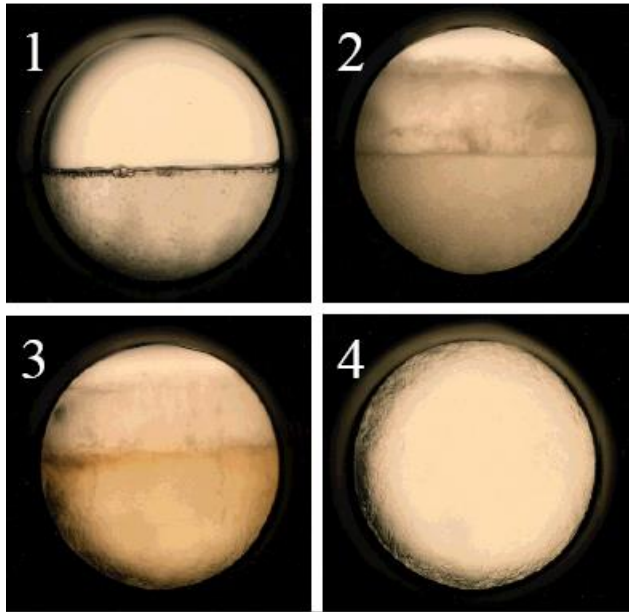


Lecture 1: What is a fluid?

A fluid is any substance that can flow. Materials in this category include liquids, gases, mixtures of liquid, gas and suspended solids, or supercritical fluids that lie somewhere between a liquid and a gas:



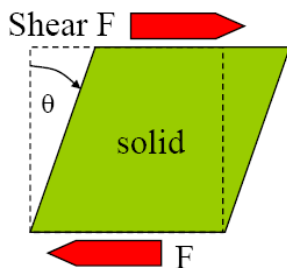
Supercritical fluid: Liquid and Gaseous CO₂ are gradually heated, causing a phase change to a fluid with properties of both liquid and gas. Note the gradual loss of the meniscus and the appearance of unstable surface waves.

What do we mean, flow?

The particles of a fluid are free to move and change their positions continuously in relation to each other. As a result, fluid motion can be initiated by any arbitrarily small force such as applied pressure or self-weight. Internal *shear* stresses due to friction develop within the fluid as a result of motion, such that shear *resisting* forces come into equilibrium with pressure or other *mobilising* forces.

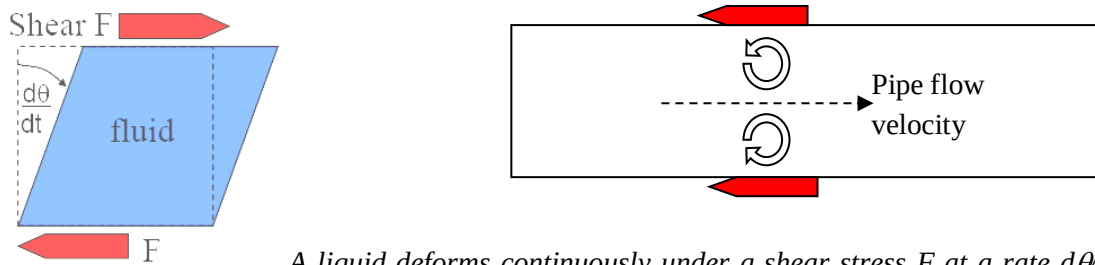
A shear force is a force that is parallel to the plane of a surface. This is in contrast to a normal force, which is directed at right angles to a plane. Similarly, as normal forces acting on surfaces produce *pressure*, shear forces on surfaces produce a type of pressure known as *shear stress*.

Shear can be envisaged by taking a block of soft rubber, placing it on a desk and attempting to push it by its top surface along the plane of the desk. The rubber adheres to the desk with ordinary static friction. With sufficient shear force an *angular deformation*, measured by the angle θ , will appear:



A solid deforms to an angle θ under an applied shear stress F .

In contrast, an element of fluid subjected to a shear force will undergo a continuous deformation, that is it will continue to deform, rotating and sliding over other fluid elements, until the shear force is resolved or contained. This can be measured by the *rate of angular deformation*, $d\theta/dt$:



A liquid deforms continuously under a shear stress F at a rate $d\theta/dt$. In a moving fluid mass such as inside a pipe, shear forces drive the internal rotation of flow elements.

The rate of deformation is proportional to the shear force. For larger shear actions we see more rapid movement and more intense internal rotation. This can produce turbulence and other induced forces.

The changing pattern of applied forces determines the behaviour of a fluid mass in any particular set of circumstances:

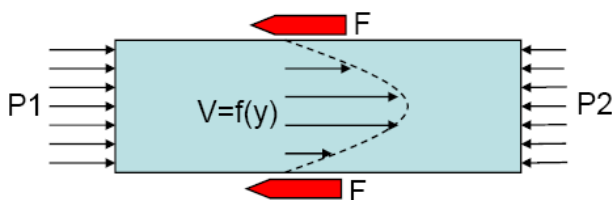


A fluid mass reacts to the shear force of its own unsupported weight in the horizontal plane.

Fluid motion results in internal stresses due to viscosity. These internal stresses balance the applied forces, such that motion can continue in equilibrium for as long as force is applied.

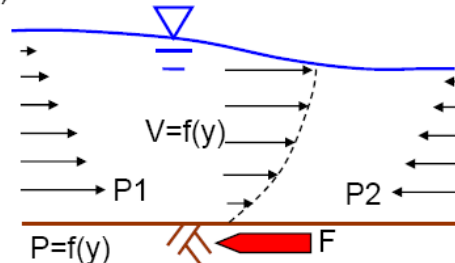
Shear forces are induced in fluids by mechanical forces: pump pressure, surface friction and weight forces for example:

a) pipe flow



Velocity profile in a pipe with a pressure gradient ($P1 > P2$): Friction with the pipe walls creates shear forces which cause the fluid to rotate internally as adjacent layers slide over each other.

b) channel flow



Velocity profile in a channel with a hydrostatic pressure gradient ($P1 > P2$): A pressure imbalance induces motion, which in turn induces shear forces and rotations.

Quasi-fluids: Granular and Plastic Materials

Some non-fluid materials, such as plastics and granular materials, will flow, but only up to a point. Above a critical or threshold shear stress, such materials will deform at a continuous rate, but below this threshold stress all movement stops: granular materials settle into a conical pile, plastic materials in the shape the applied forces left them:

a) granular materials



Granular materials flow under weight forces until the surface reaches a certain maximum angle, which depends on the degree to which particles can support each other by friction and interlocking forces.

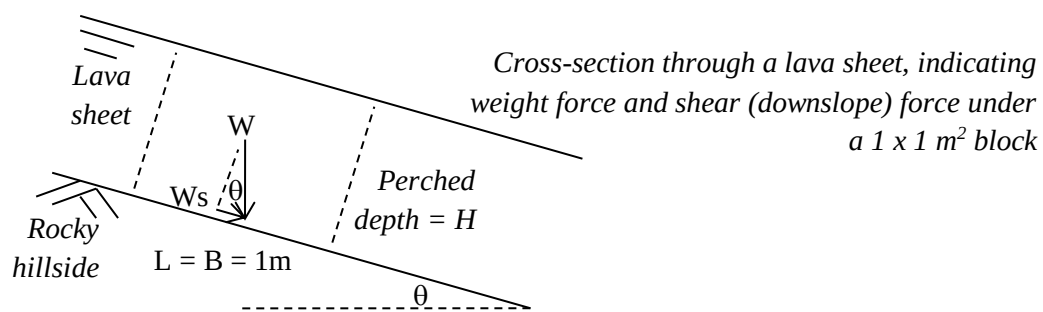
b) plastic materials



Plastic materials (such as plasticine) will flow under a certain minimum applied pressure, which depends on how well particles stick to each other. The deformation stops when the pressure falls below the minimum.

Mixtures or *colloids* of liquid, gas and suspended solids are more complex, with internal momentum and buoyant actions as well as chemical reactions taking place. Motion and suitable thermal-chemical conditions are required to keep the components of a colloid effectively mixed and stable. For example, blood is a multi-phase medium maintained as a suspension by complex biological, chemical and physical homeostasis processes.

Example: Lava is a plastic material which flows like a liquid if it is deep enough. Once the self-weight of the fluid exceeds a certain value the resulting shear stresses will initiate motion. The shear stress at the base of a layer of lava on a slope can be calculated based on the weight force per square metre (N/m^2):



The sheet of lava is analysed by dividing into a grid of $1 \times 1 \text{ m}^2$ square blocks each weighing W Newtons per square metre. Because of the slope, the weight force has a component of force down the slope which may be sufficient to initiate motion. Because it is parallel to the slope, this is a *shear force* which creates shear stress in the quasi-fluid and in the solid underlying surface:

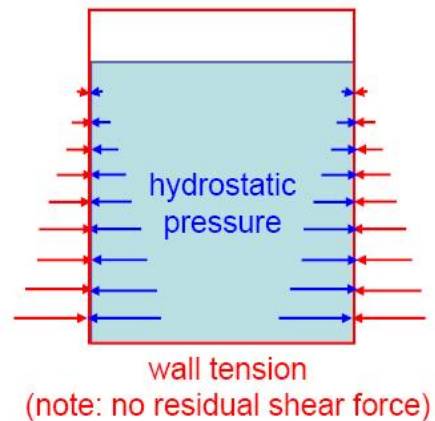
Downslope (Shear) Weight Force: $W_s = W \sin \theta$

Shear Stress $\tau = \text{Shear Force} / \text{Area} = W_s / 1 = W_s = W \sin \theta \quad \text{N/m}^2 \text{ or Pascals}$

Containment

A consequence of a fluid's reaction to shear force is that *a fluid always adopts the shape of the container it is in*, after allowance for dynamic effects. Liquids and gases can be further distinguished:

- A *liquid* has a mobile but generally horizontal free surface and fixed volume.
- A *gas* has no free surface or fixed volume: it expands to fill any closed container.



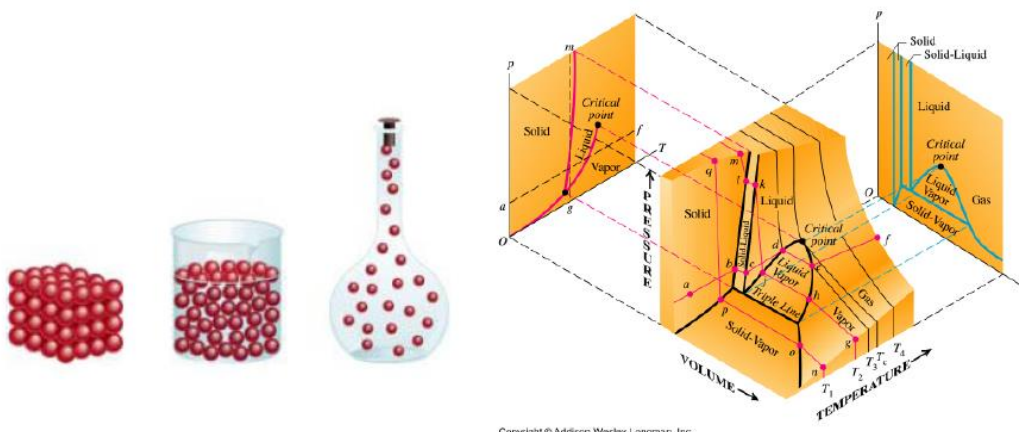
Liquids in containment. A stationary liquid adopts a horizontal surface, while a liquid in motion can have a free surface of any shape depending on the pattern of applied (eg gravity) and dynamic (eg momentum) forces.

The atmosphere as a whole is a special case of gas behaviour contained by gravity: an atmosphere becomes less dense with altitude and has no well defined edge, merging eventually with the thin and hot atmosphere of the sun. Light-weight gas particles such as hydrogen have sufficient kinetic energy to escape earth's gravity – as evidenced by the absence of free hydrogen in the earth's atmosphere despite geological sources of the gas over long periods of time.

Compressibility

Compressibility refers to a change in volume and hence density under an applied pressure force. All fluids (and indeed all materials) are compressible to a variable extent, but the phase change from liquid to gas produces an enormous increase in the compressibility of a fluid.

Liquids are said to be *effectively incompressible*, ie the compression is so small that it can be ignored for most purposes. Gases on the other hand are highly compressible, to the extent that under high pressure a gas may be compressed to a liquid. Compression absorbs energy, so the thermodynamic properties of a gas must be taken into account.



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Solid, liquid and gas phases with phase diagram showing transitions.

Gas or Vapour?

There is a subtle difference between a *gas* and a *vapour*: a gas is a single-phase mixture of individual atoms or molecules. A vapour on the other hand is a multi-phase mixture of gas particles and suspended liquid micro-droplets of varying sizes. The droplets generally are slow-moving, their motion being driven by currents and convective movements. In contrast the gas particles move rapidly and conservatively, their kinetic energy being obtained by the release of ionic bond energies at the phase change. Being conservative, all intermolecular collisions are *perfect* and no net energy is lost at any time between a gas particle and its total surroundings. The same cannot be said for the liquid droplets, which lose energy and will settle out gravitationally if convection and currents allow it.

The term vapour is also used to describe the state of a substance when its gaseous phase is in equilibrium with its liquid or solid phases, below boiling point.

Approximate Incompressibility

Calculations involving gases can be greatly simplified by assuming that they are not compressed, ie their density is regarded as constant. In such cases gases behave much the same as confined liquids, for example gases flowing at low to moderate speeds in pipes behave much the same as liquids.

If compression is a significant factor then the more complex compressible fluid theory (incorporating thermodynamics) must be applied. This is beyond the scope of this course.

The Continuum Principle

In most applications, interest centres on *average* conditions of velocity, pressure, temperature, density and so on. Therefore, instead of the actual conglomeration of separate molecules, we suppose that the fluid is a *continuum*, that is a continuous distribution of matter with no empty space. Quantities such as velocity, acceleration and the properties of the fluid are assumed to vary continuously (or remain constant) from one point to another in the fluid.

This *continuum principle* means that we can ignore the underlying molecular nature of fluids and substitute our own arbitrary divisions. Often a fluid mass can be analysed in bulk terms, without subdivision into smaller elements or components. In other cases a fluid mass need only be divided into upstream and downstream sections to create useful points of comparison.

In the more advanced analysis techniques, a fluid can be divided into mathematical elements or idealised particles that interact dynamically with neighbouring elements and boundaries to reproduce the dynamics of the real fluid. Again, these more advanced techniques are beyond the scope of this course.

Definition of a Fluid

The full definition of a fluid can now be appreciated:

A fluid is a continuous molecular medium that, at rest, cannot support or resist a shear force, but that develops resisting forces due to shear stresses as a result of motion.

The effects of both internal and external forces are causal factors in the way a fluid behaves. However it is usually not possible to determine the exact distribution of forces in a fluid, so average or approximate methods are used. It is quite difficult to visualise internal motion and force, so this definition may not be clear to you (yet).