Modified Design of Savonius Wind Turbine Blade for Performance Improvement

M.Zemamou , A.Toumi , K.Mrigua, M.Aggour

Abstract: ***In the context of worldwide energetic transition, wind energy shows up as one of the most prominent renewable energy to provide an alternative for the conventional energy source. Therefore, new technologies of a wind turbine are developed, horizontal axis wind turbines have been extensively investigated and evolved. However, the development of vertical axis wind turbines is still an open and area of research, The main objective is to develop a more efficient type of wind turbines able to operate at low wind speeds to take hold maximum wind potential, The Savonius rotor goes with such conditions, however, it faces critical drawbacks, in particular, the low performance in comparison with horizontal axis wind turbines, as well, the blade in return of savonius wind turbine generates a negative torque leading to a decrement of turbine performance. The present work aims to investigate a modified model of the conventional Savonius rotors with a focus on improving the coefficient of power, transient computational fluid dynamics (CFD) simulations are carried out in an effort to perform a validation of numerical results according to experimental data, also to conduct a comparative analysis of both savonius models.***

Keywords **: Blade design, Power coefficient, Savonius rotor , Wind turbines.**

I. INTRODUCTION

In recent years, humans have sought to provide a clean alternative to the conventional energy sources, reduce the environmental footprint and use renewable and green sources of energy rather than polluting and limited existing sources, likewise, renewable energy technologies present alternative solutions that meet the growing demand for energy due to population growth [1].

In this context, wind energy as a field for academic and professional concern has grown dramatically. Empirical research has been undertaken and new design investigations have been performed to reach optimal performance. The development of turbines operating at low wind speed gained considerable attention in an effort to benefit from wind potential. Horizontal wind turbines have been leading the wind energy market, nevertheless, wind energy production has to be present in the urban area, the horizontal axis wind turbines do not meet urban areas requirements, HAWT's make noise under certain conditions and require a strong and constant wind, On the contrary, vertical axis wind turbines (VAWT) fit perfectly, hence the recent growth of their use in urban areas. Savonius wind turbine is in the class of vertical axis wind turbines with distinguishing features, as it is quieter and starts easily at low wind speed. J. Savonius initially developed the vertical axis Savonius rotor in the late 1920s. The design of the conventional Savonius rotor consists of placing two halves cylinders so the section across generates the shape of letter S [2], Savonius rotor is simply realized but shows crucial disadvantages in terms of negative torque decreasing rotor performance. Literature review on the design of wind turbine blade revealed that recently, the improvement of Savonius rotor blade efficiency persist on being an encouraging research domain. The productivity performance of the VAWT is depending on the design of the turbine blade, which could be optimized by modifying the shape or by coupling additional constructions [3]. To enhance the rotor efficiency, It is noticed that research and investigations on parameters like aspect ratio (AR=H/D) rotor height (H) divided by diameter of rotor (D),number of blades and overlap ratio (e/D) shows a big interest to improve turbine performance. Moreover, adding an extra set such as obstacle shielding, curtain or conveyor deflector contribute also in the improvement of the performance of Savonius rotor[1][7][11]. However, this design leads to a more complex structure of Savonuis rotor and performance dependency of the wind direction. This design weakness opens the field for further research to find an agreement between rotor design simplicity and its performance.

The conventional Savonius rotors show an average performance marked by a power coefficient range values between 0.1 and 0.25 [4]. This work aims at presenting a modified design of Savonius wind Turbine blade to overcome structure complexity, provide a greater value of power coefficient and enhance the efficiency of savonius wind turbine.

II. ROTOR DESIGN

The Savonius vertical axis wind turbine consisting of two halves-cylinders slightly offset, It is a simple configuration, with suitable starting features and performs at low ranges of wind speed, it has a capacity to catch wind from all directions [5]. The wind turbine placed in the airflow deflects the streamlines arriving on the blade in advance towards the blade in return. Thus, a pressure difference is created between the concave and the convex part of the blades and the turbine is

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rotated. The kinetic energy of the wind thus transforms into mechanical energy of rotation.The difference of drag force along the two sides of the rotor blades presents the main working principle of savonius wind turbine [6].
In recent years, various investigations have been carried out to develop Savonius rotor, by performing many modifications on the shape of blades, as well mounting extra components to the conventional rotor, to improve the performance, Table I shows different modified designs investigated.

Table- I: Maximum power coefficient achieved by the different improved design of savonius rotor

design modifications	maximum C_p achieved
Obstacle shield[1]	27.3% increase
Curtain system[7]	38 % increase
V-shape blade[8]	0.37
Tower cowling[9]	0.48
Combined Blade[10]	11 % increase
Conveyor-deflector curtain system[11]	20% increase

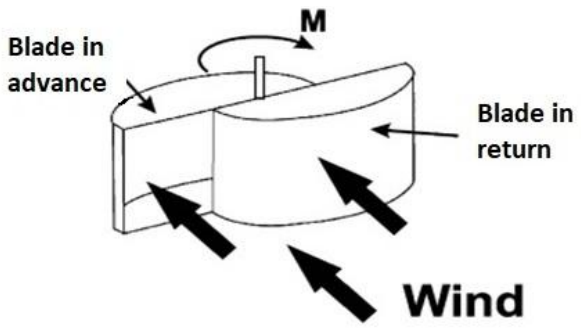


Fig. 1. The configuration of Savonius rotor wind turbine [1]

The major issue to increase the torque engendered by Savonius rotor, it's to develop the shape of the convex and concave side of blades, in this study we carry out an investigation of modified design based on elliptical shape with a straight trailing edge.
In previous studies, several values of overlap ratio (e/d) have been tested, It is revealed that the optimum value of overlap ratio belongs to the region between 0.15 to 2 [12][13].

As shown in Fig. 2, for the conventional Savonius rotor, an overlap ratio equal to 0.2 is selected, as it is defined to be the optimum configuration in [14].

We started in this work with the same overlap for the modified model and we kept for both models the same rotor radius R (m), the same swept area S (m²) and the blade thickness as 1 mm.
The performance of Savonius wind turbine is evaluated by calculating Power Coefficient C_P and Torque Coefficient C_T [15] according to the ratio between the speed of the blade extremity and actual wind speed V (m/s) noted tip speed ration (TSR) λ (1) [16] [17], with:

- ω : rotor angular velocity (1/s)
- P_T : extracted power from the wind (watt)
- P_W :available power in the wind (watt)
- ρ : air density (kg/m^3)

$$\lambda = \omega R/V \quad (1)$$

$$C_P = P_T/P_W \quad (2)$$

$$P_W = 1/2\, \rho S V^3 \quad (3)$$

$$C_T = C_P / \lambda \quad (4)$$

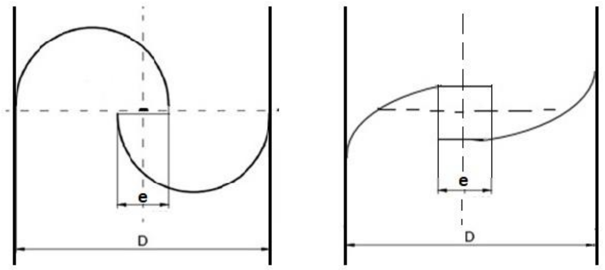


Fig. 2.(a) Conventional Savonius rotor,(b) modified Savonius rotor

III. METHODOLOGY

A. Computational description

In the present study, CFD code, Ansys Fluent, has been used to investigate the flow about Savonius blade based on a finite volume method which performs discretization of partial differential equations to algebraic equations was carried out to define both flow velocity u and v, and pressure P, field distribution. The k-ω turbulence model was applied.The equation governing the physics of the fluid flow is Navier Stokes equations (6), with :

- μ : dynamic viscosity (kg m^{-1} s^{-1})
- g : acceleration of gravity (m/s²)

$$\rho(\partial u/\partial t+u\, \partial u/\partial x+v\, \partial u/\partial y) = -\partial P/\partial x + \mu(\partial^2 u/\partial x^2 + \partial^2 u/\partial y^2) + \rho\, g_x \quad (6.a)$$

$$\rho(\partial v/\partial t+ u\, \partial v/\partial x+ v\, \partial v/\partial y) = -\partial P/\partial y + \mu(\partial^2 v/\partial y^2 + \partial^2 v/\partial y^2) + \rho\, g_y \quad (6.b)$$

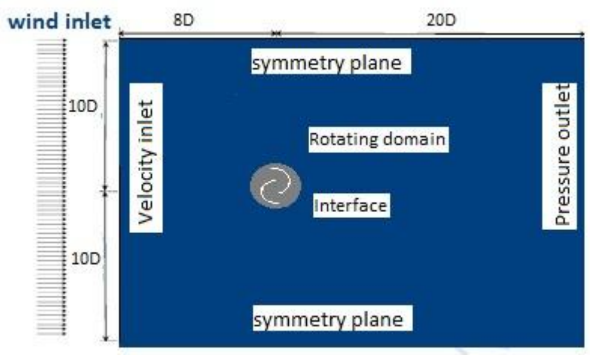


Fig.3. Simulation domains

The resolution performs the Pressure-Velocity Coupling and employs a coupled scheme, the coupled algorithm uses a relation of velocity and pressure corrections to get the pressure field.

To carry out the simulation of savonius wind turbine, the computational domain is parted into two main domains as shown in Fig.3, the first one is called rotating domain containing blades and the second larger domain is a known as stationary domain isolated by a sliding interface, the computational domain is discretized adopting unstructured grids.

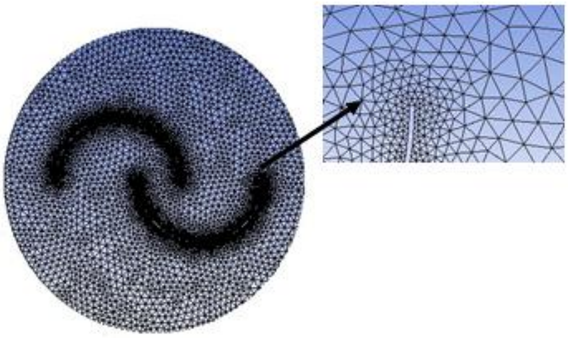


Fig. 4. Mesh generation around the rotating domain of the conventional Savonius turbine

To calculate the average torque, the mesh size should be accurate and efficient. The number chosen of cells for the modified blades is 250 520 and that for the conventional blades is 250 100. For both models, we fix the minimum size of the cell as 0.0251 m, in order to capture velocity and pressure gradient with good accuracy. Furthermore, we minimize mesh density near the blades and the size of the cell is kept as 0,006.

after setting up the mesh of numerical domain,we proceed to the implementation of boundary conditions, on the left side we consider velocity inlet (V = 6 m/s), on the right side, pressure outlet (atmospheric pressure), symmetry lines at top and bottom sides, in addition to a no-slip walls on the surface of blades.

B. Validation

n an effort to validate the accuracy of numerical results, a validation of the CFD model is carried out through the comparison of numerical results with the experimental data of Nasef [18].

Geometrical parameters of conventional savonius wind turbine have been conserved, in a two-dimensional structure, since 2D simulations have been performed in nearly all previous studies regarding Savonius rotors [19]–[23].

IV. RESULTS AND DISCUSSION

A. Numerical results

The variation of Coefficient of power (C_P) and coefficient of torque (C_T) versus tip speed ratio is plotted and compared with experimental data obtained by Nasef [18] as shown in Figures 5 and 6. For both simulation and experimental curves, the highest power coefficient is obtained at TSR = 0,9. Results show good accordance with the experimental data in particular in the range 0,4< λ< 1, The curve lines of both methods present the same behavior. The CFD method leads to somewhat overestimated results for TSR > 1. The error value between the experimental and numerical data stays below 1% for a wide range of λ, and reach a maximum value of about 8% TSR=1,2. Hence, it is tolerable to perform the numerical method to investigate the performance of savonius rotors. The difference between CFD and experiments may be due to the geometrical simplifications that may ignore some losses reducing the performance in the wind tunnel test whereas they are not present in the CFD simulations [24].

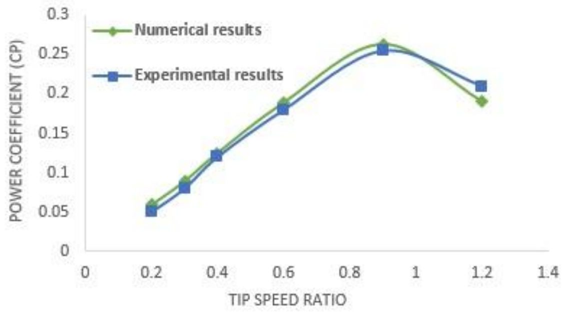


Fig. 5. Experimental [18] and numerical results of the power coefficient Cp

Fig. 6 shows variation of torque coefficient (C_T) values according to tip speed ratio the figure compares the experimental results of Nasef [18] and present numerical results.

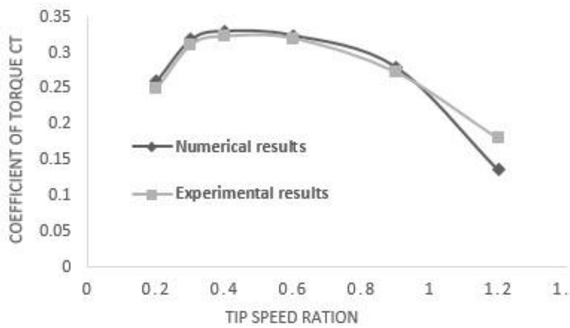


Fig.6.Comparison of experimental [18] and numerical data of the coefficient of torque (C_T)

All values obtained by both methods show similar conduct and are in close convergence. There is an increase in the coefficient of torque values (C_T) up to tip speed ratio of 0.4 and decreases afterward.

After validation of numerical results, a performance comparison between the conventional and modified design of a Savonius wind turbine is carried out.

The two configurations are investigated under identical conditions, simulation results show a performance improvement in matter of C_P for the new design compared to conventional model, The two models of savonius blade have a maximum power coefficient (C_P) at TSR = 0.9, with a maximum value of C_P 0.335 for modified blades compared to 0.26 for conventional as shown in fig. 7.

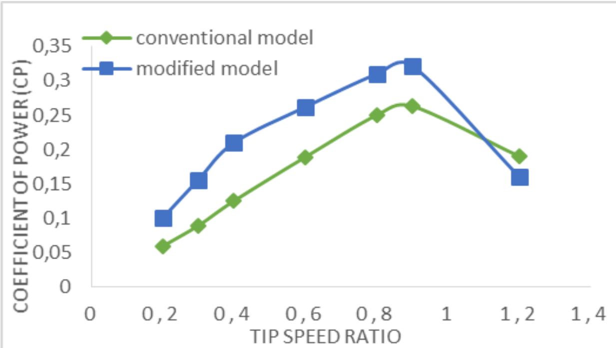


Fig.7. Variation of C_P for modified blades and conventional semi-circular blades

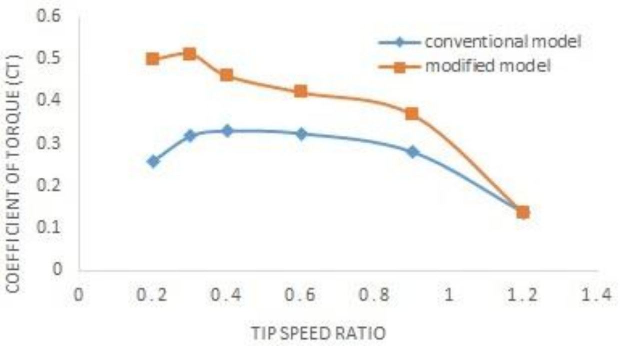


Fig.8.Variation of C_T for modified blades and conventional semi-circular blades

Savonius rotor is a drag category turbine. The same drag acting on the blade in advance to produce the power also works as a brake due to the negative torque generated by the blade in return, overall, the concave side torque (the blade in advance) is higher than the torque of the convex side (the blade in return), that leads to rotational movement of turbine rotor.

As shown in Fig.8, The torque coefficient between the two blade models shows that the one of the modified model is higher than the conventional ones, also, we notice that the curve shape of both models decreases towards the high values of tip speed ratio. In the range of low TSR there is a great difference between the two models in terms of torque coefficient and beyond a TSR=1, the values obtained become closer.

The turbine performance is highly dependent on the torque produced by wind pressure. The increase of moment arms at the concave side of the blade in advance increase directly the positive moment of the rotor, such a case goes with the modified model, which increases the distance of energy catching point from the center of rotation. The straight trailing edge of the blade in return acts in a positive way by enhancing the moment of the turbine. Therefore, the use of the modified model with the straight trailing edge produces a greater torque than that of the conventional model.

In order to highlight the obtained results, a performance comparison between the modified model, conventional and elliptical model developed in previous work [25] was realized, Fig.9 shows the three geometries of savonius blade.

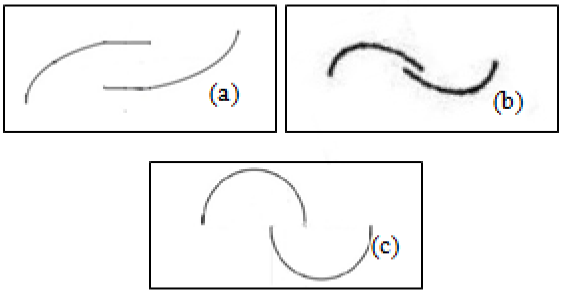


Fig.9.(a) modified Savonius rotor,(b) elliptical Savonius rotor[25] (c) Conventional Savonius rotor

Fig.10 shows the variation of power coefficient against tip speed ratio for the three models, it's observed that the performance of modified and elliptical blades show higher performance over the conventional blades, moreover, the performance of the modified savonius blade investigated in this paper reveals a higher efficiency over the conventional and elliptical blade[25],even though, the performances of modified and elliptical designs are significantly similar for $0.2 < \lambda < 0.6$, by increasing TSR value, modified Savonius start to show higher power coefficient values particularly in the range of TSR between 0.6 and 1, in that case, the performance improvement becomes quite important by 10.7% at $\lambda = 0.8$ and almost 18.5% at $\lambda = 0.9$.

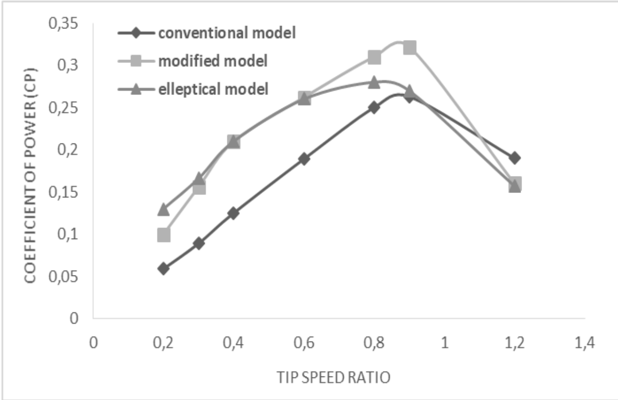


Fig.10 . Variation of C_P for modified blades, elliptical blades [25] and conventional semi-circular blades

B. Flow structures comparison:

In spite of the simplicity of savonius blades geometry, the flow around rotor involves many complications, the flow field consists of several regions, each region has many features under certain conditions, we marked the main regions specifying the flow in Fig.11-12 showing pressure and velocity distributions of the two models of savonius rotor at rotation angle 85° and TSR equal to 0,9. As shown in the fig. 11 the flow about the rotor blade has many regions, The flow acts on the concave side of the blade in advance and passes through the overlap (overlapping flow), at the tip of the blade in return, separation flow occurs resulting with low-velocity vortices, the combined result of the flow crossing the convex side of the blade in advance along its (Recuperated or recovery flow),the overlapping flow and the flow separation, form suction vortices along the concave side of the blade in return, the flow deviated by convex side of the blade in return and the concave side of the blade in advance finds the upstream flow detaches at the tip of the blade in advance and creates high-speed vortices. The flow acting on the convex side of the blade in return form the stagnation zone [26].

The velocity distribution, Fig.11 shows that the flow at the tip of blades (tip vortices) accelerates. The velocity reaches a high value of 22.7 m/s for the modified model while the conventional one reaches 16.7 m/s. The tip vortices zone gets closer to the surfaces of the modified model comparatively to the conventional. This shows that the flow is more energetic adheres longer to the surface and minimize the possibility of flow separation.

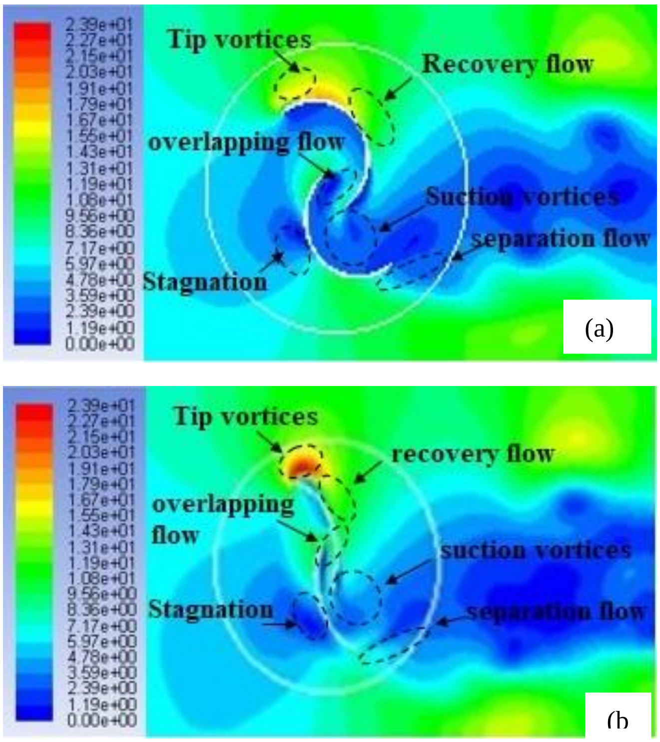


Fig.11. (a) Velocity magnitude distribution (m/s) for conventional semi-circular model and (b) modified model

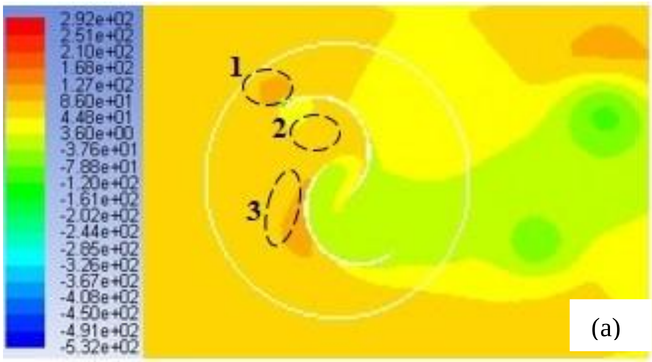
The modified Savonius has a stronger suction vortices, as a consequence of an important overlapping and recuperated flow.

The flow moving all along the convex part of the blade in return was reduced by the return flow over the concave part of the blade in advance of the modified rotor that leads to a decrease of overall torque on the convex side of the blade in return. It becomes lower than for the conventional Savonius rotor, as well, The stagnation zone moves forward towards the extremity of the blade and leads to an increase of arm length of drag, therefore a loss of negative torque occurs.

Fig.12 shows pressure contours for two models of savonius turbine. The pressure distribution diagrams indicate better flow characteristics for modified blades as compared to the conventional model.

The depression on the (zone 1) is more important for the modified design over the conventional model, this negative value indicates a reverse flow at the tip of the blade (tip vortices).

The pressure exerted on the concave side of the blade in advance (zone 2) is significantly important than the conventional design.



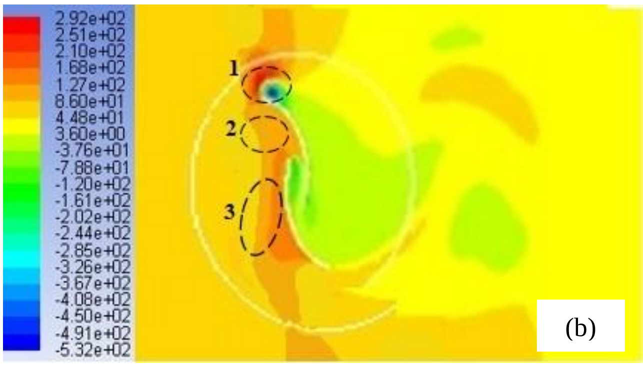


Fig. 12. (a) Pressure distribution (Pascal) for conventional semi-circular model and (b) modified model

The right trailing edge of the blade in return (upper of zone 3) also acts in positive way by enhancing the moment of the turbine. Despite the increment of the negative impact of wind pressure exercised on the blade in return of modified design (zone 3) due to a larger stagnation zone, the total torque is greater than that of the conventional model due to overall design improvement.

V. CONCLUSION

The modified Savonius rotor shows a great performance in terms of producing energy using wind potential, due to its simple design , and its ability to operate at low range of wind speed, in spite of its modest performance effected by the negative torque exerted to the convex surface of blade in return, the development of Savonius rotor blade design that overcome these major challenges and improve performance, remains an important and relevant research field, in this context we evolved a modified design of Savonius wind. turbine blade based on 2D simulations, afterward a comparative study between the two models of savonius rotor is performed.

The analysis of the performance exhibits an improvement in the power coefficient (Cp) with the modified design of Savonius blade, the modified design shows a maximum Cp of 0.335, whereas the conventional model indicates the highest Cp of 0.26. The peak power coefficient value for both cases is obtained at TSR = 0.9. Thus, a performance improvement of 23% is reached with the modified model blades over the conventional one.

The improved resultant pressure on both side of the blades justifies the performance enhancement. The performance of the modified model is explained further through the investigation of pressure variations and flow structures obtained by the numerical method, the improved flow structure contributes significantly to enhance the efficiency of the modified savonius rotor.

It should be added that the improved design delivers more performance with no added device to the structure. Finally, compromising between increasing rotor performance and ensuring system simplicity is still an open area of research.

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