Flow Visualization in a Water Channel

Nomenclature

\[ A \]
projected frontal area (for the sphere) or planform area (for the airfoil)

\[ c \]
chord length of an airfoil or wing

\[ C_D \]
drag coefficient: \( C_D = \frac{2F_D}{\rho V^2} \)

\[ C_L \]
lift coefficient: \( C_L = \frac{2F_L}{\rho V^2} \)

\[ d \]
diameter of a cylinder, sphere, or other object

\[ F_D \]
drag force

\[ F_L \]
lift force

\[ g \]
gravitational constant (9.81 m/s²)

\[ h \]
head: elevation of a fluid column or height difference between two liquid columns

\[ P \]
static pressure

\[ Re_d \]
Reynolds number based on diameter \( d \): \( Re_d = \frac{Vd}{\nu} \)

\[ T \]
temperature

\[ V \]
mean freestream velocity in a pipe

\[ z \]
elevation in vertical direction

\[ \alpha \]
angle of attack of an airfoil

\[ \epsilon \]
average surface roughness height in a pipe or on the surface of a body

\[ \mu \]
coefficient of dynamic viscosity (also called simply the viscosity)

\[ \nu \]
coefficient of kinematic viscosity

\[ \rho \]
density of the fluid

Educational Objectives

1. Develop familiarity with operation of a small closed-loop water channel, a laser velocimetry system, and flow visualization by dye injection.
2. Visualize flow separation, and reinforce the concepts of Reynolds number, drag crisis, and the effect of surface roughness on a boundary layer.
3. Visualize flow over a model automobile, and examine whether the flow separates or not.
4. Visualize and reinforce the concept of airfoil stall.

Equipment

1. closed-loop water channel, built by Engineering Laboratory Design, Inc.
2. Dantec FlowLite fiber optic laser velocimeter (LV) system, with software and traversing system
3. IBM-compatible personal computer
4. spheres of various sizes, some with roughness, sting mounted from a top cover plate:
   - Golf ball \( d = 1.68 \) inches (rough)
   - Yellow-orange ball \( d = 2.83 \) inches (smooth)
   - Yellow-orange ball, roughened \( d = 2.83 \) inches (rough)
   - Baseball \( d = 2.84 \) inches (rough)

Note: These spheres are interchangeable with those used with the wind tunnel experiment. The threads on the sting mount are 1/4 - 20, just as in the wind tunnel.
5. Model car(s)
6. NACA 0012 airfoil, with 4.0 inch chord length and adjustable angle of attack, with attached tufts, mounted from a top cover plate
7. dye, dye reservoirs, dye injection needles, and backlight system (the dye is standard household food coloring, mixed in a ratio of one part concentrated food coloring to 10 parts water)
Background

This experiment complements the wind tunnel experiment in which the drag of a sphere in a freestream is investigated. In that experiment, the concept of “drag crisis” is observed. Specifically, at a Reynolds number (based on sphere diameter and freestream velocity, $Re = \frac{Vd}{\nu}$) somewhere between $2 \times 10^5$ and $3 \times 10^5$, the drag suddenly drops. This drag crisis is due to the sudden change from laminar boundary layer separation to turbulent boundary layer separation along the surface of the smooth sphere. Since a turbulent boundary layer is much more resistant to flow separation than is a laminar boundary layer, the turbulent boundary layer clings to the surface of the sphere much further downstream before separating. Thus, the wake is narrower and the pressure drag is greatly reduced, and so is the overall drag.

Oftentimes, especially in sports, roughness is intentionally added to the surface of a ball in order to “trip” the boundary layer to become turbulent, and hence to decrease the drag. This concept seems to be well-known, but what many people (including many ME 33 graduates!) do not realize is that surface roughness does not always induce a decrease in drag! If the Reynolds number is too low, the boundary layer cannot be tripped, and remains laminar in spite of the roughness. In Figure 1, taken from Reference 1, the effect of surface roughness $\varepsilon$ on drag coefficient $C_D$ is shown. Clearly, as roughness height increases, the Reynolds number at which the boundary layer changes from laminar to turbulent decreases. Flow disturbances due to the surface roughness cause premature transition of the boundary layer from laminar to turbulent, and the drag crisis is forced to occur at a lower Reynolds number. However, the Reynolds number must still be relatively high for the roughness to be effective, even for large values of $\varepsilon$. Note for example that at Reynolds numbers below about $4 \times 10^4$, the flow over a golf ball remains laminar (and the drag remains high) in spite of the severe surface roughness.

![Figure 1](image.png)

**Figure 1.** Effect of surface roughness on the drag coefficient of a sphere.

As mentioned above, the wake of a sphere at Reynolds numbers above the drag crisis is narrower than that of the sphere at pre-transition Reynolds numbers. This is illustrated in Figure 2.

![Figure 2](image.png)

**Figure 2.** Comparison of the wakes of a sphere with laminar and turbulent boundary layer separation.

Such a significant change in flow separation location and wake width should be easily identifiable with flow visualization. In this lab experiment, you will attempt to visualize this phenomenon by injecting dye streaks into the flow of water over a sphere.

In addition to the drag crisis on spheres, boundary layer flow separation is important in many other practical flow fields as well. One well-known example is the “stall” of an aircraft wing at high angles of attack. The purpose of an airfoil-shaped wing is to generate lift with as little drag as possible. When an airfoil is tilted to an angle of attack $\alpha$ of a few degrees, the fluid travels faster over the upper wing surface than over the lower surface. By Bernoulli’s principle, the pressure on the upper surface is therefore less than that on the lower; a lifting force with very little drag is the result. As angle of attack is
increased, the lift also increases. However, the adverse (i.e. increasing) pressure gradient on the upper surface becomes stronger and stronger, and soon the upper surface boundary layer can no longer remain attached. The boundary layer separates off the upper surface, usually at first near the trailing edge of the airfoil. The point of separation moves forward rapidly as angle of attack is further increased. At a certain angle (typically between 10 to 20°, depending on airfoil shape and Reynolds number), the flow separates completely from the upper surface, with the separation point occurring very near the leading edge of the airfoil. The airfoil is then said to be stalled. Further increases in angle of attack lead to a decrease in the lift. Not only does lift force decrease with stall, but the drag force increases significantly. Stall is therefore generally undesirable in aircraft flight, and has been the culprit of numerous airplane accidents.

Airfoils come in various shapes, both symmetric and nonsymmetric. Symmetric airfoils have zero lift at zero angle of attack, while nonsymmetric airfoils (those with camber) are designed to give some lift even at zero angle of attack. In this lab experiment you will visualize the flow over a NACA 0012 airfoil (a symmetric airfoil with 12% thickness-to-chord ratio) at various angles of attack and at various Reynolds numbers. The airfoil is equipped with tufts (short pieces of string attached to the airfoil surface). The tufts enable one to visualize the direction of flow just above the surface of the airfoil. At low angles of attack, the flow over the upper surface is in the downstream direction, and the tufts point downstream, towards the trailing edge. When stall occurs, however, the flow on the upper surface of the airfoil actually reverses direction, and the tufts show this effect clearly. Flow separation and stall should thus be observable in our water channel facility when the airfoil is at high angles of attack.

Just as in the case of the sphere, boundary layer separation off the surface of an airfoil is influenced by the nature of the boundary layer, i.e. whether it is laminar or turbulent. At low Reynolds numbers, the boundary layer remains laminar; flow separation and airfoil stall occur at relatively small angles of attack. In Figure 3, taken from Reference 4, lift coefficient $C_L$ is plotted as a function of angle of attack $\alpha$ for several values of Reynolds number. (Here $Re_c = Vc/\nu$.) Notice that at the lower values of Reynolds number, the airfoil stalls at approximately 10°, where the lift coefficient levels off at about 0.8. At higher values of Reynolds number, stall is delayed because the boundary layer is turbulent, and turbulent boundary layers are more resistant to flow separation. At $Re_c \approx 3 \times 10^6$, for example, stall does not occur until about 16 or 17 degrees, where the maximum lift coefficient reaches nearly 1.6, almost twice that of the low Reynolds number cases.

For the case of flow over a sphere, surface roughness was found to induce turbulence in the boundary layer, thereby delaying flow separation. A similar phenomenon can be observed on an airfoil. Namely, at low Reynolds numbers, addition of surface roughness at the front of an airfoil can delay airfoil stall to higher angles of attack. On some aircraft, “vortex generators” or other similar protrusions from the airfoil surface are used for exactly this purpose.

References