The Effects of Airfoil Type and Wind Speed on the Aerodynamic Efficiency of Vertical Axis Wind Turbines

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Abstract. This research focuses on improving the extraction of wind energy as one of the main renewable energy sources, in vertical axis wind turbines (VAWTs). In the current study, 5 turbine types with identical geometrical structures but with completely different blades have been analysed in various wind speeds. The numerical study was performed in two and three-dimensional (2D and 3D) modes using the finite volume method. The solution results were obtained in an unsteady state and assuming incompressible fluid flow. Also, k-ε SST turbulence model was employed for modelling the turbulent flow. To ensure that the numerical results are valid, the numerical results were compared with experimental data, and it was found that the numerical and experimental results are in good compatibility. Among the simulated turbines, the S1046 airfoil had the maximum coefficient of performance, a larger operating range, and a higher average efficiency compared to other turbines. For all of the airfoils, the results showed that the coefficient of performance reduces in a specific range of rotor blade tip speed ratio. Since the 2D results were in good agreement with the 3D results, 2D simulations can be used in the designing and optimizing processes of VAWTs.

Keywords: vertical axis wind turbines (VAWT), airfoil, blade tip speed ratio, numerical simulation.

1. Introduction
Among the non-fossil fuels, wind energy is one of the best sources of energy in the world, because not only it is accessible in the entire world, it is one of the renewable energy sources. The usage of wind as a clean and free source for electrical energy production is increasing [1,2]. Based on the estimations, in 2020 more than 10% of the world’s total required energy will be produced using wind energy, and until 2040 this value rises between 10 and 30%. Wind energy has great importance because it is one of the cheapest and most accessible energy sources and can be significantly effective in the prevention of climate changes[3]. The primary form of this technology dates back to the 7th century BC in Afghan highlands, but this kind of turbine was first mentioned in Iranian historical texts [4].

Generally, wind turbines can be categorized into two main groups: horizontal axis wind turbines (HAWTs) and vertical axis wind turbines (VAWTs). Usually, the aerodynamic blades are used in HAWTs, but some VAWTs may use these blades. The efficiency of HAWTs can be significantly
affected by the angle of the flow in which the turbine is placed in, however, VAWTs are not sensitive towards the wind direction [5]. This can be considered as an important advantage for this kind of turbine. VAWTs can be categorized into two groups, including the VAWTs that are driven by the lift force and the VAWTs that are driven by the drag force. Since the maximum efficiency in the first group of VAWTs is higher compared to the second group, the first group has attracted more attention [6,7]. In 2016, Sunny and Kumar simulated the aerodynamic model of a VAWT. They also performed some experimental tests in a wind tunnel, to evaluate the influence of the wind speed on the rotation speed of the turbine rotor and the obtainable torque from it. The experimental and numerical results both indicated that these turbines have an acceptable performance. Their research just focused on one design of VAWTs [4]. In 2020, He et al. studied different numerical methods for simulating VAWTs, and they compared the results of these methods with the experimental data. They aimed to find a faster and more accurate method that required a lower computational cost. These researchers recognized the limitations of the conventional methods by simulating a turbine, and they discussed these limitations. Finally, they recommended the usage of the hybrid meta-model. This research was also performed on one type of turbine [8]. In 2018, Liang and Li tried to study the effects of the maximum tangential force coefficient on enhancing the performance of VAWTs. The simulated turbine used NACA0015 airfoil, and the simulation was performed in 3D. Even though the simulations in this research were only done on one turbine type, this study was able to show the positive effect of design optimization on the turbine performance [9]. In the current work, the influence of changing the design of the turbine rotor through changing the airfoil has been examined on the aerodynamic characteristics of the turbine. Initially, the comparisons were done in 2D for the turbines with different airfoils, and then the 3D simulations for the turbine with the best 2D results were performed again. Based on the literature review, this can be considered as the novelty of the current work.

2. Geometry selection, meshing, and boundary conditions

In this research, the numerical simulations were done in 2D and 3D. At first, five airfoils that belong to different families were selected, and they were simulated in a domain. Initially, each of these airfoils was simulated and analyzed in the computational domain, then after evaluating the performance coefficient of these turbines separately, the best one in terms of the performance coefficient was simulated in 3D and its results were analyzed. The examined airfoils were a. NACA 008, b. NACA 63415, c. S1046, d. AH93W215, e. FLXV152. Figure 1 shows the design of these airfoils.

The simulated turbines in this study had three blades, a cord length of 12 cm, and a rotor radius of 30 cm. In the 3D simulation mode, these turbines had a height of 40 cm. These values are based on one of the references [9]. Figure 2 shows the 3D view of the designed turbine.

For meshing, triangular and tetrahedron grids were used in the 2D and 3D computational domains, respectively. Also, for observing the boundary layer and the separation phenomenon more precisely, boundary layer meshing was done in the vicinity of the airfoil [10]. Figure 3 shows the 2D and 3D mesh for the examined turbine and the computational domain.

2.1. Governing equations and dimensionless numbers

The general form of continuity and Navier-Stokes equations have been written as equations 1 and 2, respectively [11]. In these equations, \( \overline{u}_i \) indicates the average speed, \( u'_i \) shows the fluctuation component of the speed, \( P \) is the mean pressure, \( \theta \) represents the kinematic viscosity, and \( \rho \) is the fluid density [12].

\[
\frac{\partial \overline{u}_i}{\partial x_i} = 0
\]  

(1)

\[
\frac{\partial \overline{u}_i}{\partial t} + \overline{u}_j \frac{\partial \overline{u}_i}{\partial x_j} = -\frac{1}{\rho} \frac{\partial P}{\partial x_i} + \frac{\partial^2 \overline{u}_i}{\partial x_i^2} + u'_j \frac{\partial u'_i}{\partial x_j}
\]  

(2)

In this study, ANSYS Fluent software was employed for simulating the fluid flow and all of the equations were discretized using the second-order upwind discretization method. Since in the fluid flows with separation and adverse pressure gradient, k-\( \omega \) SST turbulent modeling method presents accurate results and it has good performance in terms of stability and convergence, this model was
selected for the 2D and 3D simulations [15,16]. The k-\( \omega \) SST model includes two equations: turbulent kinetic energy transport (Equation 3) and the turbulent kinetic energy dissipation rate transport (Equation 4):

![Graphs showing turbulent kinetic energy and dissipation rate for different airfoils](image)

**Figure 1.** The examined airfoils [13].

![3D view of the designed turbine](image)

**Figure 2.** The 3D view of the designed turbine for the simulation [14].
The 2D generated mesh for the NACA 63415 turbine

The 2D generated mesh for the rotor of NACA 63415 turbine

The 3D generated mesh for the S1046 turbine and its surrounding computational domain

**Figure 3.** The generated grid for the geometry in 2D and 3D simulation modes.

\[
\frac{\partial}{\partial t} (\rho k) + \frac{\partial}{\partial x_i} (\rho k u_i) = \frac{\partial}{\partial x_j} \left[ \Gamma_k \frac{\partial k}{\partial x_j} \right] + \mathcal{G}_k - Y_k + S_k \tag{3}
\]

\[
\frac{\partial}{\partial t} (\rho \omega) + \frac{\partial}{\partial x_i} (\rho \omega u_i) = \frac{\partial}{\partial x_j} \left[ \Gamma_\omega \frac{\partial \omega}{\partial x_j} \right] + G_\omega - Y_\omega + D_\omega + S_\omega \tag{4}
\]

In which \(G, \Gamma, Y, S,\) and \(D\) indicate generation, diffusion, dissipation, user-defined source, and cross-diffusion items for the \(k\) and \(\omega\) terms.

Also, in this study, sliding mesh as one of the most accurate methods for simulating flow in moving reference frames with several references has been employed [17]. For analysing the performance of wind turbines, the most important parameter is their coefficient of performance. This parameter has been presented in Equation 5. According to Equation 5, the coefficient of performance \((C_p)\) is the ratio of the produced electrical energy from the turbine \((P)\) to the power of the wind, in which the turbine is affected by \((W)\).

\[
C_p = \frac{P}{W} \tag{5}
\]

The coefficient of performance can be significantly variable based on the flow velocity, turbine design, and energy conversion capability, but its maximum can be determined using the Betz coefficient. The value of the Betz coefficient shows the maximum accessible power for wind turbines. It shows that without any dissipation, and in ideal condition, the maximum obtainable energy in the wind turbines is 59.3% of the wind flow energy [7,18]. Another important parameter that is used for wind turbines is the Tip Speed Ratio or TSR. This parameter is defined as the ratio of the blade tip speed to the speed of the free flow (Equation 6) [19,20].
\[ \lambda = \frac{\omega \cdot r}{V} = \frac{v}{V} \]  
\[ \omega = 2\pi f \]

In these two equations, \( \omega \) shows the rotational speed, \( v \) indicates the rotor tip speed, \( V \) is the wind speed, \( f \) represents the rotation frequency, and \( r \) is the rotor radius.

2.2. Boundary conditions
After discretizing the governing equations, some algebraic equations are obtained. To solve these equations, the flow conditions should be solved in the boundaries of the computational domain. The used boundary conditions in the 2D simulations was velocity inlet for inlet boundary, walls for blades and pressure outlet for the rest of domain [15,21]. The boundary conditions in the 3D simulations are similar, however, in the 3D simulations, the boundaries are surfaces and not lines [22].

2.3. Validation and grid independence tests

3.1. Validation
For the validation of the obtained results for the simulations, both 2D and 3D results were validated by the wind tunnel test results that were presented in the reference [4]. Since the researchers in the reference [4] used NACA0021 airfoil, this airfoil was employed in the simulated turbine.

As it is illustrated in Figure 4, the numerical simulation results in 2D mode are in good compatibility with the experimental results of the reference [4]. After changing the simulation mode from 2D to 3D, the deviations between the simulation results and the experimental data becomes considerably smaller. The reason for this improvement is considering the effects of the 3D flow.

Figure 4. Validation of the simulations with the obtained results in reference [4].

3.2. Mesh independence test
Since the accuracy of the numerical solution can depend on the generated mesh, as shown in Figures 5 and 7, the mesh independence test was performed for both 2D and 3D simulation modes.

The results from NACA0018 airfoil in 2D simulation mode and for S1046 airfoil in 3D simulation mode shows that increasing the number of cells more than it is required, does not create a significant alternation in the obtainable results. For example, as it can be noticed in Figure 5, changing the number of cells from \( 6 \times 10^4 \) to \( 9 \times 10^4 \) changes the results less than 5%, which indicates that the results are independent of cell size. Furthermore, in the 3D simulation mode (Figure 6), the simulations were done with \( 7 \times 10^5, 7 \times 10^5, 8 \times 10^5, 10 \times 10^5, \) and \( 13 \times 10^5 \) cells. As it can be noticed from Figure 6, with one million of cells, the simulation reaches a desirable level of accuracy and increasing the cell numbers more than this, does not lead to a significant change in the results, therefore the generated grid with one million of cells is selected for the 3D simulations.
4. Results and discussions

4.1. Results of the 2D simulation

The coefficient of performance results for the turbine with different airfoils in 2D mode has been presented in Figure 7. As it can be observed in this figure, the lowest coefficient of performance belongs to NACA 63415 airfoil. The maximum coefficient of performance for this airfoil in the TSR of 2, reaches lower than 20%, which is significantly different from the Betz value. Unlike the other airfoils that have been shown in Figure 7, the AH93W215 airfoil reaches its highest performance in the TSR of 1.5-1.75. The AH93W215 airfoil presents a better performance compared to the NACA 63415 airfoil, in all of the TSRs. Furthermore, AH93W215 airfoil presents its best performance in the TSRs lower than 1.75, and overall, it has a better performance compared to NACA 0018 and FXLV152 airfoils, however, unlike these two airfoils the performance of AH93W215 decreases in higher TSRs. NACA 0018 airfoil exhibits similar behavior to the other airfoil in this family (NACA 63415), except that the overall performance of NACA 0018 airfoil is better.

By increasing the TSR, the coefficient of performance increases for the FXLV152 airfoil, and in the TSR of 2.25, the performance of this airfoil reaches its maximum, which in this TSR, is the highest performance coefficient compared to the other airfoils (except the S1046 airfoil). In almost all of the TSRs, the S1046 airfoil presents a better performance compared to other airfoils, and this difference is completely obvious in Figure 7. In the TSRs lower than 2, raising the TSR increases the performance coefficient of the S1046 airfoil, but after the TSR of 2, increasing the TSR leads to a reduction in the performance coefficient for this airfoil, so that in the TSR range of 2.25-2.5, the performance coefficient of this airfoil becomes similar to the performance coefficient of the FXLV152 airfoil. Overall, by reviewing Figure 7, it can be demonstrated that the S1046 airfoil has a better performance coefficient compared to other airfoils.

The highest coefficient of performance for each of the examined airfoils has been presented in Table 1. According to the table, NACA 63415 airfoil, at the maximum, reaches the performance coefficient of 0.18, which is half the maximum performance coefficient that can be obtained using the FXLV152 airfoil. The S1046 airfoil has a maximum performance coefficient of 0.41, which is significantly larger compared to other airfoils. Overall, the maximum coefficient of performance for all of the airfoils is far from the Betz limit, showing that there is dissipation in the fluid energy.
Figure 7. The changes in the performance coefficient ($C_p$) for the five simulated airfoils in 2D mode.

| Airfoil name | NACA 0018 | S1046 | NACA 63415 | AH93W215 | FXLV152 |
|--------------|-----------|-------|------------|----------|---------|
| The maximum performance coefficient ($C_p$) | 0.29 | 0.41 | 0.18 | 0.25 | 0.36 |

Since the aerodynamic phenomena in all of the examined turbines are similar, the contours of velocity are just presented for the S1046 airfoil. Figure 8 shows these contours in four different TSRs. In the low TSRs (Figure 8-a) a larger amount of flow enters the turbine rotor. By increasing the TSR, the flow velocity in center decreases, so that in the TSR of 2.5, the turbine almost leads to blockage in the flow. Comparing Figures 8 and 7 reveals that by increasing the TSR, the amount of entered flow in the center of the turbine increases, and this raise leads to higher momentum transfer from the fluid to the turbine and consequently, increases the performance. However, in the TSR of 2.5 (Figure 8-d), the rotational speed of the rotor prevents the flow from entering, leading to the conversion of the turbine into a rotating cylinder and formation of Karman Vortex street behind the turbine.

Figure 8. The changes of velocity magnitude around the S1046 airfoil in different TSRs.
By observing the presented velocity vectors in Figure 9, it can be concluded that the rotation of blades around their axis makes the airflow move in the blade’s movement direction. Therefore, the movement direction of the flow changes from the horizontal to rotational, and the velocity magnitude of the flow around the blade, becomes close to the velocity magnitude of the blade. In lower distances from the blade, the direction and the velocity of the flow becomes more similar to those of the blade. When the blade passes from a region, the velocity changes, and after that, the horizontal flow that enters the turbine makes the rotational flow to move toward the downstream. All of the vortexes move from the upstream towards the downstream like a trail, and they cause energy dissipations in the flow. The most noticeable phenomena in the velocity vector figures are separation from the trailing edge, rotational flows, and vortexes around them. These phenomena are observed for all of the turbines, however, their intensity and sizes are different for each of the turbines. This difference is one of the factors that determines the aerodynamic performance for each of the turbines.

![The velocity vectors around the airfoil.](image)

**Figure 9.** The velocity vectors around the airfoil.

The pressure distribution around the S1046 airfoil in the TSR of 2 has been presented in Figure 10. In Figure 10-a, the airfoil is completely in front of the flow and leads to the formation of the vortexes behind it. This increases the dissipations in the turbine. In Figures 10-b, since the airfoil is almost positioned in the direction of the flow, the low-pressure regions become weaker, and consequently the dissipation decreases.
a. The pressure distribution around the blade that is perpendicular to the flow direction.
b. The pressure distribution around the blade which is moving against the direction of the flow.

Figure 10. The pressure distribution around the airfoil.

4.2. Results of the 3D simulation

Considering the 2D simulation results, among the examined airfoils, the S1046 airfoil presented the best performance, thus, for a more exact evaluation, the 3D simulation results and their comparison with 2D results have been shown in Figure 11. Overall, it can be said that the 2D and the 3D results are very close, and the 2D results can be a considerably good estimation for the designing process. As was observed in the 2D results, the 3D results show that increasing the TSR raises the performance, however, the inclination of this rise in the 3D simulation mode is lower than it was in the 2D simulation mode. The reason is that in the 3D simulation mode, besides the dissipations behind the airfoil, due to flow transportation from high-pressure to low-pressure regions, and forming wing tip vortex as illustrated in Figure 13, more energy dissipations happen. These dissipations increase as the TSR rises, and that is the reason for increasing the difference between 2D and 3D results in higher TSRs. By comparing the 2D and 3D results, overall, it can be concluded that the 2D results can properly show the behaviour patterns of the airfoil, but for calculating the maximum coefficient of performance, the effects of the 3D flow should be considered. Figure 12 shows the velocity magnitude contours in TSR of 1. Similar to the 2D results that were presented in Figure 8, the presence of the turbine leads to velocity reduction in the downstream of the flow.

Figure 11. The comparison of the 2D and 3D results for the designed turbine with the S1046 airfoil.

Figure 12. The velocity contour and surface streamline in the 3D simulation of the S1046 turbine.
5. Conclusion

In the current study, five different airfoils, including NACA 63415, NACA 0018, AH93W215, FXLV152, and S1046 airfoils were numerically examined in different external wind speeds. The simulations were performed in an unsteady state in 2D and 3D simulation models and using the k-€o SST turbulence model. The simulation results show that by increasing the TSR, the coefficient of performance increases for all of the airfoils until it reaches a maximum value. After that, a further increase in the TSR decreases the coefficient of performance. The maximum performance coefficient value for each of the airfoils was different and this maximum value was obtained in a proper TSR that was specific for each of the airfoils. The maximum coefficient of performance for the S1046 airfoil was almost 40%, which in that TSR, was almost 10% higher than the next airfoil in terms of the highest performance coefficient. The 3D simulation results for the S1046 airfoil show that the 2D and 3D results are in good compatibility, thus the results of the 2D simulations can be used in the estimation of the performance and designing process to optimize the wind turbines.

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