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ARTICLE

Experimental Validation of NACA 6321 Airfoil Characteristics Obtained Using Different Turbulence Models

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Abstract: Numerical analysis of NACA 6321 aerofoil is conducted at different angles of attack with constant velocity using three turbulence models and the results are validated with experimental findings. The simulation study is conducted by solving the steady-state governing equation of continuity and momentum using the Spalart-Allmaras, k-omega, and k-epsilon models; the obtained results are compared with experimental data. Aerodynamic parameters are calculated and then juxtaposed with experimental data acquired from experiments performed in a subsonic tunnel. The study reveals that the results generated by the k-omega model exhibit a strong correlation with the experimental findings at low and high angles of attack when compared to other turbulence models. In contrast to the k-epsilon and the Spalart-Allmaras models, the prediction of the stalling angle of attack has an error of ± 20% in comparison to the experimental evaluation. The results of the k-omega turbulence model predict the turbulence properties pretty well in the NACA 6321 aerofoil with an error of less than 4%.

Keywords: NACA 6321, Spalart-Allmaras, k-omega and k-epsilon, Turbulence models.

1. Introduction

With the technological advancements and increasing need for performance and safety in aircraft, researchers around the globe are working on improving the aerodynamic performance of aircraft wings. In analyzing the aerodynamic performance, the numerical simulation of forces and moments acting on an aerofoil plays a vital role. Apart from the wind tunnels used to predict the performance of aerofoil structures, the use of solution schemes for simulating the conditions over the aerofoil is inevitable. However, choosing the right simulation model is a crucial aspect, as this strongly influences the outcome of the analysis and its relevance. Research has been carried out to analyze the outcomes of various solution schemes in different aerofoils.

Sadikin *et al*. [1] performed a numerical analysis on NACA 0012 aerofoil by using different turbulence models, compared the outcomes, and suggested that the k-epsilon model matches well with the results in the published literature. Eleni [2] also investigated the turbulence models using a NACA 0012 aerofoil and concluded that the results of the k-omega SST model provide accurate results close to experimental data. Li *et al*. [3] carried out a turbulence model test on NACA23012 aerofoil using three different turbulence models. Based on the experimental results, it is seen that the k-omega method provides results close to the

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experimental data. Matyushenko and Garbaruk [4] used the k-omega SST turbulent model to predict the airfoil characteristics and showed that, with minor modifications, this model can be implemented to obtain optimum results without any errors. Rogowski [5] investigated the NACA 0015 aerofoil with two different turbulence models, validated the outcomes with experimental results, and suggested that, out of the two models analyzed, the k-epsilon turbulence model provides similar results at various conditions compared to the k-omega model. Roy *et al*. [6] numerically investigated the S 809 aerofoil with five different simulation models and compared the results with experimental data for validation. It is seen from the study that the SST gamma-theta model presents results more closely to the experimental findings. Aftab [7] carried out simulation studies on NACA 4415 aerofoil used in wind turbines and UAVs based on different turbulence models and evaluated the findings with experimental analysis. The study concluded that different turbulence models provide close results for different conditions and, by and large, the γ-Reθ SST model can be used in close approximation with experimental data for all conditions. Sogukpinar and Bozkurt [8] conducted a numerical investigation on a NACA 0012 aerofoil with different turbulence models and showed that the k-omega and SST models provide accurate results that match closely with the experimental analysis. Suvanjumrat [9] conducted turbulence model studies on NACA 0015 aerofoil using the OpenFOAM tool and compared the results with wind tunnel testing data. It is seen from the study that the k-omega model is simple and reliable, matching well with experimental data at all input conditions. Zhu *et al*. [10] carried out a numerical investigation on a vertical axis wind turbine with different turbulence models, compared the outcomes with experimental data, and suggested that transition SST (TSST) models are more suitable for turbine blade analysis. Hasan *et al*. [11] conducted a numerical study on turbulence models at low speed and high speed on a rectangular model at different velocities. The study revealed that at low speeds all the turbulence models show close results whereas at high speeds the SST model provides accurate results compared to the k-epsilon model. V and A [12] performed a study on turbulence models for UAVs under different operating conditions. Six different turbulence models were selected for the study and results were compared with experimental data. The study's conclusion indicates a close agreement between the Spalart-Allmaras model and the experimental data.

El Maani *et al*. [13] performed a simulation work on ONERA M6 aerofoil to compare the performance of five different models with NASA CFD results. It was concluded that the Spalart-Allmaras, k-ε RNG, and k-ω SST models provided good results at transonic speeds. Catalano and Amato [14] conducted a numerical investigation at transonic speed over an aerofoil and found that the k-omega SST model provided results close to the experimental findings. Villalpando *et al*. [15] performed a numerical investigation on a wind turbine aerofoil to validate the performance of turbulence models compared to experimental data. It is seen from the study that the k-omega SST model provided accurate results on clean and iced wind turbine aerofoils.

Turbulence models are used to select the appropriate set of equations to obtain accurate results while performing simulation studies. Also, the choice of models depends on the flow conditions used in the analysis. The available literature shows that most of the reports are based on the simulation of aerodynamic characteristics evaluated and compared with experimental or published results. Equations selected from the literature survey vary from one equation to higher orders, depending on the problem. In this present study, first, we predict the suitable turbulence models for NACA 6321 flat bottom aerofoil, and then the results are evaluated with experimental findings.

2. Design

The coordinates of the NACA 6321 aerofoil are collected and imported into the design modeler for both models. The parameters used in the design are shown in Table 1.

TABLE 1. Aerofoil specification used in the study.

Sr.No	Details	Specifications
1	Aerofoil	NACA 6321
2	Span(cm)	30
3	Chord(cm)	30
4	Maximum Camber (%)	6
5	Maximum camber position (%)	30
6	Thickness (% of chord)	21

The CAD model created with zero angle of attack for numerical simulation to predict the aerodynamic performance parameter at different conditions is shown in Fig 1. The domain considered for the work is with the inlet at 75 cm to the leading edge and the distance between the wall is 150 cm. The outlet is located at a distance of 240 cm from the leading edge of the aerofoil. A schematic representation of the model and the computational domain representation are shown in Figs. 1 and 2, respectively.

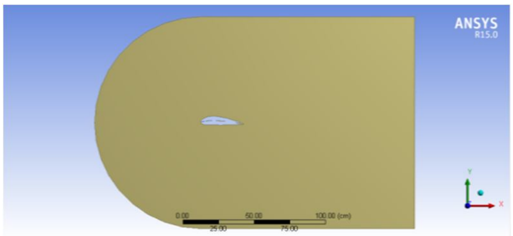


FIG. 1. Representation of the of NACA 6321 aerofoil model.

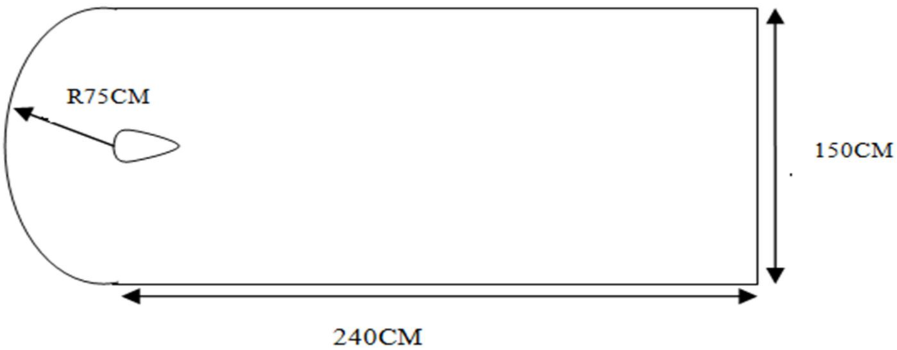


FIG. 2. Computational domain used in the present study.

3. Meshing

Subsequently, a fine mesh is created over the body using ICEM CFD. The number of elements plays a major role in fixing the mesh size to obtain accurate results. To identify the number of elements, a numerical analysis is conducted with different elements, and the results are shown in Fig. 3.

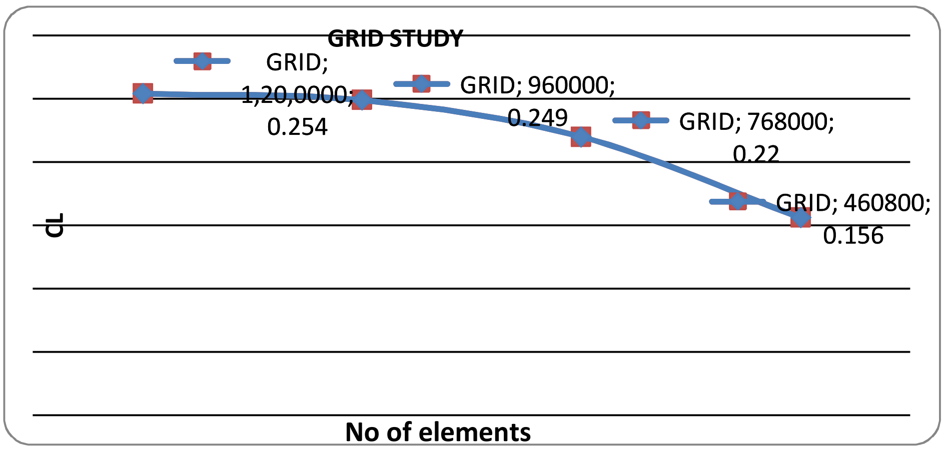


FIG. 3. Variation of coefficient of lift with the number of elements.

It is seen that, for the same operating conditions, for the mesh element numbers between 960000 to 1200000, the value of CL is almost constant, indicating that the results are independent of the quality of the mesh henceforth. Based on this, the grid size is fixed as 1200000. The modeled aerofoil is divided into tetrahedral and prism meshes to get precise results during the numerical analysis as shown in Fig. 4. For all the analyses in the grid, the same grid is used and different angles of attacks are achieved by modifying the flow direction.

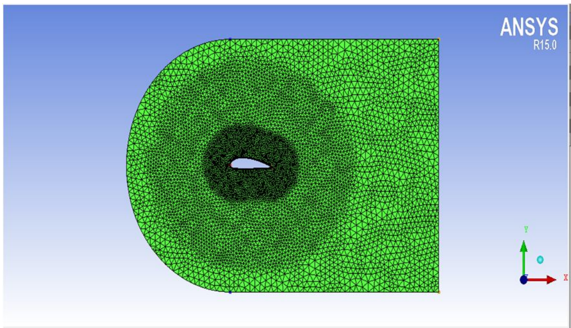


FIG. 4. Meshing of NACA 6321 aerofoil at different angles of attack.

4. Turbulence Model Studies

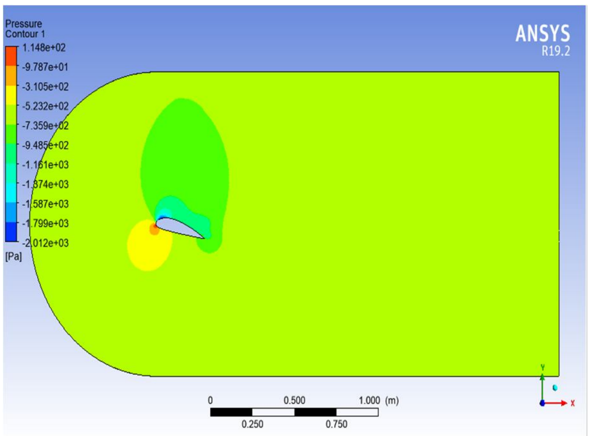
Numerical analysis is conducted by using a pressure-based coupled solver which is used to solve continuity and momentum equations in a combined manner. The pressure-based solver is used to complete the simulation in minimum duration compared to other solvers. Hybrid initialization is initiated, and the problem is observed to converge in less than 2500 iterations with convergence criteria of e^{-6}. The boundary conditions are provided separately for top and bottom aerofoils, as shown in Table 2. The different turbulence models chosen for the present study are:

- k-epsilon model
- k-omega model with SST
- Spalart–Allmaras model

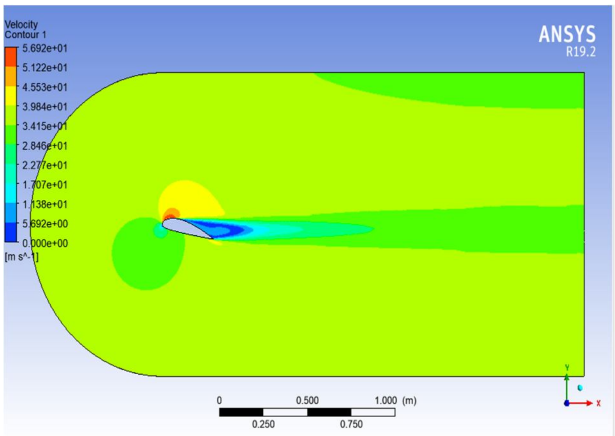
The figurative representation of the pressure and velocity contour of the NACA 6321 aerofoil used in the study with different analysis models is shown in Fig. 5.

TABLE 2. Boundary conditions used in the analysis.

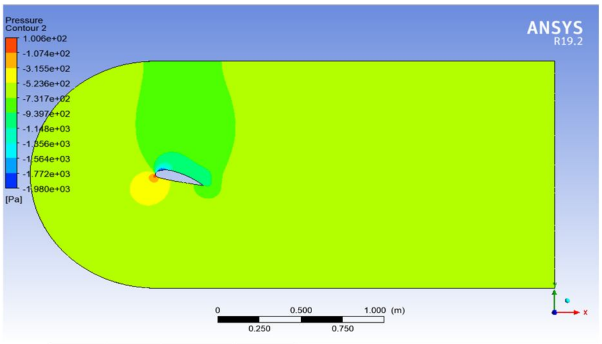
Sr.No	Details	Remarks
1	Velocity	35 m/sec
2	Reynolds number	$7.14 * 10^5$
3	Area	$0.09\ m^2$
4	Inlet	35 m/sec
5	Outlet	1 atm



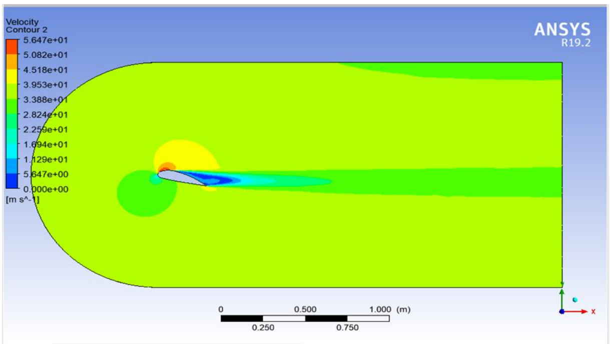
a) 14 degree S-A Pressure distribution



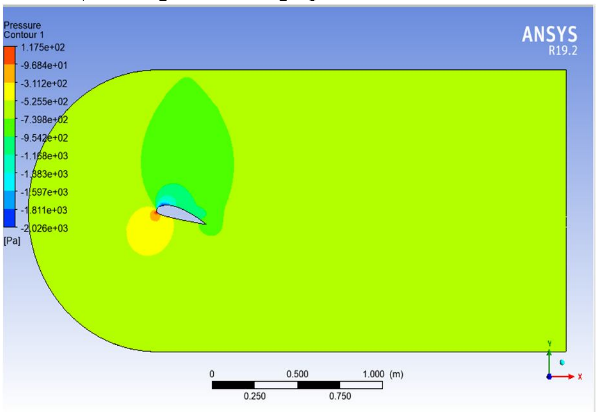
b) 14 degree S-A velocity distribution



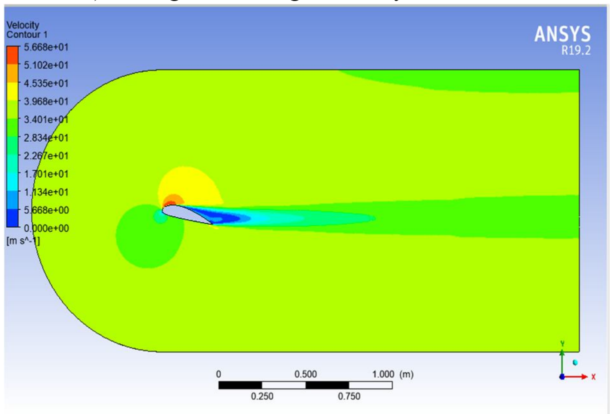
c) 14 degree k-omega pressure distribution



d) 14 degree k-omega velocity distribution



e) 14-degree k-epsilon pressure distribution



f) 14-degree k-epsilon velocity distribution

FIG. 5. Pressure and velocity distribution over a NACA 6321 aerofoil at different angles of attack.

Fig. 5 shows the pressure and velocity distribution over the aerofoil at a constant velocity of 35 m/sec. It is clearly seen that different turbulence models behave differently under the same input conditions, resulting in variations in the distribution. At low angle of attack, all the models generally yield similar results. However, at high angles of attack, the accuracy of the models varies depending on the solver used. In order to validate the results of the simulation studies and choose the appropriate model for the aerofoil presently under study, experimental evaluation was conducted.

5. Experimental Studies

NACA 6321 aerofoil model is constructed with a cross-section of 30 x 30 cm using lightweight Balsa wood and a good surface finish, as shown in Fig. 6. Pressure tabs are placed over the model to measure pressure distribution across the aerofoil. The wind tunnel facility at Karunya Institute of Technology and Sciences is used for the experimental analysis.

FIG. 6. Photographic view of the fabricated model of NACA6321 aerofoil.

The wind tunnel is calibrated before the model is mounted inside the tunnel. The results of the calibration trials are shown in Table 3 below.

TABLE 3. Calibration of the wind tunnel.

Sl.no	RPM	Inclined Manometer		Velocity(m/sec)
		hm (mm)	^h (mm)	
1	100	10	0.5	2.637
2	200	15	3	6.46
3	300	21	6	9.14
4	400	31	11	12.37
5	500	46	18.5	16.04
6	600	62	26.5	19.2
7	700	83	37	22.69
8	800	108	49.5	26.24
9	900	145	68	30.76
10	1000	176	83.5	34.08
11	1100	212	101.5	37.58

The model is fixed at the center of gravity within the wind tunnel, and the experiments are carried out at a constant velocity of 35 m/sec. The angle of attack is varied, ranging from -6° to 14° during the analysis. The pictorial representation of the subsonic tunnel used in the study is shown in Fig. 7.

FIG. 7. Subsonic Wind tunnel setup used in the study.

6. Results and Discussion

The results of the simulation and experimental studies explained earlier are tabulated in Table 4.

The comparison of the coefficient of lift at various angles of attack is estimated through simulation studies using three turbulence models. These results are then checked against the experimental values obtained, as shown in Fig. 8.

Fig. 8 shows that the k-omega model closely aligns with the experimental values, reaching a maximum stalling angle of attack of 10 degrees at the given velocity, with a corresponding flow pattern that matches the experimental data. On the other hand, the k-epsilon and Spalart-Allmaras models exhibit stalling angles of attack at 12 and 8 degrees, respectively, and their flow patterns do not correspond well with the experimental data. It is seen that, at low angles of attack, all three models in the analysis produce the same amount of coefficient of lift. However, at high angles of attack, the stall angle varies with turbulence models. In this research work, the aerofoil is analyzed with internal as well as external flow. It is clearly understood from the analysis that Spalart-Allmaras model produces a low amount of lift coefficient due to limited equations used to solve the transport equation. The k-epsilon method produces a higher lift coefficient, making it more suitable for analyses related to the free shear layer and wake regions. Upon comparison of the Spalart-Allmaras and k-epsilon models, it is observed that the k-omega model provides more accurate results in the near-wall boundary regions.

TABLE 4. Outcomes of the numerical and experimental analysis.

AOA	SA		K-EPSILON		K-OMEGA		EXPERIMENTAL		ERROR(%)	
	CL	CD	CL	CD	CL	CD	CL	CD	CL	CD
-6	0.033	0.027	-0.046	0.041	-0.001	0.029	0.000	0.009	-0.084	2.000
-4	0.147	0.023	0.100	0.037	0.123	0.025	0.080	0.012	4.258	1.260
-2	0.260	0.020	0.247	0.033	0.246	0.020	0.213	0.010	3.300	0.990
0	0.431	0.021	0.421	0.033	0.471	0.019	0.421	0.012	5.000	0.700
2	0.605	0.023	0.588	0.036	0.582	0.024	0.520	0.018	6.180	0.570
4	0.742	0.030	0.778	0.040	0.718	0.031	0.680	0.026	3.754	0.515
6	0.879	0.036	0.946	0.046	0.853	0.038	0.823	0.029	3.028	0.940
8	0.893	0.052	1.068	0.057	0.942	0.051	0.900	0.048	4.164	0.320
10	0.850	0.074	1.190	0.067	1.030	0.064	0.986	0.059	4.400	0.490
12	0.846	0.102	1.259	0.083	0.976	0.096	0.940	0.087	3.600	0.930
14	0.877	0.134	1.118	0.122	0.851	0.141	0.812	0.126	3.920	1.500

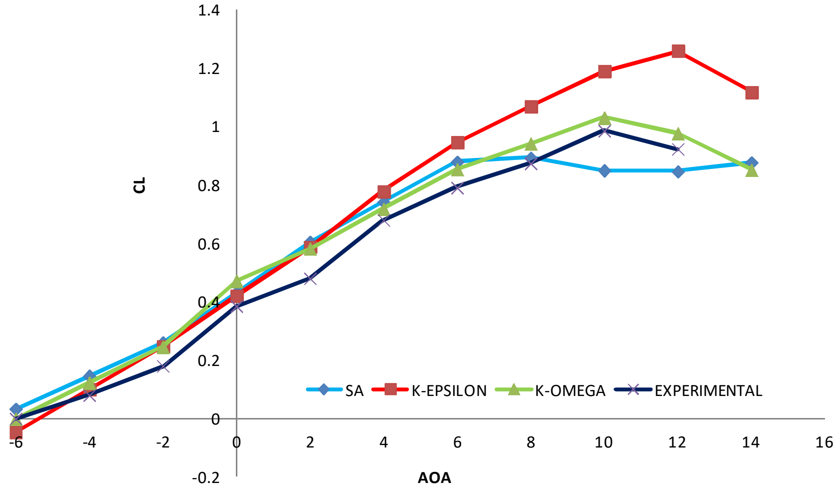


FIG. 8 Variation of coefficient of lift at different angles of attack.

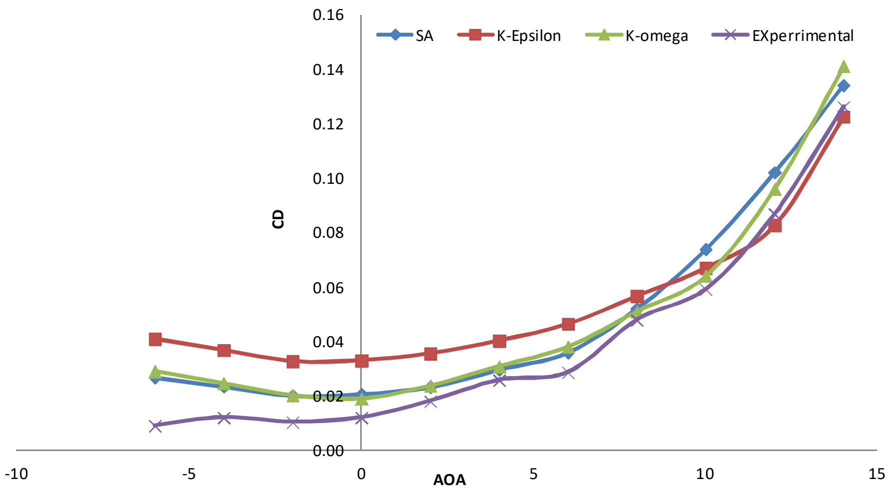


FIG. 9. Variation of coefficient of drag at different angles of attack

From Fig. 9 it can be concluded that the k-epsilon model produces more drag compared to other models. The results of the k-omega model match well with the experimental result and show low drag. Concerning the flow pattern over the aerofoil, the k-omega model is found to produce matching results with the experimental analysis. While the Spalart-Allmaras model also shows the same amount of drag, its flow pattern and other aerodynamic parameters do not match the experimental results. Hence, it is seen that the drag properties and flow characteristics depend on the turbulence model used for the analysis to a large extent. The drag values also vary, depending on whether there is a negative or positive angle of attack. In all the models, the variation of drag coefficient after the stalling angle of attack is very prominent, resulting in a huge loss of lift.

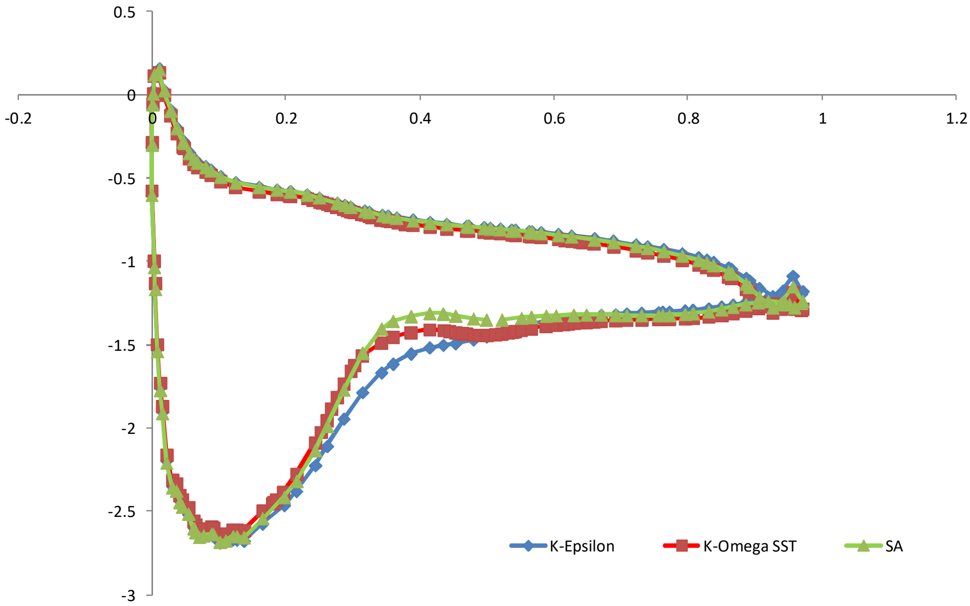


FIG. 10. Variation of coefficient of pressure with X/C.

Fig. 10 shows the coefficient of pressure versus chord length. It is clearly evident that the coefficient of pressure values vary at the chord length from 0.2 to 0.4 as compared to the remaining length of the aerofoil. Due to the prevalence of boundary layer separation, most of the turbulence models fail to predict the pressure in these locations accurately. The graph also shows the pressure distribution over an aerofoil at various angles of attack and it is seen that the boundary layer separation point is not predicted by most of the turbulence models. Hence, advanced models with modified equations are necessary to predict the boundary layer separation and to capture the exact location.

Conclusions

A numerical analysis of the NACA6321 aerofoil is conducted using three different turbulence schemes. The results are subsequently validated with the wind tunnel tests, leading to the following conclusions. Among the turbulence models in this analysis, the k-omega model provides accurate results that match well with the experimental results, as this turbulence model uses two partial differential equations for solving two variables to predict turbulence. The stall angle of attack for NACA 6321 aerofoil is found to be 10° at a velocity of 35 m/sec. Compared to the k-epsilon and Spalart-Allmaras models, the values of the stalling angle of attack predicted have an error of ± 20%. To predict the boundary layer separation, advanced turbulence models with updated equations are needed and the results produced by the k-omega turbulence model match well with the experimental results for the NACA 6321 aerofoil analyzed in the present study.

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