FLUIDS 1

BASIC FLUID PARAMETERS

This section explains the basic parameters and definitions involved in fluid calculations

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OVERVIEW

In this section we will cover:

- What a fluid is
- The engineering scope of fluid mechanics
- Fluid properties and definitions
  - Fluid statics and fluid dynamics
  - Viscosity
  - Newtonian and non-Newtonian fluids
  - Compressibility
  - Density
  - Its molecular nature of fluids

OBJECTIVE

This section lays the foundations of fluid engineering by defining important parameters and ideas

TOPIC 1 – WHAT IS A FLUID

We will get to the formal definition of a fluid shortly. However, fluids include both *gases* and *liquids*. Examples include: oil, water and blood (liquids); and air, hydrogen and carbon dioxide (gases). In addition, in extreme circumstances, gases can become ionised (that is, they gain or lose electrons) and therefore charged. Such charged gases act differently to other fluids and are called *plasmas*. Some unusual materials are also classed as fluids, including glass (which may be classified as a liquid that flows very slowly). Therefore, one simple definition of a fluid is that it is a substance which *flows*.

TOPIC 2 – THE IMPORTANCE OF FLUID MECHANICS IN ENGINEERING

Fluid Mechanics has many obvious (and some not so obvious) applications in engineering. Just a few of them are:

1. **Aerodynamics** (airflow, used in the design of cars and other vehicles and importantly in the design of aircraft).
2. **Hydrodynamics** (waterflow, used in the design of ships and other seaworthy vessels).
3. **Flow in pipes** (oil and water industries, etc).
4. **Flow in rivers and channels** (hydroelectric schemes and other civil engineering projects).
5. **Turbines** (gas (jet engines), stream (power stations), water and air (renewable energy)).
6. **Internal Combustion Engines** (as the working fluid).

Fluid Mechanics is traditionally split into two separate fields:

- **Fluid Statics** – The study of fluids at rest (mainly to do with pressure in fluids).
- **Fluid Dynamics** – The study of fluids in motion (a larger and more complex field).

In this module, we will mainly be concerned with Fluid Statics and the properties of fluids.

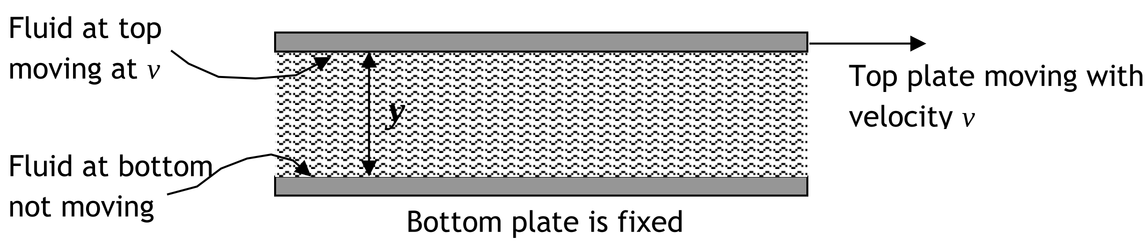
TOPIC 3 – FLUID PARAMETERS

1. Viscosity and the definition of a fluid

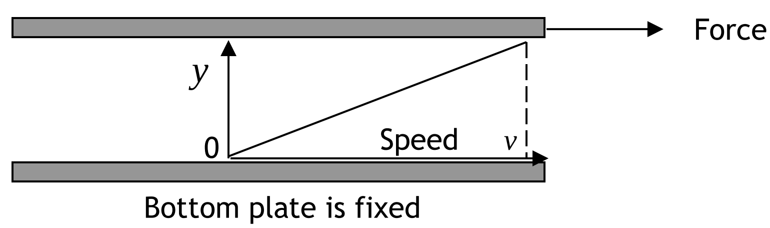
On the first page we discussed the "intuitive" definition of a fluid. However, the technical definition is this:

> *"A fluid is a substance which deforms continuously under shearing forces – no matter how small they are."*

This is usually demonstrated using two parallel plates:



If the bottom plate is fixed and the top plate is moving to the right at velocity v, the fluid in-between the two plates deforms continuously. If we subject the upper plate to a force it moves at a certain speed and drags the fluid immediately underneath along with it. The fluid right above the bottom plate isn't moving at all though. So there is a gradient of speed from zero at the bottom to v at the top.



As we travel from the bottom plate to the top, along the y axis, the rate of change of speed is $\frac{dv}{dy}$. If τ is the shear stress (in N/m^2), then $\tau = constant \times \frac{dv}{dy}$. This constant is the viscosity of the fluid μ.

Viscosity of a fluid:

$$\tau = \mu \frac{dv}{dy}$$

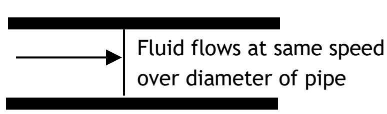
Viscosity is an extremely important property of a fluid and is a measure of its "gooiness" or "stickiness." Don't however confuse it with density (the weight of the fluid) as some heavy fluids (like mercury) can have low viscosity (because they are runny). Examples of fluids with higher viscosity than water are treacle and honey. The units of viscosity are Nsm^{-2} (or Pa s), typical values are: for water 1×10^{-3} Pas, air 2×10^{-5} Pas, honey and (cold) mineral oil 10 Pas, glass 1×10^{40} Pas.

Note that there are several other definitions and types of viscosity which are used in some calculations – the type explained above is probably the most common and is called *Dynamic Viscosity*. Other types include *Kinematic Viscosity* (which is μ/ρ), *Absolute* and *Bulk* viscosity. It is important to make sure that you use the correct type for the problem at hand.

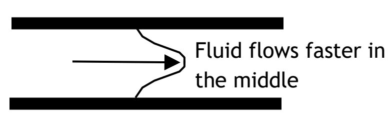
In fluid mechanics, to make calculations simpler, μ is often ignored – we say that the fluid is *Invisid*. However, all real fluids (apart from some very low temperature fluids called *Superfluids*) have viscosity and ignoring it causes inaccuracies in the calculations (actually, ignoring viscosity can sometimes give a completely wrong answer). In fact, some of the most important phenomena, like lift on an aircraft wing and drag on a car, are due to viscosity. This is because it's viscosity which causes fluid to bend around an object and follow its shape.

Viscosity is due to the internal friction between the molecules in the fluid (or between the molecules of the fluid and some other surface – like a pipe).

To show how real flow (with viscosity) differs from ideal flow (invisid flow), take the example of a fluid flowing in a pipe (flows inside things like this are called *internal flows*).



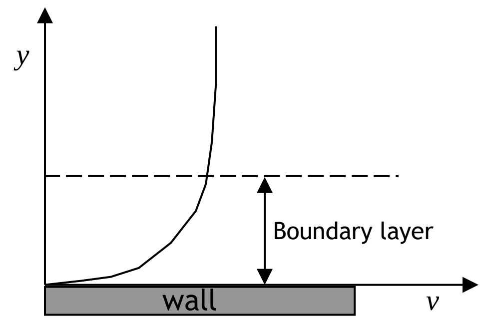
Ideal fluid



Real fluid

In a real fluid, flow near the sides is slow (in fact, it stops at the edges), due to viscosity (the fluid is "sticking" to the wall of the pipe). You can compare this with the example of the two plates on page 2. We can also see the same thing in a river or other water channel – the water at the bank is moving slowly, while that in the middle is travelling quickly.

The velocity profile of a typical flow, close to an edge of a pipe or similar structure is shown below.



The (sometimes thin) layer where the fluid speeds up is called the boundary layer and although it may be small it can have an important effect on the system.

TASK 1

a) How do you think viscosity is practically measured? Look up some methods in books or on-line.
b) What effect would you expect viscosity to have on turbulence in a fluid?

2. Newtonian and non-Newtonian fluids

We have already explained the viscosity equation:

$$\tau = \mu \frac{dv}{dy}$$

Many of the fluids which we're familiar with obey this equation - for example, water, oil and air. However, there are a large number of fluids which appear not to obey it. These are called *Non-Newtonian Fluids*.

On further investigation it is found that the reason why they don't obey the equation is that their viscosity is not constant – it varies according to the fluid's movements. A good example of this is a fluid which you can make up 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.

There are many other non-Newtonian fluids and some are very important in engineering. Examples include: Sewage, Cement, Milk, Blood and Paint. They are classified in different ways – some of the most important are listed overleaf.

i) **Plastic**. Don'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.

3. Compressibility

Liquids are generally not compressible, but gases usually are. Take a syringe and fill it with water – you cannot push the plunger any further in. Fill it with air and you can. Even in the deepest part of the ocean, where the pressures are 2000 time higher than on the surface, water is no more squashed (denser) than near the surface.

Compressibility is a big issue in gases. At slow speeds – say the speed at which you drive your car, air is not compressible. This is because a moving object generates a disturbance in the air which moves outwards, at the speed of sound, and rearranges the air molecules in front of the car. At fast speeds, however – for example, like an aircraft, - the moving object is travelling so fast that the air molecules can't get out of the way in time and get bunched up – compressed. Eventually they form what is known as a *shockwave*. This happens either when something is travelling quickly through the gas or when the gas itself is travelling fast.

TASK 2

Look up some videos on youtube about the formation of shockwaves

Generally speaking, air is considered incompressible when it is travelling at less than 0.3 times the speed of sound – sometimes known as Mach 0.3 (that is, less than about 90 meters per second).

Many of the formulae you'll come across in the course apply only to incompressible flow and it's important not to apply the wrong formula to a particular situation.

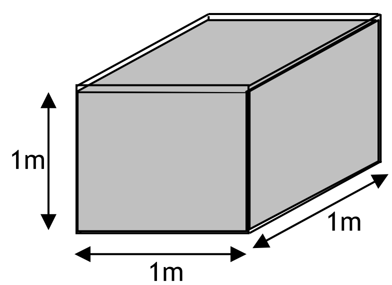
Compressible flow is more complex because, as the gas compresses, some of its kinetic energy may be transferred into internal (thermal) energy. This means that the equations which apply to compressible flow are not just derived from Newton's Laws of Motion, but from the laws of Thermodynamics as well.

TASK 3

Give the last paragraph, what would you expect to happen if a very fast gas was brought suddenly to a halt.

4. Fluid Density

We have already mentioned fluid density is several places. It's an extremely important concept, which is worth exploring in more detail. Consider a cube 1m × 1m × 1m (like a large fish tank) containing water.



This amount of water would weigh 998Kg. Therefore we say that water has a *density* of 998 Kg m^{-3}. Some other important densities are: Paraffin – 800 Kg m^{-3} (because it's less dense that water, it will sit on top) and Mineral Oil (the type which lubricates your car) – 880 to 950 Kg m^{-3}.

Although it's not obvious, because it's so light, even air weighs something. The density of air at sea level is 1.293 Kg m^{-3}. So, the air in our cube would weight around 1.3 Kg! Other important gas densities are hydrogen (the lightest gas) 0.09 Kg m^{-3} (that is, 90g m^{-3}), methane (natural gas) 0.717 Kg m^{-3} and water vapour 0.8 Kg m^{-3}.

When air gets compressed, as we discussed previously, its density increases (that is what happens locally in a shockwave).

Measuring density in bulk like this can be a problem because, in real systems, it might change from place to place and therefore we really want to know what it is *at a particular point*. Now, in the explanation above, density equals mass over volume $\rho = \frac{m}{V}$, but we want the volume to be as small as possible, so that we can localise the density to as particular point.

Density:

$$\rho = \frac{\delta m}{\delta V}\bigg|_{\substack{Lim \\ \delta \to 0}}$$

TASK 4

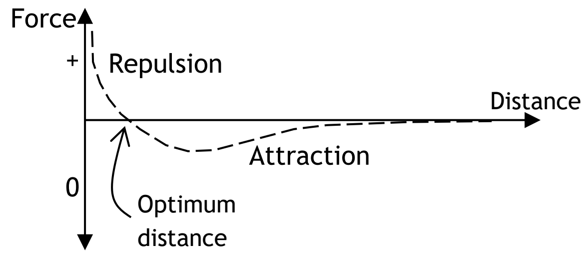
1. *How much does the air weight in a room measuring 5m x 4m x 2.5m?*
2. *How much does the water weigh in a 2cm diameter pipe 3m long?*
3. *What volume does 1Kg of hydrogen (H_2) take up at room temperature and sea-level pressure?*

5. The molecular nature of fluids

Fluids, like everything else, are made of molecules. It's the space between these molecules which defines the state (gas, liquid or solid) which matter is in. If the molecules are very close together and not moving much, then we have a solid. If their moving a bit more, we have a liquid (actually, there's not much difference in spacing between the molecules in a liquid and a solid). If they are moving fast and are far apart, we have a gas. Gas molecules are about 10 times further apart than those in a liquid.

a. Intermolecular forces

The atoms which make up molecules, are themselves made from changed electrons and protons. These charges attract and repel each other. For this reason, if you try and pack them too close, a lot of energy is required to overcome the repulsion of the atoms' individual electron clouds. Likewise, molecules try and evenly fill the space given to them, just as air tries to fill a vacuum. The spacing which molecules actually adopt is where these two behaviors balance. The graph overleaf demonstrates this.



It is these attractive and repulsive forces manifest themselves as friction within the fluid and therefore as the viscosity which we studied earlier.

In gases, the molecules are much further apart and feel very little force between them. This is why the assumption is often made that gases are invisid (of course not true in reality). Such a gas, with no internal forces is sometimes called a *Perfect Gas*.

b. The perfect gas

By assuming that a gas is perfect, we can simply derive an equation called *the equation of state for a perfect gas*. This relates that gas' pressure to its temperature and density.

Equation of state for a perfect gas:

$$p=\rho RT$$

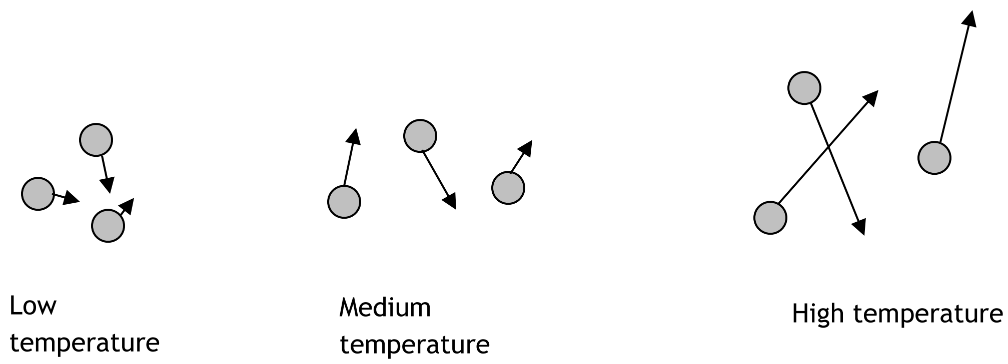
The relationship is sometimes stated as $pV=RT$. Where p is absolute pressure (Nm^{-2}), T is absolute temperature (K) and R is the *gas constant* ($JKg^{-1}K^{-1}$). Typical values for R are, for air 287 $JKg^{-1}K^{-1}$ and hydrogen 4110 $JKg^{-1}K^{-1}$

TASK 5

Given the density of air at room-temperature, calculate the air-pressure.

c. Temperature

Temperature is a measure of the average speed of molecules within a substance.



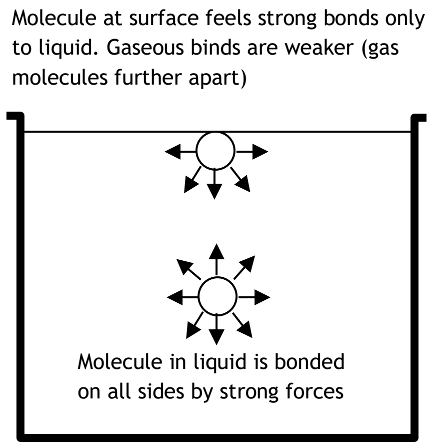
When we heat up a liquid, the temperature rises and the molecules therefore get faster and faster. Eventually, they will break their weak attractive bonds and move further apart – they will become a gas.

TASK 6

1. *If temperature is due to the velocity of molecules – what is heat. Do some research this question and write a description.*
2. *Why (from a molecular point of view) does higher temperature in a gas result in higher pressure on the container walls*

d. Surface tension

The molecular forces within a fluid also explain another phenomena – that of *Surface Tension*. The surface of a liquid appears to be under tension because the molecules on the top are attracted to the molecules within the liquid, rather then the gas above. Surface tension means that the surface of liquids will hold light objects. It is also responsible for a liquid *Wetting* a surface (spreading across it) and *Capillary Action* where a liquid travels up a thin tube. The diagram overleaf demonstrates its origin.



The study and engineering of fluids where surface tension dominates (usually in thin tubes or channels) is called *microfluidics*. In many circumstances (like large pipes or external flows) we can ignore the effects of surface tension.

SUMMARY

- Fluid Mechanics is used in a wide variety of mechanical engineering systems
- The subject is split into two disciplines:
    - Fluid statics – the study of fluids a rest
    - Fluid dynamics – the study of moving fluids
- Important fluid parameters include:
    - Viscosity
        - This is how “gooy” or “sticky” a fluid is.
        - It can sometimes be ignored in calculations – such simplified models are called “inviscid.”
        - However in many circumstances, particularly with liquids, it is important.
        - It causes the boundary layer and the parabolic flow profile seen in pipes in fluid flows.
        - There are a number of different definitions of viscosity used in different circumstances.
    - Newtonian and non-Newtonian fluids:
        - Viscosity is not constant in some (important) fluids and this results in them having some unexpected characteristics.
    - Compressibility
        - Some fluids (specifically gasses at high speed) show an increase in density in some circumstances – this results in the “standard” equations becoming inaccurate and eventually the formation of shockwaves (at supersonic speeds).
    - Density
        - Fluid density tells us the weight of the fluid (how much one cubic metre weighs).
- Fluid mechanics is fundamentally related to the molecular nature of fluids.
    - A simplified approximation of a (gaseous) fluid treats it as a perfect gas and assumes no forced between the molecules.
    - From this assumption a simple relationship (the equation of state) can be derived which related the pressure in a gas to its density and temperature.
- What we see as “temperature” is a manifestation of the average velocity of the molecules in a fluid.
- Surface tension is due to the differences between forces on molecules at the boundary of two fluids. In general it is only important when studying thin pipes and fluids in confined places.

REFERENCES AND BIBLIOGRAPHY

You may also wish to read about some of these concepts on Wikipedia or (where indicated in the text) view videos about them on youtube.