CHEMICAL ENGINEERING TRANSACTIONS

VOL. 122, 2025

A publication of AIDIC

The Italian Association of Chemical Engineering
Online at www.cetjournal.it

Guest Editors: Jeng Shiun Lim, Bohong Wang, Guo Ren Mong, Petar S. Varbanov

ISBN 979-12-81206-23-6; **ISSN** 2283-9216

DOI: 10.3303/CET25122044

CFD-Based Performance Optimization of Overlap Ratio in Savonius Hydrokinetic Turbines for Riverine Energy Systems

Muhyiddin Mohammed[a,*], Shamsul Sarip[b], Sa'ardin Abdul Aziz[b]

[a]Design Technology Department, Faculty of Applied Creative Arts, Universiti Malaysia Sarawak (UNIMAS), 94300 Kota Samarahan, Sarawak, Malaysia
[b]Faculty of Artificial Intelligence, Universiti Teknologi Malaysia, 54100 Kuala Lumpur, Malaysia
mmuhyiddin@unimas.my

This paper offers a numerical investigation of the performance of Savonius hydrokinetic turbines with three distinct blade overlap ratios: positive (+1.5), neutral (0), and negative (–1.5). The study employed two-dimensional transient simulations in ANSYS Fluent, using the Shear Stress Transport (SST) *k-ω* turbulence model, to assess turbine performance in low-speed riverine currents with an input velocity of 0.8 m/s. The overlap configurations were assessed across a range of tip speed ratios (TSR), with results compared in terms of power coefficient (Cp), torque response, and flow characteristics. The 0-overlap configuration achieved the highest efficiency, recording a peak Cp of 0.0794 at TSR 1.3. The 0-overlap configuration achieved the highest efficiency, recording a peak Cp of 0.0794 at TSR 1.3. This performance can be attributed to the balanced interaction between the advancing and returning blades, which minimizes flow interference. Compared to typical small-scale horizontal-axis turbines operating under similar flow conditions, the observed Cp remains modest but favorable for low-speed riverine applications. The standard deviation associated with this peak Cp value was approximately ±0.0021, based on time-averaged torque data over multiple cycles. The +1.5 design performed best at TSR 1.8 with Cp 0.0631, while the –1.5 case reached its peak Cp of 0.048 at TSR 0.7, offering smoother start-up performance at low rotational speeds. Pressure and velocity contours revealed distinct flow behaviors across geometries: smooth flow and minimal wake in the 0-overlap case, moderate separation for +1.5, and strong vortex shedding with wide wake for −1.5, each correlating with their respective performance trends. These findings underscore the impact of blade overlap on energy extraction and offer valuable guidance for the design of riverine small-scale hydro turbines.

1. Introduction

In many remote and riverine regions, access to reliable, sustainable energy remains challenging due to high costs, geographical barriers, and low population densities (IRNEA, 2022). Decentralised renewable technologies offer promising solutions, with Sovacool (2012) noting their potential to empower rural communities through modular, adaptable systems, and Ibrahim et al. (2021) emphasising their role in reducing energy costs via local integration. Muhyiddin Mohammed et al. (2024) further highlight the value of combining engineering, design, and environmental assessment to improve turbine efficiency and support hybrid renewable systems.

Savonius turbines, a type of vertical-axis hydrokinetic turbine (VAHT), are well-suited for river applications due to their robust construction, simple fabrication, and reliable performance at low flow velocities (Saha et al., 2008) They self-start and operate effectively under fluctuating flow directions, making them advantageous over horizontal axis designs. Karakaya et al. (2024) confirmed their suitability for shallow, irregular flows, while Mrigua et al. (2022) observed consistent torque output in similar conditions. These features make them attractive for low-head rivers, supporting uses such as water pumping, irrigation, and decentralized power generation.

Even though mechanically simple, Savonius turbines generally demonstrate lower efficiency compared to other turbine types. To improve energy conversion efficiency, several geometric enhancements have been investigated, such as blade curvature, ducting and overlap ratio. (Shanegowda et al., 2024) found that adjusting the overlap significantly influence wake recovery and torque characteristics, while (Bachtiar, 2019) discussed the structural and performance implications of different overlap ratios on turbine stability. Recent Computational

Paper Received: 5 July 2025; Revised: 16 October 2025; Accepted: 15 December 2025
Please cite this article as: Mohammed M., Sarip S., Abdul Aziz S., 2025, CFD-Based Performance Optimization of Overlap Ratio in Savonius Hydrokinetic Turbines for Riverine Energy Systems, Chemical Engineering Transactions, 122, 259-264 DOI:10.3303/CET25122044

Fluid Dynamics (CFD) research (Ayu Ramdhani et al., 2024) finds that the overlap ratio significantly influences the distribution of pressure, torque generation, and aerodynamic performance in both air and water systems.
Limited studies have examined hydrokinetic Savonius turbines under real riverine conditions, although overlap ratio effects have been explored in wind turbine contexts. Shanegowda et al.(2024) confirmed through CFD that small geometric changes can yield notable performance gains, while Ayu Ramdhani et al.(2024) showed that adjusting blade separation influences vortex interaction and turbine efficiency in aquatic flows. Karakaya et al. (2024) compared Gorlov, Darrieus, and Savonius designs, highlighting the role of inter-blade geometry on Cp and torque. Hosseini et al. (2023) integrated overlap ratio into a multi-objective optimization framework, and Singh et al. (2023) achieved significant gains using advanced surrogate-based methods.
This study investigates the performance of a two-dimensional Savonius hydrokinetic turbine with overlap ratios of +1.5, 0, and −1.5. Simulations were conducted in ANSYS Fluent R2023 R1 using a 2D transient SST k-ω turbulence model with a 0.8 m/s inlet velocity and no-slip boundaries. Torque and power coefficients (Cp) were analyzed to identify the most effective design for low-velocity river applications. The results support the optimization of cost-efficient, scalable, and low-carbon energy solutions for rural communities.
The paper is organized as follows: Section 2 reviews relevant literature on Savonius turbine design and the role of overlap ratio. Section 3 outlines the CFD modelling approach. Section 4 presents and discusses the simulation results, while Section 5 concludes with key findings and directions for future work.

2. Literature Review

2.1 Overlap Ratio Influence in Savonius Turbines

Ebrahimpour et al. (2019) conducted CFD studies on horizontal and vertical overlap ratios, identifying optimal values of +0.15 and +0.10. These yielded torque and Cp gains of about 16 % and 7.5 % over non-overlap designs. Ngalimo et al.,(2024) reported a 19 % Cp increase and a 7 Nm torque rise with positive overlap in wind turbines at high Reynolds numbers. Irawan et al.,(2024) further showed that overlap reduces downstream turbulence while boosting torque.

2.2 Blade Geometry Modifications

Mrigua et al. (2022) achieved a 20 % efficiency increase by modifying Savonius rotor geometry, confirming that blade shape combined with optimised overlap can enhance output. Mohammed et al.(2025) highlighted in a bibliometric review that recent Savonius hydrokinetic research increasingly focuses on blade profile optimisation to improve efficiency.

2.3 Separation Gap and Flow Dynamics

Ramdhani et al.(2024) investigated overlap and separation gaps in hydrokinetic settings, finding that precise gap control improved Cp to about 0.34 at TSR 0.8. Karakaya et al.(2024) compared Savonius, Gorlov, and Darrieus turbines, noting Savonius' Cp ≈ 0.257 , lower than others, yet valued for simplicity, cost-effectiveness, and self-start capability.

2.4 Hybrid Configurations and Optimizations Methods

Tantichukiad et al.(2023) reported that hybrid Savonius - Darrieus turbines with optimised overlap achieved an 18 % rise in self-start torque and Cp. Hosseini et al.(2023) used multi-objective optimisation to show that performance varies 13–35 % depending on overlap, twist angle, and flow speed.

2.5 Gap in Hydrokinetic Overlap Studies

Although several studies have assessed overlap in wind and water contexts, few have compared positive, zero, and negative overlaps under realistic river conditions. Mohammed et al.(2024) noted in a systematic review that overlap effects in hydrokinetic applications remain underexplored. This study addresses that gap by applying CFD at 0.8 m/s to evaluate these configurations for low-carbon river energy solutions.

3. Methodology

3.1 Geometry and Computational Domain

The turbine geometry (Table 1) was modelled in 2D with a 250 mm rotor diameter, following Talukdar et al., (2018) for baseline dimensions (Figures 1 and 2). The blade shape featured a modified central overlap curvature, while other dimensions were retained for performance comparison. Overlap ratios of +1.5, 0, and −1.5 were tested, defined as OR = Δ/D, where Δ is the horizontal blade offset and D the rotor diameter. The inner rotating zone was set to 3D in diameter, and the outer rectangular domain to 10D × 6D. While 2D modelling improves computational efficiency, it does not capture certain 3D effects such as spanwise vortices, so results are indicative pending 3D validation.

Table 1: Design specification of turbines (Talukdar et al., 2018)

Parameter	2 Semicircular Blade Turbine
Aspect Ratio (AR)	1.00
Overlap Ratio (OR)	0.15
Turbine Diameter (D)	250 mm
Diameter of Blade (d)	144 mm

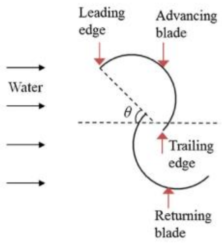

Figure 1: Schematic diagram of semi-circular blade turbine (*Talukdar* et al., 2018)

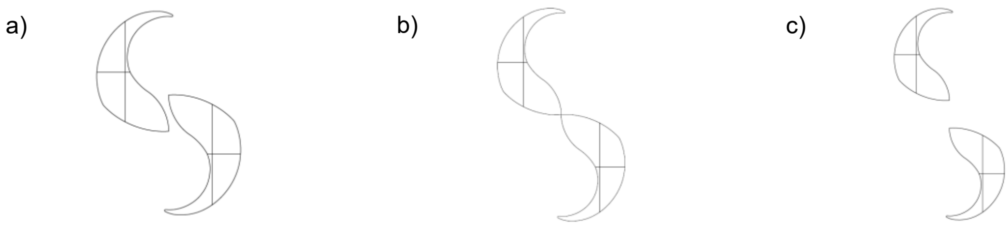

Figure 2: Schematic diagram of novel blade turbine with different overlap ratio (a) +1.5, (b) 0 and (c) -1.5

3.2 Mesh Generation and Independence

A mesh independence study was carried out for each overlap ratio to balance accuracy and computational cost. For +1.5 overlap, seven mesh levels (≈38k–1.4M elements) were tested, with convergence at Level 3 (≈110k elements, Cp = 0.0248). The −1.5 case also converged at Level 3 (≈113k elements, Cp = 0.039), while 0-overlap required Level 4 (≈197k elements, Cp = 0.0226). In all cases, Cp changes between successive refinements were under 2 %, and mesh quality met turbine simulation standards (orthogonality > 0.96, skewness < 0.06). Boundary layers were well resolved, and Grid Convergence Index values showed <3.5 % difference between the two finest meshes, confirming numerical consistency.

3.3 Governing Equations & Turbulence

The SST k-ω model was applied within an unsteady Reynolds-Averaged Navier-Stokes (URANS) framework using the SIMPLE algorithm for pressure–velocity coupling. With a Reynolds number of ~1.2×10^5, this model was chosen for its reliability in capturing near-wall behaviour and separated flows in turbine simulations.

3.4 Solver Settings and Time Stepping

A pressure-based solver with second-order upwind discretisation was applied, using 1° time-steps (360 per revolution) to ensure stable, accurate flow resolution at manageable computational cost.

3.5 Boundary Conditions

A flow speed of 0.8 m/s with 5 % turbulence was applied at the inlet, zero-gauge pressure at the outlet, no-slip blade walls, and symmetrical top/bottom boundaries, following the far-field slip-wall setup of Talukdar (2018)

3.6 Performance Metrics

Torque (T) and power coefficient (Cp) were averaged over the final two revolutions, following standard Savonius CFD definitions (Talukdar et al., 2018), as shown in Eq(1).

$$Cp = \frac{T\omega}{\frac{1}{2}\rho A U^3} \tag{1}$$

3.7 Validation

To validate the numerical model, Cp and torque values for the baseline geometry were compared with data from Talukdar et al. (2018). The Cp differed by less than 7.8 % from reported values, which is acceptable given the meshing and dimensional simplifications. This confirms the mesh and model are reliable.

4. Results and Discussion

4.1 Mesh Independence and Setup Overview

Mesh independence was tested for all configurations (+1.5, 0, –1.5) using seven mesh levels (≈38k–1.4M elements). Independence was confirmed when Cp variation between successive levels fell below 2 %.The +1.5 overlap converged at Mesh Level 3 (≈110k elements, Cp = 0.0248), the 0-overlap at Level 4 (≈197k, Cp = 0.0226), and the –1.5 at Level 3 (≈113k, Cp = 0.039). All selected meshes met quality criteria (aspect ratio 1.27–2.38), ensuring accurate boundary layer resolution. These mesh levels provided consistent results while reducing computational cost without sacrificing accuracy.

4.2 Results for Overlap Ratio = +1.5

The Savonius turbine, with a positive overlap ratio of +1.5, achieved peak efficiency at TSR of 1.8, which correlated to a rotational speed of 11.52 rad/s, resulting in Cp of 0.0631. This performance demonstrates a significant improvement relative to its output at lower TSRs, suggesting that the +1.5 overlap leverages higher angular velocities to facilitate effective momentum exchange.
The velocity contours (see Figure 3a) indicate moderate acceleration at the leading edge and a relatively stable wake structure. Nonetheless, the wake exhibits less development compared to the (–1.5) and 0 configurations, indicating restricted downstream energy extraction. Figure 3b shows high pressure near the forward blade's stagnation point, while the retreating blade lacks a clear low-pressure zone resulting in a limited pressure difference across the rotor.

a) b)

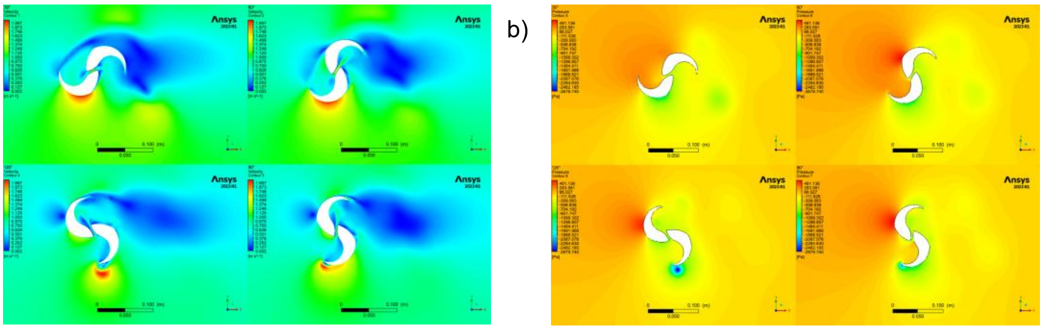

Figure 3: (a) Velocity contours (b) Pressure contours at 30°,60°,90° and 120°(clockwise) for TSR 1.8

The +1.5 configuration performed poorly at low TSRs but improved at higher speeds, making it better for fast flows, though its low torque limits use in slow rivers.

4.3 Results for Overlap Ratio = -1.5

The –1.5 overlap configuration achieved optimal performance at TSR 0.7 (Cp = 0.048), which is competitive with other low-head hydrokinetic turbines reported in literature, such as helical or ducted designs under similar flow conditions. Although this peak Cp is lower than that of the other two designs at their respective optimal TSRs, the (–1.5) configuration demonstrated superior performance in the low-TSR range, providing stable torque output and enhanced starting characteristics, which are essential in low-flow conditions.
Figure 4a reveals stronger flow separation and clearer vortices between blades, improving momentum transfer at lower speeds. The wider, uneven wake downstream suggests better energy capture. In Figure 4b, high pressure on the leading blade and low pressure on the trailing side support effective torque generation.

a) b)

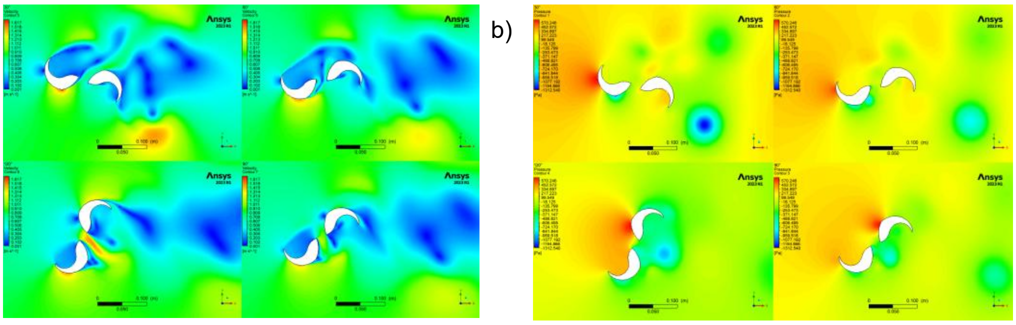

Figure 4: (a) Velocity contours (b) Pressure contours at 30°,60°,90° and 120°(clockwise) for TSR 0.7

Despite the (–1.5) design didn't yield the highest Cp, its consistent low-TSR performance makes it a strong candidate for off-grid or low-head applications, offering early rotation and improved startup in moderate river flow

4.4 Results for Overlap Ratio = 0

The 0-overlap design, commonly used as a reference in Savonius studies, showed the best performance at TSR 1.3, reaching a rotational speed of 8.32 rad/s and a Cp of 0.0794. This marked a notable improvement over the initial results and outperformed both the +1.5 and –1.5 configurations.
Figure 5a illustrates intensified vortex formation and broader wake structures, which contribute to improved momentum transfer and correlate with the observed efficiency differences across overlap configurations. Flow acceleration near the blade tips is more pronounced, indicating stronger momentum transfer and improved energy capture by the rotor. Figure 5b shows clearer pressure zones across the rotor. A standstill zone forms near the advancing blade, while low pressure surrounds the retreating blade this pressure gap boosts torque. At optimal TSR, efficient flow passage and recovery help improve rotor output, even without geometric offset.

a) b)

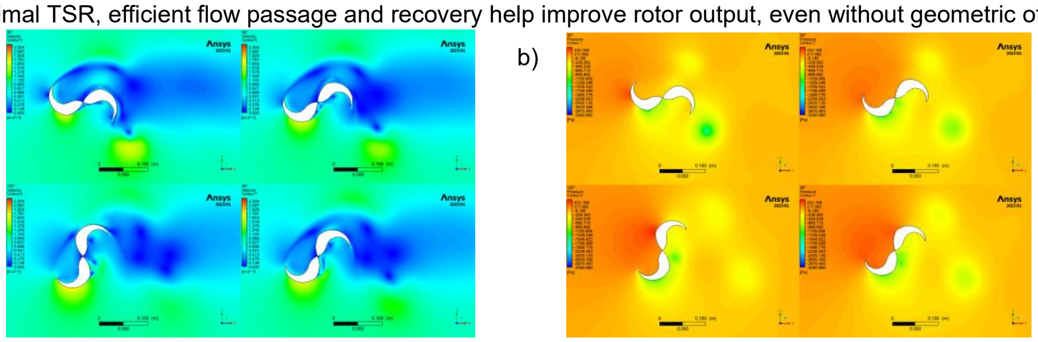

Figure 5: (a) Velocity contours (b) Pressure contours at 30°,60°,90° and 120°(clockwise) for TSR 1.3

The 0-overlap configuration showed that appropriate adjustment of operational speed can significantly enhance performance, and under certain conditions, it may exceed the efficiency of non-traditional designs. The mesh sensitivity analysis, critical for validating the CFD results, is summarized in Table 2, detailing the resulting Cp variation across different element counts.

Table 2: Mesh Sensitivity Analysis

Mesh Level	Elements	Cp (TSR1.3)	Variation (%)
Level 2	~82,000	0.0245	-
Level 3	~110,000	0.0248	+ 1.2
Level 4	~195,000	0.0250	+ 0.8

5. Conclusions

Transient CFD analysis at 0.8 m/s was conducted for Savonius turbines with overlap ratios of +1.5, 0, and −1.5. Mesh Level 3 provided Cp values within 2 % of finer grids, ensuring accuracy with reasonable cost. The 0-overlap rotor achieved the highest efficiency (Cp = 0.0794 at TSR 1.3), the +1.5 overlap excelled at higher TSRs (0.0631 at TSR 1.8), and the −1.5 overlap, while less efficient (0.048 at TSR 0.7), delivered higher low-TSR torque for rural applications. Performance trends highlight the strong influence of overlap ratio. Lower Cp values are attributed to 2D modelling limits, conservative geometry, and absence of enhancement features. Future work will involve 3D simulations, open-channel testing, and optimization to refine design performance.

Acknowledgments

The authors thank Universiti Malaysia Sarawak (UNIMAS) for facilities and funding, and Universiti Teknologi Malaysia (UTM), particularly the Faculty of Artificial Intelligence, for guidance in design, modelling, and technical support.

References

Bachtiar, I.K., 2019, The effect of blade overlap on the performance of Savonius wind turbine, Proceedings of the 2019 IEEE Conference on Energy Conversion (CENCON 2019), Kuala Lumpur, Malaysia, 236–239.

Ebrahimpour, M., Shafaghat, M., Alamian, R., 2019, Numerical investigation of the Savonius vertical axis wind turbine and evaluation of the effect of the overlap parameter in both horizontal and vertical directions on its performance, Symmetry, 11(9), 1–15.

Hosseini, S.E., Karimi, O., AsemanBakhsh, M.A., 2023, Multi-objective optimization of Savonius wind turbine, arXiv preprint, arXiv:2308.14648.

Ibrahim, W.I., Mohamed, M.R., Ismail, R.M.T.R., Leung, P.K., Xing, W.W., Shah, A.A., 2021, Hydrokinetic energy harnessing technologies: A review, Energy Reports, 7, 2021–2042.

International Renewable Energy Agency (IRENA), 2022, Renewable energy statistics 2022, Abu Dhabi, United Arab Emirates.

Irawan, N.E., Yamashita, K.I., Fujita, G., 2024, Comparison of non-overlap and overlap Savonius wind turbines in the physics aspect using computational fluid dynamics method, Journal of Physics: Conference Series, 2780(1), 012031.

Karakaya, D., Bor, A., Elçi, S., 2024a, Numerical analysis of three vertical axis turbine designs for improved water energy efficiency, Energies, 17(6), 1398.

Mancera-Apolinar, J.A., Mendoza, D.F., Riascos, C.A.M., 2023, CFD simulation and verification of distillation sieve tray hydrodynamics by clear liquid height, Chemical Engineering Transactions, 100(April), 379–384.

Mohammed, M., Sarip, S., Aziz, S.A., Mustafa, W.A., Ajmi, A.A., 2025, Savonius hydrokinetic turbine: A bibliometric analysis, Journal of Advanced Research in Applied Mechanics, 133(1), 36–51.

Mohammed, M., Sarip, S., Aziz, S.A., Mustafa, W.A., 2024, Systematic review of computational fluid dynamics modelling and simulation techniques employed in vertical axis hydrokinetic turbines, Journal of Advanced Research in Applied Mechanics, 117(1), 51–71.

Mrigua, K., Zemamou, M., Aggour, M., 2022, Numerical investigation of a new modified Savonius wind turbine, International Journal of Renewable Energy Development, 11(4), 1113–1123.

Ngalimo, Y.R., Hong, C.J., Akif, M., Nadiah, S.A., Syakir, M., 2024, Computational study on the performance of a Savonius wind turbine with positive and zero overlap rotor profile, Proceedings of a Conference on Wind Energy, Kuala Lumpur, Malaysia.

Ramdhani, A.M., George, A., Cho, I.H., 2024, Influence of separation gap on the performance of Savonius hydrokinetic turbine, Intelligent and Sustainable Manufacturing, 1(1), 10005–10005.

Saha, U.K., Thotla, S., Maity, D., 2008, Optimum design configuration of Savonius rotor through wind tunnel experiments, Journal of Wind Engineering and Industrial Aerodynamics, 96(8–9), 1359–1375.

Shanegowda, T.G., Shashikumar, C.M., Gumtapure, V., Madav, V., 2024, Comprehensive analysis of blade geometry effects on Savonius hydrokinetic turbine efficiency: Pathways to clean energy, Energy Conversion and Management: X, 24, 100762.

Singh, P., Jaiswal, V., Roy, S., Singh, R.K., 2023, Maximizing Savonius turbine performance using Kriging surrogate model and Grey Wolf-driven cylindrical deflector optimization, arXiv preprint, arXiv:2311.06378.

Sovacool, B.K., 2012, Deploying off-grid technology to eradicate energy poverty, Science, 338(6103), 47–48.

Talukdar, P.K., Kulkarni, V., Saha, U.K., 2018, Field-testing of model helical-bladed hydrokinetic turbines for small-scale power generation, Renewable Energy, 127, 158–167.

Talukdar, P.K., Sardar, A., Kulkarni, V., Saha, U.K., 2018, Parametric analysis of model Savonius hydrokinetic turbines through experimental and computational investigations, Energy Conversion and Management, 158, 36–49.

Tantichukiad, K., Yahya, A., Mustafah, A.M., Rafie, A.S.M., Mat Su, A.S., 2023, Design evaluation reviews on the Savonius, Darrieus, and combined Savonius–Darrieus turbines, Proceedings of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy, 237(6), 1348–1366.