DESIGN OPTIMIZATION OF AERODYNAMIC PASSIVE FLOW CONTROL ON NACA 0012 AIRFOIL USING VORTEX GENERATORS

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Abstract- Flow separation is a major challenge in aerodynamics. It adversely affects the performance of aircraft wings, wind turbine blades and compressor blades. It is also seen over the rear trunk of an automobile and in internal flows. A direct consequence of flow separation over an airfoil is reduction in lift and increase in drag, two aspects that adversely affect the aerodynamic performance of the airfoil. It also causes excessive vibration and loss of control. The underlying cause for flow separation is the lack of energy within the boundary layer to withstand adverse pressure gradients downstream of the airfoil. Vortex generator is a simple aerodynamic device that projects from the top surface of the airfoil. It forms a stream wise vortex that transfers high momentum fluid from the free stream to the boundary layer and low momentum fluid from the boundary layer to the free stream air. Thus the boundary layer is energized to withstand the adverse pressure gradients, hence preventing flow separation. This numerical study focuses on enhancing the lift coefficient of NACA0012 airfoil, by suppressing flow separation using passive rectangular vane type vortex generator. The effect of various vortex generator parameters such as spacing between the vortex generators (z), height of the device (h), local angle of incidence (β) and position of the device from the separation line (ΔX_{VG}), on the lift and drag coefficients of the airfoil were studied. Based on which optimum parameters were identified. The optimum configuration is at $\beta = 23^{o}$, h/C=0.004, z/C =0.025, ΔX_{VG} /C=.020 with C_L=1.0723 and C_D=0.1350. The lift coefficient has increased 43.36% from the baseline case and the drag coefficient has decreased by 41.54%.

Keywords: **Flow separation, adverse pressure gradients, boundary layer, vortex generators**

1. INTRODUCTION

Adverse pressure gradient in airfoil causes flow separation, which results in decrease in lift and increase in drag. It also results vibration and loss of control. Adverse pressure gradient may be due to high camber, high angle of attack (during takeoff, landing) or even due to sonic shock. Flow separation can be prevented by bringing the high energy fluid particle in the free stream to replace the low energy fluid particles in the boundary layer. Passive vortex generators are devices used for preventing flow separation. They do the same by shedding stream wise vortices downstream of the flow and hence brings the high energy free stream fluid to the boundary layer. The simplest vortex generator configuration is counter rotating vane type. The important device parameters are; 1.h/δ- the ratio of device height to boundary layer thickness, 2. z-the span wise distance between the devices, 3.β-the angle of incidence to the local flow, 4. e/h -device chord length to device height and 5. ΔX_{VG}- the distance upstream of the separation line. By varying these parameters, we could obtain different results and the goal of this paper is to obtain the most optimum configuration.

Hua Shan et.al [3] explains about their numerical simulation study using active and passive vortex generators. The results obtained shows that the passive vortex generators are able to reattach the separated flow in the immediate downstream region but the reattached flow was found to separate again forming the second separation bubble. The results indicate that active vortex generators are more effective than passive ones at controlling flow separation. John C Lin et.al [5] conducted experimental investigations on to evaluate boundary layer separation control on high lift system using surface mounted vortex generators. It was seen that Counter-rotating VGs with device height as small as 0.18% of reference airfoil chord could effectively control flow separation at landing conditions. Yasushi Ito et.al [7] showed that co-rotating vortex generators efficiently suppress the shock induced separation that occurred on transonic swept wings. Amith Seshagiri et.al [1] conducted a low speed wind, tunnel investigation detailing the effect of vortex generators on an airfoil at low Reynolds number (80,000 – 160,000). The results indicated that the static vortex generators were able to increase the maximum lift coefficient up to 25%. Marinos Manolesos et.al [6] conducted an experimental investigation on the use of passive vortex generators to suppress flow separation over an airfoil used for wind turbines. In total, maximum lift increased by 44%, while drag increased by 0.002% at pre-stall angles of attack.

VGs of Vane-type devices with counter-rotating configuration have been selected as the best performance passive system to delay or remove flow separation. For this configuration, we can see that the shapes of the VGs most used are triangular, rectangular and wedge shapes. Lift produced by rectangular VG is more than triangular but drag also more. The standard VGs work well with low angles of orientation relative to the mean flow direction $10° \leq \beta \leq 15°$. Whereas for micro-VGs the optimum angle is around β = 23°. The undesirable effect of the standard VGs is parasitic drag. The micro-VGs have the advantage of having a contribution to improving aerodynamic performance; increasing lift and reducing parasitic drag. But their use is limited for flows to fixed points of separation and this can be interpreted by the time limit of vortex. This paper aims to control flow separation on NACA 0012 airfoil at a higher angle of attack ($\alpha = 15^{\circ}$), using rectangular vane type vortex generators. The effect of different vortex generator parameters on the lift and drag coefficient is also studied, thus an optimum VG configuration is obtained for NACA 0012 airfoil.

2. METHODOLOGY

A CFD analysis is used to solve the problem. The software used is ANSYS 15. Finite volume method is used for discretization. The mesh was generated using the meshing software ICEM CFD. The numerical analysis is done in ANSYS Fluent.

2.1 GEOMETRY AND GRID

A 3D model was created in the design modeler in ANSYS 15. A rectangular type domain was selected for analysis as the orthogonal quality of elements were much better when compared to the C-type domain (orthogonal quality>0.4). The height of the domain is 7C and the length is 9.5C, (C- chord length 0.02244m) 3.5C upstream from the leading edge and 5C downstream from the trailing edge as per the dimensions obtained from the work of Hua Shan et.al [4]. A structured mesh was required for the application in order to capture the boundary layer effects. The structured hexahedral element mesh obtained using the 3D blocking strategy in ICEM is shown in figure 3. The total number of elements were 1,859,658.

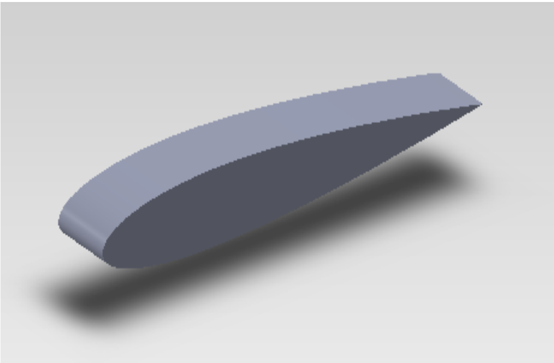


Fig.1 NACA 0012 Airfoil

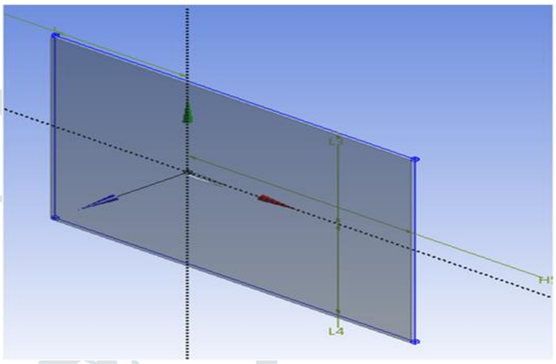


Fig.2 Airfoil with rectangular domain

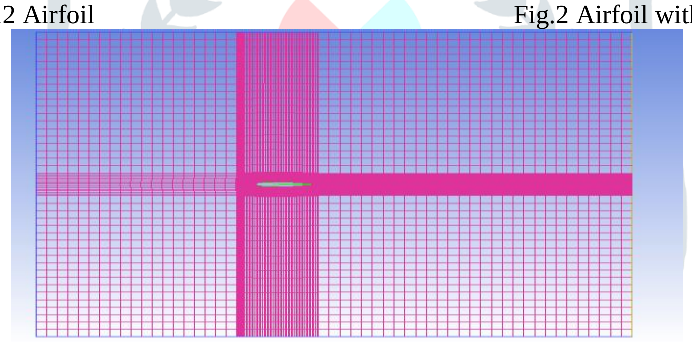


Fig.3 Structured mesh with 1859658 elements

Based on the skin friction plots from the baseline case (Fig.7) the separation line at an angle of attack of 15^{o} is found to be at 0.078C from the leading edge, corresponding to this a pair of counter rotating vortex generators (rectangular vane type) were designed with the following parameters: $\Delta X_{VG}/C = 0.015$,$z/C = 0.020, h/C = 0.004, \beta = 23°$.The mesh was generated using the meshing software ICEM CFD. The structured hexahedral element mesh obtained using the 3D blocking strategy in ICEM is shown in figure 5. The total number of elements found to be 1,869,305. A very fine mesh was generated near the vortex generator faces, 50 nodes were created on the height of the device with y+ of 0.001 and growth rate of 1.2 and 60 nodes in the z-direction.

Table1. Different parameters under study

VG's Parameters	Different Values
β	15, 23, 30
z/C	0.015,0.020, 0.025, 0.030
h/C	0.002, 0.004, 0.006
$\Delta X_{VG}/C$	0.010, 0.015, 0.020, 0.025

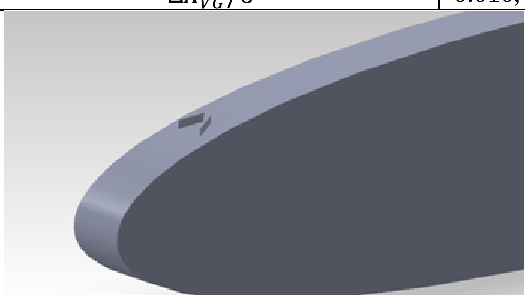


Fig.4 Airfoil with vortex generator

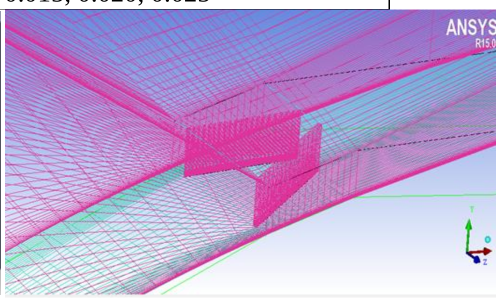


Fig.5 Structured mesh around VG's face

2.2 GOVERNING EQUATIONS

For a steady state, in-viscous, incompressible, three dimensional, turbulent flow, the equation of mass and momentum as write below,

Continuity equation,

$$\nabla.(\rho V) = 0 \quad (1)$$

Momentum equation,

$$\nabla.(\rho VV) = -\nabla p + \nabla.(\tau) \quad (2)$$

The transport equations for the SST k-ω model are given by

$$\frac{\partial}{\partial t}(\rho k)+\frac{\partial}{\partial x_i}(\rho k v_i) = \frac{\partial}{\partial x_j}(\Gamma_k \frac{\partial k}{\partial x_j})+ G_k - Y_k + S_k \quad (3)$$

$$\frac{\partial}{\partial t}(\rho \omega)+\frac{\partial}{\partial x_j}(\rho \omega v_j) = \frac{\partial}{\partial x_j}(\Gamma_\omega \frac{\partial \omega}{\partial x_j})+ G_\omega - Y_\omega + D_\omega + S_\omega \quad (4)$$

The inlet velocity of 69.206 m/s is given at the inlet (for free stream Mach number, M=0.2 and the chord Reynolds number Re=$1x10^5$). The outlet pressure is given as zero-gauge pressure. Symmetry boundary condition is imposed on the sides of the domain so that the effect of spacing between a pair of vortex generators comes into picture. The airfoil surface and the vortex generator faces are given the wall (no slip) boundary condition.

3. SIMULATION RESULTS

The numerical investigations were performed on the baseline case and on the airfoil with vortex generators. By varying vortex generator parameters the most optimum configuration was identified. The optimization strategy adopted was such that first the angle (β) was varied, an optimum angle identified, which was then retained for computations on varying the spacing (z). Similarly an optimum spacing was identified, which was used for computations on varying the height (h). Similar computations on varying the position from the separation line were also conducted.

3.1 VALIDATION

Huan Shan et al [4] conducted a numerical investigation of subsonic flow separation over a NACA0012 airfoil with a 6 ^{o}angle of attack and flow separation control with vortex generators. The numerical scheme of the present study was validated with the baseline case of their study. The free stream Mach number, M=0.2 and the chord Reynolds number Re=$1x10^{5.}$ The coefficient of pressure (C_P) plots obtained is shown in Figure 6. The results obtained from the work of Huan Shan et al has good agreement with the present study.

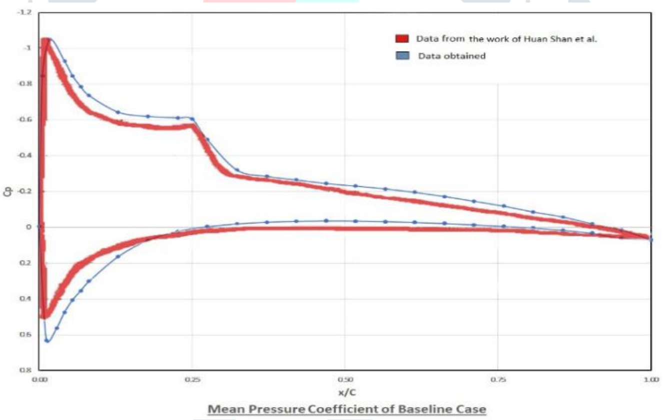


Fig.6 Variation of C_P over airfoil

3.2 SKIN FRICTION PLOTS

From the baseline case study at 15^0 angle of attack, the line of separation was identified from the skin friction plots. The variation of skin friction over the top surface of the airfoil is shown in figure 7.

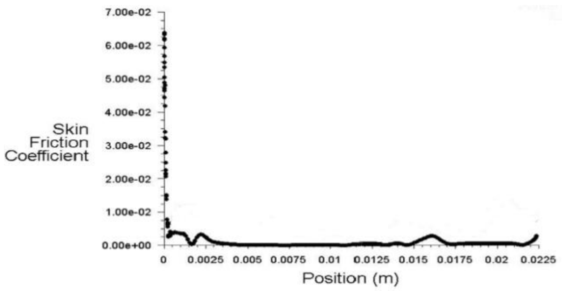


Fig.7 Skin Friction Plot without Vortex Generator

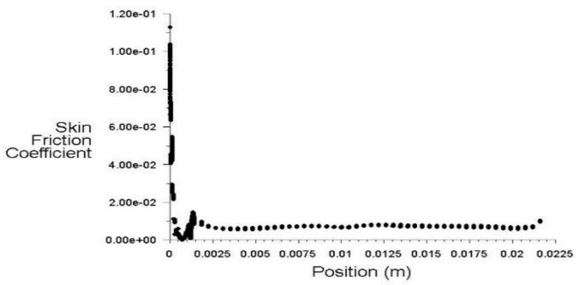


Fig.8 Skin Friction Plot with Vortex Generator

The location of separation is the position where the value of skin friction first becomes zero. This takes place x/C=0.078. Further observation from the graph suggests that the separated flow reattaches downstream and then separates again. The skin friction plot obtained with vortex generator at the optimum configuration is shown in fig. 8. The plot suggests that flow separation downstream of the vortex generator has been suppressed completely. It is also observed that at the position of the vortex generator the skin friction reduces to zero. This is probably due to slight separation immediately on the back face of the vortex generator, however this is comparatively insignificant.

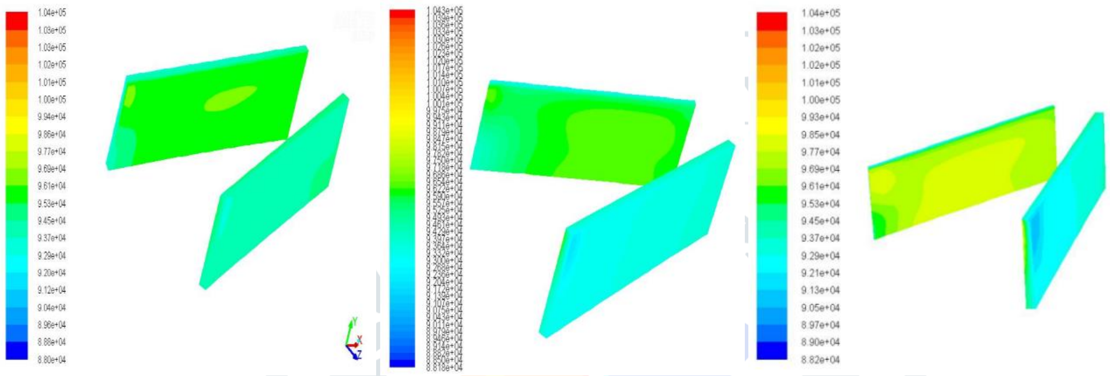
3.3 EFFECT OF ANGLE OF INCLINATION OF THE VG (β)

A summary of the results obtained for variation β is given in table 2. The remaining parameters kept constant during this study i.e z/C=0.020 $\Delta X_{VG}/C = 0.015$, $h/C = 0.004$

Table.2 Variation C_L of and C_D with β

β	C_L	C_D
Base line	0.748	0.223
15	0.985	0.053
23	1.018	0.134
30	0.947	0.139

It is seen that at all configurations C_L values are higher than the baseline case and the C_D values are lower than the baseline case. The higher C_L suggests that the flow separation has been suppressed. The lower C_D is due to reduction in pressure induced drag due to reduction in flow separated region. Further study into the pressure plots on the face of the vortex generator was conducted. The plots obtained are shown in figures 9 (a, b and c). It is seen that the main effect of varying the angle is to increase the pressure differentials across the faces of the vortex generators.



(a) (b) (c)

Fig.9 Pressure Variation across VG Faces for (a) β=15° (b) β=23° (c) β=30°

From all the above observations 23° is selected as the optimum angle with highest lift coefficient, this angle is retained for further investigations.

3.4 EFFECT OF SPACING (z/C)

The summary of results obtained from the investigations conducted on the variation of spacing is presented in table 3. The remaining parameters were maintained constant i.e $\Delta X_{VG}/C = 0.015$, $\beta = 23°$ $h/C = 0.004$ .The plots of C_L and C_D Vs spacing shown in Fig 10 and 11.

Table.3 Variation of C_L and C_D with Spacing

z/C	C_L	C_D
0.015	0.9515	0.1225
0.020	1.0184	0.1336
0.025	1.0364	0.1334
0.030	1.0310	0.1420

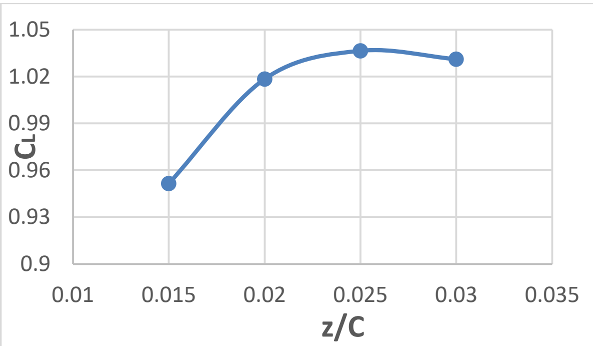


Fig.10 Variation of C_L with z/C

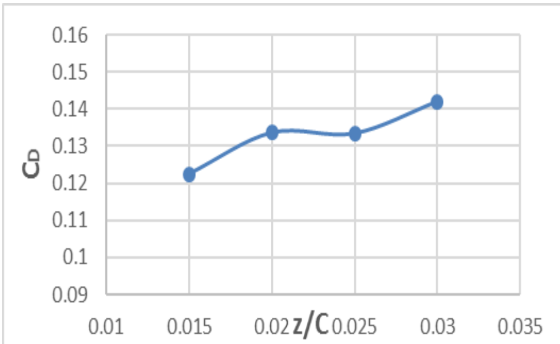
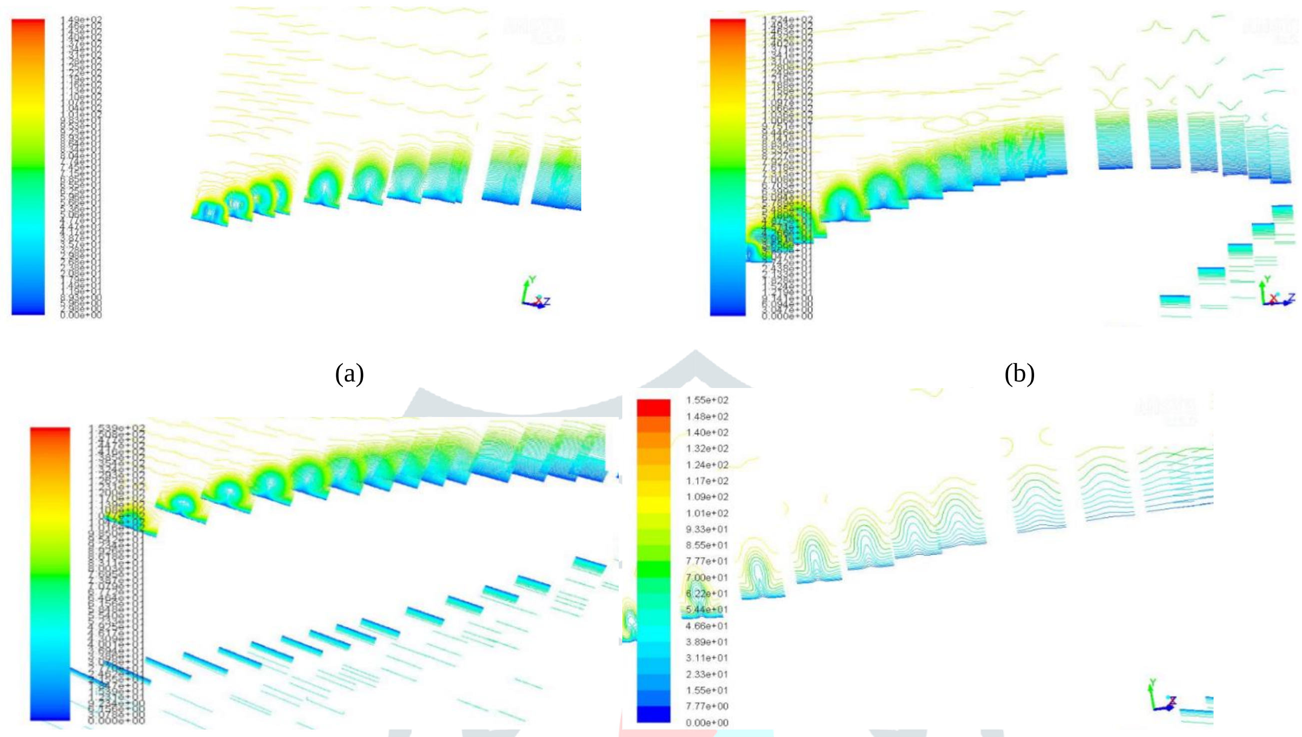


Fig.11 Variation of C_D with z/C

From the plots it is seen that C_L is maximum at z/C =0.025. The effective distance of the vortex generator is found from the velocity contours downstream of the VGs. The distance of the plane from the vortex generator at which the curvature effect of the vortex disappears on the velocity contours is considered as the effective distance. The velocity contours downstream of the vortex generator for each spacing tested is shown in figs 12 (a,b,c and d) and the results are summarized in table 4.



(a) (b) (c) (d)

Fig.12 Velocity contours downstream for (a) z/C = 0.015 (b) z/C = 0.020 (c) z/C = 0.025 (d) z/C = 0.030

Table.4 Variation of Effective Distance with Spacing

z/C	Effective distance/ C
0.015	0.187
0.020	0.225
0.025	0.362
0.030	0.349

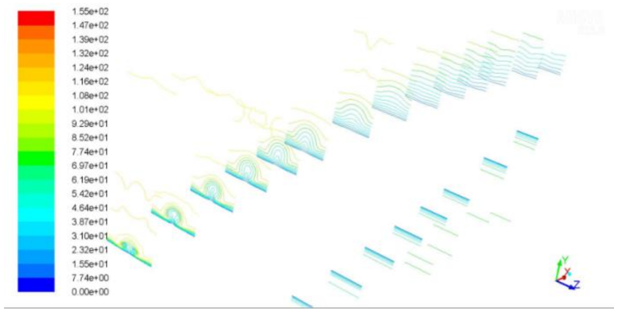
The spacing between the VG pairs plays an important role in the interaction between the vortices created. Healthy interaction between the vortices will mean that they strengthen each other and enhance effective distance of operation this is seen for z/C=0.025. If the spacing is too low, then the vortices decay quickly due to lack of interaction (z/C=0.015). Large spacing results in an insufficient amount of healthy air to be pumped into the boundary layer. An optimum spacing is seen at z/C=0.025, which has the greatest vortex effective distance and higher lift coefficient, this is retained for further investigations.

3.5 EFFECT OF HEIGHT (h)

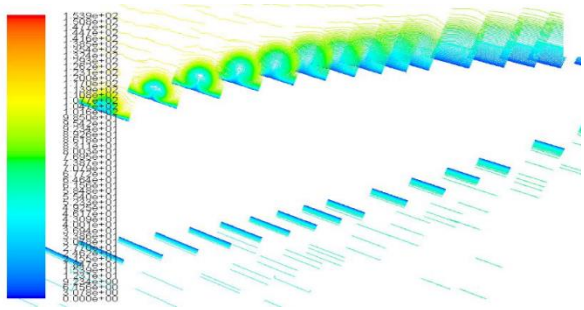
Study on the variation of height was conducted keeping other parameters constant $\Delta X_{VG}/C = 0.015$ $\beta = 23^o, z/C = 0.025$. Summary of the results obtained are tabulated in table 5.

Table 5 Variation of C_L and C_D with height (h)

h/C	C_L	C_D	Effective distance/C
0.002	0.806	0.1020	0.262
0.004	1.036	0.1334	0.362
0.006	1.024	0.1389	0.312



(a)



(b)

(c)

Fig.13 Velocity contour downstream for (a) h/C=0.002 (b) h/C=0.004 (c) h/C=0.006

The effective distance of h/C=0.002 was much lower compared to h/C=0.004, this is because the vortices formed decay quickly. Whereas increasing the height causes an increase in drag with no improvement in lift. From the above justifications h/C=0.004 is the optimum height, and is retained for further computations.

3.6 EFFECT OF POSITION FROM SEPARATION LINE ($\Delta X_{VG}/C$)

The vortex generators have to be placed upstream of the separation line such that there is enough energy within the boundary layer by the time it reaches regions of adverse pressure gradients. If it is placed too close to the separation line, then the boundary layer will not get enough energy to overcome these adverse pressure gradients. Whereas if it is too far away from the separation line, then the vortex strength will attenuate by the time it reaches the region of adverse pressure gradients.

Table 6 Variation C_L and C_D with $\Delta X_{VG}/C$

$\Delta X_{VG}/C$	C_L	C_D
0.010	0.9312	0.1152
0.015	1.0364	0.1334
0.020	1.0724	0.1304
0.025	1.0245	0.1290

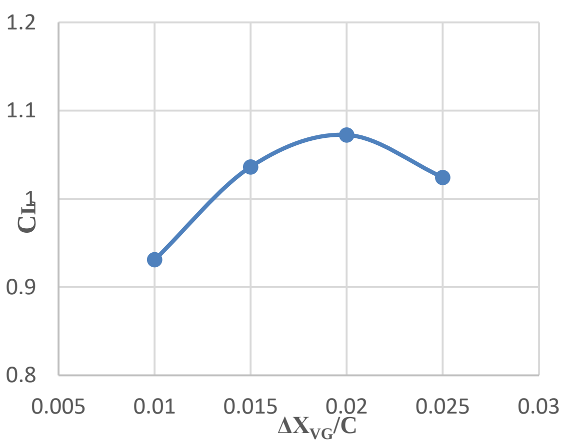


Fig.14 Variation of C_L with $\Delta X_{VG}/C$

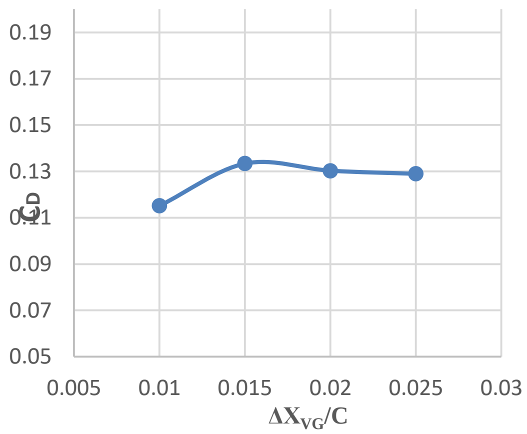
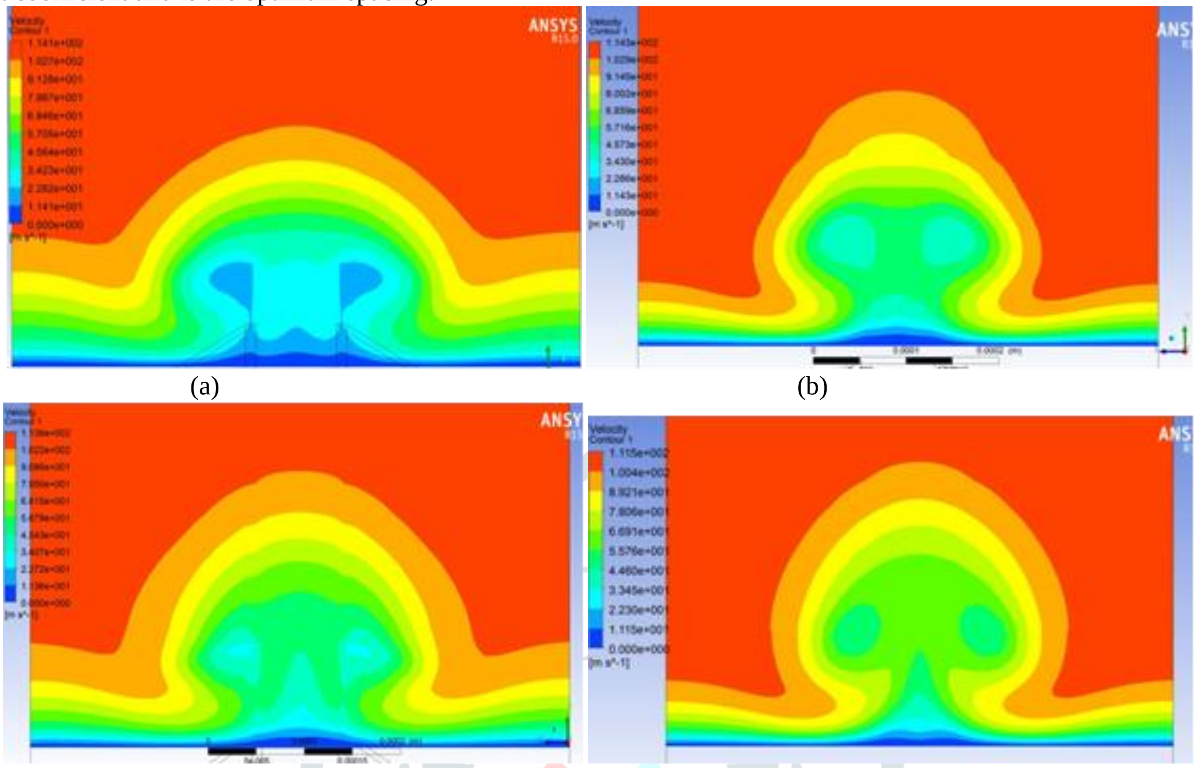


Fig.15 Variation of C_D with $\Delta X_{VG}/C$

The highest lift coefficient is seen in the case where ΔX_{VG} /C=.020. As seen from the velocity contours, sufficient mixing of the boundary layer has taken place in this case. Placing the VG close to the separation line as in $\Delta X_{VG}/C$=.010 leads to improper mixing of the boundary layer. Whereas placing it far from the separation line, $\Delta X_{VG}/C$=.0250, causes the vortex to diffuse as they reach the separation plane. The plots of ΔX_{VG} /C=.020 and ΔX_{VG} /C=.015 are similar. But from careful observation it can be seen that there is more energy within the boundary layer for ΔX_{VG} /C=.020. Hence ΔX_{VG} /C=.020 has a higher lift coefficient and is the optimum spacing.



(a) (b)

(c) (d)

Fig.16 Velocity Contour at z/C = 0.078 (a) ΔX_{VG}/C= 0.010 (b) ΔX_{VG}/C = 0.015 (c) ΔX_{VG}/C = 0.020 (d) ΔX_{VG}/C = 0.025

Hence it can be concluded that the optimized device parameters are: β=23°, z/C=0.025, h/C=0.004 and ΔX_{VG}/C = 0.020. Fig 17 shows the velocity contours in the baseline case. Flow separation is highly pronounced. Fig 18 shows the velocity contours with vortex generators, it is clearly seen that flow separation has been completely suppressed. Fig 19 shows the vortex core region. As seen high flow control obtained.

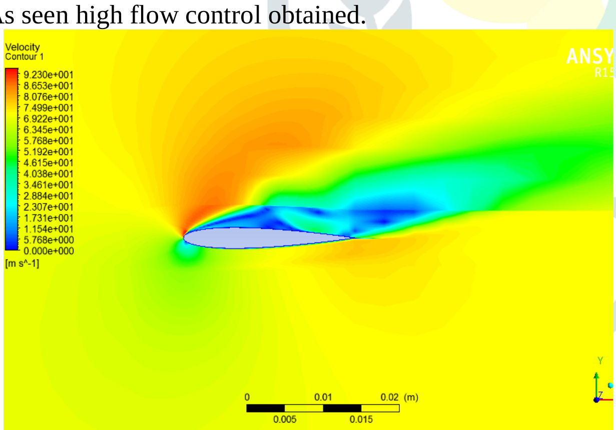


Fig.17 Velocity Contour Without VG

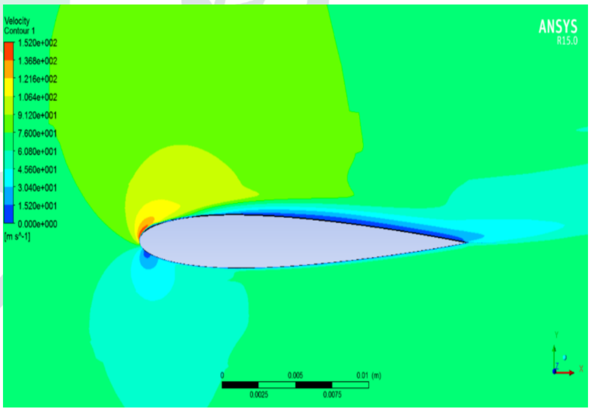


Fig.18 Velocity Contour with VG for optimum configuration

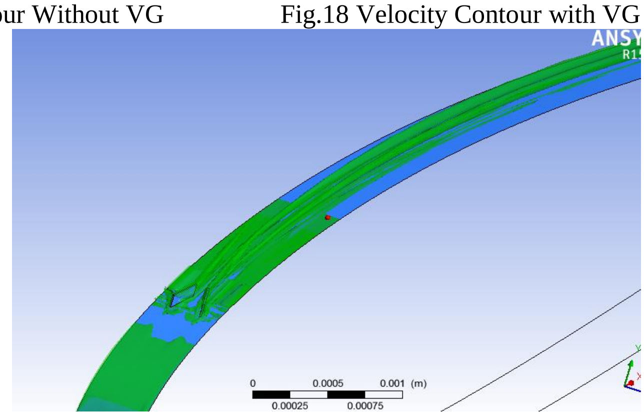


Fig.19 Vortex Core Region (Attached Flow)

4. CONCLUSION

Flow separation has been effectively suppressed by using vortex generators at the optimum configuration. This is deduced from the skin friction plots. There is a significant improvement in lift coefficient for all the configurations tested compared to the baseline case. The function of local angle of incidence of the vortex generator is to establish pressure differential across the faces of the control device. As the angle increases so does the pressure difference, this leads to stronger vortices. However very strong vortices tend to distort the flow and cause an increase in drag, as seen in the case of β=30 (for h/C=0.004, z/C=0.020, ΔX_{VG}/C=0.015)^o. The spacing between the vortex generators effects the interaction between them. An optimum spacing will cause the vortices to strengthen each other and increase the effective distances of the vortices. The optimum spacing is at z/C=0.025 (for h/C=0.004, β=23^o ΔX_{VG}/C=0.015). The height of the vortex generator determines the effective distance of the vortex and also plays an important role in the overall drag of the system. If the height is too low the vortex decays quickly and if it is too high, it increases the drag of the system.The optimum height was found to be h/C=0.004(forβ=23^o,z/C=0.025,ΔX_{VG}/C=0.015. Position from the separation line determines whether the boundary layer is properly mixed or not as it flows into regions of adverse pressure gradients. The optimum position with respect to the separation line was found to be ΔX_{VG} /C=0.020 (for β=23^o,z/C=0.025, h/C=0.004). The optimum configuration is at β =23^o, h/C=0.004, z/C =0.025, ΔX_{VG} /C=.020 with C_L=1.0723 and C_D=0.135035. The lift coefficient has increased by 43.36% from the baseline case and the corresponding drag coefficient has decreased by 41.54%.

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