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A Comparative Study on the Flow over an Airfoil using Transitional Turbulence Models

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Abstract. This work addresses the simulation of the flow over NREL S826 airfoil under a relatively low Reynolds number ($Re = 1 \times 10^5$) using the CFD solvers OpenFoam and ANSYS Fluent. The flow is simulated using two different transition models, $\gamma - Re_\theta$ and $k - k_L - \omega$ model, and the results are examined against the $k - \omega$ SST model without transitional formulations. By comparing the simulations with the available experimental data, we find that the using the transitional model can effectively improve the flow prediction, especially the drag coefficient results, before the stall.

Keywords: Computational fluid dynamics, turbulence modelling

PACS: 47.27.em

INTRODUCTION

Despite the fact that most of the airfoils are designed for aircraft, e.g the well-known NACA airfoil series, National Renewable Energy Laboratory (NREL) has developed a family of airfoils especially for the variable-speed and variable-pitch, horizontal-axis wind turbine blade [1], including NREL S826 airfoil investigated in this study. The profile of S826 airfoil is shown in Figure 1.

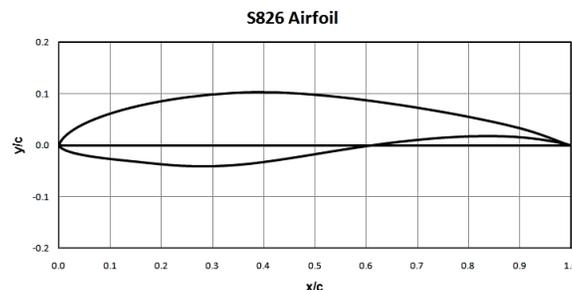


FIGURE 1. S826 airfoil profile

Several researches have been carried out on investigating the aerodynamic performance of NREL S826 airfoil using both experimental and numerical approaches. Sarlark et al. [2] measured the major aerodynamics quantities of S826 airfoil at $Re = 1 \times 10^5$ for a range of angles of attack (AoA) from -8 to 20 degree in the low speed wind tunnel at Fluid Mechanics Laboratory, DTU. The measurements of the lift and drag and pressure distribution are then used to validate the Large Eddy Simulation (LES) results performed in the in-house code EllipSys3D with the same setup. The comparison showed a satisfying agreement between the experiment and LES, despite a lift over-prediction in the large AoA. Cakmakioglu et al. [3] compared the results of 2D and 3D RANS simulation using different turbulence models and Detached Eddy Simulation (DES) in matching the experimental data of S826 airfoil's aerodynamics quantities. They reported that in the pre-stall region, the 2D $\gamma - Re_\theta$ transitional model is a preferable choice in terms of giving satisfying accuracy with less time cost.

In this report, a comparative study on the 2D simulation of the flow over NREL at $Re = 1 \times 10^5$ will be performed in ANSYS Fluent and the open-source CFD code OpenFOAM using two different transitional turbulence models: $\gamma - Re_\theta$ model and $k - k_l - \omega$ model, and the results will be compared with the $k - \omega$ SST model as well as DTU's wind tunnel experiment data [2].

SIMULATION SETUP

The scale of the 2D computational domain is shown in Figure 2(a). The half-width of the domain and the incoming distance from the velocity inlet to the airfoil are 15 times of the chord length ($15c$). The downstream distance from the airfoil to the outlet is $20c$.

The mesh for the computational domain is divided into the C-type structured mesh, shown in Figure 2(b), with the extra refinement on the leading and trailing edge of the airfoil. After a mesh independence check on the meshes from 350 to 500 nodes on the airfoil, the mesh with 400 nodes on the airfoil is selected. A total number 2.2×10^5 cells is used on the entire domain, with 200 nodes on the downstream direction and 400 nodes on the vertical direction. The near wall mesh is refined asymptotically to $y^+ = 1$ as required by the wall resolved turbulence models. The growth ratio of the nodes distance to the wall is 1.05.

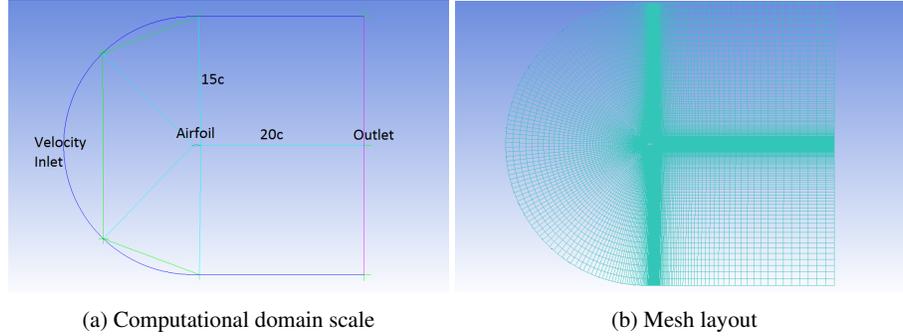


FIGURE 2. Computational domain and mesh

The boundary conditions of the turbulence quantities of the computational domain are defined based on the turbulence models used in the cases:

Velocity inlet/outlet. In $k - \omega$ SST model, the turbulence quantities k and ω are estimated by the mean velocity U , the turbulence intensity I and the viscosity ratio μ_t/μ [4]:

$$k = \frac{3}{2}(UI)^2; \quad \omega = \frac{\rho k}{\mu} \left(\frac{\mu_t}{\mu}\right)^{-1}$$

According to the wind tunnel set-up, the inlet turbulence intensity $I = 0.2\%$ and the viscosity ratio $\mu_t/\mu = 0.1$ in this external flow case. In $\gamma - Re_\theta$ model, the boundary conditions of k and ω are identical with $k - \omega$ SST model. The boundary conditions of the two extra quantities in $\gamma - Re_\theta$ model, γ and Re_θ , are specified as fixed value ($\gamma = 1$) and zero-gradient respectively. In $k - k_L - \omega$ model, the k_t is estimated in the same way as k , and the laminar energy k_L is set as a small value such as 1×10^{-8} .

Airfoil Wall. In $k - \omega$ SST model, k is set as fixed value 0 at the wall and a wall function for ω is used to get the asymptotic behaviour at wall:

$$\omega = 10 \frac{6(\mu)}{\beta_1(\Delta d_1)^2} \quad (1)$$

In $\gamma - Re_\theta$ model, the boundary condition for γ and Re_θ are defined as zero-gradient [5]. And in $k - k_L - \omega$ model, the boundary condition for ω is zero-gradient [6].

Other boundary conditions shared by all models for velocity and pressure are summarized in Table 1.

TABLE 1. Boundary condition of U and p

| | Velocity inlet | Airfoil Wall | Velocity outlet |
|---|----------------|---------------|-----------------|
| U | Fixed value | Fixed value | Fixed value |
| p | Zero gradient | Zero gradient | Fixed value |

RESULT

Based on the set-up discussed in the previous section, the simulations are performed at $Re = 1 \times 10^5$ with different attack angles from 0 to 14 degree.

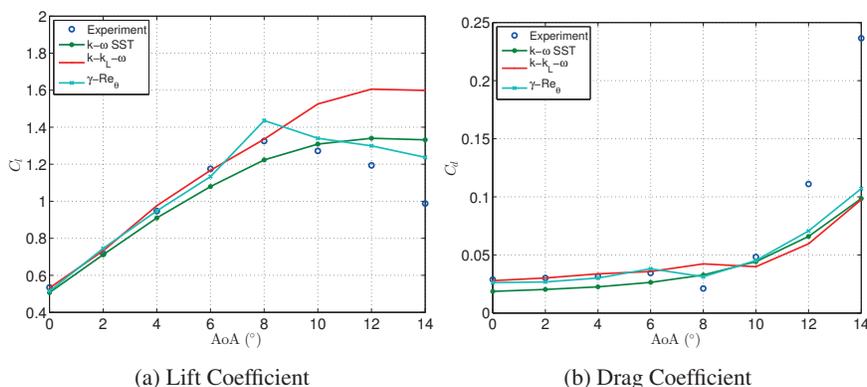


FIGURE 3. Lift and drag coefficients at $Re = 1 \times 10^5$ from experiments and different turbulence models

Figure 3 shows the results of the lift and drag coefficients of the airfoil from CFD simulation and experiment data. In C_l plot, we can see that the two transitional models, $\gamma-Re_\theta$ and $k-k_L-\omega$, give results that match the measurements quite well in the pre-stall range of AoA, both with a maximum relative error smaller than 4%. For $k-\omega$ SST model without transitional formulation, the results are still good at the small AoA, but start to underestimate the lift as AoA increases before the stall. In the post-stall range of AoA, $\gamma-Re_\theta$ model gives a correct stalling AoA at 8° while the result from other models show delay the stall from 4° to 8° , causing the deviations from the measurements in lift and drag coefficients in this range.

In C_d plot, we can see that both transitional models improve the problem of the significant drag underestimation ($> 30\%$) in the results of $k-\omega$ SST model in the pre-stall range, despite the fact that they still fail to agree with the measurement after the stall. At the stalling point, drop of the drag coefficient occurs in the experiment data and only $\gamma-Re_\theta$ model capture this phenomenon at this AoA.

Figure 4 shows the plots of pathlines for the cases of 0 AoA from three different turbulence models. We can see that the major difference between the results from two transitional models and $k-\omega$ SST model results is that transitional cases show the generation of the separation bubble at the upper surface near the tail and the concave part on the bottom surface of the airfoil. These locations are the turning points of the airfoil geometry, hence are sensitive to the flow separation. Furthermore, this difference also explains how the transitional models improve the problem of drag underestimation in $k-\omega$ SST cases: the present of the separation bubble thicken the boundary layer thickness, thus increase the total drag encountered by the airfoil in the flow [7].

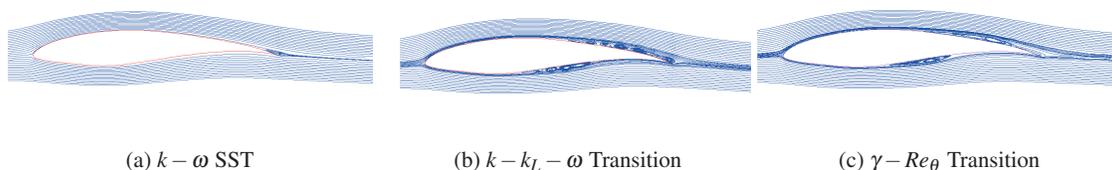


FIGURE 4. Pathlines around the airfoil at $AoA = 0^\circ$ using different turbulence models

Figure 5 shows the turbulence kinetic energy (TKE) contour for the cases of 0 AoA using different turbulence models. We can see that while $k-\omega$ SST model predicts that TKE production is mostly generated in the wake after the trailing edge of the airfoil, the results of the transitional models shows that the major TKE generation occurs in the location where the laminar separation bubbles are generated in Figure 4, indicating that the type of the transition processes in these cases is the separation-induced transition. In terms of magnitude, $\gamma-Re_\theta$ model generates the largest TKE while $k-\omega$ SST model shows the smallest TKE production.

Figure 6 shows the pressure coefficient (C_p) distribution along the airfoil surface for the 0 AoA cases (in reverse Y axis to match the airfoil geometry). We can observe the fluctuation of the C_p curve at the location where the laminar

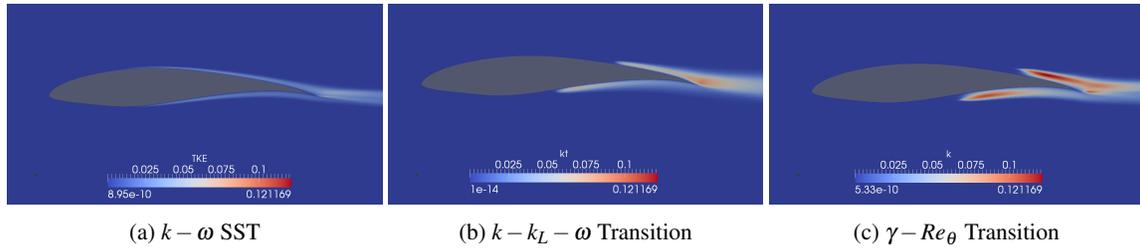


FIGURE 5. Contours around the airfoil at $\text{AoA} = 0^\circ$ using different turbulence models

separation bubbles (LSB) occur in the transitional model results. The location where the LSB start to occur in $\gamma - Re_\theta$ model result is $0.48 x/c$ (lower side) and $0.67 x/c$ (upper side). In $k - k_L - \omega$ model, the location is $0.48 x/c$ (lower side) and $0.65 x/c$ (upper side).

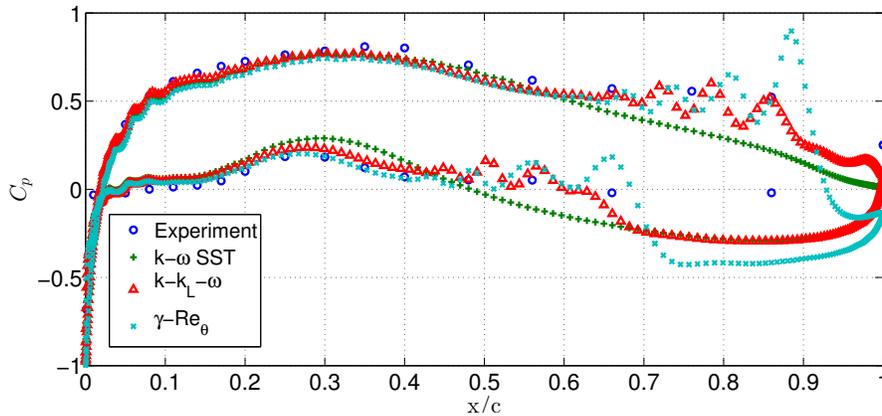


FIGURE 6. Pressure distributions on the airfoil at $\text{AoA} = 0^\circ$ using different turbulence models

CONCLUSION

According to the discussion of the NREL S826 simulation results in the previous sections, we find that using the transitional RANS model, both $k - k_L - \omega$ model and $\gamma - Re_\theta$ transitional model, improves the result of the lift and drag coefficient effectively before the stall, particularly the drag underestimation problem in the $k - \omega$ SST model. The explanation to this improvement is that the transitional model's correctly predict the critical physics feature in the transitional process such as the separation bubble generation and reattachment.

Comparing $\gamma - Re_\theta$ model and $k - k_L - \omega$ model, we find that $k - k_L - \omega$ model gives a better result of lift and drag coefficients before the stall, but it over-predict the stalling angle and result in a significant drag overestimation in the post-stall region while $\gamma - Re_\theta$ model gives the correct stalling AoA and the trend of decreasing lift after the stall.

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