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Investigation on Flow over Conventional and Supercritical Airfoils at Transonic Regimes

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Abstract- Flow over conventional and supercritical airfoils in the transonic regime is investigated and compared in this study. This study focuses on two-dimensional flow conditions with Mach numbers of 0.8 and 0.9 at Angles of attack (α)00 and 50. Flow over NACA4415 and SC(2)-0410 as examined using the Ansys software by CFD analysis. The computational results indicate that a supercritical airfoil has higher efficiency and performance and delays the formation of shock waves compared with conventional airfoils in the transonic regime. The Mach number and angle of attack affect the generation of shock waves on both airfoil surfaces. SC(2)-0410 and NACA-4415 were compared by considering factors like lift co-efficient CL, drag coefficient C¬D, lift to drag ratio(L/D), and position of formation of the shock wave on the airfoil surface. The behavior of the airfoils in the transonic flow regime was further analysed.

Keywords- Supercritical airfoil, Conventional airfoil, Transonic flow regime, Computational Fluid Dynamics (CFD)

I. INTRODUCTION

Modern civil aircraft typically operate in transonic regimes with complex nonlinear flow patterns. The shock wave inside the transonic regime generates wave drag, and the wave drag pressure increases. The transonic flow regime is where both laminar and turbulent flows exist and is between Mach numbers 0.8 and 1.2 [1]. Aerodynamicists find transonic flow to be a fascinating topic to investigate. Even now in the 21st century, significant research is being conducted on the transonic flow regime. This is the flow regime in which the drag of the airfoil or wing increases drastically. This effect is known as drag divergence. Conventional airfoils are fundamental components in many aerodynamic applications known for their specific shapes and characteristics that optimize lift, drag, and overall performance under various conditions. Their design continues to evolve with advances in technology, but they remain a cornerstone in the field of aerodynamics. Supercritical airfoils represent a significant advancement in aerodynamic design, tailored to optimize performance at transonic speeds by managing shock waves and reducing drag. The distinctive airfoil shape, which is based on the concept of local supersonic flow with isentropic recompression, is characterized by a large leading-edge radius, condensed curvature over the middle region of the upper surface, and substantial aft camber [2]. Their development has been instrumental in the efficiency and performance of modern high-speed aircraft.

Figure 1: NACA4415 convention airfoil of chord length 100mm

Figure 2: SC20410 phase-2 supercritical airfoil of chord length 100mm

A comprehensive study was conducted by Dr. S. B. Prakash and Ravikumar T during a supercritical airfoil aerodynamic study at different angles of attack (α). Their study states that the static pressure on the lower surface of an airfoil at the leading edge is greater than that on the upper surface. This results in the lift gradually increasing as long as the angle of attack attains 200. At this angle of attack, the pressure on the lower surface of the airfoil decreases and the drag increases. The pressure drag is estimated from the difference in the static pressure between the leading and trailing edges. A greater difference generates a high-pressure drag. At 200 angles of attack, pressure drag increases, but at 22.50 angles of attack, it decreases continually [3]. When a supercritical airfoil is introduced into the transonic flow, it has a buffet effect. Research was conducted to further understand the buffet in the transonic regime. Their study focused on optimizing the configuration of supercritical airfoils. These results indicate that the buffeting phenomenon is induced by the interaction between shockwaves and boundary layers [4]. Nagamani Mishra et al. conducted a comparative study to comprehend the performance of NACA and supercritical airfoils at transonic velocities. Compared with the NACA airfoil, the supercritical airfoil had less drag. Fuel economy and aircraft range are expected to significantly increase with decreasing shock strength and wave drag [5]. Many shock control methods have been proposed to achieve this goal. One such technique uses an airfoil design that can locally alter form to reduce the contact between the boundary layer and the shock wave and its strength. The contour bump is an easily installed, basic structural device that modifies the local profile of an aircraft's wing surface. When a contour bump is installed in the airfoil, it can remarkably reduce transonic drag by weakening the shock wave strength. The contour bump can reduce drag for a wide range of higher lift coefficients, including off-design conditions [6].

This study investigates and compares the flow over the supercritical airfoil SC(2)-0410 with that over the conventional airfoil NACA-4415 in transonic regimes (Mach 0.8 and 0.9) to compare the lift coefficients (CL), drag coefficients (CD), and lift-to-drag ratio (L/D) at angles of attack 00 and 50. This study was conducted to understand the behaviour of conventional and supercritical airfoils in transonic regimes and to observe the variation in the position of the shock wave.

II. METHODOLOGY

Ansys software is used for CFD stimulation over an airfoil. Ansys is a leading engineering simulation tool that provides robust and versatile capabilities for analysing and optimizing products across industries. Its comprehensive suite of tools, coupled with high accuracy and reliability, makes it a preferred choice for engineering professionals, despite the challenges of cost and complexity. For this stimulation, download the airfoil coordinate files from the airfoil tools using any browser. Now import the text file of the coordinates into Ansys design modular. The fluid domain is created over the airfoil, as shown in figure.

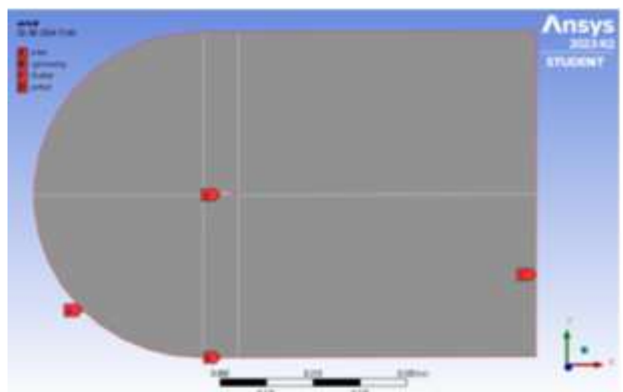

Figure 3: control volume over NACA-4415

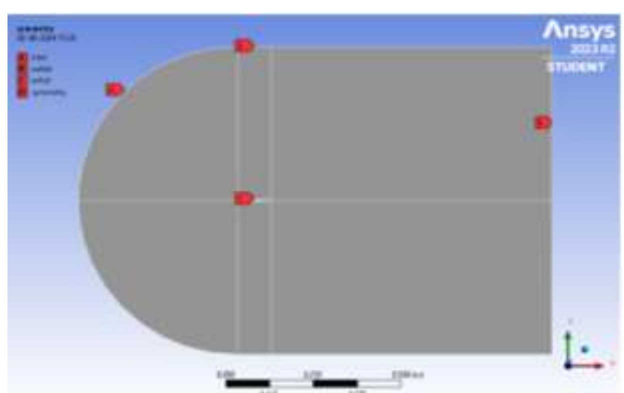

Figure 4: Control volume over SC(2)-0410

1. Discretization

Discretizing control volumes in Computational Fluid Dynamics (CFD) is an important step in converting the continuous governing equations of fluid flow into a solvable system of algebraic equations. This procedure involves splitting the computational domain into smaller, finite volumes or parts, allowing numerical solutions to the equations that govern fluid dynamics.

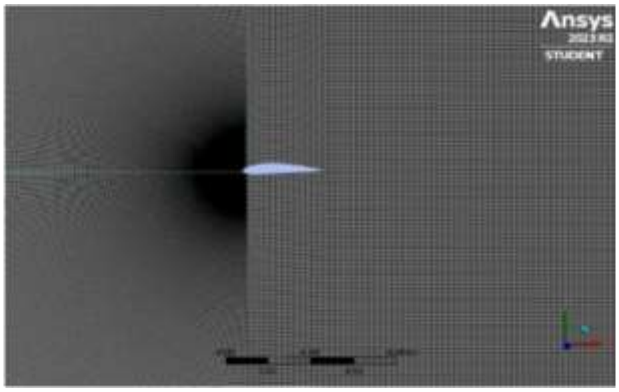

Figure 5: Ordered Mesh over the control volume of NACA-4415

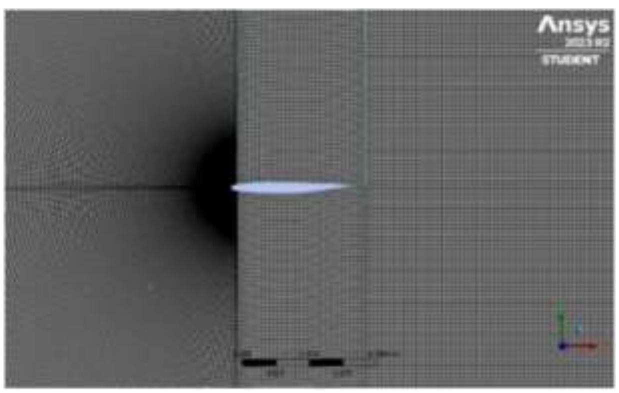

Figure 6: Ordered Mesh over the control volume of SC(2)-0410

2. Mesh Quality

Mesh quality is a crucial aspect in Computational Fluid Dynamic (CFD) analysis and is critical for achieving accurate and reliable simulation results. The quality of the mesh directly affects the ability of numerical methods to accurately capture the physics of fluid flow. This involves optimizing element shapes, sizes, and distributions, especially in critical regions like boundary layers and areas with complex flow phenomena. Using appropriate metrics and techniques to assess and improve mesh quality helps achieve reliable and accurate CFD results. To test the mesh quality factors like orthogonality, skewness, aspect ratio, and Y+ are considered. The y+ value is a non-dimensional parameter used in Computational Fluid Dynamics to describe the distance from the wall to the first cell centre in wall-bounded flows. It is especially important in turbulent flow simulations. The Y+ value of the mesh over the control volume of NACA-4415 is 0.000015 and SC(2)-0412 is 0.000019.

Table1. Quality of Mesh over control volume

Airfoil	Orthogonality		Skewness		Aspect ratio	
	Min. no. of elements with	Max. no. of elements with	Min. no. of elements with	Max. no. of elements with	Min. no. of elements with	Max. no. of elements with
NACA-	0.0306	1.0	0.000013	0.3851	1.001	50.2
SC(2)-0410	0.50966	1.0	0.000056	0.4156	1.0	47.95

3. Solver

Ansys fluent was used to stimulate the analysis over the meshed control volume of NACA-4415 and SC(2)-0410 at various boundary conditions

Table 2: Boundary conditions

S.No	Case Study	Mach Number	Angle of Attack	Turbulence intensity
1	01	0.8	0^0	5
2	02	0.8	5^0	5
3	13	0.9	0^0	5
4	04	0.9	5^0	5

III. RESULTS AND DISCUSSION

1. Case Study-01

In this case study, both airfoils are in the transonic regime where Mach- 0.8, the Angles of attack (α) of the airfoils is 00, and the turbulence intensity is set to 5%.

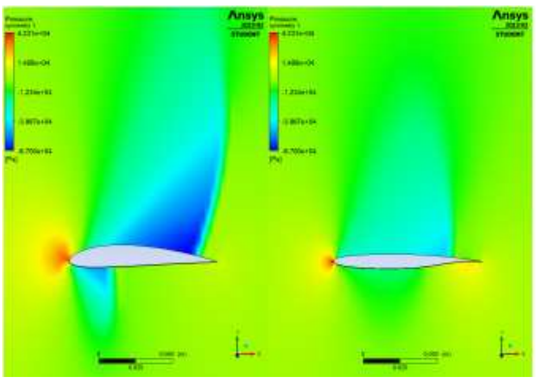

Figure 7: comparison of pressure contour at mach-0.8 and $\alpha=0^0$

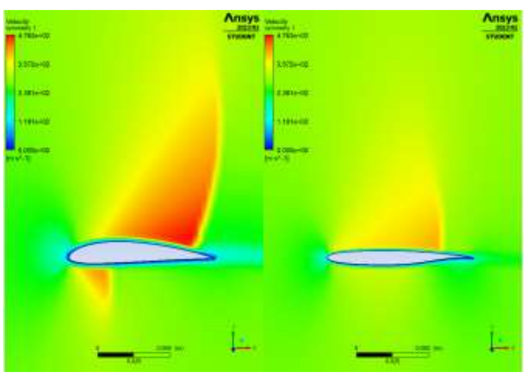

Figure 8: comparison of velocity contour at mach-0.8 and $\alpha=0^0$

Case study 01 concentrates on the behaviour of airfoils at 5% turbulence intensity at Mach 0.8 and angle of attack 0. As the flow approaches the leading edge of the airfoil, it accelerates on the top surface and decelerates on the lower surface of the airfoil. This pressure difference generates lift. However, at a transonic free-stream Mach number, the flow on the upper surface can approach supersonic speeds due to acceleration. This creates a regular shockwave in the region [7]. The shock wave increases the drag of the airfoil. In this case study, the lift coefficient (CL) and drag coefficient (C¬¬D) produced by the NACA-4415 are 0.08 and 0.013, respectively. The lift and drag forces produced were 2734.4 N and 470.4 N, respectively. Here, the lift is higher than the drag. The lift-to-drag ratio is 5.81. The lift and drag coefficients produced by the SC(2)-0410 are 0.092 and 0.00278, respectively. The lift and drag produced were 2302.2 N and 69.21 N, respectively. The lift-to-drag ratio is 33.26. Therefore, by comparing the data of airfoil lift co-efficient (CL) produced by the supercritical airfoil is higher than the conventional airfoil. The drag coefficient (C¬¬D) of the supercritical airfoil is 0.00278, which is much lower than the 0.013 drag coefficient (C¬¬D) of the conventional airfoil. And importantly, the lift-to-drag ratio (L/D) of both airfoils has much difference supercritical airfoil has 33.26 and conventional airfoil has 5.81, by this at this supercritical airfoil [SC(2)-0410] has more efficiency than conventional airfoil [NACA4415]

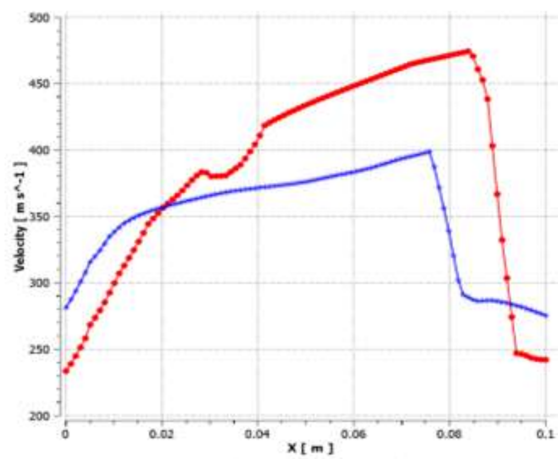

Figure 9: Pressure vs. Chord length of the airfoil

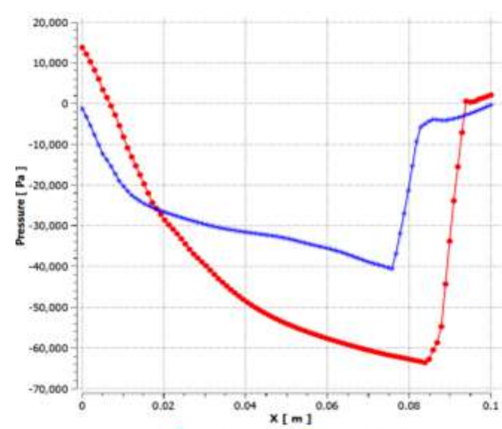

Figure 10: Velocity vs. Chord length of the airfoil

The above graph shows the variation in pressure and velocity with respect to the chord length of the airfoils. The shock wave for the NACA-4415 airfoil formed 0.0845 m away from the leading edge of the airfoil, and the shock wave of the SC(2)-0410 airfoil formed 0.076 m away from the leading edge. The shocks were observed on the upper and lower surfaces of the NACA-4415 airfoil, but only one shock was observed on the upper surface of the supercritical airfoil SC(2)-0410. Apparently, the pressure of both airfoils decreased until the formation of the shock, and the pressure increased rapidly after the formation of the shock, and the velocity increased until the formation of the shock and decreased drastically. However, the supercritical airfoil has a lower pressure and higher velocity than the conventional airfoil.

2. Case Study-02

In this case study, both airfoils are in the transonic regime where Mach- 0.8, the angle of attack (α) of the airfoils is 50, and the turbulence intensity is set to 5%.

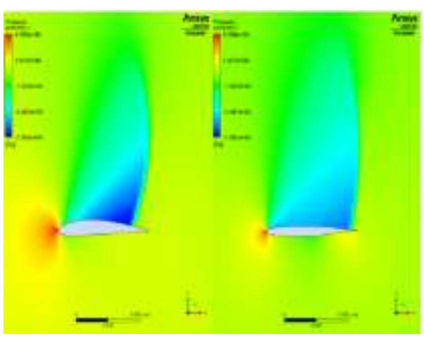

Figure 11: comparison of pressure contour at mach-0.8 and α =5^0

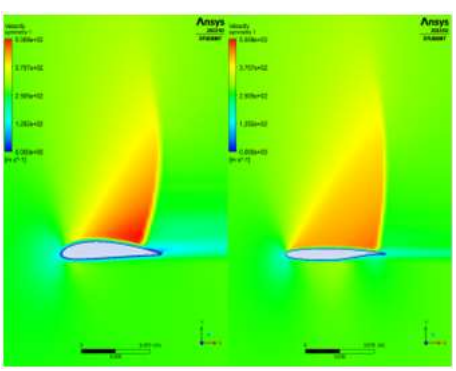

Figure 12: comparison of velocity contour at mach-0.8 and α =5^0

In this case, the airfoils are in the transonic regime where Mach is 0.8 and the angle of attack (α) is 50. Here, the angle of attack has increased 00 to 50. An airfoil's angle of attack has a major impact on both lift and drag. To a certain extent, increased aerodynamic efficiency is caused by a linear rise in lift; however, at higher angles, where flow separation and stall occur, there is also an increase in drag. Comprehending these impacts is essential for enhancing aircraft efficiency, managing flight operations, and guaranteeing aviation steadiness and security. Therefore, the lift and drag coefficients of the NACA-4415 airfoil are 0.11 and 0.098, respectively. The lift and drag forces produced were 4539.92 N and 374.10 N, respectively. The lift-to-drag (L/D) ratio of the airfoil is 12.13. The supercritical airfoil produced lift and drag coefficients of 0.13 and 0.044, respectively. The generated lift and drag forces are 5181.2 N and 167.78 N, respectively. The lift-to-drag (L/D) ratio of the airfoil is 30.8. when we compare this data with those of the previous case study-01, it is clear that the lift and lift-to-drag ratio (L/D) of the airfoil NACA-4415 has increased and drag has decreased. In the case of the supercritical airfoil, lift increased and the lift-to-drag ratio decreased from 33.26 to 30.8 due to an increase in drag. Now, when we compare both the airfoils, lift of SC(2)-0410 airfoil is higher than that of the NACA-4415 airfoil, and in this case, the drag of the conventional airfoil is also higher than that of the supercritical airfoil, even though the drag of the SC(2)-0410 airfoil increased and that of the NAC-4415 airfoil decreased.

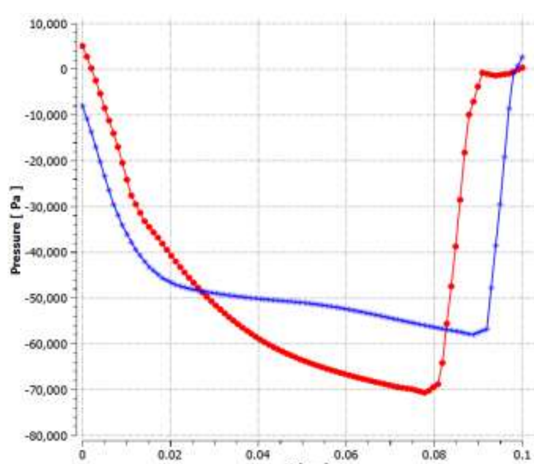

Figure 13: Pressure vs. Chord length of the airfoil

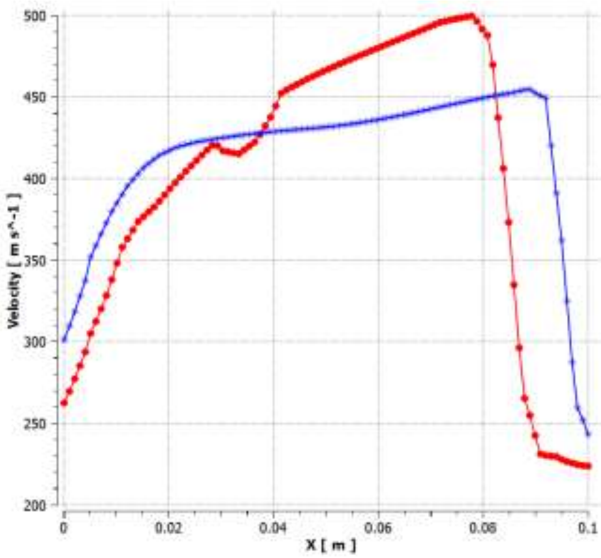

Figure 14: Velocity vs. Chord length of the airfoil

Shock wave formed at 0.0784 m of the chord length of airfoil NACA-4415 and for SC(2)-0410 shock wave formed at 0.091 m of chord length. Compared with the previous case study, a shock wave formed on the upper surface of the conventional airfoil as it moved toward the leading edge of the airfoil chord length and a shock formed on the upper surface of the supercritical airfoil as it moved away from the leading edge and toward the trailing edge of the airfoil. Shock waves were observed only on the upper surfaces of both airfoils. In this case, the pressure of both airfoils decreased until the formation of the shock, and the pressure increased rapidly after the shock formation. The velocity increased until the formation of the shock and then decreased drastically. However, in the end, the supercritical airfoil has more pressure and high velocity than the conventional airfoil.

3. Case Study-03

In this case study, both airfoils are in the transonic regime where Mach- 0.9, the angle of attack (α) of the airfoils is 00 and turbulence intensity is set to 5%.

When the airfoils are in transonic conditions of Mach 0.9 and the angle of attack (α)is 00 . In this case, the lift and drag coefficients of NACA4415 decreased to 0.0021 and 0.025, respectively. The lift and drag forces generated were 82.1093 and 1025.1, respectively. The lift-to-drag ratio (L/D) is 0.08. For SC(2)-0410, the lift and drag coefficients are 0.014 and 0.016, respectively. The lift and drag forces generated are 581.579 N and 492.708 N, respectively, and the lift-to-drag ratio (L/D) is 1.1803. Apparently, when this case is compared to previous cases, all the values of the lift coefficient, drag coefficient, forces, and lift-to-drag ratio decreased with a huge difference.

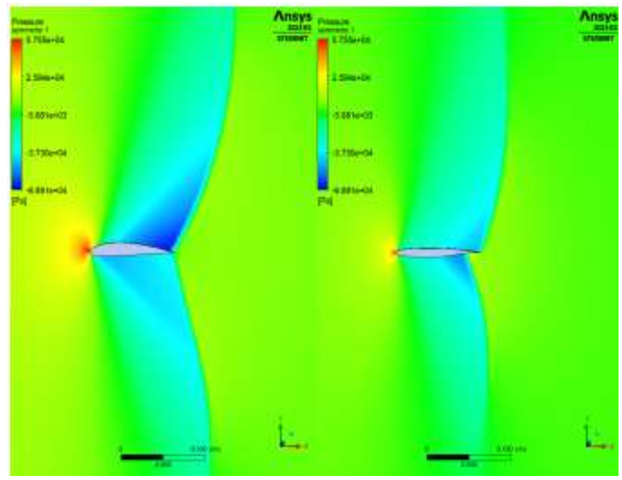

Figure 15: comparison of pressure contour at Mach 0.9 and $\alpha=0^0$

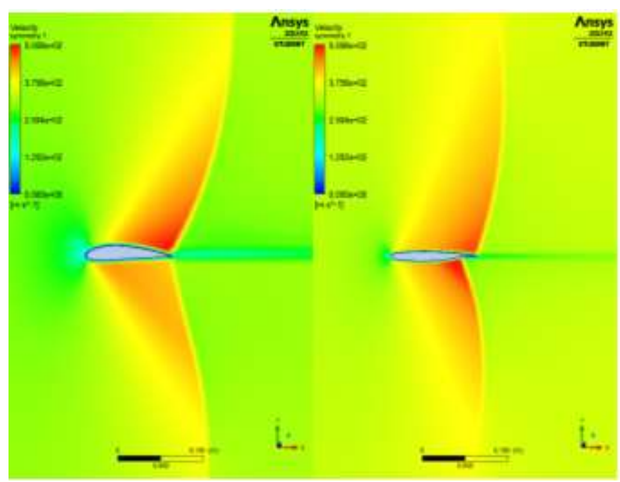

Figure 16: comparison of velocity contour at Mach 0.9 and $\alpha=0^0$

In the case of NACA-4415, the drag coefficient is higher than the lift coefficient, which implies that the lift produced is less than the drag of the airfoil. Same in case of the SC(2)-0410 lift and drag coefficients are almost equal, which implies that the lift (581.579N) produce is near to drag (492.708N). Shock waves were observed on the upper and lower surfaces of both airfoils. On the upper surface of the NACA-4415 shock wave as observed at 0.099 m away from the leading edge and near the trailing edge and on the lower surface the shock as observed at 0.112 m near the trailing edge of the airfoil. For the SC(2)-0410 airfoil, the shock wave is observed at 0.098 m near the trailing edge, and on the lower surface, it is observed at 0.081 m away from the leading edge. Both airfoils became mostly inactive in this case.

4. Case Study 04

In this case study, both airfoils are in the transonic regime where Mach- 0.9, the angle of attack (α) of the airfoils is 50, and the turbulence intensity is set to 5%.

In this case, the airfoils are in the transonic regime with Mach 0.9 and an angle of attack (α) 50. The lift and drag coefficients of the NACA-4415 airfoil are 0.096 and 0.019, respectively. The lift and drag forces produced were 4350.74 N and 858.12 N, respectively.

The lift-to-drag (L/D) ratio of the airfoil is 5.07. The supercritical airfoil produced lift and drag coefficients of 0.11 and 0.01, respectively. The generated lift and drag forces are 4495.04 N and 406.006 N, respectively. The lift-to-drag (L/D) ratio of the airfoil is 11.07. When we compared this data with that of a previous case study-03, it is clear that all the factors increased as the angle of attack increased.

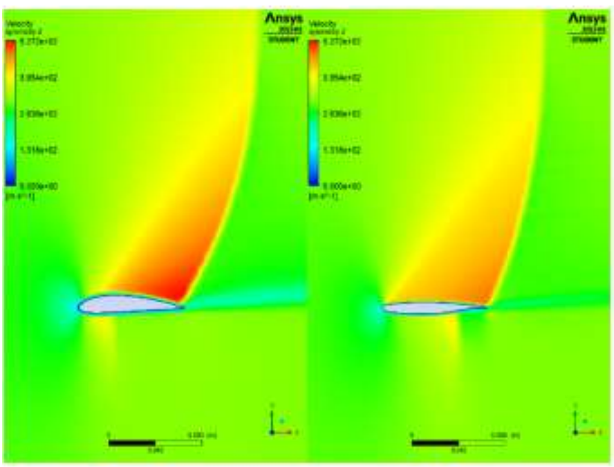

Figure 17: comparison of pressure contour at Mach 0.9 and α $=5^0$

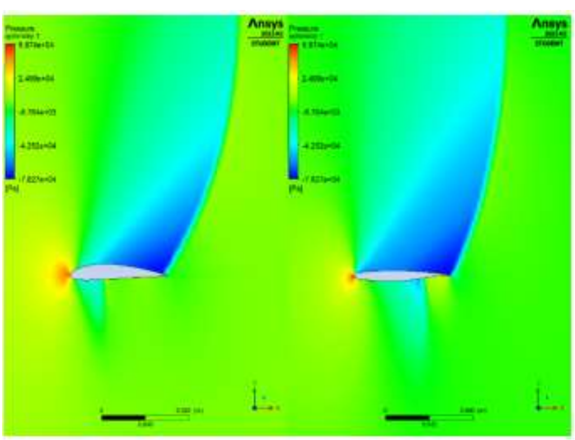

Figure 18: comparison of velocity contour at Mach 0.9 and α $=5^0$

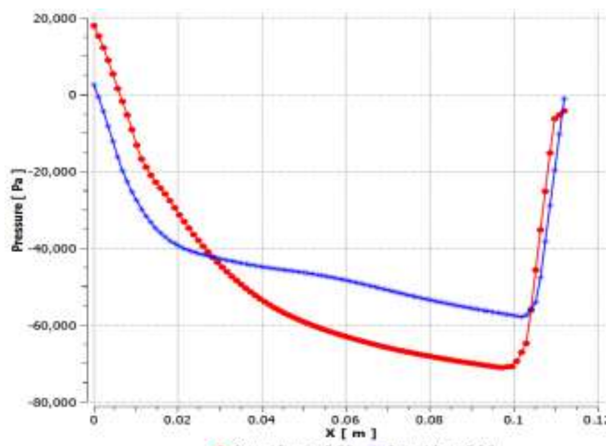

Figure 19: Pressure vs. chord length of the upper surface of the airfoils

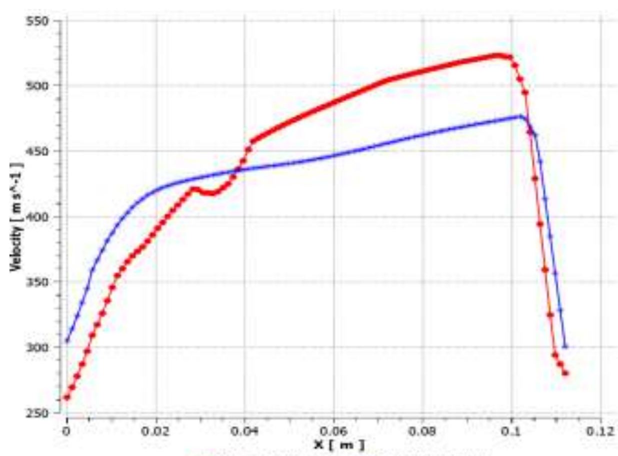

Figure 20: Velocity vs. chord length of the upper surface of the airfoils

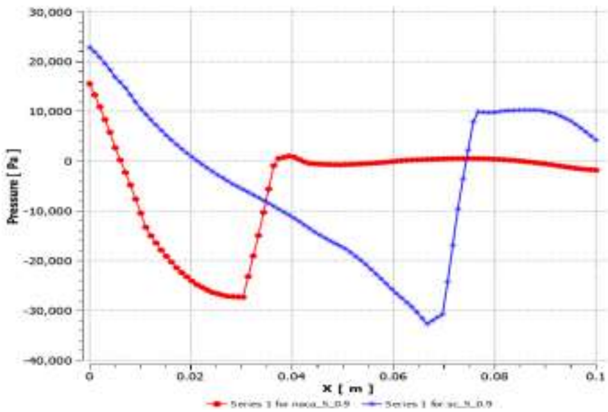

Figure 21: Pressure Vs chord length of the lower surface of airfoils

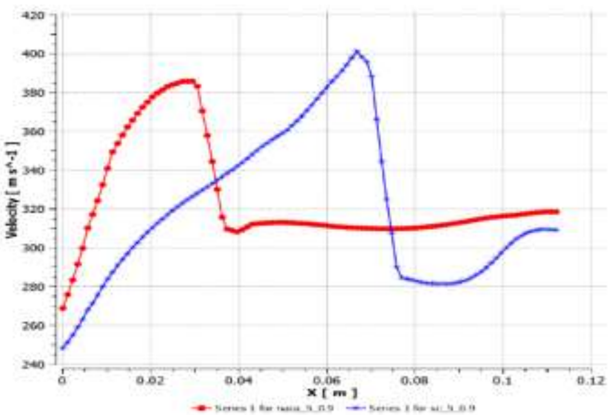

Figure 22: Velocity vs. chord length of the lower surface of the airfoils

Shock waves are observed on the lower and upper surfaces of both airfoils, but the upper surface shock wave is stronger than the lower surface shock wave. On the upper surface of NACA-4415, the shock formed at 0.098 m from the leading edge, and on the lower surface, the shock formed at 0.031 m from the leading edge. The shock wave formed at 0.15m away from the leading edge of the upper surface and on the lower surface as formed at 0.065m away from the leading edge of the supercritical airfoil [SC(2)-0410].Compared to conventional airfoils, supercritical airfoils delay the formation of the shock wave on both the upper and lower surfaces.

IV. CONCLUSION

A comprehensive analysis was performed to study the behavior of flow over the conventional airfoil [NACA-4415] and supercritical airfoil [SC(2)-0410] in the transonic regime. Computational Fluid Dynamics Simulations were performed at various boundary conditions to anticipate airfoil and shock wave behavior. The conclusions derived from the aforementioned case Studies are provided below.

The lift-to-drag ratio produced by the supercritical airfoil SC(2)-0410 is higher than that of the conventional airfoil NACA-4415 under all conditions. This proves that supercritical airfoils are more efficient and have higher performance than conventional airfoils.

The shock wave as moved toward the leading edge of the airfoil as the angle of attack (α) increased in the case of the conventional airfoil NACA-4415, but in the case of the supercritical airfoil SC(2)-0410, the shock wave as moved away from the leading edge of the airfoil. Formation of a shock wave delayed on the upper surface of the supercritical airfoil as the angle of attack increased.

Supercritical airfoil SC(2)-0410 and conventional airfoil NACA-4415, both of which become nearly inactive when the Mach number is increased to 0.9. This happened due to C¬L and CD values are almost equal or CL < CD. (In case of NACA-4415) [4]

The Mach number and angle of attack affect the generation of shock waves on both airfoil surfaces.

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