What type of fluid flow is observed?

The above pictures show how the effect of swirl on the flow around a sphere. The flow is from top to bottom. The picture on the left is for zero swirl and the flow is attached on the upstream hemisphere and separated downstream of the point of maximum thickness. A separation bubble is formed on the downstream hemisphere and this is a region of very slow reversed axial flow. When the swirl is increased a separation bubble appears on the upstream hemisphere which is shown in the middle picture. As the swirl is further increased this upstream separation bubble grows in length and becomes increasingly unsteady and finally developed into the unsteady spiral structure as shown in the picture on the right.

There are two kinds of fluid (liquids and gases) flow that are observed: *laminar* (streamline) flow and *turbulent* flow.
Particles of a continuous fluid can be considered to travel along smooth continuous paths which are given the name **streamlines**. These streamlines can be **curved** or **straight**, depending on the flow of the fluid. This type of motion is also called **laminar flow**.

This continuous substance can be regarded as being made up of bundles or tubes of streamlines (**flow tubes**). The tubes have elastic properties:

(a) A tensile strength which means that the parts of the fluid along a particular streamline stick together and do not separate from one another.
(b) Zero shear modulus, which means that each streamline moves independently of any other.

Streamline motion is not the only possible kind of fluid motion. When the motion becomes too violent, **eddies** and **vortices** occur. The motion becomes **turbulent**.

Turbulence is important because it is a means whereby energy gets dissipated. The shape of a body will, to some extent, decide whether it will move through a fluid in streamline or turbulent motion.
This is very important in aeronautical engineering. Air turbulence means increased fuel consumption in aircraft, and many cunning and intricate devices are used to reduce turbulence. Shapes of marine animals, flying birds, racing cars are important to avoid turbulent flow around them.

Transition from laminar to turbulent flow as the velocity of the water is increased by tilting a water tank.

Turbulent flow indicted by the swirls – eddies and vortices
LAMINAR (STREAMLINE) FLOW

The flow separates into "layers" that slide relative to one another without mixing. If we introduce a coloured stream into the laminar flow, the colour will stay in the stream. The flow is called steady.

Laminar flow can be represented by a set of lines known as streamlines (flow lines).
- An individual particle will follow a streamline.
- The flow pattern does not change with time. All particles starting on a streamline will continue to move on that streamline.
- A set of streamlines is called a flow tube.
- Streamlines can't cross nor intersect the "walls" of the flow tube.
- The instantaneous velocity of the particle is in the direction of the tangent to the streamline.
- Density of streamlines proportional to the velocity: streamlines close together ⇒ high velocity, streamline far apart ⇒ low velocity.
- For an ideal fluid, no kinetic energy of the particles is lost.

Velocity profile for the laminar flow of a non viscous liquid

TURBULENT FLOW

A vigorous mixing (stirring) of the fluid occurs. A complex flow pattern changes continuously with time. The velocity of the particles at each given point various chaotically with time. The erratic motion of the fluid often shows small whirlpool-like
circles called eddies (eddy currents) or vortices. Eddies absorb a great deal of energy due their rotational kinetic energy. A coloured dye added to a stream will readily disperse.

- A transition from laminar flow to turbulent flow occurs very suddenly as the flow rate increases. The flow becomes unstable at some critical speed.
- Turbulent flow occurs when there are abrupt changes in boundary surfaces. The flow of blood through a normal artery is laminar. However, when irregularities occur the flow becomes turbulent. The noise generated by the turbulent flow can be heard with a stethoscope.
- When the flow becomes turbulent there is a dramatic decrease in the volume flow rate.
- When a fluid flows around an object the shape of the object is a very important parameter in determining the type of flow.

What factors determine whether a fluid will flow in laminar or turbulent motion?

**REYNOLDS NUMBER**

A British scientist Osborne Reynolds (1842 – 1912) established that the nature of the flow depends upon a dimensionless quantity, which is now called the Reynolds number $R_e$.

$$Re = \frac{\rho v L}{\eta}$$

- $\rho$ density of fluid
- $v$ average flow velocity over the cross section of the pipe
- $L$ dimension characterising a cross section

$R_e$ is not a precise physical quantity. The quantities $L$ and $v$ are only typical values of size and speed. It is often not possible even to say which length you are talking about. For a body moving through a fluid it might be either length or breadth or thickness - or any other dimension you might
think of. For a fluid flowing through a channel or a tube, it turns out to be the diameter of the tube.

- How easily the fluid becomes turbulent is related to its viscosity \( \eta \) and density \( \rho \).

- \( R_e \) is a dimensionless number
  \[
  R_e = \frac{\rho v L}{\eta}
  \]
  \( [Re] = [\text{kg.m}^{-3}][\text{m.s}^{-1}][\text{m}][\text{Pa.s}^{-1}] = [\text{kg}][\text{m}^{-1}][\text{s}^{-1}][\text{kg.m.s}^{-2}.\text{m}^{-2}.\text{s}]^{-1} = [1] \)

- As a rule of thumb \( R_e < \sim 2000 \) laminar flow and \( R_e > \sim 2000 \) turbulent flow. \( 2000 < R_e < 3000 \) flow is unstable – may change from laminar to turbulent or vice versa.

- The Reynolds number also indicates whether the flow around an obstacle such as a ship’s hull or an aeroplane wing will be turbulent or laminar. In general, the Reynolds number at which turbulence sets in depends significantly on the shape of the obstacle and is not given by the formula for Reynolds number above and the condition above.

Here are some flow systems with their Reynolds Number

- A Sydney Harbour ferry
  Assume ferries travel at a speed \( \sim 5 \text{ m.s}^{-1} \) and are about 20 m in length.
  \[
  R \sim (5)(20)(10^3) / (10^{-3}) \sim 10^8
  \]
  It would be almost impossible to keep the flow streamlined and so there is considerable energy loss through turbulence.

- Household plumbing pipes
  Typical household pipes are about 30 mm in diameter and water flows at about 10 m.s\(^{-1}\).
  \[
  R \sim (10)(30\times10^{-3})(10^3) / (10^{-3}) \sim 3\times10^5
  \]
  In this example it would be almost impossible to keep the flow
streamlined and so energy loss through turbulence must be a serious consideration. However due to the interplay between \( L \) and \( v \) it is easier and more desirable to obtain streamline flow in the main pipes.

- **The circulatory system**
  
  Speed of blood \( v \sim 0.2 \text{ m.s}^{-1} \)
  
  Diameter of the largest blood vessel, the aorta \( L \sim 10 \text{ mm} \)
  
  Viscosity of blood probably \( \eta \sim 10^{-3} \text{ Pa.s} \) (assume same as water)

  \[
  R \sim (0.2)(10 \times 10^{-3})(10^3) / 10^{-3} \sim 2 \times 10^3
  \]

  It is impossible to tell. In fact the tubes are of good enough geometrical structure that turbulence very rarely occurs, and so the heart is not called upon to supply energy that is dissipated through turbulence. In turbulent flow, some energy is dissipated as thermal and sound. The noise associated with turbulent flow in arteries facilitates blood pressure measurements and makes it possible to detect some heart abnormalities.

- **Spermatozoa swimming**
  
  Typically length \( L \sim 10 \mu \text{m} \)
  
  typical speeds \( v \sim 10^{-5} \text{ m.s}^{-1} \)
  
  viscosity \( \eta \sim 10^{-3} \text{ Pa.s} \)

  \[
  R \sim (10^{-5})(10)(10^{-6})(10^3) / 10^{-3} \sim 10^{-4}
  \]

  Flow is streamlined.

**REYNOLDS NUMBER AND ENERGY DISSIPATION**

Poiseuille's Law shows that viscosity is responsible for loss of pressure - and hence is an energy dissipating phenomenon. We are not talking about energy loss due to turbulence, but about energy loss which occurs even when the flow is streamlined. It comes about through friction between the streamlines moving past one another.
The criterion whether or not much energy is lost in this way, is therefore whether or not there is much of a velocity gradient throughout the whole of the liquid. Since most of this gradient occurs near a boundary (in the so called **Boundary layer**, it is the ratio of the size of the system to the size of the boundary layer which is important.

So now we can appreciate another reason why the Reynolds number is important. Viscous effects can never be neglected (i.e. the energy dissipated is appreciable) in low Reynolds number situations: in thick liquids ($\eta$ large), or in small slow flow systems. On the other hand viscous effects will not be important in thin liquids or in large, fast flow systems. (However in these latter systems remember that turbulence is always possible, and energy can be lost through that means.)

In general then, flow patterns will be different in systems with low and with high Reynolds numbers. In particular, in very low Reynolds number systems, the flow is perfectly **reversible** since no turbulent effects can occur anywhere.

- The method of swimming is quite different for 
  Fishes ($R \sim 10\ 000$) and spermatozoa ($R \sim 0.0001$).

- Modes of boat propulsion which work in thin liquids (water) will not work in thick liquids (glycerine).

- It is possible to stir glycerine up, and then **unstir** it completely. You cannot do this with water.
If you were designing a circulatory system for the human body, where a prime requirement is that as little energy as possible should be dissipated, in order not to require the heart to pump any harder than absolutely necessary, what Reynolds number would you aim for? Compare this with the Reynolds number for blood, which is somewhere between 1000 and 2000.

**Home activity**

Turn on a water tap such that the flow is smooth and glassy. This is streamline flow. Increase the flow rate and observe as the flow becomes turbulent, rough and ropey. See if you can identify a flow where water leaves the tap in streamline flow but transits to turbulent flow before hitting the sink.