TFES Lab (ME EN 4650)
Flow Visualization

Textbook Reference: pp. 23–29 & 38–44 from Pritchard, 8th ed., pp. 129–139 from Cengel and Cimbala, 3rd ed., and list of terminology (on the last page of this handout)

Objectives

(i) Use dye injection and digital photography equipment to visualize the fluid flow around a variety of objects at different Reynolds numbers.

(ii) Describe fluid flow phenomena observed during the visualization using the correct scientific terminology.

Background

Most flow fields important to engineering applications are complex; many times being both three dimensional and unsteady. Flow visualization techniques often reveal spatial and temporal features of the flow, which are difficult to discern from single point measurements. For this reason, flow visualization experiments often represent an important first step when studying a new flow field of interest.

Dye injection is a relatively easy flow visualization technique that involves marking fluid particles through the addition of a visible dye. In the lab, we will use a non-toxic, non-staining, and biodegradable water tracing dye. The dye may be introduced into the water channel in two ways: using a dye injection needle or through a port in the object of interest. In the former, a thin rigid L-shaped tube is positioned upstream of the object of interest, with

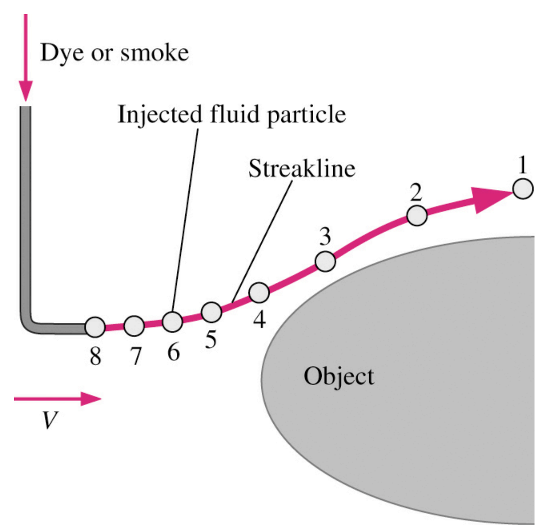

Figure 1. Illustration of a streakline with eight fluid particles marked. Particle 1 was the first particle to be injected into the flow, followed by particle 2, and so on.

Figure 2. Three snapshots of the streaklines around an object. The flow is from left to right.

the dye being feed through the top of the tube using flexible tubing connected to an elevated dye reservoir. One problem with this method is that the dye injection needle can cause some flow disturbance that interferes with the flow around the object of interest. In the lab, we also have several objects with custom-made ports to allow the dye to be released through a small hole on the surface of the object. This method of dye injection is preferred as it avoids potential flow disturbance due to the release mechanism. In either case, the dye lines released into the flow represent *streaklines*. Figure 1 shows a drawing of such a streakline. Each of the eight fluid particles marked originated from the tip of the dye injection needle, with particle 1 being injected first, and so on. Note, the streakline does not necessarily trace out the trajectory of any single particle (this is only true for steady flow), but represents the collection of fluid particles that passed through the tip of the dye injection needle at some earlier time. A sequence of snapshots showing the time evolution of dye injected around a thin object is given in Figure 2.

In the present experiments, a dye injection based flow visualization technique is used to explore the flow of water past three types of geometric bodies: (i) sphere, (ii) long flat plate, and (iii) short flat plate. In every case, at least two different flow speeds will be run to observe the effects of changing Reynolds number. The Reynolds number is an important nondimensional number defined by the following group of parameters: $Re = U\,L/\nu$, where U and L are characteristic velocity and length scales in the flow and ν represents the kinematic viscosity of the fluid. In this case, U represents the flow speed, and L represents the size of the object. The Reynolds number is important in fluid mechanics because, in nearly all flow fields, a critical Reynolds number exists whereby the flow transitions from laminar to turbulent behavior.

Several limitations of the dye injection flow visualization technique are described below.

1. Buoyancy effect: The water tracing dye used in the experiments is nearly neutrally buoyant in water, meaning that it does not tend to sink or float when the flow is suppressed. This is important, because otherwise gravitational forces on the dye may lead to anomalous flow patterns, especially at slower flow speeds. For example, a heavier dye will appear to move downward due to gravity, even though there may not be an actual downward velocity component in the flow.
2. Visual Contrast: When illuminated by flood lightening against a white background, the dye provides good photographic contrast and does not diffuse too quickly (i.e.,

the edges of the dye line remain relatively sharp for some distance downstream of the injection point). However, this also depends on the flow speed. At higher flow speeds, the dye tends to mix quickly with the water rendering the flow visualization ineffective.

3. Flow disturbance: Because the dye injection needle is physically intrusive, the dye injection needle represents a physical flow disturbance. Both the size of the needle and its orientation with respect to the mean flow direction may affect the flow around the object of interest. If the needle is not oriented parallel to the mean flow direction, then the wake behind the needle will interfere with the upstream approach flow.

4. Isokinetic dye release: If the dye is not released isokinetically with respect to the mean approach flow, then the momentum of the dye will disturb the flow as well. The dye may be released slower than isokinetic without causing any disturbance. In this case, the flow merely "picks" up the dye and carries it along. However, the concentration of the dye may not be enough to give sufficient contrast. The optimal condition is one in which the dye is released just slow enough to ensure adequate contrast to visually detect the flow phenomena of interest, but not faster than the approach flow speed.

Laboratory Procedure

Experiments will be conduced in the water channel located in the TFES Lab (MEB 1156). Figure 3 shows a photograph of the facility. The water channel has a total capacity of 40 gallons, and a test section measuring 6 in. × 6 in. × 18 in. A 0.5 HP pump with a frequency controller is used to adjust the flow rate through the test section. Figure 4 provides the calibration curve that relates frequency of the controller in Hz to average flow speed through the test section in cm/s. The range of achievable flow speeds is about 5 – 55 cm/s.

Table 1 lists the matrix of experiments that will be performed. Under the column labeled Flow Speed, the corresponding pump frequency is given in parenthesis. For each experiment,

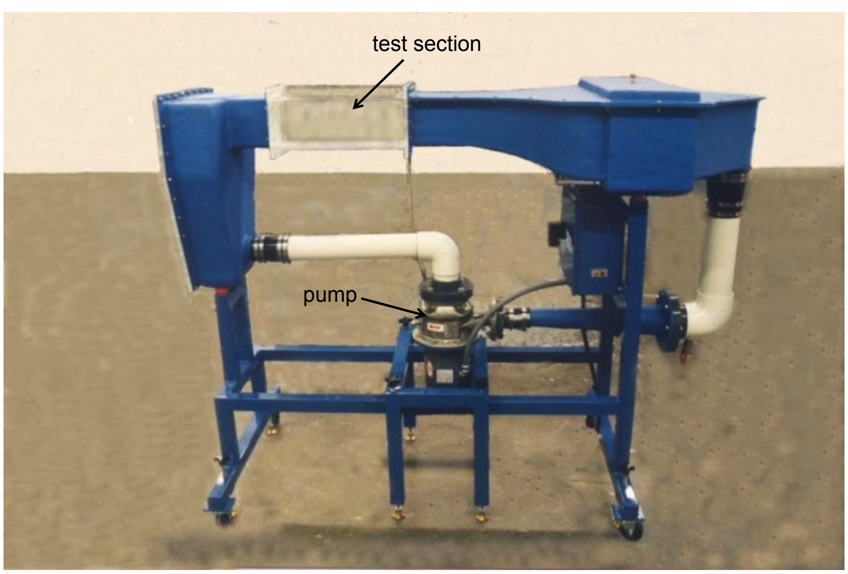

Figure 3. Photograph of the water channel used in the flow visualization experiments.

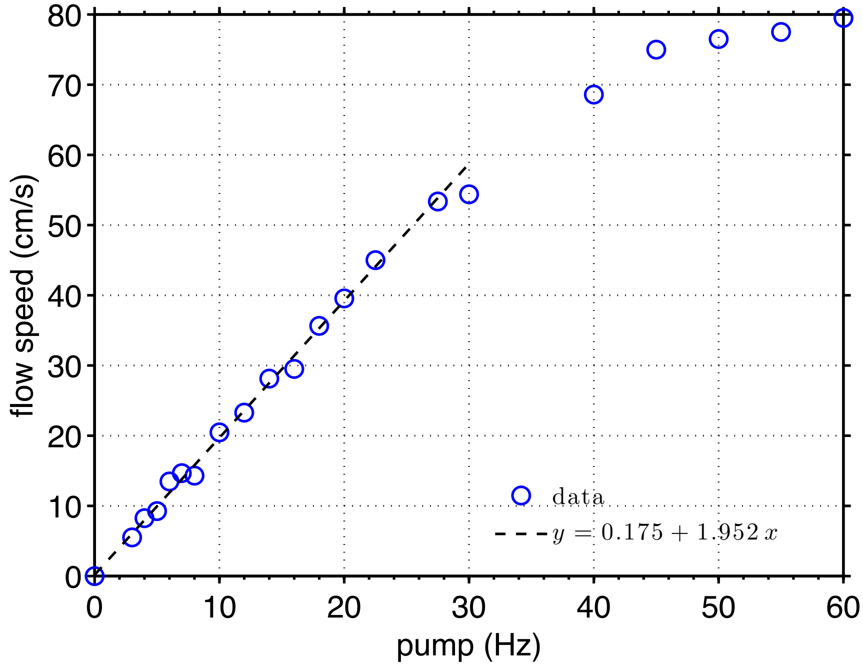

Figure 4. Calibration curve for the water channel facility relating average flow speed through the test section to pump frequency.

a short image sequence of the dye streaklines will be recorded with the provided digital camera. The lab TAs will facilitate the acquisition of these image sequences. Once the desired experiment is properly setup, the provided Nikon D810 digital camera will be used to record the fluid flow phenomena of interest. For the specific cases in bold type listed in Table 1, the student is expected to submit annotated figures (taken from the image sequences) that illustrate important flow features using the proper fluid mechanics terminology, as described in further detail below.

Table 1. Matrix of flow visualization experiments. Students are required to submit annotated figures of their snapshots for the experiments in bold type.

Object	Flow Speed	Observed Phenomena
Cylinder	**low (4 Hz)**	**separation, wake**
Cylinder	medium (8-15 Hz)	separation, wake
Long flat plate	low (4 Hz)	laminar boundary layer
Long flat plate	**medium (8.5 Hz)**	**transitional boundary layer**
Long flat plate	high (12 Hz)	turbulent boundary layer
Airfoil (0°)	medium (8–15 Hz)	laminar flow, wake
Airfoil (4°)	medium (8–15 Hz)	separation, recirculation, wake
Airfoil (8°)	**medium (8–15 Hz)**	**recirculation, vortex shedding**
Airfoil ($> 8^\circ$)	medium (8–15 Hz)	separation, wake, stall
Other shape of interest	**5–20 Hz**	**depends on shape and flow speed**

The camera's user's manual will be available in the lab and can also be downloaded from the course website. To capture image sequences, we will set the Camera Release Mode to Continuous High Speed (Nikon D180 User's Manual pages 102–104). The camera is switched to Continuous High Speed Mode by rotating the Mode Dial (top right side of camera) to the CH setting. In the CH mode, the camera will take up to 100 images at 5 frames per second with an image resolution of 5520×3680 pixels (FX format). To take an image sequence fully depress the shutter release button. A single snapshot can be taken by depressing the shutter release button quickly.

In addition, we will use Manual Focus (see page 100 in the Nikon D180 User's Manual), rather than the autofocus settings. Set the Camera Focus-Model selector to M on BOTH the camera AND the lens. The default settings should be sufficient during the lab; however, you can change these settings using the Menu button. To do a quick review of the images that you capture, press the playback button on the back of the camera (a small button with an arrow on it just above the Multi Selector. Following the lab section, the image files for each section will be uploaded to the class CANVAS webpage for Ubox for downloading. A description of each of the test cases listed in Table 1 is provided below.

1. Cylinder

   (a) Slow Flow Speed: Set the pump frequency to 4 Hz. The dye release point for the object should be located at the *stagnation point* at the front of the cylinder. This is the point on the front of the object where the fluid velocity approaches zero and the pressure reaches a maximum. Due to the low velocity in this region, a low dye release rate will be needed to ensure that the dye does not affect the flow field. You should be able to observe the dye 'wrapping' around the cylinder and 'sticking' to its surface. This is caused by the *no-slip* condition at the cylinder's surface and causes the backside of the cylinder, in particular, to appear pink. On the digital camera, this region will be denoted by a darkened *separation line* where the dye tends to accumulate. Downstream of this point, the flow separates and a *wake* forms. *What does the streakline formed by the dye represent in the region prior to separation? ANS: Streamline and pathline since the flow is steady in this region.* You should be able to observe the size of the *wake* region and the frequency of *vortex shedding*. Capture at least one image sequence of this flow from which you can identify the time evolution of the aforementioned flow features. Position the camera so that the entire object and enough of the *wake* region is in the field of view to allow you to identify the main flow features.

   (b) High Flow Speed: *Why is wake size important? ANS: Drag.* As the flow in the *boundary layer* along the cylinder becomes *turbulent*, the *separation* point should move aft along the sphere, thereby decreasing the wake region and thus the overall drag on the cylinder. Record an image sequence of the flow at "high" flow speed.

2. Long Flat Plate

   (a) Slow Flow Speed: At a pump frequency of about 4 Hz, the flow along the plate will be *laminar*. Place the dye injection needle at the tip of the leading edge so that dye is injected directly into the boundary layer region near the surface of the plate. Carefully adjust the release rate so that you are not disturbing the flow with the momentum of the dye. Note, close to the surface of the plate, the flow speed is very small; therefore in order to obtain an isokinetic release, you will need to turn the dye release rate down quite a bit. You should NOT see any "wiggling" of the dye streak. Observe the *boundary layer* that exists close to the plate, the *no-slip condition* and how the dye "sticks" to the plate, as well as the *laminar* and *steady* nature of the flow. Take an image sequence that illustrates this laminar boundary layer flow. Make sure the camera is positioned to capture a sufficient length of the plate (at least half).

(b) <u>Medium Flow Speed</u>: At a pump frequency of around 8.5 Hz, you can see the *transition* to turbulence about half way down the plate. The *Reynolds number* (which is directly related to flow speed in this experiment) represents an important parameter in fluid mechanics for characterizing whether a flow field will be laminar or turbulent. As you increase the flow speed, you are effectively increasing the Reynolds number. Position the camera to capture the transition region and take an image sequence of this phenomenon. You can get a better idea of the phenomenon if you view the flow from the top by standing on a step-stool and looking down on the flow, or by looking up from underneath the test section.

(c) <u>High Flow Speed</u>: As you increase the flow speed, the Reynolds number will reach a critical value whereby the flow becomes fully turbulent. At about a pump frequency of 12 Hz, the *boundary layer* will be fully *turbulent*, *three-dimensional*, and *unsteady*. Using the camera, capture images of the *turbulent boundary layer*. You may want to use the camera on your phone to capture an image from the top looking down, as you can really see the thickening of the turbulent boundary layer better from a top view.

3. Airfoil

(a) <u>8° angle of attack</u>: Set the pump frequency to a medium flow speed, in the range 8-15 Hz, and rotate the airfoil to a position near 8° angle of attack. You will see very nice examples of a recirculation region on the upper surface of the airfoil and *laminar* vortex street behind the tail. In terms of the former, the flow is observed to separate near the nose of the airfoil and flow back upstream. Observe whether the flow in the recirculation region *reattaches* to the upper surface of the airfoil before leaving the trailing edge.

Downstream of the tail, you can observe how the dye streak curls up into tight swirls that get advected downstream. Although the flow in the wake region is laminar and well-ordered, because of the periodicity, it is still characterized as *unsteady*. One could measure a vortex shedding frequency by inspection. *How does the dye behave far downstream of the plate? ANS: Eventually dye stops swirling and just gets advected.* Students need to be careful here in interpreting the flow visualization images. Although the dye may be kinked in the far field behind the airfoil, it is simply being advected downstream. This happens because the dye rapidly forms into a vortex structure in the wake region, but the dye does not diffuse as rapidly as the water (diffusion coefficient of the dye is much higher than the water.) In a sense, the dye becomes "fossilized", so that in the far field, it simply represents structures that did exist at one time upstream. The important thing to observe is the change in the streakline as it moves downstream and not the shape of the dye streakline at any given instant, especially far downstream of the object. Record an image sequence of the *laminar* vortex street behind the plate. Position the camera so that the entire airfoil is captured, along with at least a few wake vortices downstream of the tail. Take several snapshots of the flow in this position.

(b) <ins>$<8^\circ$ angle of attack</ins>: Keep the flow rate fixed and tilt the airfoil to shallower angles of attack. Take several snapshots of the dye streak at angles of attack of 4° and 0°. The dye streaklines should appear *laminar*. You should also be able to visualize the *no-slip condition* on both the top and bottom surfaces of the airfoil. Note, since the airfoil is symmetric, we do not expect any lift to be generated at an angle of attack of 0°. Observe whether the behavior of the dye streakline appears to be consistent with this expectation.

(c) <ins>$>8^\circ$ angle of attack</ins>: Rotate the airfoil to an angle of attack larger than 8°. By visual inspection of the dye streakline, try to find the angle of attack at which *stall* happens. Stall occurs when the flow completely *separates* from the entire upper surface of the airfoil, and is coincident with a dramatic increase in the drag force. Stall is experienced when the airfoil is rotated beyond its critical angle of attack, defined as the angle of attack at which maximum lift is generated by the airfoil. In a stall position, try to observe whether there are vortices above the upper surface of the airfoil, and whether these vortices appear to be stationary or are shed at some frequency downstream.

(d) <ins>High Flow Speed</ins>: If time permits, rotate the airfoil back to an angle of attack near 8°, and try both decreasing and increasing the flow speed. If the Reynolds number is low enough, the flow will *reattach* to the upper surface before leaving the trailing edge. As you increase the Reynolds number, the vortex street becomes *turbulent* and less ordered. A distinct *vortex shedding* frequency is still observable. *How does the shedding frequency change with Reynolds number? ANS: Appears to increase.*

4. Other object of interest — select one or more of the objects below and investigate the flow around the object at several different flow speeds. Document the fluid phenomenon observed at one of the flow speeds by using the camera equipment to capture a sequence of images. Be sure to write down the flow rate corresponding to the images that are captured.

→ <ins>Sphere</ins>: Flow around a sphere is similar to that of a cylinder, except there are inherent three-dimensional effects. In particular, the vortices shed from a sphere will be ring-shaped, rather than planar rollers as in the case of a cylinder. You should be able to visualize the separation phenomenon and wake region in flow around a sphere, analogous to the case of the cylinder.

→ <ins>Surface Mounted Cylinder</ins>: Insert a cylinder into the flow such that one end rests on the flat plate or the side wall of the channel, with the axis extending perpendicular from the plate (use the provided L-shaped rod). There is a *horseshoe vortex* that forms around the cylinder. This vortex structure carries fluid away from the vicinity of the base of the cylinder, as evidence by the lack of dye in that region. This phenomena is similar to the deposition of snow around tree trunks and other such behavior observed in nature. Note, you will need to use the separate dye-injection needle with this object and inject the dye upstream.

→ Hemisphere: Flow around a hemispherical cup is both similar and different from that around a sphere. In the case of a hemispherical cup, a boundary layer develops along the front face of the hemisphere, but then abruptly separates at the trailing edge.

→ Rectangular Rod: A rectangular rod has blunt edges that will cause the flow to separate at the corners at a high enough flow speed. This fixes the wake size. Hence, the drag coefficient of flow over a rectangular rod is expected to be constant for high enough Reynolds numbers (typically above 10^3). It is interesting to observe how the flow field varies from very low speeds (for Reynolds numbers near unity) to higher speeds.

→ Circular Disc: Flow around a circular disc will be similar to that of the rectangular rod, except with three-dimensional effects. At low enough Reynolds number (flow speeds), the streamlines/steaklines should bend around the object, since the flow will remain attached. However, at high flow speeds, the flow will tend to separate at the sharp edges of the disc, similar for the rectangular rod.

→ Golf Ball: Flow around the golf ball is interesting because the dimples tend to "trip" the boundary layer that forms around the front face of the ball to a turbulent state at high enough Reynolds number. This causes the *separation point* to be pushed further toward the back of the ball, which causes the size of the wake to decrease. This effectively decreases the drag coefficient allowing the ball to travel farther down the fairway for any given swing. Try to observe the phenomenon of the decrease in wake size as the Reynolds number (i.e., flow speed) is increased from a small value to a larger value. Take several snapshots of the flow in the different regimes (low Re where the wake is large, and high Re where the wake is smaller). Note, you will need to use the separate dye-injection needle with this object and inject the dye upstream.

→ Other: Students may work with the instructor to design and 3D print an object of personal interest that may be investigated in the water channel. Importantly, the object must be sized small enough such that the frontal area of this object (i.e., the area projected onto a plane perpendicular to the mean flow direction) is less than 10% of the cross-sectional area of the test section, which measures 36 in^2 or 232.3 cm^2. According to literature in the field, the frontal area of the object should ideally remain less than about 4% of the cross-sectional area of the test section, in order to minimize flow interference with the channel sidewalls and thus more accurately represent the flow expected in an infinite domain. This strict limitation is relaxed somewhat in the current experiment to facilitate 3D printing custom objects.

Required Figures

Importantly, you will need to edit your flow visualization images (e.g. in Powerpoint, Adobe Photoshop, Xfig, Gimp, or some other program) to crop out extraneous area in the image, highlight only the flow features of interest, and add arrows with annotations as needed. In addition, state the corresponding Reynolds number for each of the images. An example of an annotated sequence of snapshots is shown in Figure 5.

1a. Cylinder at low speed (1 snapshot). This figure needs to include annotation of the relevant fluids phenomenon along with the Reynolds number based on the cylinder diameter.

1b. Cylinder at medium speed (multiple snapshots). This figure needs to include a sequence of snapshots taken at different times, up to four images. No annotation is required.

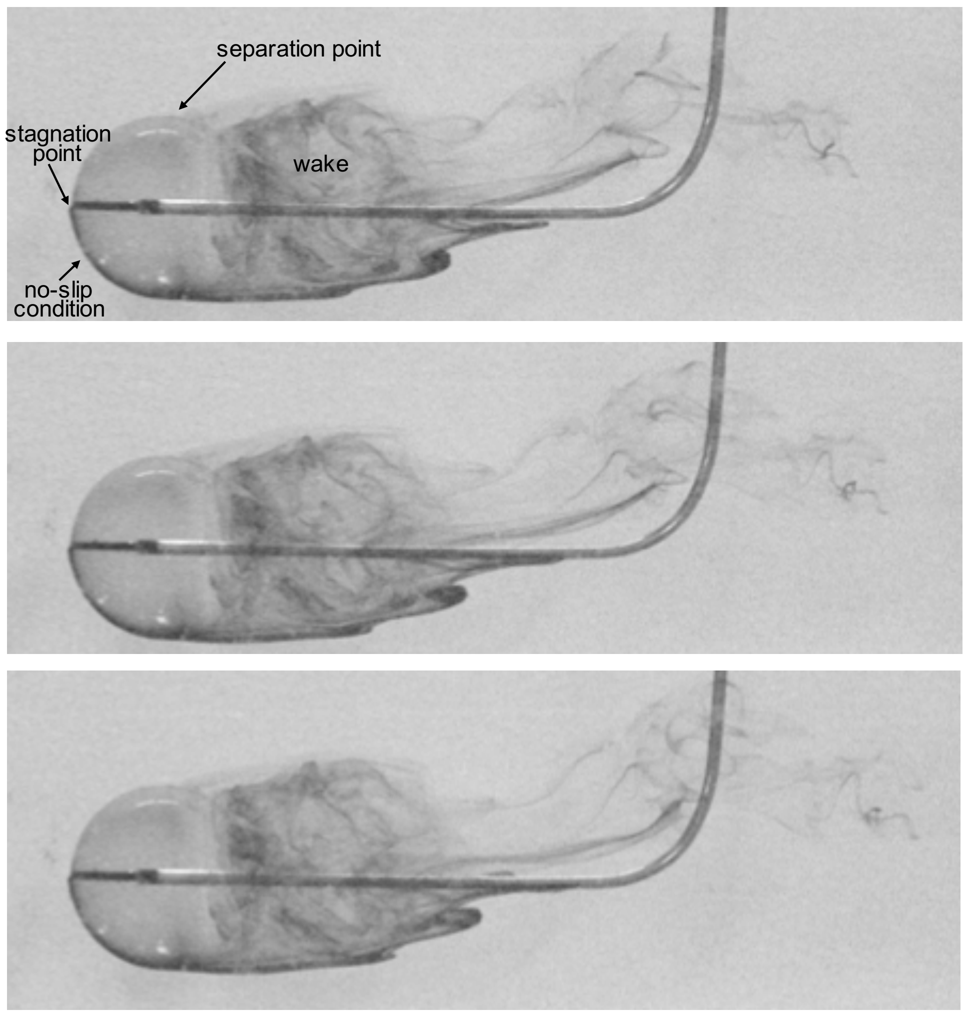

Figure 5. Streaklines around a sphere at a Reynolds number based on diameter of Re_D = 2800. A sequence of three snapshots are shown with a time of 91 ms between each snapshot. Flow is from left to right. The streaklines are marked by neutrally-buoyant dye injected from the stagnation point at the front of the sphere.

1c. Long flat plate at medium speed (1 snapshot). This figure needs to include annotation of the laminar flow region and transition region, along with the Reynolds number of the flow at the location at which transition appears to occur. Remember that the Reynolds number for a flat plate is based on the distance x from the leading edge.

1d. Long flat plate at low and high speeds (2 snapshots). This figure needs to include two images, one for laminar boundary layer flow and one for turbulent boundary layer flow. No annotation is required.

1e. Airfoil at an angle of attack of 8° and medium speed (1 snapshot). This figure needs to include annotation of the relevant fluids phenomenon along with the Reynolds number based on the chord length.

1f. Airfoil at a range of angle of attacks and medium speed (3 snapshots). This figure needs to include images taken at the following approximate angles of attack: 0°, 4°, $>8^\circ$. No annotation is required.

1g. Other shape (1–3 snapshots). Multiple images may be included in this figure, if they convey the time-varying nature of the flow. However, annotation is only required in one of the images. Include the Reynolds number of the flow in the annotation.

Short-Answer Questions

2a. Write one paragraph (using appropriate fluids terminology) that describes the differences in flow phenomena observed between the low and high Reynolds number cases for the cylinder.

2b. Write one paragraph that discusses the limitations of the dye-injection technique you used in the lab. Suggest an alternative flow visualization technique that might provide better (or additional) information about the flow fields you examined. You will need to perform some research (using the internet or textbook) to answer this question. Include a citation for the reference used.

Fluid Flow Phenomena Terminology

1. no-slip condition: the fluid in contact with the solid boundary has the same velocity as the boundary itself. This condition arises due to molecular interaction between the fluid and the solid, i.e., the fluid molecules "stick" to the molecules of the solid surface and thereby get pulled along with the solid.
2. boundary layer: the region of flow near a solid surface where the velocity transitions from zero at the surface (if the surface is stationary) to the free stream velocity far from the surface. In the boundary layer region, viscous affects are NOT negligible.
3. flow separation: when the boundary layer along a solid surface detaches from the surface. When the flow separates, the shear stress at the surface is zero.
4. reattachment: when a previously separated flow reattaches to the surface of an object.
5. stagnation point: The point in a flow field were the velocity approaches zero and the pressure reaches a maximum value.
6. inviscid flow: flows in which viscous effects are negligible, i.e., the term containing viscosity in the governing dynamical equation is zero.
7. viscous flow: flows in which the effects of viscosity are important.
8. Eulerian description: viewing the flow through a control volume fixed in space. Fluid may across the control volume boundaries, but individual fluid particles are not tracked.
9. Lagrangian description: tracking the position and velocity of each fluid particle individually as they move in the flow.
10. pathline: the path or trajectory traced out by a single moving fluid particle. The line traced out by a moving fluid particle.
11. streakline: a line joining all the fluid particles that passed through a fixed point in the flow field at some previous time, e.g., a dye line.
12. streamline: lines in the flow field that are tangent to the velocity vector at every point along the line. As such, there can be no mass flux across streamlines.
13. steady flow: a condition where the velocity (and density, pressure, etc) may vary with position, but is constant in time at every point. The flow properties change with position in space, but remain constant in time. Pathlines, streaklines, and streamlines are identical in a steady flow field.
14. unsteady flow: flow properties change with time at any point in the flow field. Streamlines vary from instant to instant. Pathlines, streaklines, and streamlines do NOT necessarily coincide in an unsteady flow.
15. laminar flow: a smooth and ordered flow.
16. turbulent flow: a random, chaotic, three dimensional flow.
17. Reynolds number: an important nondimensional number defined by $Re = UL/\nu$, where U and L are characteristic velocity and length scales in the flow and ν represents the kinematic viscosity of the fluid. The magnitude of the Reynolds number determines whether a flow will be laminar or turbulent.
18. vortex shedding: a regular pattern of vortices that often occur with flow separation.
19. wake: the region of separated, low pressure flow behind an obstacle.