Laboratory experiments

Some questions

What are laboratory experiments?
Why do we do laboratory experiments?
How do we do laboratory experiments?

Safety

Laboratories are potentially dangerous places and the Departmental and UMIST safety policies must be observed. Risk assessments have been carried out for the laboratory as a whole and for the individual experiments, and these are posted in the laboratory. These risk assessments identify the main hazards involved and you should read them before you begin your experiments.

Experimental design

Where an experiment is used as part of a scientific investigation, the aim is to construct an experiment that isolates the phenomenon under investigation. This generally results in an experimental design that is as simple as possible, excluding as many extraneous parameters as possible. This is also true of the experiments used in this course to illustrate the basic features of fluid flows. The experiments will largely be prescribed but you will have some decisions to make in terms of setting some flow parameters (e.g. flow rate) and in terms of what to measure and how many measurements to make. In some cases experiments are conducted in order to simulate a fluid flow (especially around a proposed machine or building), in which case the accuracy of the simulation is an important consideration in the experimental design.

Recording observations

Laboratory notebook

Having gone to the trouble of making an experiment, it is essential that you record what happens. A vital tool is the **laboratory notebook**, traditionally hardbound.

- It is sensible to put your name and contact details at the front of the notebook, so there's a chance it might be returned if lost.
- Give each experiment a title and remember to put the date. Begin with a short description of the experiment. A sketch of the apparatus with important dimensions is always useful.
- You should make notes directly into the handbook during the experiment (you can make further notes/calculations later, but you should date these).
- Note down all the information you can at the time: it's always much harder to find out important details later.
- A useful test of whether you've put down enough information is to ask the question "if I look at this in a year or two's time will I be able to work out what I did?"

Qualitative descriptions

The information you record should include visual observations. These can be just as important (often more important) than numerical measurements in interpreting fluid flows. Don't leave things out just because you can't understand or explain them: these are often the most interesting features.

Quantitative measurements

Record numerical measurements to as many figures as you can. You can decide later what the appropriate level of accuracy is in giving your results, but if you've only recorded measurements to the nearest centimetre instead of millimetre then you can never recover the information. In general you should try to read to 1/10th of most marked scales.

Reports

You will be expected to produce detailed reports on all your experiments. Your account should contain a reasonably detailed description of the experiment (at the level you might find in a research paper). Suggested format for the report is (though the precise number/arrangement of sections is up to you, and will depend on the experiment):

1) Introduction, including an outline of the fluid dynamics.
2) Apparatus/method: main features of apparatus (dimensions, etc), experimental techniques

3) Experiments: what experiments did you do? Ranges of parameters, etc
4) Results: basic experimental results (raw measurements), processed results (e.g. integrated, etc)
5) Discussion/conclusion: how do the laboratory results relate to the fluid dynamics?

Flow visualisation techniques

Streamlines, streaklines and particle paths: recap

Streamlines are lines which are everywhere parallel to the flow. They give a picture of the instantaneous flow field. **Steaklines** are lines made by a fixed source of tracer (e.g. dye, smoke, bubbles) released continuously into the flow. A **particle path** is the path traced out by a marked fluid element as it moves in the flow. Neutrally buoyant particles will follow the fluid flow to a good approximation. For steady flow, streamlines, streaklines and particle paths are all the same, but this is not true of unsteady flows.

Dyes and tracers

As well as releasing dye at a point, some region of the flow may be marked by mixing dye throughout the region. The dyed fluid can be used to estimate the flow and also to estimate mixing with undyed fluid. Other tracers of the flow (e.g. temperature, salinity) may also be monitored (e.g. by thermocouples and conductivity probes).

Shadowgraphs

This technique depends on variations in the refractive index of the fluid caused, for example, by changes in temperature, salinity or alcohol content. Light is shone through the fluid onto a translucent screen (e.g. tracing paper, frosted glass) to form an image. The variations in the refractive index focus and unfocus the light to give dark and light patches on the image.

Image processing

In addition to providing qualitative information about the flow, visualisation techniques are increasingly used to give quantitative information about the flow. Digitised images of the flow are captured on computers and processed to give information about concentrations (dye intensities) and velocities (various forms of particle-tracking). This allows us to get detailed information about all parts of the flow in a way which was hitherto only available in numerical models. For accurate simulation of high Reynolds number flows in complex geometries, laboratory experiments still have a very important role.

Flow visualization experiments

These are described in detail below. You will use a smoke tunnel (using streaklines formed by injecting smoke at fixed positions into an air flow) and a water channel (using particle paths by sprinkling the surface with a fine powder).

A range of bluff and streamlined bodies (cylinders, spheres, aerofoils, etc.) will be available for you to experiment with.

Visualisation experiments

Smoke tunnel (Experiment 1)

You will use a small smoke tunnel to visualise a range of different flows. Air is drawn upwards through a vertical duct by an adjustable fan at the top of the duct. The working section has a transparent side to allow you to view the flow, with lights either side. WARNING: The lights get hot! The transparent side is removable so that you can change the models in the flow. Two transparent sides are available, one completely clear and one with a set of vertical parallel lines which may help in recording the flow. The flow is visualised by injecting smoke through a set of outlets upstream of (i.e. below) the working section. The smoke outlets can be moved from side to side to adjust the streaklines that you are viewing. The smoke is generated by vapourising paraffin. The smoke supply should be clamped off, and then the fan turned off, before changing the model in the working section.

A range of models is available, including a cylinder, a sphere, an orifice and an aerofoil. The sphere has a "seam" running around a circumference, which may be opened up, and it may be mounted so that the seam can be tilted at different angles to the flow. The aerofoil can have smoke introduced at its leading edge.

There is no direct way of measuring the flow speed in this experiment but you can record the fan power setting. A plot of fan setting against flow speed is provided, but this should be treated as only a rough guide. Working in small groups you will have approximately one hour to use the apparatus. Particularly look for where flow separates from a body and where the flow is turbulent.

Water channel (Experiment 2)

A shallow water channel will allow you to look at a range of flows past various obstacles and make some more detailed measurements. The flow will be visualised by sprinkling the water surface with powder - please don't use too much! You can measure flow speeds by watching the motion of larger particles (e.g. scraps of paper) on the water surface (a very simple form of particle tracking). You will be provided with rulers and stopwatches. You may also have access to a video camera and recorder which will enable more accurate time measurements to be made. As well as single obstacles you can look at the flow past more than one obstacle to examine more complicated interactions.

Each group will have approximately two hours to use the equipment.

Report

Experiments 1 and 2 should be reported together in a single report. This could have separate sections for the two experiments or be arranged (for example) to treat flow past particular types of obstacle. The report should include sketches (approximately to scale) of the various flows you observe, with as much quantitative information as you can derive.

Introduction to fluid flows

Definitions

Fluid deforms continuously ("flows") under the action of a force (solids deform a finite amount). Gases and liquids are fluids. Gases are more compressible and their thermodynamic behaviour is easier to calculate (kinetic theory). The properties of liquids are generally more complex (especially water).

Continuum Real fluids are made up of discrete molecules but it is easier mathematically to treat the fluid as if it had a continuous structure. This allows us to attach a definite meaning to the notion of values and derivatives "at a point." In practice we mean an average over a volume small compared with the scales of the fluid flow but large compared with the molecular separation.

Density of a fluid is the mass per unit volume, usually denote by ρ, SI units: kg m^{-3}. The density may vary with position, though we often deal with fluids of **uniform** density (in which we can regard ρ as a constant).

Pressure is a scalar function of position and time, force per unit area, SI units: N m^{-2} or Pa.

$$p(\mathbf{x}, t)$$

Velocity of a fluid is a vector function of position and time, SI units: m s^{-1}.

$$\mathbf{u}(\mathbf{x}, t) = (u, v, w) \text{ or } (u_x, u_y, u_z) \text{ where } \mathbf{x} = (x, y, z).$$

Typically, velocity is measured by an instrument placed at a particular position **x** in the flow. For example: hot wire probes, pitot tubes, anemometers, current meters, LDA, acoustic Doppler. This way of thinking of the velocity as a function of position is called **Eulerian** representation. The disadvantage of the Eulerian representation is that you're not measuring the same piece of fluid.

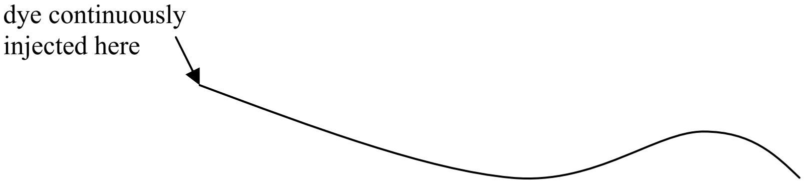
Alternatively, flow can be measured by following the motion of particular fluid elements (e.g. using tracers, dyes, floats, bubbles, or small particles). Thinking of the flow in this way is called the **Lagrangian** representation. Forces act (of course) on fluid elements and not on positions in space. Thus we need to consider accelerations in a Lagrangian frame when deriving the effect the forces acting on a fluid have on the fluid flow. However, fluid properties (such as velocity, pressure and density) are easier to measure and represent as functions of position (Eulerian description).

Path line or particle path

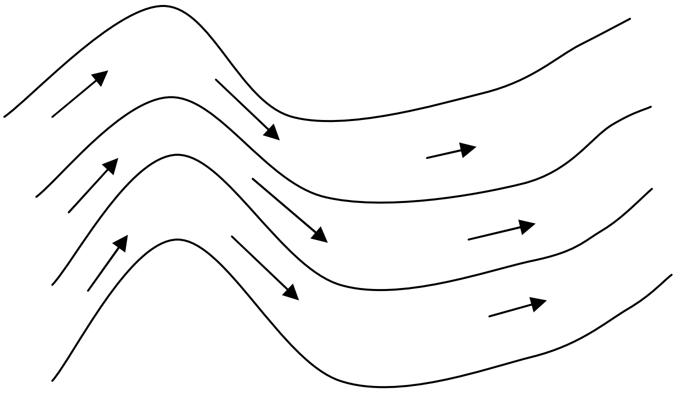
The line followed by a particle in the fluid released at some point in the flow (what you would see with a long exposure photograph of the flow).

Streakline or dyeline

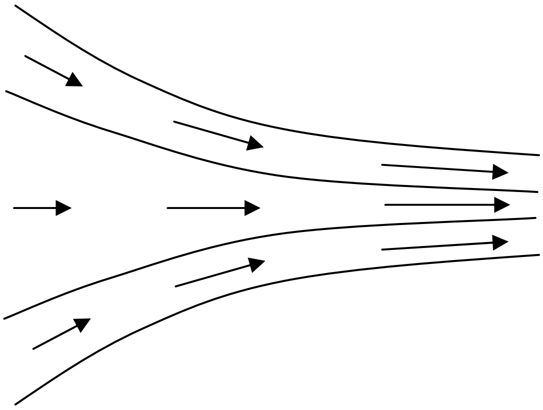
The line of dye resulting by continuously injecting dye at a particular point in the flow.



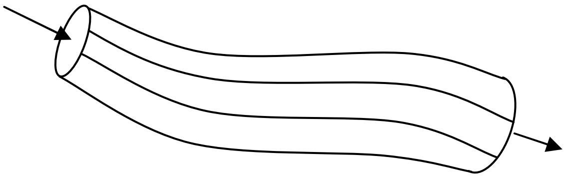
Streamlines
Lines everywhere tangent to the flow direction. This gives an overall picture of the flow field (at a particular instant in time).



Flow speed increases where streamlines converge.



Streamtube
Bounded by a set of streamlines, so fluid remains within the tube (a "virtual pipe").



Steady flow
Flow that doesn't change in time (though the velocity may be different in different parts of the fluid).

$$\frac{\partial \mathbf{u}}{\partial t} = \mathbf{0} \quad \text{(at constant } \mathbf{x}\text{)}$$

For steady flow, streamlines, streaklines and particle-paths are all the same. Note that just because the velocity at a point isn't changing, this doesn't mean that fluid passing that point isn't accelerating.

Reynolds number and flow types

Features of the Navier-Stokes equations
Recall the Navier-Stokes equations for an incompressible flow are:

$$\frac{D\mathbf{u}}{Dt} \equiv \frac{\partial \mathbf{u}}{\partial t} + \mathbf{u} \bullet \nabla \mathbf{u} = -\frac{\nabla p}{\rho} + \nu \nabla^2 \mathbf{u} + \mathbf{g},$$

$$\nabla \bullet \mathbf{u} = 0.$$

The equations are **non-linear** (because of the advection term in the material derivative) and **second order** (because of the viscous term). At a rigid boundary, moving with velocity **U** and having normal **n**, there are two types of **boundary conditions**. No normal flow: there can be no flow through the boundary, so **u.n** = **U.n** at the boundary. No-slip condition: the fluid in contact with the boundary must have the same tangential component of velocity at the boundary, else the viscous stresses would give an infinite restoring force. Taken with the no normal flow condition this gives **u** = **U** at the boundary. The no-slip condition can be relaxed if we are ignoring viscous effects, leaving the no normal flow condition. Ignoring viscous effects reduces the equation to first order.

Non-dimensionalisation and Reynolds number

It is often useful to transform from the standard units of measurement (metres, seconds, etc) to scales that are "natural" for the problem. For example, for flow past a cylinder the natural length scale would be the diameter, D (or possibly radius, R) of the cylinder while the natural velocity scale would be the speed of the flow, U, far from the cylinder. The natural time scale would then be T = D/U. If the dimensional velocities and positions are **u*** and **x***, then in non-dimensional variables we have,

$\mathbf{u} = \mathbf{u}^*/U$, $\mathbf{x} = \mathbf{x}^*/D$, …boundary conditions $\mathbf{u} = \mathbf{0}$ on $|\mathbf{x}| = 1/2$, and $\mathbf{u} \to (1, 0, 0)$ as $|\mathbf{x}| \to \infty$.

In the non-dimensional variables the boundary conditions are the same for all cylinders. The equation of motion becomes (in non-dimensional variables),

$$\frac{D\mathbf{u}}{Dt} = -\frac{\nabla p}{\rho} + \frac{\nu}{UD}\nabla^2\mathbf{u}\,.$$

If both the boundary conditions and the equation are the same, then the solutions and flow behaviour must be the same. This will be true if the quantity ν/UD is the same. The reciprocal of this quantity R = UD/ ν, is known as the **Reynolds number**. The Reynolds number is the ratio of the order of magnitude of the inertial and viscous acceleration terms, and thus low Re implies viscously dominated flow while high Re implies inviscid flow (flows where the viscous forces are small).

Laminar and turbulent flow

In practice we find that for low Re flows (in which viscosity dominates), disturbances in the flow field tend to be damped leading to smooth, stable, laminar flows. At high Re, the flow is likely to be unstable, and may break down into chaotic, turbulent flow. For example, for flow through pipes laminar flow is observed for Re < 2000 (where Re = UD/ν, U average flow speed, D pipe diameter), while turbulent flow is generally observed for flows with Re > 4000.

Viscous flow

At very low Re, the equation of motion reduces to a balance between pressure and viscous stresses. Both the non-linearity and the explicit time-dependence are removed, so that the flow is reversible and the flow field adjusts instantaneously to applied conditions. Reversibility results in symmetric flows since, for example, the flow past a cylinder from right to left must look identical to flow from left to right with the flow direction reversed but the streamlines remaining the same.

Flow past cylinders

At low Reynolds number the flow must have forward/backward symmetry but as Re increases the flow separates at the rear of the obstacle and a recirculating region (vortex pair) is formed. Initially this region is steady and symmetric about an axis through the obstacle but as Re increases further (Re ~ 40) waves develop downstream. For Re > 70 the vortices alternate in size and are shed forming a "vortex street." If the frequency at which the vortices are shed (e.g. number per second) is σ, then we relate this to the flow parameters through the **Strouhal number** (a non-dimensional frequency) S = σD/U. Typical value for cylinders is S ~ 0.2. The alternating vortex shedding produces an oscillatory force on the cylinder.