Iranica Journal of Energy and Environment 15(3): 279-286, 2024

BNUT

Iranica Journal of Energy & Environment
Journal Homepage: www.ijee.net
IJEE an official peer review journal of Babol Noshirvani University of Technology, ISSN:2079-2115

Analyzing the Impact of a Curved Stator on the Performance of a Savonius Wind Turbine using Computational Fluid Dynamics

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P A P E R I N F O

Paper history:
Received 02 August 2023
Accepted in revised form 03 December 2023

Keywords:
Aerodynamics
Savonius
Stator
Wind Turbine

A B S T R A C T

Wind energy is a prominent renewable energy source, and Vertical Axis Wind Turbines (VAWTs) offer distinct advantages, including adaptability to changing wind directions and reduced noise levels. This paper conducts a numerical investigation into the impact of flat and curved stator blades on VAWTs, specifically the Savonius turbine, under 2D, viscous, turbulent, and steady flow conditions. Four stator blade configurations were examined, including no stator blades, smooth stator blades, twisted stator blades (Case A), and both blades being concave (Case B). The study reveals that curved stator blades enhance VAWT performance, with Case B exhibiting the most efficient performance. The results show pressure distribution on the turbine blades is non-uniform, with high and low-pressure zones, predominantly on the windward side. The presence of stator blades enhances pressure on all turbine blades, with Case B exhibiting the most optimal pressure distribution. Detailed observation of streamline and velocity distribution reveals improved flow lines for Case B, leading to more effective turbine blade performance. Case B consistently produces the highest turbine torque, with a maximum value of approximately 2.1 N·m achieved at Re = 15750. The torque demonstrates a positive correlation with increasing Reynolds numbers. The study further introduces a non-dimensional torque ratio analysis, where Case B attains 7.59 times higher torque than the reference case at Reynolds number 15750. The sensitivity of torque increase with respect to Reynolds number change highlights that Case B (with a slope of torque increase at around 4.5e-04) is the most responsive within the studied Reynolds number range.

***doi**: 10.5829/ijee.2024.15.03.06*

NOMENCLATURE

ρ	Density (kg/m^3)	S	The mean rate of strain tensor (s^{-1})
u	Velocity (m/s)	k	The turbulence kinetic energy(m^2·s^{-2})
μ	Dynamic viscosity (Pa·s)	T	Torque (N.m)
ε	Dissipation rate of turbulent kinetic energy(m^2/s^3)	**Index**	
P	Pressure (P)	i , j	Cartesian component
x	Length (m)	t	Turbulent
σ	The turbulent Prandtl numbers (m^2 s^{-1})		

INTRODUCTION

As fossil fuels continue to decrease, leading to an energy crisis, the demand for sustainable energy sources is growing. In the past decade, there has been a push for immediate and effective solutions to the climate of world challenges. Wind turbines are one such solution that is gaining more political support due to their potential as a

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Please cite this article as: P. Hedayati, A. Ramiar, N. Hedayati. Analyzing the Impact of a Curved Stator on the Performance of a Savonius Wind Turbine using Computational Fluid Dynamics, Iranica Journal of Energy and Environment, 2024 July, 15(3): 279-86. Doi: 10.5829/ijee.2024.15.03.06

sustainable and low-cost energy source. Utilizing wind energy to generate electricity can lessen the reliance of world on fossil fuels, while also being a non-polluting and environmentally friendly alternative. Among wind turbines, horizontal axis wind turbines (HAWTs) are the most commonly used, while vertical axis wind turbines (VAWTs) are also popular due to their straightforward design, lower noise, lower maintenance, and omnidirectional operation. HAWTs have their rotor axis parallel to the wind direction, while VAWTs have their rotor axis perpendicular to the wind direction.

The Savonius rotor is a unique fluid mechanical device that has been studied since 1920s and is still used in developing countries because of its simple construction, cost-effectiveness, and strong starting torque even in low wind speeds . The turbine examined in this study operates based on the basic concepts of the Savonius rotor. In this type of rotor, wind energy is transformed into mechanical torque by utilizing aerodynamic drag. The Savonius rotor has various uses, such as powering an electric generator, ventilating spaces, and stirring water to prevent the formation of ice in pools during the winter months. These applications have been explored in previous research (1, 2). Initial research has demonstrated promising starting characteristics for twisted blades. When choosing a wind site to install wind turbines for power generation, it is essential to extract as much energy as possible from the wind. This study was conducted to analyze the performance of a Savonius wind turbine equipped with a stator blade. According to Sarma et al. (3), the purpose of utilizing computational fluid dynamics (CFD) is to investigate the distribution of velocity and torque. Their study explored the adaptation of wind turbine technology to water in response to the depletion of traditional energy sources. The study focused on evaluating the performance of a Savonius wind turbine when driven by water currents at low velocities, using both experimental and computational methods. The findings demonstrated superior performance of the hydrokinetic turbine compared to its wind counterpart, with insights gained through detailed velocity and torque distribution analysis. Nasef et al. (4) carried out numerical simulations to analyze the aerodynamic performance of stationary and rotating Savonius rotors with different overlap ratios using four turbulence models. Comparative analysis with experimental data favors the SST k-ω turbulence model for accuracy. Increasing overlap ratio, particularly on the returning blade, improves static torque coefficient due to pressure recovery, while the best performance is achieved at an overlap ratio of 0.15 for rotating rotors. Kacprzak et al. (5) conducted a study on the performance of a Savonius wind turbine with fixed cross-sections using quasi-2D flow predictions in ANSYS CFX. The simulations carried out in this study facilitated a comparison with wind tunnel data presented in a related paper, which investigated two designs: the Classical and Bach-type Savonius rotors. This comparison emphasized the importance of employing a laminar-turbulent transition model. Additionally, the paper introduces a novel elliptical blade shape and systematically analyzes power coefficients, torque coefficients, flow structures, and wake characteristics at various tip speed ratios. Dobrev and Massouh (6) aimed to analyze the flow through a Savonius-type turbine using a three-dimensional model with the K-ε and Detached Eddy Simulation (DES) methods. They observed strong unsteady effects, including separation and vortex shedding, due to the continuous variation of the flow angle with respect to the blades and turbine principles of operation. The flow analysis helped to validate their wind turbine design. McTavish et al. (7) created a new vertical axis wind turbine (VAWT) that comprised of multiple asymmetric vertically stacked stages. The torque characteristics of the VAWT were investigated using CFD design 2010 software. Validation with a Savonius rotor showed good agreement. Results indicate that the new VAWT generates dynamic torque that decays faster at higher tip speed ratios due to its asymmetric design and rotor wall curvature.

In contemporary times, the numerical approach has emerged as a potent computational tool and is frequently employed to address diverse fluid flow issues (8–10). CFD models furnish comprehensive details about the characteristics of the moving flow field surrounding the turbine blades, such as the pressure and speed distribution, as well as the overall efficiency of the wind turbine blade. However, the simulations were confined to a two-dimensional computational domain, which simplified the solution significantly and enabled reasonable computation times on a personal computer. As the VAWT operates in two dimensions and the axial flow is negligible, it rotates in the same plane as the wind approach. Therefore, a two-dimensional model was deemed sufficient for the comparative analysis of the stator effect. Fluent version 18 was used for the CFD simulations in this study. The software solves the time-averaged Navier-Stokes equations and momentum equations iteratively using a control volume approach. The computational domain is divided into control volumes using the finite volume approach. The governing differential equations are expressed in general transport equations that include convection, diffusion, and source terms. These transport equations are then integrated over all the finite control volumes. Substitutions of finite-difference type are made for the various terms in these integrated equations, resulting in a set of algebraic equations for the flow parameters. Suitable iterative methods are used to solve these simultaneous algebraic equations for the flow parameters.

The k-ε turbulence model was selected for this study to determine the turbulent parameters at a constant state within the flow area. A new design for a Savonius wind turbine was tested in an open-air wind tunnel, and its performance was compared to other standard blade designs. The reported data included corrections for wind tunnel blockage (11).

To investigate the effect of wind boosters on power generation of vertical axis wind turbines and improve their performance at high wind speeds, a CFD study was conducted (12, 13). This study aimed to optimize energy harvest at low wind speeds.

Recent studies have indicated that the interactions between Savonius wind turbines in a cluster can significantly enhance the output power of individual rotors. This effect leads to improvement in the performance and efficiency of the turbines, resulting in a substantial increase in their power generation (14, 15). To improve the aerodynamic performance of Savonius wind rotors, two different approaches have been introduced: the use of innovative airfoil-shaped blades and a new curtain system (16). These methods aim to enhance the efficiency and performance of Savonius wind rotors. The Savonius wind turbine is a promising option for low-power applications in urban areas due to its simple and cost-effective design, despite its poor performance compared to more complex and expensive alternatives. The paper aims to improve the Savonius wind rotor's aerodynamic performance through innovative airfoil-shaped blades and a self-orienting curtain system. Using a validated numerical model, the study demonstrates significant energy performance enhancements with both approaches.

El-Askary et al. (17) investigated the enhancement of the performance of Savonius rotors by eliminating negative torque and increasing positive torque. To achieve this goal, three wind direction control designs were numerically studied. This paper introduces a solution to the limitations of Micro Wind Technology by proposing a Rotor House (RH) for vertical-axis wind turbines. The RH is shown to capture a larger wind parcel and enhance wind velocity, leading to improve micro vertical-axis wind turbine performance. Experimental tests reveal an increase in the power coefficient from 0.125 to 0.218 with the optimized RH design. The results of the study showed that these designs could significantly improve the efficiency and power generation of the Savonius rotor, thereby enhancing its overall performance.

Promdee and Photong (18) conducted a study to investigate the influence of wind angles and speeds on the performance of a Savonius wind turbine. The purpose of this research was to identify the optimal operating conditions for the turbine and determine how different wind angles and speeds affect its overall performance. The results of the study showed that wind speed had a significant impact on the power output of the turbine, while wind angle had a relatively minor effect. These findings can be used as valuable insights for future improvements in the design and operation of Savonius wind turbines.

The study conducted by El-Deen et al (19) aimed to significantly enhance the performance of Savonius Bach-type rotor by adding a new stator composed of a shield, obstacle, and guide plate around it. They performed a comprehensive parametric study, varying eight geometrical parameters for the stator, and utilized a 2D numerical model with ANSYS Fluent 18.1 to find the optimum shape for maximum rotor power coefficient value. The results of the study revealed that the main effective element in the turbine stator was the stator obstacle. The maximum power coefficient for the rotor with optimum stator configuration achieved a value of six times greater than that of the bare rotor under the examined conditions.

The study conducted by Shashikumar et al. (20) used computational fluid dynamics simulations to compare the performance of conventional and tapered turbine blades for hydrokinetic power generation. The simulations were carried out using ANSYS Fluent and involved the use of the sliding mesh technique to study the influence of taper on a conventional Savonius turbine. The study found that the conventional turbine outperformed the tapered turbine blade by 5%, with a maximum coefficient of power of 0.21 and a tip speed ratio of 0.9. The flow field around the conventional and tapered turbine blades at different angular positions was also analyzed, and it was discovered that the tapered turbine had a 5% reduction in performance due to energy loss at the exit side of the advancing blade.

Considering previous studies, one of the aspects that affects the performance of wind turbines is the geometry of the rotor blades. There are two main types of wind turbines based on the orientation of their rotor axis: horizontal axis wind turbines (HAWTs) and vertical axis wind turbines (VAWTs). VAWTs have some advantages over HAWTs, such as lower noise, lower maintenance, and omnidirectional operation. However, VAWTs also have some drawbacks, such as lower efficiency, higher torque ripple, and high drag force. To overcome these drawbacks, researchers have proposed various modifications and innovations in the geometry of VAWT blades. For example, some studies have investigated the effects of blade curvature, blade twist, blade tapering, blade number, blade profile, and blade angle on the performance of VAWTs. Considering the importance of this issue, this paper examines a new type of geometry in vertical axis wind turbines, specifically the Savonius turbine, that can improve system performance.

Governing equations

The Reynolds-averaged Navier-Stokes (RANS) method is employed as it is deemed the most appropriate approach given the available resources for this particular case. The RANS method is governed by two equations (21):

$$\frac{\partial}{\partial x_i}(\rho u_i) = 0 \quad [1]$$

$$\frac{\partial}{\partial x_i}(\rho u_i u_j) = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_i}\left(\mu\left(\frac{\partial u_i}{\partial x_i} + \frac{\partial u_i}{\partial x_i} - \frac{2}{3}\delta_{ij}\frac{\partial u_i}{\partial x_i}\right)\right) + \frac{\partial}{\partial x_i}\left(-\rho\overline{u_i' u_j'}\right) \quad [2]$$

Considering that i and j represent the Cartesian axes; $\boldsymbol{u}$ denotes the mean velocity; $\boldsymbol{x}$ is the length; and $\overline{u_i' u_j'}$ represents Reynolds stresses. The turbulence model utilized in this study is the Realizable K-ε model with enhanced wall treatment. The transport equations for the Realizable K-ε model are (21).

$$\frac{\partial}{\partial x_j}(\rho k u_j) = \frac{\partial}{\partial x_j}\left(\left(\mu + \frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial k}{\partial x_j}\right) + G_k + G_b - \rho\varepsilon - Y_m + S_k \quad [3]$$

$$\frac{\partial}{\partial x_j}(\rho \varepsilon u_j) = \frac{\partial}{\partial x_j}\left(\left(\mu + \frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial x_j}\right) + \rho C_1 s\varepsilon - \rho C_2\frac{\varepsilon^2}{k+\sqrt{\upsilon\varepsilon}} + C_{1\varepsilon}\frac{\varepsilon}{k}C_{3\varepsilon}G_b + S_\varepsilon \quad [4]$$

$$C_1 = \max\left(0.43, \frac{\eta}{\eta+5}\right) \quad [5]$$

$$\eta = S\frac{k}{\varepsilon} \quad [6]$$

$$S = \sqrt{2S_{ij}S_{ij}} \quad [7]$$

where, G_k denotes the turbulent kinetic energy generation owing to mean velocity gradient, G_b denotes the turbulent kinetic energy generation owing to mean buoyancy, k is the turbulent Prandtl number for k and is the turbulent Prandtl number for . C_1, C_2 , C_3 and C are the constants, whereas, S_k and S are the assumed source terms, Y_M is the effect of the changing dilatation in compressible turbulence to the overall dissipation rate.

Geometry

In this Paper, four different geometries are investigated: a rotor positioned at a 90-degree angle, a flat plate stator, a curved stator with one convex blade (referred to as Case A), and a curved stator with both blades convex (referred to as Case B) Figure 1.

Grid independency

An investigation into mesh independence was conducted. Figure 2-a displays the mesh structure, and Figure 2-b illustrates the correlation between the number of elements and static torque. The results indicated that for 50,000 and 100,000 elements, the static torque values were nearly identical. Therefore, a mesh composed of 50,000 triangular elements is recommended as a cost-effective option due to its shorter computation time.

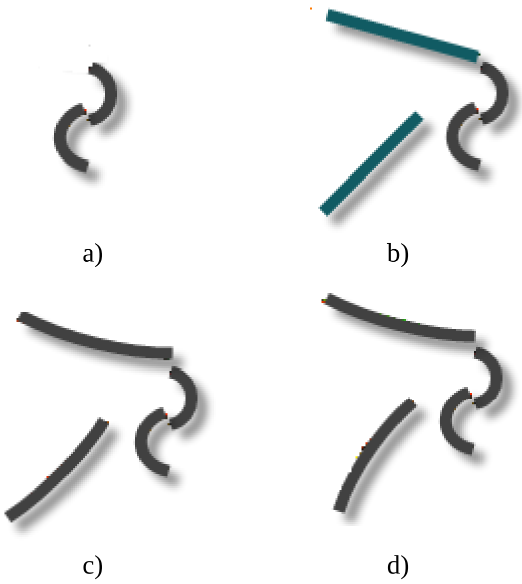

Figure 1. Schematic of Geometries, a) rotor positioned at a 90-degree angle, b) flat plate stator, c) curved stator with one convex blade, d) curved stator with both blades convex

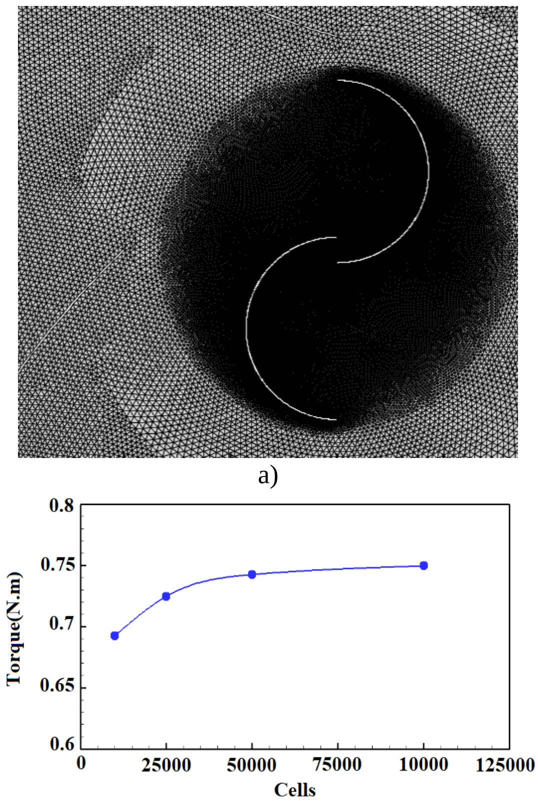

Figure 2. a) Mesh structure b) Mesh independency

Physical conditions

Simulations were conducted at different wind speeds, with reference pressure set at 105 kPa and the reference temperature used to calculate the density and dynamic viscosity of air under reference conditions. The air was assumed to be incompressible.

Validation

The static torques of the Savonius wind rotor with and without curtains were analyzed at three different rotor positions (45°, 60°, and 90°) using both experimental measurements (16) and the Fluent program. The results were compared in Figure 3. For the Savonius wind rotor without blades, the static torque values were obtained through experiments (16) and numerical analysis at the three rotor positions. As shown in Figure 3, both experimental and numerical analyses found that the static torque values were highest at 45°. The numerical accuracy of algorithm was verified through Figure 3, and the maximum error between simulation results and experimental results was found to be 2%.

RESULTS AND DISCUSSION

The pressure distribution around the surface of the turbine blades is depicted in Figure 4 with and without a stator. It can be observed from these illustrations that the distribution of pressure across the wind turbine is not uniform and includes significant pockets of high and low pressure. The highest pressure is found in the areas of the turbine that are directly exposed to the air flow (windward). Moreover, it is clear that each blade has a pressure side as well as a suction side. The pressure distribution colored on the figure highlights that the pressure is greater in all blades in the wind turbine with a stator blade. The function of stator is to direct the flow towards the effective part of the turbine. Among the presented cases, Case B yields the most optimal pressure distribution on the pressure surface of the turbine.

Figure 5 provides a more detailed observation of the variation in streamline and velocity distribution across the blades. The flow field exhibits several characteristics, such as the acceleration of the flow around the edges of

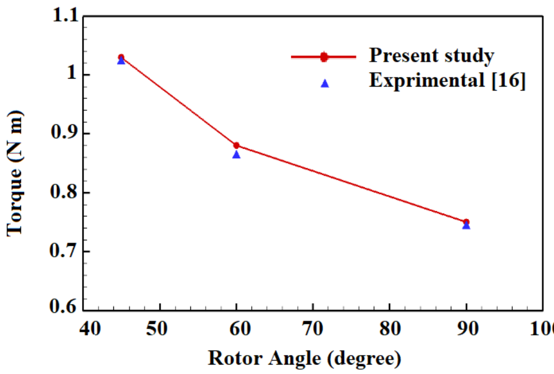

Figure 3. Validation of the present work with El-Deen et al. (16)

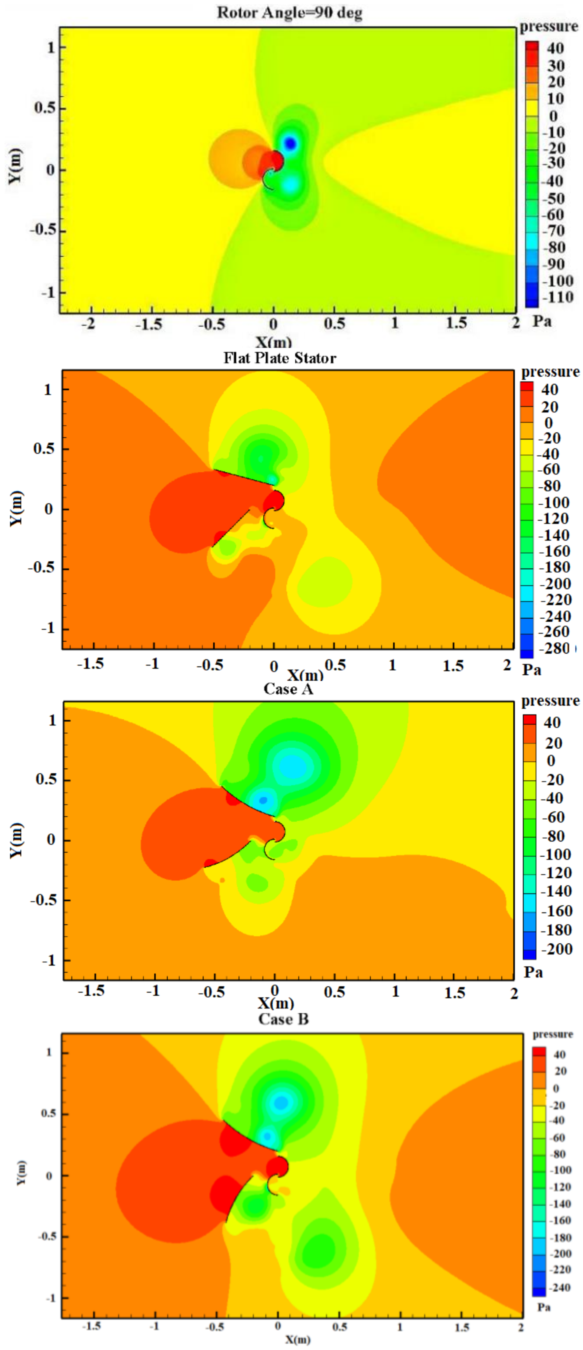

Figure 4. Pressure distribution around the the Turbine blade (wind from left to right)

the turbine and the presence of a low-velocity wake behind it. In Cases B, both convex surfaces offer improved flow lines leading to the effective part of the turbine blade.

To determine the torque of wind turbine for a given inlet flow velocity, four tests were conducted on the incoming flow. Figure 6 displays the obtained results for the torque. It is evident that the rotor produces greater torque and lower drag than the turbine with a stator blade.

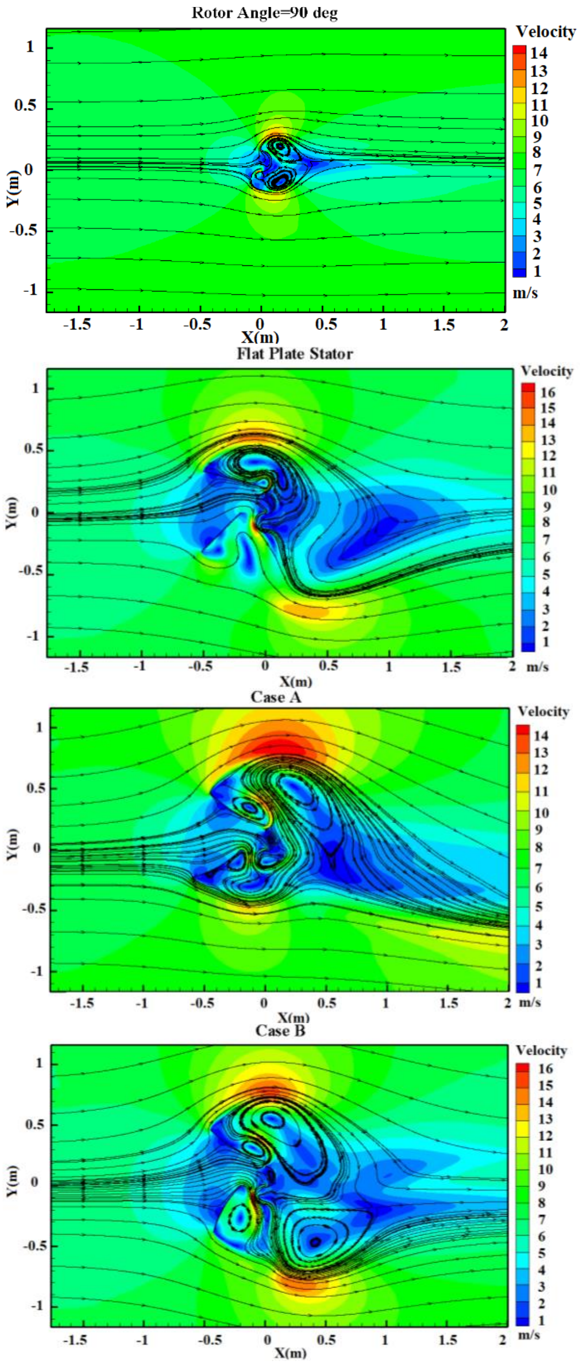

Figure 5. Velocity magnitude distribution and tream lines around the the Turbine blade (wind from left to right)

This is attributed to the orientation of the blade with respect to the incoming free stream flow. Therefore, the impact of the stator on the performance of the Savonius wind turbine is significant. Among the cases studied, Case B generates the optimal amount of turbine torque. As the Reynolds number increases, the torque also increases. The effect of the stator on the torque of the turbine is less pronounced at lower Reynolds numbers.

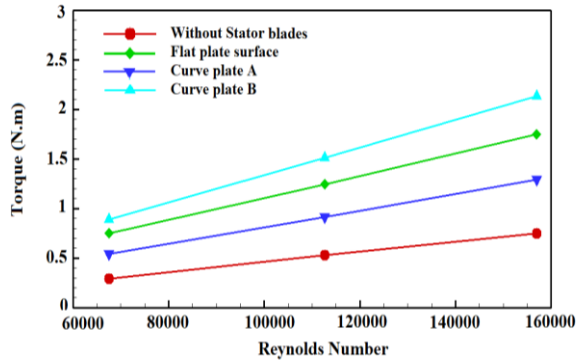

Figure 6. Torque variation with Reynolds number of four cases

Table 1 presents the non-dimensional torque ratio, which represents the ratio of the desired torque force to the reference torque. The reference torque in the present study is the stator torque at 90 degrees without stator blades, at a Reynolds number of 6750.

The results indicate that the maximum torque for Case B occurs at a Reynolds number of 15750, which is 7.59 times greater than the torque in the reference case.

Figure 7 illustrates the slope of torque (S) increase with respect to the increase in Reynolds number for each case. The results indicate that Case B exhibits a higher sensitivity compared to other cases (with a slope of torque increase at around 4.5e-04). Therefore, within the investigated Reynolds number range, Case B experiences a greater increase in torque with increasing rotational force.

Table 1. The variation of non-dimensional torque (**τ***) with different cases and Reynolds numbers

Re	τ^*			
	90-degree angle	Flat blades	A	B
6750	1	1.87	2.63	3.13
11250	1.83	3.22	4.40	5.35
15750	2.61	4.59	6.17	7.59

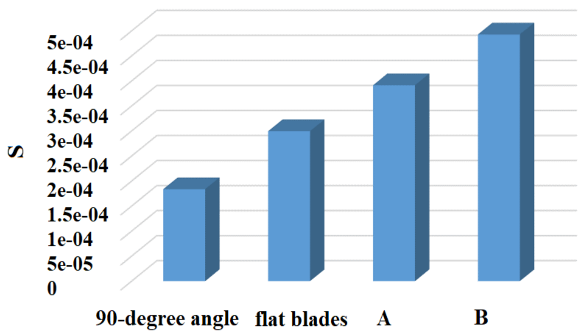

Figure 7. Increase in torque slope in different cases

CONCLUSION

Wind power is a renewable energy source with numerous advantages. Vertical Axis Wind Turbines (VAWTs) are a type of wind turbine known for their adaptability to varying wind directions and minimal noise emissions. This study aimed to enhance wind turbine performance by exploring different stator blade configurations, including cases with no stator blades, smooth stator blades, twisted stator blades (referred to as Case A), and stator blades with a concave shape (referred to as Case B).

Numerical methods were employed to investigate the impact of these stator blade shapes, particularly on the Savonius turbine, under 2D, viscous, turbulent, and steady flow conditions. The results from the four tests on the incoming flow indicated that stator orientation significantly influenced turbine torque and drag. The pressure distribution across the wind turbine was found to be non-uniform, featuring high and low-pressure pockets. The highest pressure was observed on the windward side of the turbine, and pressure was generally greater in all blades when a stator blade was present.

The findings revealed that Case B offered the most optimal torque (around 2.1 N.m at a Re =15750) and pressure distribution. Additionally, an increase in Reynolds number had a positive effect on torque. These results underscore the importance of careful stator blade orientation design for achieving optimal wind turbine performance. A non-dimensional torque ratio analysis was conducted, comparing the desired torque force to the reference torque at a Reynolds number of 6750. Case B demonstrated the highest torque at a Reynolds number of 15750, exhibiting 7.59 times higher torque than the reference case. Moreover, the results indicated that Case B was more sensitive to changes (with a slope of torque increase at around 4.5e-04), experiencing a greater increase in torque with higher rotational force within the studied Reynolds number range. Since Case B is the preferred option, future work can focus on optimizing this case with regards to the angle of placement, curvature, and the length of the curve.

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Persian Abstract

چکیده

منابع انرژی تجدیدپذیر قابلیت‌های بسیار خوبی دارند و توربین‌های بادی برای بهره‌برداری از این انرژی به طور گسترده استفاده می‌شوند. توربین بادی عمود محور به دلیل توانایی کار در جهت‌های مختلف باد و تولید صدای پایین‌تر نسبت به توربین های بادی افقی محور، گزینه جذابی برای مطالعه می‌باشند. در این مقاله به بررسی عددی تاثیر پره‌های استاتور خمیده در توربین بادی عمود محور سانیوس پرداخته می‌شود. به همین دلیل چهار هندسه در کار حاضر مورد بررسی قرار می‌گیرد که شامل هندسه بدون پره استاتور، پره استاتور صاف، پره استاتور خمیده‌ی A که در آن یکی از پره‌ها مقعر و دیگری محدب است و کیس B که در آن هر دو پره مقعر هستند. نتایج فشار و گشتاور برای چهار حالت مختلف نشان می‌دهد که پره‌های استاتور خمیده B راندمان عملکردی بهتری نسبت به دیگر هندسه‌های مورد بررسی دارد. وجود پره‌های استاتور باعث افزایش فشار بر روی همه پره‌های توربین می‌شود و کیس B بهترین توزیع فشار را ایجاد می‌کند. نتایج نشان می‌دهد کیس B همواره در رینولدزهای مختلف بیشترین گشتاور توربین را تولید می‌کند که در این بررسی در رینولدز ۱۵۷۵۰ گشتاور در حدود ۲.۱ نیوتن متر است. بررسی اثر رینولدز بر چهار کیس مورد نظر نشان می‌دهد نیروی گشتاور برای کیس B در رینولدز ۱۵۷۵۰، به اندازه‌ی ۷.۵۹ برابر نسبت به کیس مرجع افزایش می یابد. علاوه بر این با افزایش رینولدز افزایش نیروی گشتاوری در کیس B با شیب (حدود 4.5 e-04) بیشتری نسبت به حالت‌های دیگر مورد بررسی، رشد می‌کند.