Three Dimensional Transition Flow of Vortex Formation Behind a Cylinder

Nicholas Travers

with Scotty Hamilton

- - -

Team2 Assignment – Flow Visualization 2012

University of Colorado at Boulder

An investigation was undertaken to observe and capture the intricate patterns of fluid flow around a cylinder using digital photographic techniques. Inspiration for this investigation is the phenomenon of the Kàrmàn vortex street, as presented in *An Album of Fluid Motion,* assembled by Milton Van Dyke (particularly figures 94-97). An open water channel, flume, was used; the cylinder was custom manufactured with small holes for injecting dye into the boundary layer, which allowed visualization of vortex development. In a discussion of the physics and fluid principles involved, the transition flow regime and the flow's three dimensional characteristics are discussed. The photographic setup and technique is presented and reviewed. The image was produced in collaboration with Scotty Hamilton, for the fourth assignment, titled *team2 assignment*, of the mechanical engineering course Flow Visualization[1] at the University of Colorado at Boulder. The purpose of the assignment is for students to design and setup an experiment to investigate a fluid phenomenon, and use an imaging technique to demonstrate the phenomenon in an artistic and visually pleasing manner.

Introduction

Various patterns may be observed in the flow of a fluid past an object. Vortices will begin to form behind an object as the flow increases, and the flow transitions from laminar to turbulent. Cylinders cause visually appealing flows, which have been extensively studied, see examples in (Van Dyke, 1982). To explore this flow transition region, and the development of vortices behind a cylinder, the flume located in the Integrated Teaching and Learning Laboratory at the University of Colorado at Boulder was used.

Methods

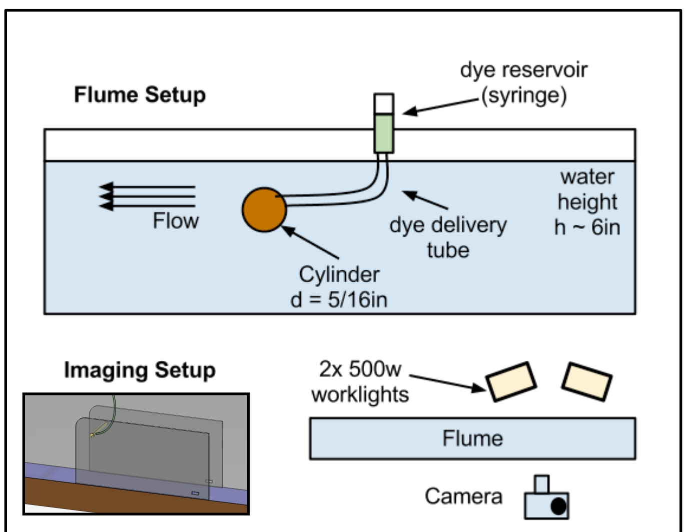


Figure 1 – Flume setup used for imaging vortex shedding from a cylinder: dye from the reservoir is injected into the flow boundary layer to visualize streamlines, work-lights provide illumination.

To visualize the development of vortices behind a cylinder the setup presented in Figure 1 was used. The flume is 3 inches wide, and the water level was 6.1 inches high (Figure 4). The cylinder consists of a 3 inch section of 5/16 inch brass tubing with small holes for injecting dyed fluid into the boundary layer. The cylinder has two rows, located 75° from the cylinders leading stagnation point, with five holes each that are of 1/64 inch diameter (see appended drawing). Dyed water was provided to the cylinder using a tube connected to a small reservoir. The ends of the cylinder were plugged using moldable clay. Two sheets of acrylic with

[1] The flow visualization course website can be found at: http://www.colorado.edu/MCEN/flowvis/

circular cutouts were used to support the cylinder 3.75 inches from the bottom of the flume (see appended Figure 4). The flow was imaged, by a digital camera on a tripod, through the clear walls of the flume. Illumination was provided by two 500W work-lights on the opposite side of the flume; their light was diffused using a white sheet of semi- transparent acrylic.

Flow Description

There are three general classifications of fluid flow: laminar flow, transition flow, and turbulent flow. Qualitatively, in laminar flow streamlines are well ordered, and flow transitions, for example around curves or over obstacles, are smooth. Turbulent flow by contrast has little order, and is characterized by complex mixing of fluid components. Between these two regimes is the transition flow region, where the flow is relatively ordered but streamlines begin to have complex interactions, and instabilities leading to turbulent flow develop. The flow imaged behind the cylinder is expected to occur in transitional flows that exhibit both laminar and turbulent characteristics.

The flow can be characterized by the Reynolds number. The Reynolds number for this flow is calculated from the diameter of the cylinder *d*, the upstream velocity *U*, and the properties of water using Equation 1. The upstream velocity, 1.1 in/sec, was calculated from volumetric flow measurements taken at the flume, average 630in^3 in 30 seconds; and using the dimensions of the flume upstream of the cylinder: 6.1 inch water depth, 3 inches wide. This velocity agrees with the time resolution of the imaging technique, as the image shows no motion blur, which indicates that an object velocity of 2.4 in/sec is required for the object to appear in two pixels. Water has a dynamic viscosity (υ) of approximately 1.56x10^{-3} in^2/s at room temperature (Engineering Tool Box). The Reynolds number is then:

$$\mathrm{Re} = \frac{Ud}{\nu} = \frac{(1.1 in/\mathrm{sec}) \times (5/16 in)}{(1.56x10^{-3}\, in^2/\mathrm{sec})} = 220 \pm 20 \qquad \text{Equation 1}$$

The uncertainty of the reported Reynolds number is primarily due to large uncertainty in the measurement of the volumetric flow rate. The calculated Reynolds number is slightly higher than values published in Van Dyke's *An Album of Fluid Motion* of 105-200 for the formation of vortex streets behind cylinders.

The vortices of this investigation were observed to mix with the flow and dissipate down stream, rather than forming a steady vortex street behind the cylinder. Two possible explanations are considered. The dyed water injected into the stream had a slightly higher density than the water of the flume. This density difference could promote instabilities in the vortex, which increases mixing with the surrounding fluid and the rapid decay of the vortex. Additionally, for flow behind a cylinder at Reynolds numbers of 200-300 the wake transitions to turbulent flow (Sumer & Fredsøe, 2006). Turbulent vortices will interact more with freestream fluid elements, and result in the exchange of dyed fluid elements of the vortex for transparent fluid elements of the free stream; i.e. lead to mixing, and the dispersion of the dye. The effects of density inhomogeneities and of turbulent vortex shedding both likely contribute to the transient nature of the vortices observed.

Separation of two of the streamlines from the other three streamlines, where the curling vorticity is most clearly seen, indicates three dimensional flow effects. Three dimensional flow effects have been studied extensively by C.H.K. Williamson. The transition flow region mentioned above has two notable modes of three dimensional flow as Reynolds number increases from 190-260. In mode A vortex loops develop along with streamwise vortices, as Reynolds number increases there is a transfer of energy to mode B which has finer scale spanwise vortices (Williamsen, Vortex Dynamics in the Cylinder Wake, 1996). A simple schematic is reproduced in Figure 2 to illustrate the three dimensional phenomena of mode A, and the formation of vortex loops (Williamsen, Three Dimensional Wake Transition, 1995).

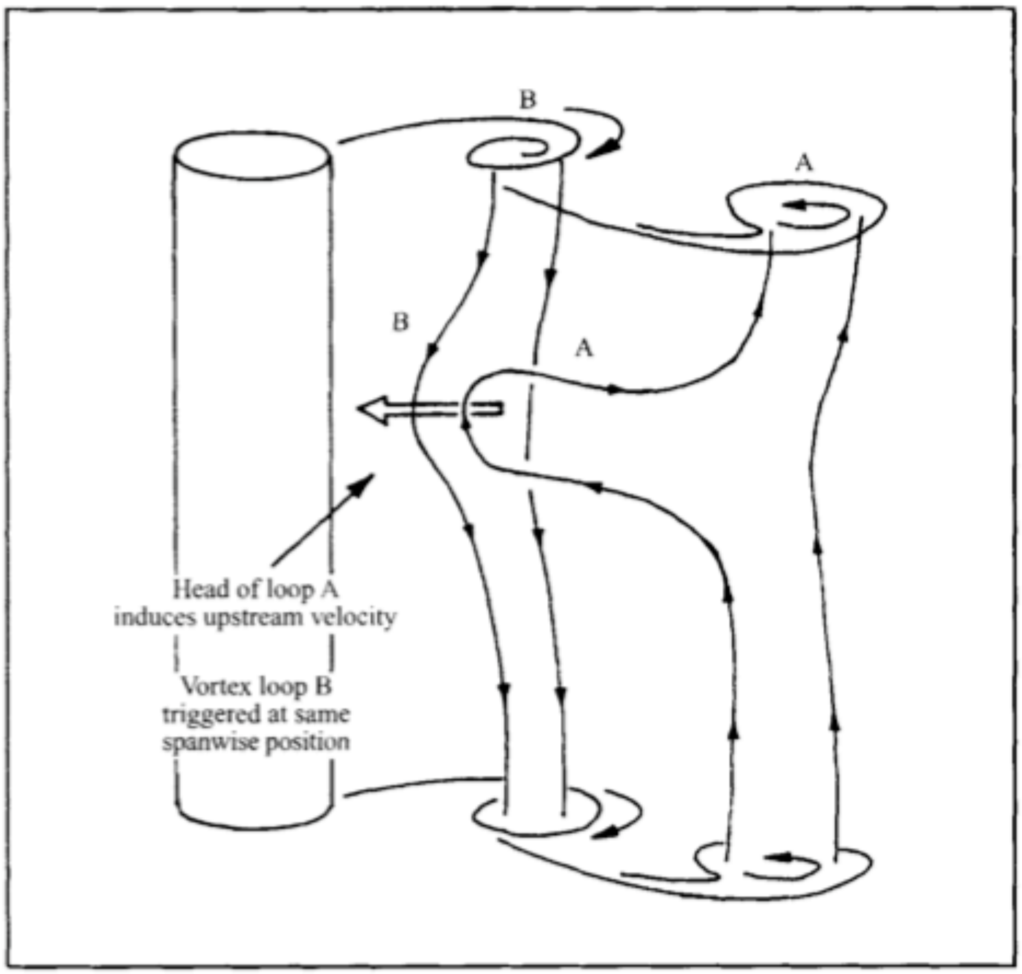


Figure 2 - Formation of a vortex loop in 3 dimensional transition flows of Re 190-260, the vortex becomes distorted and elongated to form a tongue upstream towards the cylinder which produces vorticity in the spanwise direction. Reproduced from Williamson (1995).

Vortex loops form due to wavy instabilities in the spanwise direction of the vortex, which is the result of an initial disturbance in the vortex core during the shedding process. The waviness is then accentuated by the interaction of subsequent vortices, which draw the vortex loop backward towards a recirculation region behind the cylinder. Spanwise vortices will develop as a result of the vortex loops at the sides of the flow, and rarely near the center of the flow (Williamsen, Three Dimensional Wake Transition, 1995). Examining the unedited image captured in this investigation reveals that the faint dye traces directly behind the cylinder are the vortex loops of previous vortices shed from the cylinder, and demonstrates the three dimensional structure of the flow.

Visualization Technique

To effectively visualize the vortex formation behind the cylinder dyed water was injected into the boundary layer of the cylinder. Approximately 10 drops of food coloring were added to a 100ml water reservoir. This reservoir was located approximately 2 inches above the water level of the flume, to create a gravity driven injection system. Note that if the reservoir's potential is too great, the dye will act as a jet and enter the freestream around the cylinder. The dye is injected into the boundary layer through two rows of five 1/64in diameter holes, each positioned 75° from the leading stagnation point. The dye was visualized against a semi transparent background, backlit by two sets of 500W work lights. The white background provided a strong contrast for the dye and eliminated distracting objects of the laboratory. The walls of the flume itself are transparent, allowing easy photography of the flow by hand or using a tripod.

The final image is 1052 x 2366 pixels in size, and shows a 0.64 x 2.87 inch section of the flow, which has been mirrored about the axis of the cylinder. The center of the flow is approximately 4 inches from the camera. The acrylic background blocked a surprising amount of light, requiring that a moderately low ISO setting be used. To avoid the noise and color aberrations inherent in low ISO settings, while setting the shutter speed to a fast 1/1000th of a second, the aperture was set to f/5 which allowed some depth of field. The resulting time resolution is such that the image is well resolved, and without motion blue. However, the focal plane is enough out of alignment with the imaged streamlines such that they are not as crisp as this time resolution would suggest. The effects of dye diffusion may also be contributing to a loss of crispness. The camera was in macro mode with an effective focal length of 6mm. The camera used was a NIKON Coolpix P7100 which has a 6.0-42.6mm, f2.8 lens with image stabilizer. The camera settings are summarized in Table 1.

Table 1: Camera's Image Capture Settings

Original Image Size	3648x2736 pixels
Final Image Size	1052x2366 pixels
Resolution	240 pixels/inch
Shutter Speed	1/1000
Aperture	f/5
ISO Speed Rating	400
Focal Length	6.0 mm
Lens	6.0-42.6 mm f/2.8
Camera	NIKON P7100

Editing of the original image (appended) was done to produce a clean, interesting, and visually appealing final image. The Image was cropped, rotated, and mirrored to highlight the formation of one vortex. The primary reason was to highlight the color of the brass cylinder, and it's symmetry. Also, this eliminated the edge of the cylinder support, as well as a black blotch due to excess moldable clay on the end of the cylinder. While playing with different crops I found that mirroring the image created wonderful and lively symmetry. I was attracted to the *sprite* that appeared, while others have seen and enjoyed: a heart, a mouse with raised hands, a dragon, and a preying mantis. To increase the impact of the image curves were adjusted to bring out more contrast. The green dye was made darker through individual saturation and hue adjustments. The noise from using a 400 ISO setting was reduced using the luminance and detail recovery functions. The initial and final images are appended to this report for comparison.

Concluding Remarks

Using the flume is very rewarding, and we were able to visualize several interesting variations in both the formation of vortices, and in the persistence of a vortex street downstream of the cylinder. Improvements to the visualization technique would allow the acquisition of more useful flow data. However, vortex shedding in the transition region, Re 190-260, was successfully visualized. The lack of a steady vortex street due to diffusion of dye and turbulent mixing layers was discussed. The image also illustrates the three dimensional character of the flow, the features of which are explained.

The image would be more appealing with a greater depth of field to bring the fluid into sharper focus. Future visualizations using this apparatus could be improved by increasing the length of the acrylic support, or eliminating it altogether. Using a larger reservoir (broader) to provide more consistent injection of dye into the boundary layer would provide more consistent results. Injecting a different fluid could also provide clearer effects, possible suggestions include: a darker fluid for more contrast, or a less apt to diffuse fluid to reduce blurring. A suggestion taken by example from the literature is to use Rhodamine dye, which has a metallic green color when excited by laser light. The use of this dye with laser sheet illumination produces good results (Hu & Zhou, 2008). Other visual improvements could be made by varying number, size, location and spacing of the holes in the cylinder, or using a slit instead. The setup is available for students to use in future investigations.

While I chose to use a new medium and a simpler setup for this investigation, I would have liked to use a soap film, and techniques similar to those used by Gharib & Derango (1989). After investigating more of the literature on vortex shedding I realize there are many more wonderful situations to visualize and study regarding the wake behind cylinders. Specifically, the imaged turbulent transition regime has been investigated less than the laminar or fully turbulent cases of vortex shedding. Also, the interactions of vortex shedding from two cylinders appears to hold magnificent flow visualizations, see figures 25 and 42 in Sumner (2010). I hope future groups at the University of Colorado will continue to utilize the flume to explore and visualize these wonderful fluid interactions.

References

Engineering Tool Box. (n.d.). *Water - Dynamic and Kinematic Viscosity*. Retrieved March 28, 2012, from The Engineering Toolbox: http://www.engineeringtoolbox.com/water-dynamic-kinematic-viscosity-d_596.html

Gharib, M., & Derango, P. (1989). A liquid film (soap film) tunnel to study two-dimensional laminar and turbulant shear flows. *Physica D , 37*, pp 406.

Hu, J. C., & Zhou, Y. (2008). Flow Structures behind two staggered circular cylinders. Part 1. Downstream evolution and classification. *Journal of Fluid Mechanics , 607*, 51-88.

Schnipper, T., Andersen, A., & Bohr, T. (2009). Vortex Wakes of a Flapping Foil. *Journal of Fluid Mechanics , 633*, 411-423.

Sumer, B. M., & Fredsøe, J. (2006). Hydrodynamics Around Cylindrical Structures. In P. L. Liu (Ed.), *Advanced Series on Ocean Engineering* (Revised Edition ed., Vol. 26). Ithica, NY: World Scientific Publishing Co. Pte. Ltd.

Sumner, D. (2010). Two circular cylinders in cross-flow: A review. *Journal of Fluids and Structures , 26*, 849-899.

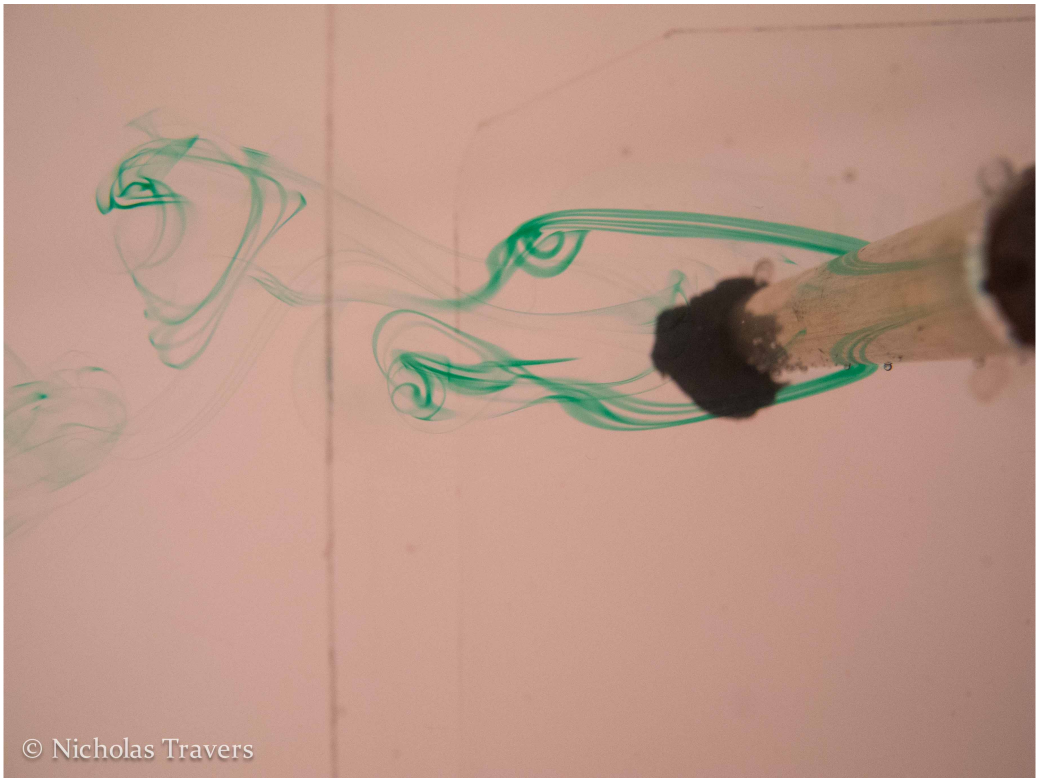
Van Dyke, M. (1982). *An Album of Fluid Motion.* Stanford, CA: The Parabolic Press.

Williamsen, C. (1995). Three Dimensional Wake Transition. *Journal of Fluid Mechanics , 328*, 345-407.

Williamsen, C. (1996). Vortex Dynamics in the Cylinder Wake. *Anuual Review of Fluid Mechanics* , 477-439.

Yang, T. S., Wen, C. Y., & Lin, C. Y. (2001). Interpretation of Color Fringes in Flowing Soap Films. *Experimental Thermal Fluid Sciences* (25), 141-149.

Zhu, L. (2007). Viscous flow past a flexible fibre tethered at its centre point: vortex shedding. *Jounal of Fluid Mechanics , 587*, 217-234.

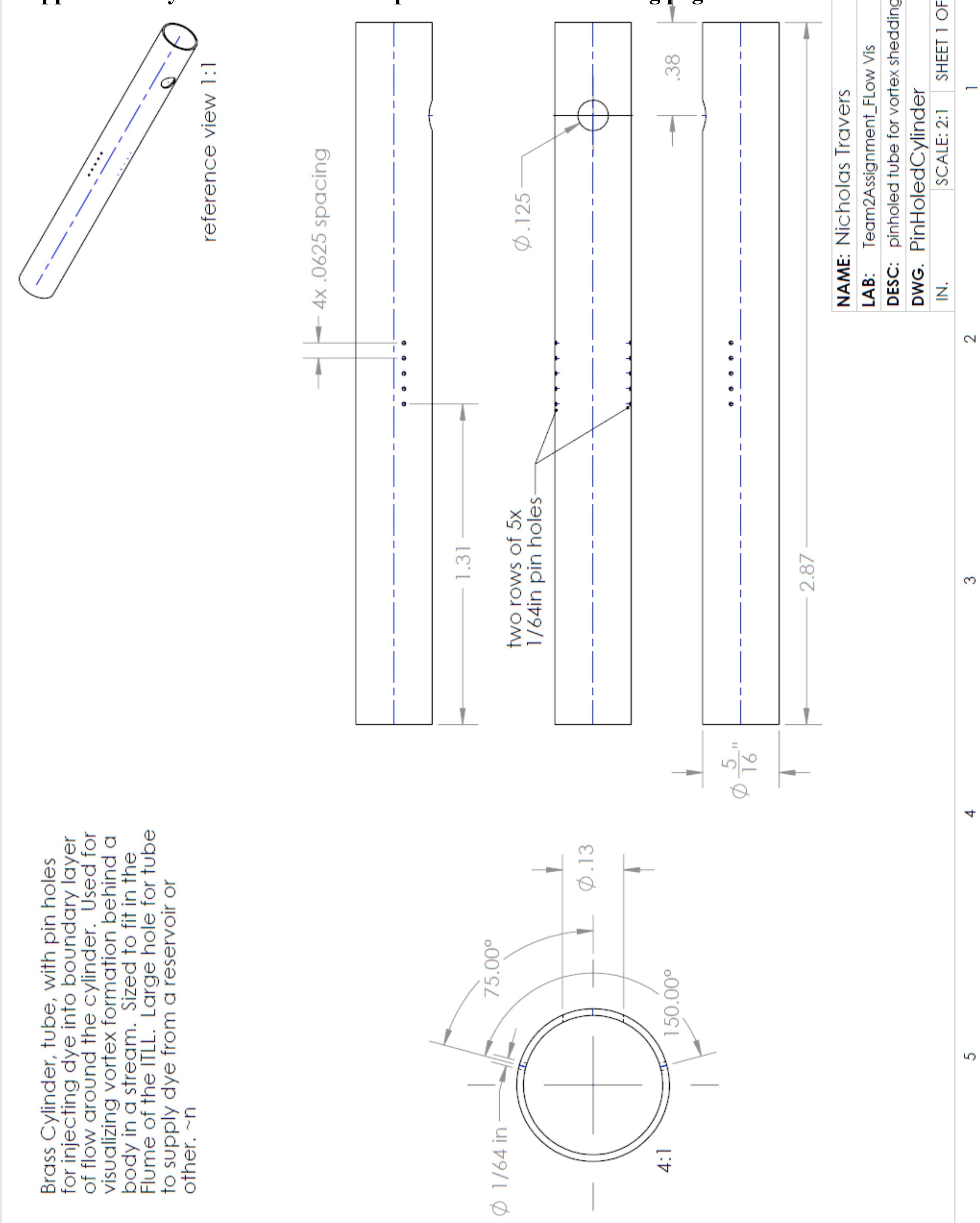


Original, as shot, image of boundary layer separation behind a cylinder and the developing a vortex with three dimensional effects shown by diverging streamlines. The very faint dye traces behind the cylinder, between the two main streams, is the 'tongue' of a vortex loop.

Edited Image:

Cropped, rotated and reflected about the axis of the cylinder.
White balance adjustments, curves adjustments, and individual color adjustments to bring out more contrast between dyed streamlines and background.
Minor noise reduction.

Drawing of Cylinder with holes used for flow visualization. The assembly of acrylic supports and cylinder in the flume is presented on the following page.



Schematics of Flume setup:

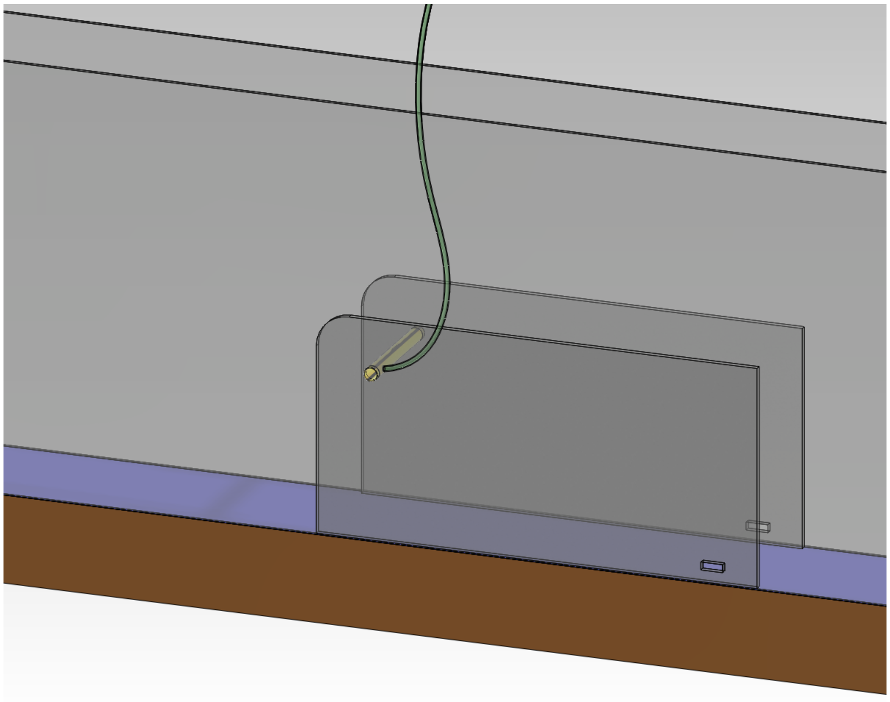


Figure 3 - Assembly schematic of cylinder and cylinder supports in flume. (Scotty Hamilton)

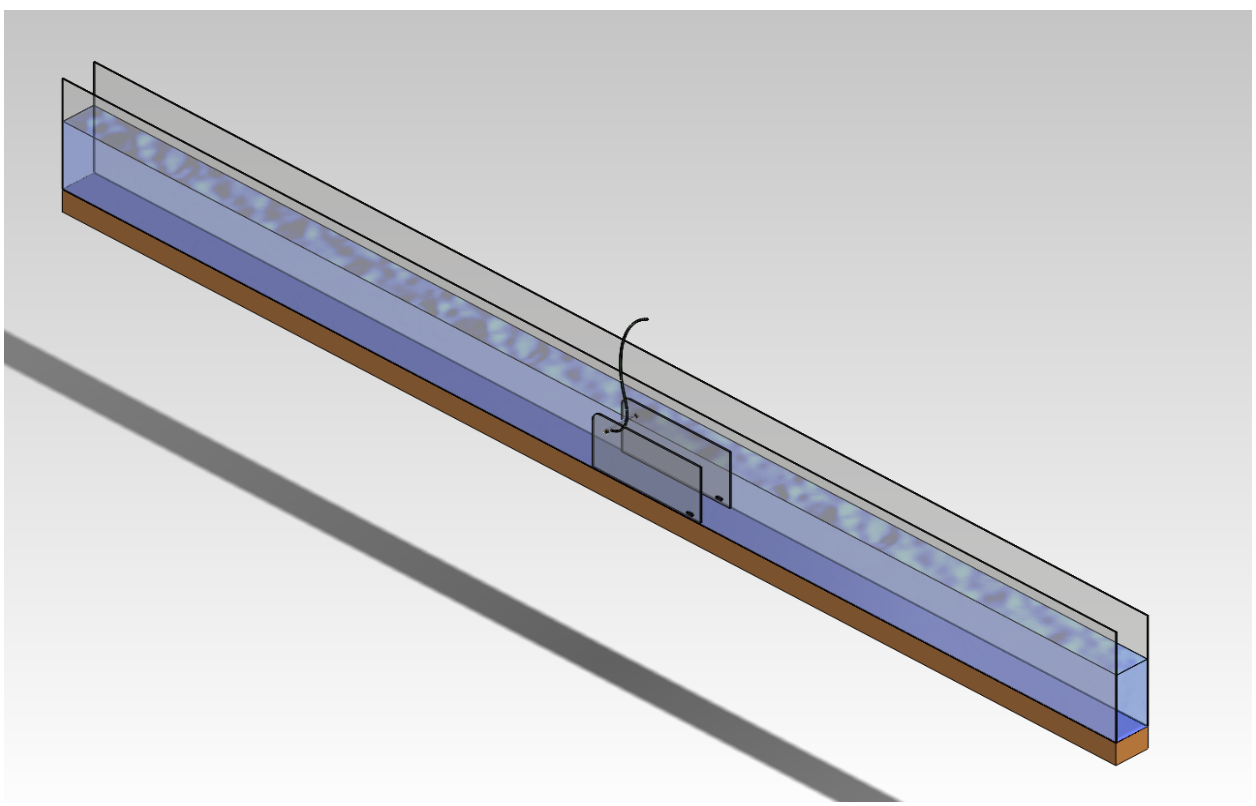


Figure 4 - Schematic of Flume with cylinder support components and filled with water. (Scotty Hamilton)