Two-Equation Turbulence Models for Turbulent Flow over a NACA 4412 Airfoil at Angle of Attack 15 Degree

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ABSTRACT:

This paper presents computational study of the mean flow and Reynolds stresses results, of a NACA 4412 airfoil, covering the boundary layers around the airfoil and the wake region at angle of attack, $\alpha_a = 15^\circ$. The ability of using different turbulence models to predict unsteady separated flows over airfoils is evaluated. Two-equation turbulence models are tested for the ability to predict boundary layer separation on NACA 4412 airfoil at the position of maximum lift ($\alpha_a = 15^\circ$). These models are the two-equation Realizable, RNG k-ε models and the Reynolds Stress Model (RSM). It was found that the developed turbulence models had captured the physics of unsteady separated flow. The resulting surface pressure coefficients, skin friction, velocity vectors, shear stress and kinetic energy are compared with flying hot wire experimental data, and it was found that the models produced very similar results with the experimental data. Also excellent agreement between computational and experimental surface pressures and skin friction was observed.

INTRODUCTION:

Turbulent boundary layer separation from a surface is an important problem because it is usually responsible for setting an upper limit to the performance of aerodynamic devices. The maximum performance occurs near to the separation conditions; an ability to predict boundary layer separation has been and remains a major aim of fluid mechanics research. Although the topic is not new, there has been only limited progress made to predict the separation flow behavior adequately. A central reason holding back development of separating flow is that until recently the data had high uncertainties.

Various experimental and theoretical studies have been published relating to the trailing edge flows. The most detailed data in the separated flow region over airfoils were measured by Seetharam and Wentz (1997), Burns and Mueller (1982), Hastings and William (1984), Johnston and Horton (1986), Nakayama (1985), Adair and Horne (1989). The aerodynamic properties of NACA 4412 airfoil section have been investigated in a number of previous studies, such as Wadcock (1978), Nakayama (1985), Badran (1993) and Badran and Bruun (2003). Detailed studies of separated boundary layers on airfoils and downstream wakes are limited in number and can be divided according to the measuring technique. Flying X hot-wire techniques have been used by Adair (1987) Thompson and Whitelaw (1984), Wadcock (1978), Badran (1993), and Maddah and Bruun (2002). The theoretical studies performed by some researchers to study the separated flow zones. Rodi (1986, 1991) used the two layer model through the combination of the k-ε model with a one-equation model near the wall. Wilcox (1993) did a comparison of the two-equation turbulence models for boundary layers with pressure gradients. While Menter (1992, 1994) investigated the performance of popular turbulence models for attached and separated adverse pressure gradient flows. All authors found that their models responded well with pressure gradients effect, and the boundary layer behavior was detected accurately. Rumsey and Gatski 2001 investigated the use of a one-equation linear turbulence model and a two-equation nonlinear explicit algebraic stress model (EASM) to the flow over a multi-element airfoil. The effect of the $K–\varepsilon$ and $K–\omega$ forms of the two-equation model were explored, and the $K–\varepsilon$ form is shown to be deficient in the wall-bounded regions of adverse pressure gradient flows. A new $K–\omega$ form of EASM was introduced as well. They showed that nonlinear terms present in EASM improved the predictions of turbulent shear stress behind the trailing edge of the main element and near the mid-flap.

The present research describes the application of different turbulence models for flow around NACA 4412 aerofoil at angle of attack 15 degree. It is designed to investigate the change in the structure of the flow as a function of using different turbulence models, to investigate the performance of these turbulence models and to compare them with the available accurate experimental data.

Turbulence models

The inlet boundary velocity U_∞, was set to 18.4 m/sec for all turbulence models for direct comparison with the flying hot-wire measurements. The corresponding Reynolds number is 0.36×10^6 based on the chord c of the airfoil (250 mm). A computational grid of 150 ×150 was fixed for all models. Three different turbulence models were used, two equation models such as Realizable and RNG k-εReynolds and Reynolds Stress Model (RSM). These models selected because they are most widely used in aerodynamic industry, and they have well documented strength. Also these models proved to have a superior performance for flows involving strong streamline curvature. All computations have been performed on the same grid to ensure that the presented solution for each model will be compared with each other. Flow conditions around the airfoil were built up by finite element analysis using FLUENT 5 software by Fluent Inc.

Results and Discussion:

The present study concentrated on the overall flow behavior and especially in the separated flow region and the associated wake. The test flows cover a significant range of flow situations typically encountered in aerodynamic computations and are believed to allow some conclusions about model's ability to perform in engineering applications. The only way to establish the validity of computational results is to carefully test the resulting models against a number of challenging and well-documented experimental data. The results of the computations will be compared with each other and against the experimental data reported by Badran 1993, and Badran and Bruun 2003. Badran and Bruun 2003 found that at $\alpha_a = 15^\circ$ an intermittent turbulent separation is observed to occur at the trailing edge on the upper surface.

Figure1 shows the wall pressure distribution (Cp) for NACA 4412, as computed by the different models and compared with the experimental results. The RSM model gives superior results to the other models due to its ability to account for the transport of the principal turbulent shear stress. As expected, the Realizable and RNG k-ε model are being close to each other in the middle of the curve on upper surface.

In general, the pressure on the surface of an aerofoil is not uniform. From Figure 1 for $\alpha_a = 15^\circ$ it is seen that at this angle the reduction in the pressure on the upper surface (suction side), in particular near the leading edge, is the primary cause of the lift created. From $x/c \cong 0.4$ to the trailing edge the value of C_p varies only slowly. As shown from the flying hot-wire results (Badran 1993), in the rear position of the aerofoil between x/c = 0.7 to 1 there exists an intermittent low separation near the trailing edge region. The magnitudes of C_p in this region are about -0.7. From the foregoing, the following conclusions may be drawn:

(i) At $\alpha_a = 15^\circ$ the lift is principally caused by the pressure reduction on the front part of the upper surface and to a smaller extent by a pressure increase on the lower surface.

(ii) The pressure coefficient (C_p) distribution over the aerofoil were similar in all turbulence models and the experimental data showing the successful prediction of these models to the pressures around the airfoil and specially in the separated flow on the upper surface.

(iii) The angle of attack $\alpha_a = 15^{o}$ corresponds to the position of maximum lift a NACA 4412 aerofoil section. Figure 2, depicting the wall shear-stress distribution for different turbulence models and the experimental results, shows that the RSM model predicts the largest amount of separation, whereas the other two models predicted smaller regions. Thence, the Realizable and RNG k-ε models produce very similar results.

The differences between the models can also be seen in term of velocity vectors, as shown in Figures 3a to c The RSM model clearly produces the best agreement with the experiments. The larger separation predicated by this model is reflected in the similarity of the c_p distribution as was observed in Fig.1. The small differences between the solutions of different two equation models, allowed us to extract the final conclusion about the abilities of the models to predict adverse pressure gradient flows. It appears that the flow over NACA 4412 does pose a sufficiently strong challenge to the models to assess their potentials for these types of configurations.

Conclusion:

One of the most important aspects of a turbulence model for aerodynamic applications is its ability to accurately predict adverse pressure gradient boundary-layer flows. It is especially important that a model be able to predict the location of flow separation and the wake behavior associated with it. This study found that the turbulence models had captured the physics of unsteady separated flow. The resulting surface pressure coefficients, skin friction, velocity vectors, and Reynolds stresses are compared with flying hot wire experimental data, and the models produce very similar results. Also excellent agreements between computational and experimental surface pressures and skin friction were observed. It can be concluded that there is an important need to test these models under different conditions ($\alpha_a = 20^{o}$ $\alpha_a = 22.5^{o}$) with stronger adverse pressure gradients and larger separation, while in the present angle of attack the pressure gradient is not strong enough to cause larger separation region.

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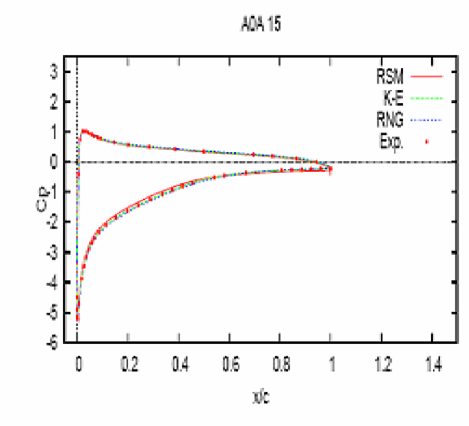

Figure 1 pressure coefficient

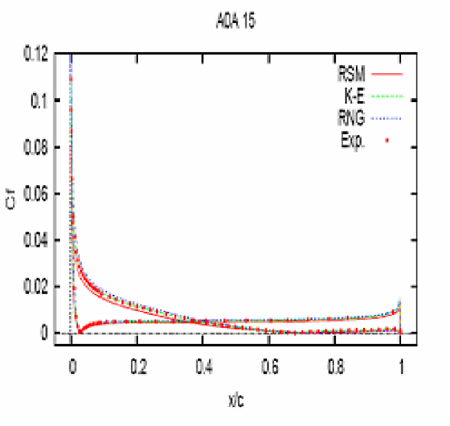

Figure 2 Friction coefficient

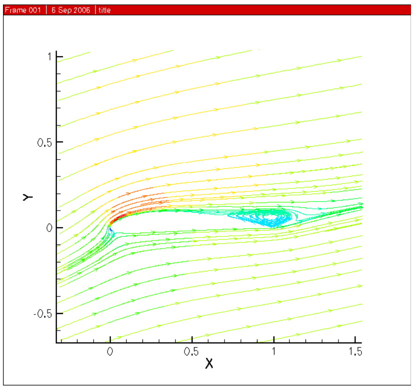

Figure 3a k-e model.

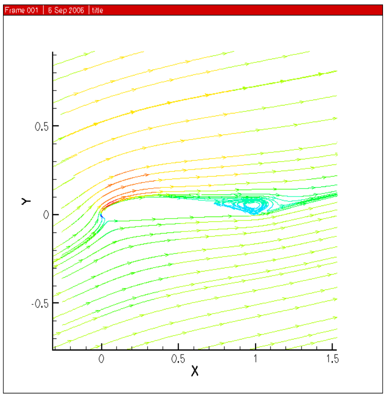

Figure 3b RNG model.

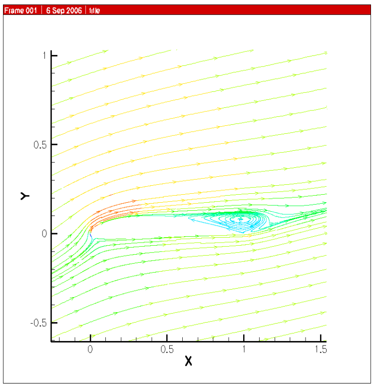

Figure 3c RSM model