Turbulent Boundary Layer

Team Third 2019, Group 5, MCEN 5151

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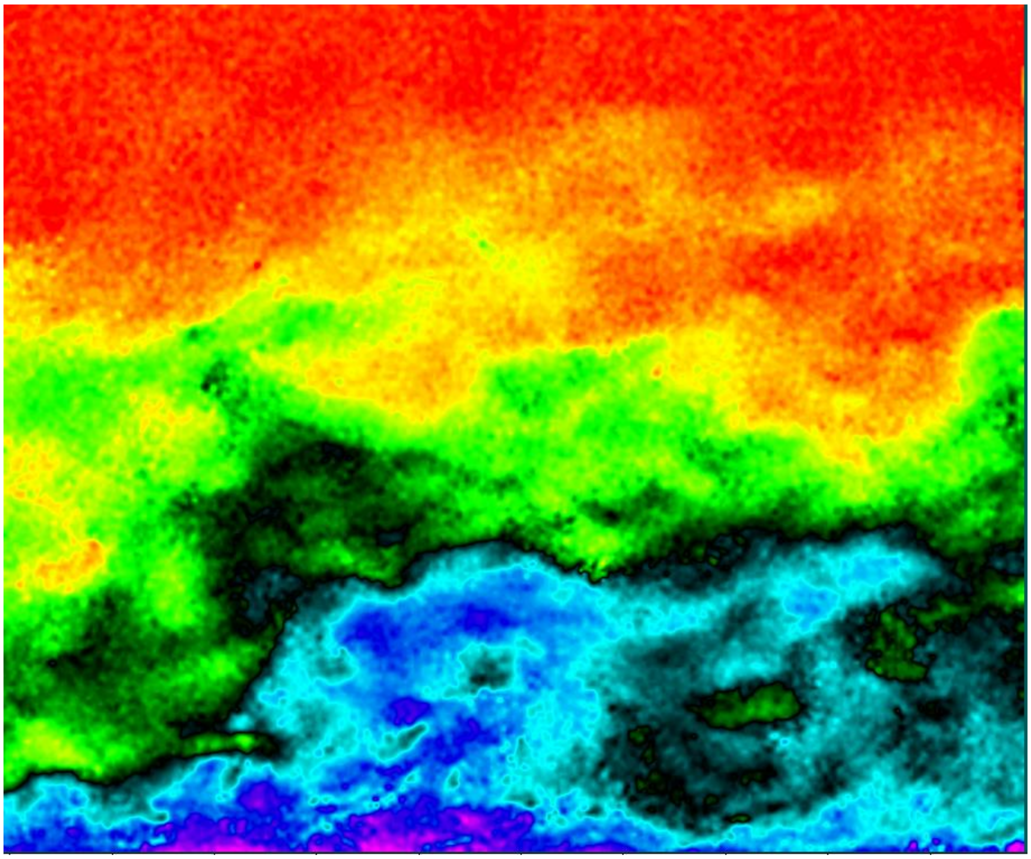

Introduction

The purpose of this paper is to document and describe the experimental process that was followed to produce a series of flow visualization photos that were captured as a requirement for the third team assignment of MCEN 5151 - Flow Visualization called Team Third. The original post which is a 10-photo series in .gif format can be found at http://www.flowvis.org/2019/11/20/team-third-matt-knickerbocker/. The task of the assignment was to capture a photo of fluids that both (1) clearly demonstrate the phenomenon being observed and (2) is a good photo. The intent of the photo series for this assignment was to observe the flow physics of a wall bounded flow. The experiment for this photo series was performed by me alone.

Flow Description

The apparatus used in this flow experiment involved a particle image velocimetry (PIV) setup, a flat plate, and the low speed wind tunnel in the experimental aerodynamics lab at CU Boulder. The PIV setup included a double pulse Nd: YAG laser, an LaVision Imager sCMOS camera, and the accompanying LaVision processing software. A sketch of the experimental setup can be seen below in Figure 1. The wind tunnel test section is 10 feet long with a 30-inch by 30-inch cross section. The flat plate matched the span and length of the tunnel, had a modified super elliptical leading edge, and was mounted horizontally, roughly in the center of the tunnel.

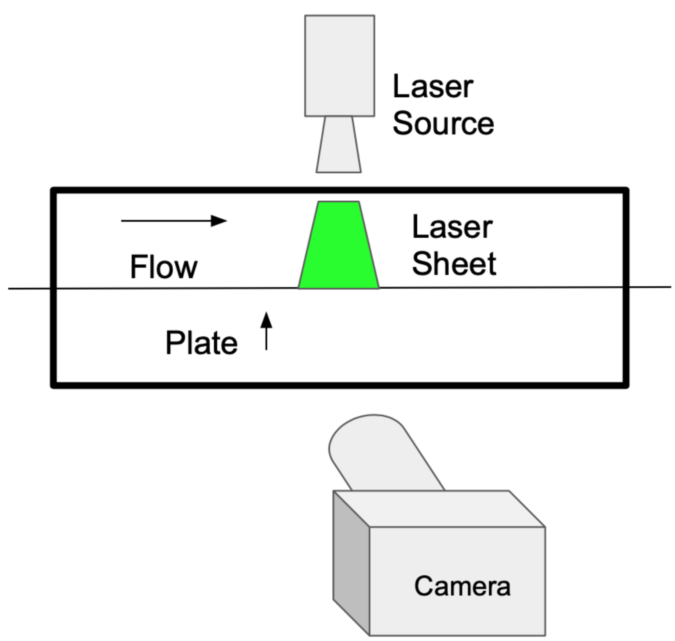

Figure 1: Experimental Setup.

The camera was positioned to view the boundary layer flow near the upper surface of the plate about 7 feet downstream of the leading edge while the wind tunnel was running with a flow speed of 25 m/s. The PIV technique provided a visualization of the flow velocity in the turbulent boundary layer. The final image series (.gif) was composed of 10 consecutive PIV frames with the velocity gradient depicted with different colors. The red color indicates the freestream velocity of 25 m/s and the magenta indicates about 13 m/s.

When a fluid flows near a solid surface there will be a finite region called the boundary layer where viscous effects dominate the behavior of the fluid [1]. The boundary layer originates from the no-slip condition that must be enforced at the fluid-solid interface. The no-slip condition states that the velocity of the fluid and the solid structure must be equal at the interface. If the solid surface is at rest, this inherently results in a fluid velocity profile that ranges from zero at the wall up to the freestream velocity at some finite distance normal to the wall. This distance defines the boundary layer thickness and it will grow with distance in the downstream direction. There are two main flow regimes which occur within boundary layers called laminar and turbulent. An initially laminar boundary layer will transition to turbulence at some downstream location due to instabilities in the flow. The flow regime can be predicted by the Reynolds number which is defined in Equation 1 below where ρ is the density, u is the flow velocity, L is length from the leading edge, and μ is the dynamic viscosity.

$$Re = \frac{\rho u L}{\mu}$$

$$Re = \frac{0.96\ kg/m^3 \cdot 25\ m/s \cdot 2.5\ m}{18.13 \cdot 10^{-6}\ N \cdot s/m^2} = 3,309,432 \tag{1}$$

As shown above, plugging in the parameters from this flow experiment yields a Reynolds number of over 3 million. Values above 1 million indicate a turbulent boundary layer and this agrees with the observed turbulence in the PIV photo series.

Boundary layers serve as the main focus of most viscous fluid flow problems since their analysis can lead to a better understanding of the origin of fluid dynamic forces. Specifically, parameters like the skin friction drag and heat transfer coefficient can accurately be predicted with boundary layer analysis. Blasius [2] first provided a solution to the laminar boundary layer equations over a zero-pressure gradient flat plate in 1908. Even today, the Blasius solution is still a staple reference on laminar boundary layers, and it was used in the characterization of the flat plate boundary layer of the experimental apparatus used in the present paper. Turbulent boundary layers are also of great interest as most engineering flows operate entirely in the turbulent regime. Compared to a laminar boundary layer, a turbulent boundary layer produces larger skin friction drag but also delays flow separation [3]. Due to these differences, turbulent boundary layers have been the focus of many studies related to aerodynamic applications.

Flow Visualization Technique

As mentioned above, the flow visualization technique used in this experiment was performed with the use of a PIV system. In PIV, the air is first seeded with smoke which is composed of many small oil particles that are carried by the flow. Next, a 532-nanometer laser sheet is fired parallel to the flow which illuminates the individual smoke particles. Simultaneously, a camera perpendicular to the flow captures a frame of the illuminated particles. By taking two photos in quick succession, the change in position of individual particles can be measured. This change in position is then used to calculate the velocity vectors of individual particles, allowing us to calculate the full velocity profile of the flow visible in the camera frame. The flow seeding was produced by a Pea Soup smoke machine which vaporizes oil into 0.2 to 0.3-micron particles. The laser was an EverGreen dual pulse Nd: YAG machine.

Photographic Technique

The camera used to produce the final image was an LaVision Imager sCMOS camera. Each of the ten PIV images used in the photo series of this paper was produced by two camera images. The effective shutter speed was 5.4 micro seconds (1/185185 of a second) with an interframe time of 120 nanoseconds (1/8333333 of a second). The image resolution was 2578 x 2164 pixels at a focal length of 963 mm, and an aperture of f/8. The field of view was 50 mm x 50 mm, positioned at the plate surface and about one meter from the focal point. The lens used was a Canon 200 mm lens with an aperture range of 1:4-22. Prior to the experiment, the camera had to be focused precisely on the laser sheet position. This was performed with the laser firing in a low power mode and a calibration target that was positioned to be in plane with the laser sheet. This ensured that the illuminated smoke particles were in focus. The double frames were captured at a rate of 15 Hz which means that there is $1/15^{th}$ of a second between each processed PIV image. Since 10 consecutive images were used, the real time duration of the series was only two thirds of a second.

The post-processing of the images involved the use of the DaVis software package which performs the velocity vector calculations based on the information in the double frame. The calibration information and the particle position change is correlated to the velocity at each point in the flow. The software also provided the means to manipulate the display of the velocity information. A color gradient that suitably highlights the beauty and time evolution of the flow was chosen for this series. No other modifications were performed, and an example image can be seen in Figure 2 below.

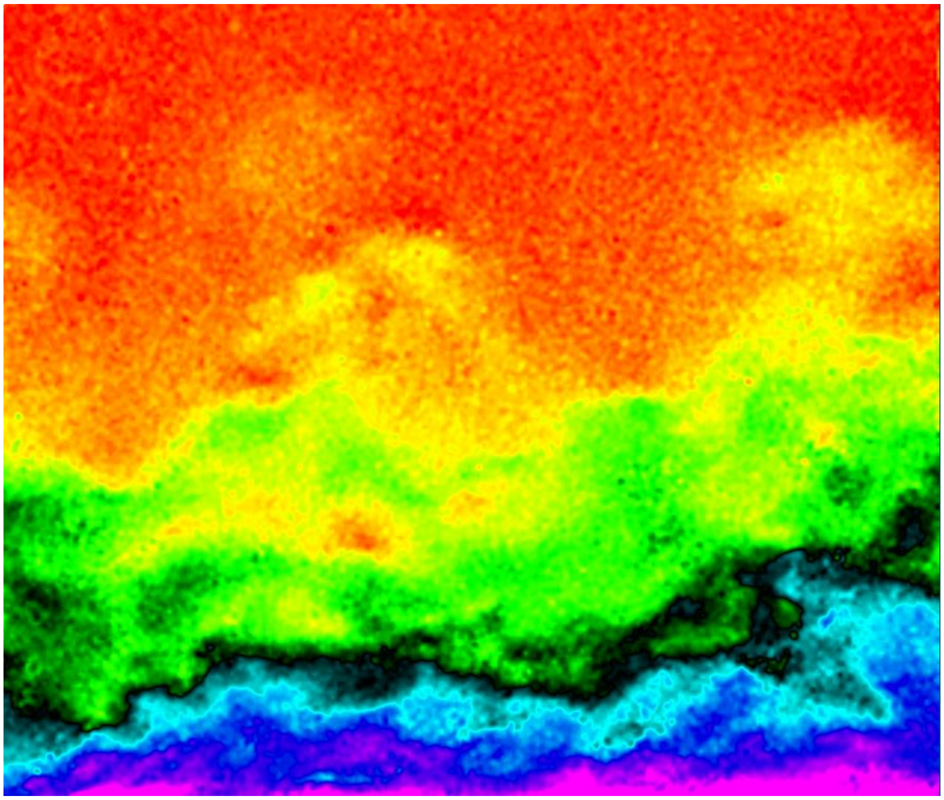

Figure 2: Example Processed Image.

Conclusion

The photo series produced in this experiment reveals the nature of wall bounded flows and specifically how a turbulent boundary layer appears through time. Understanding the context of the photo series displays the chaotic and rapid behavior of the moving fluid near the surface of a flat plate. The velocity information also shows how steep the velocity profile is very near to the wall. We know that the velocity must go to zero at the wall, however the smallest velocity we see is about 13 m/s. The bottom edge of the frame is less than a millimeter away from the plate surface, so this highlights the intensity of a turbulent boundary layer velocity profile and why we see large increases in skin friction drag. Aesthetically, this image provides a fascinating view of the nature of fluid motion highlighted by pleasing colors. It seems to display how things that were once calm and smooth (laminar) are bound to end up disorderly and random (turbulent). I definitely fulfilled my intent with this photo and am very happy with the result. I am also glad that I chose to use an image series rather than a single shot. This allowed me to highlight how rapidly the flow was changing and to present more of the fluid dynamics.

References

[1] Kundu, P. K., Cohen, I. M. (2008). “Fluid Dynamics”. 4th Edition. Academic Press.

[2] Blasius, H. (1950). The boundary layers in fluids with little friction. NACA Technical Memo 1256.

[3] White, F. M., & Corfield, I. (2006). Viscous fluid flow (Vol. 3, pp. 433-434). New York: McGraw-Hill.