Numerical Analysis of Passive Device for Aerofoil Performance Enhancement

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Abstract:

The objective of this paper is to identify the precision location for passive devices over an aerofoil to improve aerodynamic performances. The numerical analysis is carried out using the k-epsilon turbulence model to analyse the lift and drag coefficient at various angles of attack. The results show that the dimple is placed at the location of 20% of the chord and the vortex generator at the location of 15% to 20% provides better results that are used to enhance the lift coefficient of 4% and stall angle of 33% compared to the baseline aerofoils. The novelty of the work is to identify the suitable passive device and optimum location to enhance the aerodynamic performances. This method can be suitable for all types of subsonic wings, which improve the performance of an aircraft at various flying conditions.

Keywords: Aerofoil, Dimple, Drag Coefficient, Lift Coefficient, Vortex Generators

1. Introduction:

Nowadays airline transport services are increasing all over the country. It shows the demand to develop the new model aircraft which needs to meet the future requirements. One of the future developments in aircraft is to enhance the aerodynamic performances using various active and passive methods. In that, active methods need the requirement of power and operating mechanism. But in the passive mechanism is easy to execute due to the easy installation and no maintenance cost. The following literature explains the various vortex generator and dimples-related research work carried out.

Dubey, A., et al.,[1] investigate the efficacy of bump-shaped vortex generators placed at the roof end of Sedan and Hatchback car models to mitigate flow separation, a primary cause of aerodynamic drag. CFD analysis reveals that while vortex generators are not highly sensitive to design parameters, their use effectively reduces drag and lift coefficients in both car types. Udartsev, E., et al.,[2] explore novel aerodynamic strategies by employing complex volume vortex generators on wing leading edges, disrupting conventional cross-connected vortex patterns and mitigating hysteresis-induced drag increase. Implementing these generators on leading-edge slats induces an optimally organized longitudinal helical flow pattern, effectively eliminating hysteresis, enhancing the critical angle of attack, and improving momentum characteristics in wing vortex flow for unmanned aerial vehicles. Balaji, K., et al.,[3] investigates the impact of minute vortex generators (VGs) positioned at 50% chord on NACA 6321 and NACA 0021 aerofoils, enhancing stall AOA by 4 and 2 in simulation and experiment, respectively, without increasing drag. These VGs optimize boundary layer control, leading to improved aerodynamic efficiency for subsonic aircraft. Balaji, K., et al.,[4] investigate the placement of minute-sized vortex generators near separation points on various aerofoils, aiming to reduce parasite drag and enhance aerodynamic performance. Simulation results show an 18% increase in stalling angle of attack and a 1% drag increase for cambered aerofoils, with efficient performance observed particularly on symmetrical aerofoils. Experimental validation demonstrates good agreement with simulation, indicating the promising effectiveness of vortex generators in aerodynamic enhancement. Hasan, A., et al., [5] aimed to design an efficient electric-powered RC aircraft meeting SAE competition criteria. Using numerical simulations and wind tunnel tests, optimal winglet configurations and vortex generators were identified to enhance aerodynamic performance. Goharshadi, M., and Mirzaei, M.[6] study introduces Powerful Vortex Generators (PVGs) to delay stall points and increase maximum lift coefficient in low-wing aircraft. Computational fluid dynamics analysis validates PVG efficacy, showcasing up to 46% enhancement in maximum lift coefficient across various aircraft configurations. Ayudia, S. A., et al.,[7] investigates the effect of straight vortex generator application on NACA-4412 airfoil aerodynamics using computational fluid dynamics. Results indicate that vortex generator application increases lift coefficient compared to plain airfoil, with an optimum 13% increase observed at a 5º angle of attack. Hao, L., et al.,[8] study investigates the impact of variable height distribution of ramp vortex generators (VGs) on wing aerodynamics, revealing improved performance and stall inhibition. Optimal layouts, such as "Triangular translation 3" and "Trapezoidal translation 2," offer valuable insights for enhancing VG effectiveness. Priyanka, K. S., et al.,[9] research investigates airflow detachment prevention using vortex generators and passage vanes on a NACA 5 series 23013 airfoil, employing CATIA for 3D modelling and ANSYS 19.1 Workbench with K-epsilon SST model for analysis. Computational comparisons of lift and drag variations highlight the effectiveness of these flow control devices in maintaining airflow attachment to the surface. Chen, H., & Chen, B.[10] explore the effect of vortex generators on V-22 airfoil aerodynamics, revealing significant enhancements in lift coefficient and stall angle with optimal configurations. Double-row vortex generators show superior potential in suppressing flow separation, while height adjustments further enhance performance at large angles of attack. Subramanian, V., et al.,[11] investigate surface modifications on NACA 2412 airfoil, aiming to delay flow separation and enhance lift using dimples. Computational and experimental analysis, employing the K-ε turbulence model, demonstrates significant lift improvement with square dimples, promising enhanced aircraft maneuverability and performance. Manikandan, P., et al., [12] investigate the impact of passive outward dimples on aircraft wing surfaces, aiming to delay flow separation and reduce pressure drag. Through varied dimple configurations and Reynolds numbers, the research explores their effectiveness in maintaining flow attachment and minimizing energy loss and structural risks. Sowmyashree, Y., et al.,[13] performed aerodynamic improvements on the NACA 2412 airfoil via semi-circular dimples, showcasing decreased pressure drag and increased lift through CFD analysis at varied angles of attack. Inward dimples emerge as more effective, suggesting the potential for enhanced aerodynamic efficiency. Sett, R., et al., [14] study investigates the aerodynamic impact of golf ball-like dimples on 3D cambered wings, revealing superior performance of inward dimples over outward ones across varying velocities and angles of attack. Employing a multi-platform approach, the research highlights the potential of inward dimples for drag reduction and enhanced flight control. Khater, M. M., & Govindaraj, V.[15] explores how surface dimples on airfoils affect aerodynamics, revealing their potential to reduce pressure drag and enhance lift, particularly at different angles of attack. Through simulations of inward and outward dimple configurations, it demonstrates improved aerodynamic efficiency, validating their effectiveness in enhancing lift and decreasing drag. Vimal M, R., et al.,[16] investigates the impact of surface patterns, such as circular and square dimples, on winglet aerodynamics, aiming to reduce induced drag. Utilizing computational simulations with varying cant angles and dimple configurations, the study demonstrates decreased drag coefficients with dimpled winglets, showcasing potential improvements in aerodynamic efficiency. Ishrak, M. S., et al., [17] compares the aerodynamic performance of unmodified and modified NACA 2412 airfoils at various angles of attack, revealing changes in lift and drag coefficients under the same flow conditions. Utilizing FVM numerical method with the k-epsilon turbulence model, the study demonstrates that adding dimples reduces the stall angle by 10%, alters lift generation, and accelerates flow separation. Sukardin, M. S., et al.,[18] study investigates the aerodynamic effects of inline dimple rows on plate surfaces using Computational Fluid Dynamics (CFD) simulations. Results reveal that while pressure coefficients remain relatively stable with 2 to 4 rows of dimples, configurations with 5 to 6 rows show decreased coefficients, indicating changes in flow characteristics and potential drag reduction. Krishnamoorthy, V. [19] study aims to enhance aircraft aerodynamics by introducing dimples on the wing, reducing drag and delaying stall. Computational analysis on a NACA 0018 airfoil with square dimples shows improved aerodynamic efficiency, favouring dimple-induced turbulence for increased lift-to-drag ratios and enhanced aircraft performance. Abdullah, A. Q., & Dol, S. S. [20] investigate dimpled airfoil aerodynamics for UAV propellers, revealing significant enhancements in lift-to-drag ratios and stall angle by up to 39.9%, indicating potential efficiency improvements for drone applications. Computational analysis using ANSYS FLUENT showcases the beneficial effects of dimples in reducing pressure drag and delaying flow separation on NACA 2412 airfoils. Stolzman, J. E., & Manoharan, S.[21] examines the aerodynamic effects of dimples on

NACA 4414 and 0014 airfoils through computational analysis, revealing no improvement in performance despite various dimple configurations. Using ANSYS FLUENT, the investigation delves into flow structures to elucidate the reasons behind dimples' inefficacy on airfoil performance, contrasting with previous literature findings.

The various active methods used to enhance the aerodynamic parameters are listed in upcoming paragraphs.Balaji, K. & Wessley, G. J. J. [22] conducted a study on an Improving Blowing and Suction System (IBSS) that enhances aircraft wing performance by delaying boundary layer separation and increasing lift without the need for additional control surfaces. Their numerical analysis indicates that IBSS increases the stalling angle by 33% and lift by 37.5% compared to standard designs, outperforming existing methods such as the co-flow jet (CFJ). In a separate study, Katkar, A., et al [23], modified a NACA 6321 airfoil using a CFJ system with specific injection and suction slots to improve performance. Their results show a 27% increase in lift coefficient and a 33% rise in stalling angle of attack, suggesting that the CFJ method improves boundary layer control, thereby reducing aircraft weight and maintenance costs. In another study, Karuppiah, B., & Wessley, J. J. [24], presented a 3D analysis of the NACA 6321 airfoil using the Improved Blowing and Suction System (IBSS) to minimize the boundary layer. The results indicate that increasing the mass flow rate enhances aerodynamic performance, with a flow rate of 0.11 kg/s improving the stalling angle of attack by 60% and the lift coefficient by 50% compared to the baseline airfoil. Furthermore, Balaji, K., & Wessley, G. J. J. [25] provided a comprehensive review of the CFJ method for enhancing aircraft aerodynamic performance, highlighting its application in all wings, wind turbines, and ducts to reduce weight, drag, and runway distance. The review identified research gaps, emphasizing the importance of parameters such as injection velocity and Reynolds number in delaying flow separation, and noted the limited experimental studies in wind tunnels. Finally, Balaji, K., et al [26], experimentally validated the aerodynamic performance improvements of the IBSS on a NACA6321 aerofoil by regulating the layer on its top surface. The results show a 40% increase in stall angle, a 54% rise in lift coefficient, and a 33% reduction in drag compared to the baseline aerofoil, demonstrating that optimal slot placement near the aerofoil's peak thickness enhances performance across all flight phases while reducing power consumption. Anish, J., et al. [27], aimed to enhance the aerodynamic performance of the trainer wing by using the CFJ active flow control method. They conducted a study using a velocity of 20 m/s and a k-epsilon model. The results showed that implementing CFJ increased the stalling angle by 40% and the coefficient of lift by 52%, thereby reducing take-off and landing distances. Chavaj, V. S., et al. [28], conducted a numerical study of aerofoil performance using the Blowing Suction Pipe Vent (BSPV) method under take-off, landing, and cruise conditions. The findings revealed that this novel design improved the stall angle and lift coefficient by 50% and 60%, respectively, while reducing drag. Moreover, a 15-degree injection angle was found to significantly enhance aerodynamic performance by effectively controlling boundary layers across various flight phases.

Balaji, K., & Wessley, G. J. J. [29] study explores the performance of a Modified Co-Flow Jet (MCFJ) aerofoil with a converging nozzle at the leading edge, aiming to reduce pumping power. Results show a 43% lift increase and an advanced stalling angle, improving aerodynamic efficiency compared to the baseline aerofoil. Vigneshwaran et al.[30] examines the fluid-structure interaction of a NASA SC (2)-0412 airfoil to determine its performance and deformation limits at various Mach numbers. Numerical methods like CATIA for wing design and CFD for flow analysis, along with ANSYS for structural analysis, are used to assess aero elasticity. Rajan, E. Z., et al.[31] explores how delaying flow separation can improve aircraft performance by using a co-flow jet (CFJ) system. The study shows that adding injection and suction slots to the airfoil enhances circulation control, leading to better performance. Arunkumar, A et al. [32] investigate how dimples on an aircraft wing can reduce drag and delay flow separation, improving aerodynamic performance. Both computational and experimental analyses using a NACA 6321 airfoil show that dimples create turbulence, increase the stall angle, and reduce drag at higher angles of attack. Balaji, K., et al [33] analyze the stress on wing-fuselage lug joints of a two-seater trainer aircraft using numerical and theoretical methods. The results show that finite element analysis improves the strength and lifespan of the attachment, validating the findings with theoretical values. Balaji, K., & Yadav, A. [34] identify the optimal angles for different winglets to improve aerodynamic performance by controlling the boundary layer on a cambered aerofoil. Numerical and experimental analysis revealed that the blended winglet at a 95° angle offered the highest aerodynamic efficiency by reducing induced drag. Balaji, K., & Wessley, G. [35] analysis of the NACA 6321 aerofoil was conducted using three turbulence models at different angles of attack and compared with experimental data. The study found that the k-omega model provided the most accurate predictions, with less than 4% error, closely matching experimental results. Vijayan, S. N., et al [36] study develops a composite material using an aluminium alloy matrix (LM13) and zirconium diboride (ZrB_2) reinforcement for automotive applications. Finite element analysis and experiments show that adding 10 wt% ZrB_2 significantly improves hardness (82.5%), tensile strength (28.03%), impact resistance (73.3%), and compression (25.09%), making it ideal for automotive use. Balaji, K., et al [37, 38] introduce a passive flap system on the front wing of a formula car to improve downforce and stability at high speeds. Analysis shows that the flap increases downforce by up to 8.76% at speeds up to 350 km/h, enhancing vehicle stability without reducing speed during turns. Balaji K et al [39] use Computational Fluid Dynamics (CFD) and Finite Element Method (FEM) to analyse load distribution on a helicopter's main rotor blade. It focuses on pressure and velocity tests and thermal behaviour, with particular attention to stress analysis on glued joints between metal and honeycomb composite segments.

The literature shows the various passive and active methods used in the aircraft to control the boundary layer separation and performance improvement. Active methods use an additional power source, which leads to increases the weight of an aircraft. It proved that the passive methods of vortex generators and dimples are used to improve the performance of an aircraft wing. Many papers focus on using any one passive method to improve performance. However, there is no evidence that the single aerofoil with the precision location of the vortex generator and dimples are not mentioned in any paper. The objective of the paper is to identify suitable passive methods as well as the appropriate location to improve the performance of an aircraft wing.

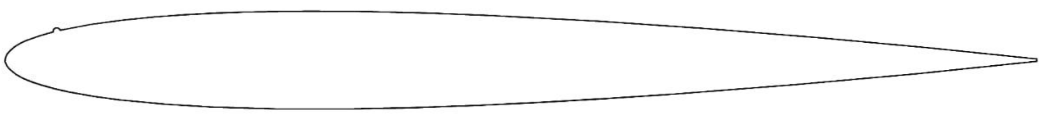
2. Methods:

The Numerical analysis was carried out by the regular design procedure in the CAD software then meshing and numerical analysis performed in actual flight conditions. This proposed method was implemented in NACA 0010 aerofoil with various location configurations.

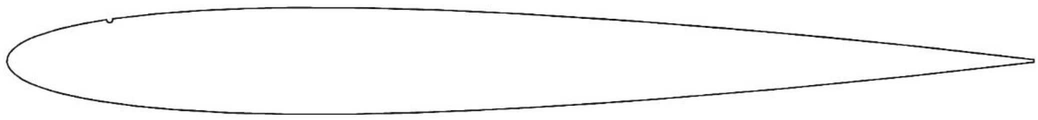
2.1 Design:

The NACA 0010 aerofoil with a chord length of 30 cm used for this study was shown in figure 1. In that three different sets of models are designed baseline aerofoil, vortex generator and dimple models. Again those models are designed by placing the various locations of vortex generator and dimples with the locations of between 5 % to 20 % along the chord length with 5% deviation as shown in figure 2. The domain created for this work is based on the literature [3].

Baseline Aerofoil



(b) Vortex Generator Aerofoil



(c) Dimple Aerofoil

Fig 1. Schematic Diagram of various Aerofoils

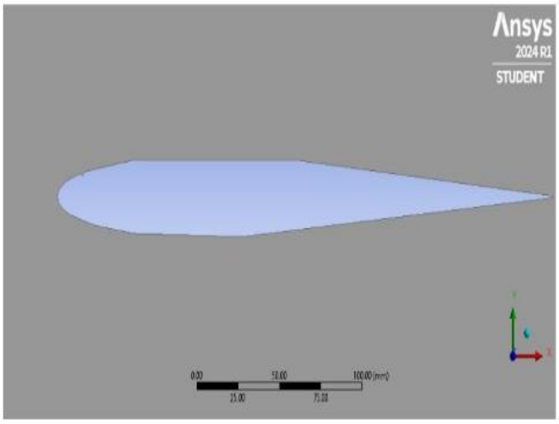
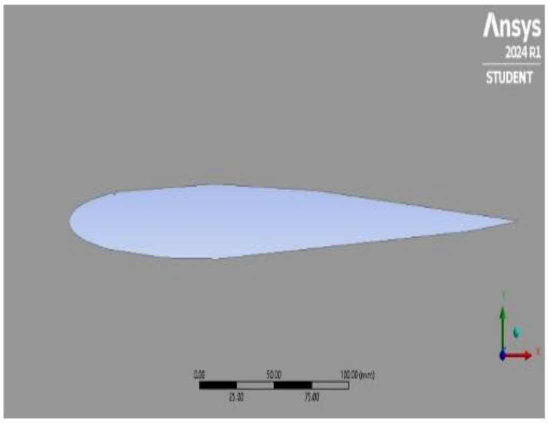
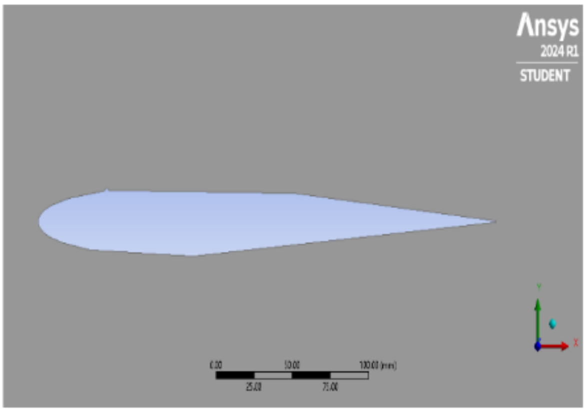
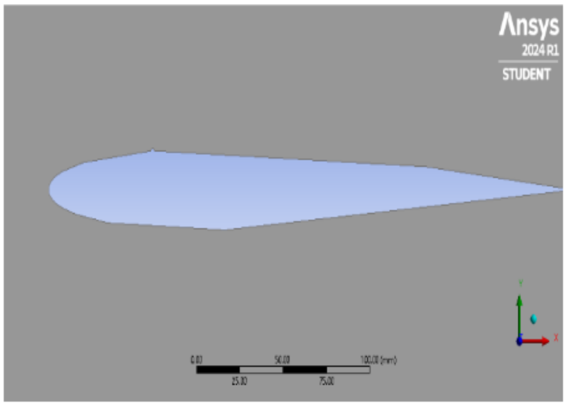
	
5% passive method placing	10% passive method placing
	
c) 15% passive method placing	d) 20% passive method placing

Fig 2: Various locations placing of passive methods

2.2 Meshing

The meshing plays a major role in obtaining accurate results by discretization of big elements into the small elements. The grid-independent study was carried out to finalize the elements and node count. The y plus value is defined with one and the number of layers is defined as 28 as per literature [4]. Based on that the number of nodes and elements are fixed at 129970 and 254530 respectively. The mesh images are shown in the figure 3.

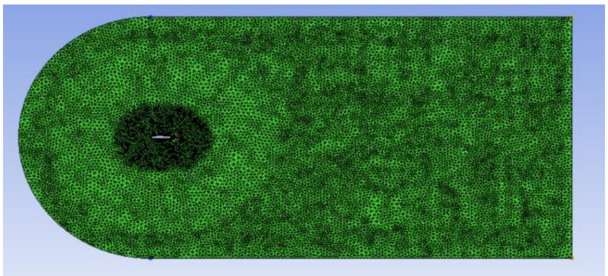


Fig 3: Meshing of aerofoils

2.3 Numerical Analysis:

The analysis was carried out using the Reynolds Average Navier Stokes equation with k epsilon turbulence models are used based on the literature study [3] .The physics used for this study is defined based on the literature [4]. Every model is analysed independently with various angle of attack. The boundary conditions used for this study to meet the actual flying conditions are mentioned in the table 1.

Table 1: Boundary conditions used for this study

Sr.No	Description	Details
1	Inlet	Velocity Inlet
2	Outlet	Pressure Outlet
3	Wall	Symmetry
4	Aerofoil	Wall
5	Velocity	20 m/Sec

2.4 Validations:

The fig 4 shows that the validation curves of lift and drag coefficient of aerofoils. The baseline simulation results are validated using the line integral method. Using this approach, pressure and shear stresses are integrated inside the computational domain along predetermined lines or surfaces. These coefficients can be precisely calculated by drawing the right lines or surfaces around the object of interest. The variation of simulation and line integral methods are following the same trends with less than 2% of results variation. It proved that the proposed simulation methods are correct in order to conduct the further analysis.

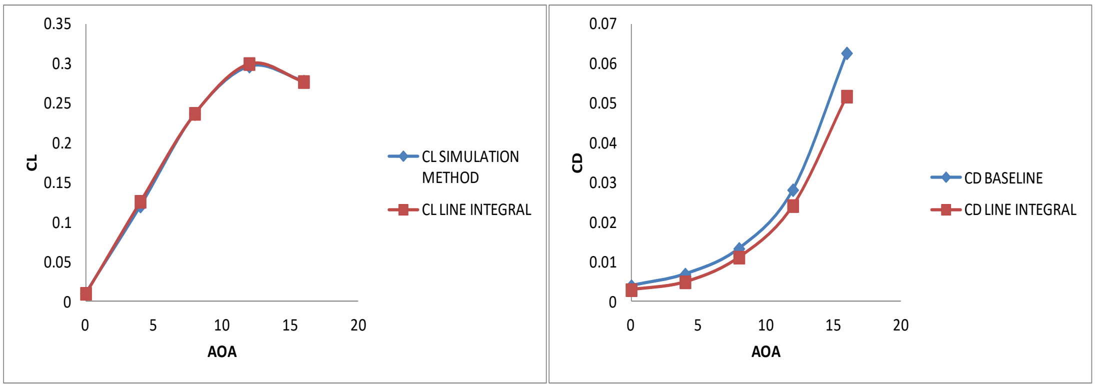


Fig 4: Validation Graphs

3. Results and Discussions

The simulation study of dimple and vortex generators are placed at various locations over an aerofoil and analysed at different angle of attack.The details results are discussed in the upcoming portions with the graphical form with three different cases. The cases are discussed over here is Dimple analysis, Vortex analysis and comparison of optimum dimple and VG Analysis.

3.1 Case 1: Dimple analysis at various locations:

In this case the placement of dimple at 5%, 10%, 15% and 20% are analysed numerically at different angle of attack is compared with the baseline study. The data's are analysed in the graphical form to identify the performance improvement in detail.

3.1.1 Lift coefficient of Dimple Aerofoil

Fig 5 shows that the analysis of aerofoil with various dimple placement with different angle of attack. It displays that the placement of dimple leads to increase the lift coefficient. The dimple placement also indicating that the near to the leading edge its increasing the lift coefficient slightly when it moves to the 20% of location it provide the better lift enhancement. The amount of lift coefficient increase upto 4% without changing the stall angle. The dimple make the vortex flow that make the flow attachment at downstream of the aerofoil while the dimple is placed close at the mid of the chord placed leads to efficiently minimize the boundary layer. At the same time if its placed close to leading edge is slightly enhance the coefficient. This method proved that the placement of dimple near the mid portion of aerofoil increase the lift coefficient performances.

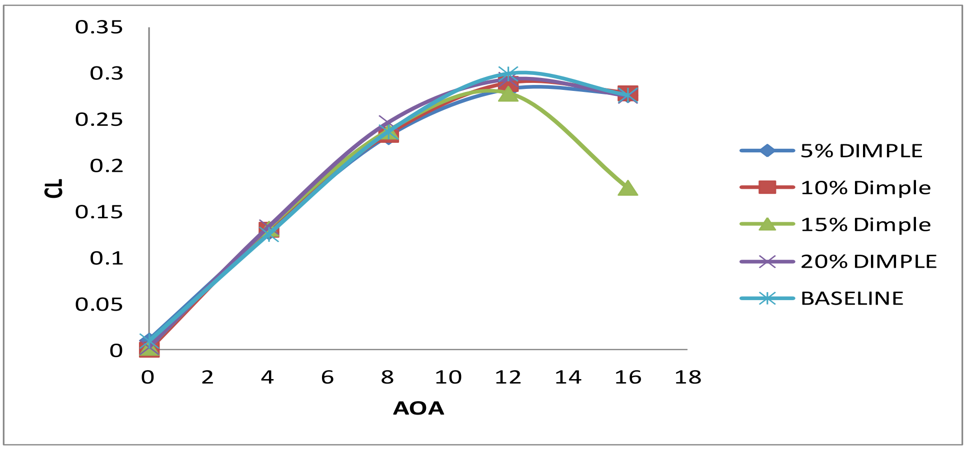


Fig 5: Lift coefficient curve of Dimple aerofoil

3.1.2 Drag Coefficient Curve of Dimple aerofoil

Fig 6 shows that the placement of dimple at various locations to analyse the drag performances of an aerofoil at various angle of attack. It reveals that the low angle of attack drag coefficient is increased compare to the baseline aerofoil. The dimple placement at various angles of attack is increasing the negligible amount of drag. The dimples are used to create the lift at the same time the vortex formation leads to make the slight increment in drag. The overall study of drag coefficient improve the drag at various locations of dimple is 1% due to the lift induced drag.

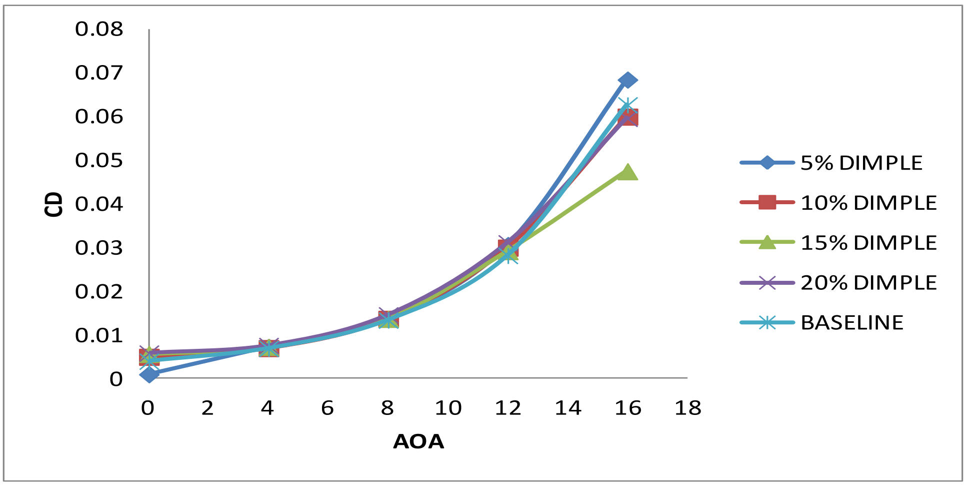


Fig 6: Drag coefficient curve of Dimple aerofoil

3.2 Case 2: Vortex generator analysis at various locations:

In this case the placement of vortex generators at 5%, 10%,15% and 20% are analysed numerically at different angle of attack is compared with the baseline study. The data's used for this case is lift and drag coefficient of VG models

3.2.1 Lift coefficient of VG aerofoil:

The figure 7 shows that the Vortex generator performances at various locations are analysed in terms of lift coefficients. It shows that the placements of vortex generators are used to increase the lift coefficient considerable amount. The placing of VG at 15% and 20% are used to increase the stalling angle of attack by 33% in comparison with baseline aerofoil. The reason behind that is placement of 15% and 20% are the flow separation location, in that place VG is creating the vortices formations which leads to suppress the flow separation and make the flow more attachment. It leads to enhance the results of stall angle. The overall analysis proves that the vortex generator needs to be placed at the right positions to enhance the performances.

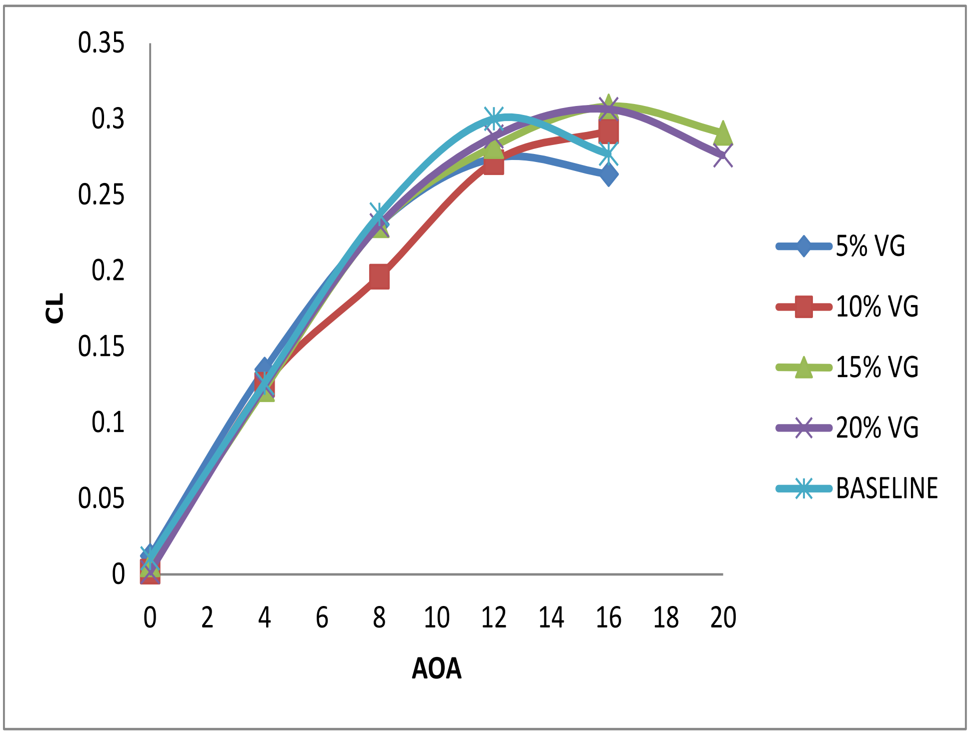


Fig 7: Lift coefficient curve of VG aerofoil

3.2.2 Drag coefficient of VG aerofoil:

Fig 8 shows that the drag coefficient of the vortex generator placed aerofoils at different angles of attack. It shows that the 15% location of VG is producing a very low amount of drag compared to the baseline and other location-placed VG aerofoils. The 10% location of VG is making a huge disturbance in flow and generating more drag and the 15% and 20% place of VGs are creating the vortices and making the flow attachment downstream of the aerofoil. This attachment of flow leads to the lift increment and drag reduction. The overall analysis revealed that the placement of the vortex generator near the middle of the aerofoil leads to minimizing the drag and made flow attachment.

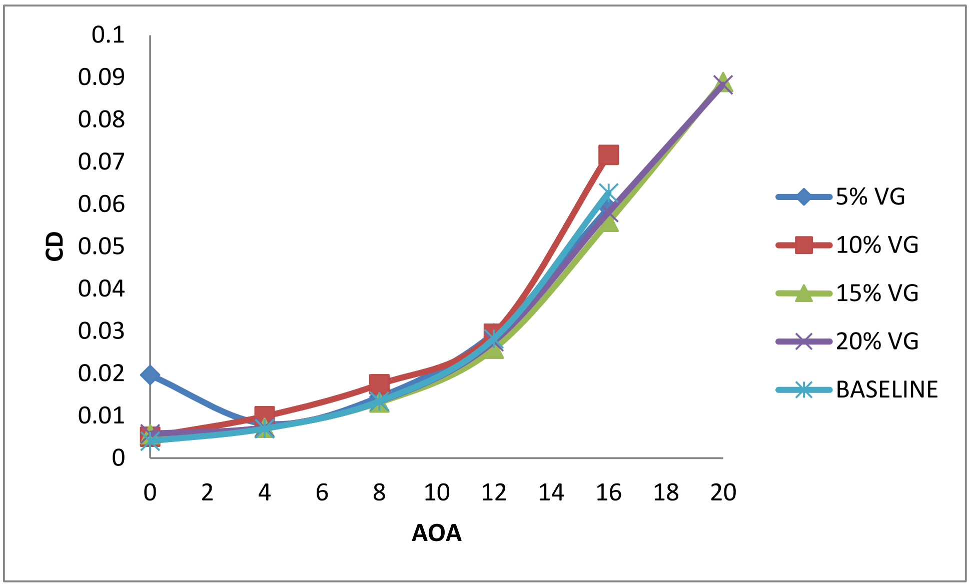


Fig 8: Drag coefficient of VG Aerofoil

3.3 Case 3: comparison of VG and Dimple:

This case deals with the optimized location of case 1 and case 2 proved results that are compared and analysed the baseline aerofoil to identify the properties of both methods in single graph.

3.3.1 Lift coefficient:

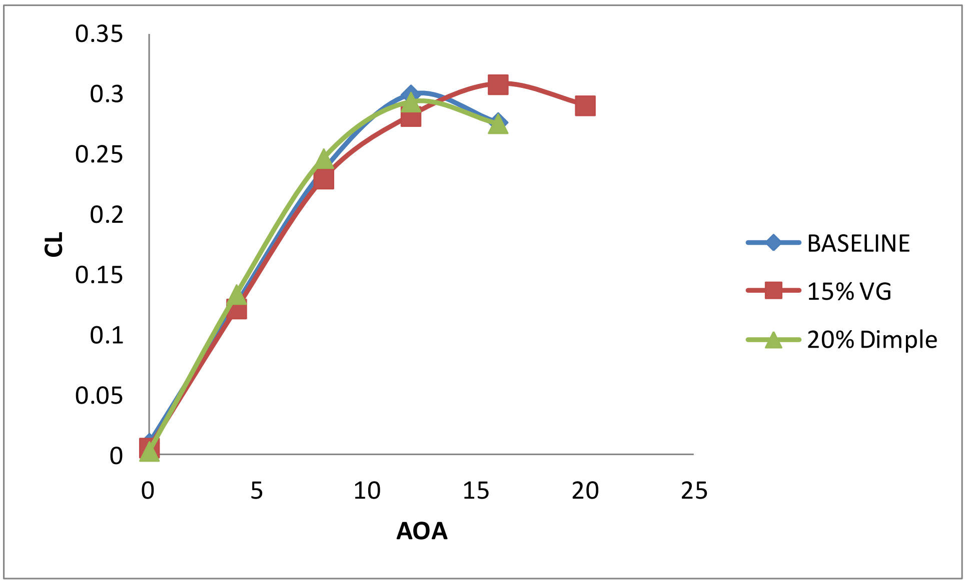


Fig 9: Lift coefficient curve of various aerofoil

Fig 9 shows the variations of lift coefficient curve VG, Dimple, and baseline aerofoil. It shows that the Dimple over an aerofoil is used to improve the lift coefficient up to 4% and VG over an aerofoil is used to improve the stall angle of attack by 33%.In that, VG forms a high amount of vortices, which results the more flow attachment, and enhances the stall. At the same time, dimples are making fewer vortices due to the shape of the dimple, which leads to an increase in the lift coefficient. The overall study proved that the VG was used to increase the stall and the dimple was used to increase the lift coefficient.

3.3.2 Drag Coefficient:

Fig 10 shows the Drag coefficient of VG, Dimple, and baseline aerofoils. It shows that the up to 10-degree angle of attack baseline and both passive methods are producing the same point of drag. At the same time after the 10 degrees, the VG and dimple airfoils are making more drag due to the development of lift-induced drag. The overall analysis proved that drag will increase according to the angle of attack and the flow control mechanism will increase the drag at a higher angle of attack.

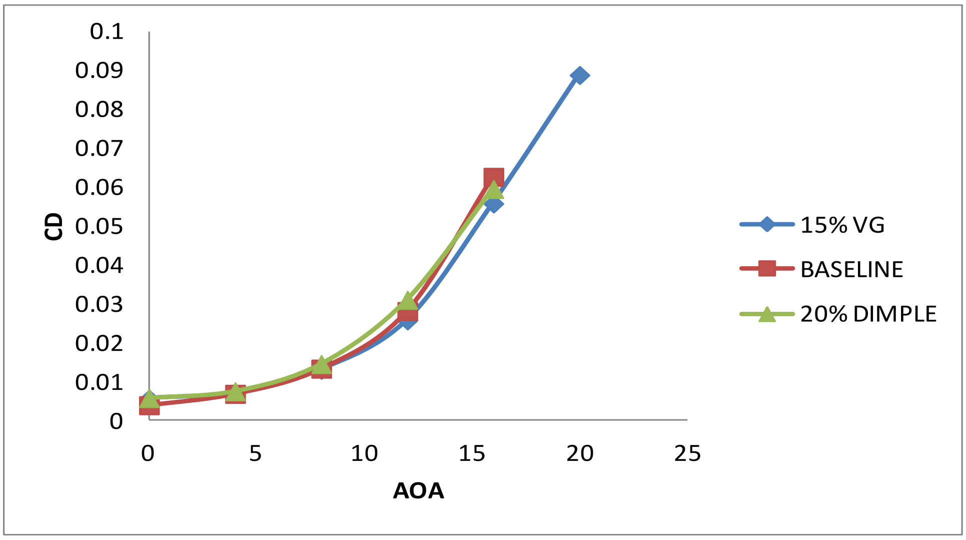
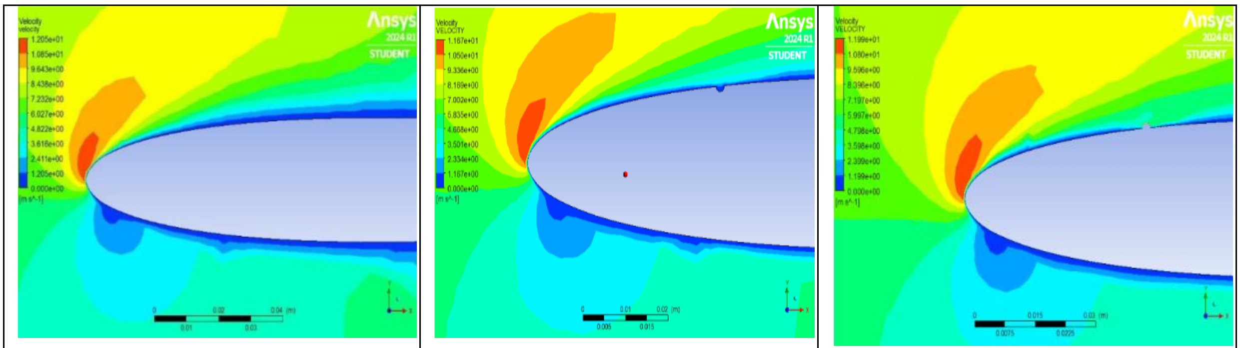


Fig 10: Drag coefficient curve of various aerofoil

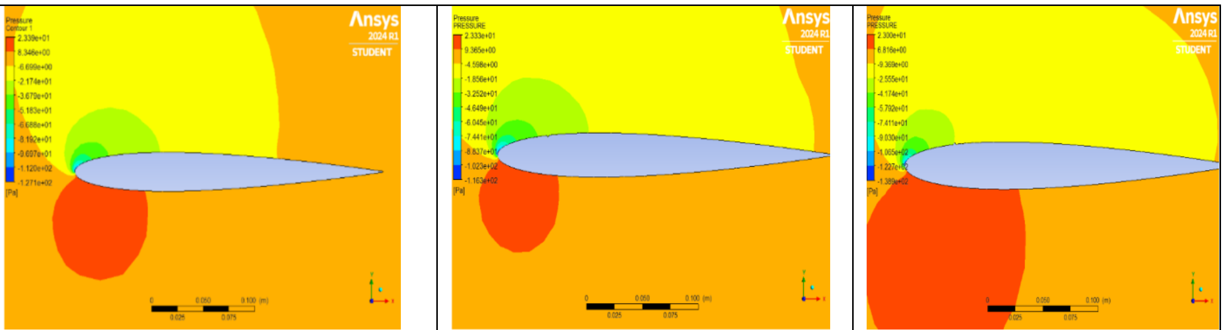
3.3.3 Flow visualization



Baseline Aerofoil at 12 AOA	**15% position Dimple at 12 AOA**	**15% position VG at 12 AOA**

Fig 11: Velocity magnitude of various aerofoil configurations at 12 degree AOA

Fig 11 shows the velocity magnitude of various aerofoils with an angle of 12 degrees. In baseline, aerofoil flow separation starts close to the leading edge. In the 15% position of dimple placed aerofoil, the flow remains attached due to the effect of dimple. The 15% position of VG aerofoil is making the more flow attachment compared to the dimple shape passive mechanism. The study reveals that the passive mechanism effectively controls the boundary layer.



Baseline Aerofoil at 12 AOA	**Dimple at 12 AOA**	**VG at 12 AOA**

Fig 12: Pressure contour of various aerofoil configurations at 12 degree AOA

Fig 12 displays the pressure contour over a baseline, dimple and vortex generator at the angle of attack of 12 degrees. It shows that the baseline creates more pressure at a high angle of attack due to the detachment of the flow. In the dimple method, vortex generators are used to minimize the pressure over an aerofoil due to the shape of the passive device. The pressure decrement over at the top surface leads to allow the more amount of velocity and makes the flow more attached.

4. Conclusions:

The symmetrical aerofoil of NACA 0010 is used for this study and placed with the passive methods of vortex generator and dimple. This study proved that both passive methods are used to improve the aerodynamic performances of aerofoil at specified locations. It brought the following conclusions

- The vortex generators used for this study indicate that the placing of the 20% chord is used to improve the stalling angle of attack by 33%. If the location of VG moved towards the leading edge, it minimizes the lift coefficient and stall angle.
- The Dimple needs to be placed with the positions of 15% of chord is used to improve the lift coefficient of 4% compared to other aerofoils. If the location is moved further backward or forward leads to minimizing the lift coefficient
- In comparison with the VG and Dimple, it's concluded that the VG is used for stall enhancement and the dimple is used for lift enhancement. This variation happened due to the position and size of the passive methods.
- The overall analysis of this study proved that the placement of passive methods near the leading edge reduces the aerodynamic performances and towards the middle of the chord if it is placed performances are increased higher amount.

This paper proved that the aerodynamic performances are enhanced by any passive mechanism that is used to control the boundary layer. In the future, the same work can be conducted for the experimental study and vary the size and design of the passive methods.

Declaration:

On behalf of all authors, the corresponding author states that there is no conflict of interest

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