

Lecture 8: Classifications of Fluid Flow

Introduction

Fluid flow is characterised by the relative freedom of movement of very large numbers of individual particles or fluid elements. Only the most advanced methods of analysis require a detailed accounting of fluid elements, while some simpler software packages are based on particle models.

The most common methods consider only the bulk characteristics of the flow, in particular as they change along the main direction of flow. These are based on the identification of quantities carried and exchanged by fluid elements, in particular mass, energy and forces due to friction and impact. The key variables relate to the *conserved* quantities of the three fundamental empirical laws of physics:

1. Conservation of Mass
2. Conservation of Momentum
3. Conservation of Energy

These quantities vary from place to place in a system, creating variable velocity and pressure distributions, but most importantly when traced systematically through a system they are conserved or constant, providing a way of relating different parts of the flow.

For example energy is constant along a streamline so long as all expressions of kinetic, potential, and thermal energy including friction losses are accounted for. From upstream measurements, downstream unknowns can be inferred, or vice versa.

Fluid flows are classified using a hierarchy of simplifying assumptions regarding the distribution of these quantities, which in turn lead to methods of solution of varying complexity. The standard classifications and an overview of methods (*methodology*) are set out in this section, as a precursor to more detailed study of the conservation laws (Section 4).

Flow Classifications

Uniform and Non-uniform Flow

A uniform flow is one in which all variables of interest are constant from place to place, ie as fixed values throughout the volume. This usually means that these variables are constant in time as well.

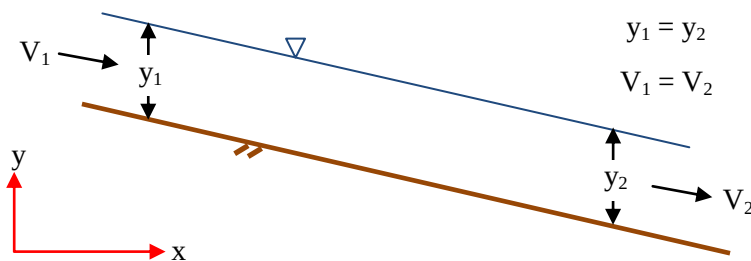
For velocity V , pressure P and density ρ :

$$\frac{dV}{dx} = 0 \rightarrow \frac{dV}{dt} = 0$$

$$\frac{dP}{dx} = 0 \rightarrow \frac{dP}{dt} = 0 \quad \} \text{ Descriptions of uniform flow}$$

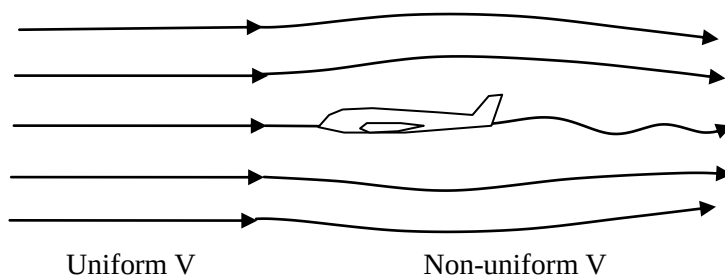
$$\frac{d\rho}{dx} = 0 \rightarrow \frac{d\rho}{dt} = 0$$

For example, fully developed uniform open channel flow. V_1 and V_2 are average velocities:



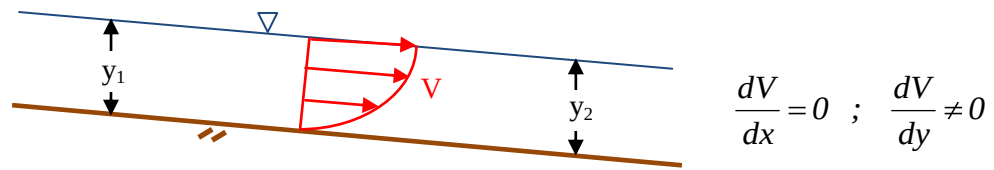
A long, straight and uniform channel develops a uniform flow of constant depth and velocity. The channel itself must be uniform in cross-section and slope for this to develop.

For another example, mid-atmosphere airflow:



At high altitude airflow velocities are approximately constant in small regions of interest such as a plane's airspace. The aircraft's velocity V can be added to the airflow velocity – the relative velocities can be modelled in a wind-tunnel with similar results.

Flows are often of mixed uniform and non-uniform velocity in different directions: For example an open channel flow that is uniform along the longitudinal direction will have a varying *velocity distribution* through the depth of the flow:

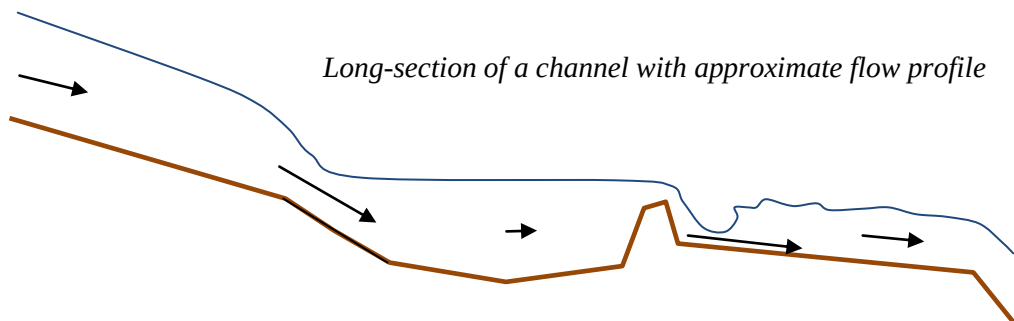


Uniform channel flow with non-uniform vertical velocity distribution. Note that channel slopes are typically so shallow that the direction of flow can be considered effectively horizontal.

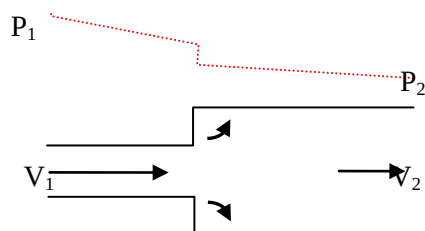
A non-uniform flow is variable in the space direction that is under consideration, ie we would consider the channel of figure to be uniform if we are only interested in changes along the direction of flow. Non-uniform flow may or may not involve variability in time as well.

$$\begin{aligned} \frac{dV}{dx} \neq 0 &\rightarrow \frac{dV}{dt} \ll 0 \\ \frac{dP}{dx} \neq 0 &\rightarrow \frac{dP}{dt} \ll 0 \\ \frac{d\rho}{dx} \neq 0 &\rightarrow \frac{d\rho}{dt} \ll 0 \end{aligned} \quad \} \text{ Descriptions of non-uniform flow}$$

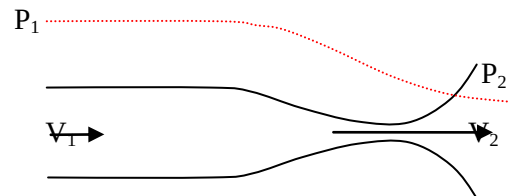
For example, general open channel flow:



General conduit flow:



Liquids in pipes



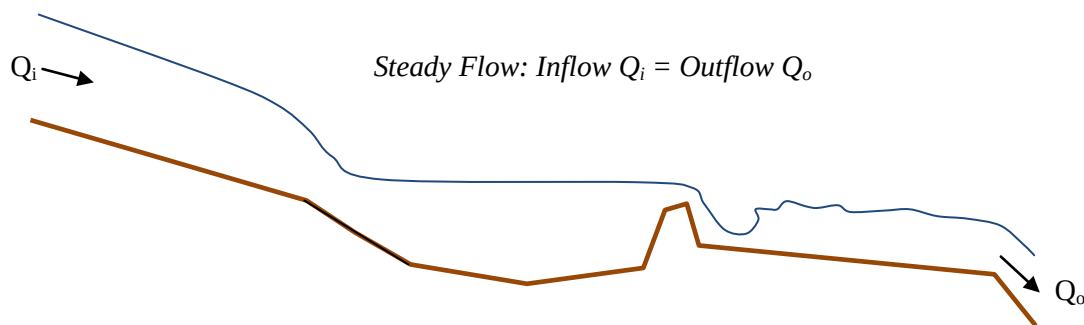
Gases in ducts

Steady and Unsteady Flow

A steady flow is one in which all the parameters of interest are constant in time, at least approximately or on average over the time scale of interest. This in no way requires the flow to be uniform:

$$\begin{aligned}\frac{dV}{dt} &= 0 \rightarrow \frac{dV}{dx} \ll 0 \\ \frac{dP}{dt} &= 0 \rightarrow \frac{dP}{dx} \ll 0 \\ \frac{d\rho}{dt} &= 0 \rightarrow \frac{d\rho}{dx} \ll 0\end{aligned} \quad \} \text{ Descriptions of steady flow}$$

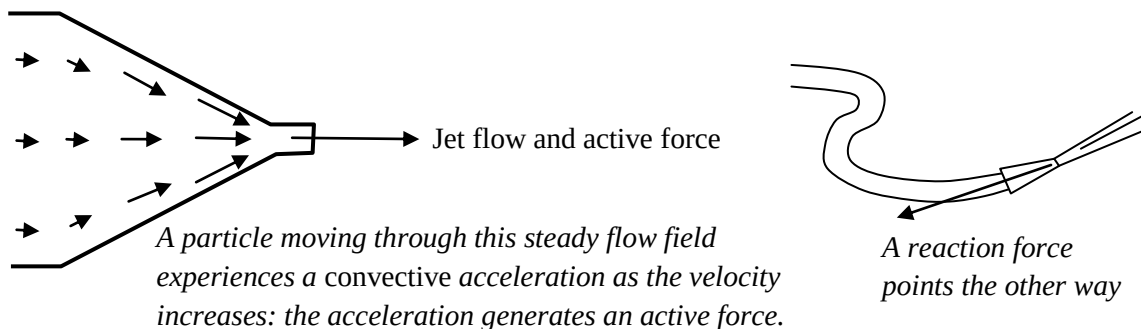
For example any of the previous examples of uniform or non-uniform flow:



An open channel in non-uniform flow can settle into a steady (unchanging) pattern where inputs (Q_i) equal outputs (Q_o). For slowly varying inflow and outflow rates, a non-uniform flow can be approximately constant ($Q_i \sim Q_o$) over a time interval of interest such as the peak flow period.

Convective acceleration: Steady flow has no change in velocity as a function of time. However, spatial changes in velocity result in significant accelerations and reaction forces:

For example a contraction or nozzle in steady flow:



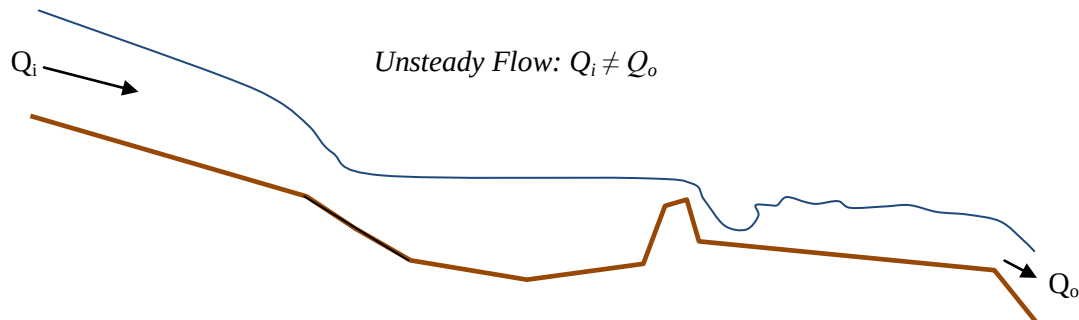
An unsteady flow is variable in time. This usually implies variation in space as well:

$$\frac{dV}{dt} \neq 0 \rightarrow \frac{dV}{dx} \neq 0$$

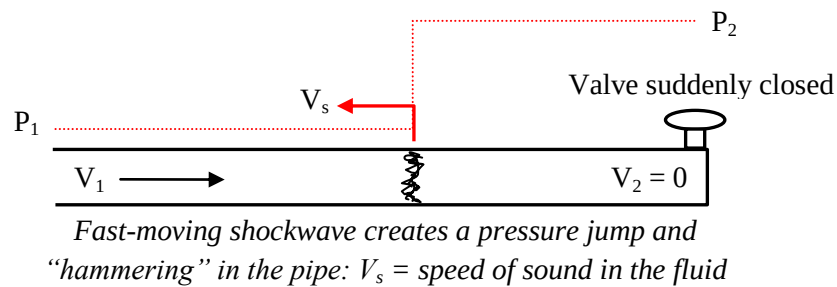
$$\frac{dP}{dt} \neq 0 \rightarrow \frac{dP}{dx} \neq 0 \quad \} \text{ Descriptions of unsteady flow}$$

$$\frac{d\rho}{dt} \neq 0 \rightarrow \frac{d\rho}{dx} \neq 0$$

For example a flood wave:



For example the water hammer phenomena:



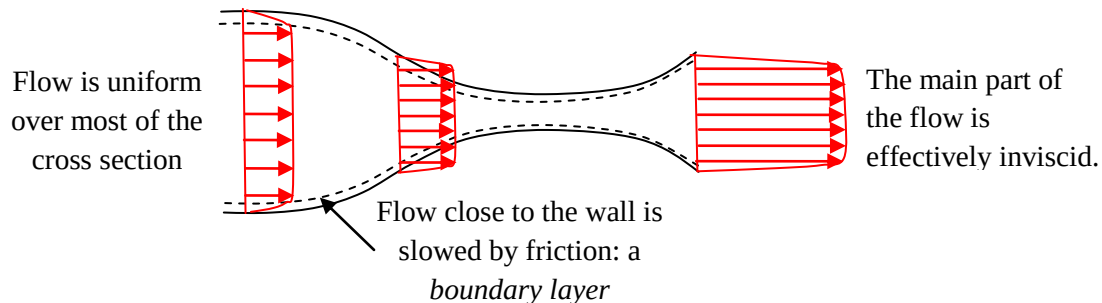
In principle all flows are both unsteady and non-uniform. In practice, many flows can be treated more simply as steady and/or uniform.

Viscous and Inviscid Flow

In principle all flows are viscous, since all real fluids have the property of viscosity. Viscous flows are subject to internal friction, resulting in an internal transfer of momentum in addition to other forces.

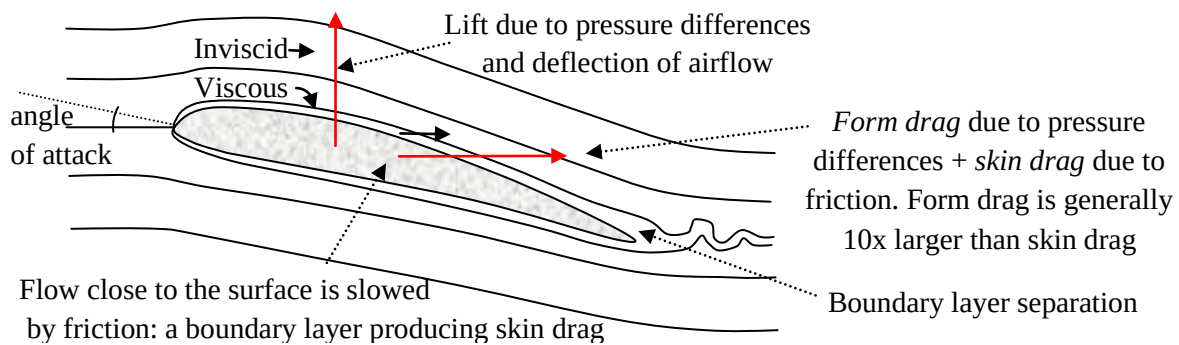
Flows can be treated as approximately *inviscid* or frictionless if the effects of viscosity are small compared to other dynamic factors, or are confined to regions that are small compared to the region of interest.

For example gas flow through a converging-diverging nozzle: a throat:



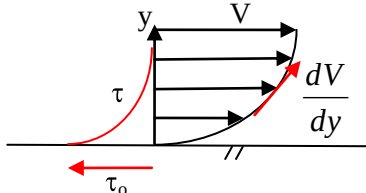
Viscosity produces significant effects near walls and boundaries, but conservation of mass, momentum and kinematic energy predominate through the body of the flow. The uniform flow region can be treated as inviscid.

For example, aerofoil lift and drag:



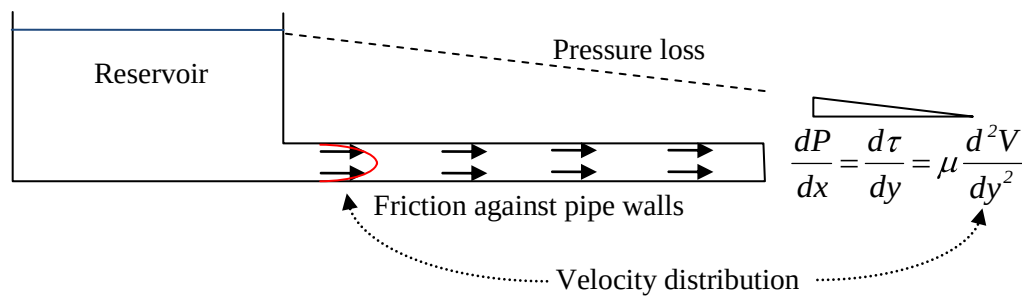
An aerofoil can be modelled to a high degree of accuracy by neglecting skin friction and treating the flow as inviscid. This simplified model breaks down at higher angles of attack as the viscous boundary layer separates into a turbulent region producing significant pressure differences.

Viscous flows are those in which viscous effects dominate the form and dynamics of the flow. A useful starting point is Newton's law of viscosity:

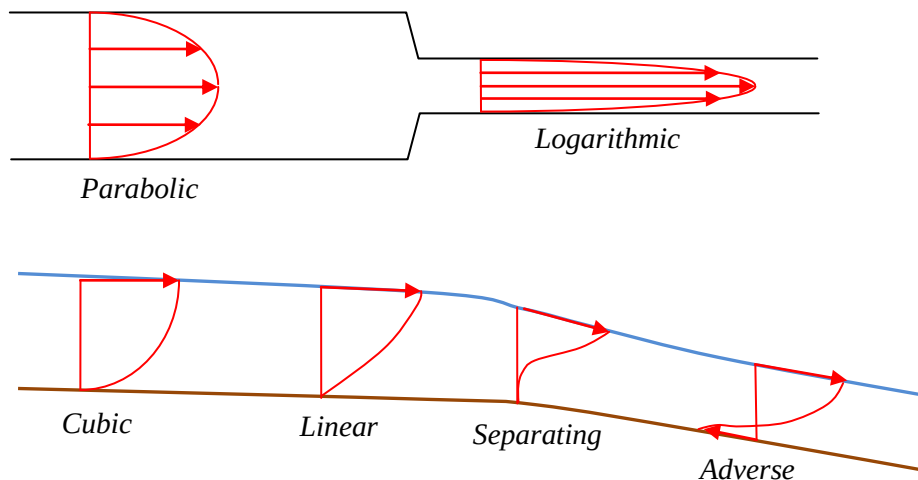
$$\tau = \mu \frac{dV}{dy}$$


Shear stresses (τ) produce drag, energy loss and momentum exchange. Velocity gradients are determined by pressure and shear gradients, which can be measured or approximated.

For example headloss in conduit flow (see Section 5):



As a result, we can determine velocity profiles in pipes and channels:



Skin friction and boundary layers:

