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IMPROVING THE EFFICIENCY OF SAVONIUS WIND TURBINE THROUGH SHIELDING: NUMERICAL AND EXPERIMENTAL STUDY

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Abstract

The quest for renewable energy sources has led to increasing interest in harnessing wind energy using various wind turbine designs. The Savonius wind turbine, with its simplicity and ability to operate under low wind speeds, has gained attention for its potential applications in urban areas. However, its major drawback remains its relatively low efficiency. In this context, this paper presents a comprehensive numerical and experimental study aimed at improving the efficiency of the Savonius wind turbine through the implementation of shielding techniques. Various shielding configurations were investigated via computational fluid dynamics simulation. The main objective is redirecting the airflow from the returning blade towards the advancing one. A small-scale prototype was tested in a wind tunnel with different shield configurations to validate the numerical findings. Both numerical and experimental results demonstrated the significant impact of shielding on the turbine's efficiency. The 30°–60° curtain shield configuration exhibited remarkable improvements in power output and torque generation compared to the unshielded turbine. This study contributes to the ongoing research on wind turbine optimisation and provides valuable insights into the potential of shielding techniques for enhancing the efficiency of Savonius turbines.

Key Words

Computational fluid dynamics, power generation, Savonius wind turbine, shielding, wind tunnel testing

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Nomenclature

Variable	Description
C_p	Power coefficient
D	Blade diameter
e	Offset distance
d	Shield gap
M	Moment, torque
p	pressure
Re	Reynolds number
u	x-velocity
v	y-velocity
α	Shield angle
β	Overlap ratio
λ	Tip speed ratio (TSR)
μ	Dynamic viscosity
ρ	Air density
φ	Shaft diameter

1. Introduction

Throughout history, human development has been sustained by different forms of energy, from nutrition as the initial source to fire for warmth, and ultimately to fossil fuels powering the industrial era. As a result, global energy demand is perpetually increasing, with the growing population amplifying this trend and worsening climate change. Consequently, various countries started working on finding new sources of energy to meet the national energy demand and decrease the negative implications

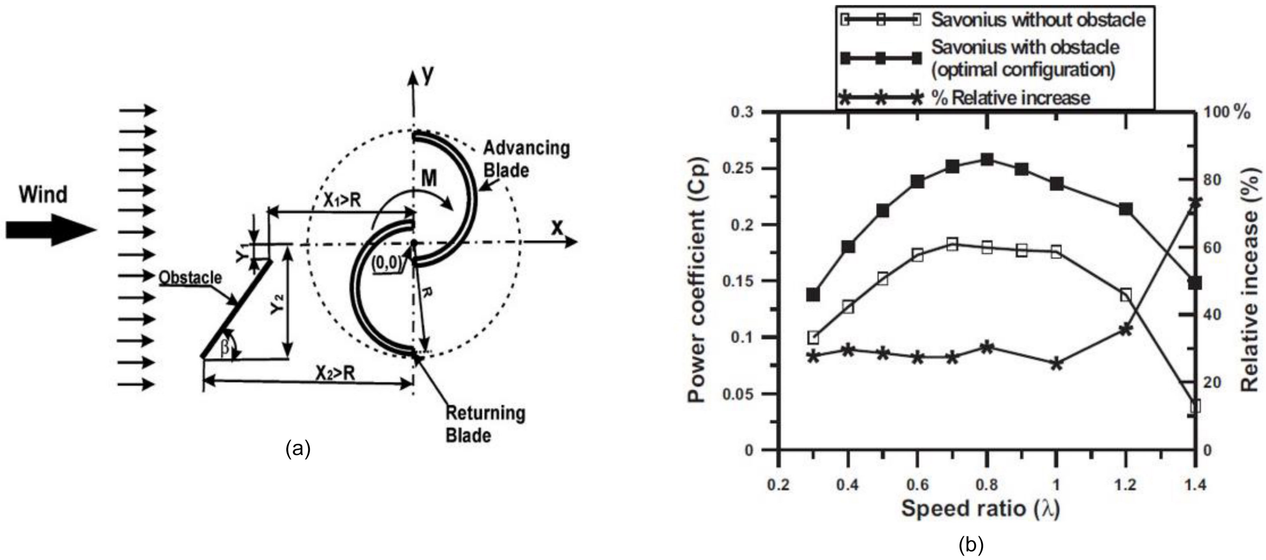


Figure 1. (a) Schematic of the S-rotor partly shielded with the optimisation parameters and (b) Performance of the optimised configuration compared to the conventional unshielded S-rotor [4].

on the environment. Hence, they started relying on more environmentally friendly sources of energy, such as solar, water, and wind. In particular, wind energy has become widely adopted as a reliable source of electricity at a relatively low cost. Many countries have integrated wind turbines into their energy systems and have become one of the main pillars of generating energy [1]. According to the World Wind Energy Association, the total capacity of wind turbines grew from 7 GW in 1997 to 830 GW in 2021. Moreover, in 2021, the total power produced by wind energy contributed to 1870 terawatt-hours (TWh) to the worldwide electric supply. Aligning with the Net Zero Scenario's wind power generation level of about 7900 TWh in 2030 calls for an average expansion of approximately 18% per year during 2022–2030. Reaching a 100% renewable energy supply is the aim of several countries. Iceland became the first country ever to achieve this goal in 2011 [1].

Henceforth, scientists and engineers have been working extensively on increasing the efficiency and improving the performance of wind turbines, particularly vertical axis wind turbines (VAWTs). Although VAWTs have lower efficiency than horizontal axis wind turbines (HAWTs), they offer many advantages that encouraged many scientists to work on increasing their efficiency [2]. For instance, a VAWT can operate at relatively low wind speeds in different wind directions, it has a simple geometry which results in an ease of manufacturing. Moreover, due to its relatively low noise production, it can be placed on rooftop arrays either at small-scale applications (households) or large-scale applications (wind farms) [3]. Recent studies have focussed on optimising wind turbine placement to improve energy production and system efficiency [4]. In parallel, increasing attention has been given to the coupling of different renewable energy sources to enhance overall performance and integration [5].

In this context, the current work aims to enhance the performance of the Savonius wind turbine, a traditional VAWT, by implementing different shielding concepts in order to increase the power output and consequently the efficiency. The adopted methodology consists of conducting numerical simulations using ANSYS Fluent coupled with experimental validation through wind tunnel testing on small-scale prototypes and concluded with an overall assessment of the different configurations investigated. Several existing shield designs are assessed in addition to newly proposed ones. Results are compared for the different designs in terms of produced torque and generated power. The outcome of this work will enable setting an optimised configuration for Savonius wind turbines.

2. Shielding

2.1 Shielding Concept

The shielding concept has been widely introduced as a means to enhance the efficiency of VAWT systems without changing the basic rotor arrangement. Generally, shields are sets of obstacles used to control the flow around the rotor in order to minimise the negative torque produced by the returning blade at some angles of rotation. Another feature of the shield could consist of redirecting the flow towards the advancing blade and therefore increasing the positive torque. Mohamed *et al.* [4] investigated numerically the effect of a simple plate partly shielding the returning blade of the S-rotor [Fig. 1(a)]. A mathematical optimisation method was used to determine the best position and angle of the shield plate. This automatic process is carried out by coupling an optimisation library (OPAL) with an industrial flow simulation code (ANSYS-Fluent). It takes into account the output power coefficient as target function, considers the position and the angle of the shield as optimisation parameters, and relies on evolutionary algorithms [4]. It was observed that the value of the torque remained positive for all angles indicating that the rotor will self-rotate at any starting position.

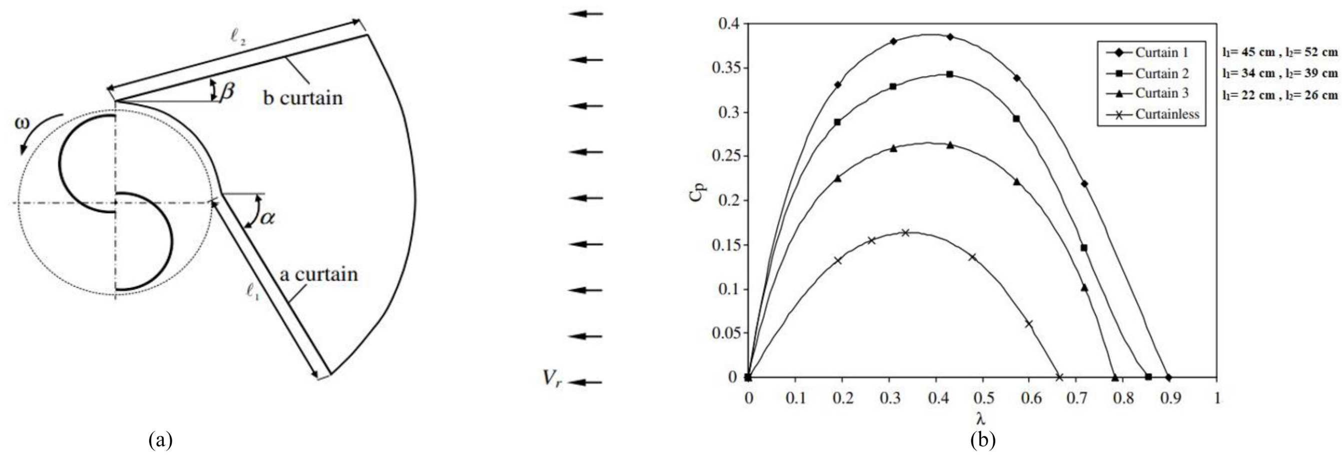


Figure 2. (a) Geometrical parameters of the curtain arrangement and (b) The power coefficient of different arrangements with respect to λ ($\alpha = 45°$ and $\beta = 15°$) [5].

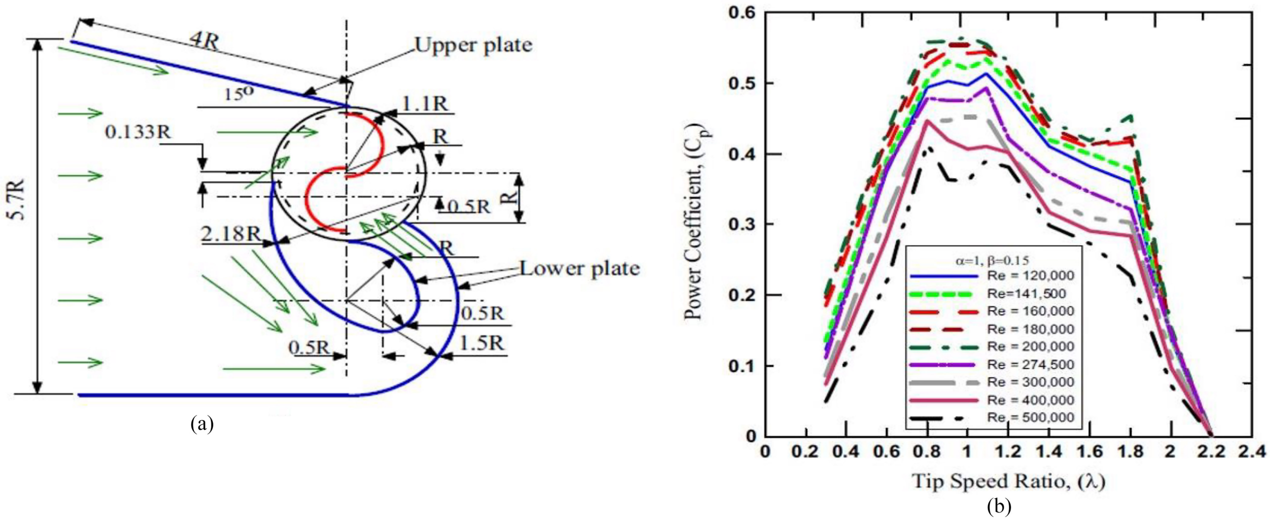


Figure 3. (a) Shielding design to control the wind direction and (b) The corresponding power coefficient with respect to λ at different Re [6].

Additionally, a 27.3% increase in the power coefficient was recorded [Fig. 1(b)].

Altan *et al.* [5] used two deflective plates, known as curtains [Fig. 2(a)], to block the air hitting the returning blade while at the same time channel the flow towards the advancing blade. Three different curtain arrangements were tested and a power coefficient of 0.38 was obtained [Fig. 2(b)]. To further increase the efficiency, El-Askary *et al.* [6] added an additional component to direct the incoming flow towards the concave side of the returning blade [Fig. 3(a)]. A remarkable power coefficient of 0.52 was attained for a wind speed ranging between 7.6 and 8.5 m/s corresponding to Reynolds number of 180,000 and 200,000 respectively [Fig. 3(b)]. Recently, the same baseline casing design was adopted by Antar and Elkhoury [7]. The authors conducted numerical 2-D and 3-D parametric optimisation processes in order to adequately size the casing of the turbine. The maximum power coefficient obtained was much lower than the value claimed by El-Askary *et al.* [6]. Nevertheless, the gain in performance was still evident in comparison with the caseless turbine. A relative increase of 27% and 48% in the power coefficient (C_p) value occurred at a TSR of 0.76 and 1.19, respectively. In conclusion, all studies confirm the positive effect of shielding on the turbine performance.

2.2 Shield Design

As previously mentioned, shielding a wind turbine consists of inserting one or several barriers in front of the returning blade to reduce the negative torque, also known as the convex force which has a major effect on decreasing the turbine efficiency. Consequently, recent setups of Savonius wind turbines include additional deflector plates to cover the returning blade generating negative drag. In addition to reducing the convex force, these plates will systematically increase the positive torque (concave force) by directing and concentrating the air towards the advancing blade. As a result, the power coefficient (C_p) will increase, hence increasing the extracted power. In this paper, several

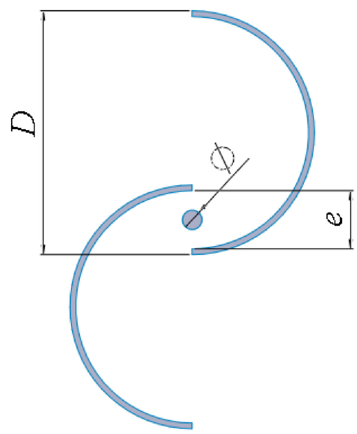


Figure 4. Schematic of the Savonius wind turbine.

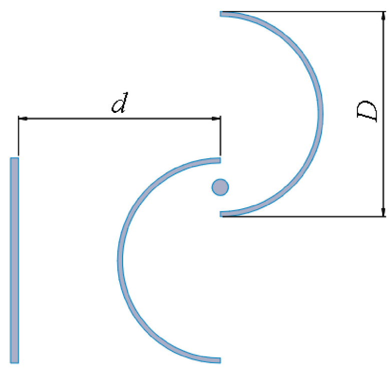


Figure 5. Single normal flat plate shield.

shielding designs are studied numerically (via ANSYS Fluent) and experimentally (via wind tunnel testing). Figure 4 presents a schematic of the turbine rotor with a blade diameter D, a shaft diameter φ, and a blade overlap ratio $\beta = e/D = 18\%$ based on the results of a previous study [8].

2.2.1 Single Normal Flat Plate Shield

The first shield design considered is a vertical flat plate placed directly in front of the returning blade perpendicular to the flow direction (Fig. 5). In order to assess the effect of the shield position, the shield was placed at four different locations: $d = D$, $d = 1.4D$, $d = 1.53D$, and $d = 2D$, where d is the distance from the shield to the centre of the shaft.

2.2.2 Single Rotated Flat Plate Shield

The second shield design consists of rotating the flat plate shield by an angle α (Fig. 6). This configuration also allows redirecting the flow towards the advancing blade thus increasing the output power. The effect of the angle of rotation on the turbine performance is investigated by varying α between 0 and 60° while maintaining the distance d constant ($d = D$).

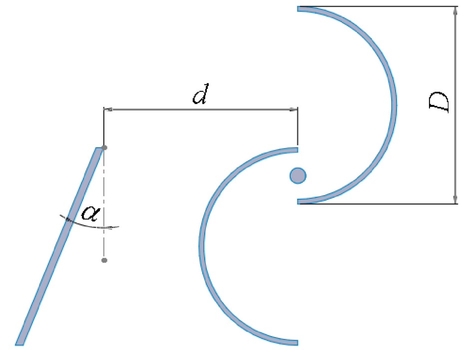


Figure 6. Single rotated flat plate shield.

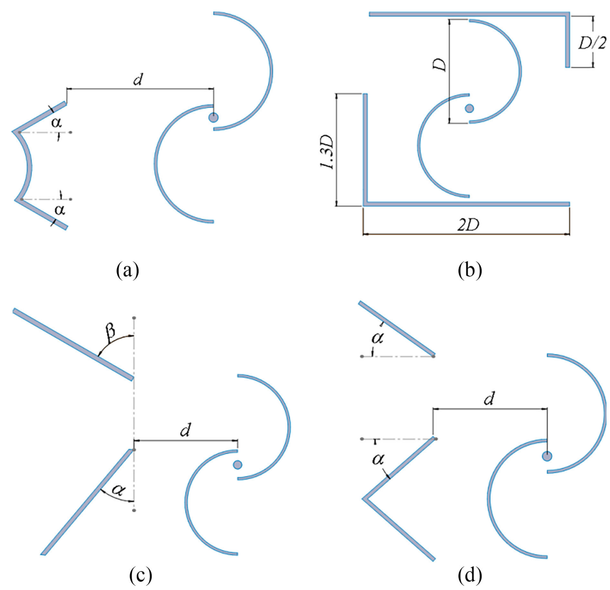


Figure 7. Complex shield designs.

2.2.3 Complex Shield Designs

Several complex designs were investigated numerically using ANSYS Fluent. Some of these designs were previously studied by other researchers [9]–[12], while others are genuine to this work and are outlined in Fig. 7.

3. Numerical Modelling

3.1 Setup

3.1.1 Governing Equations

In order to simplify simulation setup and hence reduce computational cost and time, 2-D steady-state simulations are conducted. Previous works [13], [14] show that 2-D models yield reasonable results compared to 3-D models, especially in the case with endplates that contribute to limiting 3-D effects. Moreover, a static mesh configuration is considered at one position of the S-rotor. A previous study conducted by the authors [8] thoroughly investigated the variation of the produced torque with respect to the angle of rotation. Therefore, the comparison of different shield configurations at only one angle would still yield

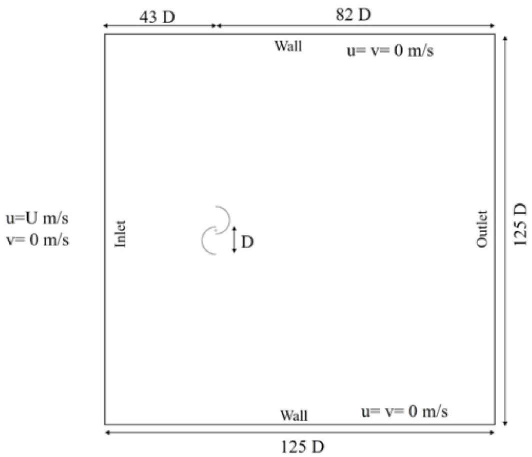


Figure 8. 2-D computational domain with boundary conditions.

qualitative results that help in selecting the optimised shield design.

ANSYS Fluent is used to solve the governing equations in a 2-D system to provide results for various parameters, such as pressure, moment, and velocity. It is based on the finite volume method. These equations are the continuity (1) and the Navier–Stokes equations (2) and (3) [15].

Continuity:

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 \tag{1}$$

x-momentum:

$$\rho\left(u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y}\right) = -\frac{\partial p}{\partial x} + \mu\left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2}\right) \tag{2}$$

y-momentum:

$$\rho\left(u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y}\right) = -\frac{\partial p}{\partial y} + \mu\left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2}\right) \tag{3}$$

3.1.2 Geometry and Mesh

In this study, the adopted rotor type is the conventional S-rotor of the Savonius turbine. Hence, the blade shape is semi-circular with an overlap of 18%. Afterward, both the turbine and the shield are positioned inside a rectangular enclosure. Concerning the boundary conditions, the left-hand side of the domain is set as velocity inlet, whereas the opposite side is set as pressure outlet. Both the upper and lower horizontal edges of the enclosure are considered stationary walls (Fig. 8).

In order to obtain accurate results at a reasonable time, mesh generation is of utmost importance. Therefore, a mesh sensitivity study is conducted to find a compromise between results accuracy and computational time. Herein, a triangular mesh is used as it can provide faster computational simulations and precise results [16].

For the numerical results to be mesh independent, more than 600 divisions per face of each blade are required (Fig. 9). Consequently, the mesh is refined in the vicinity of the rotor blades, and coarsened progressively further away

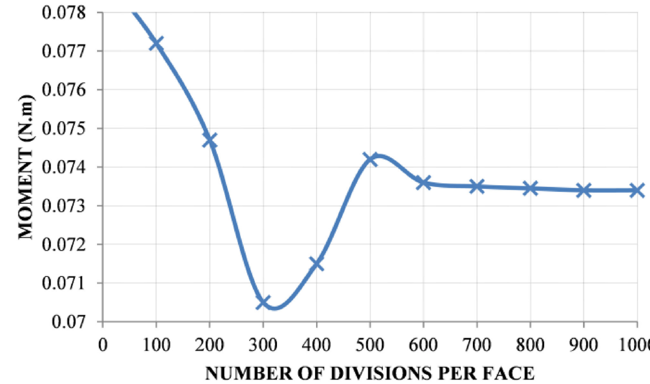


Figure 9. Mesh grid independence study.

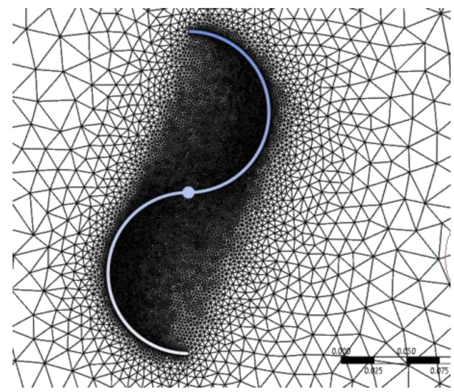


Figure 10. Mesh topology about the S-rotor.

from the blades (Fig. 10). The overall domain includes a total number of 20,815 nodes and 38,822 elements.

3.1.3 Turbulence Model

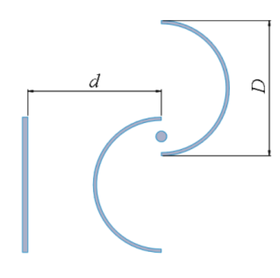
Since the flow is turbulent, it is essential to choose wisely the turbulence model. Among the available models (*i.e.*, k-ε, k-ω, and *SST* models), the k-ε model is chosen for this study for two main reasons. First, it is commonly adopted in numerical simulations for its simple implementation. Second, the k-ε is a cheaper model than the k-ω in terms of computational cost. The latter performs better at low Reynolds numbers, in complex and separated flows, and with high-pressure gradients. In this study, the presence of high Reynolds numbers coupled with low pressure gradients favors the Standard k-ε model [17].

3.2 Results

3.2.1 Single Normal Flat Plate Shield

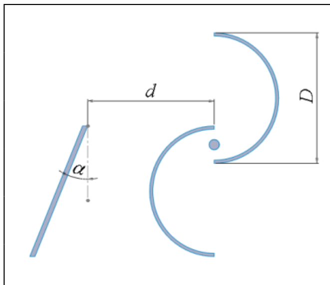
As previously mentioned, the single normal flat plate shield was simulated in different configurations by varying the gap between the shield and the turbine shaft. The moment was reported by ANSYS Fluent and presented in Table 1 with the percentage variation compared to the unshielded configuration. It was found that when $d = D$, a moment increase of 130% is observed compared to the unshielded system. On the other hand, when moving further away

Table 1
Moment Variations at Different Distances



Distance d	Moment
No shield	M
D	$2.296M$
$1.38D$	$1.921M$
$1.54D$	$1.667M$
$2D$	$1.126M$

Table 2
Moment Variations at Different Orientations



Angle α	Moment
No shield	M
0°	$2.296M$
30°	$2.131M$
45°	$1.962M$
60°	$1.486M$

from the rotor (*i.e.*, for $d > D$), the shield still improved the performance of the turbine, but to a lower extent.

3.2.2 Single Rotated Flat Plate Shield

Based on the previous analysis, the orientation of the shield was only examined for $d = D$. Consequently, the moment values were computed for different shield orientation angles and reported in Table 2.

The obtained results clearly show that the shield presence positively affects the produced moment. However, further rotating the vertical plate shield affects negatively the performance of the rotor particularly for higher angles (above 45°). Therefore, for a single shield plate, it is preferable to maintain the shield perpendicular to the flow. Another idea could be resizing the rotated shield to cover a portion of the returning blade, but this necessitates further investigation.

3.2.3 Complex Shield Designs

In the same context, several shield designs were also investigated and the results of a few of them are presented in Table 3.

It can be seen that most complex shield designs have improved the performance of the turbine, with Design 3 (30°–60° curtains) producing the highest moment.

In conclusion, the various shield designs helped in enhancing the performance of the turbine. The single normal flat plate shield placed at $d = D$ produced an increase of 130% in moment value compared to the unshielded rotor. However, further rotating the shield plate did not seem highly beneficial. Nevertheless, combining two different plates with different rotation angles (curtain shield) delivered the best performance.

4. Experimental Study

Wind tunnel experimentation was conducted to evaluate the performance of the Savonius wind turbine with different shield configurations and to validate qualitatively the numerical results. The experimental setup and results are presented next.

4.1 Experimental Setup

A Savonius wind turbine prototype was assembled (Fig. 11) using the same dimensions and parameters as in numerical simulations. The blades constituted of 5-inch PVC pipe cut in half. Two 2-mm-thick circular wood plates were used as endplates to hold the S-rotor. The turbine shaft consisted of a 5-mm-diameter aluminium rod.

Following assembly, the prototype was placed inside a PLINT wind tunnel (Fig. 12), and connected to a 200-W alternator placed above the test zone. An electric circuit, including the alternator, a variable resistor, a voltmeter, and an ammeter, was mounted in order to measure the net output power. The angular velocity of the turbine was measured using a digital tachometer. The wind speed at the turbine inlet was also recorded using a digital hot wire anemometer.

Numerous sets of experiments were conducted on the unshielded configuration in addition to several shielded ones that had shown promising results from numerical simulations. These include the single normal flat plate shield, the single rotated flat plate shield, and several curtain shield designs with different angles. The wind speed was increased up to 20 m/s and the produced moment, the output power, the TSR, and the power coefficient were calculated for each recorded value.

4.2 Experimental Results

4.2.1 Single Normal Flat Plate Shield

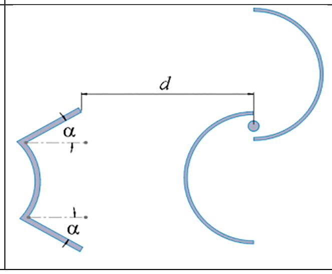
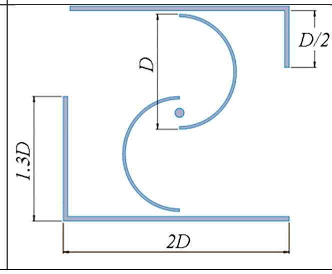
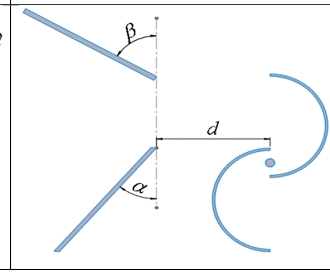
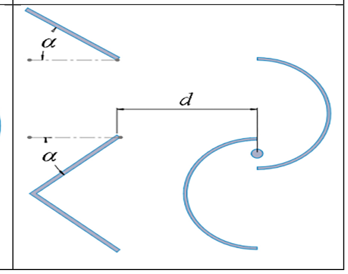
This set of experiments consisted of varying the distance between the single normal flat plate shield and the turbine shaft. The shield plate was fixed at three different distances: $d = D$, $d = 1.38D$, and $d = 1.54D$ from the turbine's shaft.

Figure 13 shows the power curve for several distances d. It is noticeable that shielded turbines perform better than unshielded ones. All three cases delivered comparable results yielding an increase in the power coefficient value compared to the unshielded turbine. In particular, the case closest to the turbine, at $d = D$, achieved the best results.

4.2.2 Single Rotated Flat Plate Shield

In order to evaluate the effect of rotating the original parallel shield, 3 shield orientations (in addition to the normal one) were tested. The distance from the shaft was fixed at $d = D$. The results are shown in Fig. 14.

Table 3
Moment Values for Different Shield Designs

Design	Design 1	Design 2	Design 3	**Design 4**
Moment	$2.322M$	$0.587M$	$3.156M$	$3.005M$
				

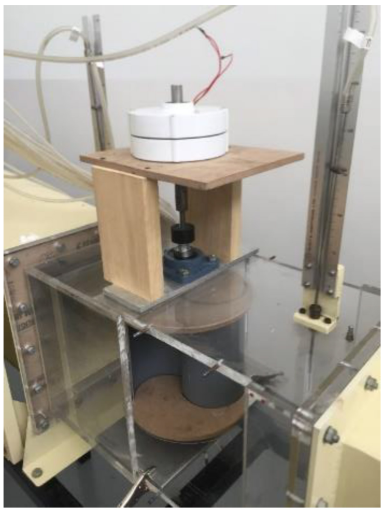


Figure 11. Savonius wind turbine prototype.

Figure 12. Prototype installation in the wind tunnel.

Clearly, all four shielded turbines (0°, 30°, 45°, and 60°) performed better than the unshielded one. These experiments also demonstrated that the 0° and 30° shield designs delivered the highest power coefficient. Rotating the shield by more than 30° seems to negatively affect the results. This came in good agreement with the numerical results is Section 3.2.2.

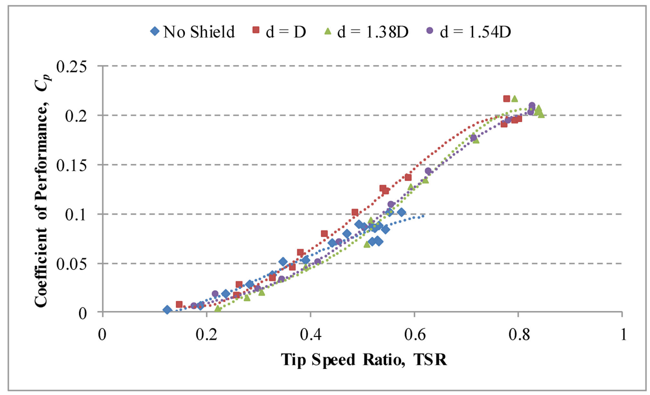


Figure 13. Power curves for single normal flat plate shields at different positions.

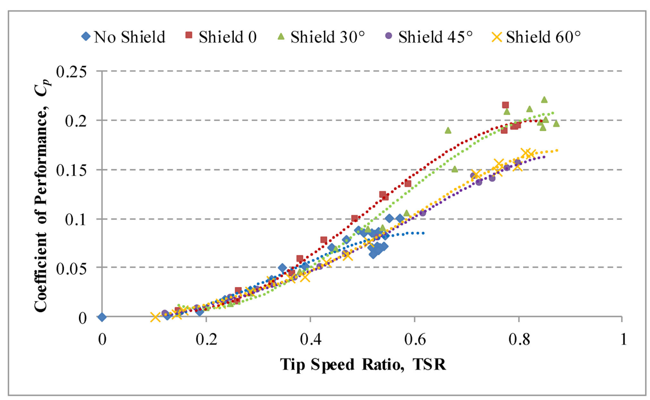


Figure 14. Power curves for single rotated flat plate shields at different orientations.

4.2.3 Curtain Shield Design

A final set of experiments was conducted with curtain shield designs. It is basically a combination of two shield plates with different rotation angles. The chosen configurations consist of combinations of shields mounted at 0°, 30°, or 60° angles. The results are presented in Fig. 15. It was proven that for low wind speed and therefore low TSR, all tested curtain configurations had similar performance and gave close results; however, for high wind

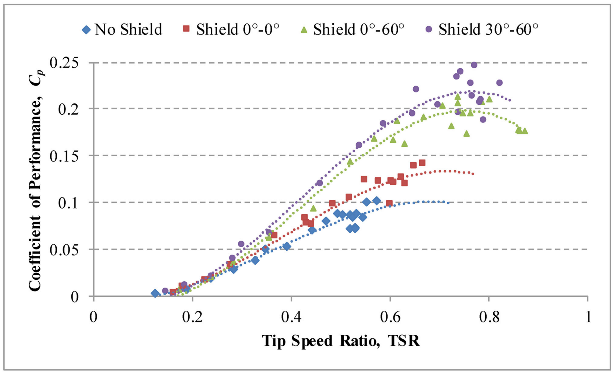


Figure 15. Power curves for curtain shields.

speed (TSR > 0.5) the 30°–60° curtain shield rendered the best output.

5. Discussion

The presence of a shield upstream of the wind turbine has shown several advantages in increasing the produced torque and consequently the generated power. Each shield type has an optimal configuration for optimised performance. However, the maximum values were obtained with complex shield designs like the curtain shield. Particularly, the 30°–60° curtain shield appears to have the highest power coefficient among all tested shields. This was confirmed via both numerical and experimental studies, although direct benchmarking was not possible. In the experimental part, both the produced power and angular velocity were recorded, which would allow calculating the produced torque. However, due to several reasons, such as experimental uncertainty, friction losses, electric losses, 3-D effects, *etc.*, the direct comparison between numerical and experimental results could not be achieved quantitatively. However, a qualitative comparison was conducted and both numerical and experimental results were in good agreement regarding the shield type providing the best performance. Furthermore, the effect of having losses and uncertainties did not alter the qualitative behaviour of the turbine.

On the other hand, despite having obtained increased values of moment and power, and therefore better performance, one must not neglect the fact that wind conditions are highly unsteady. The wind velocity and direction are strongly fluctuating. In consequence, and in order to maintain a reliable operation of the shielded wind turbine, a shield adjustment mechanism must be considered.

6. Conclusion

In this paper, the performance of a Savonius VAWT was investigated with and without the presence of a shield. This shield is intended to block the airflow impinging on the returning blade and redirecting it towards the advancing turbine blade. The purpose is to increase the produced moment on the blade and consequently the generated power of the turbine. Several shield types were tested: normal flat plate, rotated flat plate, curtain shield, *etc.*

First, a numerical study was conducted on ANSYS fluent and moment values were investigated. The obtained results showed that the presence of a shield would increase the produced moment. For a normal flat plate, the optimal position of the shield was at a distance equal to the diameter of the blade. For the rotated flat plate, it was shown that the angle of rotation should be minimised to produce higher moments. Finally, curtain shields yielded the highest moment among all studied cases but require a more complex design.

In the second part, experimental measurements were carried out in a wind tunnel to validate numerical findings. Power curves for several cases were obtained after measuring the output voltage and current and subsequently the power of the turbine. The highest power coefficient was obtained with a 30°–60° curtain shield placed upstream of the rotor.

A final conclusion that could be deduced from this paper is that the effect of installing a shield upstream of a Savonius wind turbine is beneficial. However, a full-scale in-service wind turbine is usually subjected to strong variations of wind velocity and direction. This requires real-time adjustment of the shield position to continuously produce the desired power. The major challenge remains how to control this shield to maintain a reliable operation in unsteady wind conditions.

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References

[1] H. Allamehzadeh, Wind energy history, technology and control, in *Proceeding IEEE Conf. on Technologies for Sustainability (SusTech),* Phoenix, AZ, 2016, 119–126. DOI: https://doi.org/10.1109/sustech.2016.7897153

[2] C. Diyoke, A new approximate capacity factor method for matching wind turbines to a site: Case study of Humber region, U.K., *International Journal of Energy and Environmental Engineering*, *10*(4), 2019, 451–462.

[3] F. Porté-Agel, M. Bastankhah, and S. Shamsoddin, Wind-turbine and wind-farm flows: A review, *Boundary-layer meteorology*, 2020, *174*, 1–59.

[4] C. Jing, W. Weiqing, Y. Zhi, and H. Ebrahimian, Improved fluid search optimization algorithm to solve wind turbine placement problem, *International Journal of Power and Energy Systems*, *39*(4), 2019, 200–207.

[5] Z. Lu, J. Yu, L. Sun, Y. Xiong, B. Yang, R. Yin, and L. Wang, Capacity optimisation configuration of hybrid energy storage system considering primary frequency regulation output of wind farm, *International Journal of Power and Energy Systems*, *44*, 2024, 1–11.

[6] M.H. Mohamed, G. Janiga, and E. Pap, and D. Thévenin, Optimization of Savonius turbines using an obstacle shielding the returning blade, *Renewable Energy*, *35*(11), 2010, 2618–2626.

[7] B.D. Altan, M. Atılgan, and A. Özdamar, An experimental study on improvement of a Savonius rotor performance with curtaining, *Experimental thermal and fluid science*, *32*(8), 2008, 1673–1678.

[8] W.A. El-Askary, M.H. Nasef, A.A. Abdel-Hamid, and H.E. Gad, Harvesting wind energy for improving performance of Savonius rotor, *Journal of Wind Engineering and Industrial Aerodynamics*, *139*, 2015, 8–15.

[9] E. Antar and M. Elkhoury, Parametric sizing optimization process of a casing for a Savonius Vertical Axis Wind Turbine, *Renewable Energy*, *136*, 2019, 127–138.

[10] Z. Alomar, G. Khoury, J. Rishmany, and M. Daaboul, Numerical and experimental study on the effect of overlap on Savonius wind turbine, *International Journal of Power and Energy Systems*, *43*(10), 2023, 1–9.

[11] N. Korprasertsak and T. Leephakpreeda, Analysis and optimal design of wind boosters for vertical axis wind turbines at low wind speed, *Journal of Wind Engineering and Industrial Aerodynamics*, *159*, 2016, 9–18.

[12] N.P. Putri, T. Yuwono, J. Rustam, P. Purwanto, and G. Bangga, Experimental studies on the effect of obstacle upstream of a Savonius wind turbine, *SN Applied Sciences*, *1*, 2019,1–7.

[13] C. Stout, S. Islam, A. White, S. Arnott, E. Kollovozi, M. Shaw, G. Droubi, Y. Sinha, and B. Bird, Efficiency improvement of vertical axis wind turbines with an upstream deflector, *Energy Procedia*, *118*, 2017, 141–148.

[14] W. Tian, Z. Mao, and H. Ding, Numerical study of a passive-pitch shield for the efficiency improvement of vertical axis wind turbines, *Energy Conversion and Management*, *183*, 2019, 732–745.

[15] N. Franchina, G. Persico, and M. Savini, 2D-3D computations of a vertical axis wind turbine flow field: Modeling issues and physical interpretations, *Renewable Energy*, *136*, 2019, 1170–1189.

[16] S.J. Chemengich, S.Z. Kassab, and E.R. Lotfy, Effect of the variations of the gap flow guides geometry on the Savonius wind turbine performance: 2D and 3D studies, *Journal of Wind Engineering and Industrial Aerodynamics*, *222,* 2022, 104920.

[17] F.M. White, *Fluid Mechanics*, 8^{th} ed. (New York, NY: McGraw-Hill, 2015).

[18] A. Katz and V. Sankaran, Mesh quality effects on the accuracy of CFD solutions on unstructured meshes, *Journal of Computational Physics*, *230*(20), 2011, 7670–7686.

[19] F.R. Menter, Two-equation eddy-viscosity turbulence models for engineering applications, *AIAA Journal*, *32*(8), 1994, 1598–1605. DOI: https://doi.org/10.2514/3.12149

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