Abstract

The purpose of this work is to apply the $\gamma$-Re$\theta$ turbulence model, which is one of the numerical methods of shear stress transport (SST) applicable to transient flow, to examine if it shows the expected laminar separation cells or bubbles. This condition is key in the way to guarantee that the numerical modeling of lift and drag forces in aerodynamic profiles is more faithful to corresponding experimental data. For this, several two-dimensional simulations implemented with OpenFOAM, a well-known Finite Volume Method (FVM) package, were carried out for a Reynolds number range between $1 \times 10^4$ and $5 \times 10^5$, with the airfoils NACA0012, SG6043 and S826, in which the laminar separation bubbles usually form. Numerical results of lift and drag coefficients show correct prediction of experimental results and error is reduced by 3% when compared to other simulations. In particular, adequate performance of the model is observed for regions close to or greater than the angle of attack for which the aerodynamic profile stalls. On the other hand, the geometric footprint of the flow simulated with this $\gamma$-Re$\theta$ transition SST model shows great improvement compared to previous studies regarding the formation of laminar separation bubbles, which in turn means better performance when calculating lift and drag coefficients. It is also concluded that laminar separation occurs in the three studied airfoils, being symmetric or asymmetric profiles.

Key words: Airfoil performance; Turbulence model; Transitional flow; Finite Volume Method; Laminar separation bubble; Reynolds number; Intermittency.

Resumen

El objetivo en este trabajo es comprobar si el uso del modelo de turbulencia $\gamma$-Re$\theta$, que es parte de la familia de métodos numéricos de transporte de esfuerzo cortante (SST) aplicable a flujo transitorio, muestra las burbujas de separación laminar. Esta condición es clave en la ruta a garantizar que el modelado numérico de coeficientes de sustentación y arrastre en perfiles aerodinámicos sean más fieles a datos experimentales correspondientes. Para ello se llevaron a cabo varias simulaciones bidimensionales del flujo alrededor de los perfiles S826, SG6043 y NACA0012, implementadas en el paquete de método de volúmenes finitos OpenFOAM, en un ámbito de número de Reynolds entre $1 \times 10^4$ y $5 \times 10^5$, en el que es esperable la formación de burbujas de separación laminar. Los resultados numéricos de coeficientes de sustentación y arrastre, muestran una correcta predicción de los resultados experimentales y se reduce en un 3% el error ponderado promedio respecto a simulaciones de referencia. En particular, se observa un adecuado desempeño del modelo para regiones cercanas o superiores al ángulo de ataque para el cual el perfil aerodinámico entra en condición de pérdida aerodinámica. Por otra parte, la huella geométrica del flujo simulado con este modelo SST de transición $\gamma$-Re$\theta$, muestra una notable mejora respecto a estudios previos en cuanto a la formación de las burbujas de separación laminar, lo que se asocia con su superioridad en el cálculo de los coeficientes de sustentación y arrastre. Se concluye también que la separación laminar ocurre en los tres perfiles estudiados, siendo algunos simétricos y otros asimétricos.

Palabras claves: Desempeño aerodinámico; Modelo de turbulencia; Flujo en transición; Método de volumen finito; Burbuja de separación laminar; Número de Reynolds, Intermitencia.
Introduction

The Navier Stokes equations are the equations that describe the motion of a macroscopic viscous fluid. They are widely known and their development for certain types of flow is conventionally proposed in basic books on fluid mechanics [1]. One of their most challenging features is that, in general, they do not have an analytical solution, so a numerical approximation is key to their application in cases of particular interest. However, the direct numerical solution of these equations for general flow cases has an impractical computational cost, so multiple approximations are applied to solve them indirectly. A frequent technique is to use a turbulence model, such as the Reynolds Averaged Navier Stokes (RANS) [2], which simplifies the equations, but adds additional terms without adding additional equations. This situation, known as the turbulence lock problem [3], requires applying some particular formulation to the case to obtain as many equations as unknowns. For example, for the aerodynamic profiles of small-scale wind turbine blades, the k-ω SST (Shear Stress Transport) [4] and k-ε RNG (Renormalization Group) [5] models have been used. In particular, the k-ω SST model is suitable for high Reynolds numbers, which is a condition in which no separation occurs, as it is far from the transition region. Accordingly, [6] these models do not give adequate results in turbulent cases, as they do not correctly calculate the boundary layer separation point. For the case of Reynolds numbers (Re) below $5 \times 10^5$, the flow over the upper face of the blades is mainly laminar and the formation of laminar separation bubbles occurs, resulting in a loss of aerodynamic performance, in the particular case of small scale wind turbines [7]. It is relevant to clarify that in any case it is a single phase flow, the separation bubbles are regions of the flow where the boundary layer is detached and flow recirculation occurs, but no distinct phase is generated in that region [8]. These bubbles are dependent on the Reynolds number, the airfoil curve and the pressure distribution; for Re = $1 \times 10^5$ the bubble is longer and affects the flow drastically [9].

In the case of real operating conditions of wind turbines, turbulence in the flow can favour the detachment of the boundary layer and therefore be an element that generates laminar separation bubbles. The effect of turbulence on the efficiency of wind turbines is conventionally proposed in basic books on fluid mechanics [1]. One of their most challenging features is that, in general, they do not have an analytical solution, so a numerical approximation is key to their application in cases of particular interest. However, the direct numerical solution of these equations for general flow cases has an impractical computational cost, so multiple approximations are applied to solve them indirectly. A frequent technique is to use a turbulence model, such as the Reynolds Averaged Navier Stokes (RANS) [2], which simplifies the equations, but adds additional terms without adding additional equations. This situation, known as the turbulence lock problem [3], requires applying some particular formulation to the case to obtain as many equations as unknowns. For example, for the aerodynamic profiles of small-scale wind turbine blades, the k-ω SST (Shear Stress Transport) [4] and k-ε RNG (Renormalization Group) [5] models have been used. In particular, the k-ω SST model is suitable for high Reynolds numbers, which is a condition in which no separation occurs, as it is far from the transition region. Accordingly, [6] these models do not give adequate results in turbulent cases, as they do not correctly calculate the boundary layer separation point. For the case of Reynolds numbers (Re) below $5 \times 10^5$, the flow over the upper face of the blades is mainly laminar and the formation of laminar separation bubbles occurs, resulting in a loss of aerodynamic performance, in the particular case of small scale wind turbines [7]. It is relevant to clarify that in any case it is a single phase flow, the separation bubbles are regions of the flow where the boundary layer is detached and flow recirculation occurs, but no distinct phase is generated in that region [8]. These bubbles are dependent on the Reynolds number, the airfoil curve and the pressure distribution; for Re = $1 \times 10^5$ the bubble is longer and affects the flow drastically [9].

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According to [9], [15] and [16] the SST $\gamma$-Re$_\theta$ transition model reproduces the behaviour of the flow under the conditions where laminar separation bubbles are generated. In the case of [8] an analysis is performed for Re = $10^5$ with a transition model, studying airfoils having irregularities at the leading edge. It is found that the irregularities affect the formation of the laminar separation bubbles, but have a negligible effect on the lift force.

In a study with another fluid, water in this case, the $\gamma$-Re$_\theta$ transition model is also used to simulate the transition from laminar to turbulent flow, under conditions of Re = $7 \times 10^5$, over the blades of a propeller. This research concludes that the transition model accurately reproduces the experimental results, in particular the position and shape of the boundary layer, and thus of the laminar separation bubble [17].

The $\gamma$-Re$_\theta$ model has even been tested to simulate the flow of airfoils with high Reynolds numbers, between $3 \times 10^6$ and $6 \times 10^6$, where it has been shown that the applicability under these conditions depends on the critical angle of attack of the airfoil and that the model predicts with a high deviation the static pressure values in the areas precisely where the transition from laminar to turbulent occurs [18].

Other approaches to determine the points where the transition between laminar and turbulent flow occurs can also be found in the literature, such as the e$^N$ method presented in [19].

The aim of this work is to apply the transition SST model $\gamma$-Re$_\theta$, to the modelling of a flow around three airfoils, namely NACA0012, SG6034 and S826, at conditions of $1 \times 10^4 < \text{Re} < 5 \times 10^5$ where is laminar separation bubbles usually form. It is intended to observe the laminar separation bubble in the simulation, with the hypothesis that, if the model shows it, then the drag and lift coefficient results will have adequate agreement with the experimental results available in the literature.

Materials and methods

Mathematical model

In this work, the transition $\gamma$-Re$_\theta$ SST model described in [15] and [20] will be used, which has four transport equations and is based on the k-ω SST model. The first transport equation is for $k$ which is the turbulent kinetic energy.

$$\frac{\partial k}{\partial t} + \nabla \cdot (\rho U k) = \nabla \cdot \left( \mu + \frac{\mu_t}{\sigma_k} \right) \nabla k + \gamma P_k - D_k \frac{\partial (\gamma \cdot k)}{\partial (\gamma \cdot k)}$$

Where $\rho$ is the density, $U$ is the fluid velocity, $\mu$ is the dynamic viscosity, $\mu_t$ is the dynamic turbulent viscosity, $\sigma_k$ is a constant, $P_k$ is the turbulent kinetic energy production and $D_k$ is the turbulent kinetic energy dissipation. The value of the constants and the definition of each term can be found in [15].

In the turbulent kinetic energy transport equation, the $P_k$
Density $\rho$ 1.18 kg/m³
Turbulence intensity IT 0.2 %
Angle of Attack AoA $[0 – 14]$ °
Density $r$ 1.18 kg/m³
Chord $c$ 0.1 m
Kinematic viscosity $\mu$ $1.1516 \times 10^{-5}$ m²/s

Within the computational domain the airfoil of interest is placed, in this case three airfoils are studied, namely, the S826 which is also used in [16] and it is with respect to which the results obtained are compared; then the airfoils SG6043 and NACA0012, in which it is known that laminar separation occurs according to [17]. In the case of the three profiles, the no-slip condition is imposed on the entire contour. Subsequently, a triangular meshing is performed in the computational domain and refined in a stepwise manner by manipulating the element size factor, in order to ensure that the simulation is mesh-independent. This is illustrated in Figure 1 for the S826 airfoil, with an angle of attack of 8°; where it was found that from 10⁶ elements the response variable, the lift coefficient in this case, varies by less than 0.3 % in a sustained manner, when comparing the actual value with that obtained by increasing the number of elements by 10² times. We then proceeded to work with a 10⁶-element mesh for the rest of the simulations.
It is important to highlight that in Open FOAM the pre-existing libraries have been used with the SST $\gamma$-$Re_\theta$ transition model, in addition, from the same program it is possible to obtain the results of the lift and drag coefficients for each simulation.

Results and discussion

Lift and drag coefficients for profile S826

The results of the simulation performed in this work are compared with those available in the literature in Lin and Sarlak [16], where the S826 airfoil for Re = $1 \times 10^5$ is simulated with OpenFOAM and tested experimentally at DTU (Technical University of Denmark). The specific characteristics of the experimental values used in the comparison correspond to a chord length of 0.1 m; a blade length of 0.5 m; a wind speed of 15 m/s, a sampling frequency of 125 Hz and a sampling time of 10 s for each angle of attack. Figure 2 presents the results for the lift coefficient while Figure 3 shows the results for the drag coefficient. In these comparative curves only the results obtained with the $\gamma$-$Re_\theta$ transition SST model are shown, as it is the focus of interest of this research. In addition, experimental results are presented for validation purposes. However, simulations with other turbulence models have been performed in [16], which are beyond the scope of this research.

It can be seen in Figure 2 how both simulations have a consistent behaviour to the experimental data, especially at low angles of attack, below 6°. A feature of the SST transition $\gamma$-$Re_\theta$ model is that the angle of attack at which the aerodynamic stall occurs is correctly predicted. Particularly for the 12° angle of attack, both the reference simulation of [16] and the present one tend to overestimate the lift coefficient, but in the simulation presented in this research, using the SST transition $\gamma$-$Re_\theta$ model implemented in OpenFOAM, the overestimation is smaller and the results are closer to the experimental values.

Laminar separation bubbles in profiles SG6043 and NACA0012

In order to visualise the effect of different turbulence models in terms of capturing laminar separation bubbles in the flow, the result for the velocity field around an SG6043 profile, of special interest for small-scale wind turbines, is presented below [21]. Figure 4 shows the results of the k-$\omega$ SST model and Figure 5 the results of the $\gamma$-$Re_\theta$ transition SST model. In both cases with Re = $10^5$ (to broaden the range of Reynolds numbers under investigation) and an
angle of attack of 15° (so defined to show the phenomenon only). Although the flow separation is distinguishable in both images, the \( \gamma - \text{Re}_\theta \) transition SST model in Figure 5 shows an improved capture of the flow behaviour, as the separation bubbles are more easily distinguishable and therefore the flow along the whole profile is better presented.

The difference between the two models is that the transition model is able to more accurately model the separation and bubble formation. It is for this reason that the results of the lift and drag coefficients in the airfoil at small angles of attack were similar in Figures 2 and 3. The difference is crucial when approaching the angle of attack at which it enters the separation zone. In these cases, the error of the transition model is smaller and that separation moment can be simulated, whereas the SST model underestimates the lift along the airfoil, so that the simulated pressure is incorrect over the entire separation zone. In addition, the drag coefficient is underestimated by the non-transition model because it does not adequately capture the vortices in the wake, which are known to be responsible for the distortion in the fluid pressure field, which causes the drag to increase.

Additionally, a similar case is presented in Figure 6, for the well-known symmetric profile NACA0012, with \( \text{Re} = 5 \times 10^5 \) and an angle of attack of 15°. It is possible to observe a bubble near the leading edge and detachment of the boundary layer towards the middle of the profile. This would place it in an aerodynamic stall condition.

The results obtained indicate, for the particular profiles and conditions of this study, that the \( \gamma - \text{Re}_\theta \) transition SST model is able to capture the phenomenon of laminar separation bubbles for Reynolds numbers between \( 1 \times 10^4 \) and \( 5 \times 10^5 \).

**Conclusions**

After implementing in OpenFOAM the \( \gamma - \text{Re}_\theta \) transition SST model and performing several simulations, it is possible to conclude the following:

- The turbulence model that contemplates the transition through intermittency is able to reproduce the experimental results, with an average weighted percentage error up to 3% lower. In the case of the lift coefficient, with a smaller error than in the case of the drag coefficient.

- The SST \( \gamma - \text{Re}_\theta \) transition model offers advantages mainly for angles close to or above the angle at which the airfoil enters the stall condition, for the cases analysed in this research.

- For the same flow condition, both the \( k-\omega \) SST model and the transition \( \gamma - \text{Re}_\theta \) SST model allow to visualise the flow separation, in the case of the model with transition the bubbles are much clearer than in the model without transition. Therefore, the pressure field is better simulated, since the lift and drag values are more faithful to the experimental ones.

- The laminar separation bubble phenomenon occurs in the three profiles studied, namely the symmetric profile NACA0012 and the asymmetric profiles S826 and SG6043, for Reynolds numbers between \( 1 \times 10^4 \) and \( 5 \times 10^5 \).
under the particular conditions of this research.

With the results obtained in this research, it is possible to continue with the line of research related to the performance of airfoils in transition flow, adding variants in the airfoils, which allow improving their aerodynamic performance in the particular Reynolds conditions between 1x10^4 and 5x10^5.

References


