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Aerodynamic Analysis of Dimple effect on Airfoil

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Abstract— ***The main objective of aircraft aerodynamics is to enhance the aerodynamic characteristics and maneuverability of the aircraft. This enhancement includes the reduction in drag. At present different kinds of surface modifications like Vortex Generators commonly known as Dimples are being studied to improve the maneuverability of the aircraft. Present paper attempts to evaluate the effects of such artificial modifications on the surface of a NACA 4412 Airfoil and analyze the impact on its aerodynamic performance. An external flow study was performed using commercially available software. Simulations for external flow configuration with and without dimples were carried out and analyzed in detail. The resulting pressure drop and drag were observed. The objective is to clarify whether or not dimples cause reduction of the skin friction drag and if it would provide better lift.***

Index Terms— ***Airfoil, Lift, Drag, Dimple, Pressure Drop.***

I. INTRODUCTION

An aircraft is basically a machine, which is able to fly by gaining support from the air within the Earth's atmosphere. The interaction between the aircraft and air is termed as aerodynamics, which deals with the forces and motion of aircraft through the air. Enhancing the aerodynamic efficiency (L/D ratio) is one of the key parameters that determine the performance of an aircraft [1].

At present different kinds of surface modifications are being studied to improve the maneuverability of the aircraft. Vortex Generators/Dimples are most frequently used modification. These create turbulence by creating vortices, which delay the boundary layer separation resulting in decrease of pressure drag [2,3]. From Fig.1, a golf ball with a dimpled surface can travel higher and farther than a smooth surfaced ball when subjected to an identical force. The dimples induce turbulence at lower Reynolds Number, providing extra energy to the boundary layer and causing delay in the flow separation, thus reducing the drag.

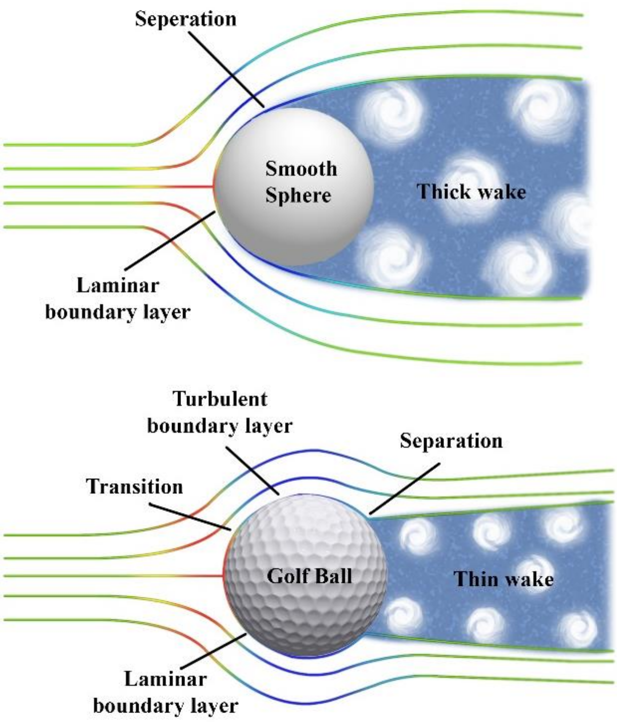

Figure 1. Delay of flow separation[6]

Surface modifications considered in this paper are inward dimple on upper surface and inward dimple on lower surface of NACA 4412 Airfoil. Further investigations are carried at higher angles of attack with an increase in dimple numbers. A 2-Dimensional Computational Fluid Dynamics (CFD) Analysis [4-6] is carried out using Spalart Almaras model, thereafter based on its results the better of the three is chosen [7]. The main objective is to shorter the takeoff distance of the aircraft by creating sufficient lift with minimum drag at low velocity.

II. METHODOLOGY

A. *Geometry generation*

In order to validate the proposed analysis, a NACA 4412 airfoil profile was selected on which the whole study is based. The 2D model for various cases used in simulation were developed and the simulations were carried out using commercial software packages. The model was debossed with dimples on different surfaces of airfoil. With reference to previous research papers, the semi spherical shaped dimple is selected as it generates more turbulence than the other shapes like square. Table 1 shows the NACA 4412 wing geometrical details.

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Table 1. NACA 4412 wing geometry

Input	Value
Length of airfoil	1 m
Wing Span	1m
Area	$1m^2$
Angles of Attack	-15 degrees to +15 degrees

B. Mesh generation

A commercial grid generator is used to mesh the fluid domain. A grid dependency check is carried out for various mesh configurations in order obtain the accurate results for the generated mesh. Meshed model is as shown in Figure 2.

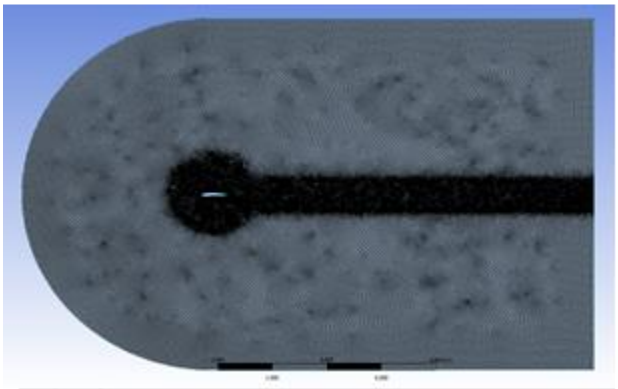

Figure 1: Meshed domain

C. Turbulence Model

The Spalart Allmaras (SA) model [8] is a simple one used to solve one transport equation for the turbulence viscosity. It is able to calculate a local shear layer thickness for the length scale with one equation. The SA model is designed especially for wall-bounded flows and adverse pressure gradient boundary layers in aerospace applications.

The one-equation model is given by the following equation:

$$\frac{\partial\hat{\nu}}{\partial t}+u_j\frac{\partial\hat{\nu}}{\partial x_j}=c_{b1}(1-f_{t2})\hat{S}\hat{\nu}-\left[c_{w1}f_w-\frac{c_{b1}}{\kappa^2}f_{t2}\right]\left(\frac{\hat{\nu}}{d}\right)^2+\frac{1}{\sigma}\left[\frac{\partial}{\partial x_j}\left((\nu+\hat{\nu})\frac{\partial\hat{\nu}}{\partial x_j}\right)+c_{b2}\frac{\partial\hat{\nu}}{\partial x_i}\frac{\partial\hat{\nu}}{\partial x_i}\right] \quad (1)$$

and the turbulent eddy viscosity is computed from:

$$\mu_t=\rho\hat{\nu}f_{v1} \quad (2)$$

Where

$$f_{v1}=\frac{\chi^3}{\chi^3+c_{v1}^3} \qquad \chi=\frac{\hat{\nu}}{\nu}$$

and ρ is the density, $\nu=\mu/\rho$ is the molecular kinematic viscosity, and μ is the molecular dynamic viscosity. Additional definitions are given by the following equations:

$$\hat{S}=\Omega+\frac{\hat{\nu}}{\kappa^2 d^2}f_{v2} \quad (3)$$

Where $\Omega=\sqrt{2W_{ij}W_{ij}}$ is the magnitude of the vorticity, *d* is the distance from the field point to the nearest wall, and

$$f_{v2}=1-\frac{\chi}{1+\chi f_{v1}}$$

$$f_w=g\left[\frac{1+c_{w3}^6}{g^6+c_{w3}^6}\right]^{1/6}$$

$$g=r+c_{w2}(r^6-r)$$

$$r=min\left[\frac{\hat{\nu}}{\hat{S}\kappa^2 d^2},10\right]$$

$$f_{t2}=c_{t3}exp\left(-c_{t4}\chi^2\right)$$

$$W_{ij}=\frac{1}{2}\left(\frac{\partial u_i}{\partial x_j}-\frac{\partial u_j}{\partial x_i}\right)$$

The constants are:

$$c_{b1}=0.1355 \qquad \sigma=2/3$$
$$c_{b2}=0.622 \qquad \kappa=0.41$$
$$c_{w2}=0.3 \qquad c_{w3}=2$$
$$c_{v1}=7.1 \qquad c_{t3}=1.2$$
$$c_{t4}=0.5 \qquad c_{w1}=\frac{c_{b1}}{\kappa^2}+\frac{1+c_{b2}}{\sigma}$$

D. Boundary conditions

Simulations are carried out at different angles of attack, taking inlet velocity as 25m/s and Uy, Uz as zero. Density of air and dynamic viscosity are as shown below. Domain is of rectangular shape with velocity inlet boundary condition set as inflow and pressure outlet condition set as outflow. Table 2 shows the boundary conditions used.

Table 1. Boundary conditions

Input	Values
Velocity Vector	Vx=25,Vy=0,Vz=0 m/s
Operating temperature	300 K
Operating Pressure	101325.00 Pa
Turbulence Model	Spalart- Allmaras (1 equation)
Fluid	Air as ideal gas
Density of fluid	1.176674kg/m3
Kinematic viscosity	1.7894e-05 kg/m-s
Reynolds number	1.4e06

III. VALIDATION

The CFD results obtained were validated with UIUC Airfoil Data [9]. Table 3 brings out the experimental data of UIUC along with the Commercial software simulation results for the purpose of model validation.

Table 3. Model Validation

	UIUC Airfoil Data	Analysis Data
Angle of Attack	C_L	C_L
-10	-0.6249	-0.6095
-5	-0.0799	-0.0891
0	0.4773	0.4270
5	1.0135	0.9385
10	1.4293	1.4315
15	1.6603	1.5925

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Figure 3 shows validated data with UIUC for Co-efficient of lift with respect to Angle of attack and it is found that set boundary conditions are in agreement with the UIUC data.

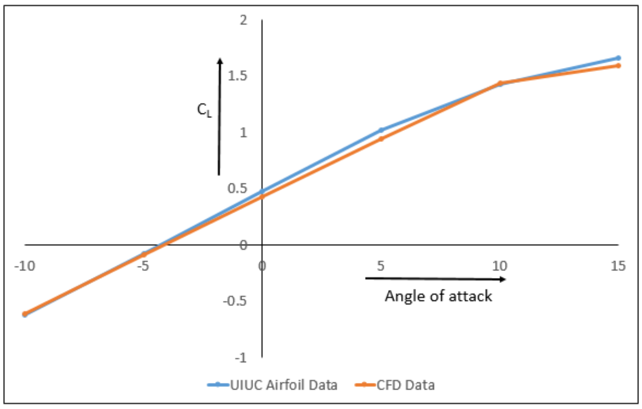

Figure 3. Data Validation

IV. RESULTS AND DISCUSSIONS

The study starts with CFD Analysis of 2-D NACA 4412 Airfoils at different angles of attack with single inward dimples at upper and lower surfaces and multiple inward dimples at the upper surface. Coefficients of Lift and drag are analyzed.

From the graph it is seen that the dimple surface airfoil increases the aerodynamic performance considerably as note in the C_L plot. However, when analyzing the C_D and L/D plots it is seen that at high Angle of attack, drag effects play a substantial role in reducing L/D performance. It is suggested that at high Angle of attack, the drag effects can be reduced by provision of additional thrust. Also, a retractable cover may be provided over the dimples so as to open the dimples only when need arises in the low Angle of attack region (i.e. up to 10^0.)

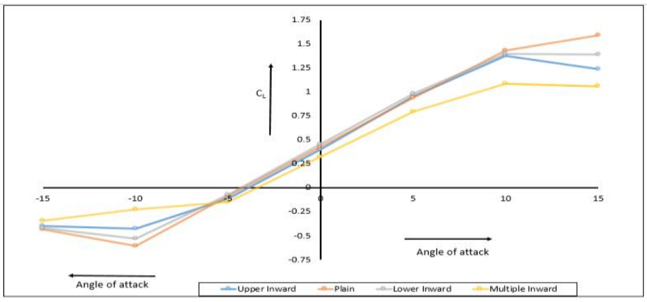

Figure 4. Coefficient of Lift Vs Angle of Attack

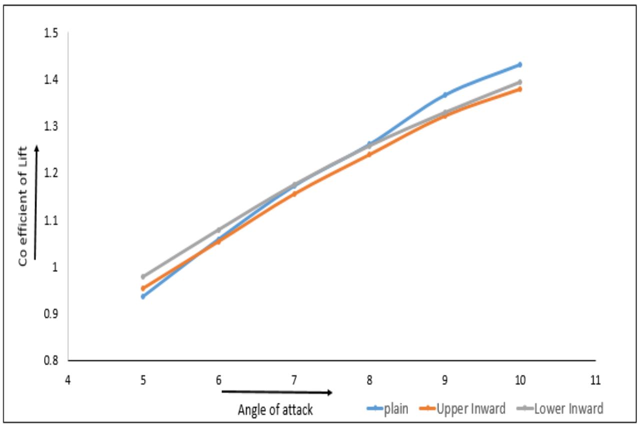

Figure 5. Coefficient of Lift comparison for different airfoils

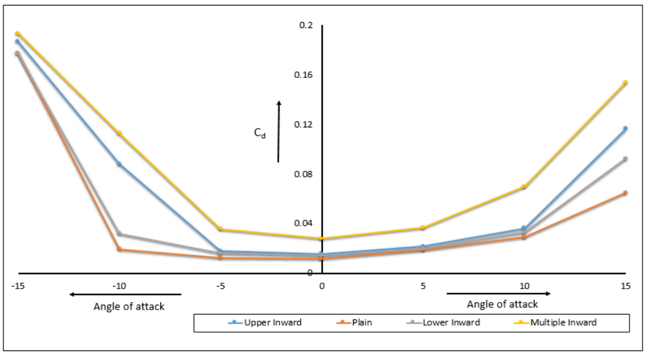

Figure 6. Coefficient of Drag for different airfoils

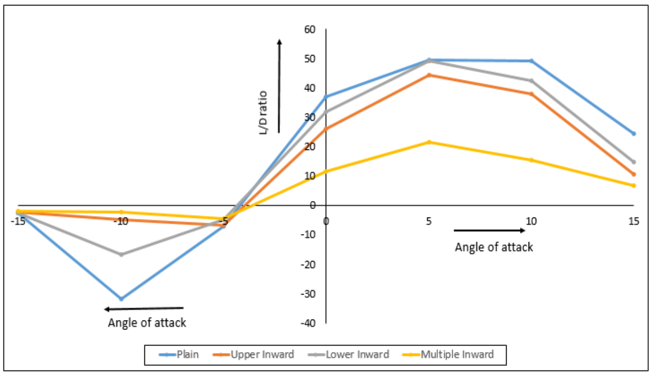

Figure 7. Lift to Drag ratio Vs Angle of Attack

Figure 8,9,10,11 shows the contours of eddy viscosity at 5^0 angle of attack for Plain, Upper inward, Lower inward and Multiple upper dimple and it is observed that there is a delay in flow separation. The trailing edge vortex is an important phenomenon of Lift generation by circulation effect, whereas the vortex about the leading edge deteriorates aerodynamic performance since it contributes heavily to induced drag as observed in multiple dimple airfoil.

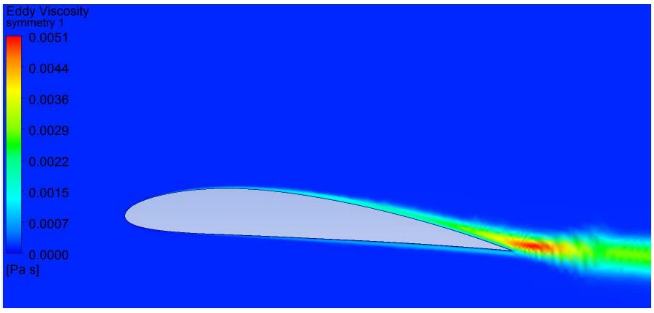

Figure 8. Contours of Eddy Viscosity: Plain

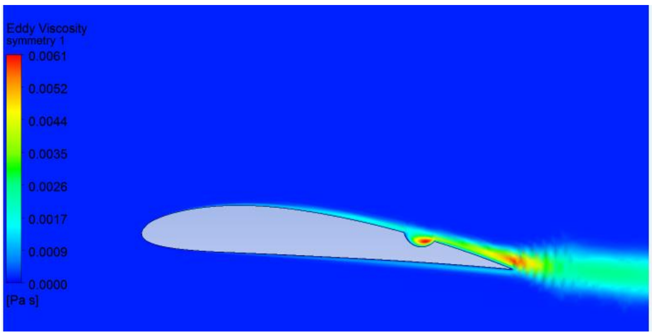

Figure 9. Contours of Eddy Viscosity: Upper Inward

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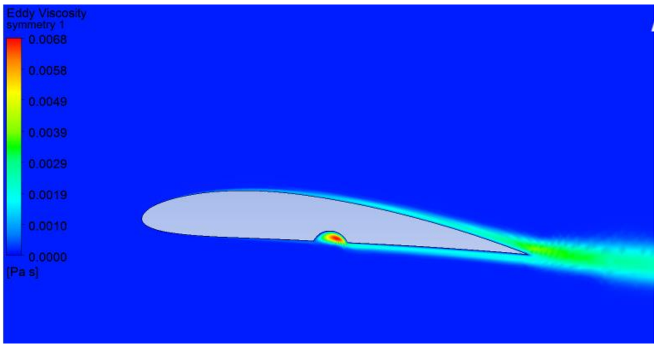

Figure 10. Contours of Eddy Viscosity: Lower Inward

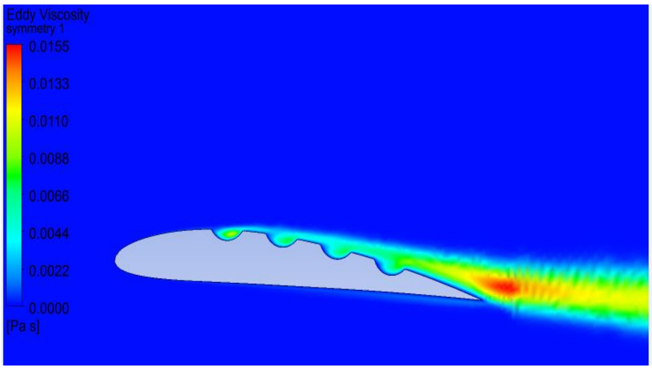

Figure 11. Contours of Eddy Viscosity: Multiple Upper

Figure 12,13,14,15 shows contours of pressure at 5^0 angle of attack for Plain, Upper inward, Lower inward and Multiple upper dimple. It is found that the low pressure region above the airfoil is about 1/3rd of the airfoil length from the leading edge. Beyond this region the flow is separated, that is, no more Lift is generated at this region. The pressure variation from low pressure to high pressure signifies the presence of laminar separation bubble. The pressure transition from low to high has been identified as the location wherein dimples could be located.

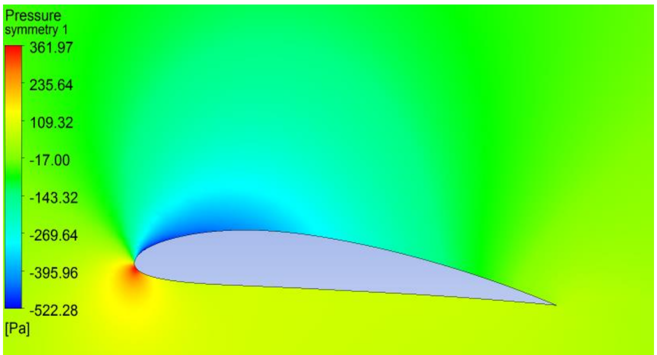

Figure 12. Contours of Pressure: Plain

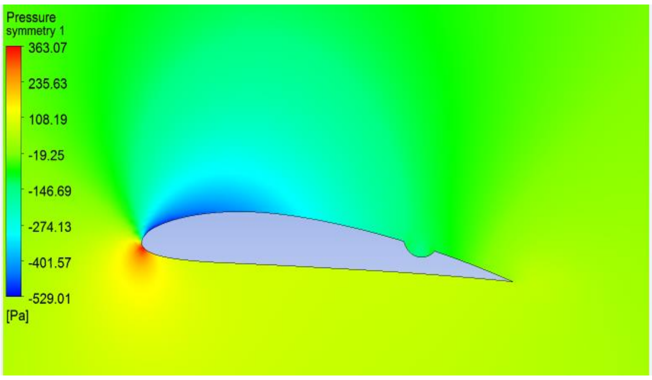

Figure 13. Contours of Pressure: Upward Inward

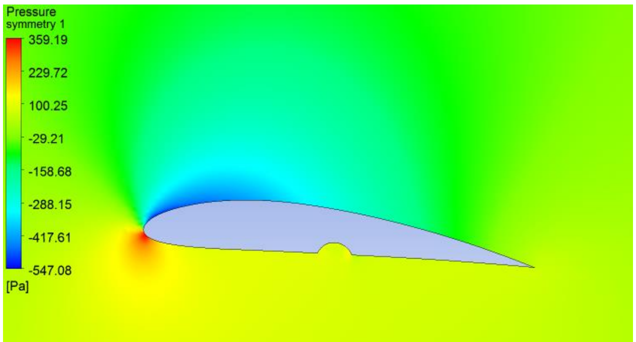

Figure 14. Contours of Pressure: Lower Inward

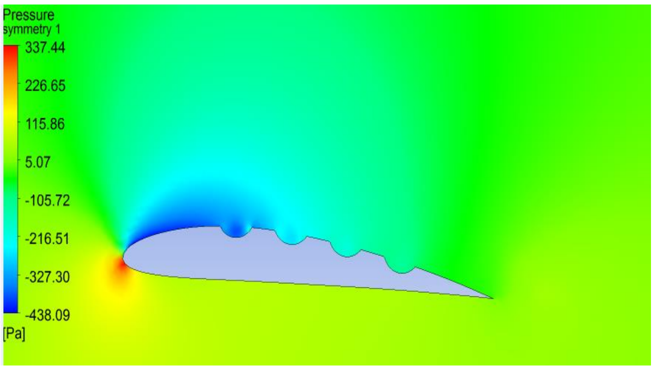

Figure 15. Contours of Pressure: Multiple Upper

Figure 16,17,18,19 shows streamline coloured by velocity of pressure at 5^0 angle of attack for Plain, Upper inward, Lower inward and Multiple upper dimple

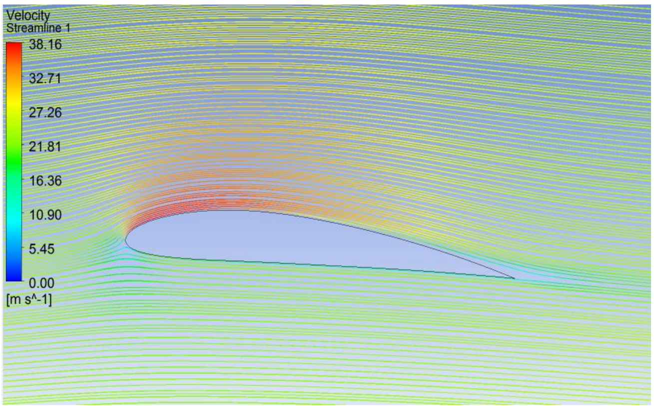

Figure 16. Streamline coloured by velocity: Plain

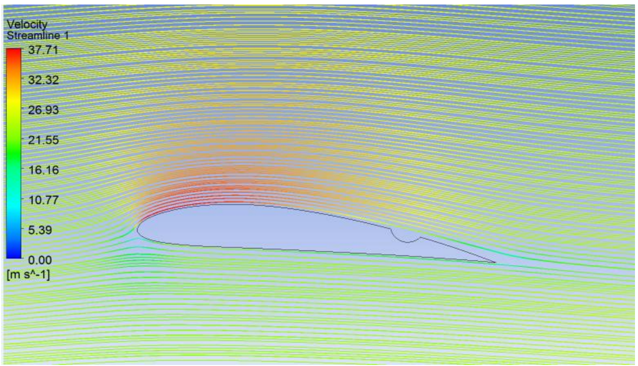

Figure 17. Streamline coloured by velocity: Upward Inward

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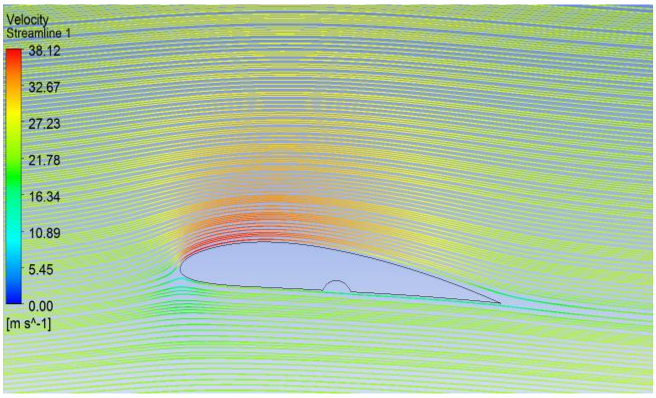

Figure 18. Streamline coloured by velocity: Lower inward

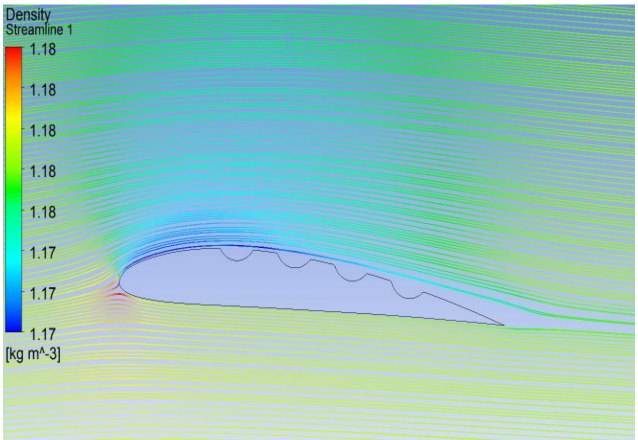

Figure 19. Streamline coloured by velocity: Multiple Dimple

V. CONCLUSION

- Analysis is carried out for the varied angle of attack ranging from -15 to +15 degrees for 3 different dimpled positioned configuration of NACA 4412 airfoil and Analysis results were compared with the plain airfoil.
- For single inward dimple on upper and lower surface, significant increase in lift is observed up to certain angle of attack in comparing with plain airfoil.
- For multiple inward dimples on upper surface there is no significant improvement in lift is observed.
- For the angle of attack from 6 to 9 degree, a significant improvement in lift is observed for single inward dimple on upper and lower surfaces.
- From the pressure and velocity contours, the position of the optimum placement of the dimple can be found by realizing the region of velocity drop and pressure rise, owing to the flow separation that occurs at the given angle of attack.

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