3D Karman Vortex Street in the Wake of a Cylinder in Water

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MCEN5151: Flow Visualization

Mechanical Engineering

University of Colorado, Boulder

Objective

The objective of the “Team Third” assignment was to develop an idea for a flow visualization experiment, to collectively gather materials and design the experiment and then to photograph the results. The image should embody the essence of the art of flow visualization by striking a balance between revealing the physics of the flow and achieving an aesthetically appealing picture. In this assignment Team 10 set out to photograph a Karman vortex street in the wake of a cylinder in water.

Background

When a fluid flows over a closed body the fluid near the body initially accelerates due to the profile blockage up to a point near the location of maximum thickness after which the fluid decelerates as it diffuses towards the trailing edge. In flows over non rotating cylinders with Reynolds number greater than 5 (calculated using cylinder diameter) the boundary layer separates due to the adverse pressure gradient in the diffusing region [1,2]. The flow in the wake of the cylinder has low velocity due to the viscous interaction with the body while the flow outside of the wake remains relatively high. At the interface between the wake and the free stream a shear layer forms where vorticity production is high. At Reynolds numbers between 5 and 40 the separation takes the form of a steady, symmetric pair of counter-rotating vortices that remain fixed behind the cylinder in its wake [1]. If Reynolds number is increased above 40 the symmetric steady wake gives way to an unsteady vortex shedding phenomenon [1,2]. In the flow regime between Reynolds number of 40 and 200 vortices of opposite sense are alternatingly shed from the top and bottom side of the cylinder[1][3]. The offset and staggered rows of vortices resemble the footsteps of a person walking on the street and so the shedding phenomenon has come to be known as a Karman vortex street after Von Karman who was an early scientist to publish a paper on the subject [2,3]. The alternating shedding of vortices with opposite rotational sense induces an oscillatory lift force on the cylinder which when coupled with a structural mode of the cylinder can be destructive [2]. For Reynolds number between 40 and 200 the flow in the cylinder boundary layer and its wake are laminar therefore the wake can be purely 2D. But as Reynolds number increases to 200-300 the flow in the wake transitions to turbulent and so the wake becomes 3D [1]. Going further to Reynolds number between 300 and $3x10^5$ the wake becomes fully turbulent [1]. At these higher Reynolds numbers the unsteady vortex shedding phenomenon persists but the wake becomes irregular due to the three dimensionality and high mixing of turbulence and so an organized vortex street becomes harder to distinguish [2].

Method

<u>Experimental Facility: ITLL Flume</u>

This experiment was conducted in the University of Colorado, Boulder ITLL building using the Armfield C4-MKII open channel flume. The test section consists of two 2.5m long acrylic panels which are 7.6cm apart and 25cm tall (Fig 1 & 2). One of several challenges in this experiment was in achieving a flow rate low enough in the flume to match the desired Reynolds number on the cylinder. Through trial and error it was determined that the pump mounted to the flume could not reliably achieve a flow rate low enough for the experiment. So instead a garden hose was run to the upstream side of the test section and used as the fluid supply. On the downstream side the water was allowed to exit into the reservoir below the discharge tank where the spent water was removed by a self-priming sump pump. In addition to enabling the flume to run at a sufficiently low flow rate the hose and sump pump technique prevented the recirculation of dyed water which would have significantly limited the run time of the experiment and degraded contrast in the experimental images due to dye build up. The water flow rate was determined by measuring the amount of time it took the reservoir below the discharge tank to fill up to a particular volume.

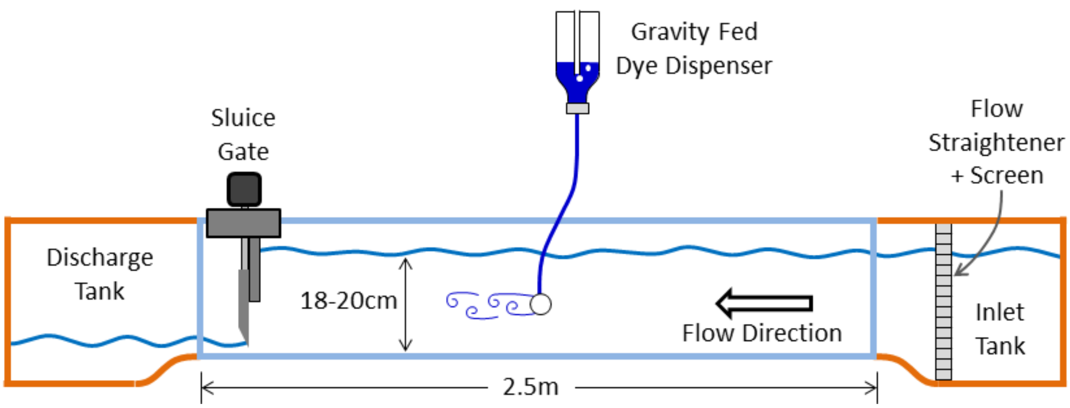

Figure 1: Flume and experimental set up side view

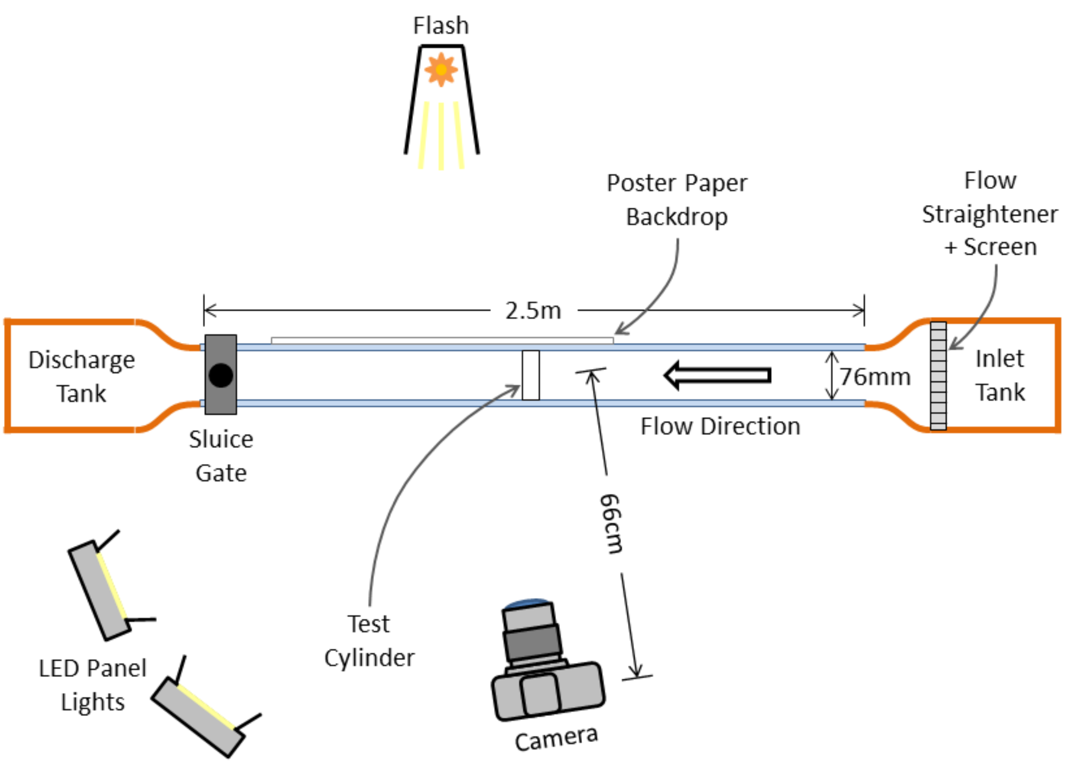

Figure 2: Flume and experimental set up top view

The angle of the flume can be adjusted using a jack but for this experiment where a low flow rate and high water column was desired the slope was set to 0°. To increase the water column height in the test section a sluice gate was added just upstream of the outlet reservoir. The depth of insertion of the sluice gate and the flow rate from the hose were iterated on to achieve the desired flow velocity and a water column of roughly 20cm in height. In the final configuration the sluice gate was almost fully inserted. In an effort to condition the incoming flow a flow straightener and turbulence screen were built that fit just upstream of the contraction before the test section inlet. The flow straightener was cut down from a plastic overhead lightning louvre consisting of 15mm x 15mm square holes and a 8mm depth in the flow direction. The turbulence screen was made from a porch screen and had square holes that were roughly 2mm x 2mm in size. See figures 1 and 2 for a schematic of the flume.

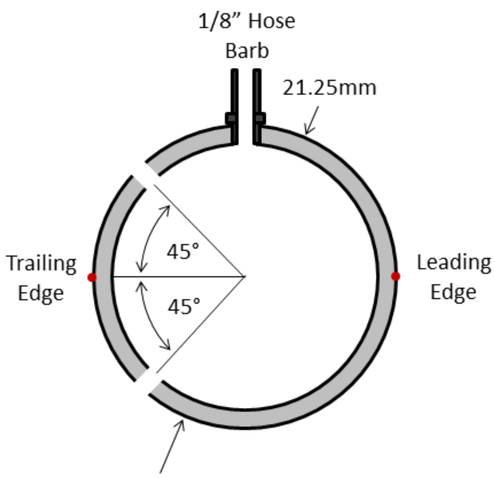

Figure 3: Cylinder end view cross section

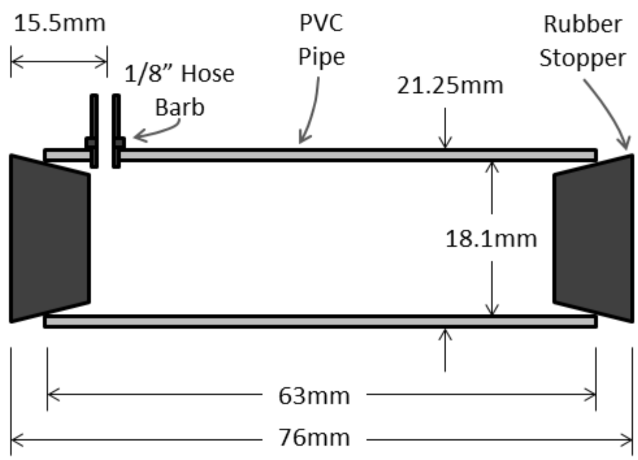

Figure 4: Cylinder rear view cross section

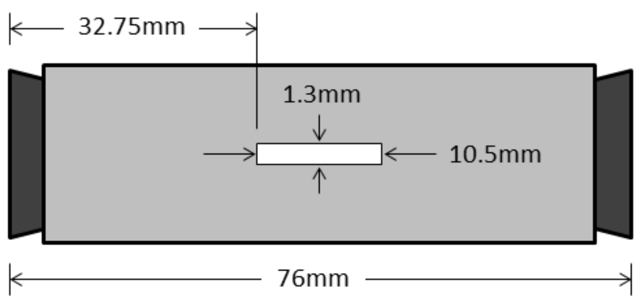

Figure 5: Cylinder exterior view

<u>Test Subject: Cylinder</u>

The test subject was a thin walled white PVC pipe section. It had an outer diameter of 21.25mm and a length of 63mm. To seal the ends of the cylinder and provide a means for compressing the cylinder between the flume's acrylic panels a solid rubber stopper was inserted into each end bringing the cylinder's total length to 76mm i.e. the width of the flume's test section. At 20% span or 15.5mm from the cylinder end a 1/8" hose barb was glued into the cylinder using epoxy to provide an entry port for dye injection. At the center of the cylinder two axially oriented rectangular slots 1.3mm wide and 10.5mm long were cut through the wall of the cylinder. The two slots were cut 90° from each other and covered 14% of the span. In this image the slots were oriented towards the downstream side of the flow with one slot 45° above the trailing edge point and the other slot 45° below the trailing edge. The design and measurements for the cylinder are depicted in figures 3-5. The cylinder was mounted roughly 12cm from the bottom of the channel and just downstream of the lengthwise center point.

Dye and Dye Delivery

Dye was delivered to the cylinder via a 1/8" clear rubber tube that was connected to a dye reservoir. The reservoir consisted of a soda bottle with a hose barb glued into a hole cut in the bottle cap and a straw glued into the bottom side of the bottle to provide an air inlet. Dye was delivered via gravity from the reservoir through the tube into the internal cavity of the cylinder (Fig 1). The dye flowed out of the cylinder cavity through the two rectangular slots into the water flow (Fig 3, 5). By varying the height of the dye reservoir relative to the cylinder the flow rate of the dye could be adjusted.

The dye used was a blue gel food dye. The density of the food dye was higher than that of water so it was mixed with 95% ethanol, which has a lower density than liquid water, to bring down its density. Achieving the correct proportion of dye and alcohol was one of the bigger challenges of the experiment. Attempts to get accurate volumetric measurements of the dye for a density computation were thwarted when the food dye dripped down the side of the graduated cylinder and obscured the location of the meniscus. A best attempt at the correct mixture proportions was made and then the mixture was diluted with water from the flume. Towards the beginning of the experiment the dye was slightly negatively buoyant and so additional ethanol was added to the dye reservoir. By the end of the experiment the buoyancy swung the other way and the dye became slightly positively buoyant. Access to a more appropriately sized graduated cylinder and a scale with a larger mass range would have removed some of the guess work in achieving a neutrally buoyant mixture.

Photographic Set-up

Photos were taken with a Canon 7D DSLR mounted on a tripod at roughly the height of the cylinder with the sensor plane 66cm away from the center span of the cylinder. A Canon 24-70mm F2.8 lens was used and the barrel axis was oriented slightly off orthogonal to the flume's acrylic panel to make the view of the cylinder closer to end-on (see figure 2). For lighting two 160 LED panel lights were set up on tripods so that the scene was front lit but were pointed towards the trailing edge side of the cylinder such that the cylinder's shadow was cast upstream. The LED lights were also positioned so far off orthogonal with the acrylic panels to eliminate reflections of the light source from the camera field of view. To the back acrylic panel a sheet of white poster paper was taped to provide a clean backdrop. An off camera flash was mounted on another tripod behind the flume and pointed at the white poster paper. The back lighting from the flash on the poster board increased the whites in the backdrop and helped mitigate shadows cast from the cylinder and wake onto the backdrop. In addition, overhead room lights above the flume provided some additional lighting for the scene. See figure 2 for a schematic of the photographic equipment layout.

Photo Settings

For this experiment the camera exposure was set manually. Aperture was set at f/6.3 because that sits in the sharp range for the lens and provided sufficiently depth of field to spatially resolve the cylinder wake. Shutter speed was iterated on with ISO to a value of 1/200s which was fast enough to time resolve the wake but slow enough to avoid excessive ISO levels. The ISO was set to 1000 which still has relatively low noise for a camera of the quality used. The 42mm focal length was set to capture the desired frame and the resulting field of view was roughly 16.5cm x 25cm. Focus was set automatically by the camera by holding a target focus object in the flume channel at the center span of the cylinder. Once focus was achieved the focus target was removed and the focus drive was set to manual mode to prevent the focus from being reset. The shooting mode on the camera was set to continuous high speed so that a series of frames could be captured in short succession. The camera was triggered by a wired shutter release remote and the flash was triggered directly by the camera. Additional details about the photo settings can be found in table 1.

Focal Length	42mm
Shutter Speed	1/200s
Aperture	f/6.3
ISO	1000
Autofocus	Off
White balance	Auto
Gamut	sRGB
Format	RAW
Pixels WxH	5200x3417

Table 1: Photo settings

Post processing

The original image was shot in Canon RAW format. A TIF file was written out using Canon's raw file post processor. The image was then edited in Photoshop Elements 5.0 and GIMP 2. Much of the post processing for this image involved isolating the cylinder and its wake from distracting elements in the frame. The largest challenge was to remove air bubbles that had developed on the acrylic side panels of the flume. The shadows cast by the wake on the backdrop were also removed where possible. Near the top of the frame a layer of dyed water that collected at the water-air interface was removed in addition to the interface itself. The dye injection tube that was connected to the top of the cylinder was also edited out. The color curves for the image were adjusted to push the background a little further towards true white and the image was flipped left to right to make the flow direction consistent with convention. An unedited version of the image can be found in the appendix.

Results

To achieve the goal of photographing a Karman vortex street behind a cylinder in water a very low free stream velocity had to be achieved. For a laminar vortex street the cylinder Reynolds number has to be below 200. In the photograph (Fig 6) the flow rate through the flume was roughly Q=0.207 L/s. The water column was 18cm high and the flume width was 7.6cm.

$$Q = U_{avg} * A$$

$$U_{avg} = Q/A$$

$$U_{avg} = 0.207\frac{L}{s} * \left(\frac{1m^3}{1000L}\right) * \left(\frac{1}{18cm * 7.6cm}\right) * \left(\frac{100cm}{1m}\right)^2 = 0.0151m/s$$

Therefore the average velocity was 0.0151m/s. At this speed the free stream flow takes 11 seconds to traverse the image frame. For water at room temperature the kinematic viscosity is $\nu=1.005 \times 10^{-6}\ m^2/s$. So the Reynolds number on a 21.25mm dimeter cylinder can be calculated as follows:

$$Re = \frac{U_{avg}D}{\nu}$$

$$Re = \frac{(0.0151m/s)(21.25mm)}{(1.005x10^{-6}m^2/s)} * \left(\frac{1m}{1000mm}\right) = 319$$

Thus the average Reynolds number in the photo was roughly 319. Due to the blockage in the boundary layer the centerline velocity, where the cylinder slots were located, would have been higher than the average velocity, however.

Figure 6: Karman vortex street behind a cylinder in water

Thus the boundary layer on the cylinder was probably laminar but that much of the wake may have been turbulent. During the experiment Reynolds numbers as low as 188 were achieved but due to some non-zero buoyancy issues with the dye Rayleigh Taylor instabilities due to the density difference with the water were given time to form. By running at a slightly higher water flow velocity the Rayleigh Taylor instabilities were mostly inhibited. Looking at the upper right side of the vortex in the middle of the lower row (Fig 6) a little bit of fingering in the dye is visible due to negative buoyancy.

In the photograph (Fig 6) a staggered set of counter rotating vortices in two rows are visible in the cylinder wake. It is apparent that the wake is fairly 3D. A number of factors are believed to have contributed to this. A particularly large driver may have been the boundary layers on the acrylic panels of the flume. The vorticity in the boundary layers would have been orthogonal to the vorticity in the cylinder wake therefore any small tilting in the axis of the wake vortexes would have been accelerated by the boundary layer turbulence. Furthermore the flume was narrow enough that avoiding the boundary layer altogether was not possible but also too short to have achieved a fully developed boundary layer before the outlet. The method of inserting the cylinder by hand was not exact and so the cylinder may also have been swept slightly relative to the oncoming flow. The dye injection line also ran to only one side of the cylinder and therefore created a spanwise asymmetry.

Although scientifically the goal of producing a truly 2D, regular Karman vortex street was not achieved in this experiment the artistic goal of capturing a pleasing image of this interesting fluid dynamic phenomenon was attained. The shades of blue and green in the cylinder wake are beautiful and the delicate sheets of fluid rolled up into the spinning vortices are elegant. This experiment ended up being scientifically edifying and artistically a success.

Discussion

The experience of attempting to capture this image emphasized the difficulties of running experiments at extremely low Reynolds numbers and tightly controlling the flow field. A flume with a wider test section would surely have helped with isolating the wake vortices from the flume boundary layer and would have reduced some of the three dimensionality experienced. The buoyancy of the dye was problematic and access to better equipment for measuring density would have been very helpful. However, the need to run a tube to the cylinder to feed the dye made the set-up problematic overall and a system using electrolytic precipitation as seen in 'An Album of Fluid Motion' [4] would most likely have produced better results. Ultimately, challenges with the equipment and experimental method in addition to time constraints prevented the team from achieving vortex streets of the quality seen in some publications but regardless an interesting and beautiful phenomenon was captured in this work. The experience also gives the author a new found sense of respect for the work of the many great fluid dynamicists published in 'An Album of Fluid Motion' [4].

Acknowledgements

This experiment was conducted with Max Scrimgeour, Peter Brunsgaard and Jeremy Parsons.

This material is based upon work supported by the National Science Foundation Graduate Research Fellowship Program under Grant No. (DGE 1144083). Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the National Science Foundation.

Literature Cited

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Appendix A: Unedited image