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INVESTIGATION OF AERODYNAMIC PERFORMANCE OF THE NACA 0018 AIRFOIL AT LOW REYNOLDS NUMBERS: A COMPARATIVE STUDY OF 2-D AND 3-D MODELS USING TRANSITION SST AND K- ω SST APPROACHES

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Abstract

This paper presents an in-depth analysis of the aerodynamic performance of the NACA 0018 airfoil at low Reynolds numbers, focusing on the behaviour of laminar separation bubbles and the predictive capabilities of various turbulence models. Conducted at a Reynolds number of 160,000 and for angles of attack of 4° and 8°, this study employs both 2-D and 3-D models using the Transition SST and k-ω SST approaches to capture the nuanced aerodynamic behaviour of the airfoil in wind energy applications. Comparative simulations using the 2-D γ-Re_θ transition model with calibrated transition onset parameters, alongside the 3-D Scale Adaptive Simulation (SAS) methodology, allow for an assessment of how model dimensionality and transition calibration influence the accuracy of C_p distributions and laminar bubble prediction. Results are validated against experimental data to evaluate model precision, particularly in regions associated with pressure recovery. The study confirms that increasing the angle of attack shifts the laminar separation point closer to the leading edge, with the 3-D SAS approach aligning closely with the 2-D URANS results for pressure distribution. However, the k-ω SST model, which lacks transitional prediction capabilities, significantly deviates from experimental observations, underscoring the importance of transition-aware models for accurate low Reynolds number simulations. This work offers valuable insights into turbulence model selection for low-turbulence environments, particularly relevant to wind turbine design and optimization, where sustained efficiency and model fidelity are crucial for performance prediction and reliability.

Keywords: airfoil, laminar separation bubble, Transition SST, URANS

1. Introduction

In recent years, the famous series of four-digit NACA airfoil profiles has gained considerable interest, particularly in the context of wind energy [1-4]. Although these profiles were not originally designed for operation at low or very high Reynolds numbers, they are now being intensively studied within these ranges [5,6]. In both cases, they are typically not optimal solutions; however, they continue to be utilized, especially in vertical-axis wind turbines, for two main reasons. First, these profiles are among the most extensively studied, both experimentally and numerically, and serve as valuable references for validation and as a starting point for optimizing airfoils for specific conditions. Second, a significant amount of research, especially on the aerodynamics of vertical-axis wind turbines, has been conducted using these profiles [7].

Experimental studies show that these profiles, particularly the NACA 0018 profile considered here, perform poorly in low Reynolds number flows, and calculating their characteristics is challenging for modern analytical tools such as the Transition SST turbulence model [8]. Our previous experiences with turbulence modelling using this tool have shown significant difficulties in accurately determining the geometry of the laminar separation bubble, especially within the angle of attack range below the critical angle [1].

Our research presented in this paper concerns the characteristics of the NACA 0018 profile at a Reynolds number of 160,000. The necessity of studying this profile at such a low Reynolds number arises from the flow conditions encountered in wind turbine studies conducted in wind tunnels [9]. Reynolds numbers based on the blade's chord often reach values below 200,000 and in some cases, even as low as 20,000–30,000. Such studies are essential for subsequent upscaling and for validating numerical methods [6].

At such low Reynolds numbers, the lift characteristic is usually nonlinear due to the presence of the laminar separation bubble. The Transition SST turbulence model is a so-called general-purpose model based on correlations derived from flat plate experimental results [10]. It can be calibrated by adjusting constants related to specific physical phenomena in the wall boundary layer associated with the laminar-turbulent transition. One of the aims of this work is to examine the impact of the s_1 constant (Cs1), which affects the point of laminar separation. As Ruiz and D'Ambrosio [11] demonstrated with the SD7003 airfoil at Re=60,000, changing this parameter can significantly influence the drag coefficient characteristics by shifting the position of the laminar separation.

Additionally, traditional two-equation turbulence models, such as the k-ω SST model, generate an unrealistic lift curve that is linear up to the critical angle of attack, as bubble-related effects are entirely omitted [8]. This is due to the model's treatment of the entire boundary layer as turbulent, thus increasing drag. In contrast, the Transition SST model provides a more accurate representation by accounting for laminar regions.

An additional aim of this paper is to determine whether modelling the flow around the airfoil in three dimensions significantly alters the laminar bubble characteristics. To the best of our knowledge, the results of such a test have not yet been published. Within the angle range below the critical angle of attack, two regions exist: one below an angle of attack of 6.5°, and the other above. In the first range, laminar bubbles appear on both sides of the airfoil, while in the second, they only occur on the suction side. Therefore, the results presented in this study were compared for two angles of attack: 4° and 8°.

2. Methodology

2.1 URANS Model Description

The numerical model of the virtual wind tunnel, developed in both 2-D and 3-D configurations, was based on the experimental setup. All geometric dimensions of the working section in the actual wind tunnel were carefully preserved, including the tunnel width and the distance from the inlet to the airfoil mounting point. The simulations were conducted for two angles of attack, 4° and 8°. The 4° angle represents a region where laminar separation bubbles may form on both the suction and pressure sides of the airfoil. For an angle of attack of 8°, experimental studies indicate the presence of laminar separation bubbles only on the suction side [12].

To ensure consistent mesh topology for both angles of attack, a circular domain with a diameter of 3 times the chord len gth was defined around the airfoil (Fig. 1). This approach facilitated accurate comparison and alignment of numerical and experimental data across the chosen angles.

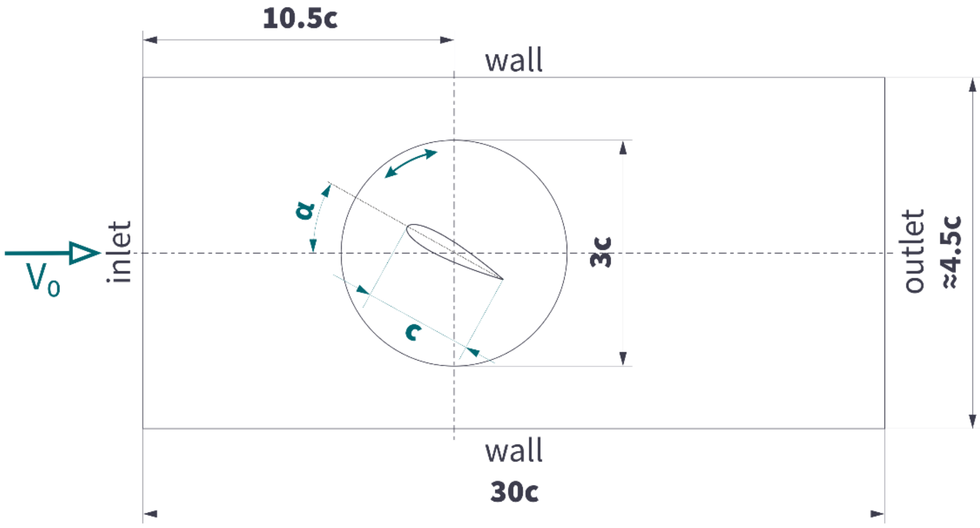

Figure 1 – Schematic of the computational domain for the virtual wind tunnel

In this study, the Unsteady Reynolds-Averaged Navier-Stokes (URANS) model was employed to analyze the flow around a NACA 0018 airfoil at low Reynolds numbers. The analysis was conducted at a Reynolds number of Re=160,000, which corresponds to a freestream velocity V_0=11,7m/s and and a chord length c=0,2m. The air properties were defined with a density ρ=1,225kg/m^3 and a dynamic viscosity μ=1,7894×10^{-5}kg/(ms).

The URANS simulations were carried out with a time step Δt=10^{-4}s to accurately capture unsteady flow phenomena, with a total of 50,000 time steps for adequate temporal resolution. To replicate realistic conditions, an inlet turbulence intensity TI_{inlet}=0.3% was set, along with an inlet turbulence length scale l_t=0,02m. These values were chosen to approximate the low-turbulence environments typically encountered in wind tunnel testing for aerodynamic profiles like the NACA 0018.

The NACA 0018 airfoil, known for its symmetrical shape and extensive use in wind turbine studies, provided a well-documented profile suitable for examining the effects of low Reynolds numbers on laminar separation and the performance of turbulence models, particularly the Transition SST model applied in this URANS framework. The model setup in this study aimed to capture both the aerodynamic forces and the onset of laminar separation bubbles at specific angles of attack, contributing valuable insights for validating turbulence models under these conditions.

The 2-D and 3-D model meshes, as shown in Figure 2, were designed based on our prior experience with simulating the NACA 0018 airfoil at similar Reynolds numbers. For the 2-D model, both edges of the airfoil were divided into 800 equal segments. Around the airfoil edges, a structured mesh was applied, with the first layer having a thickness of 1.29E-05 to satisfy the wall y+ < 1 condition. This structured mesh consists of 40 layers with a growth rate of 1.1.

In the 3-D model, the spanwise direction of the wing was divided into 40 uniform sections, with the cross-sectional cell distribution matching that of the 2-D mesh. Boundary conditions were set as follows: velocity inlet at the domain inlet, pressure outlet at the domain outlet, and wall (no-slip) on the airfoil surfaces. To simplify the model and avoid calculating the boundary layer on the tunnel walls, slip wall boundary conditions were applied to the side walls of the computational domain.

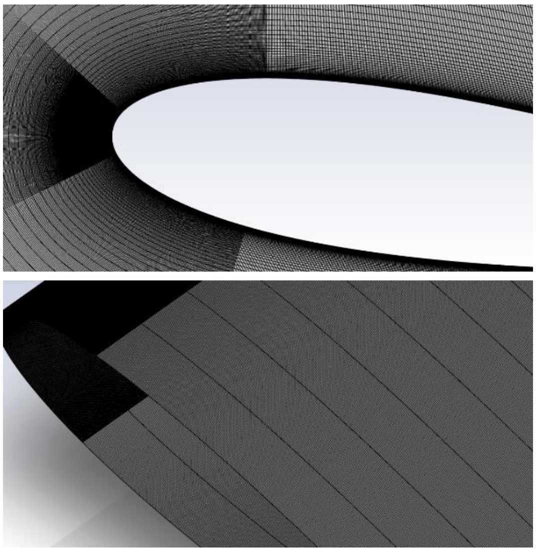

Figure 2 – Mesh around the NACA 0018 airfoil. The top view shows the structured mesh near the airfoil surface, focusing on the boundary layer, while the bottom view highlights the uniform spanwise cell distribution for 3-D simulations.

2.2 Turbulence Modeling Approaches for Transition Prediction

In this paper, the primary approach utilized is the Transition SST (Shear Stress Transport) turbulence model, which is specifically designed to handle the transition from laminar to turbulent flow. This model's ability to account for intermittency and transition onset Reynolds numbers makes it particularly suitable for applications involving low Reynolds number flows, such as those around airfoils in vertical-axis wind turbines (VAWTs). Additionally, the Transition SST model is compared with the algebraic turbulence model and the two-dimensional $k-\omega$ SST model. These comparisons provide insights into the relative performance of each model in accurately predicting transition phenomena and capturing the effects of boundary layer development, turbulence intensity, and laminar separation bubbles.

The Transition SST model is a widely-used turbulence model in computational fluid dynamics (CFD) that addresses the transition from laminar to turbulent flow, which is particularly relevant for airfoils at low Reynolds numbers, such as the NACA 0018. This model, built upon the traditional SST $k-\omega$ turbulence model, includes additional equations to predict laminar-turbulent transition, focusing on both the onset and length of transition zones. Unlike conventional models, which often assume fully turbulent flow, the Transition SST model incorporates intermittency and transition onset Reynolds numbers as variables, allowing for a more accurate representation of boundary layer development and laminar separation bubbles. This model employs local flow properties, allowing it to adapt to changes in turbulence intensity and Reynolds number within the flow, which is especially useful for modeling the unstable flow regimes typical of low-turbulence wind tunnels and the environments VAWTs encounter [1].

The algebraic turbulence model presented in this study focuses on simulating the transition from laminar to turbulent flow in boundary layers under various conditions, including bypass, separation-induced, and wake-induced transitions. This model employs the concept of intermittency, where intermittency (denoted as γ) represents the fraction of time during which the flow is turbulent at a given point. The model modifies production terms in the $k-\omega$ turbulence framework by Wilcox, incorporating mechanisms for handling high-frequency disturbances in laminar flows and providing a breakdown pathway for laminar shear layers under free-stream turbulence. Calibration and validation were performed using flat plate flows and turbomachinery cascades, showing effective performance across different turbulence levels and flow regime [13].

The Scale-Adaptive Simulation (SAS) model is an advanced turbulence model used to capture unsteady turbulent structures by dynamically adjusting the turbulence length scale to the resolved flow scales. Unlike traditional URANS models, which can only simulate large-scale unsteadiness in unstable flows, the SAS model adapts to smaller turbulent eddies, providing results comparable to Large Eddy Simulation (LES) while being less computationally intensive. This is achieved by introducing a source term in the turbulence frequency equation, which allows the model to respond to flow instabilities more effectively [14].

In this study, the URANS approach was applied to determine the aerodynamic characteristics of a 2-D airfoil profile. The primary objective was to evaluate how adjustments to the s_1 constant in the Transition SST model could enhance prediction accuracy. For the 3-D model, the SAS approach was additionally employed to achieve a more precise velocity field behind the airfoil.

3. Results

3.1 Pressure Distributions on the Airfoil

The results of static pressure coefficients from 3-D SAS k-ω SST and γ-Re_θ simulations, as well as from 2-D γ-Re_θ simulations with different transition onset values (s_1=2.0 and s_1=3.0), are presented in Figure 3. Experimental data from [2] are included for validation, highlighting differences in Cp predictions among the models, especially in the pressure recovery region. This figure clearly demonstrates the expected trend that an increase in angle of attack shifts the laminar separation point of the boundary layer toward the leading edge. The 3-D SAS approach shows very similar pressure distribution results to the 2-D URANS model. As anticipated, the predictions from the two-equation k-ω SST model deviate the most from the experimental data.

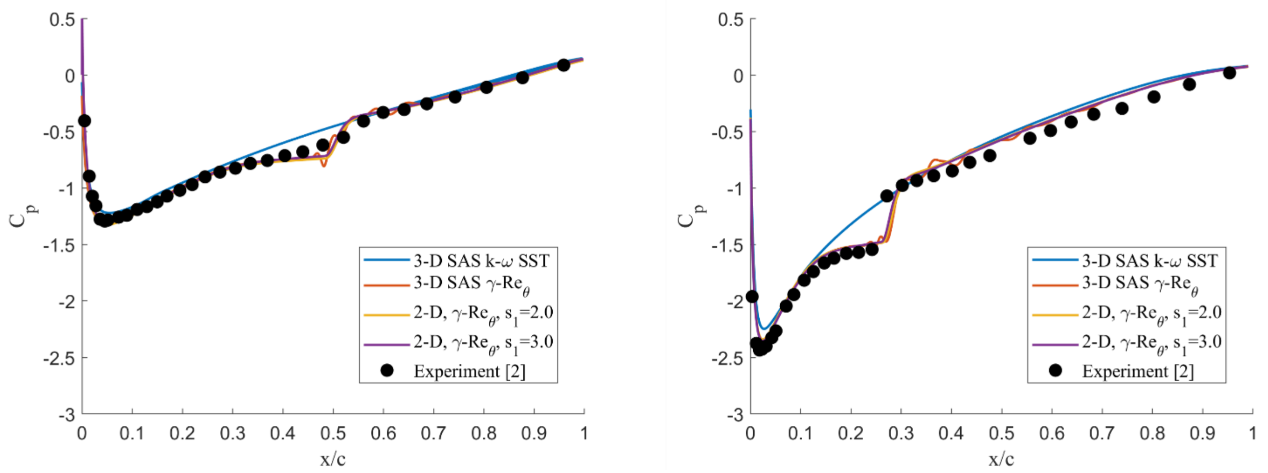

Figure 3 – Pressure coefficient distributions Cp along the NACA 0018 airfoil surface for angles of attack AoA=4deg (left) and AoA=8deg (right).

3.2 Analysis of Laminar Separation Bubble Geometry Using Transition SST Model

Figure 4 shows the geometry of the laminar separation bubble calculated using a 2-D CFD approach with the Transition SST turbulence model. The locations of the separation, transition, and reattachment points were determined based on the skin friction coefficient (C_f) distribution in the final computed time step, following the method outlined in studies [8] and [15]. The separation and reattachment points of the laminar boundary layer are identified at the two extreme points of the C_f function. The laminar-turbulent transition location was found between the separation and reattachment points, specifically at the point where the C_f curve shows a sharp rise.

The position of the separation location can be adjusted by tuning the constant s1, which accounts for the influence of Kelvin-Helmholtz instabilities on the flow within a detached boundary layer exposed to low turbulence levels outside the layer. The default value of this constant is set to 2. Figure 4 illustrates the dependency of the s_1 constant on position relative to the airfoil chord. An increase in s_1 generally causes a delay in the separation location on both the suction and pressure sides, except for the case at AoA=8deg on the pressure side, where an inverse trend is observed, albeit with minor differences.

Currently, we lack experimental data to validate the accuracy of the s_1(x/c) distribution obtained in this study. More precise experimental studies of pressure distributions on the pressure side are needed. Additionally, it is notable that reattachment on the pressure side is absent, and for AoA=8deg, the Transition SST model does not detect a transition location either. Comparison with experimental results suggests that as the angle of attack increases, the required s_1 value also needs to be higher to improve the prediction accuracy.

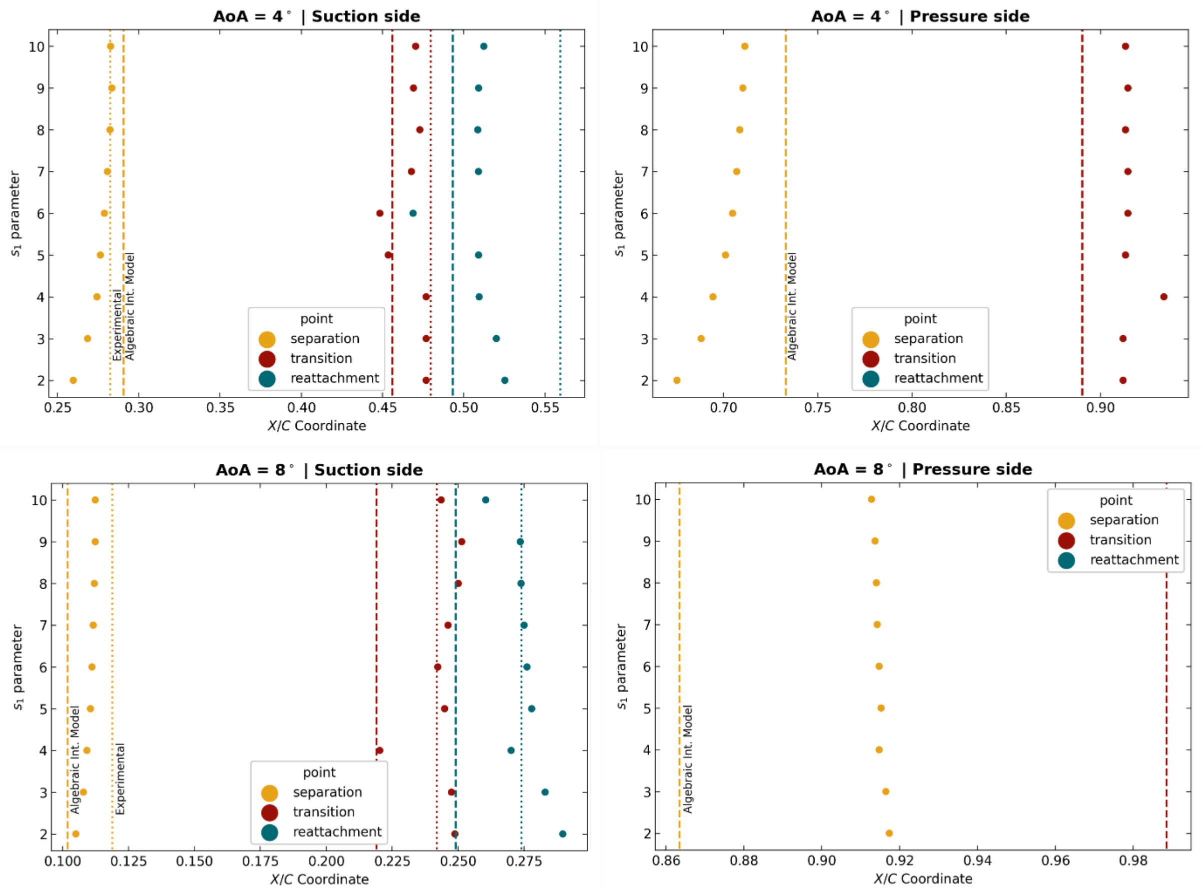

Figure 4 – Distributions of the s1 parameter as a function of the x/c coordinate for both the suction and pressure sides of the airfoil at angles of attack (AoA) of 4° and 8°.

3.3 Turbulence Modeling Approaches for Transition Prediction

Figure 5 presents normalized iso-surfaces of the Q-criterion, colored by velocity magnitude, to illustrate the vortex structures behind the airfoils at an angle of attack (AoA) of 8°, obtained using the Transition SST and k-ω SST models. The Transition SST model reveals prominent, irregular vortex structures in the wake, suggesting a more detailed capture of turbulent flow dynamics. In contrast, the k-ω SST model, even with the application of the SAS model, does not display large vortex structures, indicating a smoother, more streamlined wake pattern. This difference implies that the k-ω SST model could serve as a suitable surrogate for simulating "dirty wing" flow conditions, where large-scale vortex dynamics may be less critical. The velocity magnitude color scale further aids in distinguishing flow speeds within these vortex structures, offering insights into the intensity and distribution of turbulent regions around the airfoils.

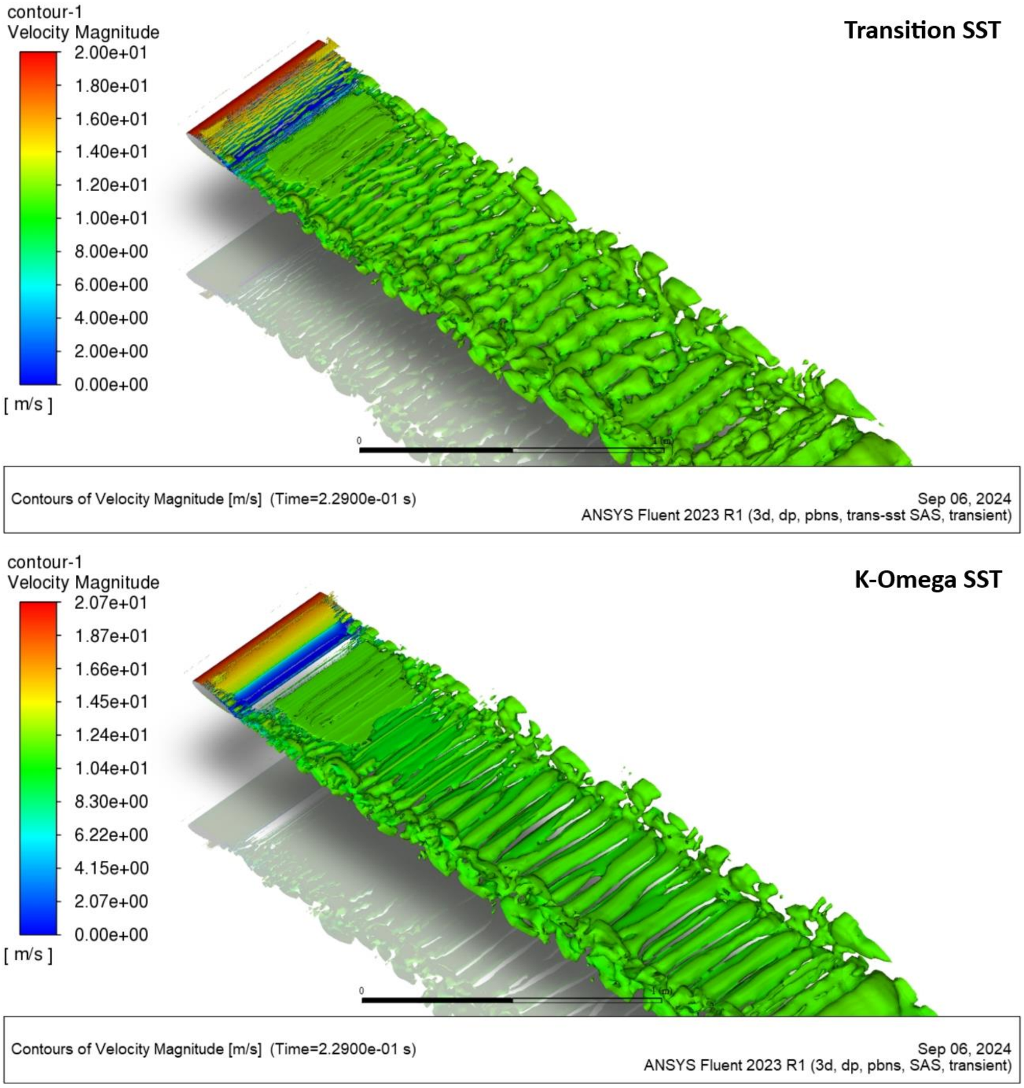

Figure 5 – Comparison of wake structures behind an object simulated using two turbulence models: Transition SST (top) and K-Omega SST (bottom).

4. Conclusions

The flow around a NACA0018 airfoil is complex due to the physical phenomena occurring in the boundary layer, and its accurate simulation requires advanced numerical tools. For a more precise prediction of the geometry of laminar-turbulent bubbles, the original formulation of the Transition SST approach requires calibration. This study also investigates whether the use of a 3-D model combined with the advanced Scale Adaptive Simulation (SAS) technique can improve the results generated by a 2-D model.

The comparison of static pressure coefficient predictions from 3-D SAS k-ω SST and γ-Re_θ simulations, along with 2-D γ-Re_θ models at different transition onset values, reveals distinct model behaviors. As angle of attack increases, the laminar separation point of the boundary layer moves closer to the leading edge, a trend consistent across simulations. The 3-D SAS model shows good alignment with the 2-D URANS approach, while the k-ω SST model demonstrates the greatest deviation from experimental trends.

The findings indicate that the geometry of the laminar separation bubble and the locations of separation, transition, and reattachment points can be effectively determined using a 2-D CFD approach with the Transition SST turbulence model, based on skin friction coefficient distribution. The study highlights the influence of the s_1 constant on the separation position along the airfoil chord, suggesting that tuning this parameter can adjust separation to improve prediction accuracy.

However, the lack of experimental data limits validation. Further experimental research, particularly on the pressure side at higher angles of attack, is recommended to refine the model and improve the predictive accuracy of laminar-to-turbulent transition locations.

The use of a 3-D model combined with the uncalibrated Transition SST turbulence model does not improve the accuracy of the laminar transition location compared to the 2-D model.

The results indicate that while the Transition SST model captures detailed and complex vortex structures in the wake, the k-ω SST model provides a smoother representation, even when using the SAS approach. This suggests that the k-ω SST model could be effectively utilized as a surrogate for simulating conditions with less pronounced vortex dynamics, such as those found in "dirty wing" flows, where large-scale turbulence structures are less critical.

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For any further question, please be free to contact authors of this work via email address: jan.michna@pw.edu.pl.

6. Copyright Statement

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