Ecole Nationale des Sciences et Technologies Avancées à Borj Cédria

Fluid Mechanics

Chapter 3

Basics of Fluid Flow
&
Dynamics of Ideal Fluids

2022-2023

Inroduction

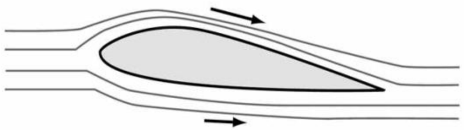
- When a fluid flows through pipes and channel or around bodies such as aircraft and ships, the shape of the boundaries, the externally applied forces and the fluid properties cause the velocities of the fluid particles to vary from point to point throughout the flow field.
- The motion of fluids can be predicted using the fundamental laws of physics together with the physical properties of the fluid.
- The geometry of the motion of fluid particles in space and time is known as the kinematics of the fluid motion.

External and internal flows

- <u>External flows</u>: aircraft, automobiles, buildings, ships, submarines, turbomachines…

Flow around a car

Flow around buildings

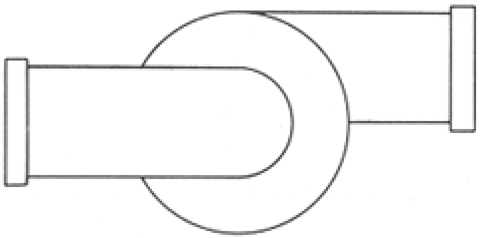


Flow around airfoil

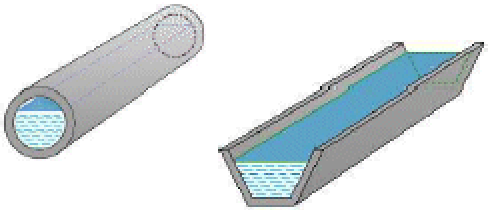
- Study of:
  - Applied forces by fluids on objects
  - Heat Transfer

External and internal flows

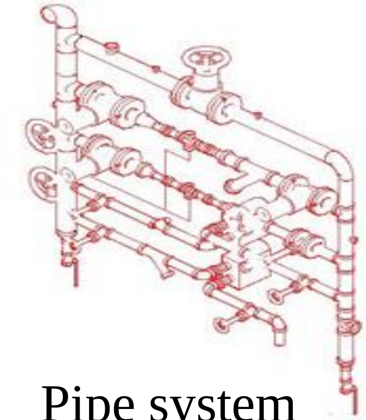
- Internal flows: Pipe flow, pomps, jets, open channels…



Centrifugal pump



Open channel



Pipe system

- Study of:
  - Flow rates,
  - Energy exchange
  - Applied forces on componants,
  - Heat transfer

Description of fluid motion

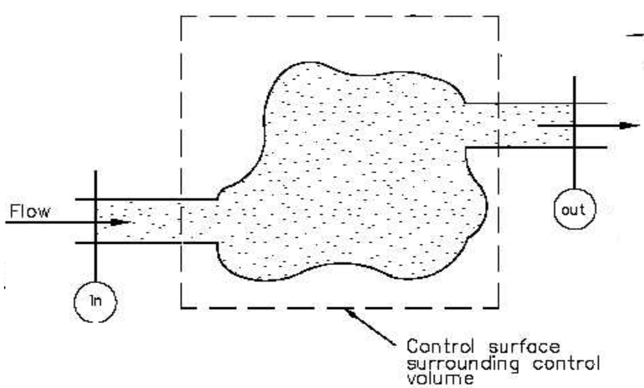
A fluid motion may be described by either;

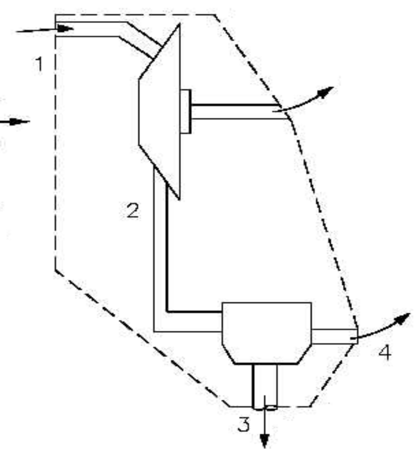
- ❑ <u>The Lagrangian approach</u>: tracing the motion of a particle (or a group of particles) through the field of flow

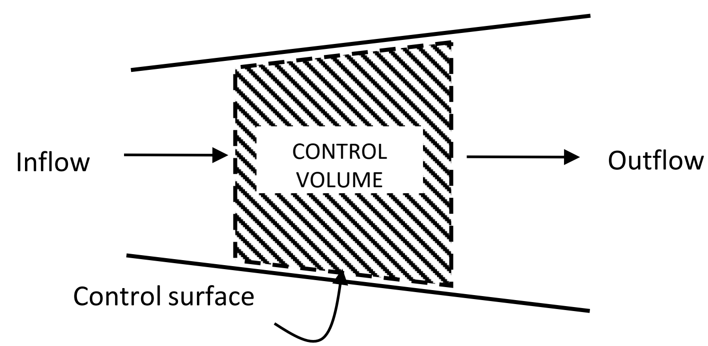
  - A group of particles forms a **system**.

- ❑ <u>The Eulerian approach</u>: or examining the motion of all particles as they pass a fixed point in space.

  - A fixed space is a **control volume**.

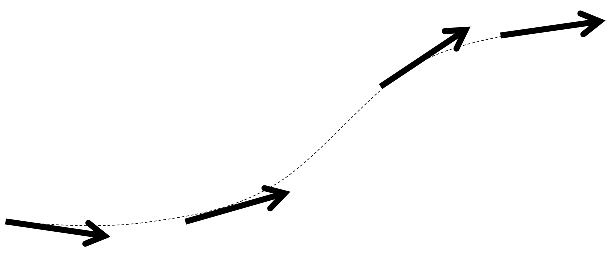






Streamline and Streamtubes

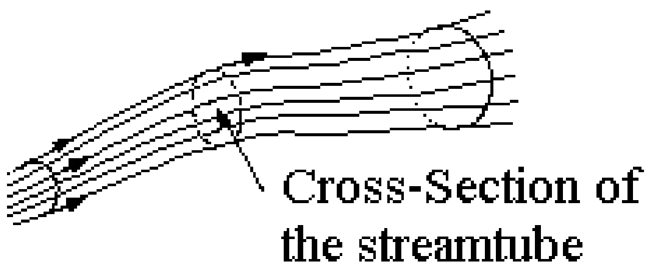
- A streamline is a line that is tangential to the instantaneous velocity direction (velocity is a vector, and it has a magnitude and a direction).
- In analyzing fluid flow it is useful to visualize the flow pattern. This can be done by drawing the *streamlines*.



A typical draw of a streamline

Streamline and Streamtubes

- Imagine a set of streamlines starting at points that form a closed loop.
- These streamlines form a tube that is impermeable since the walls of the tube are made up of streamlines, and there can be no flow normal to a streamline (by definition). This tube is called a streamtube.



Streamlines forming a streamtube

Compressible and incompressible fluids

- Compressible fluids: their density will change as pressure changes. Which is the case in most of fluids.
- Incompressible fluids: their density do not change with pressure
- Under steady conditions, and provided that the changes in pressure are small, it is usually possible to simplify analysis of the flow by assuming it is incompressible and has constant density.
- *liquids are quite difficult to compress* - so under most steady conditions they are treated as incompressible.

Flow categories and regimes

For better understanding the physics and the mathematical modeling of the flow, it is good to know the flow category or the flow regime such as

- 1, 2 or 3D flow
- Fully developed flow or developing flow
- Uniform or non-uniform,
- steady or unsteady
- Laminar flow
- transition, or
- turbulent

Uniform Flow, Steady Flow

uniform flow: flow velocity is the same magnitude and direction at every point in the fluid.

non-uniform: If at a given instant, the velocity is not the same at every point the flow. (In practice, by this definition, every fluid that flows near a solid boundary will be non-uniform - as the fluid at the boundary must take the speed of the boundary, usually zero. However if the size and shape of the of the cross-section of the stream of fluid is constant the flow is considered *uniform*.)

steady: A steady flow is one in which the conditions (velocity, pressure and cross-section) may differ from point to point but DO NOT change with time.

unsteady: If at any point in the fluid, the conditions change with time, the flow is described as unsteady. (In practice there is always slight variations in velocity and pressure, but if the average values are constant, the flow is considered steady.)

Uniform Flow, Steady Flow

Steady uniform flow: do not change with position in the stream or with time.

Example: the flow of water in a pipe of constant diameter at constant velocity).

Steady non-uniform flow: change from point to point in the stream but do not change with time.

Example: flow in a tapering pipe with constant velocity at the inlet-velocity will change as you move along the length of the pipe toward the exit.

Unsteady uniform flow: At a given instant in time the conditions at every point are the same, but will change with time.

Example: a pipe of constant diameter connected to a pump pumping at a constant rate which is then switched off.

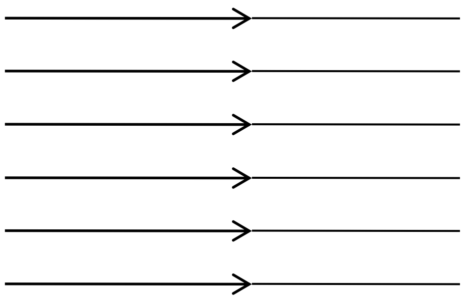
Unsteady non-uniform flow: Every condition of the flow may change from point to point and with time at every point.

Example: waves in a channel.

Flow Regimes

❑ Laminar flow:

All particles proceed along smooth parallel paths and all particles on any path will follow it without deviation.



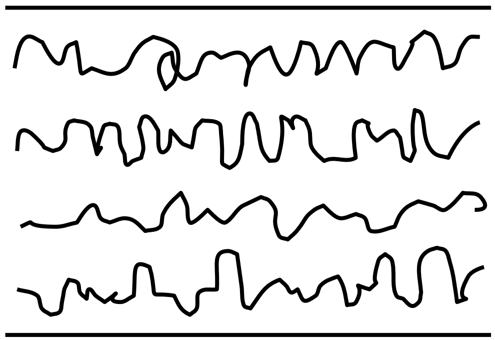
Typical particles path

❑ Turbulent flow:

Characterized by chaotic and stochastic property changes.

The particles move in an irregular manner through the flow field.

No clear path of particles can be identified.



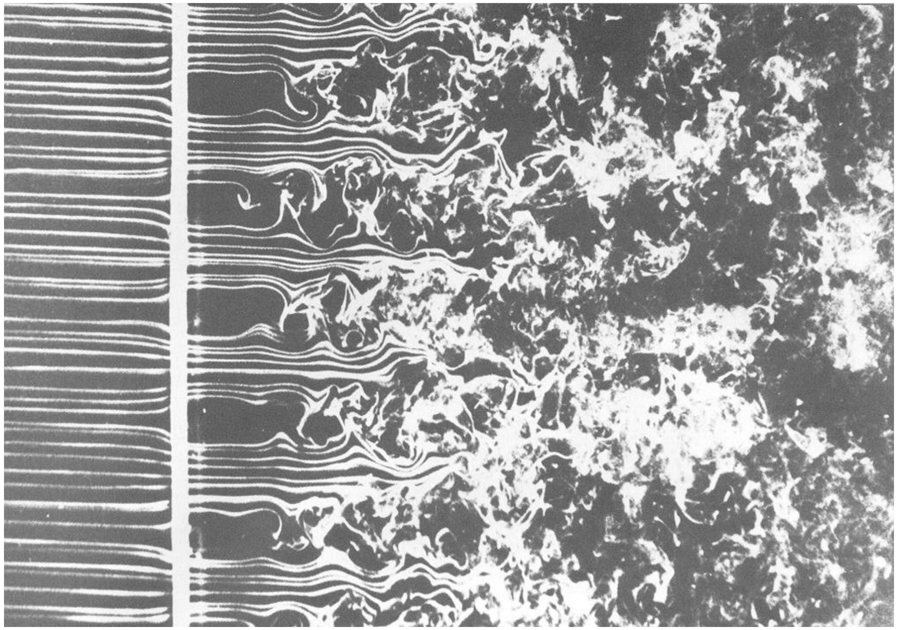
Typical particle paths

Flow Regimes

- Transition flows:

exists between laminar and turbulent flow.

In this region, the flow is very unpredictable and often changeable back and forth between laminar and turbulent states.



Reynolds Number

- Reynolds number is a dimensionless paramter that determines whether the flow is laminar or turbulent

$$Re = \frac{Inertia\ force}{Viscous\ force} = \frac{\rho DV}{\mu} = \frac{DV}{\upsilon}$$

Where

V is the velocity of the flow

D is a characteristic length (for exeample diameter of the pipe)

ρ is the fluid density

μ is the dynamic viscosity of the fluid

ν is the kinematic viscosity of the fluid ($\nu = \mu/\rho$)

Reynolds Number

- For the flow in a pipe the flow regime is
  - **laminar** when $Re < 2300$
  - **transient** when $2300 < Re < 4000$
  - **turbulent** when $Re > 4000$

Example :

If the pipe and the fluid have the following properties, at what velocity the flow in a pipe stops being laminar?

water density, $\rho = 1000\ kg/m^3$

pipe diameter, D = 0.5m

viscosity, $\mu = 0.55 \times 10^{-3}\ Ns/m^2$

Solution:

We want to know the maximum velocity for laminar flow, i.e. when Re = 2000.

$$Re = \frac{\rho D V}{\mu} \Rightarrow V = \frac{Re\mu}{\rho D} = \frac{2000 \times 0.55 \times 10^{-3}}{1000 \times 0.5} = 0.002 m/s$$

Mass flow rate and Volume flow rate - Discharge

- The mass flow rate is defined as

$$\dot{m} = \frac{mass\ of\ the\ fluid}{time\ taken\ to\ collect\ the\ fluid}$$

Then $time = \dfrac{mass}{mass\ flow\ rate}$

- the volume flow rate (discharge) is defined as

$$Q = \frac{volume\ of\ fluid}{time} = \frac{mass\ of\ fluid}{density \times time}$$

$$\Rightarrow Q = \frac{mass\ fluid\ rate}{density} = \frac{\dot{m}}{\rho}$$

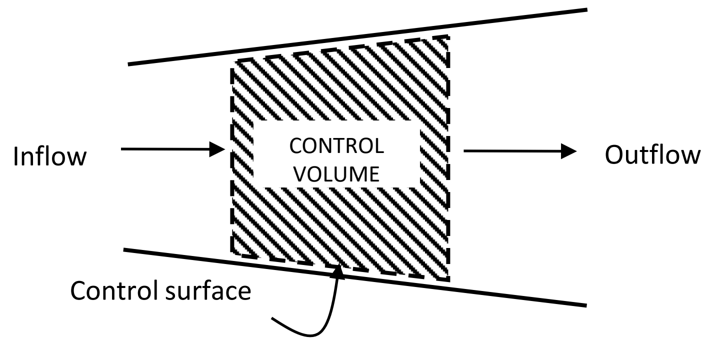
Fundamental Equations of Fluid Dynamics

All fluid mechanics problems satisfy the basic laws of:

- Conservation of mass
- Newton's second law (conservation of momentum)
- The conservation of kinetic moment
- The first law of thermodynamic (conservation of energy)
- The second law of thermodynamic

Conservation of Mass - Continuity

- Matter cannot be created nor destroyed - (it is simply changed in to a different form of matter).
- This principle is known as the *conservation of mass* and we use it in the analysis of flowing fluids.
- The principle is applied to fixed volumes, known as control volumes or surfaces



Conservation of Mass - Continuity

For any control volume the principle of *conservation of mass* says

Mass entering = Mass leaving + Increase of mass in the control

In term of equation it can be written as follows (according to the CV approach)

$$\frac{\partial}{\partial t}\int_{CV} \rho dV + \int_{CS} \rho \vec{V} d\vec{A} = 0$$

Conservation of Mass - Continuity

❑ For steady flow (there is no increase in the mass within the control volume)

Mass entering per unit time = Mass leaving per unit time

❑ For incompressible flow the mass flow, *m*, entering may be calculated by taking the product

$$\rho \times Q$$

hence $\rho\, Q\ (entering) = \rho\, Q\ (leaving)$

But since flow is incompressible, the density is constant, so

$$Q\ (entering) = Q\ (leaving)$$

This is the '***continuity equation***' for steady incompressible flow.

Conservation of Mass - Continuity

Consider V_1 constant through the cross-section A_1, then

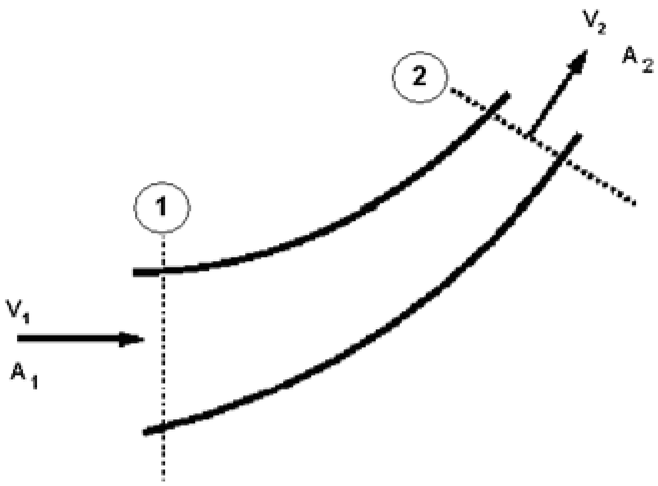
$$Q\ (entering) = V_1 A_1$$

Same for V_2 through the cross-section A_2, then

$$Q\ (leaving) = V_2 A_2$$

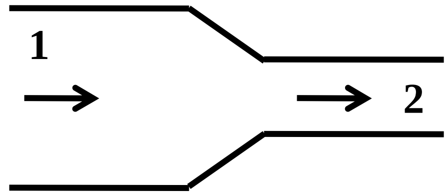
Therefore, the continuity equation may also be written as

$$\boldsymbol{V_1 A_1 = V_2 A_2}$$



Application of Continuity Equation

- ❑ Pipes with cross sections which change along their length

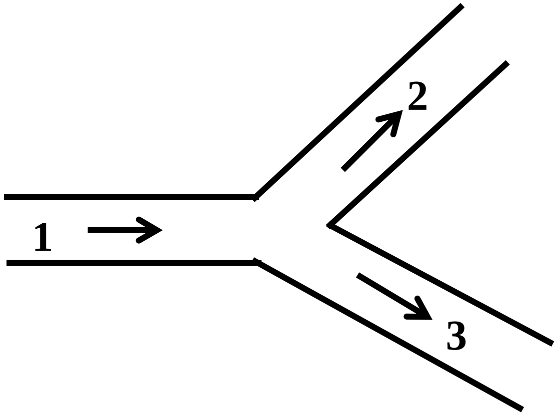


Continuity : $\rho_1 A_1 V_1 = \rho_2 A_2 V_2$

Incompressible flow (liquid): $\rho_1 = \rho_2 = \rho$

$$A_1 V_1 = A_2 V_2 \Rightarrow V_2 = \frac{A_1 V_1}{A_2}$$

- ❑ Pipes coming from a junction



Continuity : $\rho_1 Q_1 = \rho_2 Q_2 + \rho_3 Q_3$

When the flow is incompressible

(e.g. water) $\rho_1 = \rho_2 = \rho$

$Q_1 = Q_2 + Q_3$

$A_1 V_1 = A_2 V_2 + A_3 V_3$

Newton's Second Law - Conservation of momentum

- States that a body in motion cannot gain or lose momentum unless some external force is applied.
- The classical statement of this law is Newton's Second Law of Motion, i.e.

force = rate of change of momentum

- Mathematical formulation

$$\sum \vec{F} = \frac{\partial}{\partial t}\int_{CV} \rho\vec{V}\,.\,dv + \int_{CS} \vec{V}.\rho\vec{V}\,.\,d\vec{A}$$

The first law of thermodynamic - Principle Of Conservation Of Energy

- Energy can be transformed from one guise to another (e.g. potential energy can be transformed into kinetic energy), but none is actually lost.
- Engineers sometimes loosely refer to 'energy losses' due to friction, but in fact the friction transforms some energy into heat, so none is really 'lost'!
- Mathematical formulation

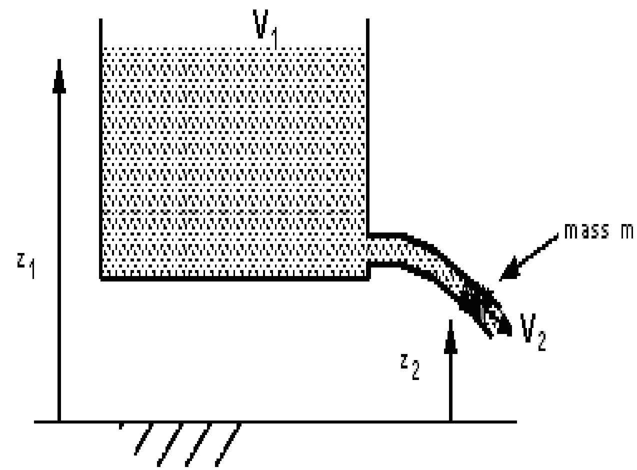
$$\dot{Q} + \dot{W} = \frac{\partial}{\partial t}\int_{CV} e\rho \, . \, dv + \int_{CS} e\rho\vec{V} . \rho\vec{V}$$

With $e = u + \frac{V^2}{2} + gz$

Application - Flow from a reservoir

- The level of the water in the reservoir is z_1. There is no movement of water so kinetic energy is zero but the gravitational potential energy is mgz_1.

- If a pipe is attached at the bottom water flows along this pipe out of the tank to a level z_2. A mass m has flowed from the top of the reservoir to the nozzle and it has gained a velocity V_2. The kinetic energy is now $\frac{1}{2}mV_2^2$ and the potential energy mgz_2.



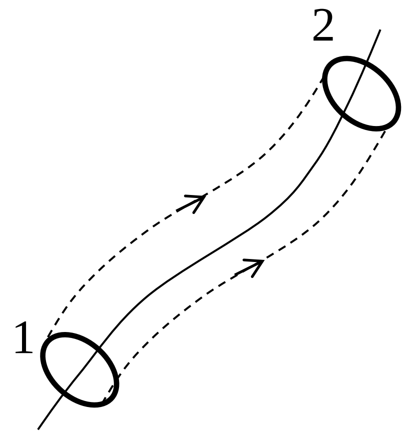
Conservation of : $mgz_1 = \frac{1}{2}\, mV_2^2 + mgz_2$

Then $V_2 = \sqrt{2g(z_1 - z_2)}$

Bernoulli's Equation

Consider

- Steady state flow
- No friction
- Incompressible flow
- Along a streamtube



$$\frac{P_1}{\rho} + \frac{V_1{}^2}{2} + gz_1 = \frac{P_2}{\rho} + \frac{V_2{}^2}{2} + gz_2$$

$$\frac{P}{\rho} + \frac{V^2}{2} + gz = \text{constant}$$

$$\frac{P}{\gamma} + \frac{V^2}{2g} + z = \text{constant}$$

Modified Bernoulli's Equation

- In practice, the total energy of a streamline does not remain constant.

$$\frac{P}{\gamma} + \frac{V^2}{2g} + z \neq \text{constant}$$

- Energy is 'lost' through friction, and external energy may be either added by means of a pump or extracted by a turbine.

$$\frac{P_1}{\gamma} + \frac{{V_1}^2}{2g} + z_1 \mp H_E = \frac{P_2}{\gamma} + \frac{{V_2}^2}{2g} + z_2 + H_f$$

where

– H_E: Added or extracted Energy

– H_f: Lost Energy (head losses)

Units : Length