Numerical investigation of flow separation control on a NACA 4412 wing using surface dimples

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***Abstract*— The aerodynamic performance of a wing is strongly influenced by boundary layer separation, especially at higher angles of attack. In the present study, a numerical investigation is carried out to analyze the effect of surface dimples on the flow separation characteristics of a NACA 4412 wing. Two configurations, namely a smooth wing and a dimpled wing, are modeled and analyzed using ANSYS Fluent. The simulations are performed at a free-stream velocity of 20 m/s for angles of attack of 0°, 4°, 8°, 12°, and 16°. The aerodynamic performance is evaluated in terms of lift coefficient, drag coefficient, lift force, and drag force. The results indicate that the dimpled wing exhibits slightly improved lift characteristics and delayed flow separation compared to the smooth wing at higher angles of attack. The study shows that surface dimples can act as a passive flow control technique for enhancing aerodynamic performance at low Reynolds number conditions.**

***Keywords*— NACA 4412, Drag, Stall, L/D Ratio, Flow Separation, CFD, Surface Dimples, Flow Separation, Lift Coefficient, Drag Coefficient and Passive Flow Control**

1) INTRODUCTION

A. *Effects of dimples*

Surface dimples are small indentations introduced on a body to modify the near-wall flow behavior. The presence of dimples can generate local vortical structures that energize the boundary layer and help delay flow separation. This concept is well known in the case of golf balls, where dimples reduce pressure drag by delaying separation and reducing the wake region. Inspired by this principle, dimpled surfaces are investigated in aerodynamic applications as a passive flow control technique.

Drag on an aircraft can be broadly classified into profile drag and induced drag. Additionally drag due to the formation of shock wave also takes the role which is called as wave drag. By reducing the profile drag the total drag can be reduced. This improvement can be gained by concentrating on reducing the drag of an aircraft. Hence stall angle should be improved by increasing the angle of attack. A stall is a condition in aerodynamics and aviation where the angle of attack increases beyond a certain point such that the lift begins to decrease. If the angle is increased the flow separation will also increase which will reduce the L/D ratio. Hence L/D ratio should be increased.

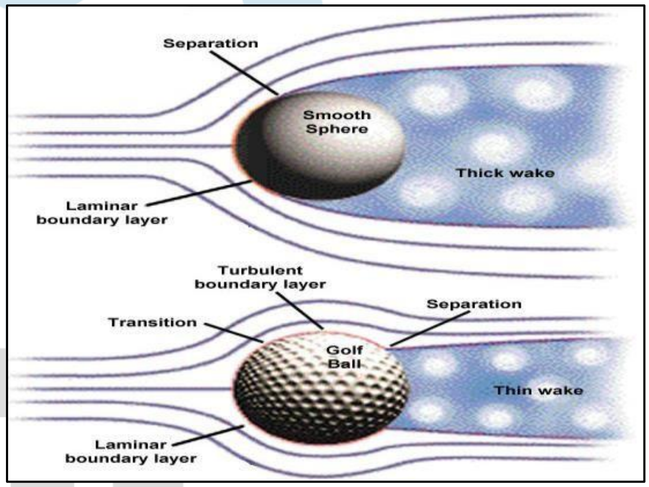


FIG 1: Flow over a golf ball with and without dimple

Modifying the aircraft wing structure by means of placing dimples will reduce the drag to considerable amount from the total drag and helps to stabilize the aircraft during stall. Delaying the boundary layer separation in the flow resulting in decrease in the pressure drag also increases the stall angle.

2. METHODOLOGY

The geometric model is designed in CATIA V5R2022 software and converted the file into IGS file then imported into ANSYS FLUENT. Symmetry is used to reduce the computing time. Before analysis grid validation is done and the grid independence is studied for the model. Then analysis is done in fluent and results are taken and compared for normal airfoil with dimple airfoil and effect of dimple shapes is studied.

- A pressure-based steady-state solver was used.
- The SST k-ω turbulence model was selected.
- Air properties were defined at standard atmospheric conditions.

- A velocity inlet and pressure outlet boundary condition were applied.
- The wing surface was defined as a no-slip wall.
- Residual convergence of 10^{-4} or 10^{-5} was adopted, along with stabilization of lift and drag monitors.
- A mesh independence study was carried out using coarse, medium, and fine meshes.

3.GEOMETRIC MODELLING

3.1) 2D Design

NACA 4412 airfoil is chosen for the computational investigation. It is an unsymmetrical airfoil.

The dimple details are as follows.

1) Transition point on wing = 40% from leading edge
2) Location of dimples = 40mm from leading edge
3) Number of dimples = 29
4) Diameter of dimples = 8mm
5) Distance between dimples = 10mm
6) Chord = 100mm
7) Span = 300mm

3.2) 3D Design

CATIA V5 application is a 3D software with adaptable UI. The software is suitable for parts of different complexities. The CATIA V52022 is used to design the NACA 4412 smooth airfoil (Fig 2) and one with dimples (Fig 3). Symmetry is used to reduce the computing time.

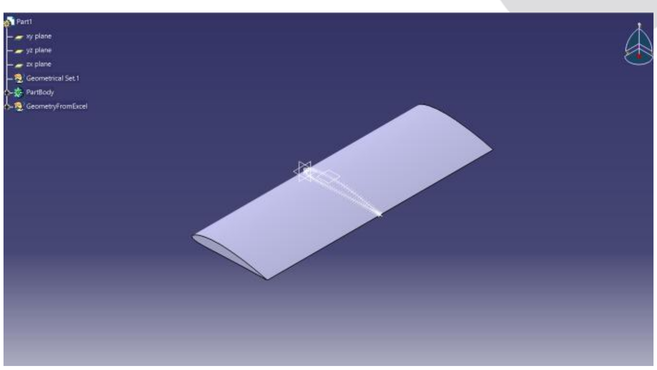


FIG 2: 3D model design of without dimples in CATIA

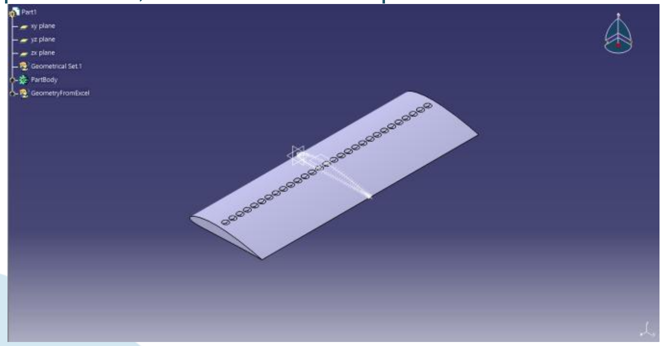


FIG 3: 3D model design of with dimples in CATIA

4.MESHING

ANSYS Meshing is a versatile, automated, and highly customizable software tool used to generate 2D/3D surface and volume meshes for Finite Element Analysis (FEA) and Computational Fluid Dynamics (CFD). It converts complex CAD geometries into smaller, discrete elements such as tetrahedrons, hexahedrons, or polyhedrons to allow Ansys to accurately compute simulation results.

An unstructured tetrahedral mesh was generated for the fluid domain with local refinement near the wing surface. Inflation layers were applied on the wing wall to capture the near-wall boundary layer effects. The global element size was set to 20 mm, while a finer local sizing of 5 mm was applied near the airfoil. A growth rate of 1.2 was used.

1) Growth rate = 1.2
2) Element size = 20mm
3) Sizing = 5mm
4) Capture Proximity = On
5) Inflation = 16layers

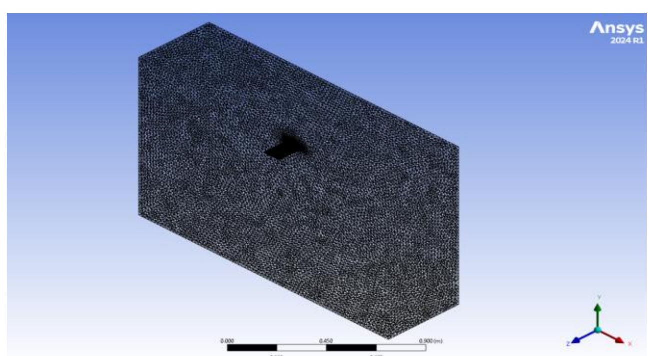


FIG 4: Domain Mesh

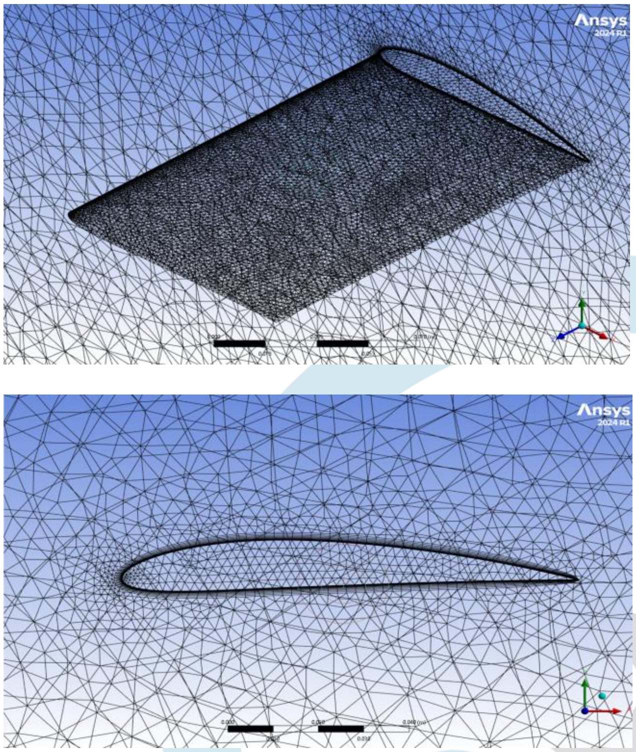


FIG 5: Meshing for airfoil without dimples

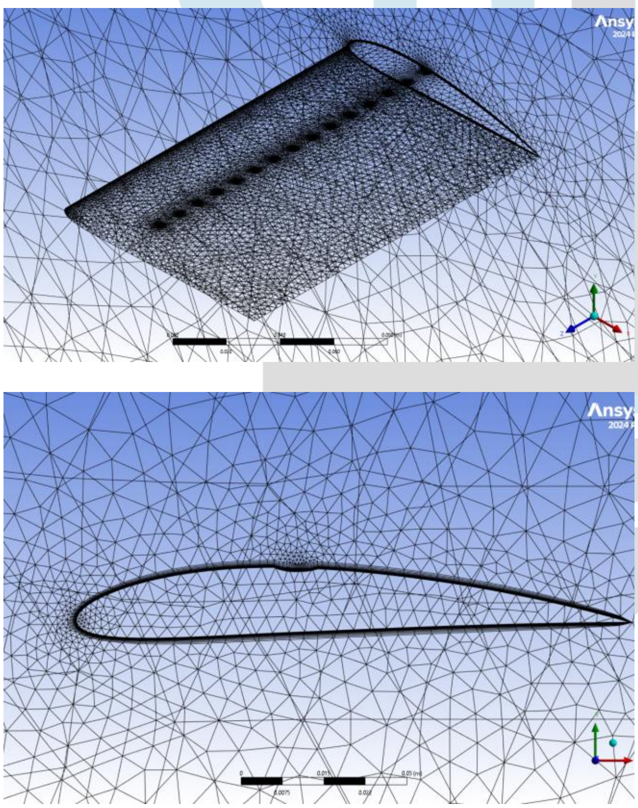


FIG 6: Meshing for airfoil with dimples

5.ANALYSIS AND RESULTS

The aerodynamic performance of both smooth and dimpled wing configurations was analyzed in terms of lift coefficient, drag coefficient, and flow behavior.

The simulations were conducted for angles of attack ranging from **0° to 16°**.

Results indicate that the dimpled wing configuration exhibits improved aerodynamic performance at higher angles of attack. The presence of dimples generates small vortices that energize the boundary layer and delay separation.

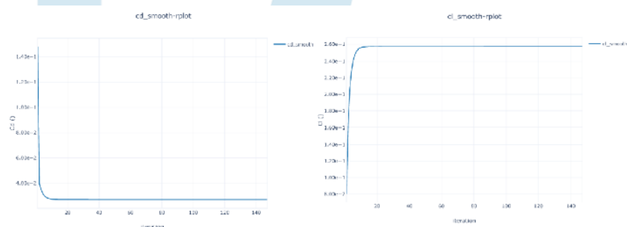
As a result, the dimpled wing produces slightly higher lift and better lift-to-drag ratio compared to the smooth wing configuration.

Flow visualization through velocity contours and pressure distribution further confirms that the dimpled surface helps maintain attached flow over a larger portion of the wing surface.

5.1 Analytical results for proposed models

5.1.1 Airfoil without dimples (Smooth wing)

1) Airfoil wing without dimples 0˚



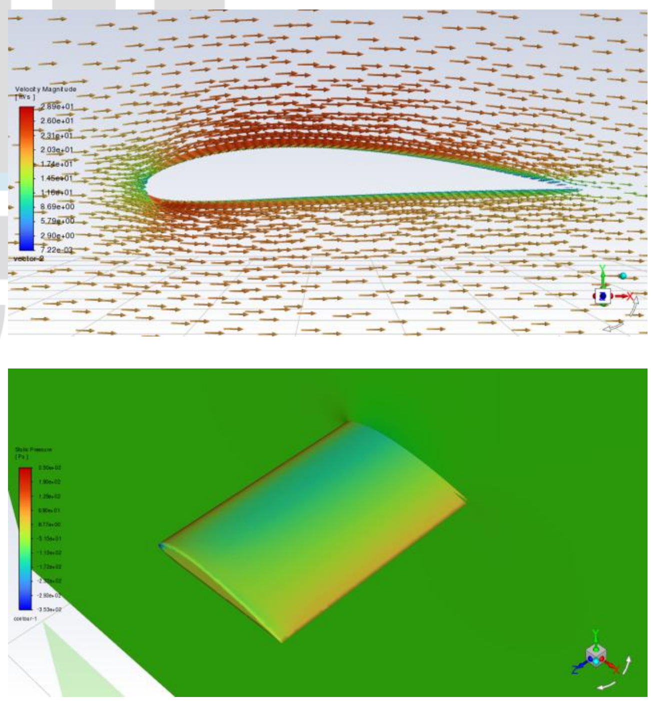
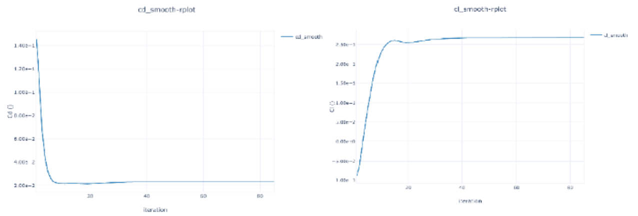
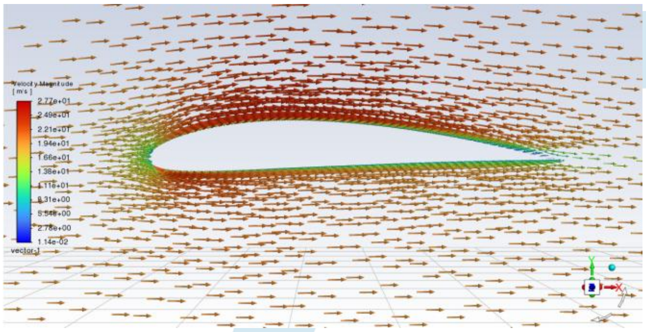


Fig 7: Contours of total Pressure and Velocity

2) Airfoil wing without dimples 4˚





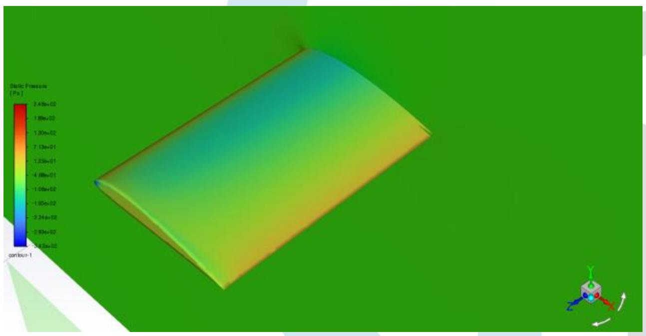
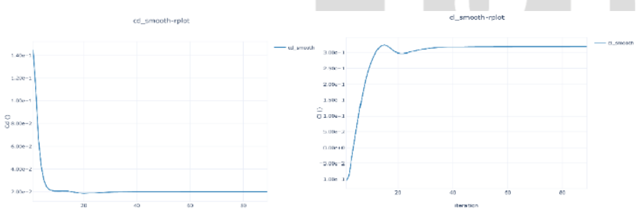
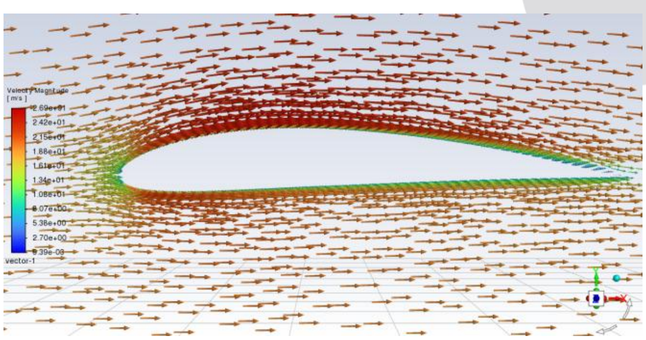


Fig 8: Contours of total Pressure and Velocity

3) Airfoil wing without dimples 8˚





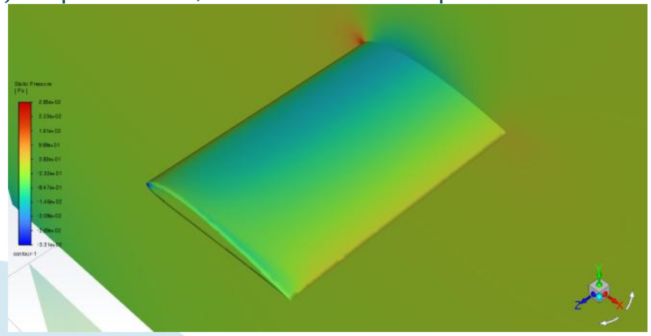
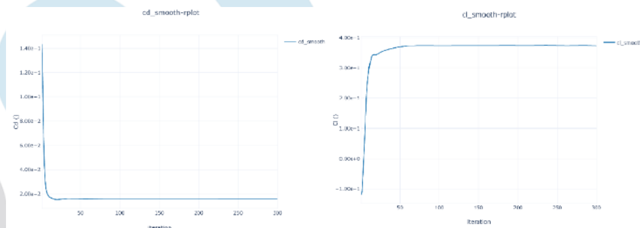
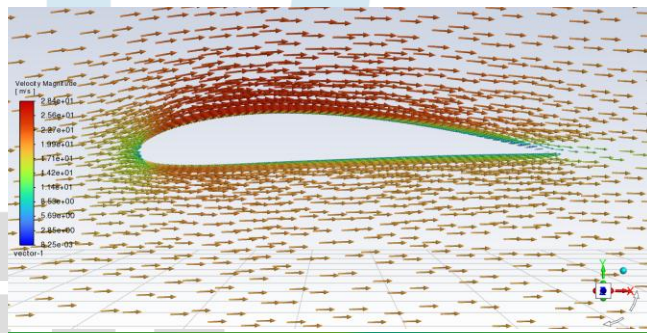


Fig 9: Contours of total Pressure and Velocity

4) Airfoil wing without dimples 12˚





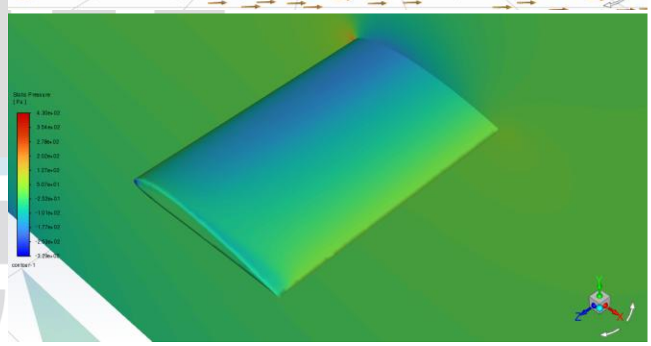
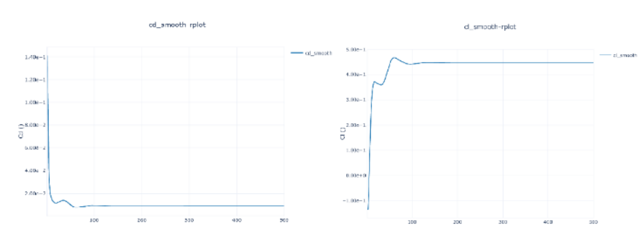


Fig 10: Contours of total Pressure and Velocity

5) Airfoil wing without dimples 16˚



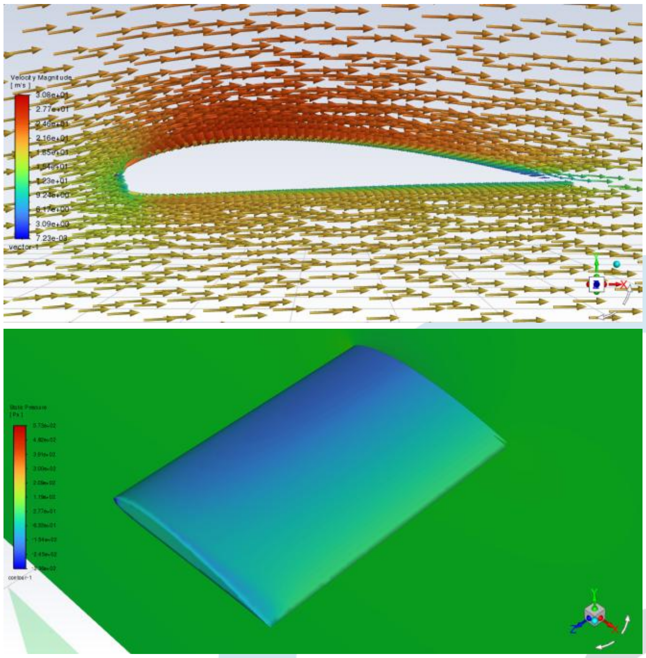


Fig 11: Contours of total Pressure and Velocity

5.1.2 Airfoil with dimples (Dimple wing)

1) Airfoil wing with dimples 0˚

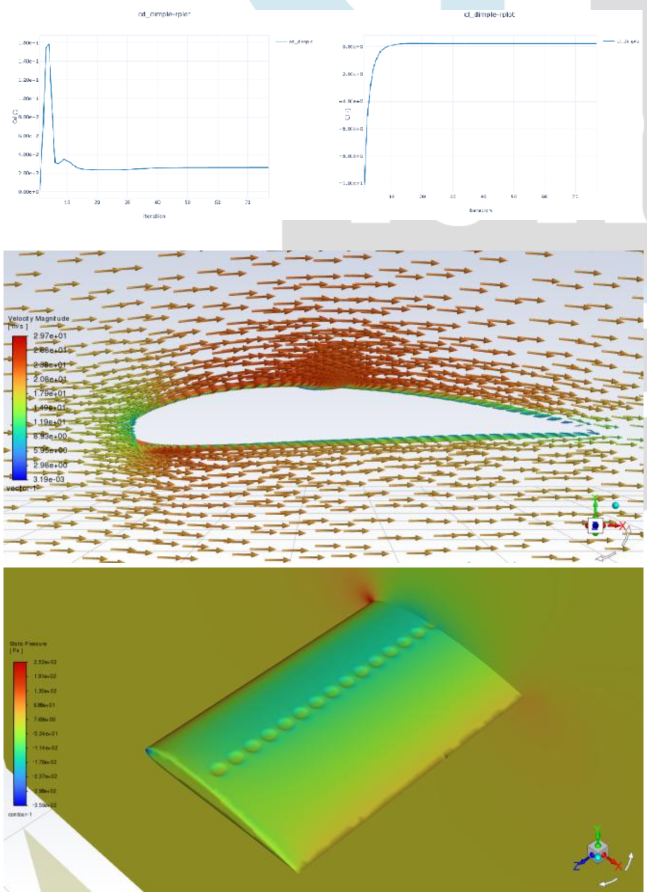


Fig 12: Contours of total Pressure and Velocity

2) Airfoil wing with dimples 4˚

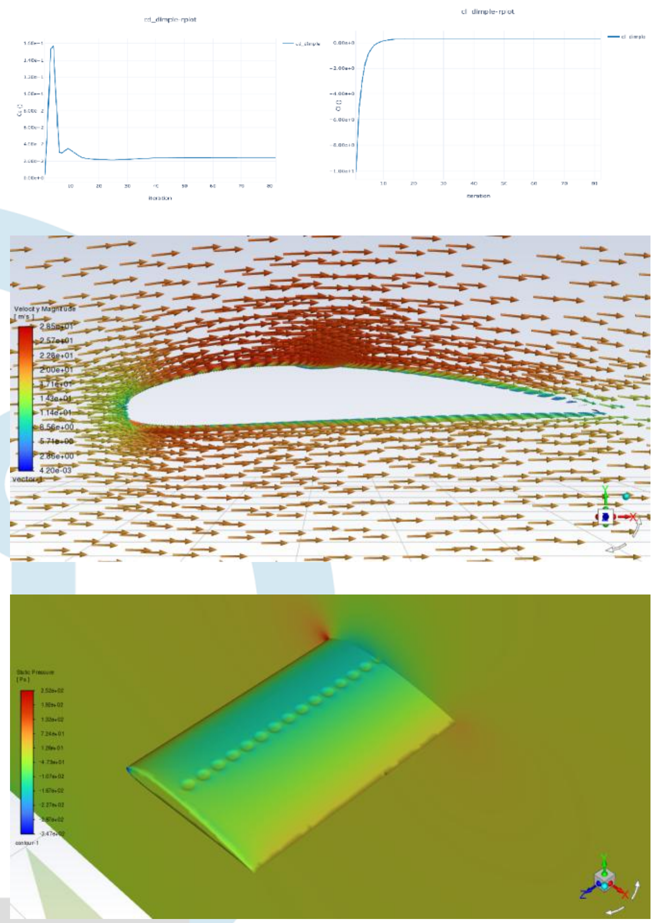
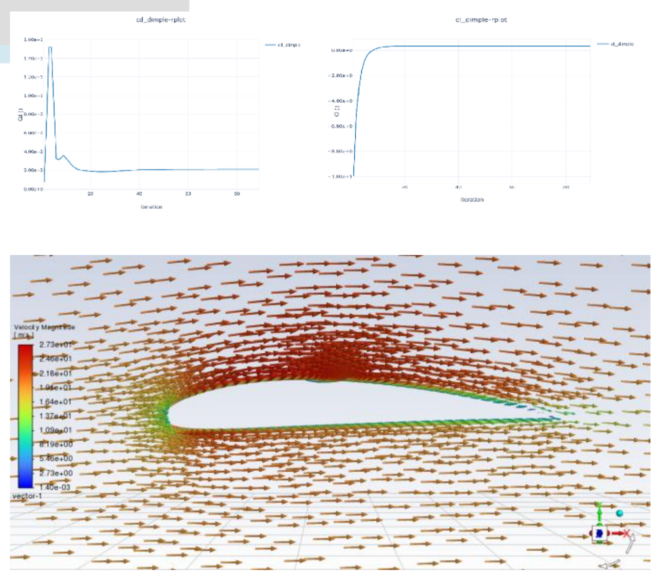


Fig 13: Contours of total Pressure and Velocity

3) Airfoil wing with dimples 8˚



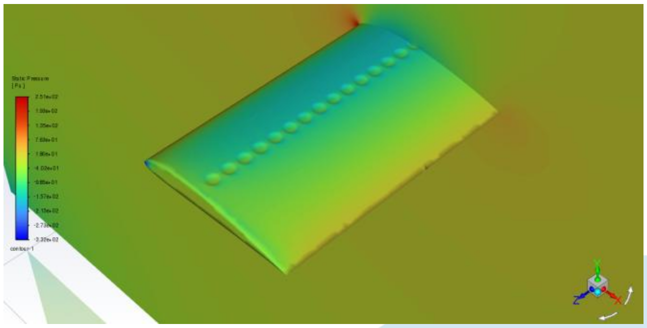
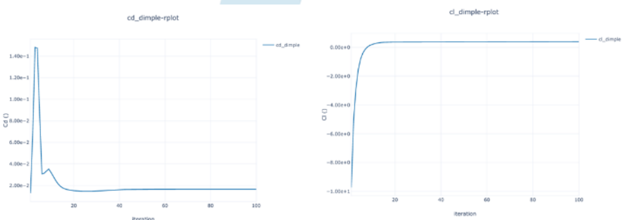
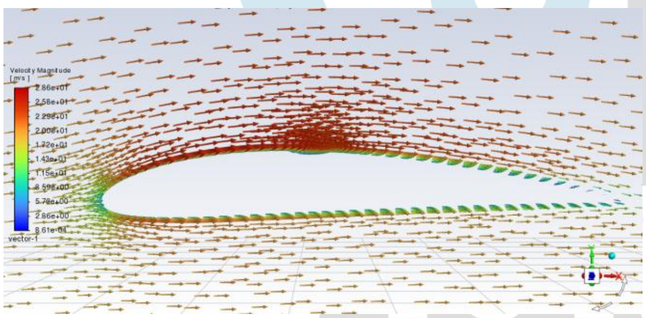


Fig 14: Contours of total Pressure and Velocity

4) Airfoil wing with dimples 12˚





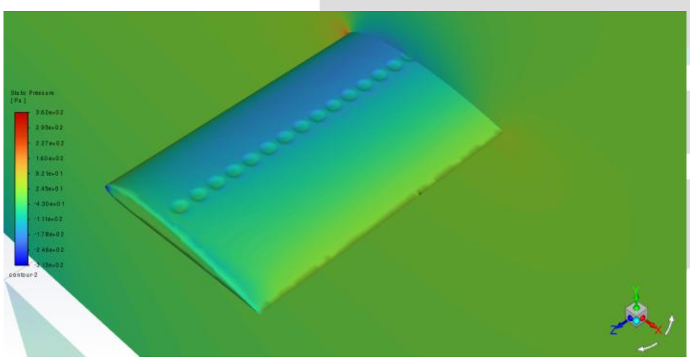
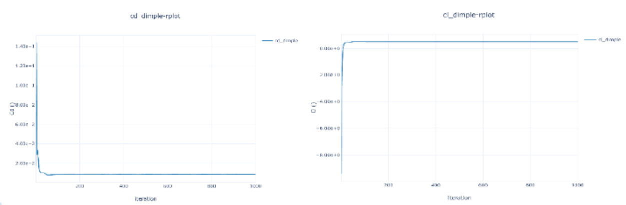
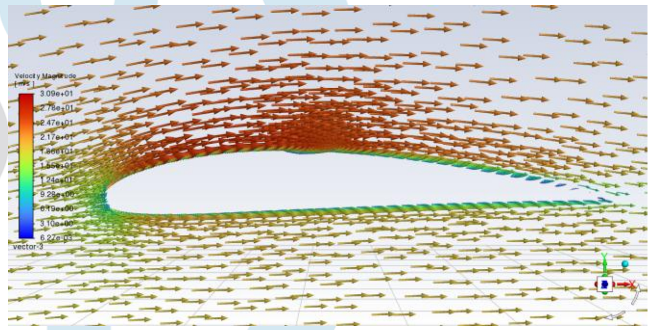


Fig 15: Contours of total Pressure and Velocity

5) Airfoil wing with dimples 16˚





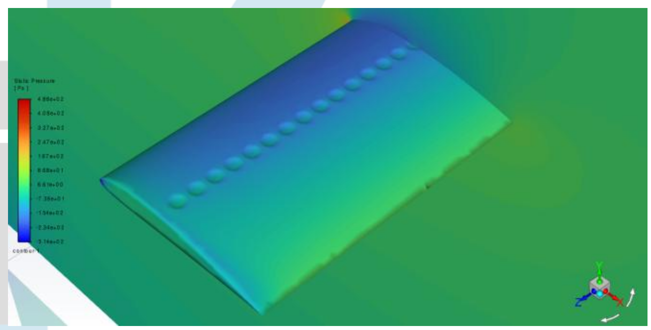


Fig 16: Contours of total Pressure and Velocity

5.2 Comparison Table

5.2.1 Smooth Wing

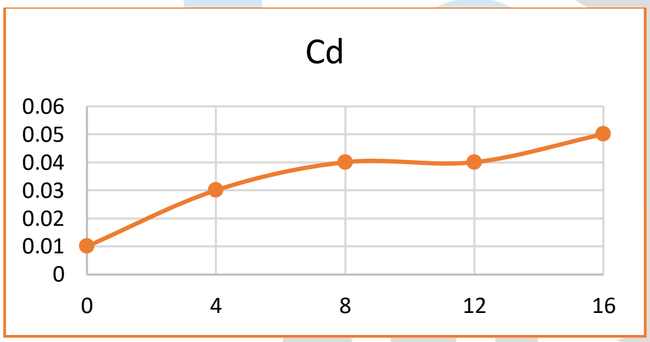
Angle of attack	**Velocity (m/s)**	**Coefficient of lift**	**Lift (N)**	**Coefficient of drag**	**Drag (N)**
0˚	20m/s	0.51	1.89	0.01	0.06
4˚	20m/s	0.53	1.97	0.03	0.11
8˚	20m/s	0.63	2.34	0.04	0.14
12˚	20m/s	0.75	2.75	0.04	0.16
16˚	20m/s	0.89	3.28	0.05	0.19

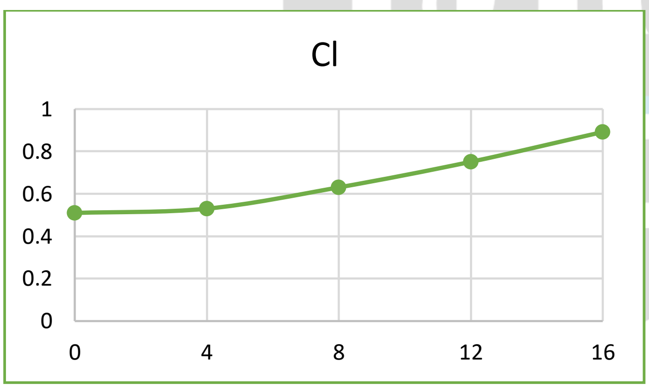
5.2.2 Dimple Wing

Angle of attack	Velocity (m/s)	Coefficient of lift	Lift (N)	Coefficient of drag	Drag (N)
0˚	20m/s	0.47	1.73	0.01	0.06
4˚	20m/s	0.57	2.10	0.03	0.12
8˚	20m/s	0.67	2.47	0.04	0.15
12˚	20m/s	0.81	2.94	0.04	0.17
16˚	20m/s	0.97	3.57	0.05	0.19

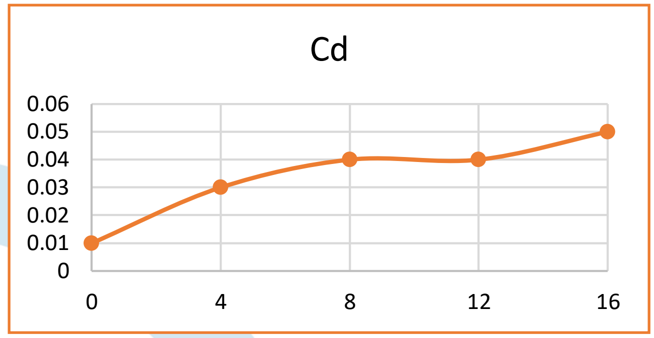
5.3 Comparison Graph

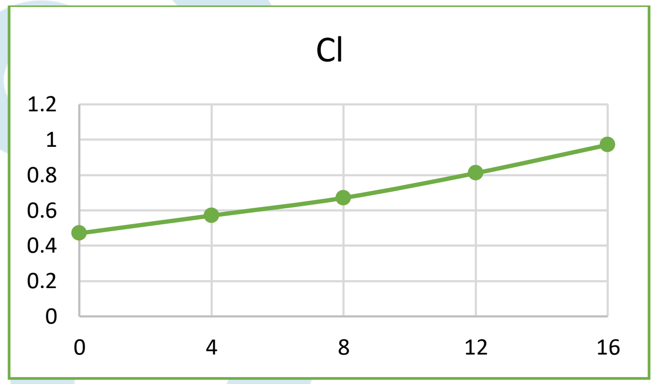
5.3.1 Smooth Wing





5.3.2 Dimple Wing





Within the investigated angle-of-attack range, the dimpled wing showed consistently higher lift coefficient than the smooth wing. However, further investigation at higher angles of attack and with experimental validation is required to conclusively establish the stall-delay effect.

6.CONCLUSION

A numerical investigation was conducted to study the effect of surface dimples on the aerodynamic performance of a NACA 4412 wing. CFD simulations were performed for both smooth and dimpled configurations using ANSYS Fluent.

The results show that the presence of surface dimples can influence the boundary layer behavior and delay flow separation at higher angles of attack. The dimpled wing configuration demonstrated improved aerodynamic characteristics compared to the smooth wing. The CFD results show that the dimpled NACA 4412 wing produced slightly higher lift coefficient than the smooth wing over the investigated angle-of-attack range. At 16°, the dimpled wing achieved a lift coefficient of 0.97 compared to 0.89 for the smooth wing, while drag coefficients remained comparable. These findings suggest that surface dimples can influence boundary layer development and may improve aerodynamic performance under low-speed conditions. However, additional mesh validation, higher-angle simulations, and experimental studies are required for confirmation.

This study suggests that surface dimples can be an effective passive flow control technique for improving the aerodynamic performance of low Reynolds number airfoils.

The present study is computational only, experimental validation is needed.

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