

Effect of Reynolds Number on the Aerodynamic Performance of NACA0012 Aerofoil

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Abstract: The present work investigates the effect of Reynolds number on NACA0012 aerofoils for various angles of attack on the aerodynamic characteristics both experimentally as well as numerically. The modifications in the flow, as well as aerodynamic characteristics of the NACA0012 aerofoil, are systematically compared using pressure coefficient, lift coefficient, vortex shedding, etc. The study was conducted for a chord wise Reynolds number of (a) 2.21×10^5 and (b) 2.81×10^5 at an angle of attack of 0° , 5° , 10° , 15° and 20° . A large difference in the pressure coefficient is observed between the top and bottom surface in the case of lower Reynolds number and thus it indicates that at low Reynolds number high lift is generated than at high Reynolds number. L/D study also reveals that with increasing Reynolds number the NACA0012 aerofoil loses its lifting aerodynamics property. From the vortex plot, it is clear that leading edge shedding has a negative impact on the lift of the aerofoil for 2D simulation. Thus, this paper sufficiently demonstrates the effect of Reynolds number on the aerodynamic characteristics of the NACA0012 aerofoil.

Keywords: Angle of attack, Aerofoil, lift and drag

1. Introduction

In the field of fluid dynamics, an area of vital practical importance is the study of aerofoils. Aerofoil finds massive application in aircraft, fans, wind turbines, propellers etc and is a highly demanding field of research. The aerodynamic performance can also be improved by tailoring the aerofoil profile according to the application. This includes considerations of the lift and drag characteristics, maximum lift coefficient, stall characteristics etc. The flow past aerofoils which basically comprise of several phenomena such as vortex formation, vortex shedding, flow separation, turbulence study etc has been investigated by the several researchers for the past few decades. In doing so, the reliable determination and evaluation of the accuracy of aerodynamic data generated in wind tunnels remain one of the most



challenging problems in aeronautics. The aerodynamic performance analysis of NACA0012 wind turbine aerofoil has been performed by Eleni *et al.*[1] using numerical simulation method. The results of different turbulence model to investigate lift, drag performance showed that k-omega shear stress transport (SST) two-equation model had a good agreement with the published experimental data of other investigators for a wider range of angles of attack. Martinat *et al.*[2], used two and three-dimensional numerical simulations to study the NACA0012 dynamic stall at Reynolds numbers 10^5 and 10^6 . The results showed that URANS approach of Organized Eddy Simulation (OES) has an improved behaviour at the high Reynolds number range. A transition model that combined existing methods for predicting the onset and extent of transition was presented by Bacha *et al.* [3]. The onset of transition is based on Michel's method for incompressible two-dimensional flow while the extent of transition is quantified by developing a model for the intermittency function. The boundary layer separation prediction on NACA 4412 aerofoil at the position of maximum lift was performed by Badran[4], using two-equation turbulence models [Realizable and RNG models and the Reynolds stress model]. Ma [5] carried out 2D numerical simulation for S825 and S827 wind turbine aerofoils with three different turbulence models (Spalart- Allmaras, standard k-omega and standard k-epsilon). Lei *et al.*[6], studied on the trailing-edge separation of a symmetrical aerofoil at a low Reynolds number. The flow of the symmetrical aerofoil SD8020 at a low Reynolds number has been simulated. Even though several studies on aerofoils are available, a detailed experimental study along with numerical simulations to understand the flow and aerodynamic characteristics of NACA 0012 aerofoil such as pressure coefficients, lift and drag coefficients, vortex shedding mechanisms, wake profiles at two different Reynolds numbers for better performance are scarce which forms the specific objective of the current study.

2. Experimental Setup and Numerical Boundary Condition and Domain

Current Experiment has been performed in the sucking type, open circuit, sub-sonic wind tunnel with a test section of 300mm x300mm x1000mm as shown in Fig.1. The maximum achievable velocity of the wind tunnel is 60 m/s with contraction ratio of 9:1. It has an axial flow fan driven by AC motor of 10Hp with AC drive for speed control. The S-type Load cell is mounted at the mid of test section for measuring Lift and Drag forces.

The physical geometry, computational domain, and boundary conditions for the present study are shown in Fig.2. The computational domain (Fig. 2) was kept as -6c and 68c in the stream wise direction and $\pm 5c$ normal to the stream wise direction. The Unstructured grid (Fig. 3) with varying mesh size was constructed using ANSYS CFD. Fine grids were used near aerofoil where the flow effects are significant in order to resolve the boundary layer properly and grids were made coarse in those regions where flow effects are absent. The simulations were done using pressure based implicit solver. The fluid was considered as incompressible (i.e., constant density) in the present computation. The two equation SAS (Scale Adaptive Simulation) turbulence model was used for present simulation with standard value of model constant ($C_s=0.11$, $\alpha^*=1$, $\alpha=0.52$, $\beta^*=0.09$, $a_1=0.31$, $\beta_i(\text{inner})=0.075$, $\beta_i(\text{outer})=0.0828$, $\text{TKE}(\text{inner})$ Prandtl=1.176, $\text{TKE}(\text{outer})$ Prandtl=1, $\text{SDR}(\text{inner})$ Prandtl=2, $\text{SDR}(\text{outer})$ Prandtl=1.168, Energy =0.85, wall Prandtl no.=0.85, Production limiter clip factor=10). The Scale-Adaptive Simulation (SAS) is an enhanced URANS formulation, which allows the resolution of the turbulent scale in unstable flow conditions to LES-like behaviour in the

unsteady region of the flow field and at the same time, the model provides standard RANS capabilities in stable flow regions.



Fig.1 Experimental Setup

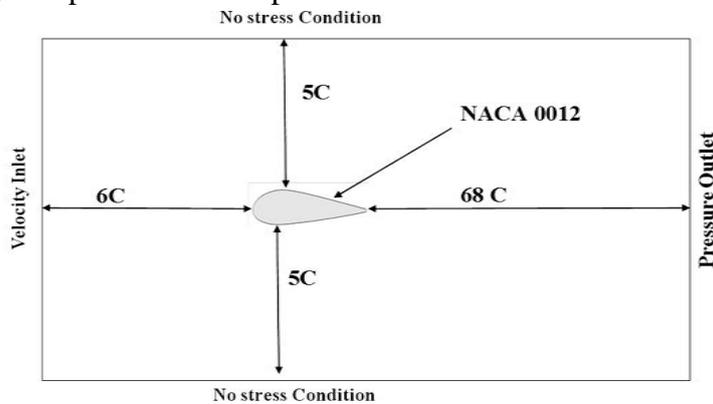


Fig. 2

Fig.2 Computational Domain and Boundary condition

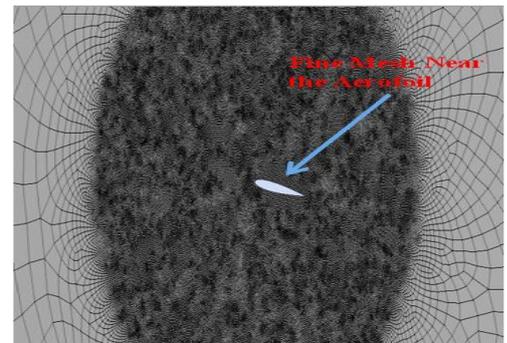


Fig. 3

Fig.3 Unstructured Mesh with Fine near the aerofoil.

2.1. Governing equations

The 2D incompressible flow equations for the flow past a flat plate aerofoil is given below.

Mass conservation equation:

The equation for conservation of mass can be written as follows:

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 \tag{1}$$

where, u, v are velocity along x and y axis respectively.

Momentum Conservation Equation:

a) Along x- axis

$$\frac{\partial u}{\partial t} + \frac{\partial(u^2)}{\partial x} + \frac{\partial(uv)}{\partial y} = -\frac{1}{\rho} \frac{\partial P}{\partial x} + \nu \left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} \right) \quad (2)$$

b) Along y-axis

$$\frac{\partial v}{\partial t} + \frac{\partial(uv)}{\partial x} + \frac{\partial(v^2)}{\partial y} = -\frac{1}{\rho} \frac{\partial P}{\partial y} + \nu \left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} \right) \quad (3)$$

where, u , v are velocity along x and y axis respectively, P is the pressure, ρ is the fluid density which is constant for the present work since flow is considered as incompressible and ν is the kinematic viscosity of the fluid.

3. Result and Discussion

The experimental data obtained from the wind tunnel were validated by using simulation results for various angles of attack using SAS turbulence modelling. The model was solved with a range of different angles of attack $0^\circ, 5^\circ, 10^\circ, 15^\circ, 20^\circ$ and at two different Reynolds numbers of 2.21×10^5 and 2.81×10^5 .

On an aerofoil, the resultant forces are resolved into two forces and one moment. The component of the net force acting normal to the incoming flow is known as the lift force and the component of the net force acting parallel to the incoming flow is known as the drag force. The curves of lift and drag coefficient are shown for the said angles of attack, computed with the turbulence model and compared with experimental data.

3.1 Comparison between the experimental data and numerical simulation results of the lift coefficient curve for NACA 0012 aerofoil

The lift coefficient (C_L) increases with increase in angle of attack and this trend of increase in lift coefficient is notice up to 13° angle of attack, after 13° angle of attack it is observed from the figure 4 that lift coefficient start decreasing. Experimental result reveals that flow remains attached to the airfoil up to angle attack of 13° , after this the flow on the upper surface of the airfoil began to separate which leads to form the vortex behind the aerofoil (both from leading and trailing edge of aerofoil) and a condition is known as stall began to develop. The comparison of the two plots reveals that with an increase of Reynolds number C_L increased. This is due to the fact that the viscous effects are relatively large at lower Reynolds numbers causing high drags and limiting the maximum lift, while at the higher values the lift-to-drag ratio improves. The SAS turbulence model had the same behaviour with the experimental data as well as after the stall angle with a maximum error of about 15%.

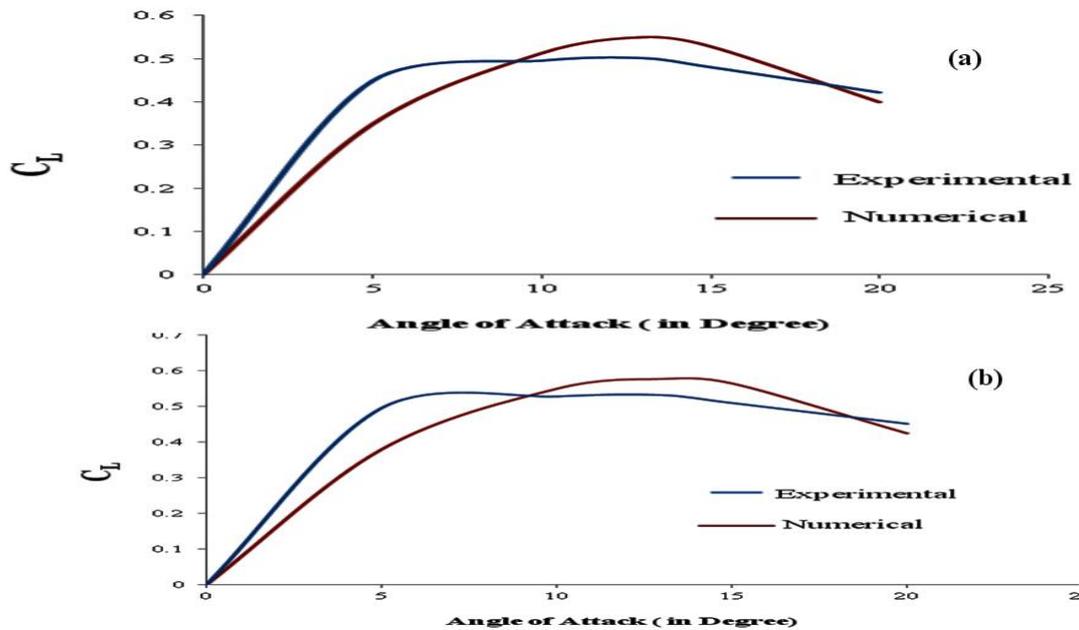


Fig.4. Comparison between the experimental data and numerical simulation results of the lift coefficient curve for NACA 0012 aerofoil at (a) 2.21×10^5 and (b) 2.81×10^5 Reynolds number.

3.2. Comparison between the experimental data and numerical simulation results of the drag coefficient curve for NACA 0012 aerofoil

Drag coefficient increases with the increase of angle of attack both experimentally and numerically (Figure 5). The predicted drag coefficients by the two equation SAS(Scale Adaptive simulation) were observed to be higher than the experimental data. This over prediction was expected because the actual aerofoil has laminar flow over the forward half. The turbulence model cannot calculate the transition point from laminar to turbulent and consider boundary layer is turbulent throughout its length. As the turbulent boundary layer carries more energy, C_d becomes much greater than at viscous boundary layer, which carries less energy. The comparison of the two plots confirms the already stated fact that with an increase of Reynolds number C_d increases.

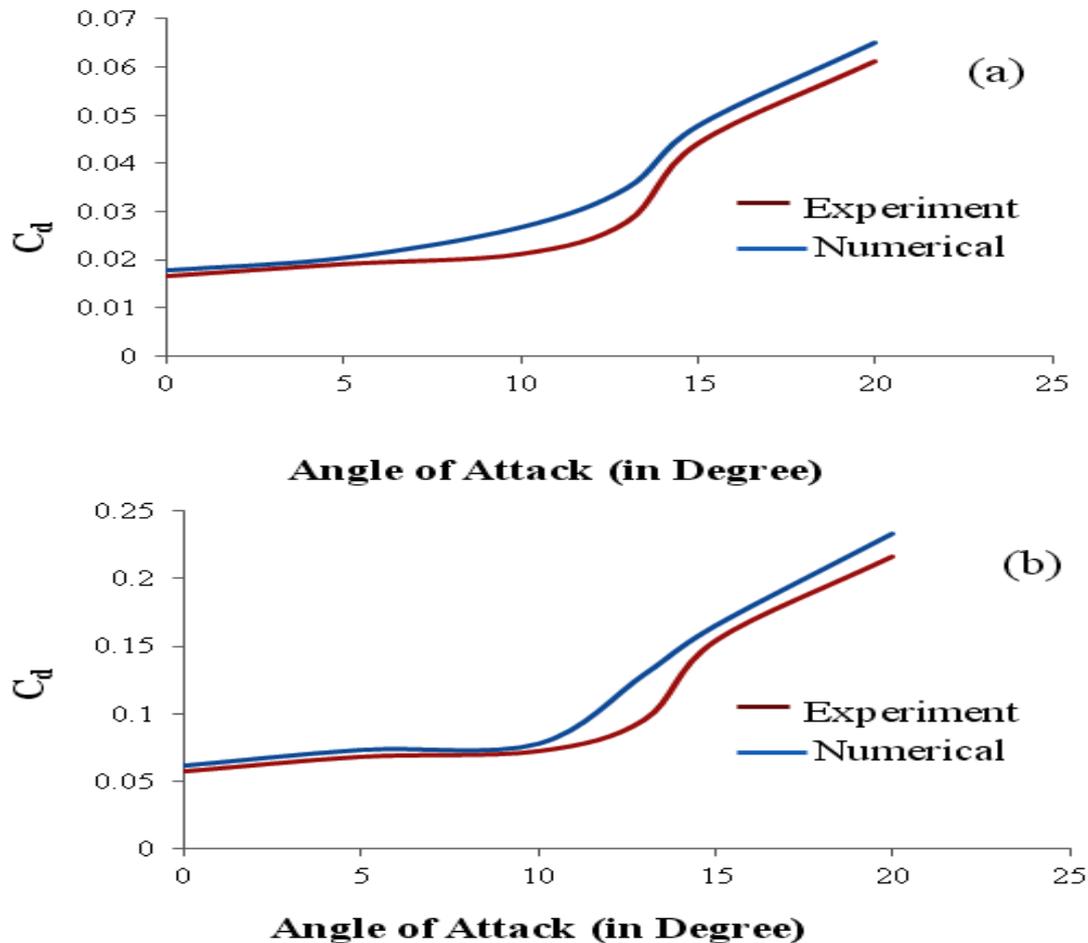


Fig.5. Comparison between the experimental data and numerical simulation results of the drag coefficient curve for NACA 0012 aerofoil at Reynolds number (a) 2.21×10^5 and 2.81×10^5 respectively.

3.3. Variation of ratio of Lift and Drag (L/D) with angle of attack

With the increase in Reynolds number, the Lift and drag ratio (L/D) is decreasing as it is clear from the figure 6. It is noticed from the figure that with 25% increase in Reynolds number there is 74% decrease in L/D ratio. The lift system of the NACA0012 aerofoil decreases with increasing Reynolds number. This is because the flow becomes turbulent and boundary layer separation occurs earlier which may cause a decrease in lift and increase in drag. So, this aerofoil shows high lift character at low Reynolds number.

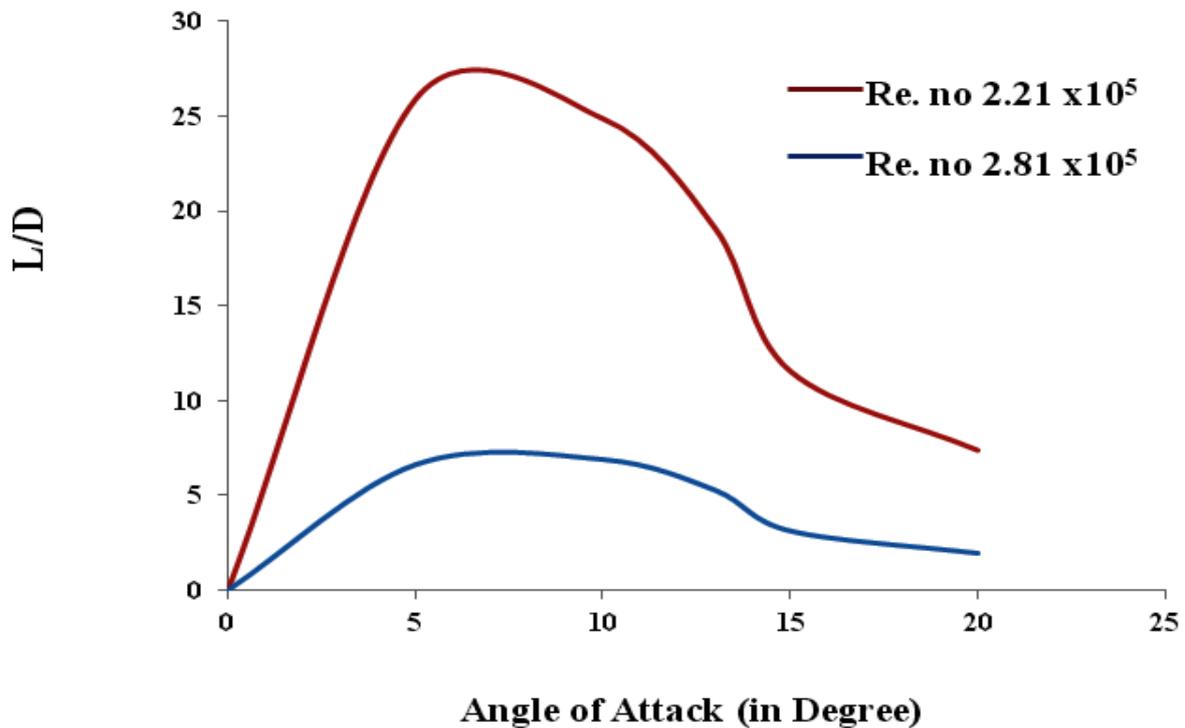


Fig.6. Variation of the ratio of Lift and Drag with the angle of attack at two different Reynolds numbers.

3.4. C_p (coefficient of pressure) variation with normalized chord length

The distribution of pressure coefficient (C_p) of the aerofoil obtained experimentally under different angles of attack is shown in the Figure7. It is observed that the pressure coefficient varied largely under different AOA (Angle of attack). Larger the AOA, greater is the difference of pressure coefficient between the lower and upper surface, hence greater lift. The coefficient of pressure difference is much larger on the front edge, while on the rear edge it was much lower, thus indicating that the lift force of the aerofoil is mainly generated from the front edge. Another feature observed here is that at each AOA, with an increase in Reynolds number, the difference of pressure coefficient between the lower and upper surface increases, thus increasing lift force.

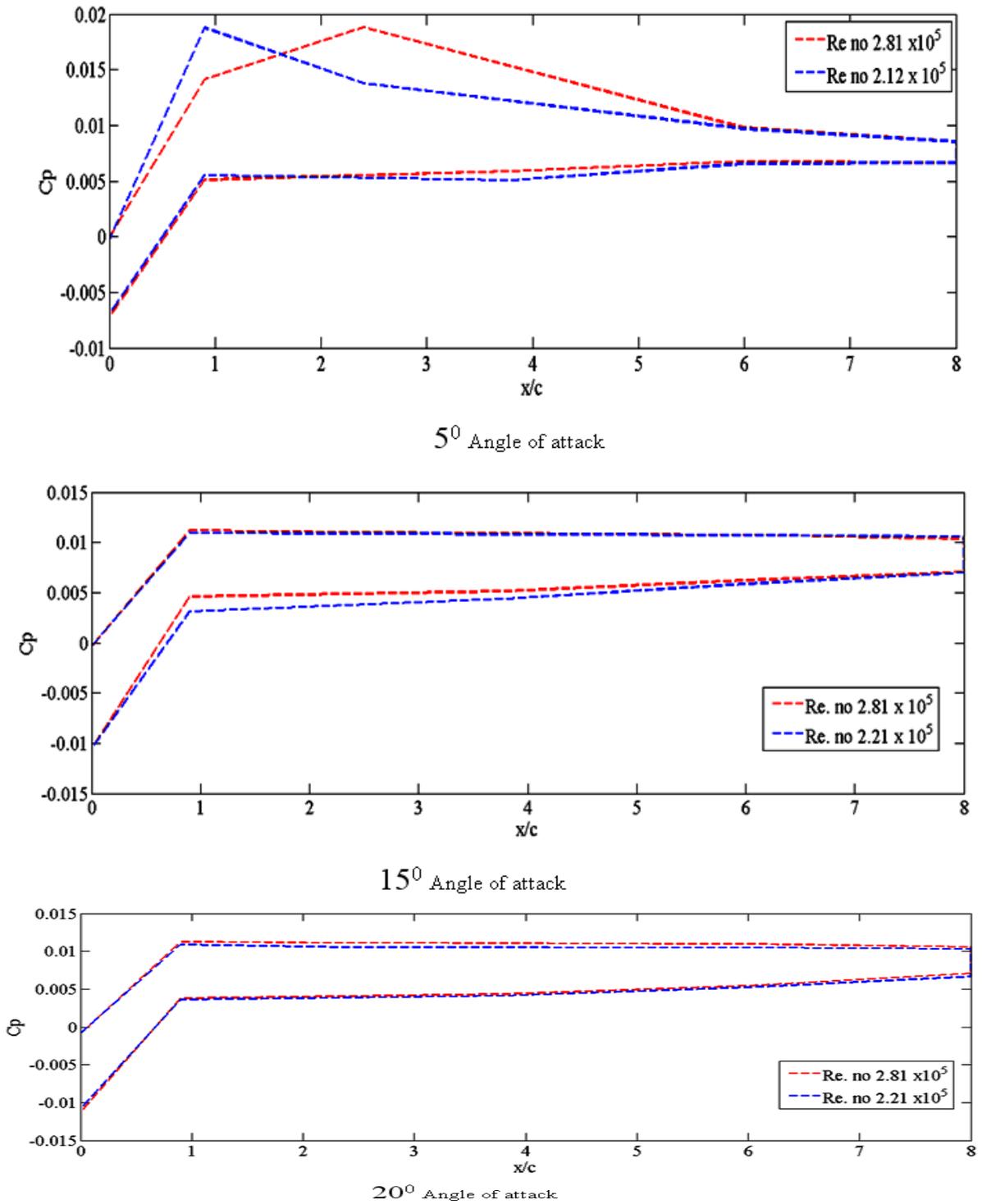


Fig.7. C_p v/s normalized chord plot for different angle of attack at two Reynolds number obtained experimentally

3.5. Vortex and contour plot for 15° angles of attack at different time interval

The velocity vectors of an NACA0012 aerofoil at a Re. no of 2.81×10^5 and 15° angle of attack are shown side by side in Fig.8 for different time instances in order to explain the vortex shedding phenomena as well as the flow features. The flow separates from the leading edge (Fig. 8(a)) and a clockwise vortex originates from the separated shear layer (Fig. 8 (b)) which grows in the stream-wise direction and reaches the trailing edge (Fig.8 (a)). The shear layer reaching the trailing edge creates higher suction pressure which causes the flow to separate from the trailing edge of the aerofoil and starts rolling in the counter-clockwise direction. This counter-clockwise vortex grows in the upstream direction and interacts with the leading edge vortex and tries to stretch it upward which causes the leading edge vortex to shed ((Fig.8c)) ; thus vortex shedding from leading edge occur. This process continues and Vortex Street formed behind the aerofoil known as Karman- Vortex Street which is shown in velocity contour plot in Fig.8 (a', b'c').

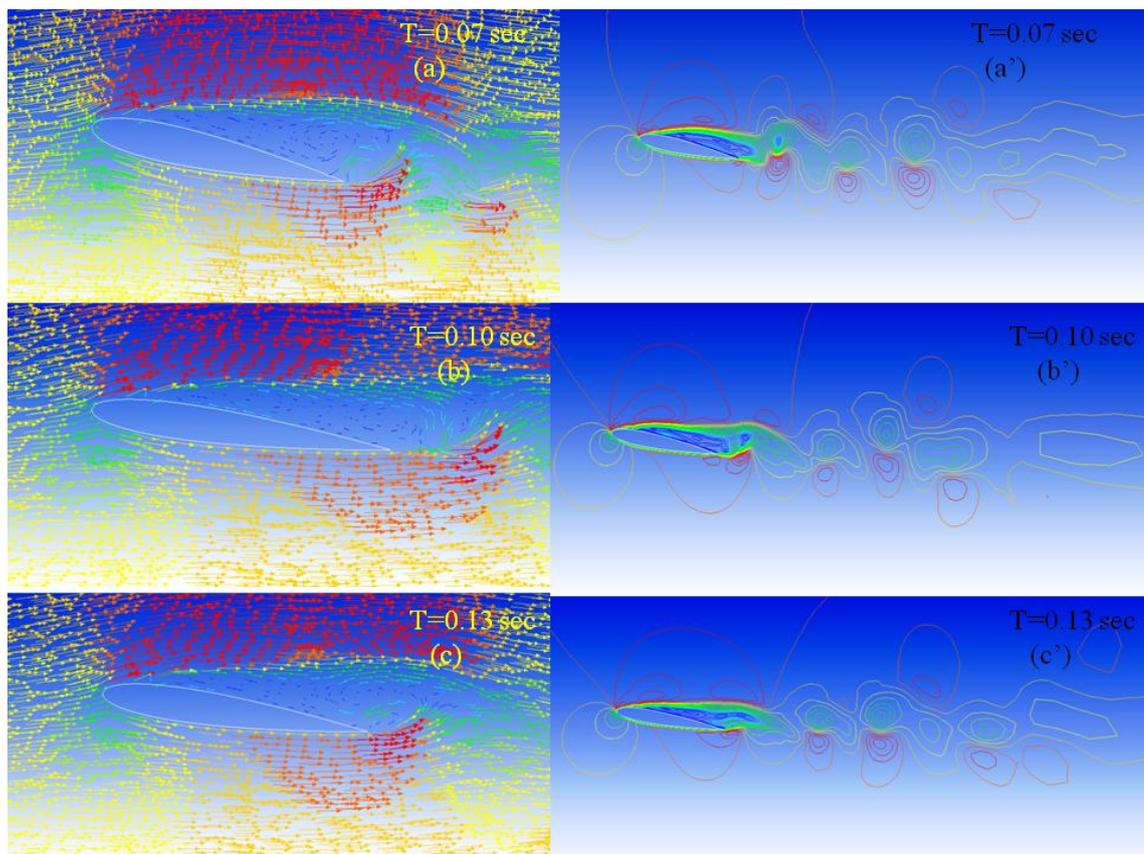


Fig.8. Vortex and contour plot for 15° angles of attack at different time interval with (a), (b) and (c) shows vortex shedding while (a'), (b') and (c') shows velocity contour for Re. no 2.81×10^5 .

Conclusion

A detailed numerical and experimental study was conducted to understand the effect of different Reynolds number on the flow and aerodynamics characteristics of the NACA0012 aerofoil for various angles of attack. It is clear from C_L and C_D plot that with increasing the angle of attack the lift of the aerofoil decreases while the drag increase and is true for both the Reynolds number which we have studied here. From L/D study we can get that NACA0012

loses its lifting performance as the Reynolds number increases. From the pressure coefficient (C_p) study one can conclude that with an increase in Reynolds number the width of the C_p plot decreases with increase in angle of attack thus the lift is decreased while drag increase. Also with increasing angle of attack vortex shedding from the leading edge increase and corresponding the lift decreases. Thus we can conclude that for 2D flow simulation leading edge vortex is dominating parameter which affects the aerodynamics performance.

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