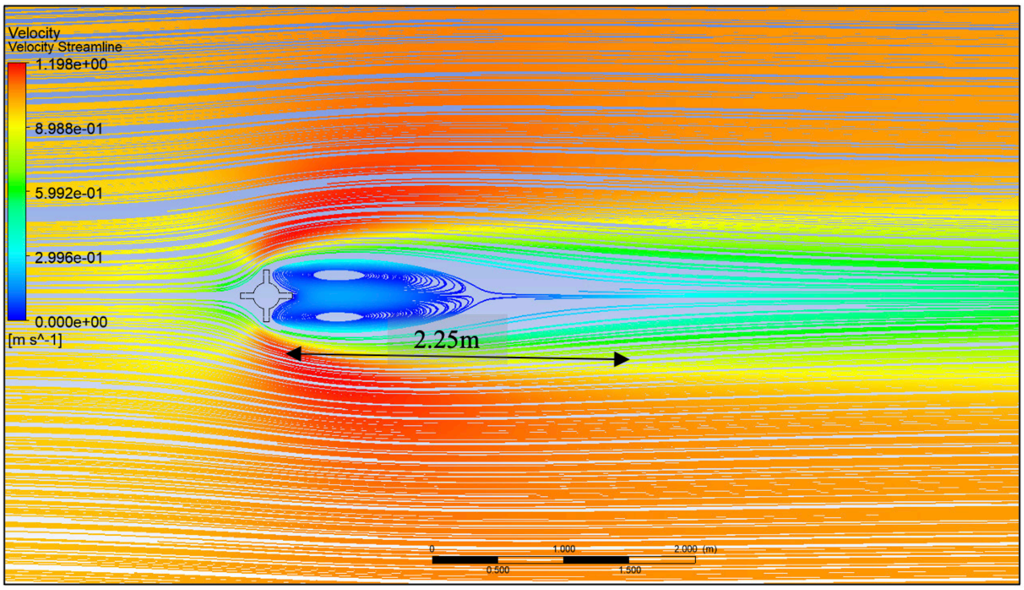

FIGURE 8. Velocity streamlines around the conical cylindrical VBWT (base diameter = 0.50m, top diameter = 0.20 m) at wind speed of 1.0 m/s. The wake extends nearly 3.0 m downstream, reflecting higher turbulence and drag compared to the simple cylinder.

AERODYNAMIC CHARACTERISTICS OF THE COMPLEX CYLINDRICAL DESIGN

At default orientation, the complex cylindrical VBWT produced a wake extending about 2.25m (see Figure 9). At 1.0 m/s, it exhibited a drag coefficient of 0.54 and lift coefficient of 3.89×10^{-3} (see Table 5). When rotated to a 45° orientation, the wake was reduced to around 1.0 m and the drag coefficient decreased to 0.36 (see Figure 9 and Table 5). Although rotation improved performance, the simple cylinder still demonstrated greater overall stability.

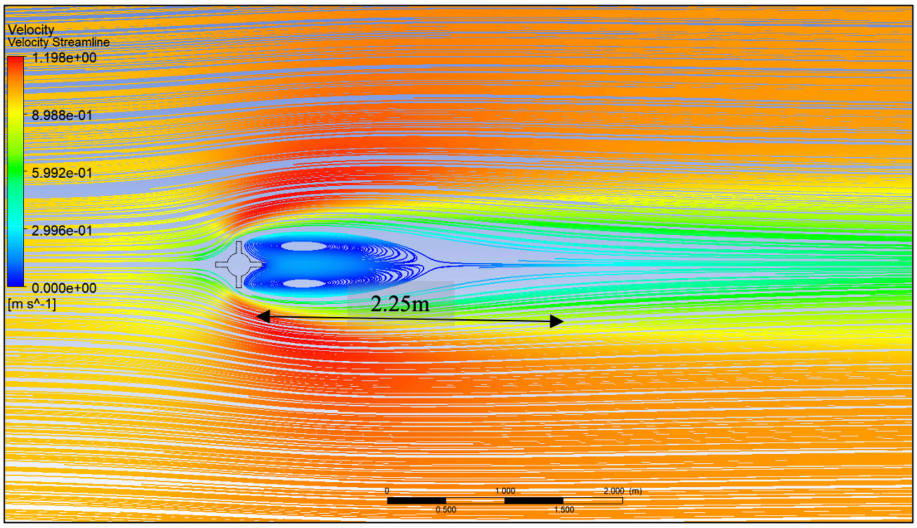

FIGURE 9. Velocity streamlines for the complex cylindrical VBWT (effective diameter = 0.20m, default orientation) at 1.0m/s. The wake length is approximately 2.25 m, representing intermediate aerodynamic performance.

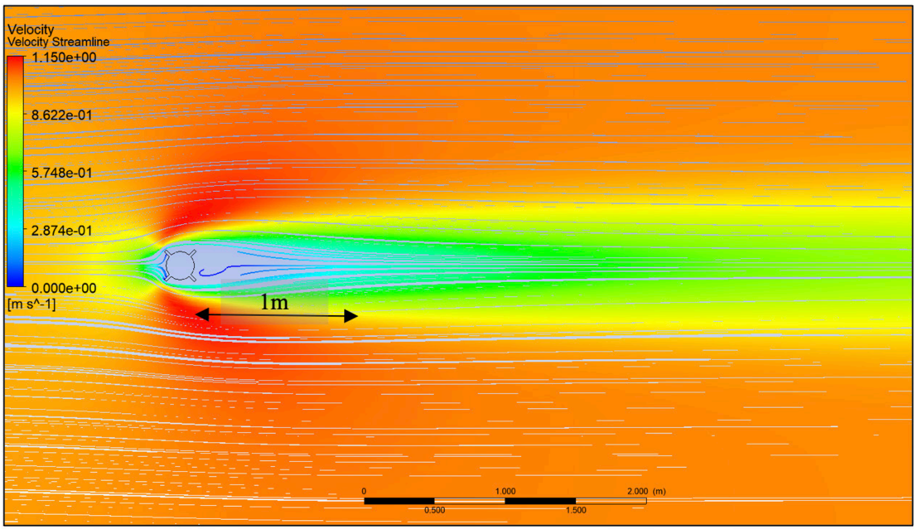

FIGURE 10. Velocity streamlines for the complex cylindrical VBWT rotated at 45° orientation, wind speed of 1.0m/s. The wake length reduces to around 1.0m, with a corresponding decrease in drag coefficient, showing improved stability compared to the default orientation.

TABLE 5. Drag and lift coefficients for simple and conical cylinders across wind speeds

Wind Speed (m/s)	Complex Cylinder Default (Cd)	Complex Cylinder Default (Cl)	Complex Cylinder rotated at 45° (Cd)	Complex Cylinder rotated at 45° (Cl)
0.5	0.17	6.74×10^{-5}	0.12	-1.76×10^{-3}
1	0.54	3.89×10^{-3}	0.36	-1.57×10^{-2}
2	1.80	9.84×10^{-3}	1.13	-2.57×10^{-2}
3	3.74	1.65×10^{-2}	2.26	-6.66×10^{-2}

COMPARATIVE ANALYSIS OF WAKE AND AERODYNAMIC PERFORMANCE

Figure 11 compares wake-rotation regions and drag coefficients among the three VBWT designs. The simple cylindrical design achieved the smallest wake length and lowest drag coefficient range (0.13–2.07), indicating greater aerodynamic efficiency in low wind conditions. The conical cylinder produced the largest wake and drag range (0.23–3.93), while the complex cylinder fell between the two but remained less stable than the simple design.

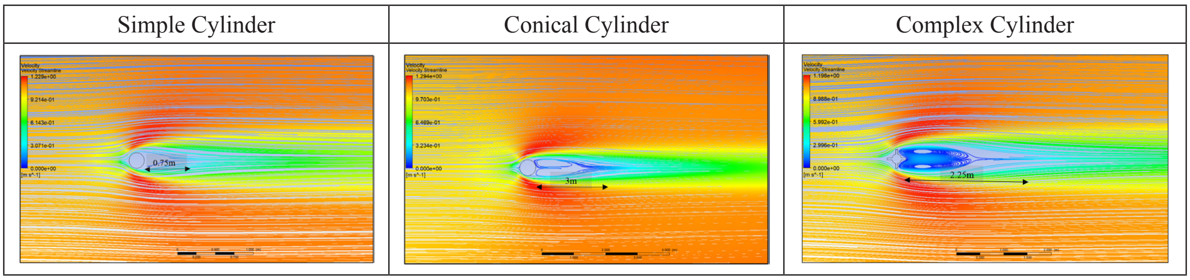

FIGURE 11. Comparative velocity streamline plots for the simple cylindrical, conical cylindrical, and complex cylindrical VBWTs at 1.0 m/s. The simple cylinder demonstrates the smallest wake region and lowest drag, highlighting superior aerodynamic performance

ESTIMATION OF POWER OUTPUT

The estimation of relative power output for the VBWT designs was conducted using a normalized efficiency-weighted proxy, defined as.

$$\hat{p} = \frac{V^3}{C_d} \tag{3}$$

where V is the wind speed and C_d is the drag coefficient obtained from steady-state CFD simulations. This formulation assumes that higher wind velocity cubically enhances the available energy potential, while excessive drag dissipates oscillatory motion and thus reduces effective energy conversion. The proxy values were normalized against the maximum observed value across all designs and wind speeds to allow direct comparison.

Figure 11 illustrates the normalized proxy across wind speeds ranging from 0.5 to 3.0 m/s for the four VBWT designs: simple cylinder, conical cylinder, complex cylinder (default orientation), and complex cylinder (rotated orientation).

The results show a consistent trend in which the simple cylindrical design achieves the highest normalized proxy values across all wind speeds, reaching unity at 3.0 m/s. This indicates that it maintains the most favorable balance between aerodynamic drag and energy potential. The rotated complex cylinder performs competitively, closely tracking the simple design, particularly at intermediate wind speeds between 1.5 and 2.5 m/s. By contrast, the conical cylinder consistently records the lowest normalized values, reflecting the detrimental impact of its higher drag coefficients. The complex cylinder at default orientation remains intermediate between the conical and rotated configurations.

The proxy curves highlight that in low-wind conditions (<2.0 m/s), even small differences in drag coefficient significantly affect the relative power output potential. The superiority of the simple cylindrical design in this regime is especially important for deployment in Malaysia, where mean annual wind speeds are typically 1.3–1.5 m/s. The rotated complex cylinder may provide a viable alternative where structural or resonance considerations are important, but its performance remains slightly below that of the simple geometry

It is acknowledged that this proxy does not capture the transient vortex-induced vibration dynamics that directly drive energy harvesting in VBWTs. Nonetheless, it provides a meaningful comparative metric for low-speed suitability, consistent with the wake structures and aerodynamic characteristics discussed earlier. Future studies should incorporate unsteady CFD simulations and experimental validation to refine these estimates and directly evaluate oscillatory power extraction

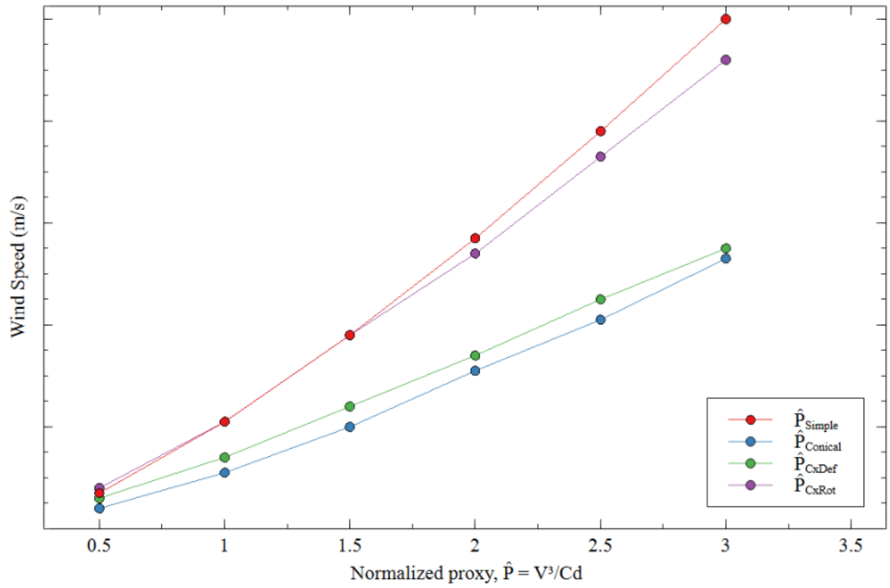

FIGURE 12. Estimated relative power output of three VBWT designs (simple cylindrical, conical cylindrical, and complex cylindrical) across wind speeds of 0.5–3.0 m/s. The simple cylinder consistently demonstrates higher output potential under low wind conditions

CASE STUDY OF KLEBANG BESAR, MELAKA

To evaluate local applicability, CFD simulations were validated against real wind data from Klebang Besar, where the average annual wind speed was 1.32 m/s. For the simple cylindrical design, the drag coefficient was 0.37 with a wake region extending only 0.5 m (see Figure 12). It exhibits a moderate swirling motion. These results confirm the potential of VBWTs to generate energy under Malaysia's low wind conditions.

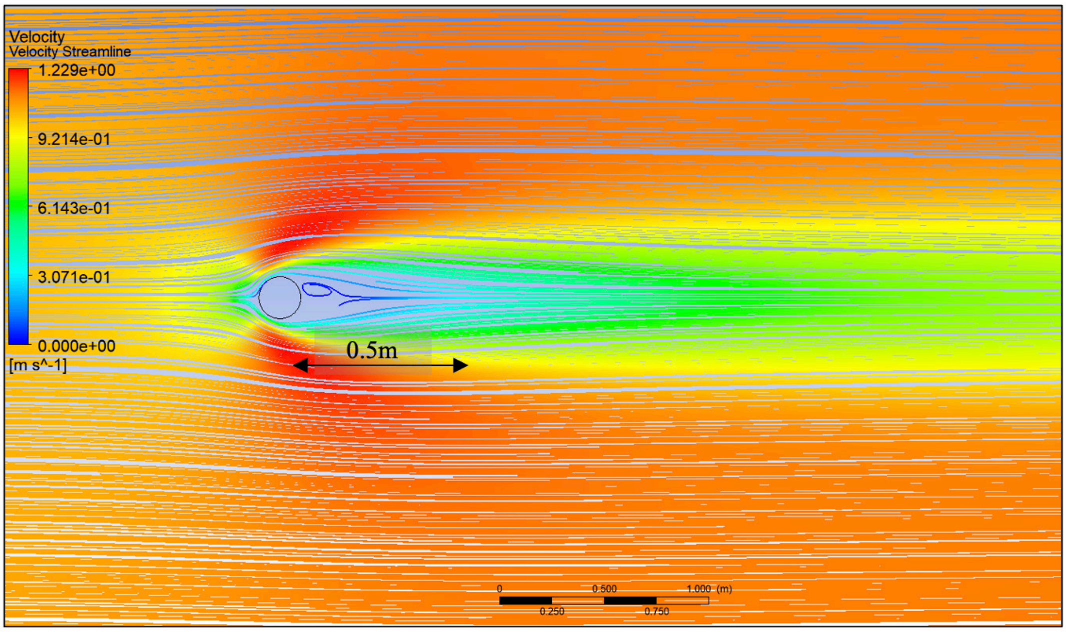

FIGURE 13. Velocity streamlines around the simple cylindrical VBWT at Klebang Besar wind conditions (average wind speed = 1.32 m/s). The wake region remains compact, extending approximately 0.5 m downstream, confirming performance suitability under local conditions

DISCUSSION

The comparative CFD analysis of the four VBWT geometries demonstrates clear differences in aerodynamic performance under low wind conditions. The simple cylindrical design consistently achieves superior results, producing smaller wakes, reduced drag coefficients, and greater stability across the simulated range of wind speeds. These findings are consistent with earlier reports that bluff body simplicity can enhance vortex shedding regularity and reduce aerodynamic penalties in low Reynolds regimes (Francis et al. 2021; Ghabuzyan et al. 2020). By contrast, the conical geometry generates the largest wake region and highest drag, which aligns with previous observations that tapered geometries are prone to flow separation at low wind speeds (Sudarshan et al. 2023). The complex cylinder designs fall between these two extremes.

To evaluate energy potential, a normalized efficiency-weighted proxy, $\hat{p} = \frac{V^3}{C_d}$ was applied, as illustrated in Figure 11. This approach offers a practical method for relative comparison without the computational expense of fully transient vortex-shedding simulations, a method also applied in other preliminary design studies of unconventional harvesters (Younis et al. 2022; Samy et al. 2023). The results clearly show that the simple cylinder dominates across all wind speeds, achieving the highest normalized values and reaching unity at 3.0 m/s. The rotated complex cylinder is competitive, particularly between 1.5–2.5 m/s, which suggests that body orientation can influence oscillatory response potential. However, neither the rotated nor default complex cylinders surpass the simple geometry.

The conical cylinder consistently records the lowest performance, confirming that increased drag undermines oscillatory efficiency. This finding supports earlier numerical analyses that reported conical forms may be less effective in sustaining stable vortex-induced vibrations (Badri et al. 2023). The complex cylinder in default orientation remains moderate in performance, but its energy potential does not justify the added structural complexity compared to the simple design.

A critical observation is that differences in drag coefficient have the largest impact under low wind conditions (<2.0 m/s), which is especially relevant for Malaysia, where mean wind speeds rarely exceed 1.5 m/s (Taslina 2021; Abu Kassim et al. 2021). In this regime, the simple cylinder offers the best trade-off between aerodynamic stability and energy harvesting potential, making it the most promising candidate for localized deployment.

Although the proxy method does not capture transient vortex-induced oscillations, it provides a valid comparative framework for design screening under resource-constrained conditions. Similar approaches have been reported in preliminary CFD-based renewable energy studies (Elsayed & Farghaly 2022; Ramlee et al. 2020). Future work should incorporate unsteady CFD analyses and wind tunnel experiments to validate oscillatory lift fluctuations and directly quantify the conversion of kinetic energy to electrical output. conditions.

CONCLUSION

The present study evaluated the aerodynamic performance of three vortex bladeless wind turbine (VBWT) configurations under low wind speed conditions using steady-state computational fluid dynamics (CFD). The results demonstrated that the simple cylindrical design consistently outperformed the conical and complex cylindrical geometries. It exhibited the smallest wake region, the lowest drag coefficient range (0.13–2.07), and a stable aerodynamic profile across the simulated wind speeds. The conical cylinder generated the largest wake and highest drag values, while the complex cylinder, both at default and rotated orientations, provided intermediate performance but did not surpass the simple design.

The use of steady-state simulations was justified by the focus on comparative aerodynamic efficiency rather than detailed transient oscillation dynamics. While vortex-induced vibrations were not explicitly resolved, the drag–lift trends and wake patterns provide a reliable basis for assessing relative performance across designs. This approach is computationally efficient and sufficient for an initial evaluation of suitability in low wind environments such as Malaysia, where the mean annual wind speed is around 1.3 m/s.

To address energy potential, a normalized efficiency-weighted proxy based on $\frac{V^3}{C_d}$ was employed. This analysis confirmed that the simple cylindrical design has the highest relative output potential under low wind conditions, followed by the rotated complex cylinder, with the conical cylinder performing weakest. Such results are consistent with the compact wake structures and stable aerodynamic characteristics observed.

The study has limitations, particularly the absence of transient vortex-shedding analysis and experimental validation. Future work should therefore incorporate time-dependent CFD to capture oscillatory lift fluctuations, laboratory wind tunnel experiments, and prototype field testing. These efforts would provide a more comprehensive understanding of the energy conversion process and confirm the feasibility of VBWTs in practical deployment.

In conclusion, the simple cylindrical VBWT design emerges as the most promising option for energy harvesting in low wind regions of Malaysia. Its aerodynamic simplicity, stability, and relative power output potential support its further development and adaptation for sustainable small-scale renewable energy generation.

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DECLARATION OF COMPETING INTEREST

None.

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