

FLUMES, FLOW VISUALIZATION, CYLINDERS AND *Re* BACKGROUND

The purpose of the laboratory this week is to gain understanding of the three states or stages of flow: laminar, transitional and turbulent. It is also our first try at flow visualization. No matter how simple or difficult the flow problem, visualization is usually a useful first step. It is foolish to jump in to start making detailed flow measurements at a point in the flow without knowing the general “geography” of the flow field or how it is changing with time. The average person is highly visual, and visualization builds intuition for how flows behave.

Flumes or flow tanks are designed to generate relatively simple flows that still have some relevance to nature. The flume that we are working with is designed to produce a fully developed, one-dimensional boundary layer by the time that the flow gets about 1.5 m from the inlet. Notice the general shape of the tank. The flow is much wider than it is deep. For the cylinder component of today’s lab, we want to stay clear of the bottom, because you already know about the no-slip condition, and that therefore there must be vertical velocity gradients in the flow tank. We also want to stay away from the “free surface” because of real or potential wave effects. Fortunately, the flow behaviors that you see will be dominated by the fastest part of the flow, so the vertical gradient in velocity will not do too much damage to your observations. But first, so you know what is happening in the flow, I need to digress on flow tank construction. Just as with drama and public speaking in general, the tricks and important parts are in the entrances and the exits. Recall that I defined Re for a steady, uniform oncoming flow, so that is what we would want for today’s exercise.

Entrance conditions

The first trick is to generate a constant volumetric rate of inflow [L^3T^{-1}]. It is not as easy as you might imagine. A motor can drive either an impeller or a propeller. Impellers produce high pressure but generally low volumes of flow. Propellers produce high volumes but low pressures. Neither is a good idea for producing a simple, steady flow, because both produce pulses that correspond with the rotation rates of their drive mechanisms. A better idea is a constant-head inflow tank. Water level at a constant height produces a steady driving force. The issue is how to get the water to adjust to the geometry of the tank quickly or how to make the geometry such that the flow adjusts quickly. The solution you see may not be obvious. It is to first spread the flow across the tank with a diffuser that produces many turbulent jets aimed upstream. A coarse mesh (fish net) is placed in front of the jets to add to the turbulence and subdivide the flows further. The underlying idea is to make it turbulent to eliminate any long-lived, large flow structures, and the turbulence takes care of going in all directions at once and helps send it to small scales. The flow collimator further strains out any remaining, large-scale flow structures. Imagine what the flow would do if we just stuck a pipe into the box at the head end, with its opening facing downstream.

Exit conditions

Exit conditions are also important in keeping the flow well behaved. The general idea is to keep the flow structure as constant as possible (directed downstream) as the flow approaches the exit. That means that the outflow needs to be distributed across the width and depth of the channel. The scheme that we have adopted is a set of ball valves. The valves should be adjusted so as to keep a plume of dye released at any point traveling as directly downstream as possible. Putting a dam across the exit to keep water at a fixed depth is a very bad idea. It forces streamlines far upstream of the dam to have an upward component in their trajectories, and it forces acceleration of the flow into the small cross-sectional area over the dam.

Flow visualization

You probably have a good intuitive feel for streamlines. More formally, streamlines are tangents to the local velocity vector. They generally are visualized as streaklines or particle paths that you can approximate by pipette and dye. A streakline is the collection of fluid parcels that pass a particular point. If you hold the pipette still and release dye steadily, you will visualize a streakline. If you release a small parcel or “spot” of dye rather than a steady stream, you will visualize the trajectory of a parcel of fluid. Fluid dynamicists call this trajectory of a fluid element a “particle path.” Please note this slightly strange name. It can get even more confusing because the flow can be visualized by suspended solid particles and time-lapse photography. Beware that the larger a solid particle is and the less well matched to the fluid density, the less accurately it will mimic the trajectory of a tiny fluid parcel. Make sure that you know the difference between a particle path, streakline and streamline.

If the flow is steady and laminar, streamlines, streaklines and particle paths are identical. If flow trajectories vary over time, however, the three do not need to coincide. Streaklines, streamlines or particle paths made at different times can cross one another. Instantaneous streamlines are defined whether the flow is steady (all time derivatives of velocity equal zero) or unsteady, but they are not in general the same as average streamlines in a flow that is unsteady (intermediate or turbulent flow regime).

Assignment

Today’s assignment is fairly simple, but it is so fundamental that I don’t want to dilute it by combining it with anything else. If you miss today’s ideas, you can stay lost in this class (or in fluid dynamics generally), for a long time. No flow is perfectly steady and uniform. At low body Re (and the length scale today is the cylinder radius), however, viscosity is strong enough to damp the perturbations. When viscosity and inertial forces are about equally matched, disturbances alternate between dying and growing, *i.e.*, become periodic in space and (or) time. At high body Re , you see a turbulent wake; the damping effect is too small to prevent the growth of perturbations. With extreme care to produce smooth surfaces and water free of particles, one can make the transitions in behavior occur at higher Re than they do under more normal conditions, supporting this idea that little perturbations grow to produce the unsteady behaviors.

Today, we will study cylinders in cross flow. The long axis of the cylinder is perpendicular to the flow direction. To keep things simple for now, keep your observations away from the flume bottom and at least 1 cm below the free surface (air-water interface). I will set the flume at two different flow velocities. Feel free to adjust the flow yourself once you know how, but don’t leave it running unattended at high velocity. Visualize flow around isolated cylinders of a range of sizes in each flow. Especially at the slowest flow velocities and smallest cylinder sizes, note the upstream-downstream symmetry in streamlines. Also make an effort to see how far to the side the object causes flow deflection. At the other extreme, make sure that you see some turbulence and convince yourself with dye that the flow is irregular, diffusive, vortical and 3D. In this style of flume, we have trouble getting a fully turbulent wake in a steady flow because it takes so much volumetric flow rate to produce the requisite velocity.

Focus on the following issues and address each in your essay for this week. Arrange your essay in a logical development rather than answering each question in series.

- Where near the cylinder is flow slower and faster than the oncoming flow and why?

- What flow structures and time variations in structures are seen as Re increases between laminar and fully turbulent flow?
- How do attachment and separation points (terms introduced below) change with Re ?
- Suggest advantages and disadvantages that might accrue to an organism (or organism with an appendage in) any or all of these three Re regimes or in the intermediate Re range of regimes.

You'll want a fairly detailed sketch from which to write and may want to include it with your essay. It is awfully hard to describe a flow from memory.

You'll get some additional, useful vocabulary this afternoon, but here is an early installment. On the upstream side of the cylinder at all Re , the flow goes around both sides of the cylinder, but what about the flow that is headed straight for the middle? Check by putting a spot of dye on the front. See how long it lasts relative to a spot on the side. Right on the centerline the flow stops. Actually, because there is a velocity gradient in the flume, there will likely be a vertical component to this flow, but concentrate on the downstream component. On a sphere, there is only one point where oncoming flow stops, called the stagnation point. It ought to be called a stagnation line on a cylinder, but it is (for historical reasons of looking down on cross sections of cylinders) still called a point, even though it is a string of points. A streamline that leads to a stagnation point has zero velocity and is thus called a stagnation streamline. A stagnation point is also an attachment point. Conceptually, that's where the flow attaches to the object, and a boundary layer starts to grow over it (more this PM). At low Re , the stagnation streamline comes right out the other side of the sphere or cylinder. At higher Re the flow tends to "separate" from some further upstream point on the sphere or cylinder for reasons that we will explore in detail in later labs and lectures. Locate a stagnation "point" by applying dye as you move the pipette across stream (y direction); it's where the dye switches from going around the cylinder in one direction to going around in the other.

The way to find an attachment point is to move the dye injection point from one side of it to the other. If the flow goes left on one side and right on the other, velocity must pass through zero somewhere in between. A very important determinant of drag on a body is where the flow separates. Locate a flow detachment or separation point by moving the dye source from one side to the other. The flow comes from the right on one side of the separation point and comes from the left on the other.