Other (more specialised and advanced) fluid mechanics areas

Fluid mechanics is a huge and diverse area and it is impossible to cover all its different aspects in any finite course.

Listed below are some important areas, relevant to particular situations and industries - but which are too advanced, specific or niche to cover in detail in other notes. These are just a quick overview – whole books have been written about each of these topics.

1. Non-Newtonian flows

The fluids which we study in class (like air, water and oil – called Newtonian fluids) have a constant viscosity. However, some important fluids don't – their viscosity varies with the fluid's static or dynamic situation (often with the stress being applied to make the fluid move). These are called Non-Newtonian Fluids. Non-Newtonian fluids are important in the food processing, construction, civil-engineering and other industries.

A good example of this is a fluid which you can make in the kitchen – cornflour and water. When this mixture is stirred very slowly, it is watery and runny. When it is stirred quickly, it becomes thick and viscous. In other words, its viscosity increases with velocity.

Other examples include: Sewage, Cement, Milk, Ketchup, Blood and Paint. They are classified in different ways – some important ones are listed below (however there are several others - and alternative ways of classifying them as well):

i) *Plastic*. Doesn't start flowing until a minimum stress is applied (sewage).

ii) *Pseudo-plastic*. Viscosity increases as stress increases (cement).

iii) *Dilatant*. The opposite of Pseudo-plastic (quicksand).

iv) *Viscoelastic*. Behave like Newtonian fluids until a certain stress is applied, then behave like plastic fluids.

Sets of equations have been developed to model the flow for some of these fluids, but many of them don't yield easily to simple calculations.

Often the properties of such fluids are written and solved as stress and strain relationships, more akin to solid mechanics, rather than with fluid equations (actually, because the fluid moves, the rate at which strain changes, rather than strain itself is used).

In some fluids, the viscosity can be approximated using a power-law:

$$\mu = k\dot{\varepsilon}^{n-1}$$

Where k and n are constants describing the flow and epsilon dot is the shear-strain rate.

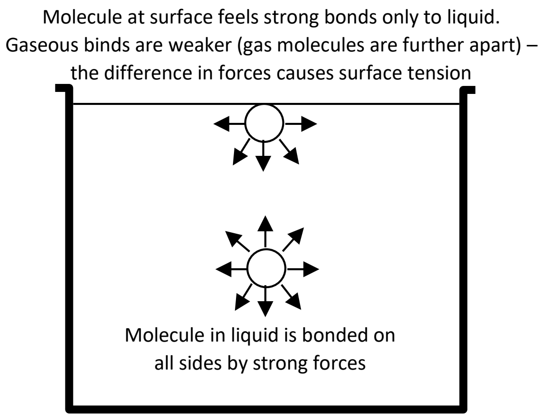
Computational Fluid Dynamics (CFD) and other types of computer simulation can be particularly useful for modelling such flows as a new viscosity value can be calculated at each step of the simulation according to the fluid's state and the forces to which it is subject.

2. Microfluidics

Microfluidics is the study of fluids moving through small gaps or channels. It encountered in biology – for example, flow in blood capillaries or through the pores in cells. But is also important in some fields of engineering – for example in modelling the flow through membranes (present in devices like fuel-cells and water purifiers) or thin tubes.

The defining characteristics of this type of flow is that certain forces which we don't have to consider on the larger scale are present – good examples are surface tension and surface adhesion forces. These forces govern such flows and make the fluid behave differently in small spaces. The process of diffusion may also be present in many such systems and this is governed by *Fick's law*.

The origin of the surface tension force is shown below:



Such forces are responsible for the well-known phenomenon of fluids climbing up the walls of thin tubes – known as *capillary action.* The height to which a fluid can creep in such a situation is given by *Jurin's law*:

$$h = \frac{2\gamma cos\theta}{\rho g r}$$

Where γ is the surface tension, θ is the contact angle of the fluid and surface (which itself depends on fluid and surface parameters, ρ is fluid density, g is gravitational acceleration and r is the radius of the tube.

Two fluids in contact with each other in such a tube can also exhibit a pressure between them due to these forces (called *capillary pressure*), given by:

$$p = \frac{2\gamma cos\theta}{r}$$

3. Open-channel flow

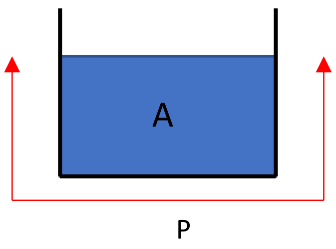
Open channel flow is important in many different areas of engineering – particularly civil and environmental. It pertains to flows in natural conduits like rivers and streams or human-made ones like channels, drains, ducts and canals. These conduits have a *free-surface* above them, where they are in contact with (usually) air. The free-surface means that the top of the flow is always at the ambient pressure of the surrounding atmosphere. Open-channel flow also importantly applies to pipes which are not completely full of liquid.

Flow-rate in open-channels is approximated using theories developed by Chezy (who developed an equation to describe it) and Manning. The Manning equation is:

$$v = \frac{\sqrt[3]{R^2}\sqrt{S}}{n}$$

Where v is the velocity of the flow, R is the *hydraulic radius* (explained below) and S is the slope (the fall in channel height per metre of length – for example if the channel went down 20cm per metre of length, S would be 0.2 – in other words if h is the total height loss and L is the total length then $S = h/L$). n is called the *Gauckler–Manning coefficient* and is a measure of the channel's opposition to flow (for example due to its roughness).

The hydraulic radius is determined as shown in the diagram below:



A = Cross-sectional area of flow

P = Wetted perimeter (length of cross-section in contact with fluid)

R = A / P

The flow-rate can be calculated from the velocity using the standard continuity equation.

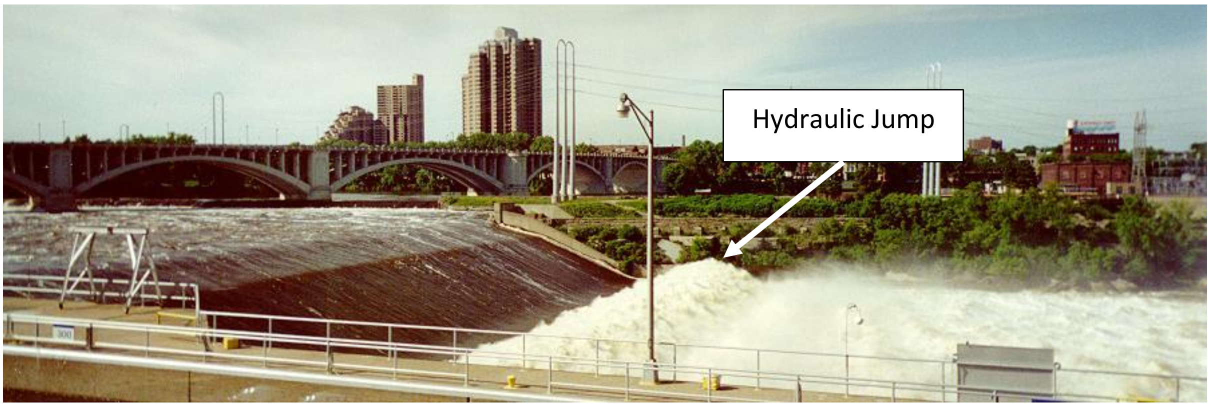
You can also re-arrange the equation to calculate the height of a flow (say in a river) from a given flow-rate (the flow-rate in such a system is sometimes referred to as the discharge-rate).

Another aspect of the flow which is sometimes important in open-channels is its surface behaviour. This is often governed by whether the flow is *Subcritical* or *Supercritical*. In a subcritical flow, the speed of the fluid is less than the velocity of waves on its surface (so waves can propagate upstream). In Supercritical flow the opposite is true – the flow is faster than the waves (so they always get swept down-stream). The Froude Number F tells you whether the flow is super or sub-critical:

$$F = \frac{v}{\sqrt{gD}}$$

Where v is velocity, g is gravitational acceleration and D is fluid depth. If the Froude number is greater than 1 the flow is supercritical, if less than 1 then subcritical.

When flow moves from a supercritical state to a subcritical one a *hydraulic jump* can occur – this is an abrupt wave-like turbulent jump in fluid level, as shown below:



(Image: Saint Antony Falls by Wahkeenah, Licence: Public domain, Source: Wikipedia)

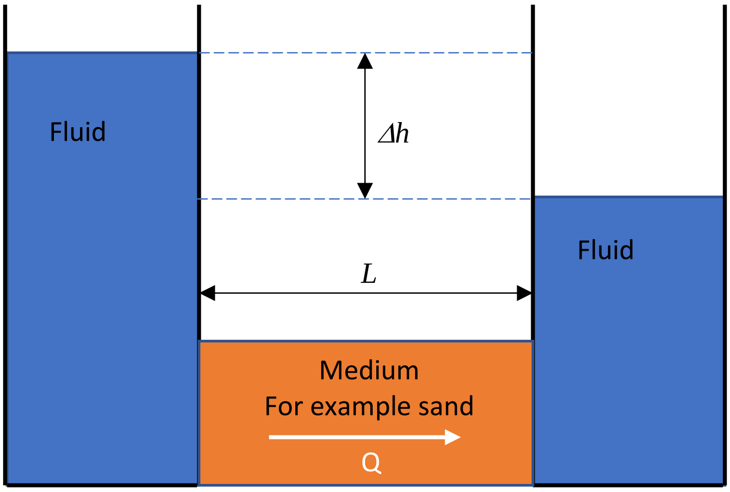
4. Flows through porous media

Like Open-channel flow, this is an important aspect of environmental engineering – but is also significant in other areas too. It describes the flow of a fluid through a granular or porous media like sand or gravel. As an example, it governs the transport of rain or flood water though the soil or fluid through a filter bed (for example to remove impurities).

One of the main tools to calculate flow through a porous medium is *Darcy's Equation*. One form of this is given below:

$$Q = Ak\frac{\Delta h}{L}$$

Where Q is the volumetric flow rate, A is the cross sectional area of the porous medium, L is the length of the medium and k is the permeability of the medium (a measure of how easy it is for the fluid to flow through it). Δh is the pressure-head difference across the medium (in metres) as shown in the diagram overleaf.



5. Multi-component flow (multi-phase/fluid)

Multi-component flows are where several fluids (and sometimes solids too) are moving together. If there are different phases present (for example gas and liquid), then the system is often referred to as multi-phase.

Such systems occur in several different engineering situations - but are particularly important in the energy industry, where (for example) different fractions of oil and natural gas may be moving down the same pipe. Often sand or other solids are also present. It is also common to have multiphase flows combined with the other types mentioned above (for example multiphase flow through a porous medium or through capillaries).

The movement of solids is also often a consideration in such systems and some solids can flow in a similar way to fluids. The study of general flowing systems (which include some solids or granular materials) is called *Rheology*.

As you might imagine, modelling multicomponent flows can be difficult and complex. There are several approaches commonly used – the best one to use depends on the components of the flow.

For example, for two components, one of which is dispersed in the other (examples might be a liquid *emulsion* or sand being carried along by a fluid), a popular strategy is to treat the carrying medium as a fluid using the Navier-Stokes equations and to treat the dispersed component as solid particles being carried along (both components can exchange energy with each other). This approach is called the *Euler-Lagrange method*.

Probably the most common approach however is to just treat each flowing component individually (this approach works well if they are actually separate and independent flowing streams – perhaps because of their differing densities). This idea is called the *homogeneous flow* model.

6. Boundary layer mechanics

Boundary layers are extremely important in many areas of fluid mechanics – for example in aero and hydrodynamics. This is because the boundary layer is the fluid in direct contact with solid bodies – like pipes, hulls and wings. As such, any fluid effect on these bodies is transmitted through the boundary layer. They therefore play a pivotal part in drag generation, fluid attachment to bodies, frictional heat generation and the transition between laminar and turbulent flow.

Designers often go to great lengths to control and optimise the boundary layer – for example by adding passive or active devices to aerofoils which shape the layer for optimum performance.

However, predicting the behaviour and parameters of the flow within the layer is complex and difficult (and the subject of on-going research). Rather than try and deal with the detailed dynamics, bulk figures representing averaged parameters are often used instead.

In general boundary layers can be divided into laminar and turbulent types. One popular model (called the *Blasius* model) gives the thickness of a simple laminar layer on an infinite plate is approximately:

$$\delta \approx 5\frac{x}{\sqrt{Re}}$$

Where δ is the thickness, x if the distance along the plate and Re is Reynolds number.

A similar derivation for a turbulent layer gives:

$$\delta \approx 0.385\frac{x}{Re^{0.2}}$$

Designers often have to carefully consider the effect of the layer – for example laminar boundary layers give lower drag, but turbulent ones give better fluid attachment characteristics.

7. Potential flows

Potential flows are a series of simple fluid flow-patterns which are easy to describe mathematically. Their ease of description is because they are irrotational – their curl is zero. Examples of such flows include uniform flow and sources and sinks.

Because of their simple mathematical form such flows can be added together to produce more complex flow-patterns which can then be solved mathematically. This was a common strategy for computer simulation of flows before the advent of currently used CFD techniques (like finite element, difference and volume) and can, for example, be used to calculate the flow parameters around aerofoils and similar structures.

Some useful Wikipedia pages

Multiphase flow:	Multiphase flow - Wikipedia
Darcy's Law:	Darcy's law - Wikipedia
Microfluidics:	Microfluidics - Wikipedia
Rheology:	Rheology - Wikipedia
Open channel flow:	Open-channel flow - Wikipedia
Potential flow:	Potential flow - Wikipedia
Boundary layers:	Boundary layer - Wikipedia
Non-Newtonian flow:	Non-Newtonian fluid - Wikipedia