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Analysis of Flow Characteristics around an Inclined NACA 0012 Airfoil Using Various Turbulence Models

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Abstract-

The current paper presents a computational fluid dynamic analyses of the flow characteristics over an inclined NACA 0012 airfoil using various turbulence models at Mach number of 0.13. The primitive continuity and momentum equations were solved using Ansys-Fluent in turn along with Spalart-Allmaras, Realizable $k - \epsilon$, and $k - \omega$ shear stress transport. The response of pressure and velocity contours, lift coefficient (C_l) and drag coefficient (C_d) to inclination angle variation from -14° to 20° are reported. Also, the values of C_l and C_d obtained from the current work were juxtaposed with the equivalent values of experimental data gotten from earlier work done by Abbott and Von Doenhoff and the comparison showed good agreement. Furthermore, the results revealed that stalling occurred between 14° and 16° .

Key words: Flow, NACA, airfoil, turbulence models

1. Introduction

Aerodynamics is the study of air flow within and around a moving object and the main purpose of aerodynamics is to understand how forces are produced when air motion interacts with the surfaces of a solid object [1]. The forces created are the lift and drag forces. Lift and drag coefficients constitute crucial considerations in the preliminary stage of airplane design and in the analysis of aircraft performance. For an airplane in steady level flight, the weight of the aircraft acts downward while the lift acts upward; thrust and drag balance each other. Furthermore, the lowest velocity possible at which an airplane can maintain steady flight is the stalling velocity and it depends on the maximum lift coefficient [2].

Airfoils are streamlined shapes that can generate considerably more lift than drag. Bluff bodies are also lift generating surfaces, but they generate much more drag compared to streamlined shapes and therefore are not generally suitable for the design of high lift generating surfaces. A lot of research works have been done over the years in analyzing the aerodynamic performance of airfoils some of which includes the work of Xu et al. [3] that analyzed numerically NACA 4409, 4412, 4415 and 4418 using $k - \Omega$ shear stress transport (SST). The results obtained showed that NACA 4412 has the maximum lift coefficient. Haci [4] used SST turbulence model to numerically investigate NACA 0008, 0009, 0010, 0012, 0015, 0018, 0021 and 0024 airfoils; the author concluded that the lift coefficients of NACA 0008-0012 airfoils showed a similar trend. Aniket et al. [5] worked on numerical simulation of S809 airfoil. Lift coefficient data values from their investigation compared favourably with those of NREL experimental results. Raghava and Rangineni [6] conducted both laboratory and numerical studies using NACA 0012



airfoil, they concluded that $K - \Omega$ (SST) two equation model gave a better prediction of the coefficients of lift and drag compared with other methods used.

Pavic, et al. [7] analyzed the domain of the boundary layer of uncambered airfoils. In their opinion, approaching ground surface would bring about a drop in local Nusselt number on the airfoil surface and consequently, the lift was not significantly affected while drag was considerably affected. Rao et al. [8] investigated the impact of a range of design modifications to improve on lift-drag characteristics of NACA 0012; it was concluded that for higher lift requirements, the flap should be oriented at 15° and slot should be attached to the trailing edge while for normal lift with low drag requirement, a gurney flap supported with a flat wedge should be used. Di Illio et al. [9] numerically analyzed fluid flow around NACA 0012 at low Reynolds number using the hybrid lattice Boltzmann method (HLBM), the results obtained show that the HLBM achieved high precision near solid curved walls. Niu et al. [10] investigated numerically the effect of variable drop leading edge on oscillating NACA 0012 airfoil dynamic stall; they opined that the method reported could reduce dynamic stall but increase considerably the aerodynamics characteristics of NACA 0012.

Amit et al [11] studied the effectiveness of the solutions of various turbulence models on NACA 0012 flow problems at different angles of attack. They found out that the $K - E$ standard model and $K - E$ RNG gave better results. Dajin Liu and Takafumi Ninshino [12] in their research used $K - E$ SST turbulence model to determine the impact of different aspect ratios within the range 2.5 and 10 and different angles of attack. Their results show a reduction in average Coefficient of lift as angle of attack increases when Reynolds number is 1×10^6 . Aftab et al [13] investigated few turbulence models including Spalart Allmaras, 2-equation $K - \Omega$ SST and $\gamma - RE_\theta$ SST at Reynolds number 1.2×10^5 . $\gamma - RE_\theta$ SST provides more precise solution in lesser time than all other models. Mrangrank et al [14] considered the effect of change in angle of attack on airflow around NACA-6409 airfoil and discovered that stall occurred at 16° and also noted that lift increases with angle of attack.

2. Materials and Methods

Mathematical Formulation and Turbulence Models

In all flow scenarios, Fluent solver solves the continuity and momentum equations. For turbulent flow situations, additional equations are solved. The continuity equation can be cast as follows:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{u}) = S_m \quad (1)$$

S_m is the source term.

The momentum equation in the x and y directions are given by equations (2 & 3) as

$$\rho \frac{Du}{Dt} = -\frac{\partial p}{\partial x} + \frac{\partial \tau_{xx}}{\partial x} + \frac{\partial \tau_{yx}}{\partial y} + \rho f_x \quad (2)$$

$$\rho \frac{Dv}{Dt} = -\frac{\partial p}{\partial y} + \frac{\partial \tau_{xy}}{\partial x} + \frac{\partial \tau_{yy}}{\partial y} + \rho f_y \quad (3)$$

The turbulence model equations are combined in turn with equations (1) – (3)

I. Spalart-Allmaras Turbulence Model

The Spalart-Allmaras model is a comparatively simple one-equation model which was mainly developed for use in Aerospace applications [15]. It has been found to be very effective in modeling flow around an airfoil with the existence of adverse pressure gradients in the boundary layer [16].

The continuity equation as presented by Spalart and Allmaras is given by equation (4) [17].

$$\frac{D\tilde{v}}{Dt} = c_{b1}(1 - f_{t2})\tilde{S}\tilde{v} + \frac{1}{\sigma}[\nabla \cdot ((v + \tilde{v}))\nabla\tilde{v} + c_{b2}(\nabla\tilde{v})^2] - \left(c_{w1}f_w - \frac{c_{b1}}{k^2}f_{t2}\right)\left(\frac{\tilde{v}}{d}\right)^2 + f_{t1}\Delta U^2 \quad (4)$$

Where

$$\tilde{S} \equiv S + \frac{\tilde{v}}{k^2 d^2} \left[1 - (\tilde{v}/v) \left(1 + \frac{(\tilde{v}/v)^4}{(\tilde{v}/v)^3 + c_{v1}^3} \right)^{-1} \right] \quad (5)$$

$$f_w = \frac{\tilde{v}}{\tilde{S}k^2 d^2} \left[1 + c_{w2} \left(\left(\frac{\tilde{v}}{\tilde{S}k^2 d^2} \right)^5 - 1 \right) \right] (1 + c_{w3}^6)^{\frac{1}{6}} \left\{ \left[1 + c_{w2} \left(\left(\frac{\tilde{v}}{\tilde{S}k^2 d^2} \right)^5 - 1 \right) \right]^6 + c_{w3}^6 \right\}^{-1/6} \quad (6)$$

$$f_{t1} = C_{t1}g_t \exp \left[-C_{t2} \frac{\omega_t^2}{\Delta U^2} (d^2 + g_t^2 d_t^2) \right] \quad (7)$$

$$f_{t2} = C_{t3} \exp \left[-C_{t4} \left(\frac{\tilde{v}}{v} \right)^2 \right] \quad (8)$$

The constants in the Spalart-Allmaras turbulence model are defined in equations (9) – (10)

$$C_{b2} = 0.622, \quad k = 0.4187, \quad C_{w1} = 3.239, \quad C_{w2} = 0.3, \quad C_{w3} = 2.0, \quad C_{v1} = 7.1, \\ C_{t1} = 1, \quad C_{t2} = 2, \quad C_{t3} = 1.2, \quad C_{t4} = 0.5 \quad (9)$$

$$g_t = \min \left(0.1, \frac{\Delta U}{\omega_t \Delta x_t} \right) \quad (10)$$

II. The Realizable $k - \varepsilon$ Turbulence Model

This model makes use of two independent continuity equations to determine turbulence velocity and length scales. The equations are given by equations (11) & (12) [17]:

$$\frac{\partial}{\partial t}(\rho k) + \frac{\partial}{\partial x_j}(\rho k u_j) = \frac{\partial}{\partial x_j} \left[\left(\mu + \frac{\mu_t}{\sigma_k} \right) \frac{\partial k}{\partial x_j} \right] + G_k + G_b - \rho \varepsilon - Y_M + S_k \quad (11)$$

$$\frac{\partial}{\partial t}(\rho \varepsilon) + \frac{\partial}{\partial x_j}(\rho \varepsilon u_j) = \frac{\partial}{\partial x_j} \left[\left(\mu + \frac{\mu_t}{\sigma_\varepsilon} \right) \frac{\partial \varepsilon}{\partial x_j} \right] + \rho C_1 S \varepsilon - \rho C_2 \frac{\varepsilon^2}{k + \sqrt{\nu \varepsilon}} + C_{1\varepsilon} \frac{\varepsilon}{k} C_{3\varepsilon} G_b + S_\varepsilon \quad (12)$$

$$C_1 = \max \left(0.43, \frac{n}{n+5} \right), \quad n = S \frac{k}{\varepsilon}, \quad S = \sqrt{2 S_{ij} S_{ij}} \quad (13)$$

The constants in equations (11) – (13) are stated as follows:

$$C_{1\varepsilon} = 1.44, C_2 = 1.9, \sigma_k = 1.0, \sigma_\varepsilon = 1.2 \quad (14)$$

III. The $k - \omega$ SST Turbulence Model

This model uses both the $k - \omega$ and the $k - \varepsilon$ models giving more precise results of the flow separation in unfavourable pressure gradients [18]. The model is described by equations (15) – (18)

$$\frac{D\rho k}{Dt} = \tau_{ij} \frac{\partial u_i}{\partial x_j} + \beta^* \rho \omega k + \frac{\partial}{\partial x_j} \left[(\mu + \sigma_k \mu_t) \frac{\partial k}{\partial x_j} \right] \quad (15)$$

$$\frac{D\rho \omega}{Dt} = \frac{\gamma}{v_t} \tau_{ij} \frac{\partial u_i}{\partial x_j} - \beta \rho \omega^2 + \frac{\partial}{\partial x_j} \left[(\mu + \sigma_\omega \mu_t) \frac{\partial \omega}{\partial x_j} \right] + 2\rho(1 - F_1) \sigma_\omega \frac{1}{\omega} \frac{\partial k}{\partial x_j} \frac{\partial \omega}{\partial x_j} \quad (16)$$

$$\tau_{ij} = -\rho u'_i u'_j = \mu_i \left[\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} - \frac{2}{3} \frac{\partial u_k}{\partial x_k} \delta_{ij} \right] - \frac{2}{3} \rho k \delta_{ij} \quad (17)$$

$$F_2 = \tanh \left\{ \left[\max \left(\frac{2\sqrt{k}}{0.09\omega y}, \frac{500\nu}{y^2\omega} \right) \right]^2 \right\} \quad (18)$$

Where

$$v_t = a_1 k / \max(a_1 \omega, \Omega F_2) \text{ and } \beta^* = \varepsilon / k \omega \quad (19)$$

3 Simulation Procedures

ANSYS Fluent 16.0 CFD software was used in the present study to simulate subsonic incompressible flow around NACA 0012 airfoil at Mach number of 0.13. The angles of attack considered were between -14° and 20° . The mesh settings consist of 68076 nodes with 133952

triangular elements in a C-type mesh formulation which is shown in Figure 1. This ensured that the simulation accurately converged. Table 1 displays the input parameters for the simulation. The turbulence models studied were Spalart-Allmaras, $k-\varepsilon$ realizable, and $k-\omega$ SST while comparison was made with the values of Abbott and Von Doenhoff [19].

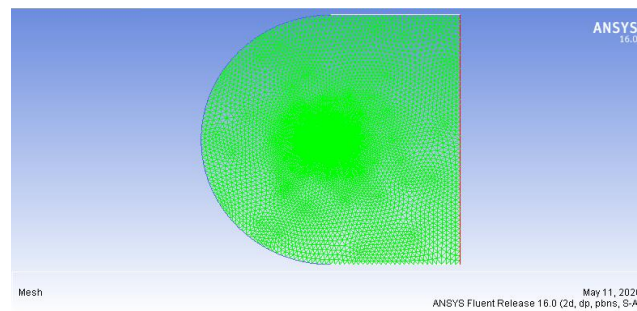


Figure 1: Mesh Distribution

Table 1: Computational condition

Input	Description	Value	Unit
p	Pressure	101325	N/m^2
μ	Viscosity	1.7894×10^{-5}	kg/ms
ρ	Density	1.225	kg/m^3
C	Chord length	1.0	m
M	Mach number	0.13	Nil
T	Temperature	288.16	K
γ	Ratio of specific heats	1.4	Nil

4. Result and Discussions

Figures (2) – (5) present the plots of pressures contours for the various turbulence models considered. At an angle of attack of 0° , Figure 2 shows that there was essentially no change in pressure between the upper and the lower surfaces of the airfoil and the stagnation point was seen to be at the leading edge; and no lift was generated in this position of the airfoil. With increasing angle of attack, Figures (3) – (5) show that the distribution of pressure between the upper and the lower surfaces becomes asymmetrical with the upper surface of the airfoil having lower pressure distribution relative to the lower surface. Furthermore, the stagnation point is observed to have moved off the leading edge to a new position on the lower surface of the airfoil. $K - \omega$ SST turbulence has the highest static pressure output compared to the other two turbulence models. Figures (6) – (9) show the plots of the velocity magnitude for the models considered. At 0° angle of attack, Figure (6) reveals that the upper and the lower surfaces of the

airfoil have similar velocity distribution. With increasing angle of attack, Figures (7) – (9) show that the velocity distributions on the upper surfaces of the plots are higher than those on the lower surfaces. Both the pressure and velocity contours are consistent with the Bernoulli's principle of lift generation.

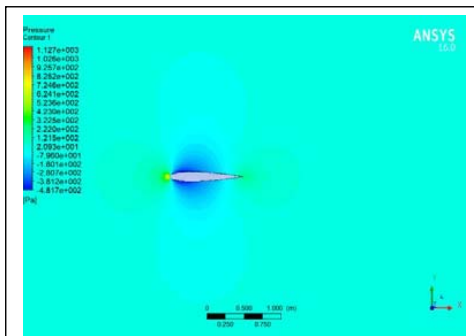


Figure 2: Contour of static pressure at 0° angle of attack

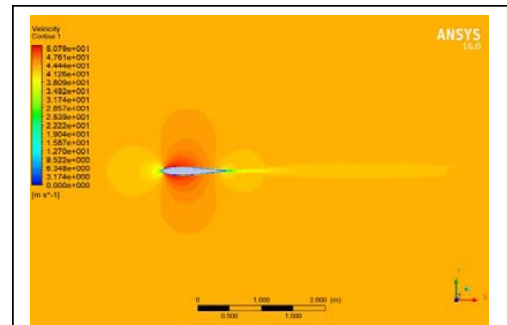


Figure 6: Contour of Velocity Magnitude at 0° angle of Attack

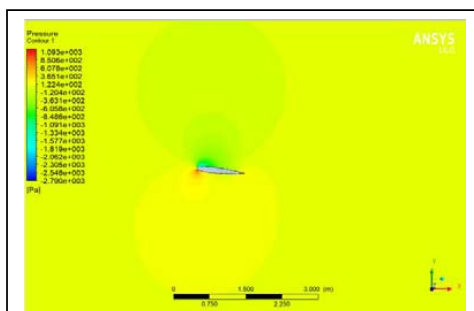


Figure 3: Contours of static pressure at 6° angle of attack with k- ϵ Realizable turbulence model

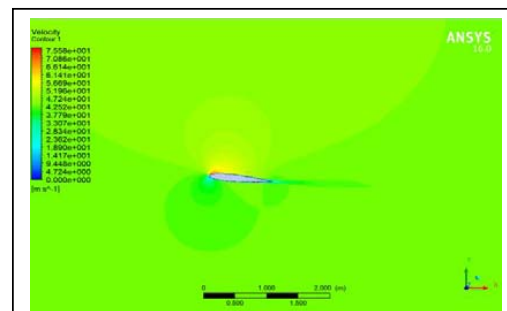


Figure 7: Contours of velocity magnitude at 6° angle of attack with k- ϵ Realizable turbulence model

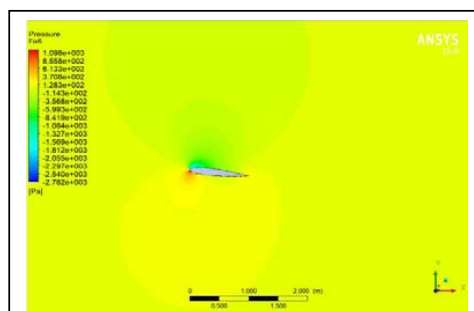


Figure 4: Contours of static pressure at 6° angle of attack with Spalart-Allmaras turbulence model

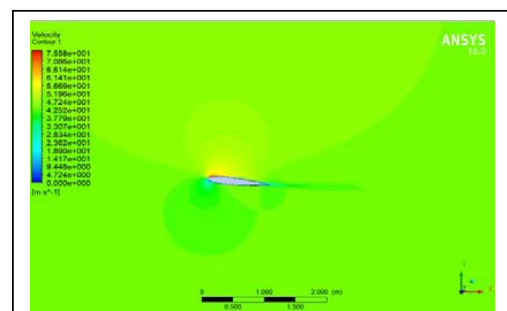


Figure 8: Contours of velocity magnitude at 6° angle of attack with Spalart-Allmaras turbulence model

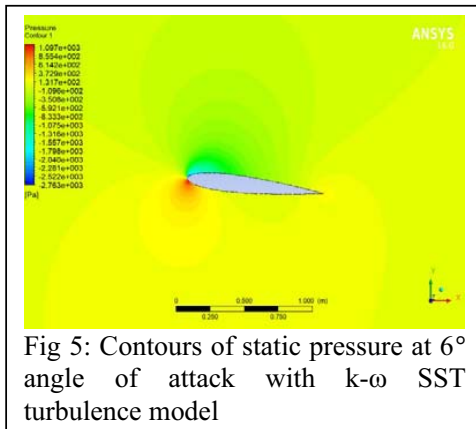


Fig 5: Contours of static pressure at 6° angle of attack with $k-\omega$ SST turbulence model

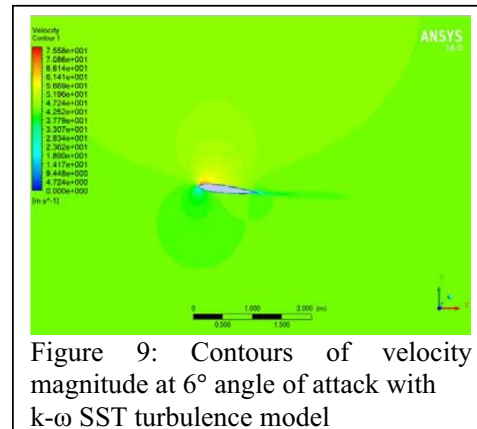


Figure 9: Contours of velocity magnitude at 6° angle of attack with $k-\omega$ SST turbulence model

The response of lift coefficient (C_l) to angle of attack is shown in Figure 10 for the various turbulence models considered. The plots show that with increasing angle of attack, the coefficient of lift for the three turbulence models investigated viz $k-\epsilon$ realizable, Spalart-Allmaras and $k-\omega$ also increases; between 14° to 16°, the value of the lift coefficient drops. This condition is called stalling. Furthermore, the results obtained from the current investigation are compared with the data gotten from Abbott and Von Doenhoff [19]; the comparison shows good agreement. Finally, $k-\omega$ turbulence model tends to be the best because around stalling, its values appear to be closest to that of Abbott.

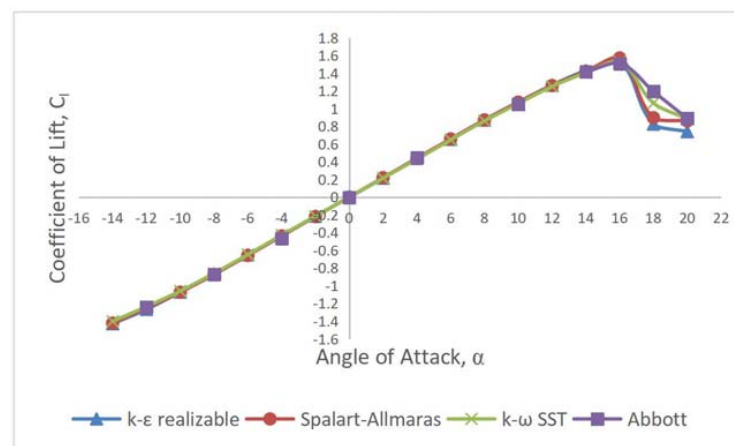


Figure 10: Graphs of Coefficient of Lift against Angle of Attack

Figure 11 is the plot of the variation of Drag coefficient with angle of attack for the three turbulence models studied. The drag reduces as the angle of attack increases until it reaches 0° when it starts to increase. The trends of the plotted data for the three turbulence models considered viz $k-\epsilon$ realizable, Spalart-Allmaras and $k-\omega$ SST agree with the results of Abbott and Von Doenhoff [19].

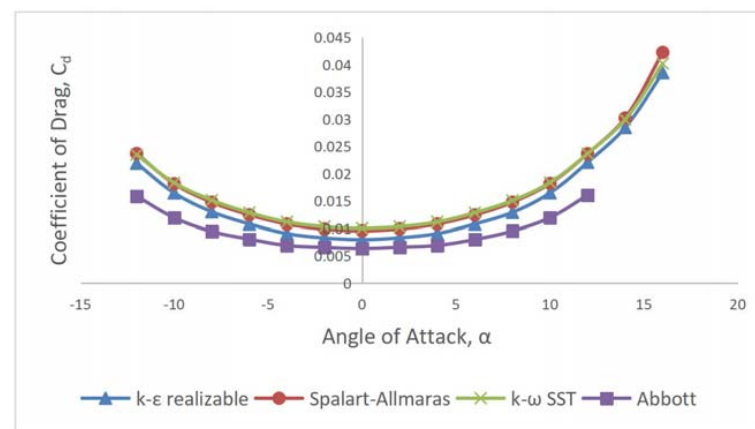


Figure 11: Plots of Coefficient of Drag against Angle of Attack

5. Conclusion

- Ansys Fluent 16.0 has been successfully used to simulate subsonic incompressible flow around the surfaces of NACA 0012 airfoil at different inclination angles.
- Stalling occurred between 14° and 16° .
- $K - \omega$ SST turbulence model gave the best result relative to Abbott and Von Doenhoff around the critical turning point as evident in the lift curve in Figure 10.
- Since stalling velocity of an aircraft is partly determined by $C_{l_{max}}$ and its maximum velocity is determined in part by $C_{d_{min}}$, therefore, it is clear that these aerodynamic parameters dictate the design and performance of airplanes.

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