The aerodynamics of a Savonius blade

Mrigua Khalid[1*], *Elmimouni Ahmed* [1], *Didi Abdessamad*[2], *Elhoujaji hakim*[1], and *Sadoune Zouhair*[1]

[1] SETIME Laboratory, Faculty of Sciences, Ibn Tofail University, Kenitra, Morocco
[2] Hassan First University of Settat, High Institute of Health Sciences, Laboratory of Sciences and Health Technologies, Settat, Morocco

Abstract Faced with the energy crisis and global warming, renewable energies are emerging as a key response, particularly wind power. Among these various technologies, vertical axis wind turbines (VAWTs) present a promising energy source in rural areas. The Savonius rotor, a drag-driven device, one of the famous vertical axis wind turbine designs, offers many advantages such as easy installation and fast automatic start-up. However, its efficiency is limited by negative torque on the return blade. Research aims to improve this rotor by optimizing many factors as the overlap ratio and blade shape, while integrating technologies such as end plates and deflectors to minimise the negative torque and increase energy production. The power factor of a conventional Savonius rotor extends from 0.12 to 0.18, but improvements could increase it to 0.52. This article provides an in-depth analysis of performance and power enhancement technologies for Savonius rotors, suggesting future prospects. In addition to examining proven solutions, the article highlights new avenues of research that could strengthen the role of this rotor in the future energy mix.

Keywords: Savonius rotor, Vertical axis wind turbine, Renewable energy, Power coefficient, Performance enhancement

* Corresponding author: khalid.mrigua@uit.ac.ma

1 Introduction

Wind turbines are an environmental technology and should in the future be better adapted to the conditions of developing countries. Wind energy will have an increasing role in the future in addressing global energy needs and in terms of global climate change, and people need to act now to reap the economic and environmental benefits of wind energy. Researchers have worked to ameliorate the aerodynamic characteristics of the Savonius vertical-axis wind turbines (SVAWTs) because it represent an interesting option for producing energy in rural areas and low wind speed regions where Darrieus vertical axis rotor and horizontal-axis wind rotors cannot operate efficiently[10] however, it represent the least efficient kind of turbines. In order, to overcome this problem, work has already been done, either by optimizing the geometric parameters of the blades, resulting in a slight increase in rotor efficiency, or by using turbines with additional accessories, the system performances are significantly improved, however, the basic system becomes bulky and complex due to the significant increase in rotor inertia, which can reduce the start-up capability. In this paper, we focus on research related to Savonius wind turbines that can facilitate energy production. All the studies about savonius rotor have focused on the geometric characteristics of Savonius rotors. We will first present the geometric parameters influencing the performance of the Savonius turbine, and then we will provide an in-depth discussion of various experimental investigations and numerical simulations reported in the open literature

2 Aerodynamic performance

The torque generated at the rotor shaft (T) can be calculated by integrating the difference in force resulting from shear and pressure on the rotor as indicated below [1]:

$$T= \sum_i (F_{i,pressure} + F_{i,\ cisaillement}).d \quad (1)$$

$$T = \sum_i \{[P_i - P_{ref}].A_i + [-\tau_i.A_i]\}_{concave} . d - \sum_i \{[P_i - P_{ref}].A_i + [-\tau_i.A_i]\}_{convexe} . d \quad (2)$$

Where $F_{i,pressure}$ and $F_{i,shear}$ are the pressure and shear force vectors acting respectively on the face surface vector A_i , and d is a local torque arm vector from the axis of rotation, about which the moment is taken. Where p and τ are the pressure and shear stresses, respectively.

The instantaneous wind power available in a cross section A perpendicular to a wind flow moving at a speed of V(m/s) with an air density ρ is expressed as follows[2]:

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

Where A is the frontal area, which is directly related to the area covered by the turbine. V is the wind speed, which is the most important variable, affecting the available power due to the cubic relationship. The expression of the mechanical power generated by the rotor is:

$$P_{turbine} = T.\omega \quad (4)$$

Where : ωis the rotational speed of the rotor.

We often express the aerodynamic performance of these turbines in terms of power coefficient (C_P), torque coefficient (C_T) and static torque coefficient (C_{TS}).

To characterize the ability of the wind turbine to extract wind energy we use the power coefficient (C_P) and it reflects its aerodynamic efficiency. Its expression is:

$$C_P = \frac{P_{turbine}}{P_{wind}} = \frac{T.\omega}{\frac{1}{2} \rho\ A\ V^3} \quad (5)$$

For the dynamic torque coefficient, we can b calculate it using the following equations:

$$C_T = \frac{4\,T}{\rho\, A\, D\, V^2} \qquad (6)$$

$$C_P = \frac{P_{Turbine}}{P_{Wind}} = \frac{T.\omega}{\frac{1}{2}\rho\, A\, V^3} = \frac{T}{\frac{1}{2}\rho\, A\, V^2 \times 2D}\ .\ \frac{R\,.\,\omega}{V} = C_T \times \lambda \qquad (7)$$

C_T and C_P coefficients play an important role in evaluating the performance of wind turbines, and are also considered as an important benchmark in studies for comparing numerical and experimental results. [3]

3 Influencing parameters on the performance of a savonius turbine

3.1 Influence of aspect ratio

The aspect ratio (AR) stands out as a crucial geometric parameter because of its relationship with turbine performance. It is defined as the ratio of rotor height to rotor diameter.

The height of the rotor (H) is that of its blades and the rotor diameter (D) is that of the circle formed by rotation of the rotor blades [7]. This ratio should be optimised based on the required output of the turbine. A higher AR leads to a higher RPM and efficiency, but a lower torque and vice versa[4], and also is more difficult to build.

Alexander et al [5] have deduced that increasing the value of the aspect ratio coefficient leads to an increase in the power coefficient. An experimental study conducted by Kamoji et al[8] showed a peak of both of power and torque coefficients for an aspect ratio of 0.7. Modi et al [6], have concluded that the optimum value of the AR that gives the highest performance is equal to 0.77. The results of an experimental study by Roy et al[7] led to a higher power coefficient (C_{Pmax}=0.178) with an aspect ratio of 0.8.

3.2 The overlap ratio

This ratio is given by:

$$\beta = \frac{e}{d} \qquad (8)$$

Where: e is the recovery distance between the turbine blades and the chord length of the blades.

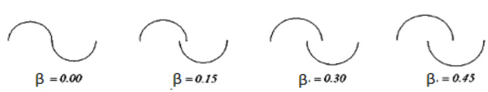


Fig. 1. Overlap ratio of two-bladed Savonius rotors[1]

The overlap optimal value changes with the variation of other design parameters and the operating wind speed. Beyond this range, higher rotational speeds may be obtained coupled with severe vibrations leading to a degradation in output power[9]. A non-zero overlap ratio has been found to exhibit better starting characteristics. This improvement is primarily attributed to the superposition of flows between blades, This flow reduces the negative torque by introducing an opposing effect on the inward curve of the returning blade[7].

An optimal recovery ratio betwin 0.15 and 0.25 is preferable to achieve better performance of these turbines [10]. Mahmoud et al. [11] concluded that a rotor without overlap yields higher mechanical power than other rotors.

3.3 gap between the blades

An airflow occurs through the gap between the blades[10] (Figure 2).

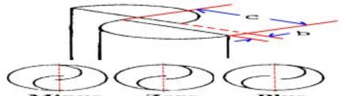


Fig. 2. Blade spacing [12].

Baktiyar Mei Hermawan et al. [13] studied the effect of TSR on the efficiency of five savonius rotors with air gap ranging from 140 mm to 200mm, at different speeds (from 4m/s to 9 m/s), they observed hthat the 200 mm air gap is optimum at low wind speeds (4 m/s) turbine with a C_P between 0.02480 and 0.15658. Meanwhile, the 170 mm air gap is optimum at high wind speeds (8 m / s to 9 m / s) with a C_P between 0.00593 and 0.14668 has optimum work [13].

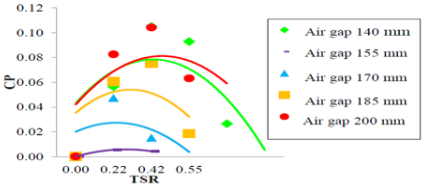


Fig. 3. Variation of the power coefficient (CP) of Savonius rotor with TSR [13].

3.4 Influence of blade's shape

The shape of the blades affects noticeably the performance of a Savonius wind turbine. It affects many quantities such as the turbine's power output, efficiency, and starting torque.

A comparative study is onducted by K.Mrigua et al.[14]on three shapes of Savonius rotor blades (figure 4) using CFD with k-turbulence model.

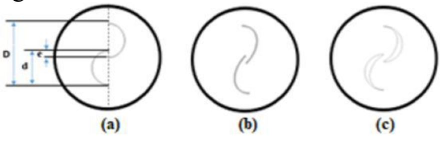


Fig. 4. (a) conventional Savonius rotor, (b) Elliptic rotor, (c) Composed rotor[14]

As result of this study, there is an improvement of the performance of the new modified Savonius blade and the elliptical blade by 20.5% and 18.2% respectively at the tip speed ratio of 0.8[14].

The performance of this device can be highly improved by twisting the blades to an optimum angle. In this context, Ujjwal K. Saha et al. [15] tested a three-bladed rotor with twisted blade in a low speed wind tunnel and showed that there is an enhancement of steady rotation, self-starting capability and performance. A.S. Saad et al. [16] assessed the effect of many geometric parameters as the twist angle, they concluded that both of power coefficient and self-starting ability of the new twisted rotor were enhanced.

3.5 Effect of Number of stage : multistage Savonius Rotors

This configuration aims to improve the turbine's overall efficiency and power output.

Saha UK et al.[17], conducted a study where they tested Savonius with one , two and three stages and they concluded that the optimum number of stages is two. By numerical study, D. M. Prabowoputra [18] showed that the 2:1 stage-ratio shape presents an optimal design with a Cp of 0,29. Mrigua et al. [19] have studied numerically the effect of the elliptical blades in multi-stage systems.

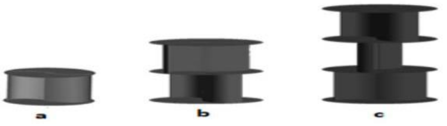


Fig. 5. Elliptical Savonius turbine with a SAR=0,7 (a) Single-stage rotor with RAR=0,7 (b) two stages with RAR=1,4 (c) three stages with RAR=2,1 [19].

Results of this study showed an increase of the maximum power coefficient with number of the stages. Moreover, rotor with two stages presented the highest performance [19].

3.6 The effect of the number of blades

F. Wenehenubun [20] found that each number of blades has an advantage: higher rotational speed with three blades, higher torque with four blades. Also, show the best performance at a lower tip speed ratio is shown by the four-bladed wind turbines, and the best performance at a higher tip speed ratio is given by the three-bladed win turbine[20]. An experimental investigation by M. Ali et al. [21], revealed that the power coefficient is 0.21 and 0.17 for two and three-bladed rotors respectively at TSR=0.80. Additionally, Saha et al. [22], and Mahmoud et al. [11] concluded that a two-bladed rotor provides better efficiency and a higher power coefficient than a three-bladed rotor, as shown in Figure 11. In 1978, Sheldahl et al. [23] reported that two-bladed configurations had better aerodynamic performance than three-bladed configurations, except for starting torque.

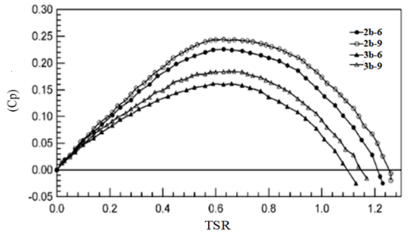


Fig. 6. Power coefficients as a function of the tip speed ratio of rotors for two and three blades and wind speeds of V = 6 and 9 m/s [24].

3.7 Influence of the TSR

The tip speed ratio (TSR) is calculated bay devinding the tip speed of the blade ($u = \omega R$) by the free stream velocity (V), it is a dimensionless parameter that influences significantly rotor efficiency[1].

Sheldahl et al. [23] found the optimum TSR between 0.7 and 1.0. This study has also been complemented by numerous researchers.

Numerical studies conducted by Fujisawa and Gotoh [25] concluded that the optimal TSR lies in the range of 0.8-0.9 . By SST k-ωturbulence model, an unsteady simulations around a SB rotor was performed by Nasef et al. [1] led to an optimal TSR of 0.90. G. Ferrari et al. [26] also conducted 3D unsteady simulations at different tip speed ratios (TSR). The results showed that for a rotor with an aspect ratio 1.1. , there is a peak of 0.202 at TSR of 0.8.

3.8 Influence of Reynolds number

Damak et al. [27] conducted an experimental study and revealed a significant effects of the Reynolds numbers (Re) on the efficiency of a Savonius helical rotor (180° twist angle and 1,57 aspect ratio). Kamoji et al. [28] performed open-jet wind tunnel tests on helical rotors, the results of this study are Depicted in Figure 7. The rotor coefficient value improves with the increase in Re from $0{,}57\times10^5$ to $2{,}019\times10^5$.

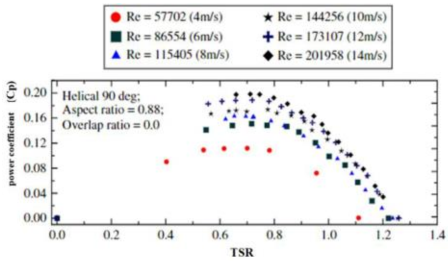


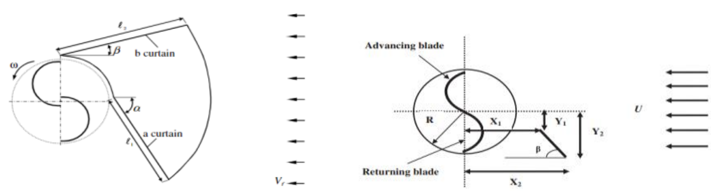
Fig. 7. Variation of power coefficient of the Savonius helical bladed at different Reynolds numbers.

4 External Parameters

4.1 Turbines with additional accessories

Some researchers have studied and analyzed certain additional devices or accessories to improve Savonius wind turbines efficiency (such as curtains, obstacles, shields, convergent nozzles, blades, etc.). The purpose of these geometries is to minimize the frictional force acting on the returning blade through external geometry[3]. Deflectors focuses the wind in the active area of the turbine blades, thus increasing the speed of the incoming wind and consequently increasing the turbine's efficiency [3].

Altan [29] investigated the use of bidirectional curtains (Figure 13, a), the optimal positioning of the curtains ameliorate the Savonius rotor efficiency by approximately 38.5%. The experimental results by Golecha et al [30] conclude that a deflecting plate placed in its optimal position increases efficiency by 50% (Figure 8, b), also, with the presence of the deflecting plate, power coefficient has a maximum of 0.21 at a TSR of 0.82 [30].



(a) Altan Bidirectional Curtains [29] (b) Deflector plate. Golecha et al [30]

Fig. 8. Performance Enhancement Techniques.

Hady Aboujaoude et al.[3] have evaluated, using a 3D CFD analysis, the effect of adding an axisymmetric truncated cone deflector to a Savonius rotor under steady wind conditions.

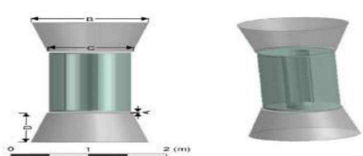


Fig. 9. Geometry of the deflector used [3]

This study showed an improvement of the efficiency in all wind directions by optimizing axisymmetric deflector. This add improved by 30% the average starting torque[3].

4.2 Endplate Turbine

The installation of endplates with negligible thickness at the top and bottom of the Svonius turbine blades enhance its performance.

Turbines with endplate yields better performance compared to rotors without endplates, that reduce the tip vortices effects resulting in a more uniform pressure distribution in the axial direction [3].

5 Conclusion

Numerous researchers have studied the conventional Savonius rotor to gain a comprehensive understanding of the flow phenomena that occur inside and around the rotor. Others have tried to enhance the overall efficiency of the turbine or enhance a specific characteristic of the turbine such as the starting torque.

However, there are few studies that maintain the simplicity of the rotor and show a significant improvement in performance. The main interest is to overcome the main drawbacks of the Savonius wind turbine by developing a new design, while retaining the simplicity of the model, resulting in a good compromise between simplicity and efficiency of the rotor design, suitable for small-scale use.

The usual method involved using experiments to study the Savonius rotor, but the current trend is to resort to cost-effective numerical simulation and validate it experimentally to study the Savonius turbine[7]. Additionally, research on techniques for enhancing the turbine has become popular in the hope of making the parameters of the Savonius rotor more efficient.

In the following, we will explore the possible technological improvement of vertical-axis wind turbines for application in urban and rural areas with low wind speeds. 2D and 3D aerodynamic investigations of the Savonius rotor have been studied numerically.

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