

Fluid Mechanics - MTF053

Chapter 1

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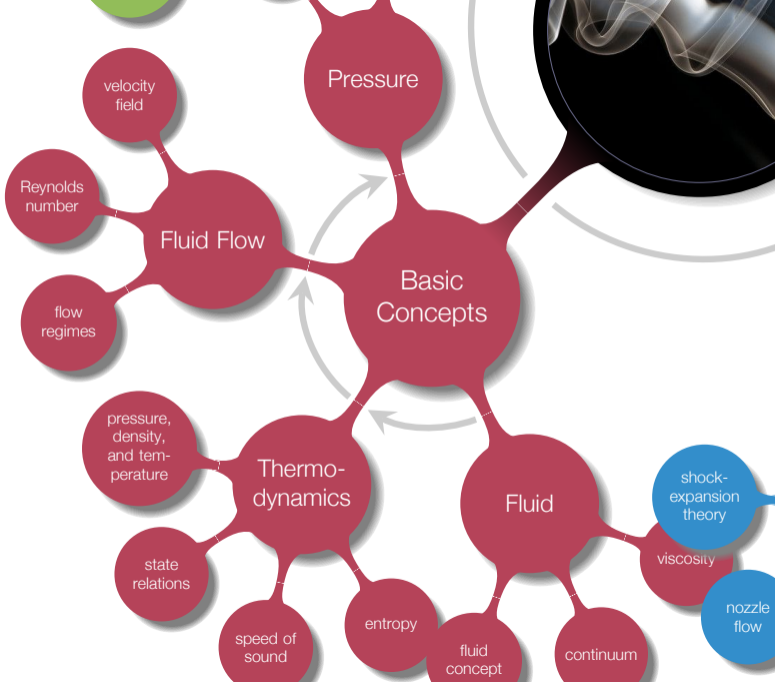




Chapter 1 - Introduction



Overview

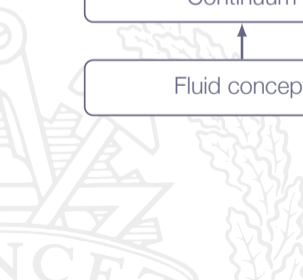
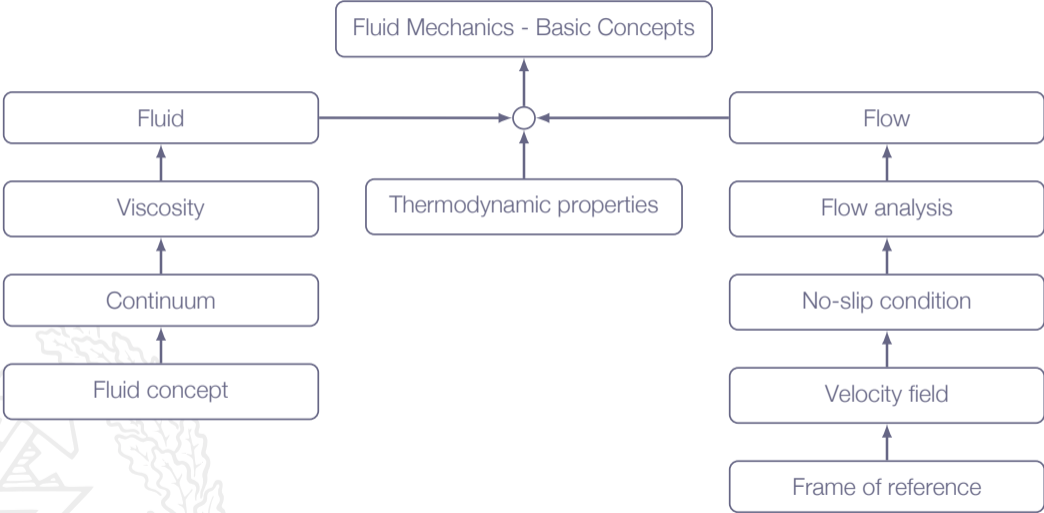


Learning Outcomes

- 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

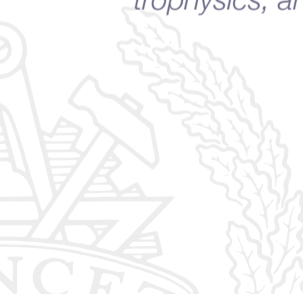
Roadmap - Introduction to Fluid Mechanics



Fluid Mechanics

*"Fluid mechanics is the branch of physics concerned with the **mechanics of fluids** (liquids, gases, and plasmas) and the **forces** on them. It has applications in a wide range of disciplines, including mechanical, civil, chemical and biomedical engineering, geophysics, oceanography, meteorology, astrophysics, and biology."*

Wikipedia



Fluid Flows in Your Daily Life

"When you think about it, almost everything on this planet either is a fluid or moves within or near a fluid"

Frank M. White



Fluid Flows in Your Daily Life



Fluid Flows in Your Daily Life



Fluid Flows in Your Daily Life



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Fluid Flows in Your Daily Life



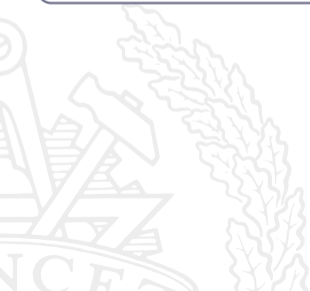
Fluid Flows in Your Daily Life



Governing Equations

Conservation of mass (continuity)

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x}(\rho u) + \frac{\partial}{\partial y}(\rho v) + \frac{\partial}{\partial z}(\rho w) = 0$$



$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x}(\rho u) + \frac{\partial}{\partial y}(\rho v) + \frac{\partial}{\partial z}(\rho w) = 0$$

Conservation of linear momentum (Newton's 2:nd law)

$$\rho \left(\frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} + w \frac{\partial u}{\partial z} \right) = \rho g_x - \frac{\partial p}{\partial x} + \mu \left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} + \frac{\partial^2 u}{\partial z^2} \right)$$

$$\rho \left(\frac{\partial v}{\partial t} + u \frac{\partial v}{\partial x} + v \frac{\partial v}{\partial y} + w \frac{\partial v}{\partial z} \right) = \rho g_y - \frac{\partial p}{\partial y} + \mu \left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} + \frac{\partial^2 v}{\partial z^2} \right)$$

$$\rho \left(\frac{\partial w}{\partial t} + u \frac{\partial w}{\partial x} + v \frac{\partial w}{\partial y} + w \frac{\partial w}{\partial z} \right) = \rho g_z - \frac{\partial p}{\partial z} + \mu \left(\frac{\partial^2 w}{\partial x^2} + \frac{\partial^2 w}{\partial y^2} + \frac{\partial^2 w}{\partial z^2} \right)$$

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x}(\rho u) + \frac{\partial}{\partial y}(\rho v) + \frac{\partial}{\partial z}(\rho w) = 0$$

Conservation of linear momentum (Newton's 2:nd law)

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$$\rho \left(\frac{\partial w}{\partial t} + u \frac{\partial w}{\partial x} + v \frac{\partial w}{\partial y} + w \frac{\partial w}{\partial z} \right) = \rho g_z - \frac{\partial p}{\partial z} + \mu \left(\frac{\partial^2 w}{\partial x^2} + \frac{\partial^2 w}{\partial y^2} + \frac{\partial^2 w}{\partial z^2} \right)$$

Conservation of energy (1:st law of thermodynamics)

$$\rho C_v \left(\frac{\partial T}{\partial t} + u \frac{\partial T}{\partial x} + v \frac{\partial T}{\partial y} + w \frac{\partial T}{\partial z} \right) = \rho \left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} \right) + k \left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \right) + \Phi$$

Fluid Flow Applications

Analytical solutions limited to very specific simplified cases

Complex geometries and flows leads to the need for experiments and Computational Fluid Dynamics (CFD)

Chief obstacles to a general theory:

Geometry

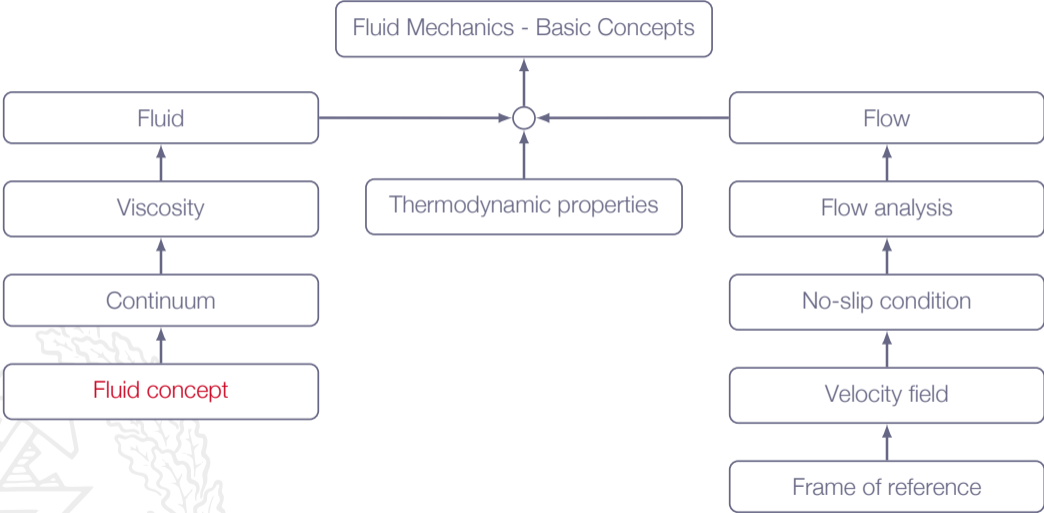
Viscosity

Non-linearity

Turbulence

Understanding the basic principles is a key factor for a correct analysis

Roadmap - Introduction to Fluid Mechanics



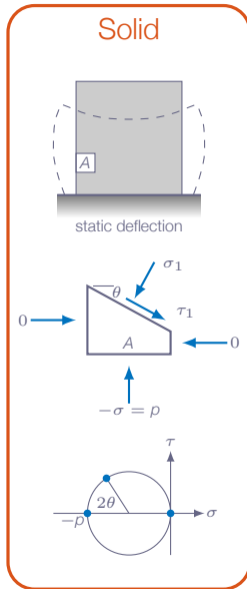
The Concept of a Fluid

*"In physics, a fluid is a substance that continually deforms (flows) under an applied **shear stress**, or external force. Fluids are a phase of matter and include liquids, gases and plasmas. They are substances with zero shear modulus, or, in simpler terms, **substances which cannot resist any shear force applied to them.**"*

Wikipedia

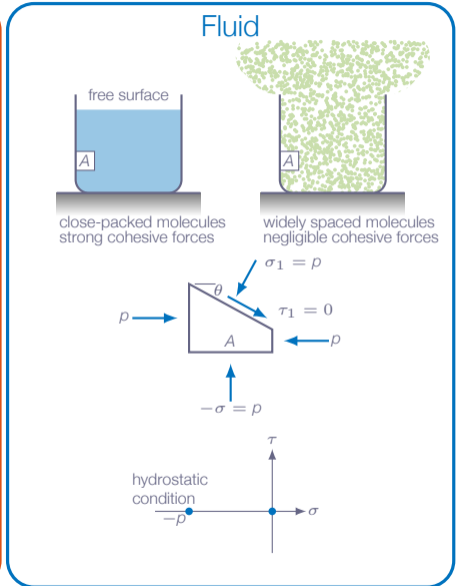
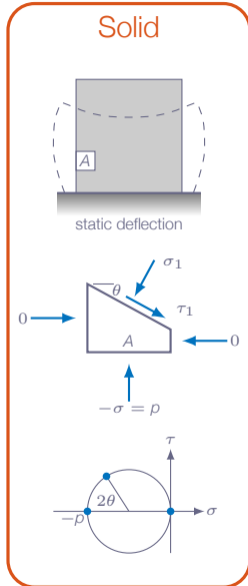


The Concept of a Fluid

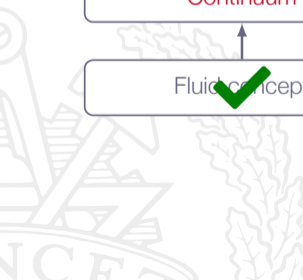
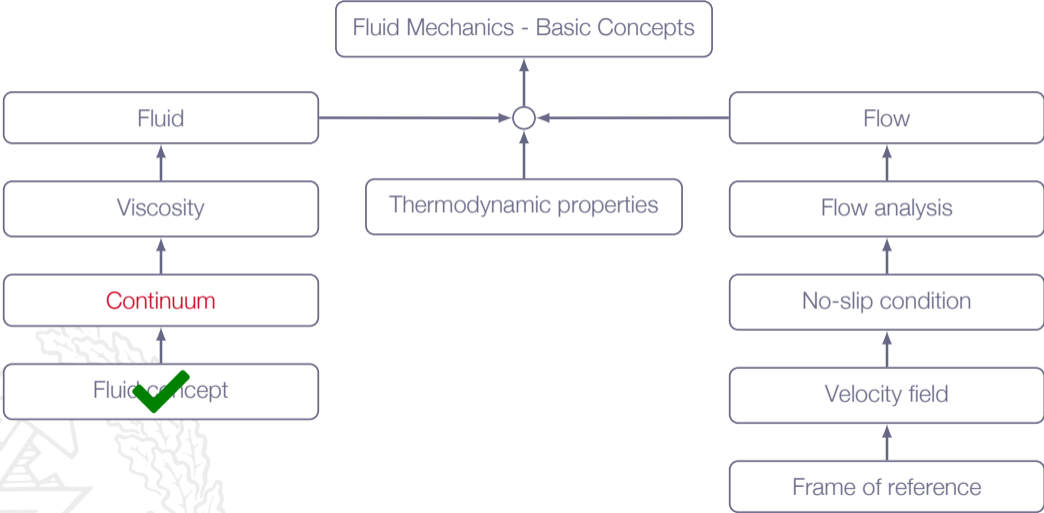


The Concept of a Fluid

"A solid can resist a shear stress by a static deflection; a fluid cannot"



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The Fluid as a Continuum

Fluid **density** is essentially a **point function**

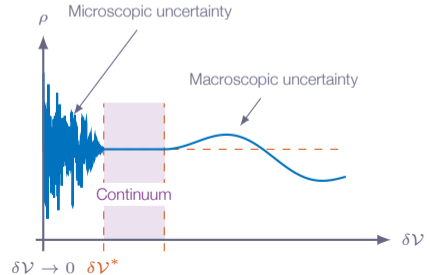
Fluid **properties** can be thought of as **varying continually in space**

Volume large enough such that the **number of molecules** within the volume is **constant**

Volume small enough **not** to **introduce macroscopic fluctuations**

$$\rho = \lim_{\delta V \rightarrow \delta V^*} \frac{\delta m}{\delta V}$$

standard air: $\delta V^* \approx 10^{-9} \text{mm}^3 \Rightarrow \sim 3 \times 10^7$ molecules

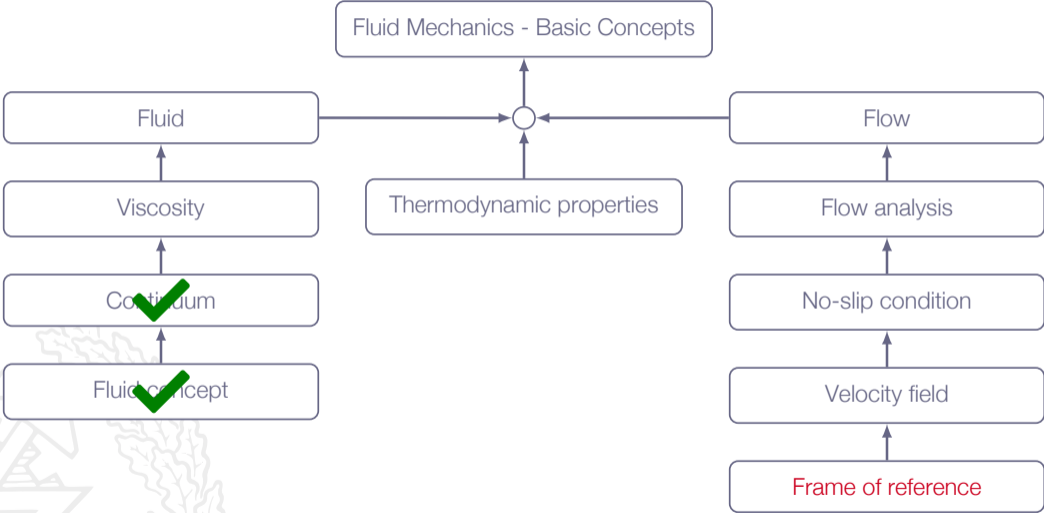


The Fluid as a Continuum

Flow properties varies smoothly \Rightarrow Differential calculus can be used



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Frame of Reference



Eulerian Frame of Reference

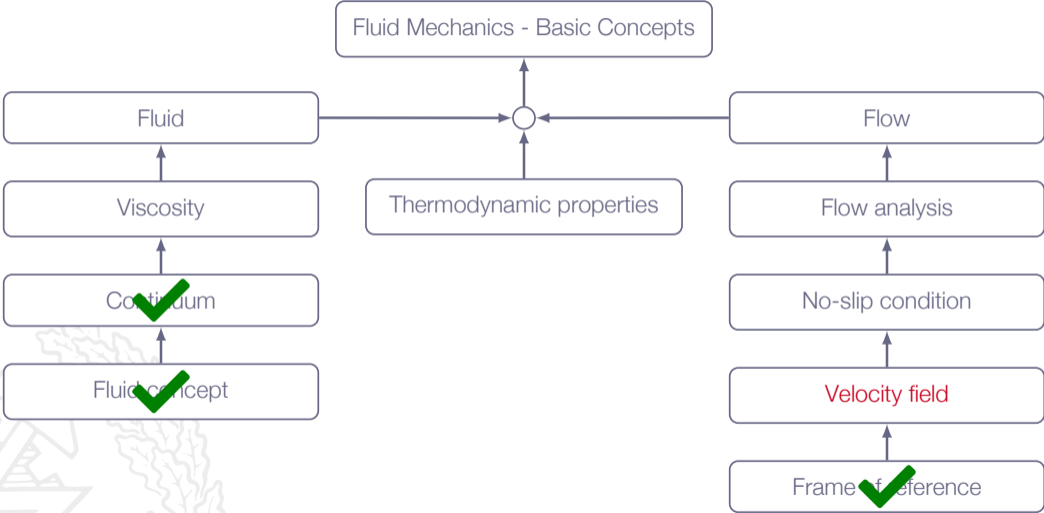
fluid properties as function of position and time



Lagrangian Frame of Reference

follows a system in time and space

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Properties of the Velocity Field

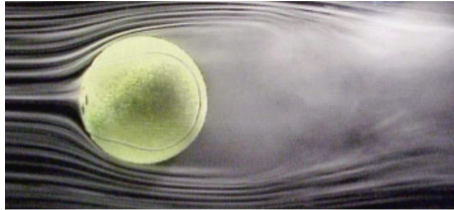
The fluid velocity is a function of position and time

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



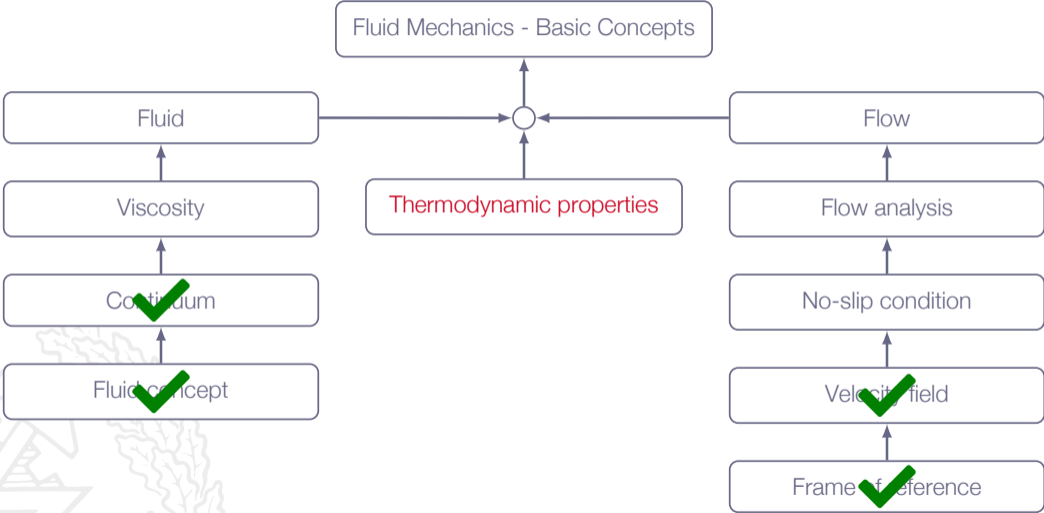
Acceleration:

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

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

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

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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

Pressure: p (Pa)

Density: ρ (kg/m³)

Temperature: T (K)

most common properties

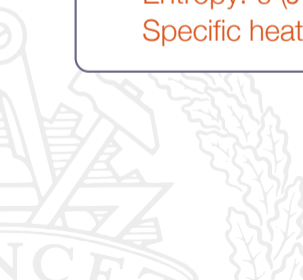
Internal energy: \hat{u} (J/kg)

Enthalpy: $h = \hat{u} + p/\rho$ (J/kg)

Entropy: s (J/(kg K))

Specific heats: C_p and C_v (J/(kg K))

work, heat, and energy balances



Thermodynamic Properties

Pressure: p (Pa)

Density: ρ (kg/m^3)

Temperature: T (K)

most common properties

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Specific heats: C_p and C_v (J/(kg K))

work, heat, and energy balances

Viscosity: μ (kg/(m s))

Thermal conductivity: k (W/(m 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 ($\rho = \rho(x, y, z, t)$)

large enough number of molecules \Rightarrow **continuum**

any changes in thermodynamic conditions are faster than the flow time scale \Rightarrow **equilibrium**

Primary Thermodynamic Properties

Pressure

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



Primary Thermodynamic Properties

Temperature

Related to internal energy

Large temperature differences \Rightarrow heat transfer may be important



Primary Thermodynamic Properties

Density

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

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

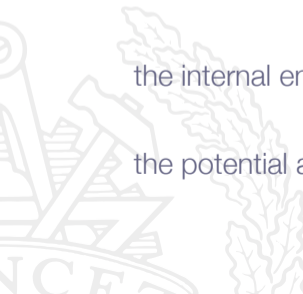
Potential and Kinetic Energies

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



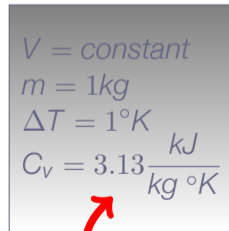
State Relations for Gases

The perfect gas law:

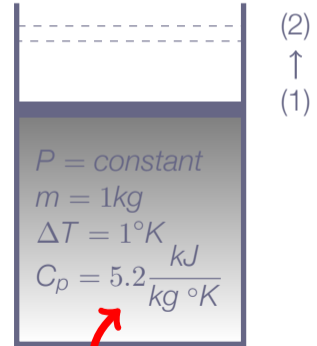
$$p = \rho RT$$

where R is the gas constant

$$R = C_p - C_v$$



3.13kJ



5.2kJ

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:

$$a = \sqrt{\gamma RT}$$

Vapor Pressure

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

Vapor pressure for water:

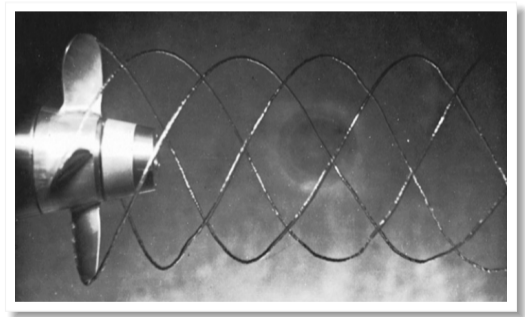
T [°C]	vapor pressure [Pa]
20	2340
100	101300



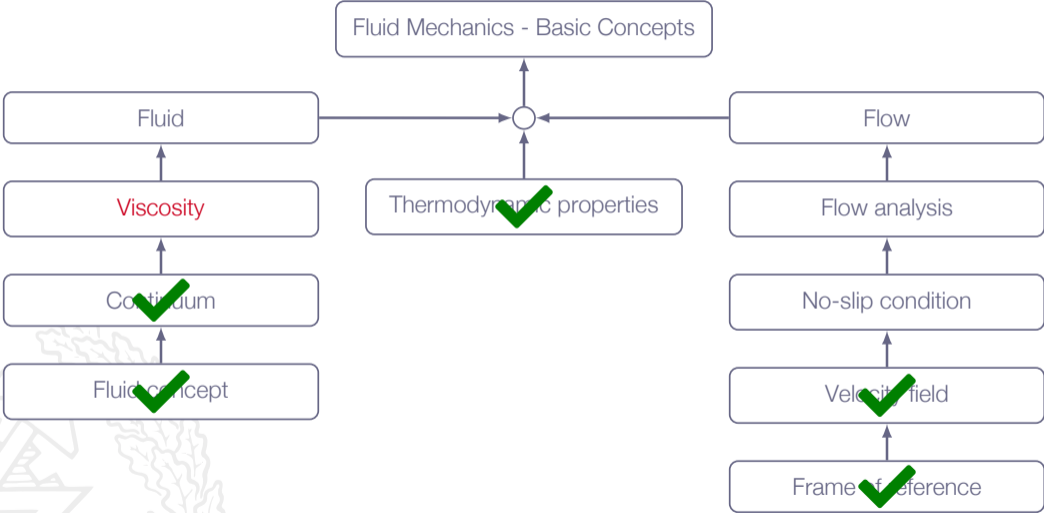
Vapor Pressure

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



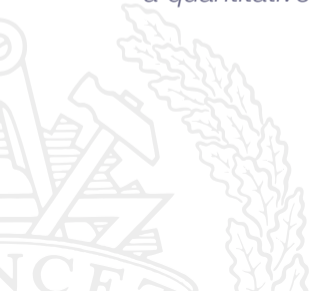


Viscosity

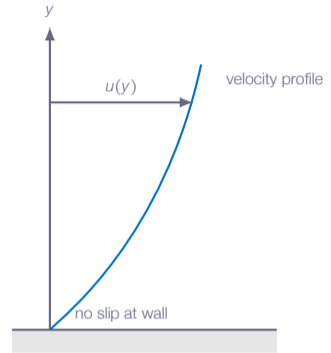
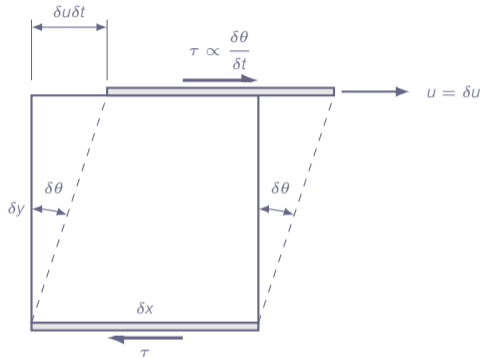
Viscosity

"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



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

Viscosity

for infinitesimal changes:

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

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

For Newtonian fluids:

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

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	μ ($\text{kg m}^{-1} \text{s}^{-1}$)	ρ (kg m^{-3})	ν ($\text{m}^2 \text{s}^{-1}$)
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

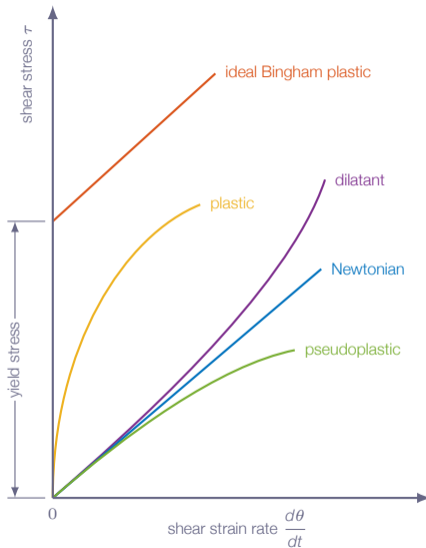


Reynolds number

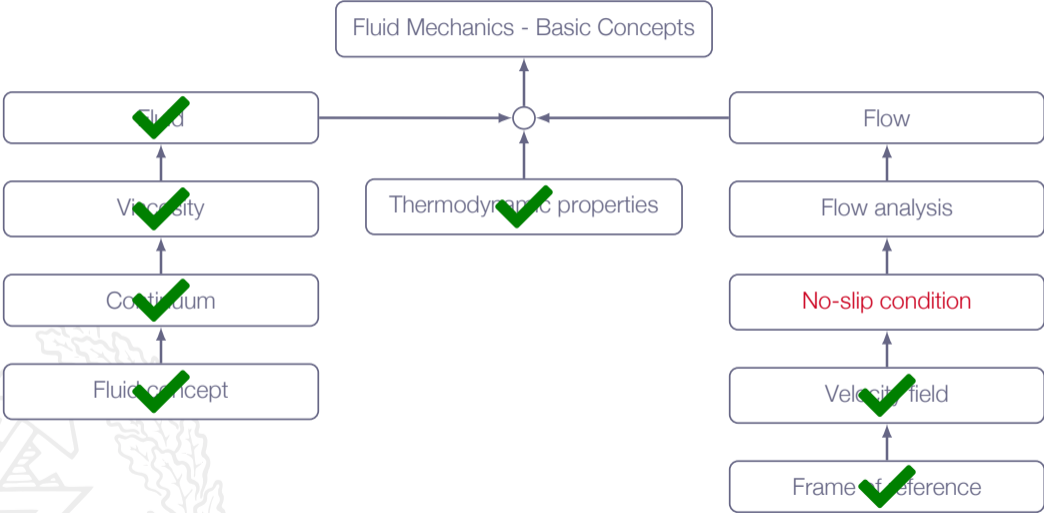
Reynolds number	flow description
low	viscous, creeping motion (inertial forces negligible)
moderate	laminar flow
high	turbulent flow



Non-Newtonian Fluids



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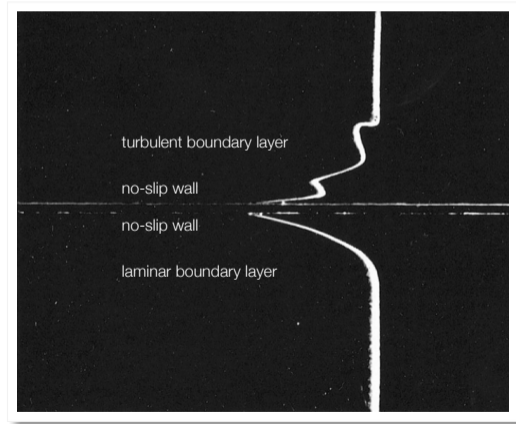
No Slip/No Temperature Jump

"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"

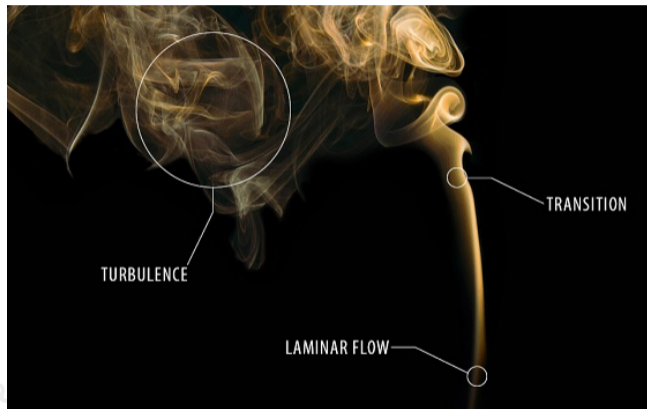


No Slip/No Temperature Jump

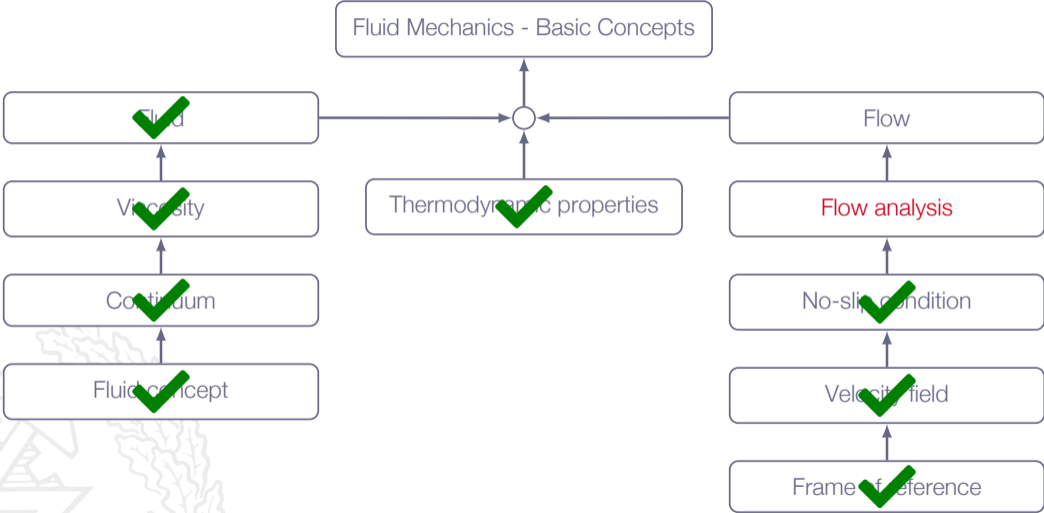
At a solid wall, the fluid will have the velocity and temperature of the wall



Laminar/Turbulent Flow



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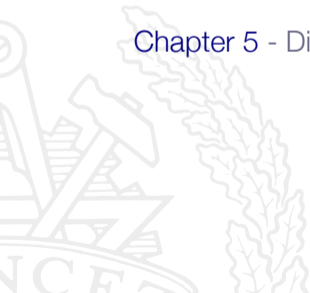


Flow Analysis

Chapter 3 - Control-volume (integral) approach

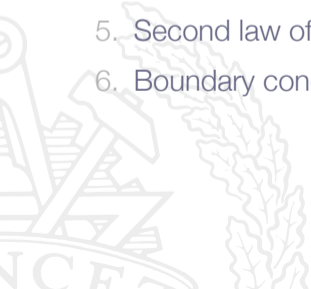
Chapter 4 - Infinitesimal system (differential) approach

Chapter 5 - Dimensional analysis approach



Flow Analysis

1. Conservation of mass (continuity)
2. Conservation of momentum (Newton's second law)
3. Conservation of energy (first law of thermodynamics)
4. State relation (for example the ideal gas law)
5. Second law of thermodynamics
6. Boundary conditions



Flow Visualization

Streamline

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

Pathline

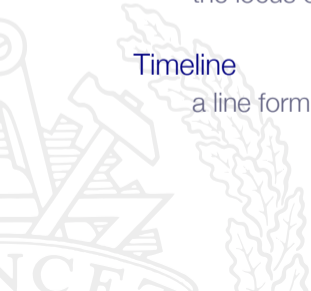
the actual path traversed by a fluid particle

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

the actual path traversed by a fluid particle

Streakline

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

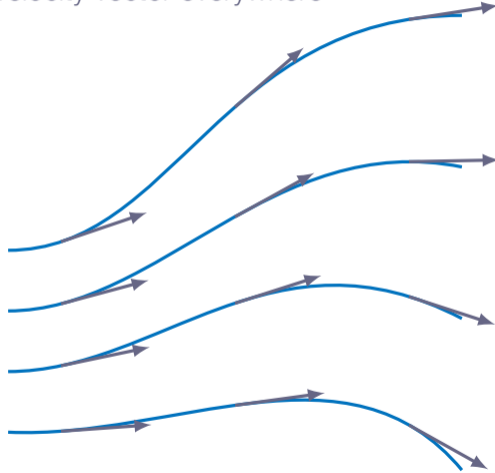
Timeline

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

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

Streamline

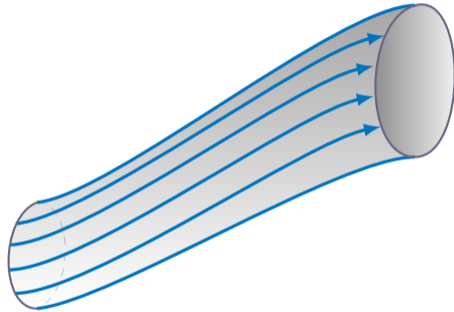
Tangent to flow velocity vector everywhere



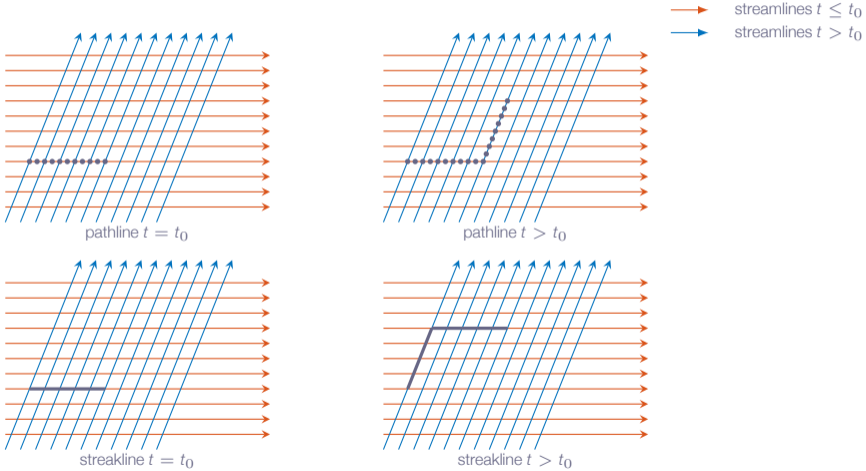
Streamtube

"Constructed" from individual streamlines

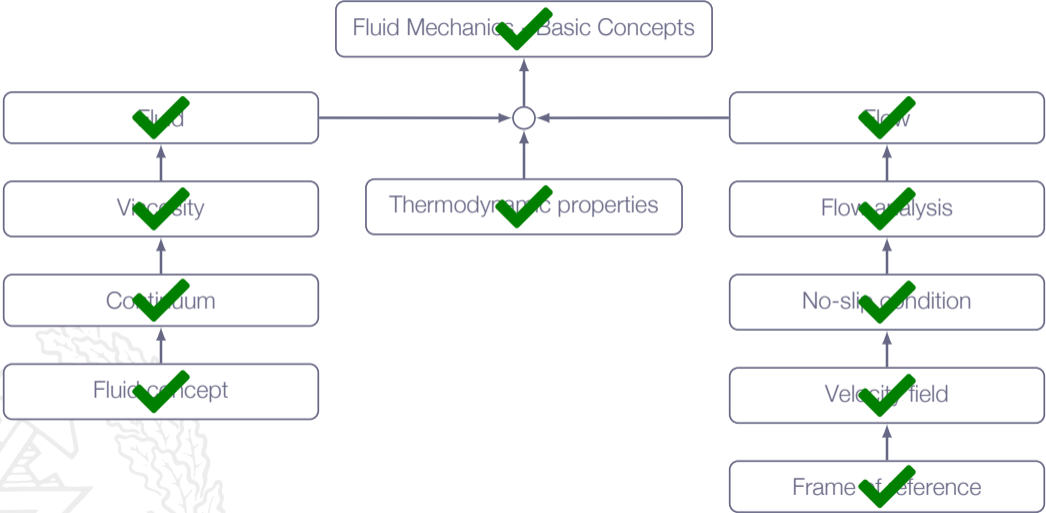
No flow across streamtube "walls" (by definition)



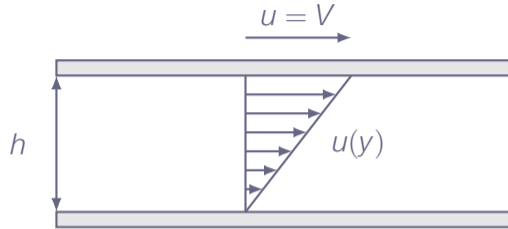
Pathline vs Streakline



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Example - Flow Between Plates

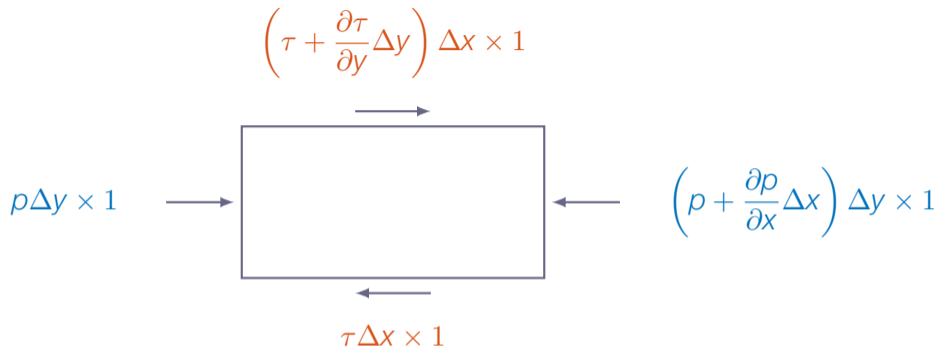


No acceleration

No pressure gradients

two-dimensional flow

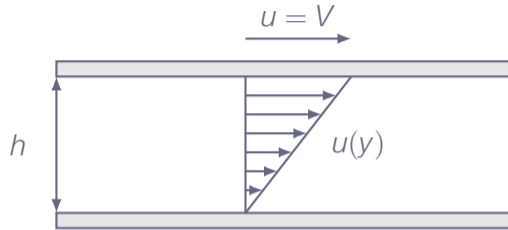
Example - Flow Between Plates



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

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

Example - Flow Between Plates



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

$$u = a + by$$

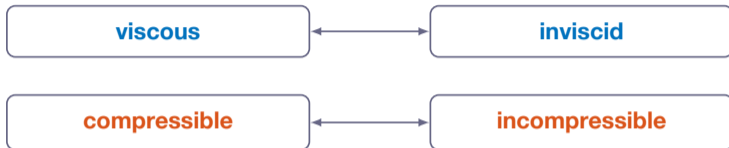
$$\begin{cases} y = 0 \Rightarrow u = 0 \\ y = h \Rightarrow u = V \end{cases}$$

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

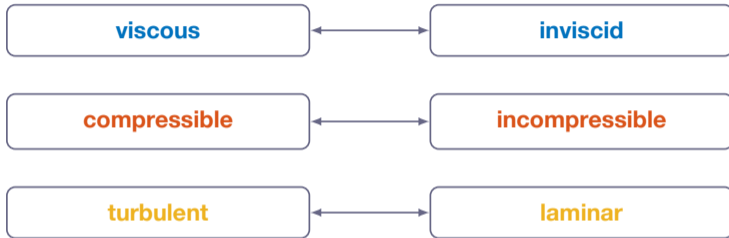
Flow Categories



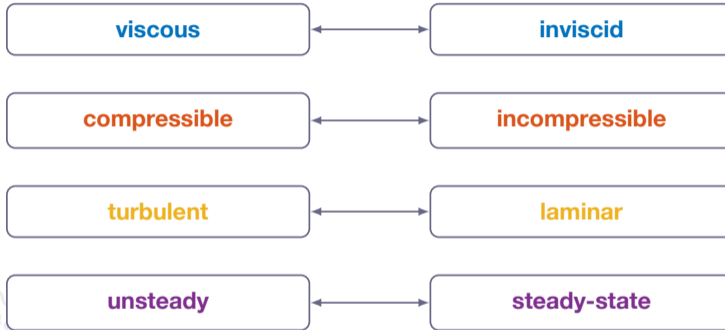
Flow Categories



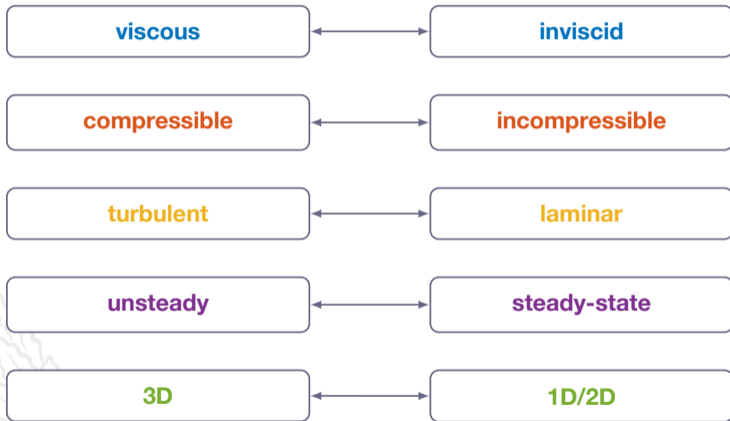
Flow Categories



Flow Categories



Flow Categories



Clouds

