2-D and 3-D CFD Investigation of NREL S826 Airfoil at Low Reynolds Numbers

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Abstract. In this study CFD investigation of flow over the NREL S826 airfoil is performed. NREL S826 airfoil was designed by the National Renewable Energy Laboratory (NREL), mainly to be the tip section of HAWTs of 10-15 meter diameters. However, it is used in the NTNU wind turbine rotor model and low Reynolds number flow characteristics become important in the validations with the test cases of this rotor model. The airfoil CFD simulations are carried out in 2-D and 3-D computational domains. The k-ω SST turbulence model with Langtry-Menter (γ-Reθ) transition prediction model for turbulence closure is used in the calculations. The Delayed DES is also performed in the stall region for comparisons. The results are compared with the available METUWIND experimental data, and are shown to be in fair agreement. It is observed that 3-D CFD analysis provides increased accuracy at increased computational cost.

1. Introduction
The S826 airfoil is designed by the National Renewable Energy Laboratory (NREL), mainly to be the tip section of HAWTs of 10-15 meter diameters. For such turbines, blade tip Reynolds number could reach around 2 - 2.5 million, and S826 airfoil is designed to have high C_{l,max} and also docile stall characteristics at the mentioned Reynolds number range [1-2]. Docile stall characteristics help damping the power and load fluctuations due to local intermittent stall along the blades.

The NREL S826 airfoil has been used in the blind test cases of Norwegian University of Science and Technology (NTNU) [3-4]. The tested wind turbine rotors use NREL S826 airfoil along the entire span of the blades. In the NTNU experiments, the tunnel wind speed is 10 m/s and the design tip speed ratio for both turbines is 6. These experimental conditions yield a blade tip Reynolds number of 103,600 [3]. For this reason, low Reynolds number flow characteristics of S826 airfoil are required. Accurate performance data is required for use in the 3-D CFD simulations with momentum source models and/or design codes based on the Blade Element Momentum (BEM) theory which needs to utilize airfoil aerodynamic coefficients database.

In the previous study of the authors, three different turbulence closure models; Realizable k-ε, k-ε-R, and Spalart-Allmaras were used to investigate the aerodynamic properties of S826 airfoil at Re=70,000, 100,000 and 145,000 by performing 2-D CFD simulations. Also, in the same study, 3-D Delayed Detached Eddy Simulation (Delayed DES) was performed to investigate the dynamic stall characteristics of S825 and S826 airfoils at Re=970,000 and compared with the experimental data. In 2-D analysis, two different grids were used; one with about 244K cells with y⁺ lower than 1 and the
other with about 47K cells with $y^+$ between 30 and 60 [5] and the results are compared. It was observed that S-A and k-ε turbulence models perform well with the wall function for the coarser grid.

In this study, 2-D and 3-D CFD simulations of flow around NREL S826 airfoil are performed at Re=100,000 and 145,000. The simulations are performed with commercial CFD++ software. For the 2-D case, RANS calculations are performed with k-ω SST turbulence model with Langtry-Menter ($\gamma$-Re$_\theta$) transition prediction model [6] and Realizable k-ε turbulence model. For the 3-D case, a blade of aspect ratio 5 is simulated using both RANS k-ω SST turbulence model and Delayed DES models. The numerical results are compared with the experimental data supplied by METUWIND [7]. The airfoil aerodynamic coefficients database obtained with the RANS simulations with k-ω SST turbulence model is also used in the 3-D wind turbine rotor CFD simulations with actuator disk model by Sert et al. [8].

2. Methodology

In this study, k-ω SST turbulence model with Langtry-Menter ($\gamma$-Re$_\theta$) transition prediction model [6] is used for both the 2-D and the 3-D CFD calculations in order to capture possible separation bubbles, and obtain more reliable numerical data. This model solves two additional correlation-based equations, which rely on local flow data in order to trigger laminar-to-turbulent transition by altering the turbulence production term (k) [6]. Realizable k-ε turbulence model is also used for 2-D case for comparison. In addition, 3-D unsteady Delayed Detached Eddy Simulation is performed for the angles of attack around the stall region of the airfoil at Re = 145,000.

The boundaries of the 2-D C-Grid is placed 100 chords away from the airfoil in all directions, and defined as Characteristic Based Inflow/Outflow (i.e. Pressure Far-Field) boundary type. The grid consists of 176,000 cells with 500 nodes around the airfoil and first node located 1e-6 units away from the airfoil, ensuring $y^+ < 1$, which is required for the baseline k-ω turbulence model. In the direction normal to the airfoil surface, the growth ratio of the cells is selected as 1.075. Figure 1 below shows the 2-D grid around the S826 airfoil.

![2-D C-grid around the S826 airfoil.](image1)

The 3-D grid is generated in order to represent the exact experimental setup used in METUWIND wind tunnel which has a 1x1x2 meter test section [7]. In the experimental setup, they used an S826 airfoil model with chord length of 0.2 meter and aspect ratio of 5. The most important difference between the 2-D and 3-D cases is the application method of the freestream velocity. In 2-D case, the angle of attack is set by applying x and y velocity components of the corresponding angle of attack. However, in 3-D case which aims to represent a wind tunnel, inlet velocity direction is fixed in only
x-direction. Therefore, the only way to set the angle of attack is rotating the airfoil itself in the domain. CFD++ software has the capability of handling overset grids, which eliminates re-meshing process for this case. Thus, two separate grids are generated as shown in Figure 2. In Figure 2 on the left, the test section of the wind tunnel, and on the right, the grid around the airfoil can be seen. Same node distribution as with the 2-D case is used around the airfoil, with clustering in the wake and at the far field walls. In Figure 3, the result of concatenation of two separate grids is shown. After combining the two separate grids, the total number of hexahedral cells becomes 11,434,420. This grid also ensures $y^+ < 1$ over the airfoil surface. In Figure 4, the views of the grids obtained by overset grid methodology for 0 degree and 12 degree angles of attack (AoA) are shown.

Figure 2. Wind tunnel test section (on the left) and the grid around the S826 airfoil (on the right).

Figure 3. Result of combining the two grids shown in Figure 2.

Figure 4. Final views of overset grids for 0° AoA (left) and 12° AoA (right).
3. Results
The simulations are performed for different angles of attack and the aerodynamic coefficients are calculated and presented at Re=100,000 and 145,000 to obtain the airfoil database. Moreover, the results and comparisons for Re=145,000 case are presented in detail. Table 1 shows the computational time required (wall time) for each method. As seen in Table 1, 3-D SST turbulence model is two orders of magnitude more time consuming than its 2-D counterpart, whereas Delayed DES is about 15 times more expensive compared to 3-D k-ω SST turbulence model used.

Table 1. Runtime per iteration/time step for turbulence models used.

| Turbulence Model          | Time / Iteration | Time / Δt |
|---------------------------|------------------|-----------|
| 2D SST Transition         | 0.22 sec         | -         |
| 3D SST Transition         | 25 sec           | -         |
| Delayed DES               | -                | 435 sec   |

Figures 5 and 6 show the lift and drag coefficients characteristics; C_l, C_d and C_l/C_d versus angle of attack, and C_l versus C_d for Re=100,000. Similarly, Figures 7 and 8 show the lift and drag coefficients characteristics; C_l, C_d and C_l/C_d versus angle of attack, and C_l versus C_d for Re=145,000. As expected, C_l is slightly lower and C_d is higher for Re=100,000 than the results of Re=145,000 case for the same angles of attack, due to the increased viscous effects. For both cases, it can be observed that the 3-D simulations with k-ω SST turbulence model offers better results than the 2-D simulations, especially after the stall, i.e., in the post-stall region. In terms of lift and drag coefficients, it can be observed there are differences between the experimental data and numerical results around stall region where the numerical estimations of C_l is over-predicting and C_d is under-predicting the experimental data. This may be due to both the experimental errors and numerical errors.

In the previous study of the authors [5], the dynamic stall characteristics of S825 airfoil was investigated using RANS and Delayed DES, and it was shown that Delayed DES offered very accurate results whereas RANS was not capable of capturing the wake accurately, hence the aerodynamic properties. However, in this study, the results suggest that Delayed DES model is not efficient for such analysis. Although Delayed DES seems to produce results similar to the 3-D k-ω SST turbulence model, the computational cost is 20-25 times higher. For this reason, Delayed DES model is not used for Re = 100,000 cases, and only the results for Re=145,000 are further presented in detail. Since 3-D k-ω SST turbulence model has been optimized for analyzing external flow over airfoils, reasonable results are obtained with this modelling.

For 0 degree angle of attack, the k-ω SST turbulence model with γ-Reθ transition prediction model is able to capture the formation of the separation bubble on both upper (~0.75 chord) and lower (~0.55 chord) surfaces of the airfoil for both 2-D and 3-D cases. This can be observed from the C_p plots (Figure 9) and the streamline plots (Figure 10). That formation of the separation bubble cannot be seen with the Realizable k-ε turbulence model. For 8 degree angle of attack (Figures 9 and 11), the separation and reattachment locations on the upper surface (~0.50 chord) are more confined in comparison to 0 degree angle of attack for the k-ω SST turbulence model. Similar to the 0 degree angle of attack, Realizable k-ε model fails to capture the separation bubble. Delayed DES model, which uses Spalart-Allmaras turbulence model at the regions close to the wall, was not be able to capture the separation on the upper surface as well, however it predicted a small region of separation at the trailing edge.

In the post-stall region at 12 degree angle of attack (Figure 9, 12, 13), the difference between 2-D and 3-D simulations with k-ω SST turbulence model becomes more pronounced. The leading edge separation is more severe for the 2-D simulation, whereas the separation region is more stretched in 3-D simulation. It can be considered that the higher accuracy in calculating the aerodynamic
coefficients (Figure 7, 8) by 3-D SST turbulence model with $\gamma$-Re$_\theta$ transition prediction model is due to the better prediction of leading edge separation.

Figure 5. Comparison of lift and drag coefficients, $C_l$ and $C_d$, versus angle of attack, for S826 airfoil at Re=100,000

Figure 6. Comparison of $C_l/C_d$ versus angle of attack and $C_l$ versus $C_d$ for S826 airfoil at Re=100,000
Figure 7. Comparison of lift and drag coefficients, $C_l$ and $C_d$ versus angle of attack, for S826 airfoil at $Re=145,000$.

Figure 8. Comparison of $C_l/C_d$ versus angle of attack and $C_l$ versus $C_d$ for S826 airfoil at $Re=145,000$. 
Figure 9. $C_p$ distribution over S826 airfoil at $Re = 145,000$, $AoA = 0, 8$ and 12 degree (top left, top right and bottom, respectively).
Figure 10. Streamlines over the S826 airfoil at Re=145,000, AoA=0 degree for different turbulence models (top left Realizable k-ε, top right 2-D k-ω SST transition, bottom 3-D k-ω SST transition).

Figure 11. Streamlines over the S826 airfoil at Re=145,000, AoA=8 degree for different turbulence models (top left Realizable k-ε, top right 2-D k-ω SST transition, bottom left 3-D k-ω SST transition and bottom right Delayed DES model).
Figure 12. Streamlines over the S826 airfoil at Re=145,000, AoA=12 degree for different turbulence models (top left Realizable k-ε, top right 2-D k-ω SST transition, bottom left 3-D k-ω SST transition and bottom right Delayed DES model).

Figure 13. Contour plots of U/U∞ at Re=145,000, AoA=12 degree for different turbulence models (top left Realizable k-ε, top right 2-D k-ω SST transition, bottom left 3-D k-ω SST transition and bottom right Delayed DES model).

4. Conclusions
2-D and 3-D CFD simulations of flow around NREL S826 airfoil are performed with different turbulence models at low Reynolds numbers. The simulation results are compared with the experimental data from METUWIND. The results show that 2-D SST turbulence model with with γ-Re0 transition prediction model gives fast results with satisfactory accuracy when compared to the other turbulence models used and to the available experimental data. Also, it is shown that the 3-D
The simulation of the actual wind tunnel setting offers very accurate results, better than 2-D analysis of the same Re number especially at high angles of attack, albeit at a higher computational cost. It is observed that increased accuracy in 3-D SST turbulence model computations is due to the better prediction of leading edge separation in the stall and post-stall regions. At the Re numbers of interest, in the pre-stall region, 2-D SST turbulence model would be the ideal candidate in calculating the aerodynamic coefficients. In the post-stall regions however, the 3-D simulations clearly has its advantages at increased computational cost. Contrary to the previous experience [5] in dynamic stall characterization using Delayed DES, in the present analysis Delayed DES does not seem to offer any further improvements over 3-D SST turbulence model, although it is computationally more demanding.

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