Fluid Mechanics - MTF053

Lecture 2

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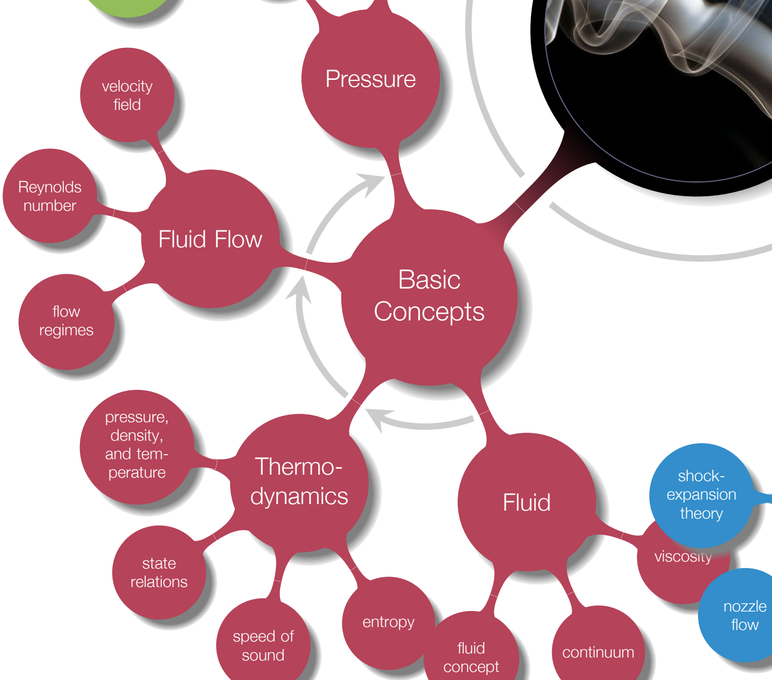
Chapter 1 - Introduction

Overview



Pressure
velocity field
Reynolds number
Fluid Flow
flow regimes
Basic Concepts
pressure, density, and tem-perature
Thermo-dynamics
state relations
speed of sound
entropy
Fluid
fluid concept
continuum
viscosity
shock-expansion theory
nozzle flow

Learning Outcomes

1 **Explain** the difference between a fluid and a solid in terms of forces and deformation

2 **Understand** and be able to explain the viscosity concept

3 **Define** the Reynolds number

5 **Explain** the difference between Lagrangian and Eulerian frame of reference and know when to use which approach

7 **Explain** the concepts: streamline, pathline and streakline

8 **Understand** and be able to **explain** the concept shear stress

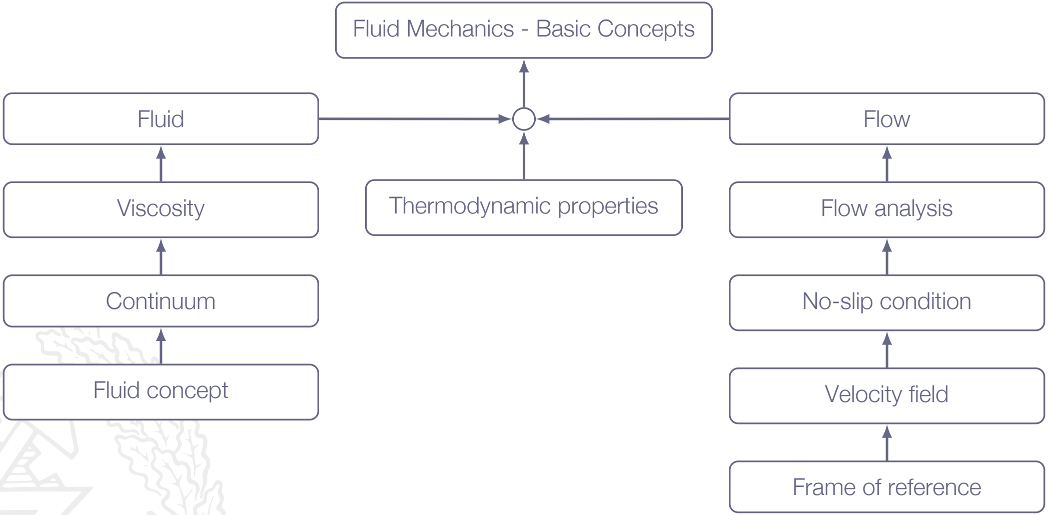
9 **Explain** how to do a force balance for fluid element (forces and pressure gradients)

10 **Understand and explain** buoyancy and cavitation

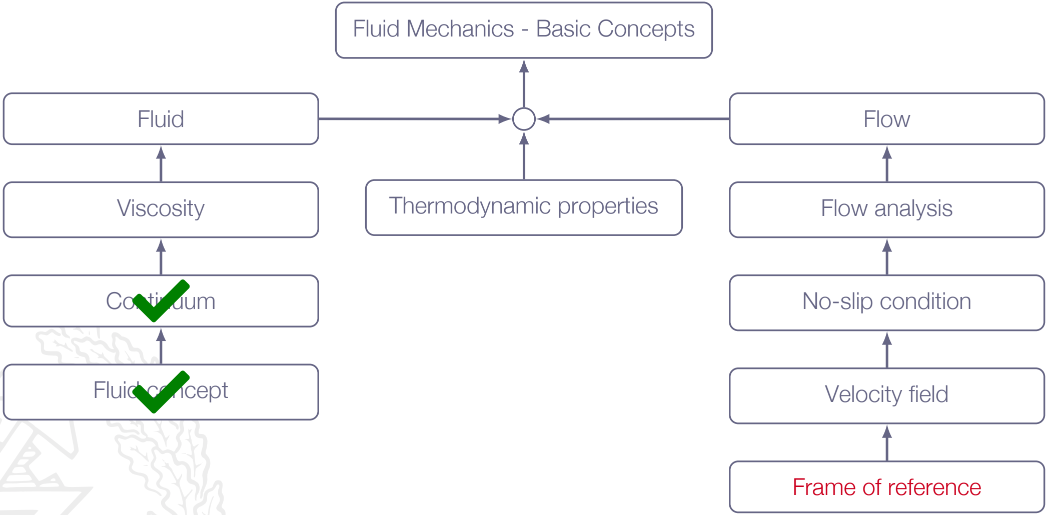
16 **Understand** and **explain** the concept Newtonian fluid

in this lecture we will find out what a fluid flow is

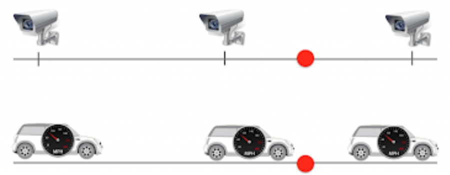
Roadmap - Introduction to Fluid Mechanics



Roadmap - Introduction to Fluid Mechanics

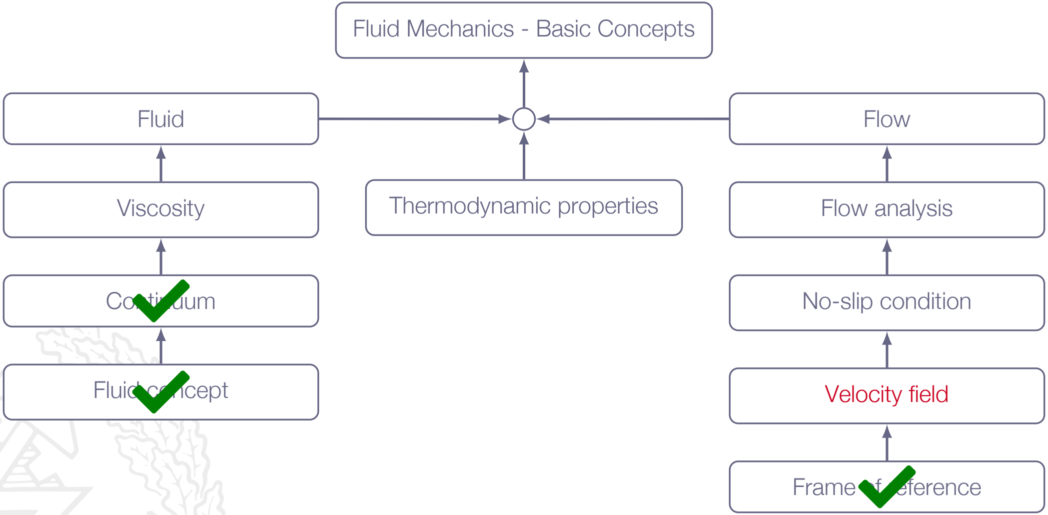


Frame of Reference



- Eulerian
  - fluid properties as function of position and time
  - most often used in fluid mechanics
- Lagrangian
  - follows a system in time and space
  - can be used in fluid mechanics
  - most often used in solid mechanics

Roadmap - Introduction to Fluid Mechanics



Properties of the Velocity Field

- The fluid velocity is a function of position and time
- Three components u, v, and w (one in each spatial direction)

$$\mathbf{V}(x,y,z,t) = u(x,y,z,t)\mathbf{e}_x + v(x,y,z,t)\mathbf{e}_y + w(x,y,z,t)\mathbf{e}_z$$

Properties of the Velocity Field

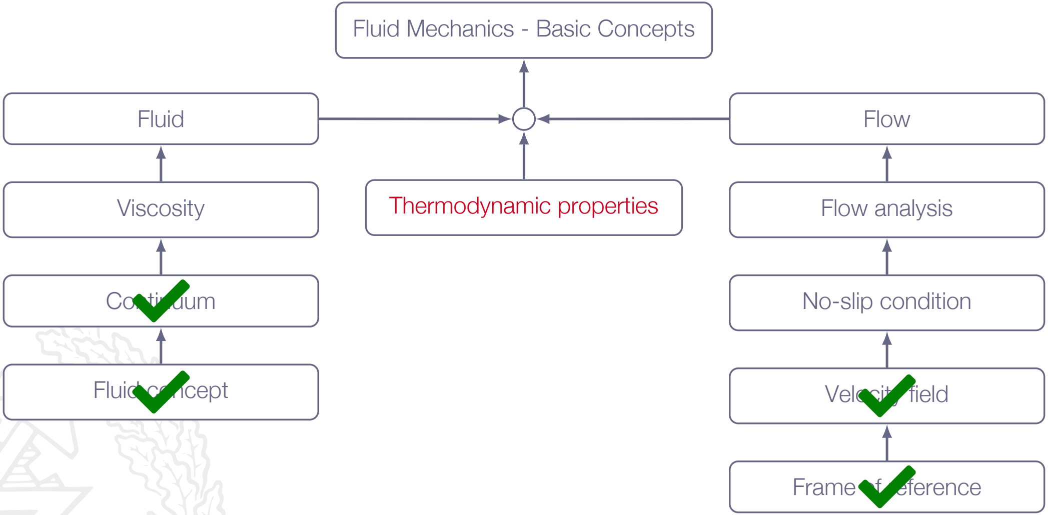
Acceleration:

$$\mathbf{V}(x,y,z,t) = u(x,y,z,t)\mathbf{e}_x + v(x,y,z,t)\mathbf{e}_y + w(x,y,z,t)\mathbf{e}_z$$

$$\mathbf{a} = \frac{d\mathbf{V}}{dt} = \frac{\partial \mathbf{V}}{\partial t} + \left(\frac{\partial \mathbf{V}}{\partial x}\right)\left(\frac{\partial x}{\partial t}\right) + \left(\frac{\partial \mathbf{V}}{\partial y}\right)\left(\frac{\partial y}{\partial t}\right) + \left(\frac{\partial \mathbf{V}}{\partial z}\right)\left(\frac{\partial z}{\partial t}\right)$$

$$\frac{d\mathbf{V}}{dt} = \frac{\partial \mathbf{V}}{\partial t} + u\frac{\partial \mathbf{V}}{\partial x} + v\frac{\partial \mathbf{V}}{\partial y} + w\frac{\partial \mathbf{V}}{\partial z}$$

Roadmap - Introduction to Fluid Mechanics



Thermodynamic Properties

- Thermodynamic properties describe the state of a system, i.e., a collection of matter of fixed identity which interacts with its surroundings

- In this course, the system will be a small fluid element, and all properties will be assumed to be continuum properties of the flow field

Thermodynamic Properties

- Pressure p Pa
- Density ρ kg/m^3
- Temperature T K

most common properties

Thermodynamic Properties

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most common properties

- Internal energy $\hat{u}$
- Enthalpy $h = \hat{u} + p/\rho$
- Entropy s
- Specific heats C_p and C_v

work, heat, and energy balances

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work, heat, and energy balances

- Viscosity μ
- Thermal conductivity k

friction and heat conduction

Thermodynamic Properties

- For a single-phase substance, two basic properties are sufficient to get the values of all others

$$\rho = \rho(p, T), h = h(p, T), \mu = \mu(p, T)$$

- In the following it will be assumed that all thermodynamic properties exists as point functions in a flowing fluid
  - large enough number of molecules
  - any changes are slower than the flow time scale $\Rightarrow$ equilibrium

Thermodynamic Properties

Pressure: $p[Pa]$

- the compression stress at a point in a static fluid
- a fluid flow is often driven by pressure gradients
- if the pressure drops below the vapor pressure in a liquid, vapor bubbles will form

Temperature: $T[K]$

- related to internal energy
- large temperature differences $\Rightarrow$ heat transfer may be important

Density: $\rho[kg/m^3]$

- mass per unit volume
- nearly constant in liquids (incompressible) - for water, the density increases about one percent for a pressure increase by a factor of 220
- not constant for gases

$$\rho = \frac{p}{RT}$$

Potential and Kinetic Energies

The total stored energy per unit mass:

$$e = \hat{u} + \frac{1}{2}V^2 + gz$$

- the internal energy is a function of temperature
- the potential and kinetic energies are kinematic quantities

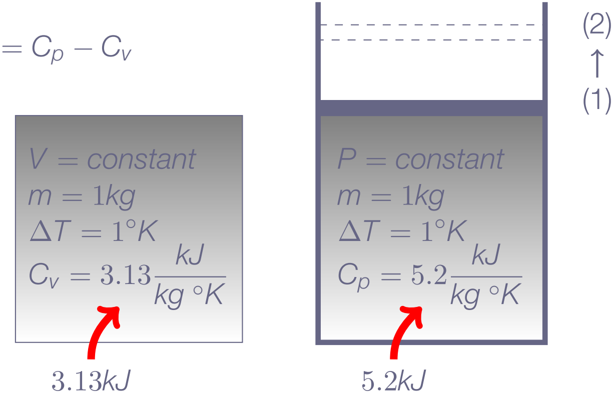
State Relations for Gases

The perfect gas law:

$$p = \rho R T$$

where R is the gas constant

$$R = C_p - C_v$$



State Relations for Gases

The ideal gas law requires: $\hat{u} = \hat{u}(T)$ and thus

specific heat (constant volume):

$$C_v = \left(\frac{\partial \hat{u}}{\partial T}\right)_\rho = \frac{d\hat{u}}{dT} = C_v(T)$$

State Relations for Gases

specific heat (constant pressure):

$$h = \hat{u} + \frac{p}{\rho} = \hat{u} + RT = h(T)$$

$$C_p = \left(\frac{\partial h}{\partial T}\right)_p = \frac{dh}{dT} = C_p(T)$$

ratio of specific heats:

$$\gamma = \frac{C_p}{C_v} \geq 1$$

State Relations for Gases

$$C_v = \frac{R}{\gamma - 1}$$

$$C_p = \frac{\gamma R}{\gamma - 1}$$

Speed of Sound

Speed of sound plays an important role when compressible effects are important (Chapter 9)

$$a^2 = \left(\frac{\partial p}{\partial \rho}\right)_s$$

$$\tau_s = \frac{1}{\rho}\left(\frac{\partial \rho}{\partial p}\right)_s \Rightarrow a = \sqrt{\frac{1}{\rho \tau_s}}$$

where τ_s is the fluid compressibility

for an ideal gas:

$$\boxed{a = \sqrt{\gamma R T}}$$

Vapor Pressure

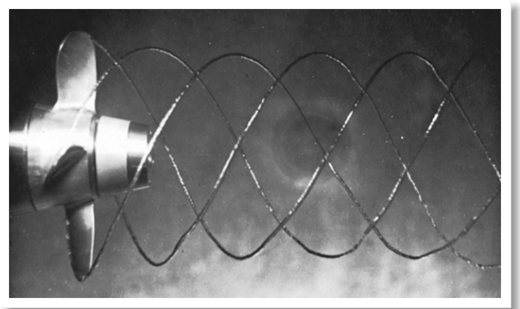
"the pressure at which a liquid boils and is in equilibrium with its own vapor"

Vapor pressure for water:

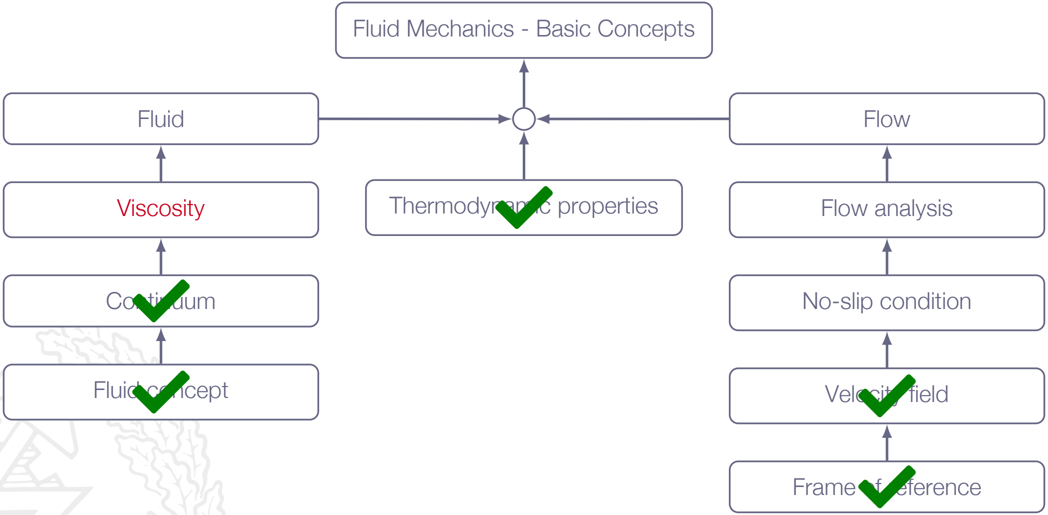
$T\,[^\circ C]$	vapor pressure $[Pa]$
20	2340
100	101300

Vapor Pressure

- If the pressure in a liquid gets lower than the vapor pressure, vapor bubbles will appear in the liquid
- If the pressure drops below the vapor pressure due to the flow itself we get cavitation



Roadmap - Introduction to Fluid Mechanics



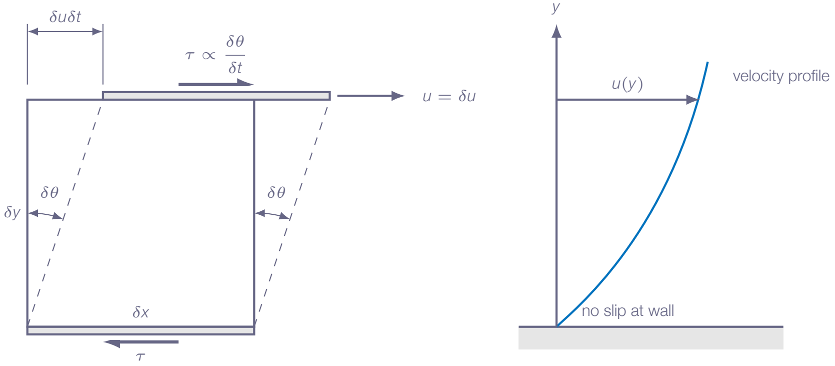
Viscosity

Viscosity

”relates the local stresses in a moving fluid to the strain rate of the fluid element”

”a quantitative measure of the fluid’s resistance to flow”

Viscosity



$$\tau \propto \frac{\delta\theta}{\delta t}, \ \tan\delta\theta = \frac{\delta u \delta t}{\delta y}$$

Viscosity

for infinitesimal changes:

$$\frac{d\theta}{dt} = \frac{du}{dy}$$

from before we know that $\tau \propto \dfrac{\delta\theta}{\delta t}$ and thus $\tau \propto \dfrac{d\theta}{dt}$

For newtonian fluids:

$$\boxed{\tau = \mu\frac{d\theta}{dt} = \mu\frac{du}{dy}}$$

where μ is the fluid viscosity

Viscosity

- Liquids have high viscosity that decreases with temperature
  - intermolecular forces decreases with temperature
- Gases have low viscosity that increases with temperature
  - increased temperature means increased molecular movement

Viscosity

Fluid	$\mu\ (kg\ m^{-1}\ s^{-1})$	$\rho\ (kg\ m^{-3})$	$\nu\ (m^2\ s^{-1})$
Hydrogen	8.8 E-06	8.400 E-02	1.05 E-04
Air	1.8 E-05	1.200 E+00	1.51 E-05
Gasoline	2.9 E-04	6.800 E+02	4.22 E-07
Water	1.0 E-03	9.980 E+02	1.01 E-06
Mercury	1.5 E-03	1.358 E+04	1.16 E-07
SAE-30 Oil	2.9 E-02	8.910 E+02	3.25 E-04
Glycerin	1.5 E+00	1.264 E+03	1.18 E-03

Note! there are two different viscosities in the table (dynamic viscosity μ and kinematic viscosity $\nu = \mu/\rho$)

Viscosity

Inviscid flows: flows where viscous forces are negligible

Viscous flows: flows where viscous forces are important

Reynolds number

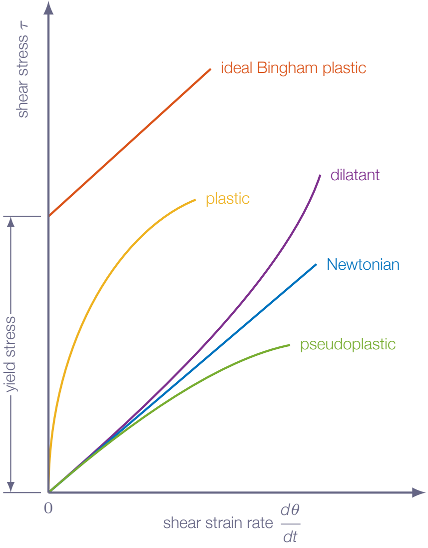
$$Re = \frac{\rho V L}{\mu}$$

- Non-dimensional number that relates viscous forces to inertial forces
- Very important parameter in fluid mechanics
- V and L are characteristic velocity and length scales of the flow

Reynolds number

Reynolds number	flow description
low	viscous, creeping motion (inertial forces negligible)
moderate	laminar flow
high	turbulent flow

Non-Newtonian Fluids



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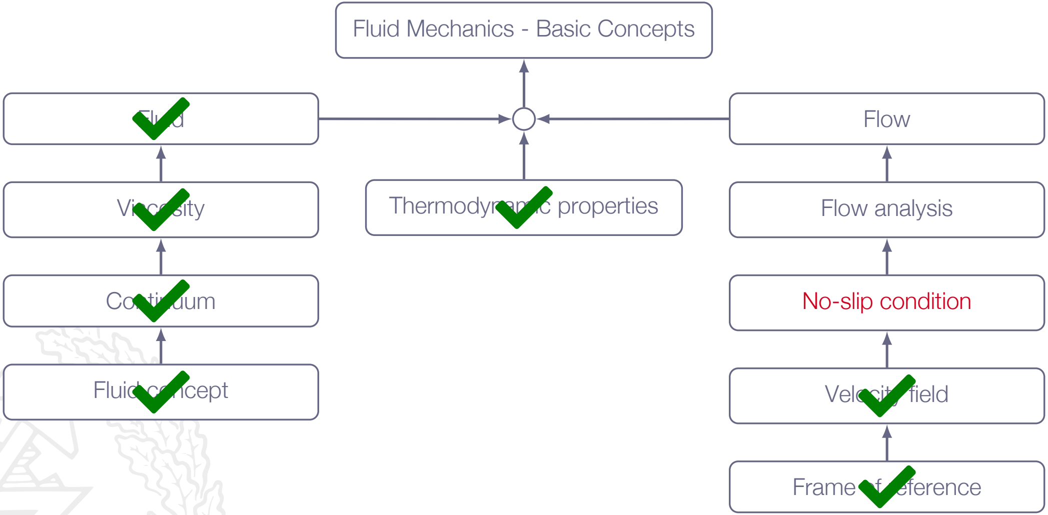
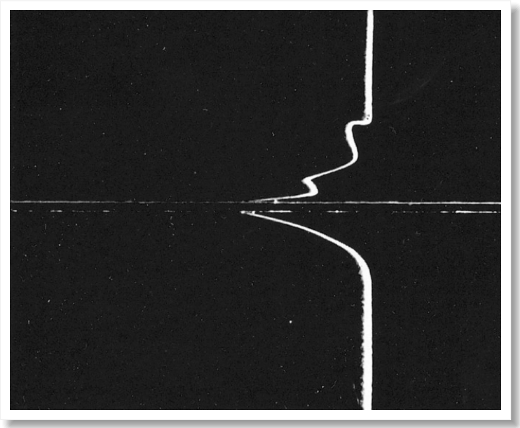


No Slip/No Temperature Jump

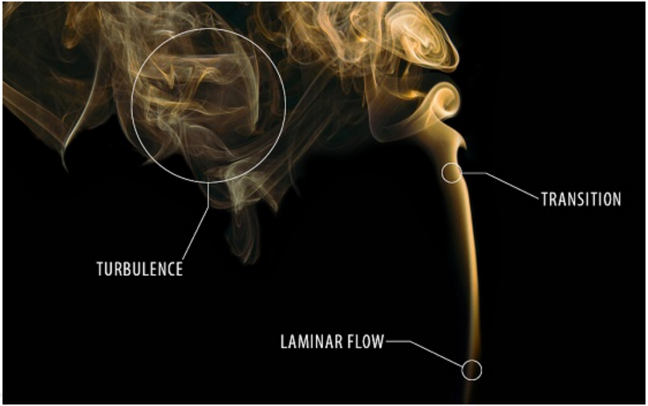
"When a fluid flow is bounded by a solid surface, molecular interactions cause the fluid in contact with the surface to seek momentum and energy equilibrium with that surface"

No Slip/No Temperature Jump

At a solid wall, the fluid will have the velocity and temperature of the wall



Laminar/Turbulent Flow



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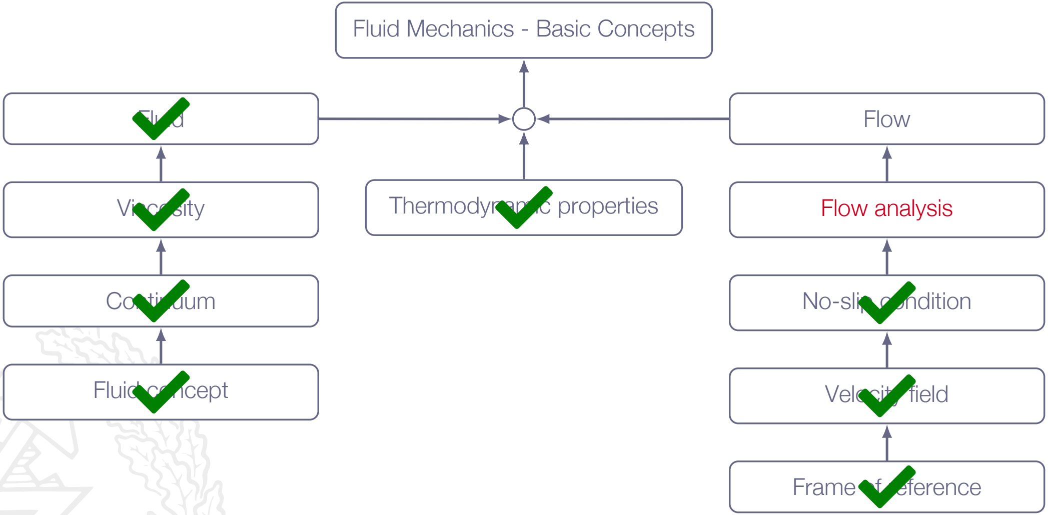

Flow Analysis

Chapter 3 - Control-volume (integral) approach

Chapter 4 - Infinitesimal system (differential) approach

Chapter 5 - Dimensional analysis approach

Flow Analysis

- Conservation of mass (continuity)
- Conservation of momentum (Newton's second law)
- Conservation of energy (first law of thermodynamics)
- State relation (for example the ideal gas law)
- Second law of thermodynamics
- Boundary conditions

Flow Visualization

Streamline

- a line that is tangent to the velocity vector everywhere at an instant in time

Pathline

- the actual path traversed by a fluid particle

Streakline

- the locus of particles that have earlier passed through a prescribed point

Timeline

- a line formed by a set of particles at a given instant

Flow Visualization

Streamline

- a line that is tangent to the velocity vector everywhere at an instant in time

Pathline

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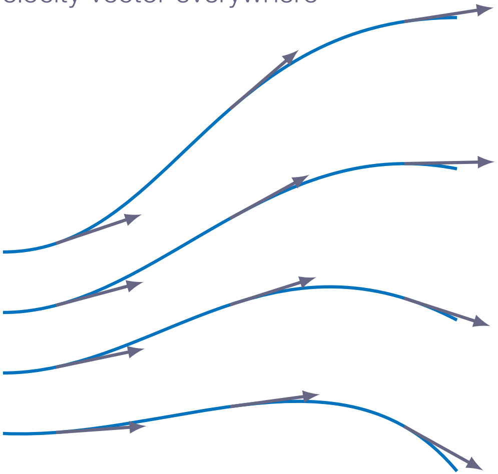
Timeline

- a line formed by a set of particles at a given instant

Note! In a steady-state flow, streamlines, pathlines and streaklines are identical

Streamline

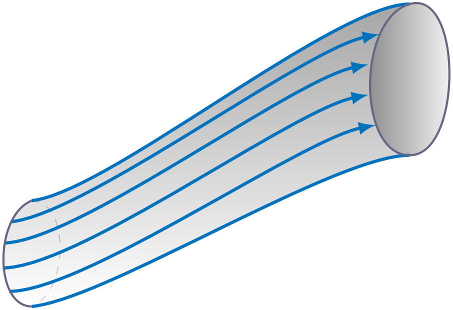
Tangent to flow velocity vector everywhere



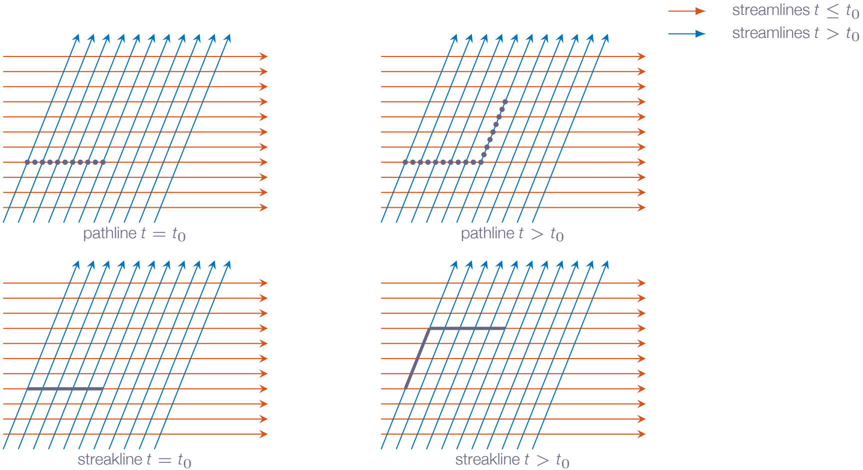
Streamtube

”Constructed” from individual streamlines

No flow across streamtube ”walls” (by definition)



Pathline vs Streakline



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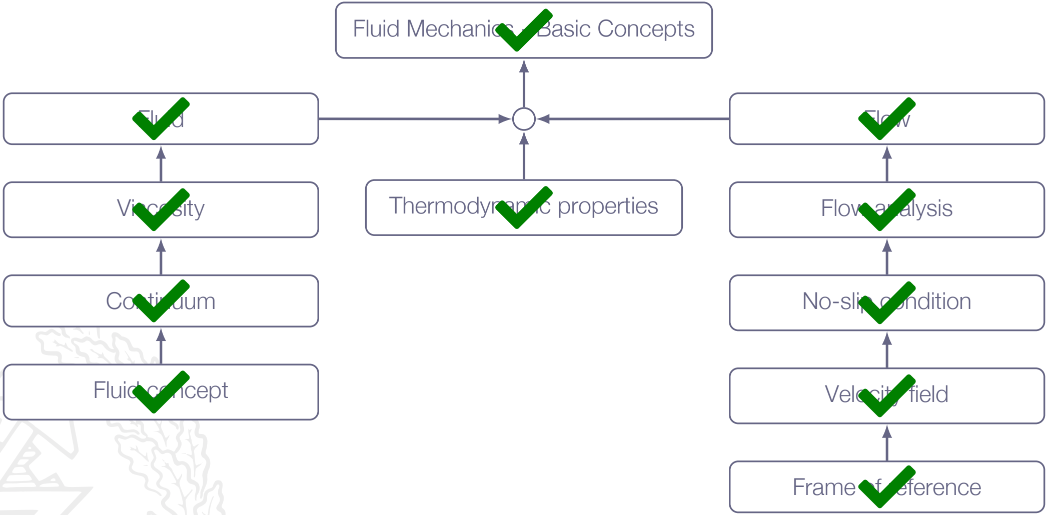
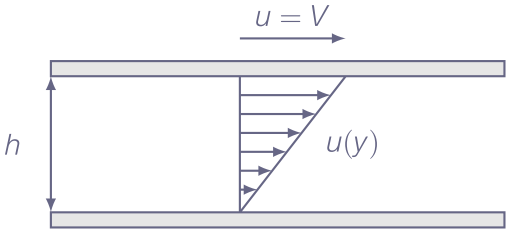
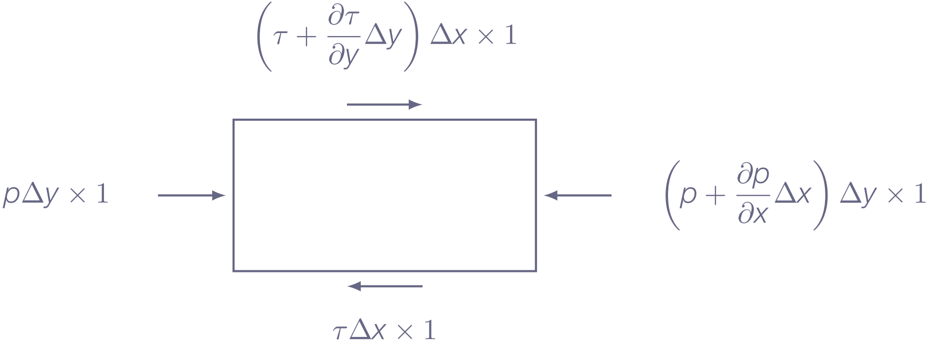


Example - Flow Between Plates



- No acceleration
- No pressure gradients
- two-dimensional flow

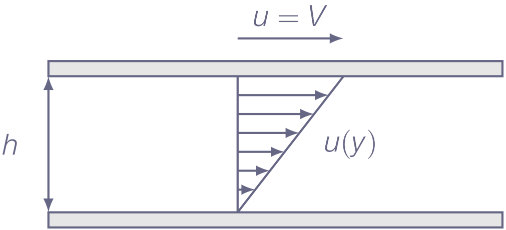
Example - Flow Between Plates



$$\sum F_x = p\Delta y - \left(p + \frac{\partial p}{\partial x}\Delta x\right)\Delta y + \left(\tau + \frac{\partial \tau}{\partial y}\Delta y\right)\Delta x - \tau\Delta x = 0$$

$$\frac{\partial \tau}{\partial y} = \frac{\partial p}{\partial x} = 0 \Rightarrow \tau = const$$

Example - Flow Between Plates



$$\frac{du}{dy} = \frac{\tau}{\mu} = const$$

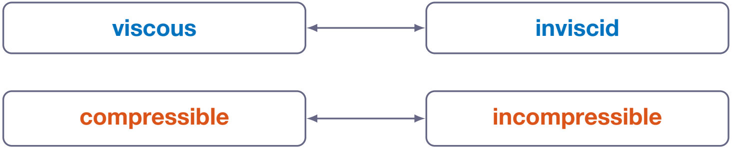
$$u = a + by$$

$$\begin{cases} y = 0 \Rightarrow u = 0 \\ y = h \Rightarrow u = V \end{cases}$$

$$u = \frac{V}{h}y$$

Flow Categories

Flow Categories



Flow Categories

viscous ↔ inviscid

compressible ↔ incompressible

turbulent ↔ laminar

Flow Categories

viscous	inviscid
compressible	incompressible
turbulent	laminar
unsteady	steady-state

Flow Categories

viscous	↔	inviscid
compressible	↔	incompressible
turbulent	↔	laminar
unsteady	↔	steady-state
3D	↔	1D/2D