

Lecture 9: Classifications of Fluid Flow Continued

Laminar and Turbulent Flow

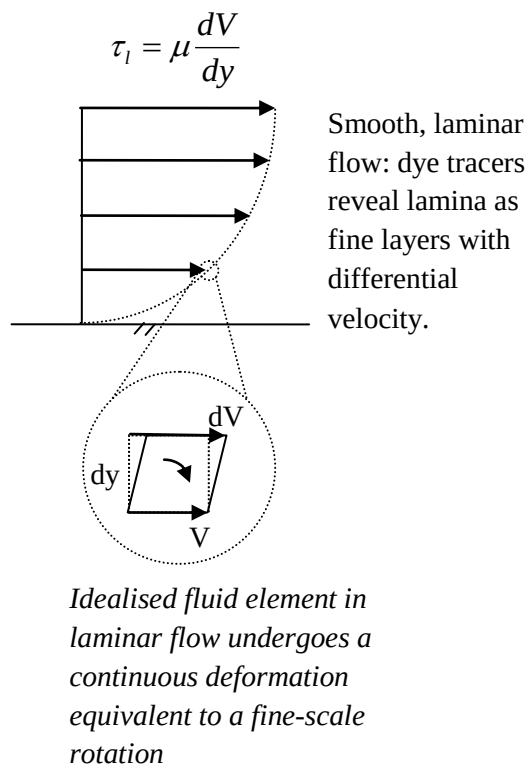
Viscosity has the general effect of transferring momentum between regions of high and low velocity via direct contact. There are at least two mechanisms behind this:

Laminar viscosity: adjacent layers of fluid slide over each other and “stick together” on a very fine scale. This can be observed by injecting dyes into slow, smooth flows: distinct lamina are visible in a range of slow flow types.

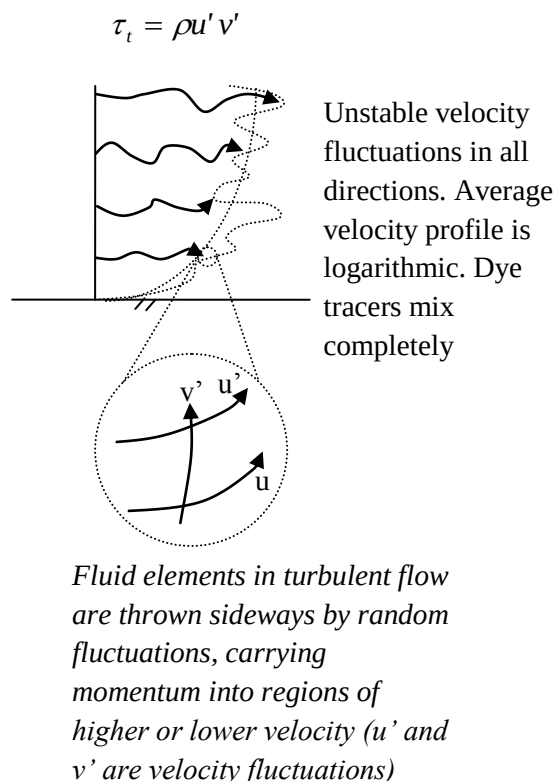
Turbulent viscosity: In more rapid flow, random fluctuations transfer mass and momentum at a medium to large scale across the flow. Turbulence is characterised by rapid *mixing*: dye tracers spread rapidly and uniformly throughout a flow.

The two types of friction produce a total shear stress (Section 5): $\tau = \tau_l + \tau_t$

Laminar:



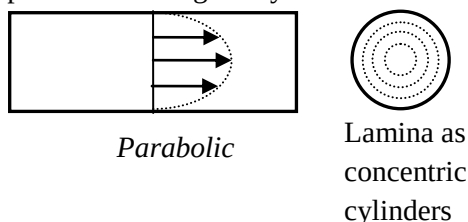
Turbulent:



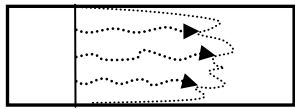
As a result, it is significant that laminar shear depends on the viscosity, while turbulent shear depends on the density.

Examples: Laminar flow is the exception, occurring at often impractically low velocities:

For example slow-flowing heavy oil:

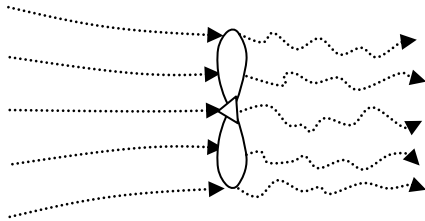


Turbulent flow on the other hand is everywhere:

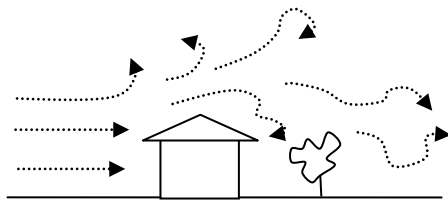


*Turbulent flow in
pipes at normal
operating velocities*

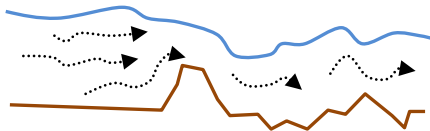
*Logarithmic on
average*



*Propellers and
vanes: accelerated
and highly mixed air*



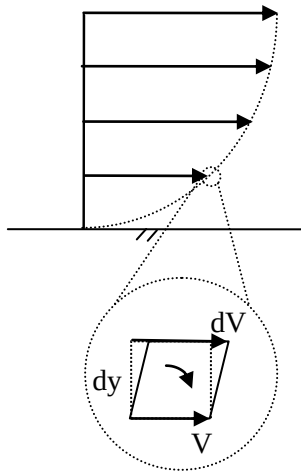
*Boundary layers on
all scales: aircraft,
vehicles, ships,
buildings,
landscapes etc...*



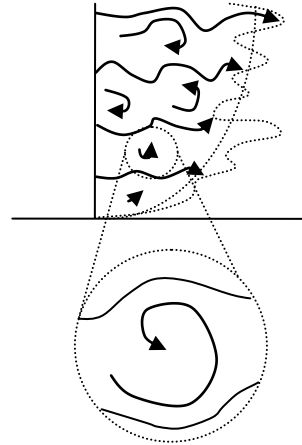
*Open channel flows
in most artificial and
natural channels*

Rotational and Irrotational Flow

Viscous flows are inherently *rotational*, again by at least two mechanisms in the laminar-turbulent range:



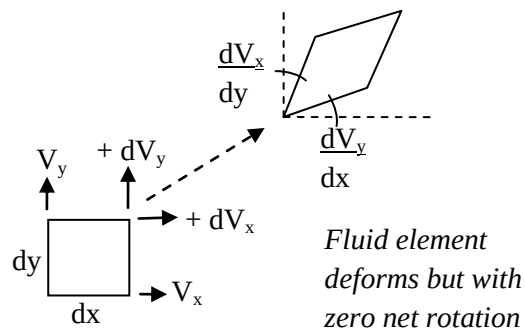
Fine-scale rotation between adjacent lamina, induced by velocity gradient



Rotations are amplified by turbulent instability, producing large-scale eddies and vortices. Intensity of turbulent motions increases with average velocity and distance from wall.

Inviscid flows are irrotational: velocity gradients in all directions are either zero or equal:

$$\frac{dV_y}{dx} = \frac{dV_x}{dy}$$



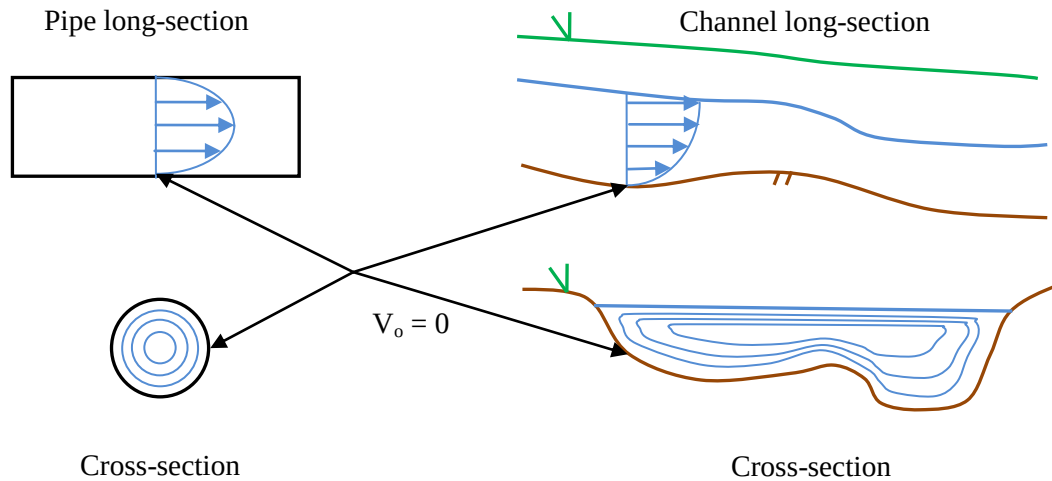
Irrotational flows are modelled as *ideal fluids* by relatively simple potentiometric methods, whereas real fluids require a solution based on partial differential equations for a similar level of analytic detail.

Internal and External Flow

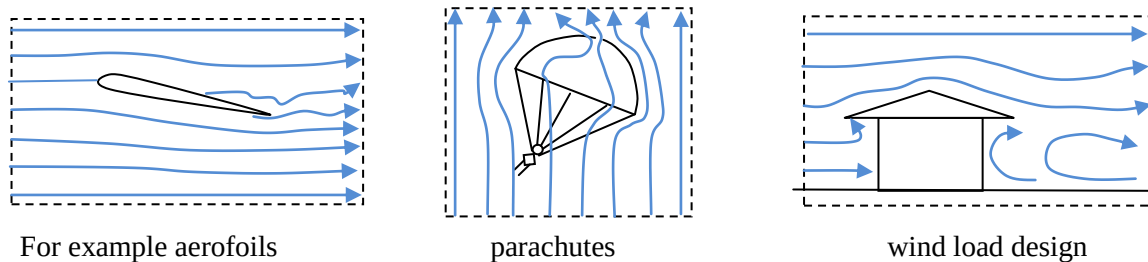
This classification is concerned with the boundary conditions of the flow, that is the assumptions that are made (or measured) regarding conditions at the edges, walls or boundaries of a model.

Internal flows are bounded by friction-inducing walls at which the flow velocity is zero:

For example pipe and channel flows:



External flows are ideally bounded by uniform external atmospheric conditions at some distance from a submerged body:



External flows are frequently modelled as ideal fluids, that is irrotational and inviscid, to a good approximation away from surfaces and boundary layers.

Incompressible and Compressible Flow

Again in principle all flows are compressible, since all fluids carry sound as a function of their compressibility:

$$c = \sqrt{\frac{dP}{d\rho}} = \sqrt{\frac{K}{\rho}}$$

c is the speed of sound in a fluid medium of elastic bulk modulus K and density ρ

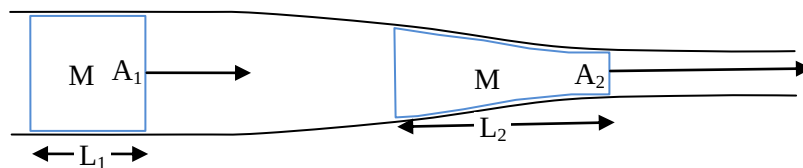
A flow may be treated as approximately incompressible depending on its velocity relative to c . High velocity gas flows contain sufficient momentum to induce compression effects, but slow gas flows and all realistic liquid flows may be treated as incompressible.

In general if $V < 0.3c$ the flow can be treated as incompressible.

Incompressible flows exchange kinetic and potential energy by changes in velocity, pressure and/or elevation. Compressible flows have a wider range of expression of energy, including thermodynamic variables such as temperature, work of expansion, enthalpy and entropy.

Compressible flows are governed by the ideal gas law $PV = nRT$ and the first and second laws of thermodynamics, in addition to the conservation laws applicable to all fluids. In general this produces more complex flow behaviours than for incompressible flows.

Continuity: Compressible and incompressible flows are subject to the conservation of mass, often referred to in fluid mechanics as *continuity*:



A defined group of fluid particles moves as a system through a control volume, accelerating as the available flow area decreases:

The mass of the system is constant:

$$\rho_1 \forall_1 = \rho_2 \forall_2 \quad \forall \text{ is volume}$$

$$\rho_1 A_1 L_1 = \rho_2 A_2 L_2$$

The length can be defined as the distance travelled at V in a small time period t : $L_1 = V_1 t$ $L_2 = V_2 t$:

$$\begin{aligned} \rho_1 A_1 V_1 &= \rho_2 A_2 V_2 \\ \text{thus} \quad &= \dot{m} \end{aligned} \quad \text{where } \dot{m} \text{ is the constant mass flowrate in kg/s:}$$

Compressible continuity equation

If the flow is incompressible, $\rho_1 = \rho_2$ and the continuity equation reduces to:

$$A_1 V_1 = A_2 V_2$$

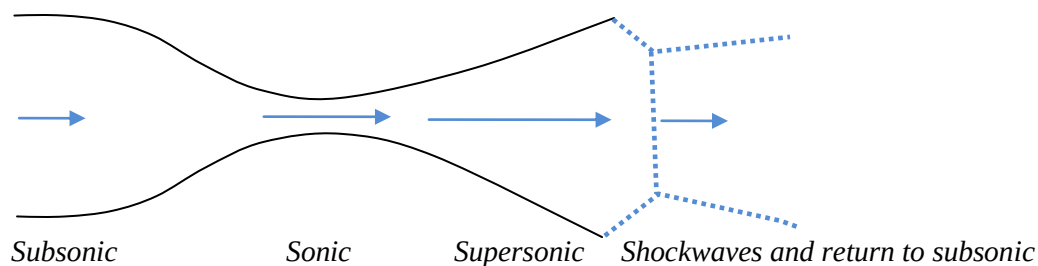
$$= Q \quad \text{where } Q \text{ is the volumetric flowrate in m}^3/\text{s}$$

Examples of incompressible flow:

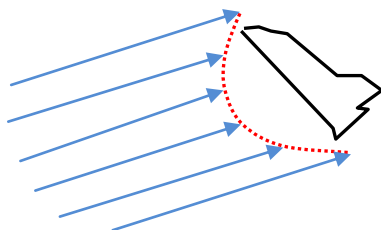
- Aircraft takeoff and landing
- Vehicle drag
- Parachute and spoiler operation

Examples of compressible flow:

- High speed gas flows
- Aircraft at cruising speeds, supersonic aircraft and atmospheric spacecraft operations
- Sonic and supersonic diverging nozzle flows:



- Spacecraft re-entry:



*Supersonic relative flow velocity
with superheated shockwave.
Intense thermodynamic effects
require heat shielding of
spacecraft*



Upper atmosphere re-entry in the Orbiter space flight simulator (<http://orbit.medphys.ucl.ac.uk>) .
Earth's g field produces initial re-entry velocities of ~7 km/s with very fine safety margins on re-entry.

Reading

Çengel and Cimbala 2006 (Reading 5) Section 1-2 and 1-3