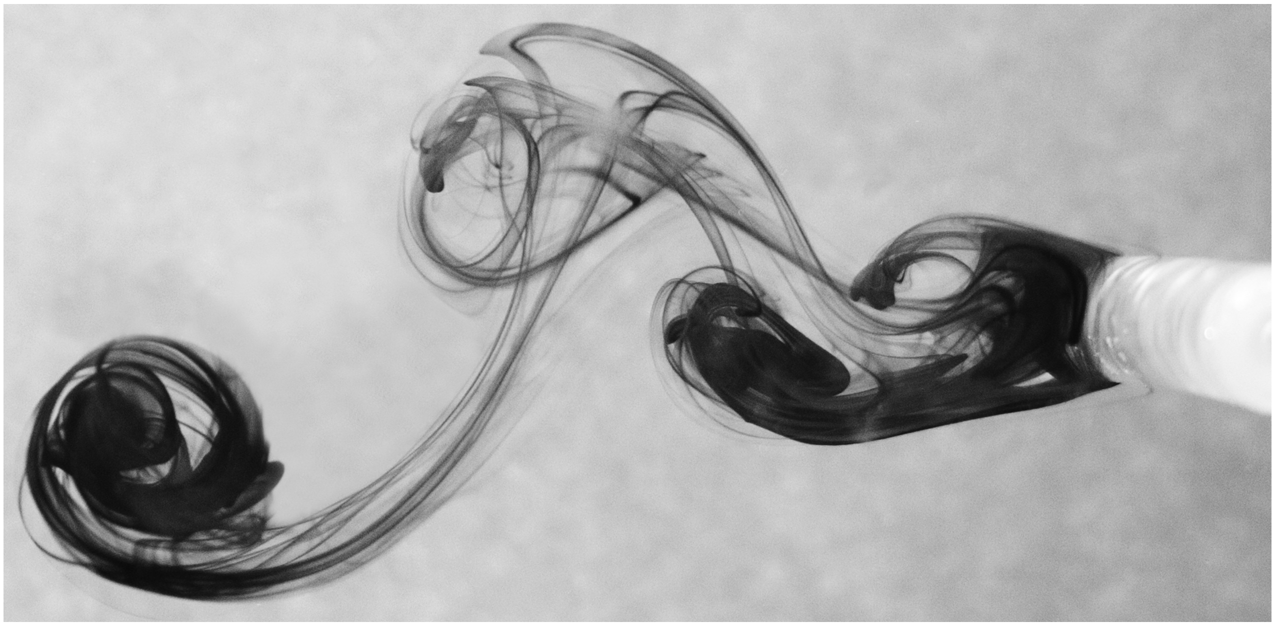
MCEN 5141: Flow Visualization

Team Second



Andrew A. Van Der Volgen

1 Introduction

This project was intended to provide an opportunity for application of the techniques covered thus far in the MCEN5141 course curriculum. Its aim was to create a fluid flow indicative of an arbitrary fluid mechanic phenomena and image it effectively. The project was undertaken collectively by a group of four students who shared materials and expertise, but each student within the group produced their own unique final product. The team was comprised of Dylan Cook, Finn Ostrem, Kyle Samples, and the author.

It was ultimately decided that the group would generate Kármán vortex streets in a laminar flow and image them in order to illustrate the flow dynamics induced by the phenomena.

2 Major Materials

2.1 Open Channel Flume

An open channel water flume was readily available to the group for use, and so it was decided to utilize the flume rather than construct a purpose built setup for generation of vortex streets in air or other media. The flume is a commercially available model C4-MKII-2.5-10 Multi-Purpose Teaching Flume manufactured by Armfield Ltd. (Figure 1).

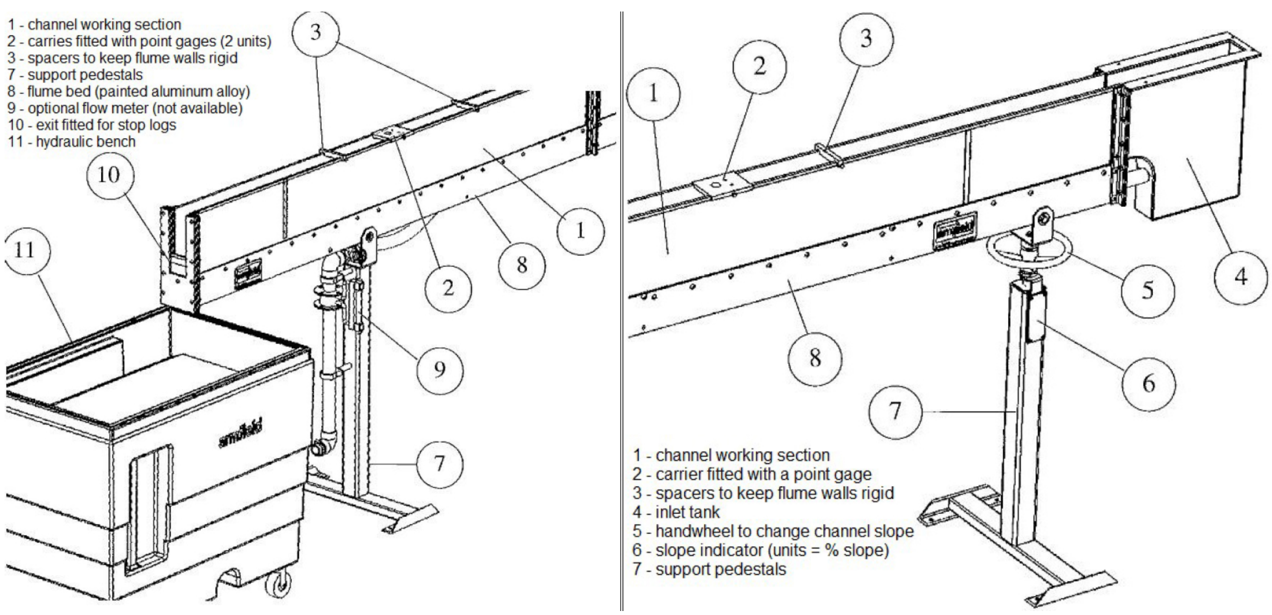


Figure 1: Armfield Open Channel Flume

Although the flume has many features, for this project it was only necessary that it produce a steady, laminar, flow of water through its test section at velocities appropriate for generation of vortex streets. It accomplishes this by pumping water retained in the reservoir of an Armfield F1-10 hydraulics bench to an inlet tank on the flume. From the inlet tank, water flows through the test section which measures 2.5m long × 76mm wide × 250mm high, and has clear acrylic sides to allow visualization of the flow. At the end of the test section water flows back into the hydraulic bench reservoir to await being pumped back through the system [5].

2.2 Bluff Body

A Kármán vortex street is a repeating pattern of vortices that forms as a result of unsteady separation of flow around a bluff body. To generate the vortex streets, it was necessary to obtain a suitable bluff body for insertion into the flow. Although any bluff body can generate vortex streets, circular cross-section bodies are most widely available and so a suitable characteristic length (diameter), L, for a circular body was determined through Reynolds number calculations.

Experimentation showed that the slowest flow velocity which the flume was capable of producing was around 4.5cm/s. Given this minimum velocity, an exceptionally small diameter body would be required to produce a characteristic Reynolds number $\lesssim 150$. Accordingly, assuming a water temperature of 10°C and a desired Reynolds number of 150, the necessary characteristic length calculation is [4][6]:

$$L = \frac{(\mathrm{Re})(\nu)}{U} = \frac{(150)(1.3075 \times 10^{-6}\,\frac{\mathrm{m}^2}{\mathrm{s}})}{0.045\,\frac{\mathrm{m}}{\mathrm{s}}} = 4.4\mathrm{mm} \qquad \text{where} \quad \begin{array}{l} \text{Re is desired Reynolds \#} \\ \nu \text{ is kinematic viscosity} \\ U \text{ is flow velocity} \end{array}$$

As a result of the above calculation, a rigid plastic tube with 4.5mm outer diameter was purchased from a local hardware store. The tube was cut to an axial length slightly longer than 76mm so that it could be wedged into the flume test section and remain in place without support.

2.3 Flow Dye

A dye was used to highlight the vortex streets within the flow. Many dyes were experimented with but the image on the title page of this document was produced using ProArt PRO-4100 India Ink injected into the flow upstream of the bluff body. The ink worked particularly well in this application as it diffused into the bulk flow more slowly than other dyes which allowed it to highlight the flow dynamics further downstream than its alternatives.

3 Setup and Video Capture

The flume was operated at a flow velocity of 4.5cm/s with the plastic tube from Section 2.2 obstructing flow through the test section. A Canon EOS Rebel SL1 camera was positioned on a tripod in front of, and level with, the bluff body. A plain white piece of A5 paper was taped to the backside of the flume test section to serve as a uniform background for the photo. The plastic tube was illuminated by a 5000K color temperature, 2000 lumen, LED work light which was positioned on top of the flume test section and directed straight down through the flow at the tube. A 2400K color temperature, 2500 lumen, 3M-9100 model overhead projector was utilized to illuminate the A5 paper from behind in order to provide increased contrast between the dye and its background.

India ink was injected into the boundary layer on the upstream side of the bluff body with a syringe and allowed to be slowly stripped off the surface and carried downstream through the vortex streets. Images of this were taken at 5184 × 3456 resolution, 1/320s shutter speed, f/5.6 aperture, ISO 400, and with a focal length of 31mm. The resultant raw image chosen to represent this project is presented in Figure 2.

This photo was then post-processed in Adobe Photoshop. The image was cropped down to 1915 × 932 resolution so that it included only the well formed vortices, and was then desaturated to turn it

Figure 2: Raw Image

black and white. The *Clone Stamp* tool was used to erase ink that connected the vortices on opposite sides of the downstream crop line, and contrast was adjusted using Photoshop's *Curves* tool. The resultant image depicts a 75 $\times$ 35mm field of view and is shown on the title page of this document.

4 Fluid Mechanics

4.1 Flow Separation

When fluid flows past an immersed cylinder it is slowed near the cylinder wall by shear force, τ_w, arising from the liquid/solid interaction and transmitted through the fluid by viscous forces. The result is development of a velocity gradient profile that increases from zero at the wall (assuming no-slip condition), to free stream velocity, U_∞, far from the wall. The region in which this occurs is known as the boundary layer which has thickness, δ, and is traditionally defined as the region where fluid velocity $U < 0.99U_\infty$ [7].

The boundary layer flow velocity is highest at the top of the cylinder (Figure 3) which corresponds to the point of lowest pressure as well. Because this pressure is lower than that present further down the lee side of the cylinder, the boundary layer experiences an adverse pressure gradient, $\frac{dp}{dx} > 0$, as it travels the downstream side of the cylinder. Given appropriate cylinder diameter and free stream velocity, this adverse pressure gradient will overcome the fluid momentum near the cylinder wall and velocity there will drop to zero or reverse direction. When this occurs the flow is said to have separated [7].

As shown in Figure 4, flow separation due to adverse pressure gradients can generate vortical motion in the boundary layer. In the case presented, which is applicable to the portion of the cylinder shown

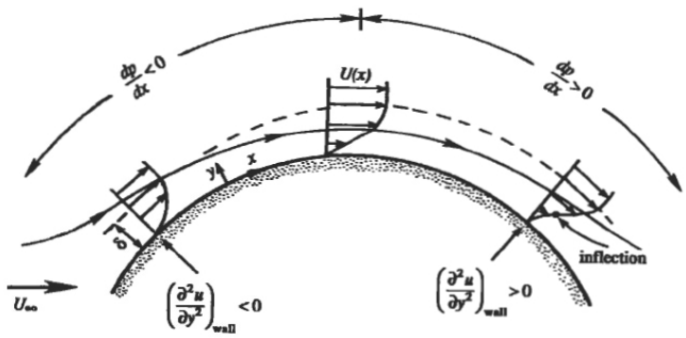


Figure 3: Flow Past a Cylinder [7]

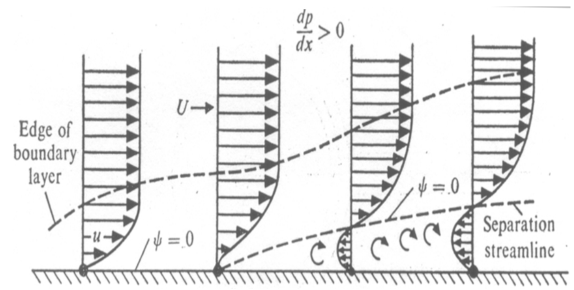


Figure 4: Flow Separation [7]

in Figure 3, this motion is clockwise. However, an equivalent effect on the lower half of the cylinder produces counterclockwise motion. In this way, the cylinder induces vortices with opposite rotation directions at two locations on its leeward side.

4.2 Kármán Vortex Streets

Given appropriate flow conditions, the aforementioned leeward vortices will grow in size until they are shed alternatively from the cylinder and travel downstream in the bulk fluid. This alternative shedding is a function of Reynolds number dependent wake instability (Hopf bifurcation) that is beyond the scope of this paper, however, it results in the characteristic Kármán vortex street [3]. Well defined laminar flow vortex streets are formed where $40 \lesssim \text{Re} \lesssim 160$ [1]. Given the minimum flow velocity restriction imposed by the flume, this drove the desire for $\text{Re} \approx 150$ from Section 2.2.

Because Kármán vortex streets are periodic, they are frequently described by the dimensionless Strouhal number which characterizes flow mechanisms with oscillatory behavior. Given parameters of the project setup, the Strouhal number, St, appropriate for the vortex street pictured on the title page is:

$$\text{St} = \frac{fL}{U} = \frac{(\frac{1.5}{\text{s}})(0.0045\text{m})}{0.045\frac{\text{m}}{\text{s}}} = 0.15 \qquad \text{where} \quad \begin{array}{l} f \text{ is vortex shedding frequency} \\ L \text{ is characteristic length} \\ U \text{ is flow velocity} \end{array}$$

This falls into a 'intermediate' range of Strouhal numbers commonly defined between $10^{-4} \lesssim \text{St} \lesssim 1$ which is characterized by oscillatory shedding of vortices [1].

5 Conclusion

It was hoped that this project could produce and image well formed Kármán vortex streets that closely resembled the 2D theoretical behavior of flow past a cylinder at appropriate Reynolds numbers. It quickly became clear, however, that doing so takes incredible environmental control to eliminate even the slightest turbulence, flow perturbation, viscous effects of the flow visualization technique, etc. This control was not achievable in the available flume and it shows in the raw image. Nevertheless, the resultant post-processed photo reasonably depicts the dynamics of fluid flow past a bluff body and does so in an aesthetically pleasing manner.

References

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