Effect of Moving Surface on Aerodynamic Characteristics in NACA0012 Airfoil

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Abstract

This study focuses on the effects of moving surface on aerodynamics characteristics in NACA 0012 airfoil through numerical simulation. Two particular cases are considered: (i) Single moving surface (ii) Double moving surface. When 'single moving surface' is considered, only one moving surface of 10% of the chord length(c) is placed at upper surface of the airfoil starting from 0.05c to 0.15c. When 'double moving surface' is considered, one moving surface of 10% of the chord length is placed at upper surface at position starting from 0.05c to 0.15c and the other moving surface of same size is placed at lower surface at same position. Momentum injection into the flow field moves the point of boundary layer separation in the vicinity of trailing edge of the airfoil. By momentum injection through single moving surface with the surface velocity twice the free stream velocity and for different angle of attack, it is possible to reduce the average drag coefficient by 23.9%, compared with no moving surface. For the same condition with double moving surface, it is possible to reduce the average drag coefficient by 25.9%. For using moving surface, boundary-layer separation is delayed along the chord length on the upper surface of the airfoil. The value of lift coefficient increases slightly for moving surface. For single and double moving surface, average increment of lift to drag ratio are 37.3% and 41% respectively.

Keywords: Moving surface, boundary layer separation, momentum injection.

Nomenclature:

C_d	Drag coefficient
C_p	Pressure coefficient
C_l	Lift coefficient
c	Chord length (m)
U	Free stream velocity (m/s)
u	Moving surface velocity (m/s)

1.0 Introduction

Flow separation around the trailing edge (TE) has significant effects (e.g. lift reduction, drag enhancement, greater fuel consumption as well as lower flight endurance and lower achievable speed) on aerial application. The wake formation attenuates the pressure differential on airfoil, especially at high angle of attack. The application of momentum injection via moving surface in the flow field energizes the flow field and reduces the adverse pressure gradient and attenuates the wake formation. For the past years, considerable effort had been devoted to the investigation of the application of suction, blowing, vortex generation etc. However, the introduction of moving surface in an airfoil for reducing drag is comparatively a new concept. So, there is a great opportunity in lift augmentation, drag reduction and manipulating other aerodynamic behavior by incorporating moving surface.

A practical application of Moving Surface Boundary Layer Control was demonstrated by Favre [1]. He studied an airfoil with an upper surface formed by a belt moving over two rollers. The separation was delayed until the angle of attack reached to 55 degrees, where the maximum lift coefficient of 3.5 was realized. Mokhtarian et al. [2]. investigated the effect of the shape of the rotating cylinder on the lift coefficient of the airfoil. He used a scooped cylinder on the airfoil leading edge and proved that the resulting lift coefficient was increased for low cylinder speeds. Garni et al. [3] conducted a study where they experimentally analyzed the flow separation over a NACA 0024 airfoil with a leading-edge rotating cylinder. Their results indicated that an increase in the lift coefficient (C_l) when the ratio of the cylinder speed to the free stream velocity was increased. For moving surface velocity 4 times than the free stream velocity, the maximum lift coefficient was 1.6 and the stall angle was approximately 30°. Modi and Deshpande [4] performed experiments to investigate the effect of a rotating cylinder on the leading edge of a Joukowski airfoil. A 37-mm diameter rotating cylinder was positioned on the leading edge of a 370 mm chord airfoil. The pressure coefficient (C_p) plots indicated much lower pressure on the top surface of the airfoil when the ratio of the cylinder's circumferential speed over the free stream velocity increased. Modi et al. [5] investigated the lift coefficient of an airfoil with rotating cylinders. They used both splined and smooth cylinders and compared their effects on the lift coefficient of the airfoil. They concluded that the lift coefficient increased when the ratio of the cylinder speed to the free stream velocity increased. Thom [6] also compared the lift and drag coefficients of rotating cylinders with different end shapes. He concluded that the rotating cylinder with square ends produced higher lift coefficient than the round ended cylinder. But the square ended cylinder also produced higher drag coefficient values. Modi et al. used two rotating cylinders at the front and back of a flat plate [7]. They produced the drag coefficients for different ratios of cylinder speed to the free stream velocity for $0 \leq$ angle of attack $\leq 90°$. They concluded that the rotating cylinders reduced the drag coefficient of the plate as the velocity ratio increased.

In this present research, numerical simulation on boundary layer control is done by moving surface in NACA 0012 airfoil. This simulation is done by ANSYS Fluent 15.0 software by using Transition SST-4 Equation model. The air stream of Mach 0.15 and Reynolds number 3×10^6 are used for the analysis. Different moving surface velocity is applied for this present study, while keeping constant free stream velocity of 43.8 m/s. The objectives of this research are: (i) to reduce drag of the airfoil, (ii) to retard the growth of the boundary layer by minimizing the relative motion between the surface and the free stream (iii) to create a region of high suction and thereby accelerates the flow in its neighborhood outside of the boundary layer and (iv) to minimize the adverse pressure gradient and to delay the boundary layer separation.

2.0 Geometry and computational domain

NACA 0012 airfoil is used for the geometry. For single moving surface condition as shown in Figure 1(a), the moving surface starts from x=0.05c and ends at x=0.15c on the upper surface. The length of moving surface is 0.1c. The moving surface angle is 9° with the horizontal. For double moving surface condition as shown in Figure 1(b), the moving surface starts from x=0.05c and ends at x=0.15c on both the upper and lower surface. The moving surface lengths are 0.1c. The moving surface angle in upper and lower surface is +9° and -9° respectively. The computational domain with boundary conditions is shown in Figure 1(c). The domain is discretized by structured mesh having 1,20,000 grids.

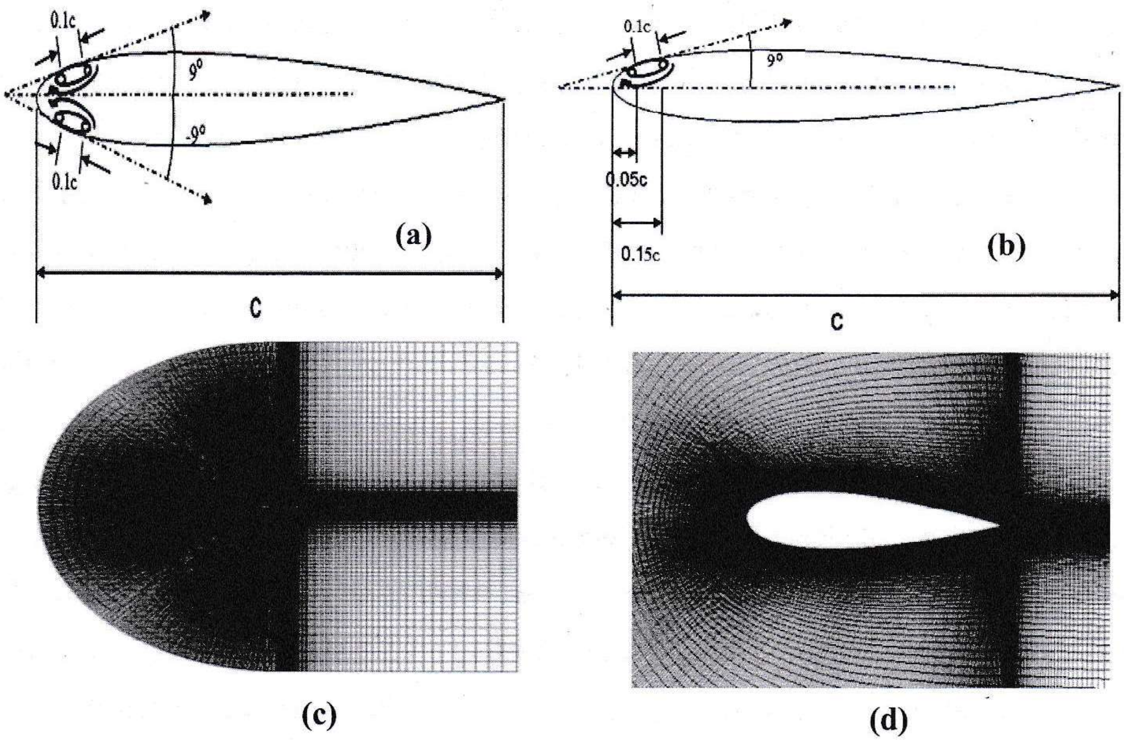


Fig. 1. (a) Geometry of NACA 0012 airfoil with single moving surface (b) Geometry of NACA 0012 airfoil with double moving surface (c) Computational Domain (d) Mesh around the airfoil.

3.0 Numerical method and validation

In the present study, the fluid is air and it is considered as ideal gas. The present numerical computation is performed in ANSYS Fluent 15.0. The flow field is considered to be viscous, incompressible and turbulent. In this paper, the NACA 0012, the well documented airfoil from the 4-digit series of NACA airfoils, is utilized. The free stream temperature is 300 K, which is the same as the environmental temperature. The density of the air at the given temperature is $\rho=1.225$ kg/m^3 and the viscosity is $\mu=1.7894\times10^{-5}$ Ns/m^2. For present Reynolds number, the flow can be described as incompressible. This is an assumption close to reality and it is not necessary to resolve the energy equation. Governing equations for present RANS computation are the continuity equation and conservation of momentum equation written in 2-dimensional coordinate system. The governing equations are discretized spatially using finite volume method of second order scheme.

$$\text{Continuity equation: } \frac{\partial v_x}{\partial x}+\frac{\partial v_y}{\partial y}=0 \tag{1}$$

$$\text{X – Momentum equation: } \rho\left(v_x\frac{\partial v_x}{\partial x}+v_y\frac{\partial v_x}{\partial y}\right)=-\frac{\partial p}{\partial x}-\left(\frac{\partial \tau_{xx}}{\partial x}+\frac{\partial \tau_{yx}}{\partial y}\right)+\rho g_x \tag{2}$$

$$\text{Y – Momentum equation: } \rho\left(v_x\frac{\partial v_y}{\partial x}+v_y\frac{\partial v_y}{\partial y}\right)=-\frac{\partial p}{\partial y}-\left(\frac{\partial \tau_{xy}}{\partial x}+\frac{\partial \tau_{yy}}{\partial y}\right)+\rho g_y \tag{3}$$

For present research, Transition SST-4 Equation Turbulence Model is used. The Transition SST model is based on the coupling of the SST k–ω transport equations with two other transport equations, one for the intermittency and one for the transition onset criteria, in terms of momentum-thickness Reynolds number. The performance of the present computational methods is verified against experimental data. Reynolds number for the simulations is Re=3x10^6 which is same as the reliable experimental data from Abbott and Von Doenhoff [8] in order to validate the present simulation.

Figure 2(a) presents the values of C_d and C_l for different angle of attack are obtained by simulation and are compared with the experimental data from the book of Abbot and Doenhoff [8]. In Figure 2(b), lift coefficient (C_l) is plotted for different angle of attack and compared with the experimental data of Abbot & Doenhoff [8]. From the curve, it is found that values of C_l is almost aligned with the experimental value within the range of angle of attack (AOA) between -8^o to 16^o. The result of simulation agrees qualitatively and quantitatively with experimental data and hence the code used for the present investigation is valid.

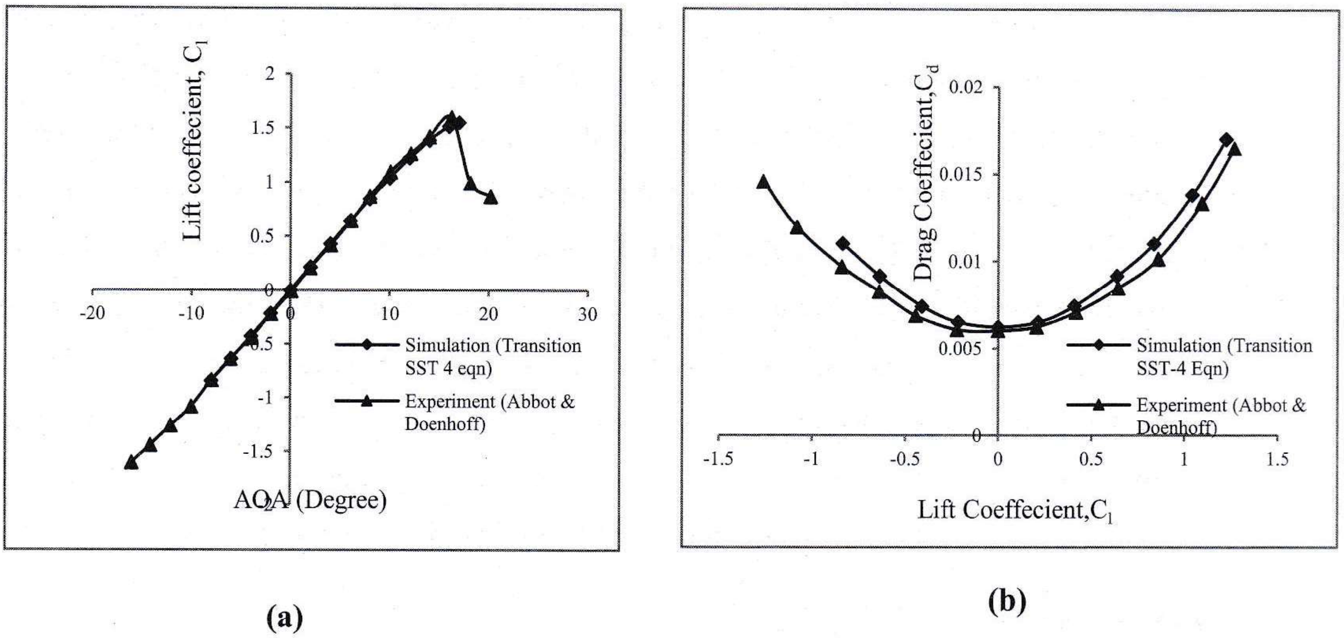
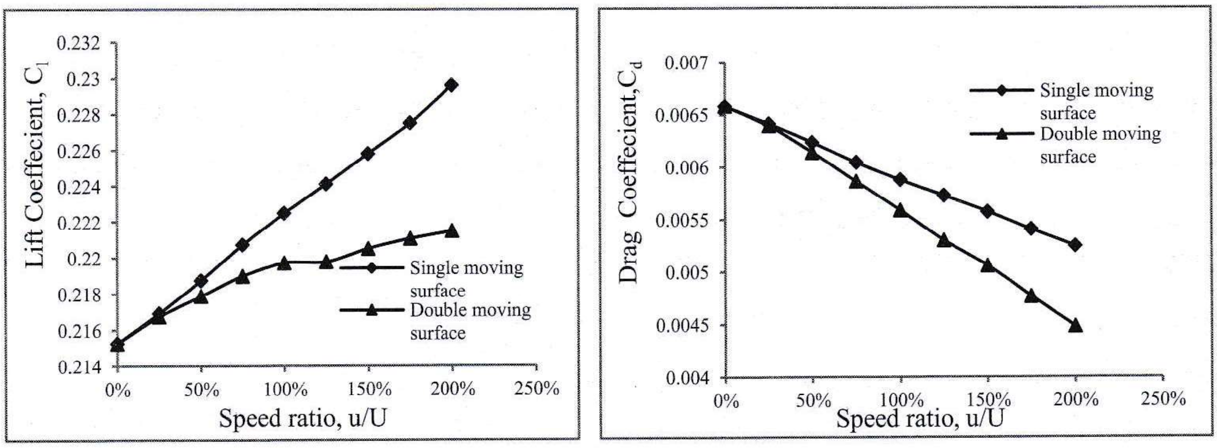


Fig. 2. (a) Variation of drag coefficient (C_d) for different lift coefficient (C_l) (b) Variation of lift coefficient (C_l) for different angle of attack.

4.0 Result and discussion

Figure 3(a) shows that the value of lift coefficient gradually increases with the increase of both single and double moving surface velocity. In the figure, 'u' denotes the moving surface velocity and 'U' denotes the free stream velocity. It can be pointed out that u/U=0 means there is no moving surface. For angle of attack of 2 degree, lift coefficient increases linearly for single moving surface, for double moving surface lift coefficient increases very slowly than that of single moving surface. It is found that initially for low speed ratio up to u/U=0.25, lift coefficient increases at the same rate for both cases. For maximum speed ratio (u/U=2) lift coefficient increases about 6.7% for single moving surface and 2.9% for double moving surface with respect to no moving surface condition. The value of lift coefficient is 3.7% higher in single moving surface than that of double moving surface at maximum speed ratio.

Figure 3(b) shows that the drag coefficient decreases linearly for both cases, but reduction rate is higher for double moving surface. Initially drag coefficient reduces at the same rate for both cases for low speed ratio (u/U=0.25). At maximum speed ratio, the drag coefficient is 15% lower for double moving surface than that of single moving surface. The drag coefficient reduces about 20.3% and 32% for single and double moving surface respectively compared to no moving surface condition.



(a) **(b)**

Fig. 3. (a) Variation of Lift coefficient (C_l) for different speed moving surface, AOA = 2° (b) Variation of Drag coefficient (C_d) for different speed moving surface, AOA= 2°.

Figure 4 illustrates that the values of lift coefficient to drag coefficient ratio (C_l/C_d) gradually increases with the increase of both single and double moving surface speed. But the rate of increase is higher for double moving surface than that of single moving surface. For single moving surface C_l/C_d increases about 33.9% and for double moving surface C_l/C_d increases about 51.1% compared to no moving surface. Initially the rate of increase is almost same for speed ratio up to u/U=0.25 for both cases. At maximum speed ratio (u/U=2), the rate of increase is higher by 13% in double moving surface compared to single moving surface.

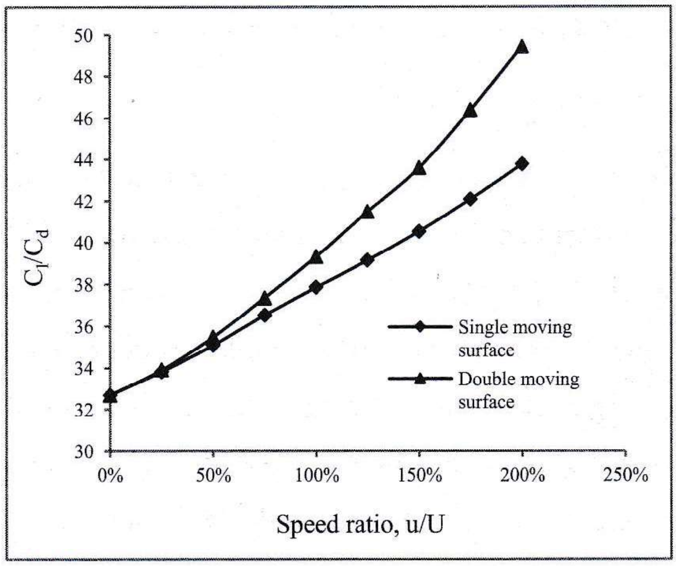


Fig. 4. Variation of Lift coefficient to Drag coefficient ratio (C_l/C_d) for different speed of moving surface, AOA = 2°.

Flow separation begins when $dU/dy \leq 0$. Figure 5(a) illustrates that for single moving surface of velocity u/U=2, separation delays significantly in upper surface of airfoil as momentum is injected into the flow field adjacent to the surface wall. Because of the energy injection the adverse pressure gradient reduces and results in aerodynamic advantage.

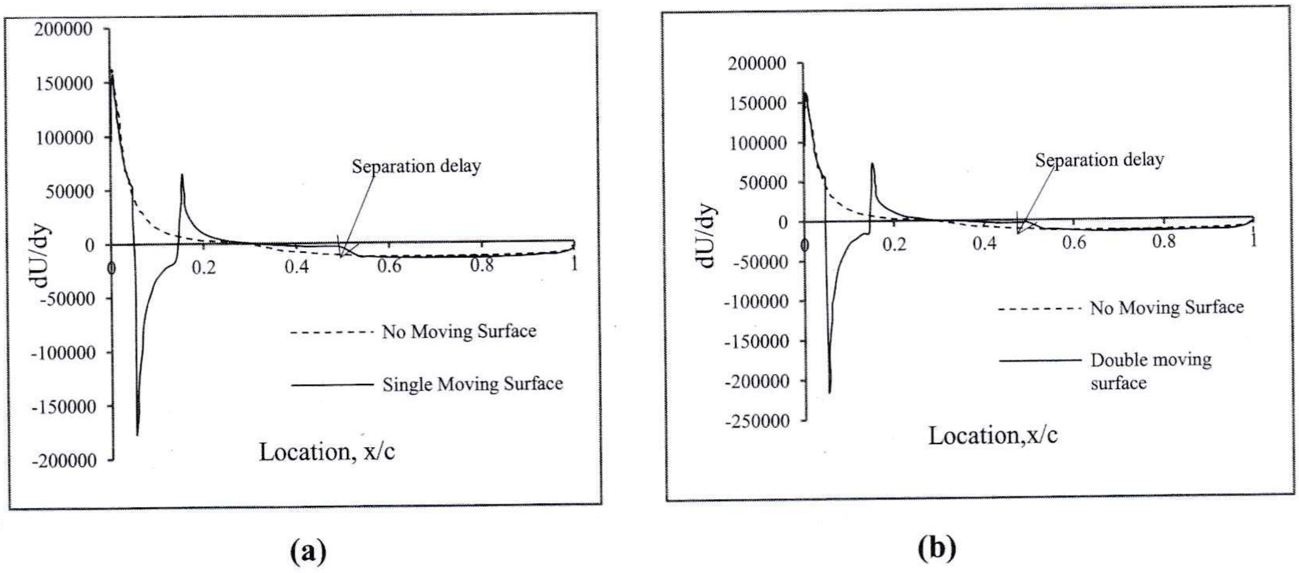
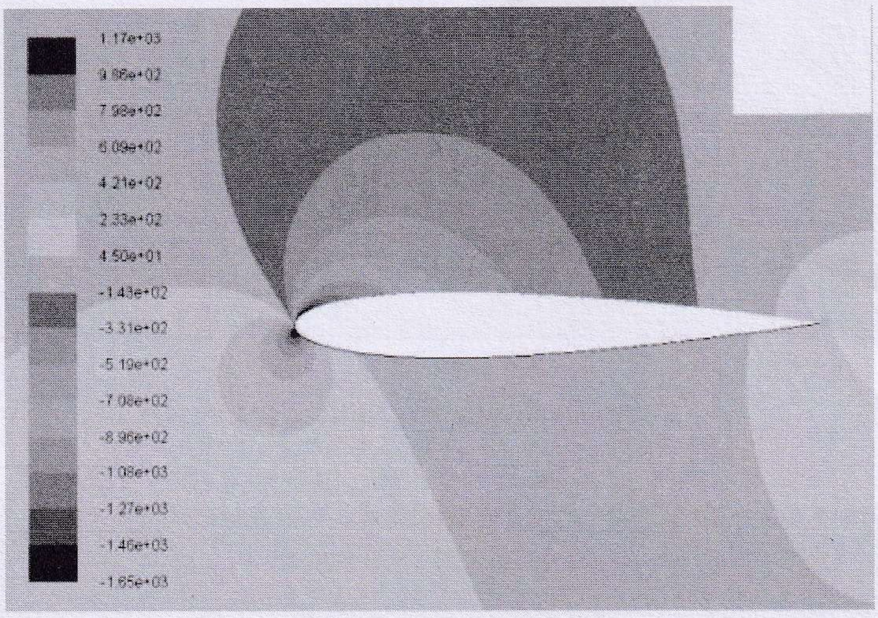


Fig. 5. Variation of differential velocity along y axis (dU/dy) across the airfoil for different wall condition (a) single moving surface (b) Double moving surface.

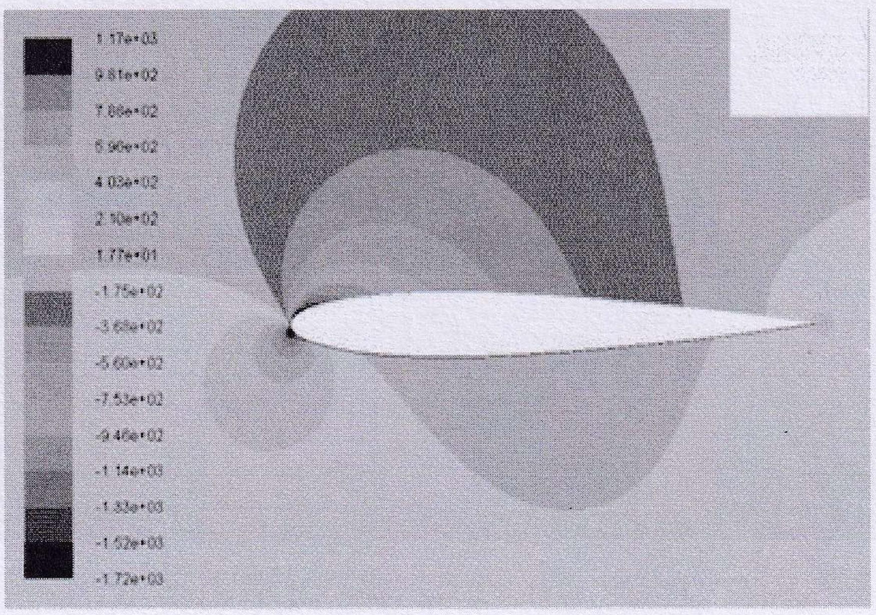
In Figure 5(b), for double moving surface of velocity u/U= 2, it is observed that separation delay is almost same as the case of single moving surface. In both cases, the initial sudden change of dU/dy is due to the momentum injection by moving surface. In the following figures, x is the distance measured along the chord.

Figure 6 illustrates the contours of static pressure variations around the airfoil at different angle of attack and moving surface conditions. In all cases moving surface velocity is considered 200% of free stream velocity. Figures 6(a), 6(b) and 6(c) show the pressure variations around the airfoil. The pressure increases around the lower surface of airfoil and low pressure region increases on the upper surface of airfoil for using single and double moving surface compared with no moving surface at 4^{o} angle of attack. The lowest value of the low pressure region above the upper surface is $-1.14e^{+03}$ Pa and the highest value of the high pressure region below the lower surface is $+2.10e^{+02}$ Pa. In case of 9^{o} angle of attack, Figures 6(d), 6(e) and 6(f) show the increment of high pressure region increases mainly at the leading edge of lower surface of airfoil for using single and double moving surface compared with no moving surface. The lowest value of the low pressure region above the upper surface is $-3.65e^{+03}$ Pa and the highest value of the high pressure region below the lower surface is $+2.97e^{+02}$ Pa.

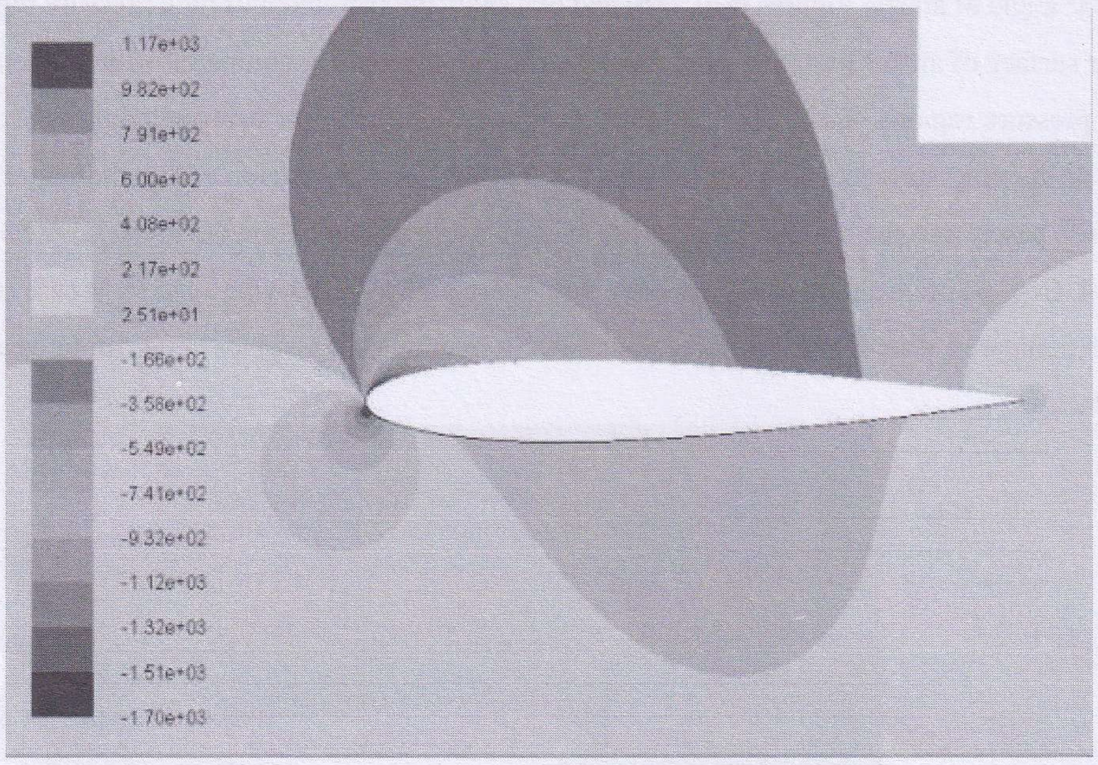
For 14° angle of attack, Figures 6(g), 6(h) and 6(i) show the increment of high pressure region near the lower surface of airfoil for using single and double moving surface compared with no moving surface. Low pressure regions on the upper surface do not change much for using moving surface compared with no moving surface. The lowest value of the low pressure region above the upper surface is -1.48e^{+03} pascal and the highest value of the high pressure region below the lower surface is +1.86e^{+02} pascal. Both positive and negative pressure values are higher for moving surface in case of 9° angle of attack compared with 4° and 14° angle of attack. So moving surface gives better lift in case of 9° angle of attack.



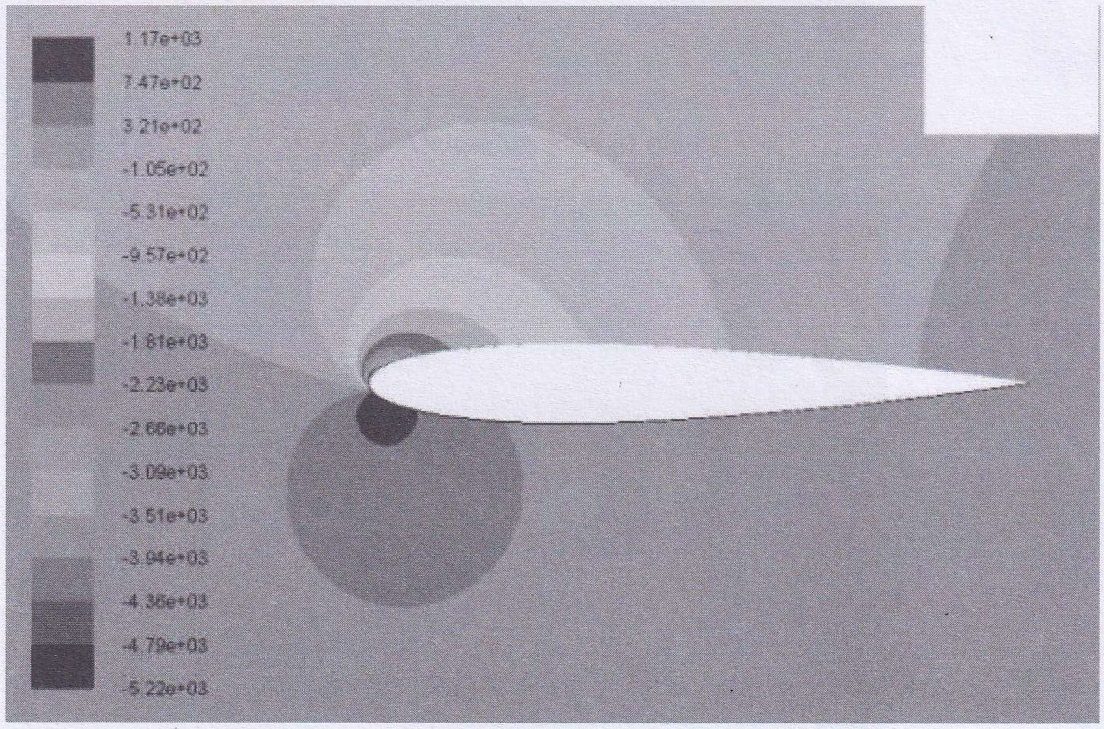
(a) No moving surface (AOA=4°).



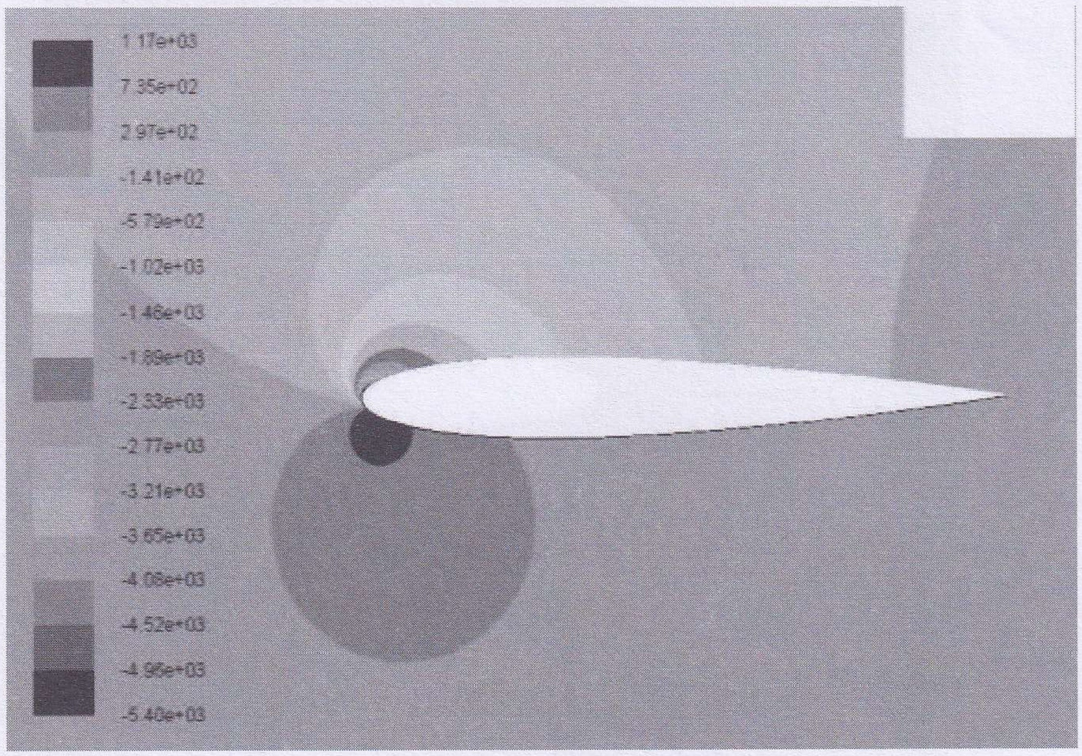
(b) Single moving surface (AOA=4°).



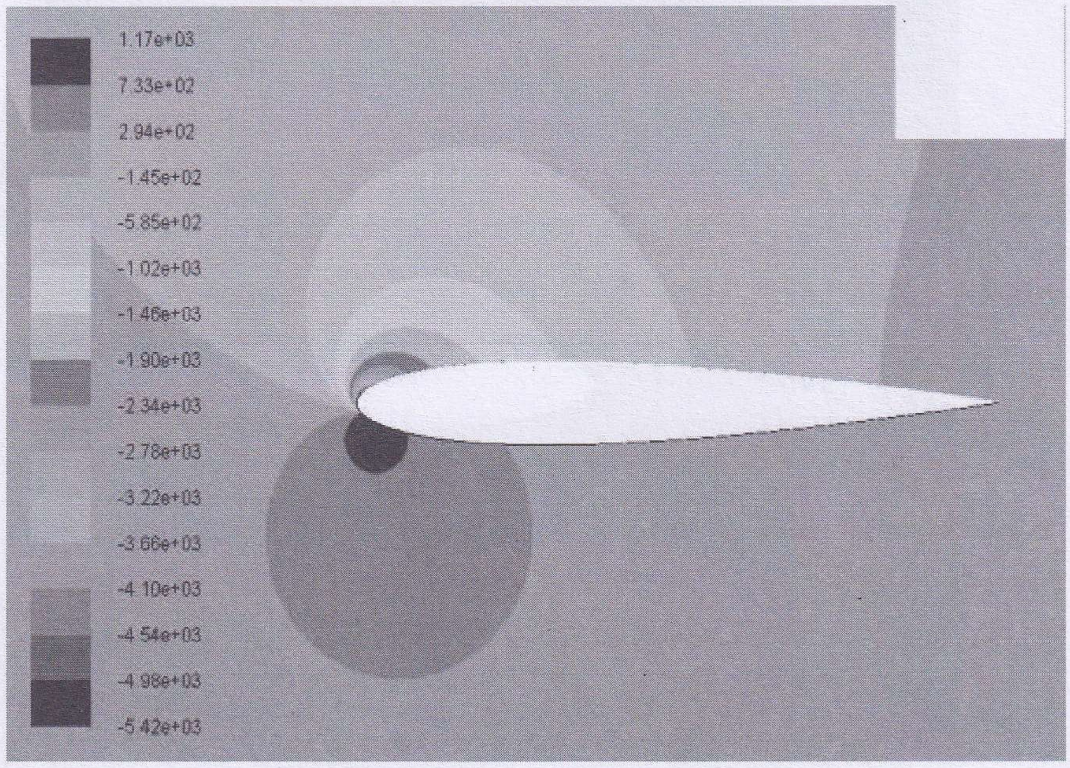
(c) Double moving surface (AOA=4°).



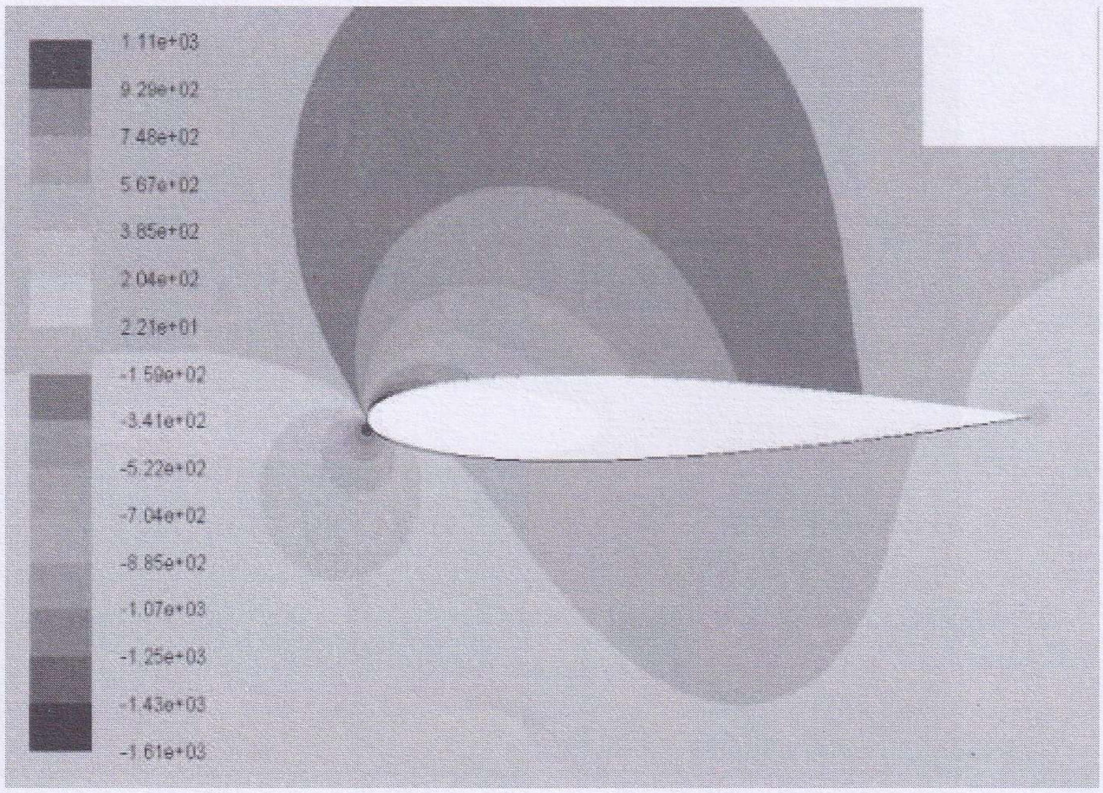
(d) No moving surface (AOA=9°).



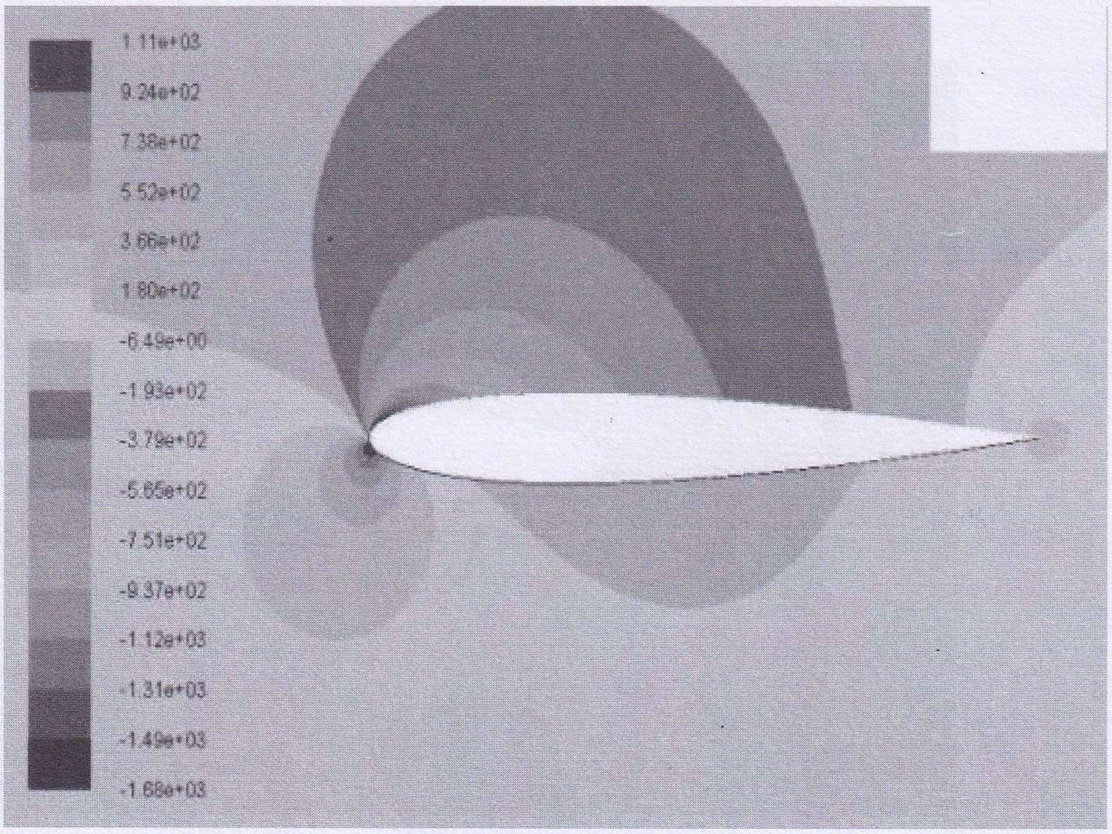
(e) Single moving surface (AOA=9°).



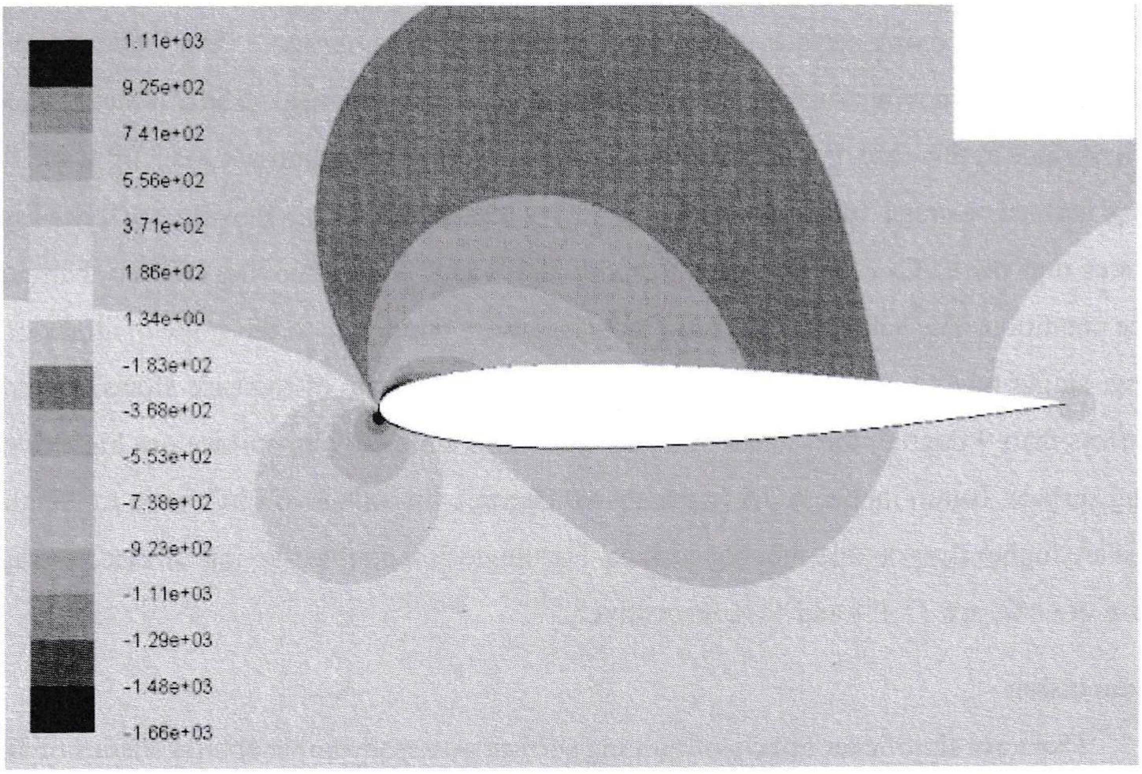
(f) Double moving surface (AOA=9°).



(g) No moving surface (AOA=14°).



(h) Single moving surface (AOA=14°).



(i) Double moving surface (AOA=14°)

Fig. 6. Static pressure contours of airfoil for various conditions.

Figure 7(a) shows that the values of C_d are lower for both single and double moving surface than no moving surface condition for different angle of attack (AOA). But in lower AOA (less than 9 degree) less drag is created for double moving surface, so performance of double moving surface is

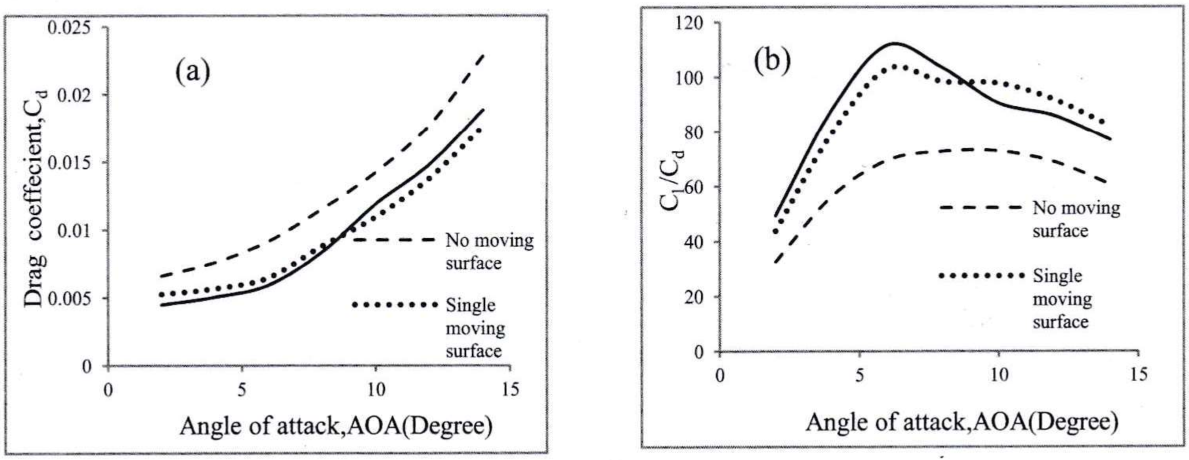


Fig. 7. (a) Variation of Drag coefficient (C_d) for different AOA for no moving, single moving and double moving surface. (b) Variation of Lift coefficient to drag coefficient ratio (C_l/C_d) for different AOA for no.

better than single moving surface in this case. But in higher AOA (more than 9 degree) less drag is created for single moving surface, so performance of single moving surface is better than double moving surface in this case. For single moving surface average reduction of C_d is 23.9% and for double moving surface average reduction of C_d is 25.9% compared to no moving surface. Figure 7(b) illustrates that the C_l/C_d ratio is higher for both single and double moving surface than no moving surface condition. The value of C_l/C_d ratio increases more rapidly up to the angle of attack of 6°. After moving, single moving and double moving surface. that the rate of increase slows down. In lower AOA (less than 9 degree) the values of C_l/C_d ratio for double moving surface are higher than single moving surface. But in higher AOA (more than 9 degree), the values of C_l/C_d ratio for single moving surface are higher than double moving surface. For single and double moving surface, average rate of increase of C_l/C_d are 37.3% and 41% respectively.

5.0 Conclusion

There are significant effects of moving surface on aerodynamic characteristics of airfoil. For using moving surface, boundary layer separation is delayed along the chord length on the upper surface of the airfoil. Momentum injection on the boundary reduces adverse pressure gradient. Drag coefficient decreases more rapidly for double moving surface than the single moving surface. But lift coefficient increases more rapidly for single moving surface than the double moving surface. For different angle of attack, using single and double moving surface average lift coefficient increases by 4.3% and 3.7% respectively. Besides drag coefficient reduces significantly for both single and double moving surface. For lower angle of attack, the performance of double moving surface is better than single moving surface for reducing drag coefficient. In case of higher angle of attack, the performance of single moving surface is better than double moving surface for reducing drag coefficient. For single and double moving surface approximate average drag reductions are 24% and 26% respectively compared to no moving surface. Lift coefficient to drag coefficient (C_l/C_d) ratio increases with the increase of angle of attack and reaches to a maximum value for 6° AOA and then it starts to decline. C_l/C_d ratio decreases more rapidly for double moving surface than the single moving surface after 9° angle of attack. For single and double moving surface, the average increase of C_l/C_d are 37.3% and 41% respectively.

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