IV4 – Flow Around an Airfoil Illustrated by Dye

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Flow Visualization – MCEN 5151
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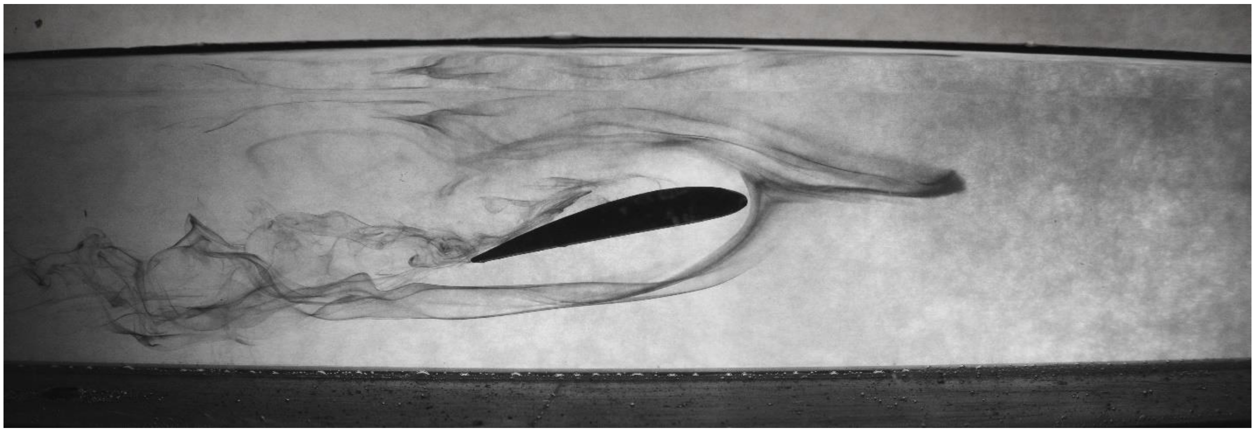
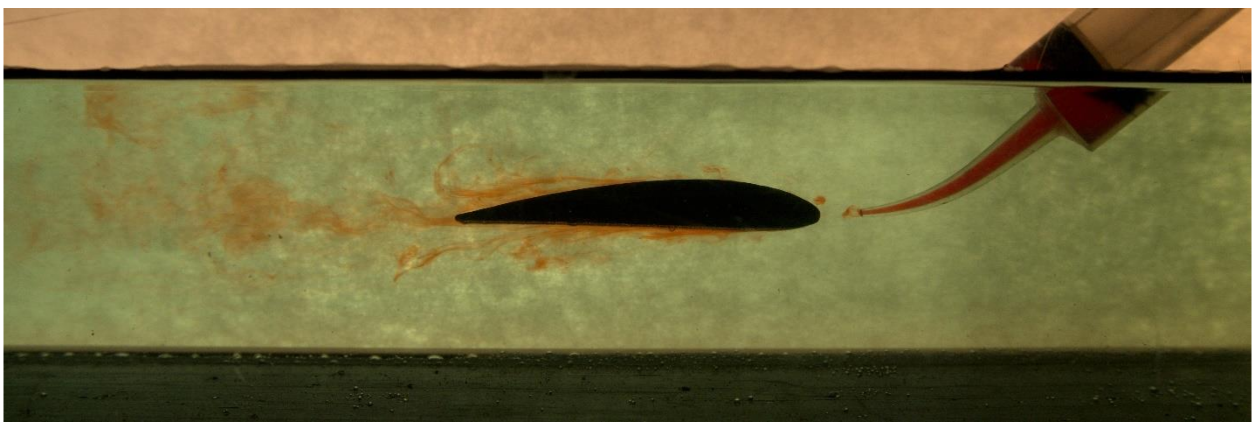


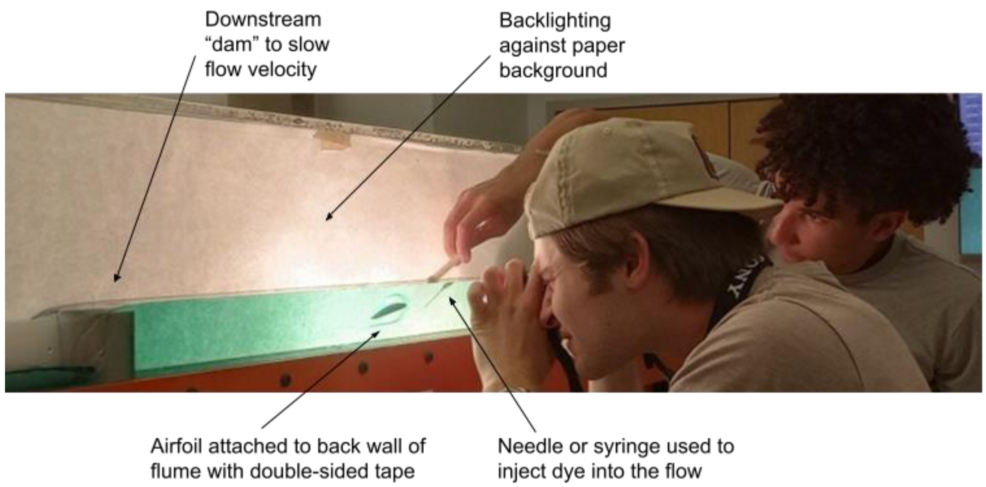


Context and Purpose

I have included two images for this visualization of the disturbance in the fluid around an airfoil in open channel flow as illustrated by a seeded dye. The context and purpose of this image is to demonstrate the various effects that can occur in the fluid surrounding airfoils. Specifically, the main differences between these two images are the angle of attack of the airfoil, the position along the airfoil where the dye is injected, and the fluid speed of the water within the flume. My intent is to get some fascinating images in long format that both demonstrate the various effects of these conditions, as well as produce an image that could be selected as a contender for the new CU Mechanical Engineering Wing window-film. The original image that I submitted was the black and white one with a steeper angle of attack. However, after discussing with Prof. Hertzberg during critiques, I included and submitted the second image as well per her request as it better demonstrates the simple physics of airfoils wherein the boundary layer begins as laminar and then transitions to turbulent over the surface of the wing as a function of Reynolds number, distance along the wing, and time after the dye is seeded in the flow. There were many other great images that I had difficulty choosing between, however I ultimately decided on these two as they are the most beautiful yet also demonstrate the fluid physics in the most visible and understandable manner. My teammates for this project were Robbie Cooper, Kendall Shepherd, and Lana Pivarnik, and I'd like to thank them for their assistance in setup of the flow apparatus. In this report, I will lay out the phenomena, techniques, and insights behind this beautiful airfoil induced dye flow disturbance.

Flow Apparatus

The basic flow type that is captured in this image by the dye marked boundary is the tripping of flow from laminar to tubulent in the boundary layer around a water submerged airfoil. The flow apparatus used here was the open channel flow flume in the ITLL. The airfoil is approximately 2.5in long from leading edge to tail, 0.33in thick, 0.5in deep (into the image), and is approximately 1-1.5in above the bottom of the flume channel. The flow rate of the water in these images was 0.275L/s, the water level in the first image was 3.1in, the water level in the second image was 1.9in, and the width of the channel was 3in. The reason why the water level is different between the images is downstream damming of the flow with a steel block in order to decrease fluid velocity over the airfoil. We did this becuase we found that it allowed for the dye to track with the water better. This is because at higher bulk fluid velocities the dye would need to be injected into the flow also at a higher velocity, but this would cause the dye to exit the syringe or needle and be already turbulent, preventing proper visualization of the development from laminar to turbulent flow in the boundary layer along the airfoil.



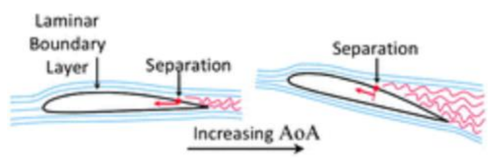
Fluid Phenomena

In terms of the fluid phenomena, as described previously, because of insight from Prof. Hertzberg that the initial image I chose for this report may not best represent the flow physics that I intended to capture, I decided to include the second image. This image is what I will be primarily covering in this section, because the fluid phenomena visualized and demonstrated in it are more readily describable and relevant to fluid boundary layers over airfoils, the phenomena which will be covered here. In order to understand what we we're attempting to visualize, especially in the context of how the seen phenomena are applied to aeronautics, it's important to note that we attempted to create a 2D wing scenario. As described by Ives et. al. "a 2D wing is an aerofoil of infinite span with identical span-wise location and flow," whereas 3D wings have, "span-wise flow differences and vortices," which, "are introduced by the presence of the wingtips," such that, "the lift generated by a 3D wing is lower than that of the 2D wing." [3] Lift is generated by a wing due to the pressure differential between its upper and lower surfaces along its length, however this effect is diminished at the wingtips, which alongside downwash inducing vortices, explains the lower generated lift by a 3D wing. While our goal was to create a visualization flow around a 2D wing, we printed one that was too short to span the width of the flume. We tried to mitigate wingtip effects by seeding the dye further from that part of the wing, however it's interesting and important to consider how these effects could have altered our visualizations. In terms of describing the transition from laminar to turbulent and where the flow separates from the airfoil it is important to consider the Reynolds Number, of which the calculations are as follows. First it is necessary to solve for fluid flow speed, and then Reynolds number can be found based on a characteristic length defined as the chord length of the airfoil.

$$velo_{flow} = \frac{rate_{flow}}{CSA} = \frac{0.000275\frac{m^3}{s}}{0.048m*0.076m} = 0.075\,\frac{m}{s}$$

$$Re = \frac{velo_{flow}*L}{\nu} = \frac{0.075\frac{m}{s}*0.064m}{0.00000105\frac{m^2}{s}} = 4570 \qquad [5]$$

While I do believe this Reynolds number of 4570 is correct, and does fairly accurately describe the flow behavior pictured, it is lower than I would have hoped in order to accurately reference my image against existing literature. For example, Winslow et. al. published a paper on *Basic Understanding of Airfoil Characteristics at Low Reynolds Numbers*, however the lowest that any of their analyses went were Reynolds Numbers of ~10000. I believe that this can be explained by the exceptionally low flow velocity over our airfoil as compared to practical applications, which have been the cases analyzed in literature. Despite this, the literature still describes the behavior of the flow in both images to some extent, as can be seen in the figure a) shown here. It says that, "at sufficiently high angles of attack [AoA], the turbulent boundary layer will begin to separate close to the trailing edge, resulting in increased pressure drag," which can be seen by the more pronounced turbulent areas in the first image, as well as the tendency of the flow to suck back towards the airfoil near the tailing edge. Furthermore, "as the angle of attack is further increased, the turbulent separation point propagates along the airfoil surface toward the leading edge," which can be seen by the much earlier separation of flow from the foil in the first image as opposed to the second image. [5]



a) 10,000 < Re < 50,000

Visualization Technique

The visualization technique used here was the marked boundary technique, specifically in regard to dye used to block out backlit light from entering the camera sensor. The background was made up of pieces of white paper taped to the far outside of the flume, and the airfoil was 3D printed from a grabCAD design. [2] The dye and syringe used in the second image were from Prof. Hertzberg, and the needle used to inject the dye in the first image was from the ITLL machine shop. The dye in both images is food coloring, which is green and undiluted in the first image, and is red and is quite diluted in the second image, approximate 1 part dye and 9 parts water. As described in the Flow Vis textbook, the marked boundary technique implemented in this way, "shows a bright background, visible through the transparent medium, while the fluid marked with ink absorbs light." Similarly, the reason why we only backlit the image was because, "shining additional light on this dark ink would not enhance the contrast, but adding light to just the backdrop would," which is what we did, as much as possible. [1] The paper background that we used introduced some difficulties in terms of distinguishing the background from the lighter portions of the dye, which I've attempted to mitigate in post-processing. One method that we use to try to minimize the effects of this was implementing very bright lighting, however it only helped to a certain extent. The lighting that we used consisted of two separate bright incandescent bulb spotlights, attached to rolling chairs on the far side of the flume from where the image was taken, and positioned approximately a foot away from the point they were illuminating directly behind the airfoil. The image was captured around 8 PM on Wednesday, November 2nd, 2022 in the ITLL basement. The temperature of the water was approximately 70F, the same as the temperature of the room.

Photographic Technique

In this section, I will be referring only to the first, black and white, captured image for simplicity, and because many of the details between the two images in terms of photographic technique are very similar. The abstract technique that I used was taking photos against a paper background that was backlit in the open channel flow flume in the CU ITLL basement. The size of the FOV was approximately 10 by 6 inches and the distance from the object to the lens, as stated previously, was 13 inches. The lens focal length was 22 mm, and the other lens specs are a thread diameter of 40.5 mm, however I didn't use any lens filters. The camera used is a Sony a6500 which is a mirrorless camera. My original photo is 6048 by 4024 pixels and 24 megabytes in ARW format, and the exported high-quality photo is 5984 by 2027 pixels and is 71 megabytes. The aperture was f/8.0, shutter speed was 1/1000, and ISO was 500. In terms of post-processing in Darktable I did a lot to get the image to be black and white and show such contrast of the dye to the background. I turned up the velvia to near max, the contrast to +.18, brightness down -.93, color zone was put to the "red, black, white" preset, expose was turned up +2.534 with black level correction at -.0174, and white balance temperature at 4676 and tint at 1.024. Additionally, it was sharpened, rotated to be flat along the plane of the borders, and cropped to have a ratio near 1/6 height to width. The FOV was chosen qualitatively to best show the artifacts that we were seeing with our eyes, the size of the photo was the max that I was able to get with the raw capturing setting on my camera, and the aperture was chosen to let in enough light during the capture period, given that it a big issue was too little light, not too much, even though we had multiple high-powered spotlights backlighting the image. The ISO was chosen to make the dye and its details as visible as possible against the relatively monochromatic background, while limiting any overexposure or excessive detail of the background. The distance from the object to the lens was chosen such that I was able to get the width of image I desired with respect to the height of the flow, and still have the flow within focus. Finally, the focal length was chosen through experimentation additionally to get the dye and airfoil in focus, and as a secondary product of the aperture chosen.

Image Insights

As discussed in this report, this image reveals some of the fluid physics behind airfoils, their pressure regions, and the transition from laminar to turbulent flow due to solely the existence of an airfoil in a flow both, as well as the angle of attack (AoA) of this airfoil. I like these images because they allowed me to investigate an aspect of engineering which I had never ventured into before: aerodynamics. Additionally, I think they're both beautiful images that provide stark contrast to their surroundings and have a pleasing, singular focus. As described in the *Fluid Phenomena* section, there is absolutely room for improvement in terms of how well the fluid physics that I was hoping to show are actually shown. While I think that artistically, and somewhat scientifically, I've fulfilled my intent, I wish that the detachment points were more distinct than they are in these images. Additionally, I would like to run this visualization again with an airfoil that spanned the width of the flume to reduce tip vortex interference, and use slightly higher fluid velocities in order to get Reynold's Numbers that could be analyzed against existing literature. Artistically, I would like to get a more monochromatic background that didn't have blotches, I would like for more evenly distributed, brighter lighting, and I would like for a black dye that would show up even with even starker contrast against the background. Additionally, I would like to use cleaner flume water so as to not have the flow coloration tainted, and I would like more peer feedback on black and white versus colored images. In order to develop this idea further it would be fascinating to experiment with different sizes and profiles of airfoils and see how these variables affect flow characteristics.

References

[1] Hertzberg, Jean. “Overview 2: Visualization Techniques.” *Flow Visualization*, 28 May 2022, https://www.flowvis.org/Flow%20Vis%20Guide/overview-2-choices-2-and-3/.

[2] Singh Thakuri, Bibek. “Naca 4412 Airfoil.” *Free CAD Designs, Files & 3D Models | The GrabCAD Community Library*, 22 Oct. 2022, https://grabcad.com/library/naca-4412-airfoil-2.

[3] Ives et. al., Rob. *Investigation of the Flow around an Aircraft Wing of Section NACA 2412 Utilising ANSYS Fluent*. 2018, https://www.researchgate.net/publication/323693344_Investigation_of_the_flow_around_an_aircraft_wing_of_section_NACA_2412_utilising_ANSYS_fluent.

[4] “Approximate Viscosities of Some Common Liquids.” *Michael Smith Engineers Ltd*, 2022, https://www.michael-smith-engineers.co.uk/resources/useful-info/approximate-viscosities-of-common-liquids-by-type.

[5] Winslow, Justin, et al. “Basic Understanding of Airfoil Characteristics at Low Reynolds Numbers (104–105).” *Aerospace Research Central - Journal of Aircraft*, 15 Dec. 2017, https://arc.aiaa.org/doi/10.2514/1.C034415.