ASEN 3111 Project: Computational Fluid Dynamics with Fluent

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I. Introduction

Understanding and analyzing wing performance of an aircraft is a fundamental part of the field of aerodynamics. There are many different strategies in the engineering world that are used to determine the necessary fluid dynamics involved some of these strategies are better than others. In theory, aircraft wing performance can be determined accurately by solving the Navier Stokes equations the set of equations that govern the motion of viscous fluids. However, solving for the general solution to these equations analytically cannot be done because the theory involved is incredibly complex. Though a mathematical approach is fruitless, solving the Navier Stokes equations can be done numerically. Direct numerical simulation (DNS) is a method used to analyze fluid dynamics over a wing, and it involves solving the Navier Stokes equations directly. This approach, while it provides the most accurate results, can take a long time to compute due to its complexity. DNS programs can run for months at a time at an enormous computational cost, and thus DNS methods are usually impractical for engineering needs. This impracticality causes aerodynamic study to turn to simpler models the lowered cost and computational time makes up for the loss of accuracy that simpler models provide.

There are two simpler models in use that can provide relative accuracy if certain assumptions are made: the thin airfoil theory and the vortex panel method. Thin airfoil approximation works well in specific areas and is simple enough that it can be solved with linear theory providing analytical approximations. The vortex panel method is slightly more sophisticated and encompasses a wider range of variables this method can be solved computationally with highly accurate results. One drawback that exists for both of these models is that the fluid flow that is analyzed must be steady - flow separation is not included in the methods. However, turbulence and flow separation play a vital role in studying aerodynamics: this phenomena is abundant in nature despite the difficulty it causes in study. Flow separation is what leads to stalls in wings, and neither of the methods addressed above can accurately predict when a wing will stall. Thus, more complicated approaches must be used.

In this lab, a turbulent Reynolds-Averaging Navier-Stokes (RANS) model is used to predict the lift slope, zero lift angle of attack, stall angle, and maximum sectional coefficient of lift of two different airfoil meshes: a NACA 0012 airfoil and a NACA 4412. Ansys Fluent software is implemented to compute these values a RANS model is an acceptable middle-ground between Direct Numerical Simulation and simple analytical models. The values obtained are analyzed for accuracy against experimental data.

II. Methodology

This lab uses a Reynolds Average Navier Stokes (RANS) turbulence model to find necessary values to describe turbulent airflow. The RANS model, while less accurate than the DNS model, is much more efficient

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to run because it averages all solutions. Though the approximate solutions obtained by RANS lose the small intricacies of turbulent flow, the overall characteristics are preserved and computational costs are cut. Thus, the use of this model is an acceptable compromise in the engineering field. Figure 1 shows a comparison of the various methods used for solving the Navier Stokes equations.

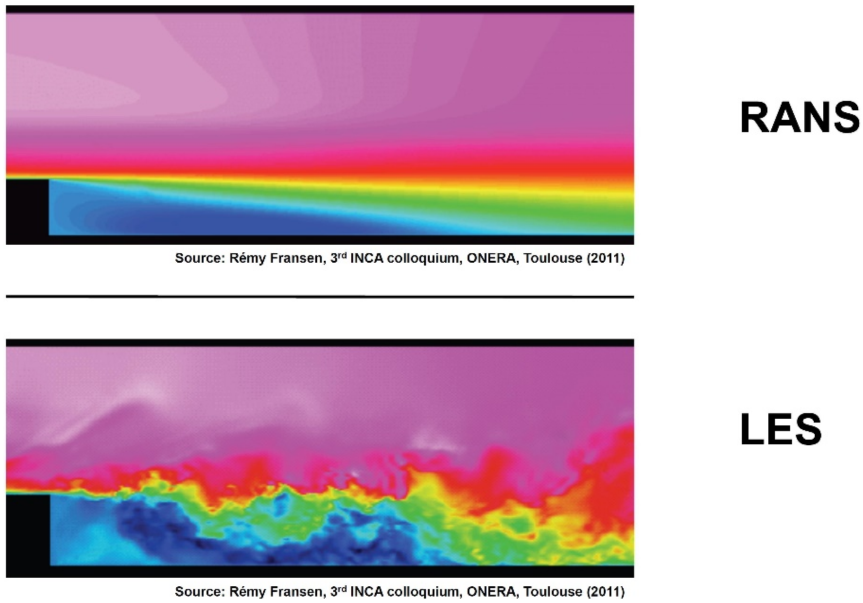

Figure 1: A comparison between RANS acquired data and LES acquired data for a fluid flow.

As shown in Figure 1, RANS analysis captures the essence of flow separation: the simulation captures just enough information to provide a rough estimate of the flows behavior even though the smaller dynamic characteristics calculated from DNS are left out of the computation.

The flow that is modeled in this lab is important to understand, because it allows the intermediate level dynamics to be ignored and the RANS model to be applicable.

Several modifications were made to the flow parameters to obtain the required Reynolds number for each airfoil. For the NACA 0012, a value of six million was used, and for NACA 4412, the Reynolds number was three million. Two different values were used because we wanted to compare our simulation results with experimental results the experimental results provided were obtained using the two different RE numbers. Also, it is useful to test more than one RE value to expand our results. These Reynolds numbers were acquired by adjusting the flow state and viscosity of the farfield. The flow state was considered to be steady in the far field to ensure constant velocity, and the viscosity was also held constant. Enforcing these conditions ensured the Reynolds number remained constant as well, though the air was considered an ideal gas to keep the density, and thus the viscosity, constant. An ideal gas assumption also allowed for compressibility properties compressible air is more accurate in nature, so our results would reflect this change. These changes ensured that the turbulent flow was as accurate as possible.

Once the Reynolds numbers were established for each airfoil, the RANS program was implemented. The software involved solves the RANS equations and Turbulence equations at the same time through a method called coupled solving. The solver converges to the correct answer given infinite time since time was limited, the constraints were loosened to allow convergence within a given tolerance (the tolerances varied with each angle of attack). The method used, though computational time is increased, provides accurate results. Meshes of each airfoil were provided to expedite the process. Each mesh was tested for different angles of attack ranging from _ to _, and for each angle, the maximum iteration number was set to 3000 to ensure that, in the event that there is no convergence, data oscillations would be removed from the calculations. The maximum iteration number introduces error within the data because the final values are affected. Overall, this process took a significant amount of time, but the software was user- friendly while providing relatively accurate results.

III. Results and Discussion

III.A. NACA 0012 RANS Results and Comparisons

A plot of the sectional coefficient of lift versus angle of attack was made using the turbulent RANS flow model, thin airfoil theory, the vortex panel method and experimental data as shown in Figure 2. Additionally, a plot of sectional coefficient of drag versus sectional coefficient of lift was made using the turbulent RANS flow model and experimental data as shown in Figure 3. Results for the zero-lift angle of attack, lift slope, stall angle and maximum coefficient of lift are shown in Table 1. The plot of sectional coefficient of lift versus angle of attack shows an expected linear region leading up to stall. At stall there is the expected decrease in lift as well as a corresponding increase in drag. The trends shown given by the RANS model show a linear relationship between the coefficient of lift and the angle of attack (for small angles) and the drag polar has a parabolic shape. These results are validated with results obtained from thin airfoil theory, the vortex panel method, and experimental results.

Thin airfoil theory is valid for thin airfoils at small angles of attack. Since thin airfoil theory disregards viscous effects and cannot predict stall, the plot of sectional coefficient of lift versus angle of attack found using RANS analysis is similar to thin airfoil theory up until larger angles of attack where the two models diverge. Thin airfoil theory predicts a lift slope of 2π per radian. This lift slope is similar to that found using RANS analysis since the NACA 0012 has 12 percent thickness and thin airfoils are defined up to and including airfoils with 12 percent thickness. The zero lift angle of attack found using thin airfoil theory is 0 for the NACA 0012 since it is a symmetric airfoil. This is very similar to the data found by the RANS model.

When comparing the data found using RANS and the vortex panel method, the results are also very similar since the vortex panel method disregards viscous effects the plots diverge around stall. Both thin airfoil theory values and vortex panel method values can be found in Table 1 as a visual comparison to the RANS model data.

The experimental data for the NACA 0012 was found from relatively recent NASA turbulent flow models. The experimental data for the NACA 0012 and the data found using RANS are very similar. This is because the NACA 0012 data was obtained recently and was actually made in part to validate CFD software by employing optimal conditions for creating 2D airfoil/"infinite wing" data.

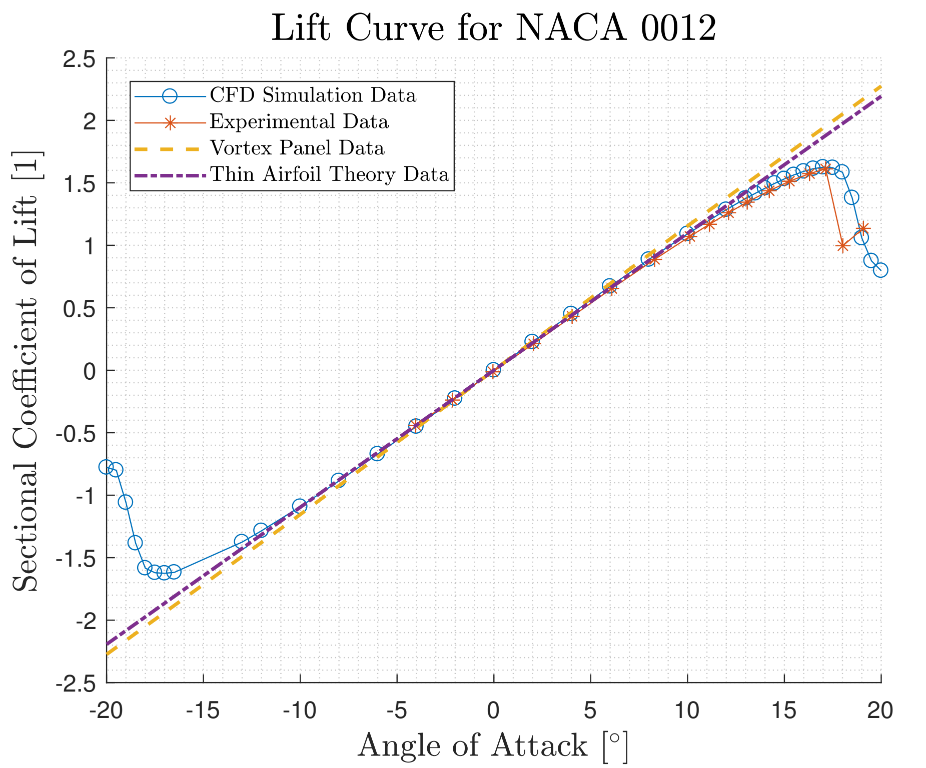

Figure 2: Lift curve for NACA 0012 using several models.

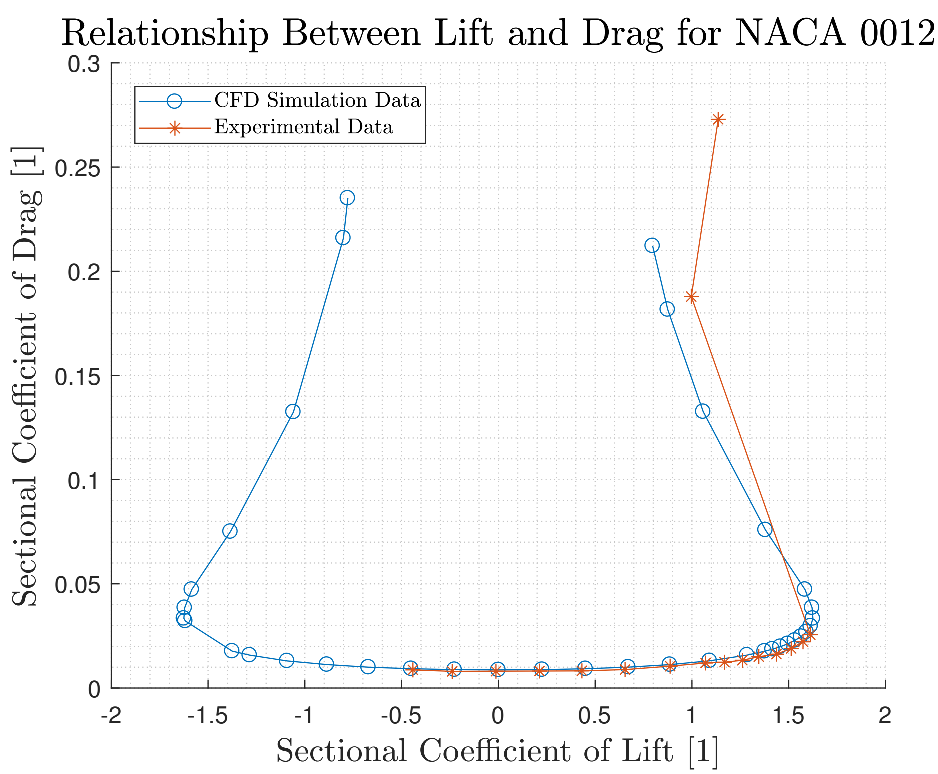

Figure 3: Relationship between lift and drag for the NACA 0012.

Table 1: NACA 0012 Results

Data Source	Lift Slope	Zero Lift AOA	Stall Angle	Max. c_l
Experimental	6.151 rad^{-1}	0.061°	17.13°	1.612
RANS Simulation	5.867 rad^{-1}	-0.169°	17.0°	1.625
Vortex Panel Method	6.535 rad^{-1}	0.000°	—	—
Thin Airfoil Theory	2π rad^{-1}	0.000°	—	—

III.B. NACA 4412 RANS Results and Comparisons

The RANS computation detailed above was repeated for a NACA 4412 airfoil mesh shape. The coefficients of lift and drag are recorded in Table 2, and are also plotted in Figures 4 - 5. It must be noted that the NACA 4412 airfoil is not symmetrical, and therefore the zero lift angle of attack is not zero due to the camber. Stall was found at 17 degrees by finding where the lift slope versus coefficient of lift is no longer positive. The results obtained and shown in 5 show expected trends as the coefficient of lift linearly increases as the angle of attack increases at low angles of attack. Figure 4 gives a parabolic trend with a center at zero.

To ensure the accuracy of the RANS results, the same analytical methods used for the NACA 0012 airfoil were utilized again: thin airfoil theory and the vortex panel method. Table 2 shows the zero-lift angle of attack and the lift slope computed by both methods as well as the RANS data for comparison. The values shown in the table establish a similar trend as the symmetrical airfoil in that the RANS data falls very close to both the vortex panel results and the thin airfoil theory predictions.

The NACA 4412 experimental data came from NACA report No. 824. The RANS model was, once again, compared to experimental data for the NACA 4412. Figure 5 shows the experimental results that were used to obtain the values listed in 2. These results show that the RANS model and the experimental data align very consistently, with minor discrepancies that stem from the simplification of the RANS model.

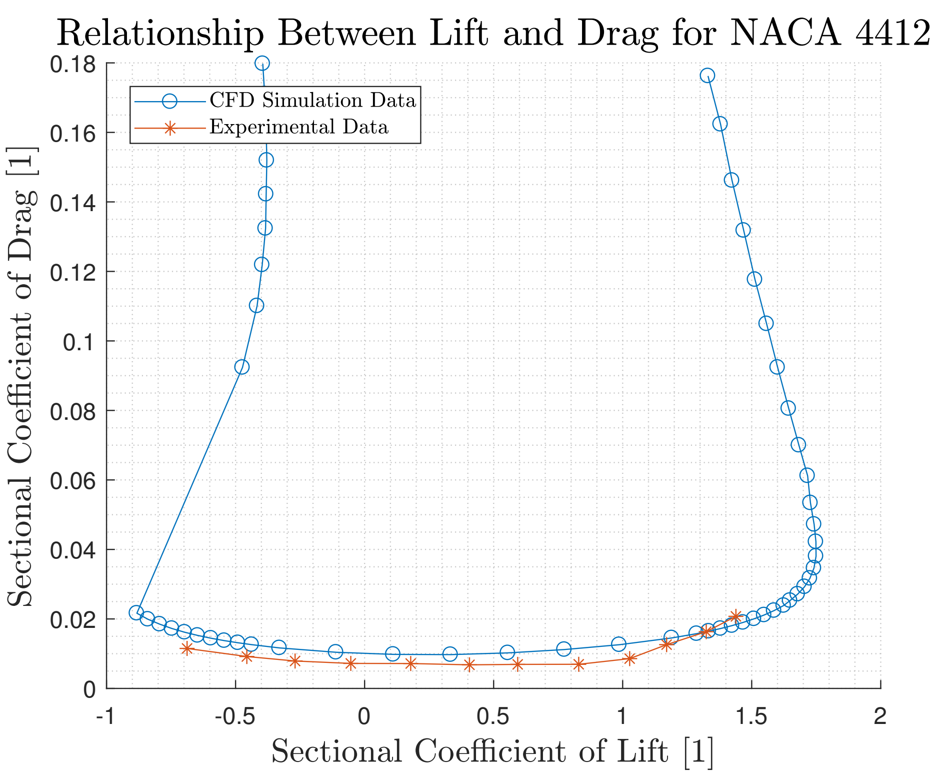

Figure 4: Lift curve for NACA 4412 using several models.

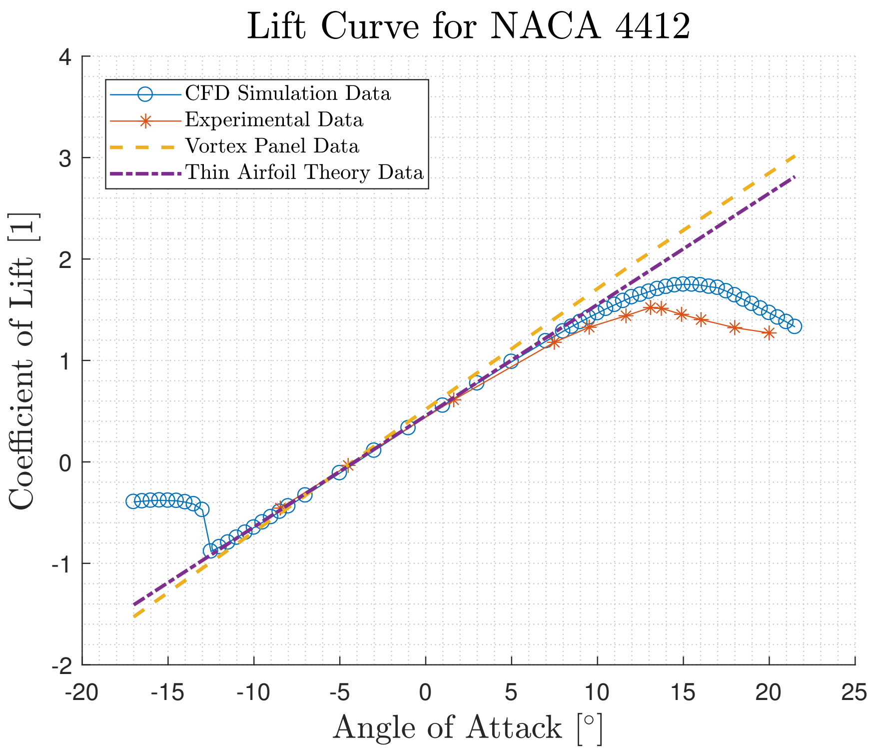

Figure 5: Relationship between lift and drag for the NACA 4412.

Table 2: NACA 4412 Results

Data Source	**Lift Slope**	**Zero Lift AOA**	**Stall Angle**	**Max. c_l**
Experimental	5.878 rad^{-1}	-4.139°	13.086°	1.522
CFD Simulation	5.819 rad^{-1}	-4.187°	15.0°	1.749
Vortex Panel Method	6.783 rad^{-1}	-4.23°	—	—
Thin Airfoil Theory	2π rad^{-1}	-4.15°	—	—

The RANS model seemed make a few predictions that differ from the experimental data. In both cases, post-stall lift was greater than the experimental data. This is likely because this CFD model does not completely accurately model the flow separation behind the airfoil after and near stall. In addition, the NACA 4412 experimental data exhibited a smaller lift slope than any of the other models. This is because the data that was taken was from a finite wing and when less sophisticated wind tunnels existed.

IV. Conclusion

This lab compared computational and experimental results for the performance of a NACA 0012 airfoil and a NACA 4412 airfoil. Both airfoils provided insight into the accuracy of a RANS simulation and showed results for both a symmetrical airfoil configuration and a cambered airfoil.

Since understanding aerodynamic flow over airfoils is such a crucial aspect of Aerospace Engineering, four methods for obtaining data were compared: thin airfoil theory, vortex panel method, Reynolds Average Navier Stokes, and experimental data. The thin airfoil method and the vortex panel method are both highly simplified models that do not account for any turbulent flow - and thus cannot interpret stall. However, despite these limitations, both models can predict zero-lift angle of attack and lift slope with relative accuracy at a very low computational cost. The RANS model, while more sophisticated, takes a long time to solve the Navier Stokes equations. This lengthy process is highly prized, however, due to its ability to interpret flow separation and stall accurately. The results of this lab show that RANS modeling alignes very well with any results predicted by the vortex panel method and the thin airfoil theory. The experimental results used in this lab were the most accurate, and were thus used as a reference point in determining accuracy. Overall, RANS model results were consistent with experimental data, though for the symmetrical airfoil, the RANS model tended to obtain values higher than the experimental data, while the opposite was true for the non-symmetrical airfoil. This was due to the simplification of the RANS model causing nonlinear effects. Also, the difference in Reynold's numbers between the two airfoils must have caused some discrepancy, though proving this would require additional experimentation.

One surprise encountered during the performance of this lab was the sharp introduction of stall in the NACA 4412 during negative angles of attack as shown in Figures 6 and 7 in the Appendix. This drop off was surprising because the drop off of lift did not present itself in the NACA 0012 - further experimentation would be necessary to explore this phenomenon, however we believe it is due to the camber of the airfoil.

Moving forward with this lab would obtain more accurate results from the RANS model if the program was allowed to run for longer and converge with a smaller tolerance - this could provide insight in to some of the discrepancies noticed among the various models. Also, it would be interesting to test different modeling strategies like a Large Eddy Simulation (LES) to better understand how different simulations provide different results. Overall, this lab was enriching to our understanding of turbulent airfoil and the strategies used in the aerodynamics field.

Acknowledgments

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References

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[3]Kuethe and Chow "*Aerodynamic Characteristics of Airfoils*","*The Airfoil of Arbitrary Thickness and Camber*",*Desire2Learn*' University of Colorado Boulder.

Appendix

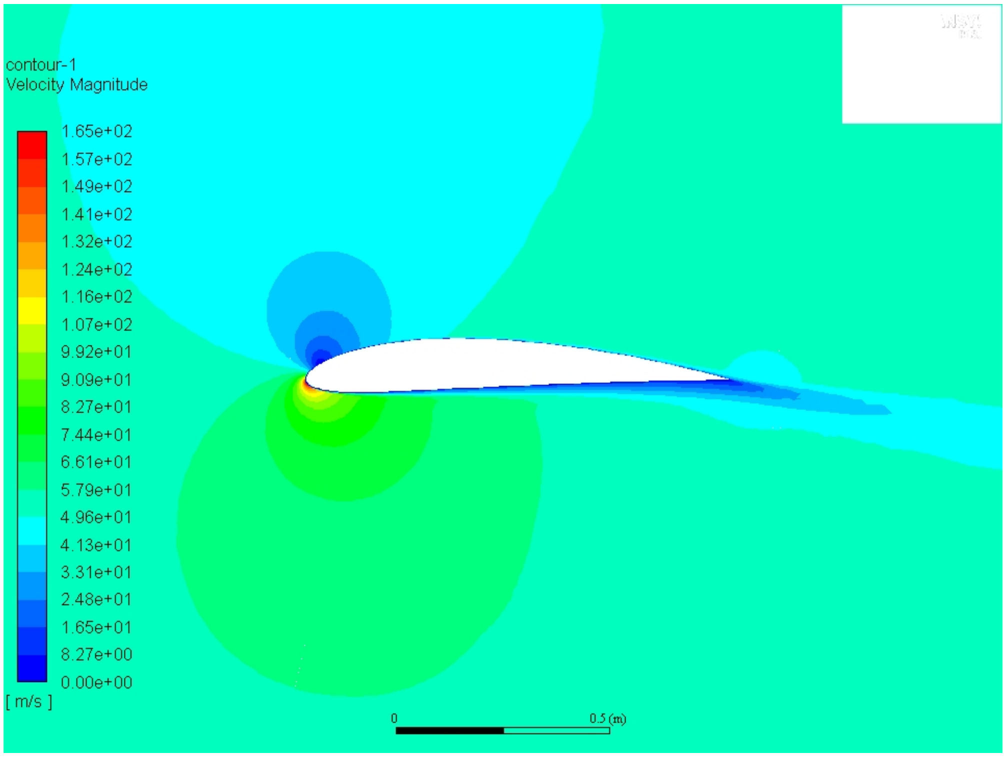

Figure 6: Velocity Contour behind NACA 4412 at -12.5° angle of attack.

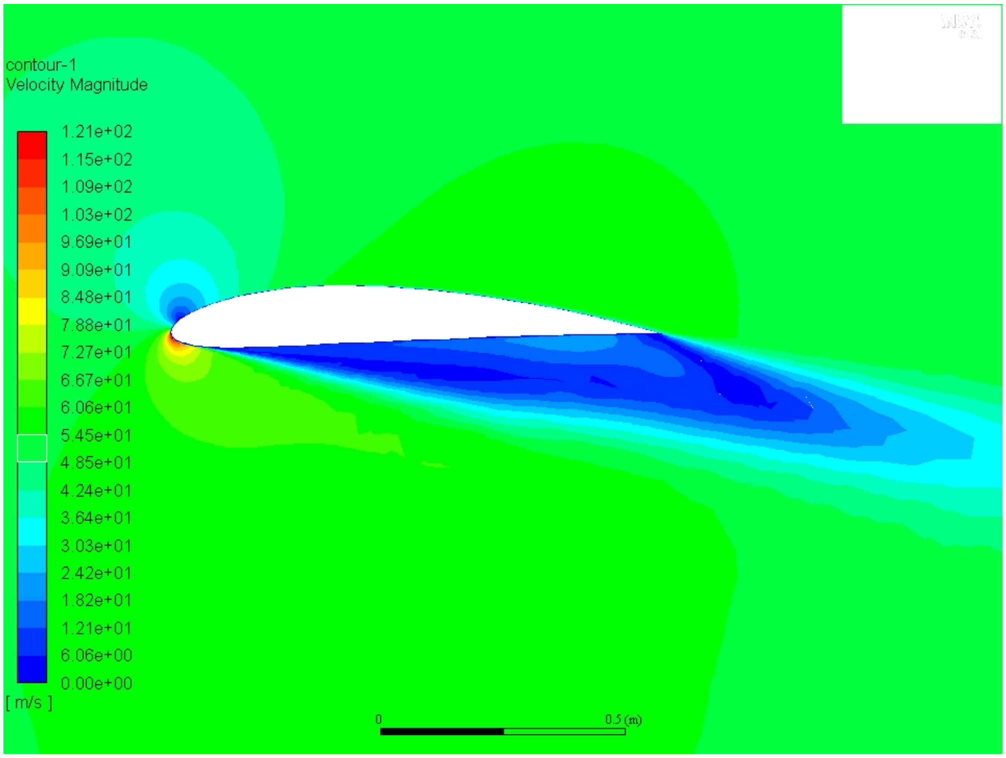

Figure 7: Velocity Contour behind NACA 4412 at -13° angle of attack.