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Research Article

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Flow Visualisation by Laser Sheet in a Smoke-Tunnel

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Abstract

The application of wind tunnel for visualizing flow over any bluff or streamline body plays an indispensable role in concepting various aerodynamical phenomenon such as formation of vortices, generating lift and drag, calculation of velocity vector and pressure profiles etc. Flow visualization through smoke and laser optics in a subsonic wind tunnel to capture vortex formation over airfoils, cylindrical and conical bodies is the experimental approach which has been studied and manifested elaborately in the article. Using smoke as a seeding material, the flow of the same is allowed to pass over the model which is illuminated via a double pulse laser beam to visualize the formation of vortex and capture the same for future references. The experimentation of the above models is carried out in a Honeycomb subsonic wind tunnel in the Aerodynamics Lab of Aerospace Engineering in the university. The article will cover Computational Fluid Dynamics (CFD) performed on ANSYS for the particular NACA series, Cross correlation PIV for plotting velocity vector for the captured images of the seed particles and the respective images of the entire experimental set-up. The images captured during this experiment can be later used by the aerodynamicists for optimizing aerodynamic efficiency of the experimented models depending on the vortex formation and flow pattern. The images can also be used for advance calculations required in Particle Image Velocimetry (PIV) for calculating velocity of every speed particle.

Keywords: NACA 54118; Wind Tunnel; DSLR Camera; Cylindrical Lens; Smoke; LASER; Flow-Visualization.

1. Introduction

The primary usage of wind tunnel is to examine scale models of various aerodynamical bodies like aircrafts and spacecrafts but at the same time it has also been an indispensable area of research in numerous fieldss for aerodynamicists. Apart from testing and analysing the models, wind tunnels are also used for observing different phenomenon experienced by a body while subjected to a flow. One such area of interest is the concept of visualising the formation of vortices over any bluff or streamline body in order to insinuate the efficiency of the flow and further to optimize the same for designing or modifying bodies. Practices like Smoke visualisation, Laser visualisation and Combined visualisation are current such methods to achieve the necessary visuals for the research out of which Combined visualisation has been adopted by us to perform the experiment and further carry out the probation.

There are two methods usually followed after capturing the vortices i.e. Laser Doppler Anemometry (LDA) and Particle Image Visualisation (PIV) where the velocity vector of the seeding material is calculated by determining the relative axial distance with respect to the change in time period. PIV has been chosen out of the two because of its non-invasive method of optics to determine the movement of seed particle over a body subjected to a flow.

2. Objective

I. To visualize the flow of air in a wind tunnel: The first objective is to generate smoke in the wind tunnel and use laser beams to visualize the flow of air. This will help researchers to understand how the air moves through the wind tunnel.
II. To identify the areas of turbulence: By using smoke and laser beams, researchers can identify areas of turbulence in the air flow. This will help to improve the design of wind tunnels and reduce turbulence in future experiments.
III. To capture vortices: Another objective is to capture vortices that form in the air flow. Vortices are areas of swirling air that can affect the performance of objects moving through the air. By understanding how vortices form and behave, researchers can improve the design of aircraft, cars, and other vehicles.
IV. To improve the accuracy of wind tunnel experiments: By visualizing the flow of air in a wind tunnel, researchers can improve the accuracy of their experiments. This will help to ensure that wind tunnel data is reliable and can be used to make informed decisions about the design of vehicles and other objects.

V. To advance the field of aerodynamics: Ultimately, the main objective of visualizing the flow in a wind tunnel by smoke generation and laser beam and capturing vortices is to advance the field of aerodynamics. By gaining a better understanding of how air flows, researchers can improve the performance and efficiency of vehicles, reduce energy consumption, and make transportation safer and more sustainable.
VI. To utilize cross correlation: To plot the velocity vector of the seed particles computationally.

3. Literature Review

The visualization of flow in a wind tunnel is essential to understand the aerodynamic behaviour of an object in motion. Smoke generation and laser beam techniques are commonly used to study the flow pattern and capture vortex in a wind tunnel. This literature survey aims to provide an overview of the research conducted in this field.

Smoke Visualization: Smoke visualization is a popular method to visualize the flow pattern in a wind tunnel. The method involves the injection of smoke particles into the test section of the wind tunnel, which are then carried away by the flow. Smoke visualization can be used to study the effects of different flow parameters, such as velocity, pressure, and temperature, on the flow pattern.

According to a study by smoke visualization was used to investigate the flow pattern around a bluff body [1]. The study demonstrated that smoke visualization is an effective tool to visualize the flow pattern and capture vortex in a wind tunnel.

Smoke generation is a cost-effective and straightforward method of visualizing the flow pattern in a wind tunnel. In this method, smoke particles are injected into the wind tunnel, and their movement is tracked to understand the flow pattern. Smoke visualization is particularly useful in identifying regions of turbulence and separated flows around objects.

Laser Visualization: Laser visualization is another method to study the flow pattern in a wind tunnel. The method involves the use of a laser beam to illuminate the flow field. The light scattered by the particles in the flow field is then captured by a camera, providing a visual representation of the flow pattern.

A study by Jambunathan et al. used laser visualization to study the flow pattern around a circular cylinder [2]. The study demonstrated that laser visualization is an effective tool to visualize the flow pattern and capture vortex in a wind tunnel.

Laser visualization, on the other hand, uses a laser beam to illuminate the flow field [3]. The scattered light from the particles in the flow field is then captured using a high-speed camera to create a visual representation of the flow pattern. This technique can provide high-resolution images of the flow field and can be used to study the details of the flow around objects in the wind tunnel.

Combined Visualization: Smoke and laser visualization can also be combined to provide a more comprehensive understanding of the flow pattern in a wind tunnel. A study by Zhang et al. used smoke and laser visualization to study the flow pattern around a delta wing [4]. The study demonstrated that combined visualization is an effective tool to visualize the flow pattern and capture vortex in a wind tunnel.

Smoke generation and laser beam visualization are effective techniques to visualize the flow pattern and capture vortex in a wind tunnel [5]. These methods have been widely used in the field of aerodynamics to study the effects of different flow parameters on the flow pattern. Combining smoke and laser visualization can provide a more comprehensive understanding of the flow pattern in a wind tunnel.

The combined use of smoke and laser visualization techniques offers the advantage of both methods. The smoke particles provide a visual representation of the flow pattern, while the laser beam can be used to obtain quantitative data about the velocity and direction of the flow [4]. The combination of these techniques has been used to study complex flow patterns, such as those around delta wings and other complex geometries.

Moreover, recent advancements in digital image processing techniques have made it possible to obtain more accurate and reliable flow visualization data. For instance, Particle Image Velocimetry (PIV) is a non-intrusive technique used to obtain quantitative data about the velocity of the flow field [6]. This technique involves the use of two laser beams and a high-speed camera to track the movement of particles in the flow field. The PIV technique has been widely used to study the flow pattern around objects in a wind tunnel.

Flow visualization techniques, such as smoke generation and laser visualization, have been widely used to study the flow pattern and capture vortex in a wind tunnel [5]. The combination of these techniques and recent advancements in digital image processing techniques have improved our understanding of aerodynamic behaviour and can be used to design and optimize various engineering applications.

Flow visualization can also be used to study the effects of different geometries on vortex capture. For example, a researcher might compare the vortex patterns formed by a circular cylinder to those formed by a square cylinder, or study the effects of varying the angle of attack or the aspect ratio of an aerofoil.

4. Proposed Approach

PIV cross correlation: It's a method in which we use two consecutive frames, shot by a camera with a shutter speed of 50 Hz. With the help of cross correlation, we can find how much distance a particle has moved in a particular window by comparing the two consecutive photos. We divide the whole photo into 4 or more windows and then find the relative distance a particle has moved in the x-direction and y-direction with respect to the first shot. PIV cross-correlation is commonly used in wind tunnel testing to measure the velocity field of the airflow around a model or object. In a wind tunnel experiment, the PIV system captures a series of images of the flow around the object, with the tracer particles seeded into the airflow.

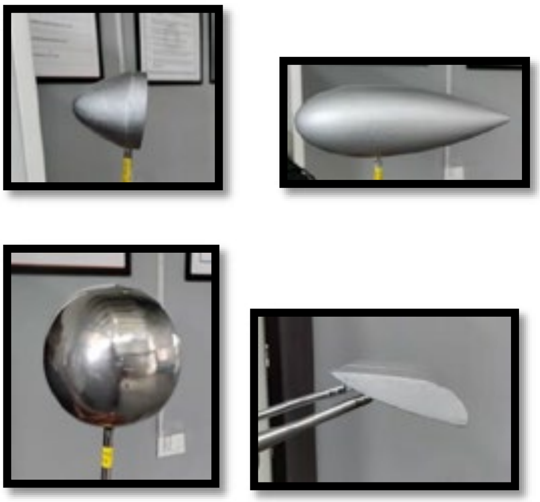
The PIV cross-correlation analysis then calculates the velocity field of the airflow by comparing the positions of the tracer particles between successive images. This allows researchers to study the flow properties of the wind tunnel experiment in detail, such as the turbulence levels, vortices, and pressure distribution.

Wind tunnel experiments using PIV cross-correlation can be used to optimize the aerodynamic design of objects, such as aircraft, cars, and wind turbines. The PIV results provide insights into how airflow interacts with the object, allowing researchers to adjust the design to optimize performance, reduce drag, and increase efficiency.

PIV cross-correlation is a powerful tool for understanding the complex flow behavior in wind tunnel experiments and can provide valuable insights into the design and performance of various objects and systems.

5. Components Used

COMPONENTS	VISUALS
1. Subsonic Wind Tunnel.	
2. Smoke Generator.	
3. Laser Diode (530nm).	

4. Prisms -2 (power of prisms = 10D & 5D) (D = Diopter).	
5. Thermocol foam block.	
6. NACA 54118 and force models.	
7. DSLR Camera.	

8. Propylene Glycol (Aqueous Solution of Propylene Glycol is used as the seeding material)	

Table 1: Components

6. Research Methodology

I. Cover the wind tunnel with black sheet of paper to ensure complete blackness while performing experiment so that illumination is proper and the vortices are captured appropriately.
II. Mount an aerofoil or a cylindrical body or any force model in the test section of subsonic wind tunnel.
III. Switch on the smoke generator and heat it up to 250 Kelvin (K).
IV. Mount the laser beam at an angle perpendicular to the body and place it at a focal length of 5 cm from the lens.
V. Place a DSLR camera in the settling chamber or the test section of the wind tunnel and set its frequency to 50 Hz.
VI. Switch on the laser and allow the smoke to flow over the body in the test section.
VII. Start the recording.
VIII. Observe the vortices.
IX. Capture the vortices formed over the body.
X. Segregate two consecutive frames from the images captured and use it to calculate the relative distance between two seeding particles.
XI. Obtain the velocity vector by importing the images into MATLAB and coding for the same in it.
XII. Validate your results with the Computational Fluid Dynamics (CFD) simulated on ANSYS.

7. Wind Tunnel Specifications

1.	Test Section Size	600 mm x 600mm x 2000 mm
2.	Contraction Ratio	9:1
3.	Settling Chamber	2300 mm x 2300 mm
4.	Maximum Speed	50 m/s
5.	Fan	Axial Flow fan, max rpm 1440

Table 2: Wind Tunnel Specifications

8. Calculations

We know, $f = 50$ Hz and $\Delta x = 0.1303$ cm
since, $\Delta v = \Delta x/\Delta t$
and $f = 1/t$
$t = 1/f$
$t = 1/50$
therefore, $\Delta v = 0.1303 \times 50$
$\Delta v =$ **6.516 m/s**
Percentage Error (%) = $\frac{6.516 - 6.34}{6.516} \times 100$
∴ % error = 2.7 %

9. Computational Observation

a) 3D Analysis:

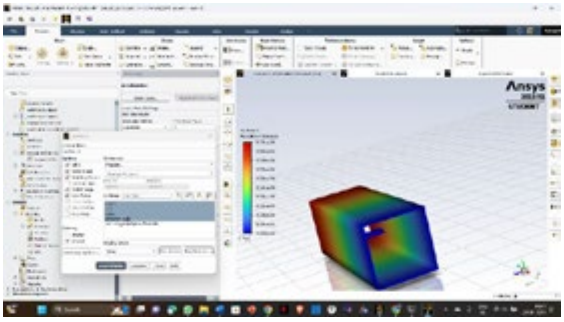


Figure 1 Absolute pressure analysis over test section

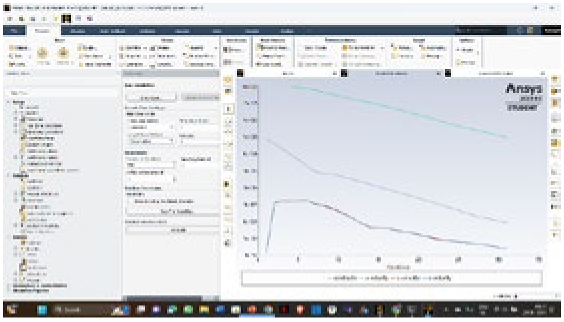


Figure 5 Velocity Profile

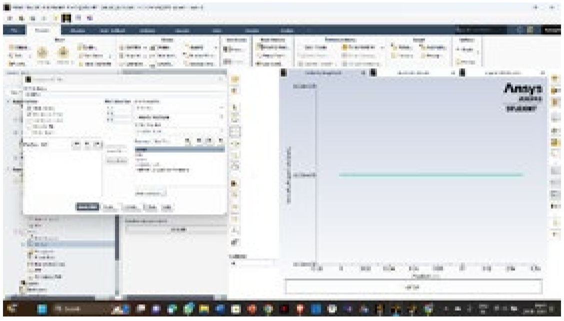


Figure 7 Velocity v/s Distance

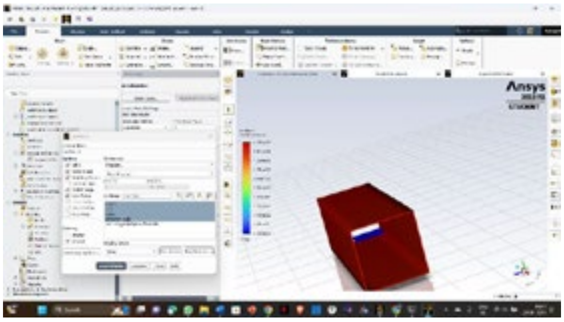


Figure 2 Total pressure analysis over test section

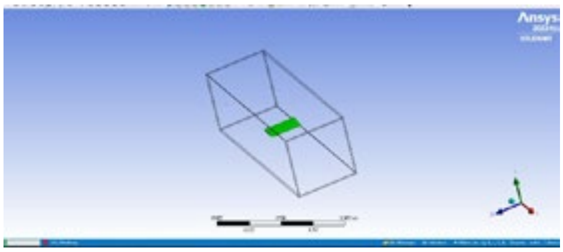


Figure 3 Aerofoil in Test Section

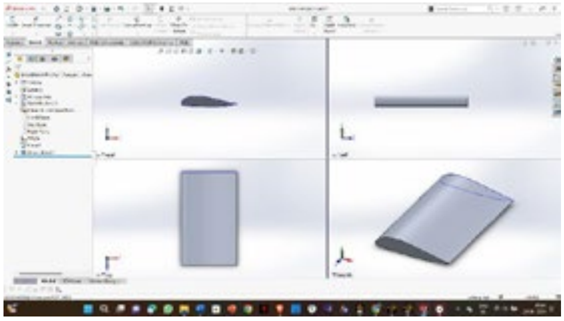


Figure 4 NACA 54118

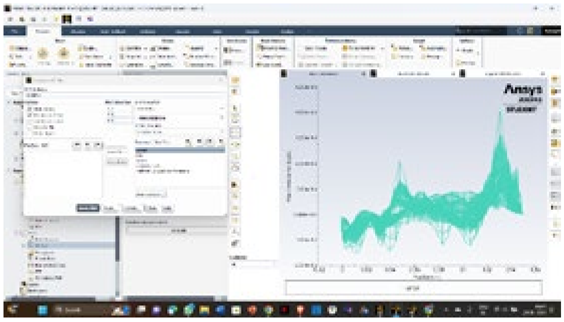


Figure 6 Mass flow rate v/s Distance

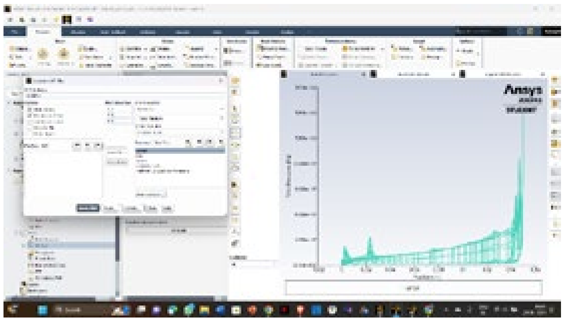


Figure 8 Pressure v/s Distance

b) 2D Analysis

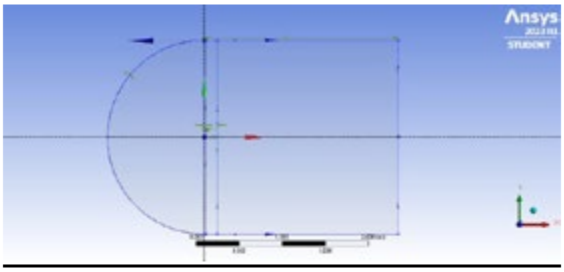


Figure 9 Geometry

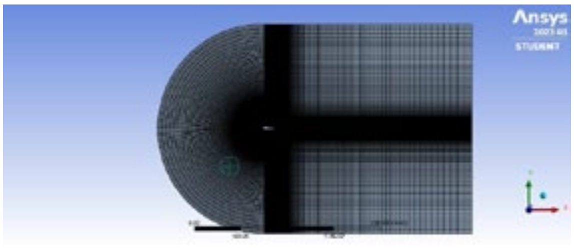


Figure 11 Mesh

Details of "Mesh"	
Display	
Display Style	Use Geometry Setting
Defaults	
Physics Preference	CFD
Solver Preference	Fluent
Element Order	Linear
Element Size	Default (202.81 mm)
Export Format	Standard
Export Preview Surface Mesh	No
Sizing	
Quality	
Inflation	
Batch Connections	

Figure 12 Mesh Details

Sizing	
Use Adaptive Sizing	No
Growth Rate	Default (1.2)
Mesh Defeaturing	Yes
Defeature Size	Default (1.0141 mm)
Capture Curvature	Yes
Curvature Min Size	Default (2.0281 mm)
Curvature Normal Angle	Default (18.0°)
Capture Proximity	No
Bounding Box Diagonal	4056.2 mm
Average Surface Area	1.1732e+006 mm²
Minimum Edge Length	3.0801 mm

Figure 13 Mesh Sizing

Quality	
Check Mesh Quality	Yes, Errors
Target Skewness	Default (0.9)
Smoothing	Medium
Mesh Metric	None
Inflation	
Batch Connections	
Advanced	
Statistics	

Figure 14 Mesh Quality

Inflation	
Use Automatic Inflation	None
Inflation Option	Smooth Transition
Transition Ratio	0.272
Maximum Layers	2
Growth Rate	1.2
Inflation Algorithm	Pre
View Advanced Options	No
Batch Connections	
Advanced	
Statistics	

Figure 15 Mesh Inflation

Details of "Mesh"	
Batch Connections	
Mesh Based Connection	No
Advanced	
Number of CPUs for Parallel...	Program Control...
Straight Sided Elements	
Rigid Body Behavior	Dimensionally R...
Triangle Surface Mesher	Program Con...
Topology Checking	Yes
Use Sheet Thickness for Pin...	No
Pinch Tolerance	Default (1.8253 ...
Generate Pinch on Refresh	No
Sheet Loop Removal	No

Figure 16 Batch connections and Advanced Mesh

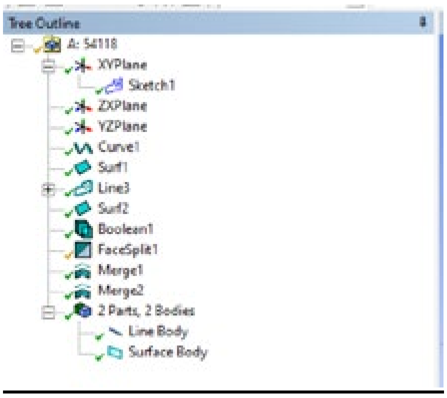


Figure 10 Geometric Tree Outline

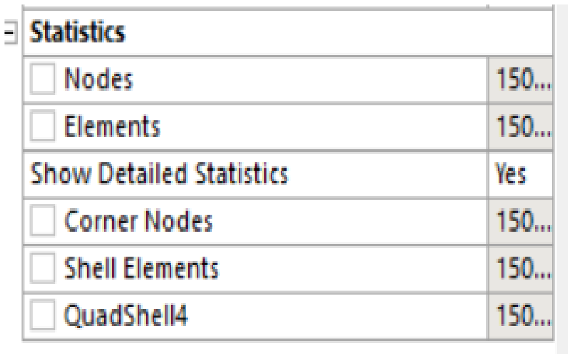


Figure 17 Statistics of Mesh

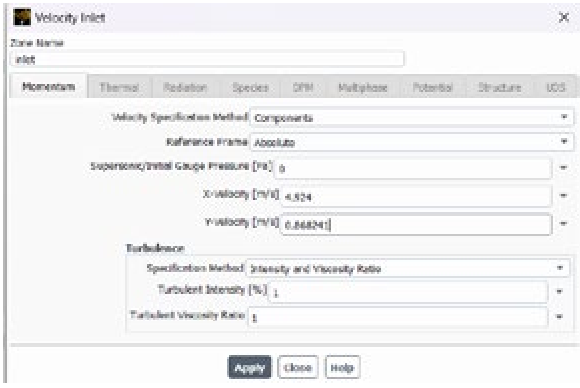


Figure 19 Boundary Condition for Inlet Velocity @ 5 m/s @ 5-degree AOA

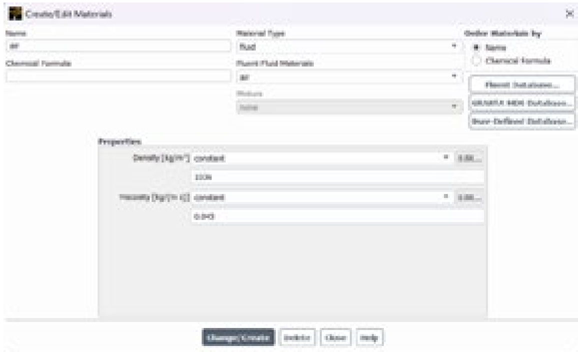


Figure 18 Density and Viscosity of Propylene Glycol used as the Flow Material

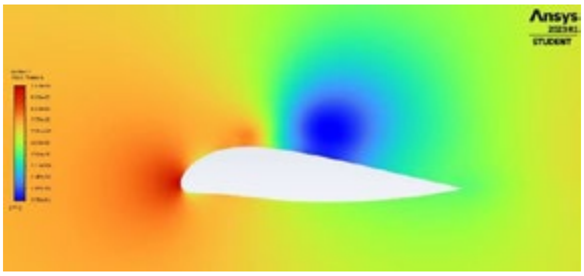


Figure 21 Pressure contour of NACA 54118

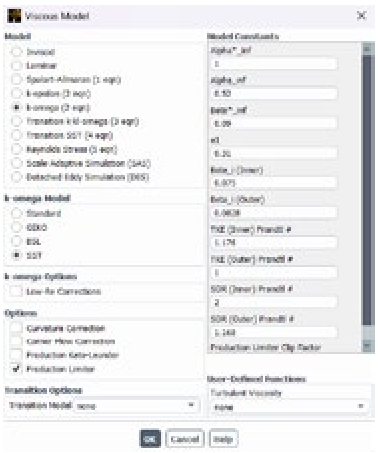


Figure 20 Boundary Condition for Viscous Model

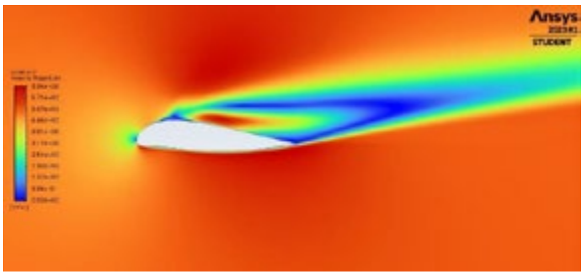


Figure 23 Velocity contour of NACA 54118

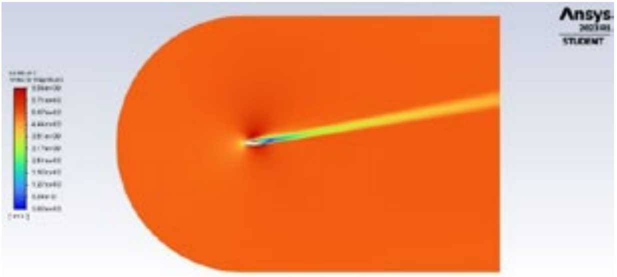


Figure 24 Velocity contour of NACA 54118

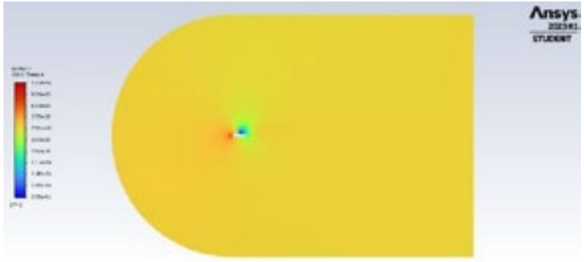


Figure 22 Pressure contour of NACA 54118

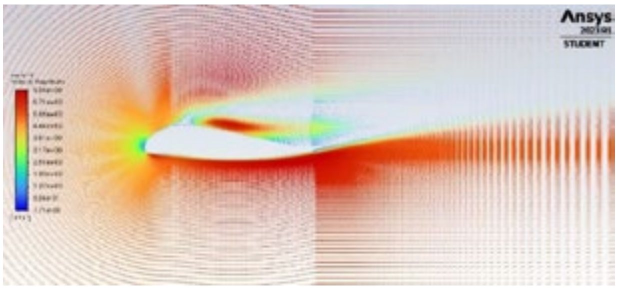


Figure 25 Velocity vector of NACA 54118

Figure 26 Velocity Vector

10. Experimental Observation

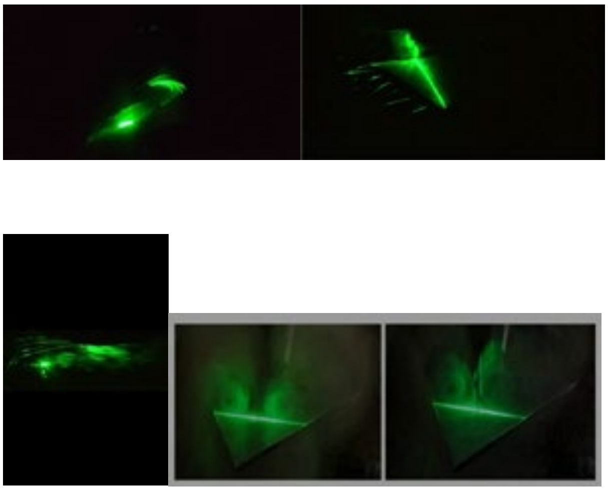


Figure 27 Smoke – Laser Visualisation

11. Results and Discussions

The computational velocity of the seed particle is 6.34 m/s.
The experimental velocity of the seed particle 6.516 m/s.
Percentage error = 2.7%.

Since the experimental values are approximately equal to the theoretical values, we can successfully use the above method to optimise the efficiency of any bluff or streamline body according to the requirements and can even save the data for future references. The observation needed to be discussed are as follows:

- The black sheet of paper used to cover the wind tunnel ensured that there was complete blackness during the experiment, enabling proper illumination and the accurate capture of vortices formed over the airfoil. The smoke generator was heated to 250 K to produce smoke, which allowed the visualization of the flow over the airfoil.
- The laser beam was mounted at an angle perpendicular to the airfoil, and a DSLR camera was used to capture the vortices formed over the airfoil. The frequency of the camera was set to 50 Hz, which provided a high-speed capture of the vortices formed over the airfoil.
- The images captured by the camera were imported into MATLAB to obtain the velocity vector. This enabled the calculation of the velocity distribution over the surface of

the airfoil.
- The results obtained from this experiment were validated with the CFD simulated on ANSYS. The comparison between the results obtained from the experiment and the CFD simulation showed a good agreement, validating the results obtained from the experiment.
- In conclusion, the experiment successfully captured the vortices formed over the airfoil, and the results obtained were validated with CFD simulation. The method used in this experiment could be applied to study other aerodynamic phenomena, making it a valuable tool in aerodynamic research.

12. Limitation and Future Work

Limitations

I. The full-scale measurements of velocity at very high mixtures could not be determined as a limitation of PIV method.
II. LDA method was costlier to adopt.

Future Work

Flow visualization techniques using smoke and lasers in wind tunnels have long been instrumental in studying and understanding fluid dynamics. In the future, these techniques are expected to continue playing a crucial role in various scientific, engineering, and industrial applications.

The use of smoke as a flow visualization tool involves introducing a smoke source into the wind tunnel, which allows researchers to observe and analyze the movement and behavior of the smoke particles as they interact with the flowing air. This technique provides valuable insights into the complex patterns and structures of the airflow, enabling a better understanding of aerodynamic phenomena.

Looking ahead, the future of flow visualization using smoke and lasers in wind tunnels appears promising. Here are some potential areas of application and scope:
I. Aerodynamics and Aerospace Engineering: Wind tunnels equipped with smoke and laser-based visualization techniques will continue to be crucial in studying and optimizing the aerodynamic performance of aircraft, spacecraft, and other vehicles. Researchers can gain insights into boundary layer separation, turbulence, vortices, and other flow phenomena, leading to improved designs and increased efficiency.
II. Automotive Industry: Smoke and laser-based flow visualization will aid in developing more streamlined and fuel-efficient vehicles. By studying the flow around cars and trucks, engineers can optimize designs to reduce drag, enhance vehicle stability, and improve overall performance.
III. Energy and Environmental Engineering: Wind turbines, thermal power plants, and other energy systems require efficient airflow management. Flow visualization techniques can assist in understanding the complex flow patterns within these systems, leading to improved efficiency, reduced emissions, and better design of air pollution control devices.
IV. Architecture and Urban Planning: The impact of wind on buildings and urban environments is crucial for ensuring safety and comfort. Flow visualization can help architects and urban planners understand how airflow interacts with structures, identifying potential areas of turbulence or discomfort. This knowledge can guide the design of buildings, cities, and public spaces for improved ventilation and pedestrian comfort.
V. Sports and Athletics: Flow visualization techniques can be used to study the aerodynamics of athletes and sports equipment. Understanding the flow patterns around cyclists, runners, or sports equipment like balls can lead to improved performance and equipment design.

13. Conclusion

I. In conclusion, Visualizing air flow through smoke generation and laser beams is essential for understanding how air moves through different structures in a wind tunnel.
II. Identifying areas of turbulence and capturing vortices are critical for improving the design of vehicles, buildings, and other objects that move through the air.
III. The accuracy of wind tunnel experiments is improved through the use of smoke generation and laser beams, leading to reliable data for making informed decisions.
IV. The study of aerodynamics has numerous applications in different industries, and advancements in this field have the potential to revolutionize transportation.
V. The use of smoke generation and laser beams in wind tunnel experiments is a powerful tool for visualizing air flow, capturing vortices, and improving the accuracy of experiments in the field of aerodynamics [7].

14. Availability of Data and Materials

No datasets were generated or analysed during the current study.

Acknowledgements

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Also, various research papers and other such sources helped us a lot to gain valuable information on the respective topic and further aided us to complete the paper for which we are highly grateful.

At the last, we would like to take this as an opportunity to thank our parents and families who supported us all the time and guided us through all the difficulties we faced.

Competing Interest

The authors declare no competing interest.

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