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CFD Investigation of Transitional Separation Bubble Characteristics on NACA 63415 Airfoil at Low Reynolds Numbers

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ABSTRACT

The wind turbine blades performance is strongly influenced by transitional separation bubbles, which may occur at low Reynolds numbers. Such a separation bubble is caused by a strong adverse pressure gradient, which makes the laminar boundary layer to separate from the curved airfoil surface. In the present paper, a CFD investigation is conducted to document the structure and behaviour of transitional separation bubbles at different Reynolds numbers. A two-dimensional incompressible Navier-Stokes equation and the transition SST turbulence model are used. The wind-tunnel tests of the NACA 63415 airfoil at Reynolds number 1×10⁶ are used to compare with the time-averaged results of the present steady computations. The simulations were carried out at Reynolds number range of 150×10³ - 460×10³ at different angle of attacks. This study presents the effects of angle of attack and Reynolds number on the separation characteristics and airfoil performance.

Keywords: Wind Energy; Low Reynolds Number; Wind Turbine Blade; Transitional Separation Bubble

1. Introduction

Wind energy is one of the most important renewable energy resources [1, 2]. The performance of wind turbine blades operating in low Reynolds number, incompressible flows has been of increasing interest. Many significant aerodynamic problems appear to occur at small Reynolds number ranges. Most of the previous research studies concentrated on the behavior of the boundary layer, such as, transitional separation bubble, transition, turbulent reattachment, etc., due to its significant influence on the performance of devices based on lifting bodies such as the wind turbine blades [3]. The transitional separation bubble has been studied for many years. Most of these studies have focused on angle of attack, Reynolds number, and freestream turbulence effects on bubble characteristics and length [4-9]. Transitional separation bubble was classified into short and long separation bubbles. For a short bubble, the length of the turbulent separation shear layer is about the same as the laminar shear layer and the bubble usually extends for only a few percent of the airfoil chord. The long bubble has a turbulent shear layer that extends over most of the airfoil chord with a correspondingly large interaction with the external flow [10].

This paper studies the effects of angle of attack and Reynolds number on the separation characteristics and airfoil performance. Thus, the wind turbine designers have an accurate prediction of transitional separation bubble existence and extent for airfoils operating at low Reynolds number.

2. Model Description and Simulation Details

2.1. Governing Equations

The flow past the airfoil NACA 63415 was modelled by the Full Navier-Stokes equation for two-dimensional, viscous, incompressible flow. The continuous equation and Momentum equation based on Reynolds averaged N-S equations are as follows:

\[
\frac{\partial u}{\partial x} = 0
\]
\[ \rho (\nabla \cdot \mathbf{V}) = -\nabla p + \nabla^2 \mathbf{V} - \rho \mathbf{u}' \cdot \mathbf{u}' \] (2)

2.2. Mesh Refinement Investigation

The whole computational zone consists of a semicircle with the radius of 12.5 m and a rectangle with the length of 25 m as shown in Figure 1(a). The chord length of numerical airfoil which locates near the center of the semicircle is 1 m. The number of the grid nodes is 120,878. The height of the grid near the airfoil surface is \(7 \times 10^{-6} \) m as shown in Figure 1(b). The range of values of the dimensionless wall distance \(Y^+\) through the airfoil were less than 1. Coupled algorithm was used to solve the coupling problem between velocity components and pressure in momentum equations. Turbulence kinetic energy was taken as third-order MUSCL scheme in calculation. However, momentum and specific dissipation rate were solved using second-order upwind scheme.

![Figure 1: (a) C-H Computational Domain (b) General Mesh with Boundary Adaptation](image)

2.3. Turbulence Model and Validation Method

The numerical simulation of the 2D NACA 63415 was made using the CFD software Fluent to compare with the wind tunnel experimental data taken from Bak et al [11] to ensure that the numerical model is available for the free-stream flow past the airfoil. The experiment was performed at Reynolds number \(1.6 \times 10^6\). The lift and pressure coefficients of the NACA 63415 airfoil were computed under the angle of attack (AOA) between 0 and 10 degree. The governing equations were Navier-Stokes equations, and turbulence models were applied. The calculation results of Transition SST model of four equations [12] were closest with the experimental data. The comparison between numerical results and experimental data is shown in Figure 2. It was obvious that the numerical results at Reynolds number \(460 \times 10^3\) had a good consistency with the experimental data. After this validation works, the continuing works uses the same model but the analyses were for airspeeds such that the Reynolds Numbers are \(150 \times 10^3\), \(300 \times 10^3\) and \(460 \times 10^3\).

![Figure 2: Numerical Validation Results](image)
3. Results and Discussion

Transitional separation bubble occurs when the boundary layer separates from the airfoil surface due to an adverse pressure gradient. Figures 3 and 4 describe the flow separation phenomenon occurred at the three Reynolds number values $150 \times 10^3$, $300 \times 10^3$ and $460 \times 10^3$ at AOA $2^\circ$ and $10^\circ$ respectively. The pressure rise is related to the velocity drop towards the trailing edge of the airfoil. The fluid particles in the inner part of the boundary layer is slower, it is more affected by the increasing of the pressure gradient. As a result, this fluid may slow to zero velocity. After the laminar boundary layer separation, a highly unstable detached shear layer forms and transition to turbulence takes place in the detached shear layer. The enhanced momentum transport in the turbulent flow enables reattachment and a turbulent boundary layer develops downstream. In contrast, as shown in both figures, the height and length of the transitional separation bubble at Reynolds number $460 \times 10^3$ is quite small. Thus, the transitional separation bubble effect on the aerodynamic performance of the airfoil is very limited. However, as the Reynolds number decreases, the height and length of the transitional separation bubble increases. This could be observed in the figures 3 and 4 at Reynolds number $150 \times 10^3$. Increasing angle of attack causes boundary layer separation to occur further upstream and produce a shorter transitional separation bubble. The separation bubble thickens the boundary layer and thus increases the pressure drag of the airfoil. The drag increase can be several times the drag of the airfoil without a separation bubble. In addition, lift is influenced by a transitional separation bubble, which can lead to problems with the aerodynamic performance of the airfoil. Figure 5 shows the lift and drag coefficients degradation due to the increase of transitional separation bubble length. Comparing the lift and drag coefficients at both Reynolds number values $150 \times 10^3$ and $460 \times 10^3$, there was a decrease in lift (20% reduction at $10^\circ$ AOA) and an increase in drag that exceeded 80%.

![Figure 3: Transitional separation Bubble at AOA 2° for the Three Reynolds Number Values](image)

![Figure 4: Transitional separation Bubble at AOA 10° for the Three Reynolds Number Values](image)

![Figure 5: Drag and Lift Coefficients vs AOA for the Three Reynolds Number Values](image)
4. Conclusion

A four-equation steady incompressible turbulence Transition SST model is applied in this study to simulate the flow around a two-dimensional wind turbine airfoil NACA 63415 in three Reynolds number values. The angle of attack range was from 0° to 10°. The effects of angle of attack and Reynolds number on the transitional separation bubble characteristics and airfoil performance were investigated and studied. Results showed that the decrease in lift could exceed 20 percent and the increase in drag could exceed 80%.

References