DRONACHARYA
College of Engineering

Fluid Mechanics

Introduction

Fig. 1.1 Flow processes occur in many ways in our natural environme

Fig. 1.2 Effects of flows on the climate of entire geographical regions

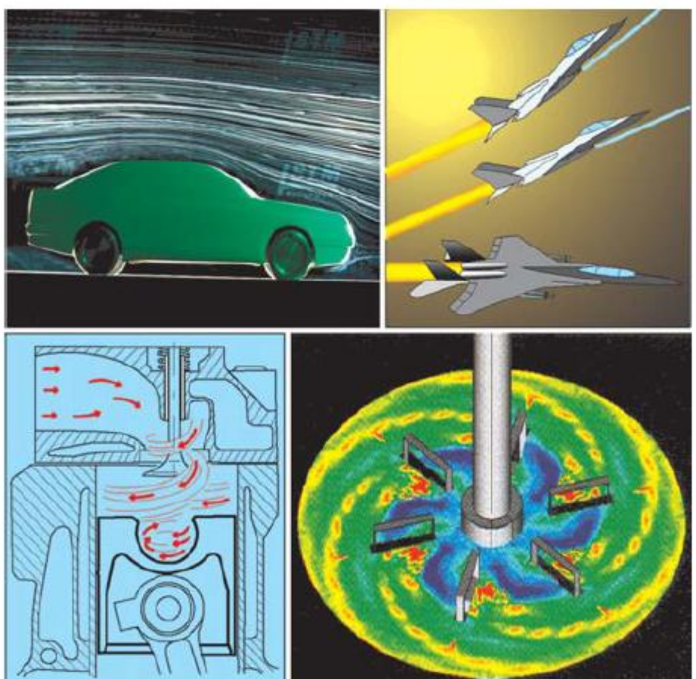
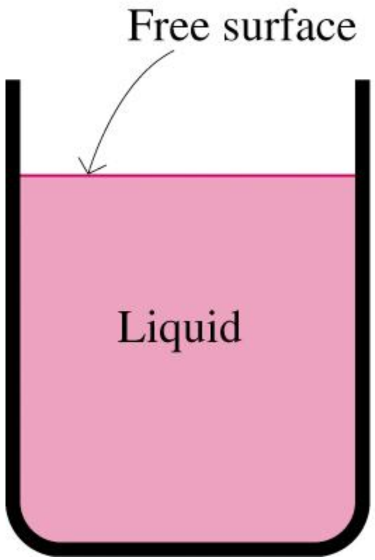
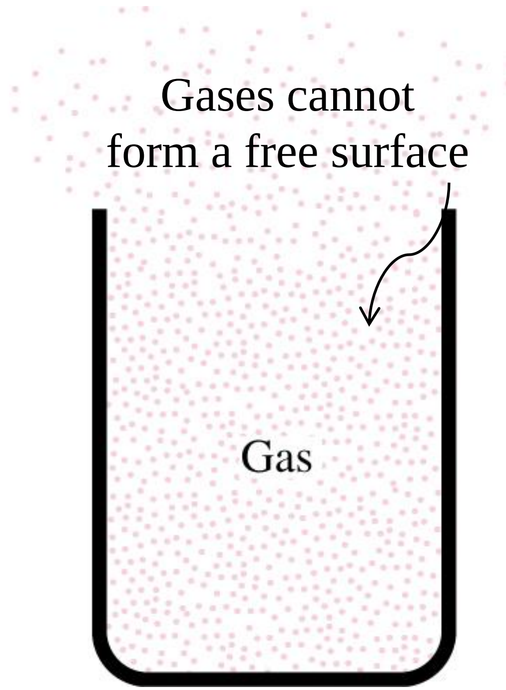
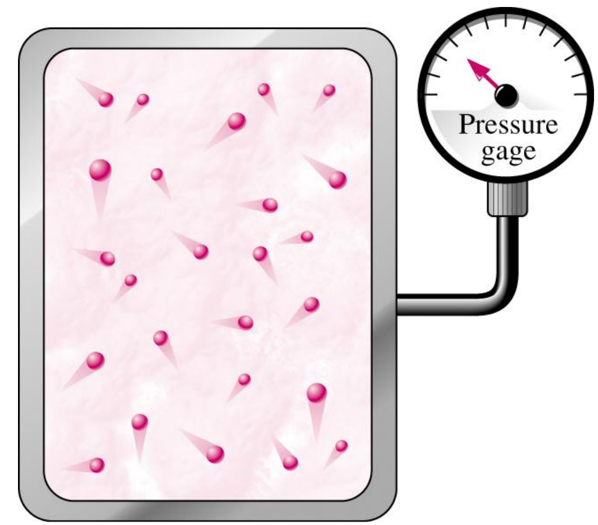
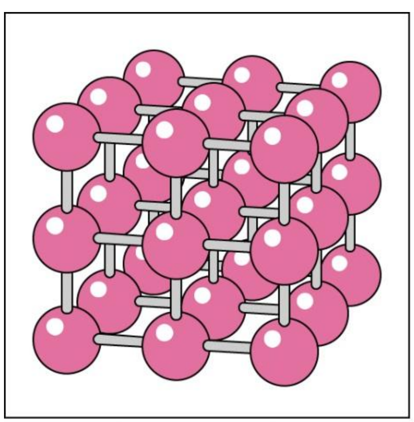


Fig. 1.3 Fluid flows are applied in many ways in our technical environment



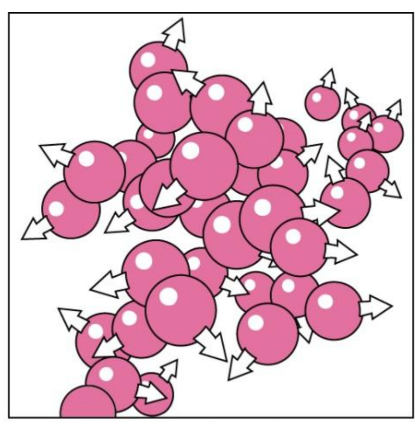






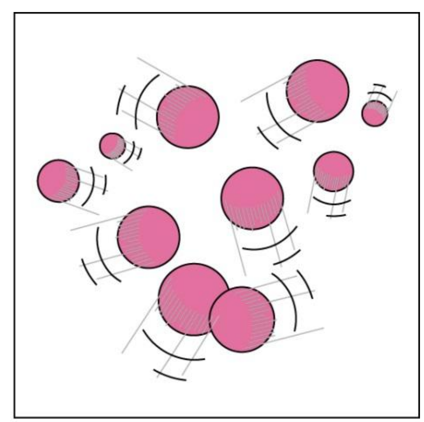
(a)

solid



(b)

liquid



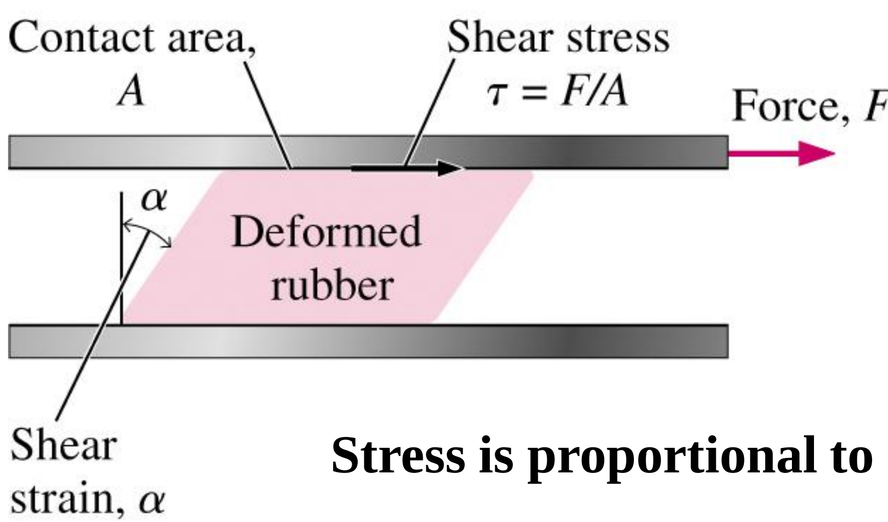
(c)

gas

Gas and vapor are often used as synonymous words ???

Distinction between solid and fluid

- Distinguish fluid from solid when subjected to a shear force
  - Shear force & normal force
- Consider a solid element shown below
  - The bottom surface is fixed
  - A small horizontal force `F' is applied on the surface
  - The surface is 'sheared'
  - The element deforms
  - An equilibrium position is achieved when the deformation stops
  - The top layer is finally stationary
  - The solid has, therefore, resisted the applied shear force.



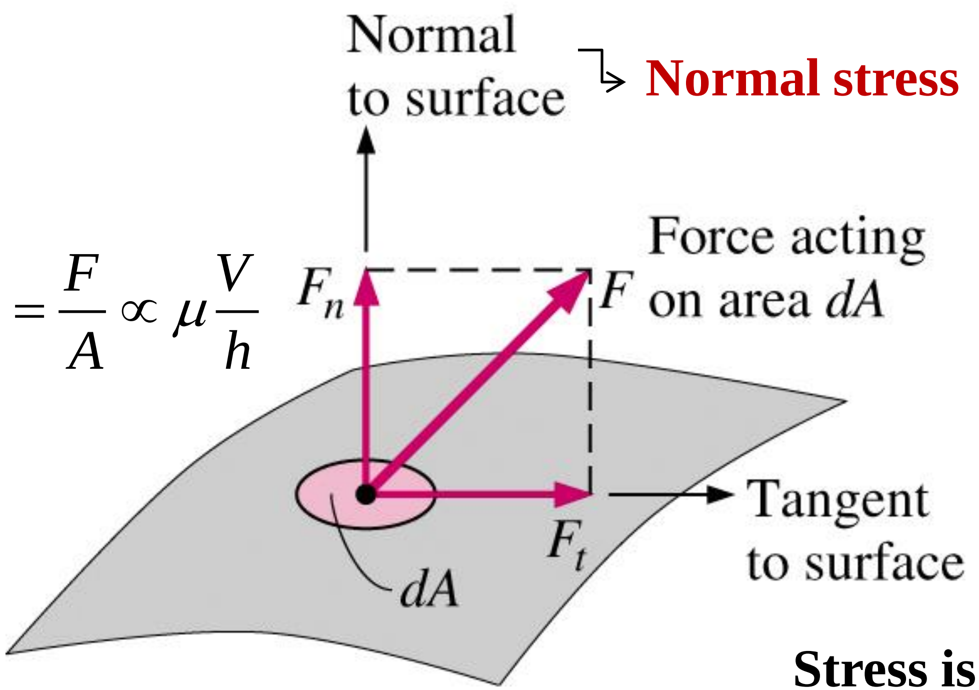
$$\tau = \frac{F}{A} \propto \alpha$$

Stress is proportional to strain

Distinction between solid and fluid

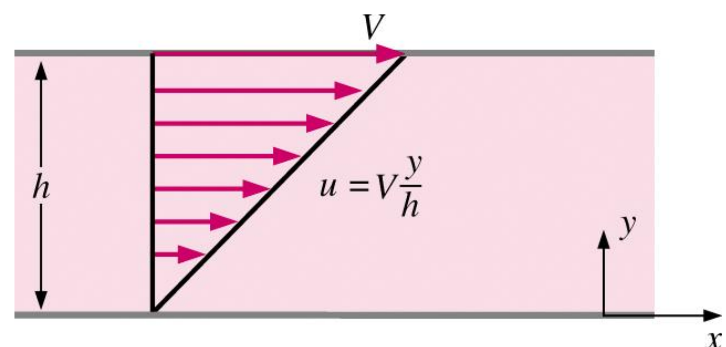
- Consider a fluid element
- Application of a shear force (no matter how small it is!), the top surface will continue to move as long as the force is applied
- There will not be an ‘equilibrium' position of any fluid element on the surface
- Such behaviour has been validated experimentally, using a dye- marker test.

$$\tau = \frac{F}{A} \propto \mu \frac{V}{h}$$



Normal stress

Tangential stress



Stress is proportional to strain rate

Rheology

Range of Rheological Material Behavior

- Rheology: The study of deformation and flow of matter *at specified conditions*.

<u>Range of material behavior</u>

Solid Like ---------- *Liquid Like*

(Ideal Solid ------------- Ideal Fluid)

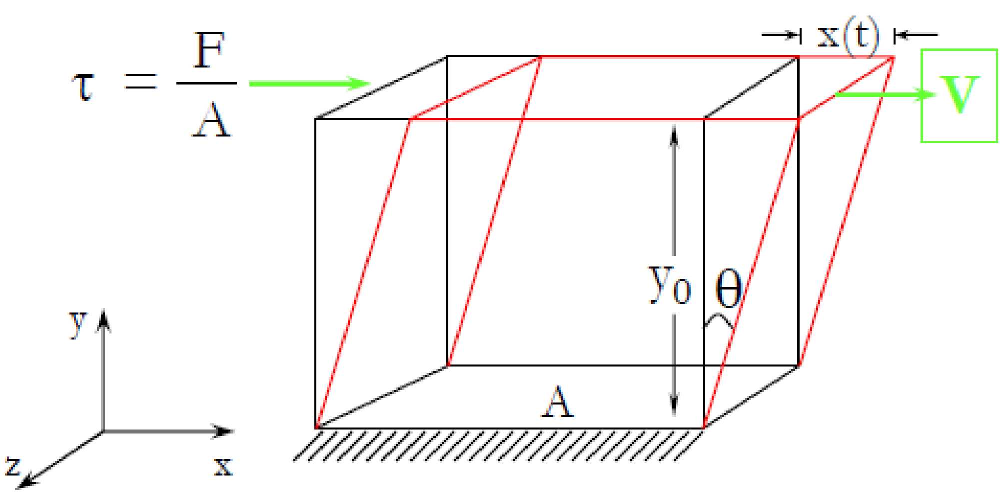
Classical Extremes

Deformation, Strain, Strain rate

Simple Shear Deformation and Shear Flow

Shear Deformation

$$\tau = \frac{F}{A}$$



$$\text{Strain, } \gamma = \frac{x(t)}{y_0}$$

$$\text{Strain Rate, } \dot{\gamma} = \frac{V}{y_0} = \frac{1}{y_0}\frac{d\,x(t)}{d\,t}$$

$$\text{Viscosity, } \eta = \frac{\tau}{\dot{\gamma}}$$

$$\text{Shear Modulus, } \mathbf{G} = \frac{\tau}{\gamma}$$

$$\dot{\gamma} = \frac{\Delta\gamma}{\Delta t}$$

Constitutive Relation

$$\frac{Stress}{Strain} = Modulus$$

$$\frac{Stress}{Shear\ rate} = \text{Viscosity}$$

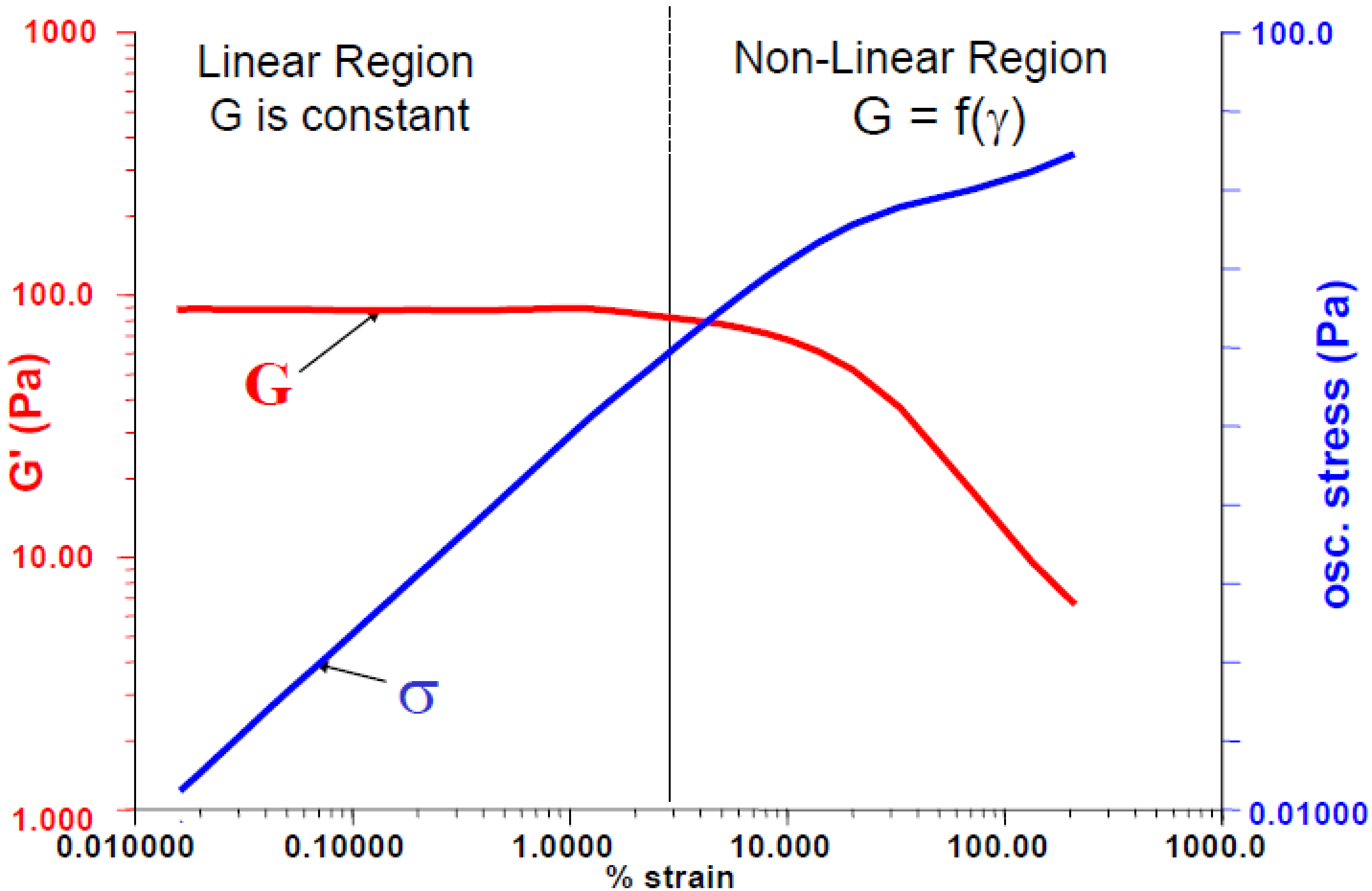
Stress to Strain in Solid

Classical Extremes: Elasticity

- 1678: Robert Hooke develops his
  "True Theory of Elasticity"
  - "The power of any spring is in the same proportion with the tension thereof."
  - Hooke's Law: $\tau = G\,\gamma$ or (Stress = G x Strain)

  where G is the RIGIDITY MODULUS

Linear and Non-Linear Stress-Strain Behavior of Solids



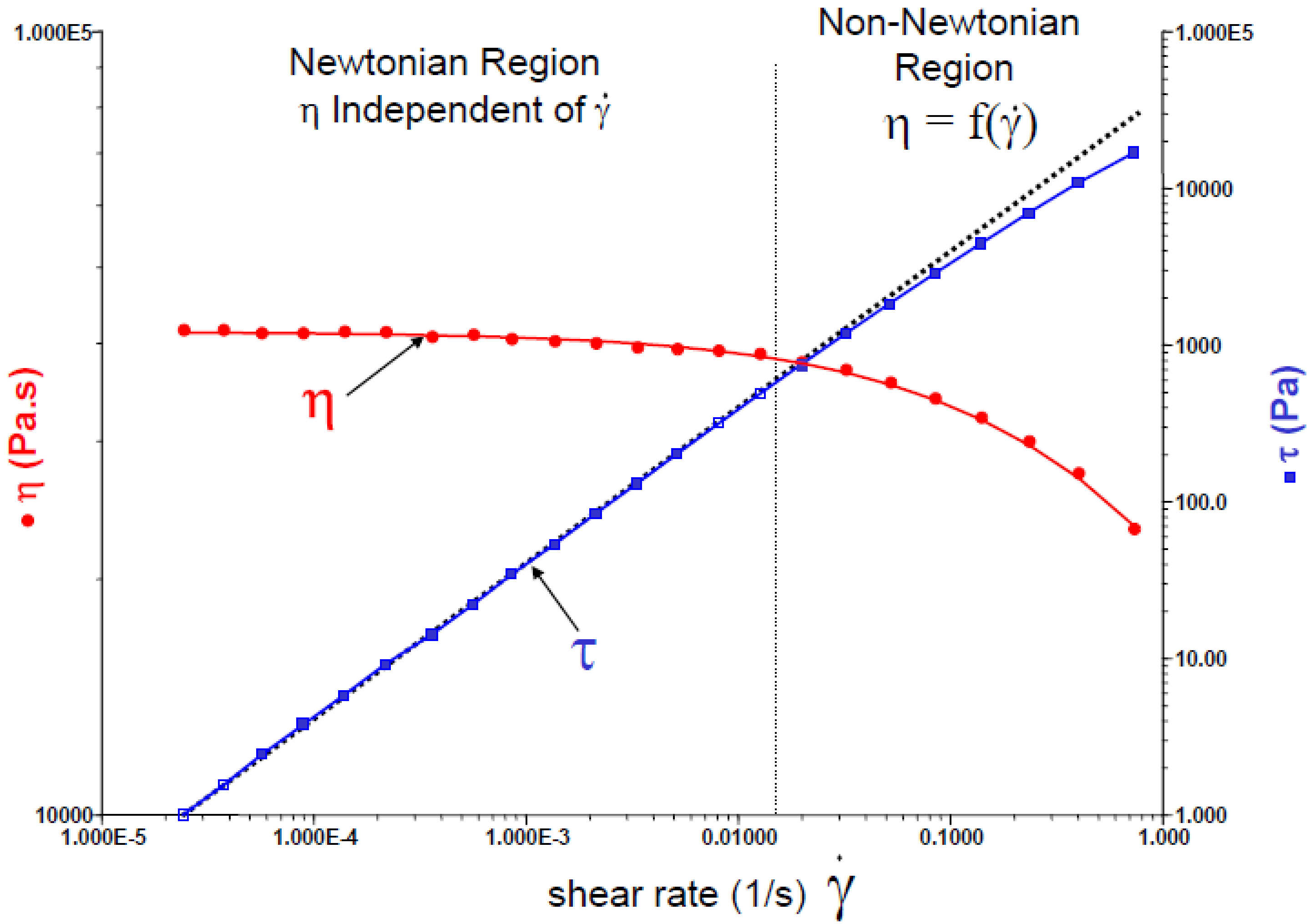
Stress to Strain Rate in Liquid

Classical Extremes: Viscosity

- 1687: Isaac Newton addresses liquids and steady simple shearing flow in his "*Principia*"
  - "The resistance which arises from the lack of slipperiness of the parts of the liquid, other things being equal, is proportional to the velocity with which the parts of the liquid are separated from one another."
  - Newton's Law: $\tau = \eta\dot{\gamma}$

where η is the Coefficient of Viscosity

Newtonian and Non-Newtonian Behavior of Fluids



Ideal Fluid vs. Ideal Solid

PARAMETERS for Rheological Properties

Classical Extremes

Ideal Solid	-- [External Force] --	*Ideal Fluid*
STEEL		**WATER**
Strong Structure		**Weak Structure**
Rigidity		**Fluidity**
Deformation		***Flow***
Retains/recovers form		**Losses form**
Stores Energy		**Dissipates Energy**
(Purely Elastic – R. Hooke, 1678)	*[Energy]*	*(Purely Viscous – I. Newton, 1687)*
ELASTICITY		**VISCOSITY**
Storage Modulus		**Loss Modulus**

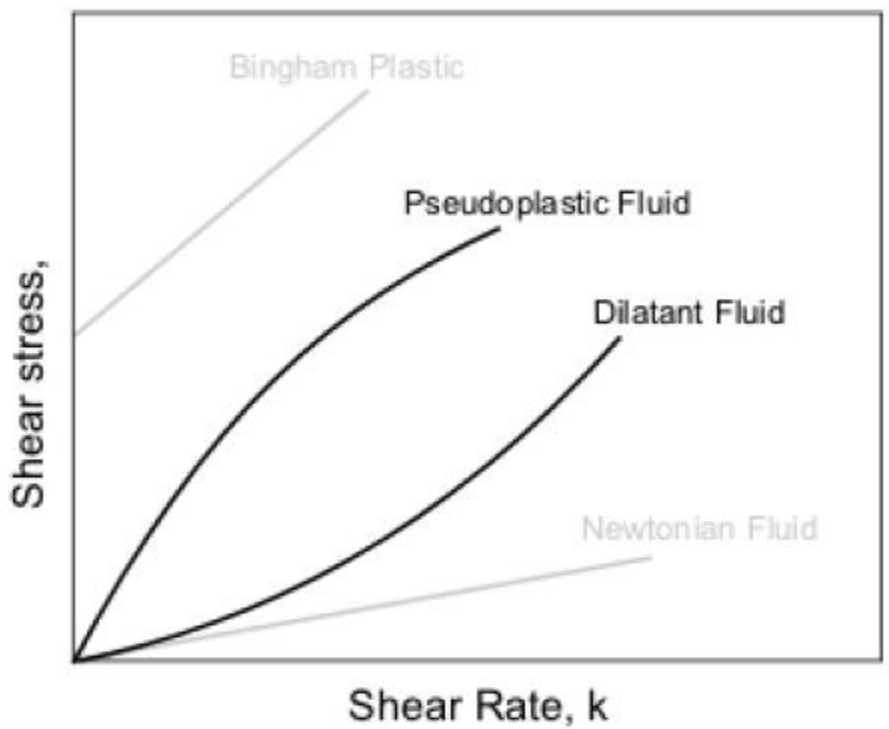
REAL Behavior

Apparent Solid	*[Energy + time]*	*Apparent Fluid*

- viscoelastic materials -

Shear Thinning vs. Shear Thickening

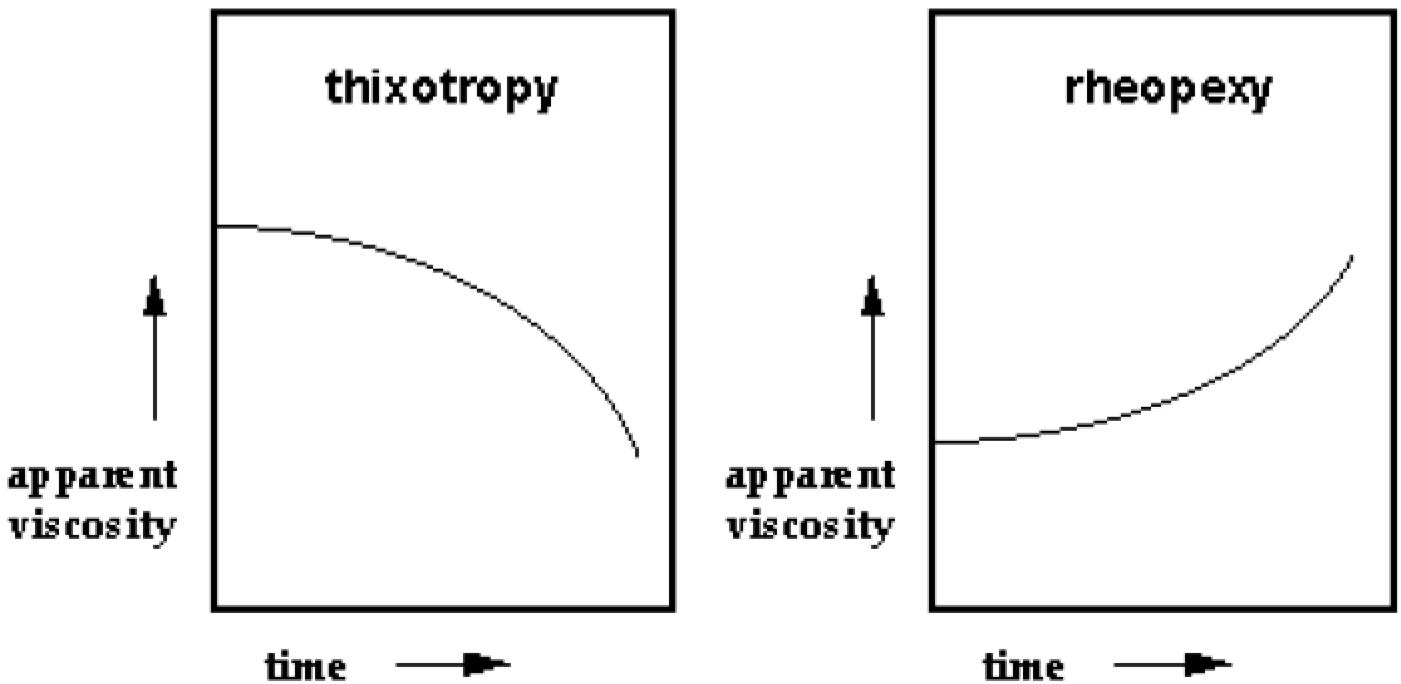
Stress-strain rate curve



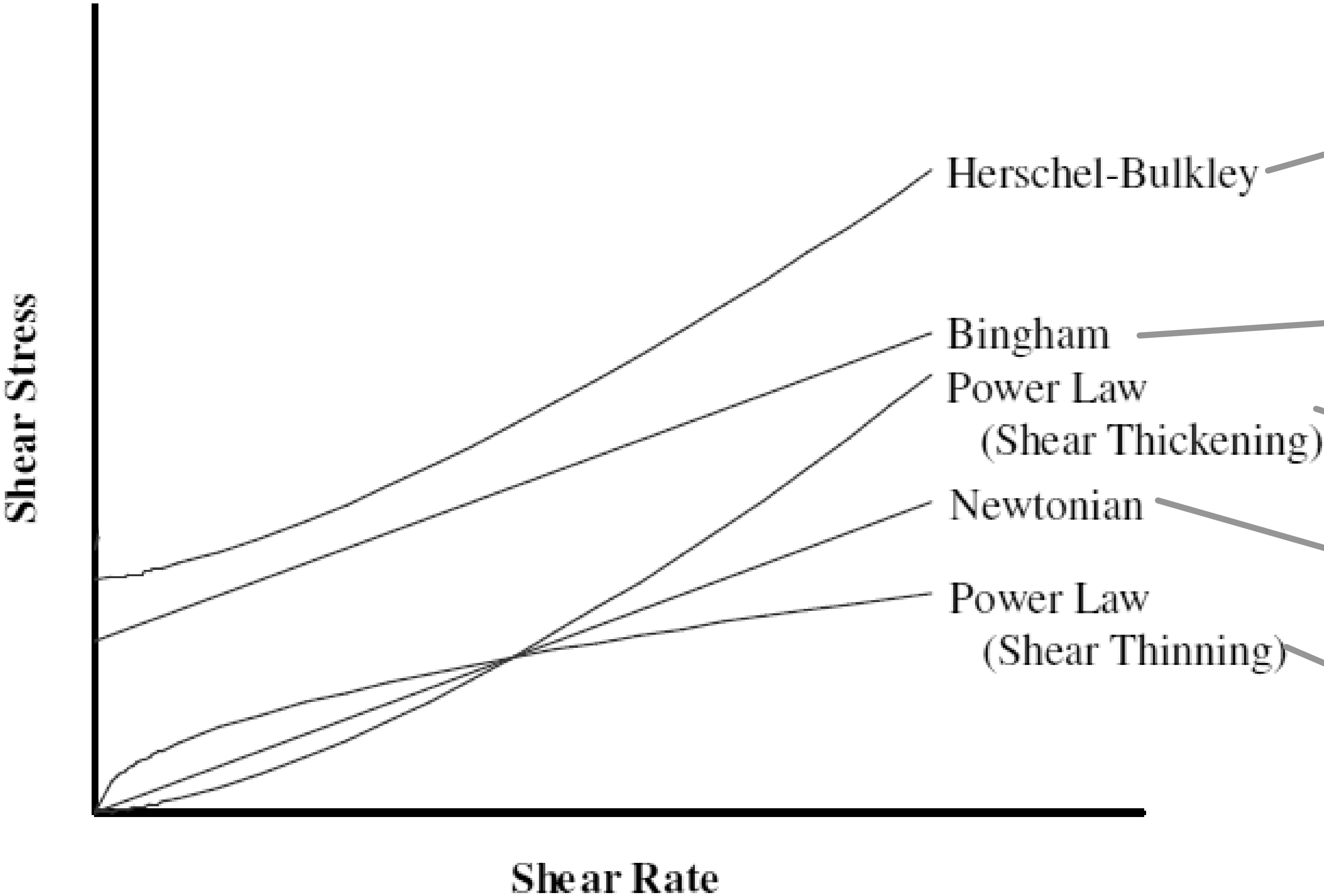
Dilatancy (shear thickening)
Plastic and Pseudoplastic (shear thinning)

Thixotropy vs. Rheopexy

apparent viscosity as a function of time



Popular Constitutive Relations



$$\tau = \tau_0 + a\dot{\gamma}^b$$

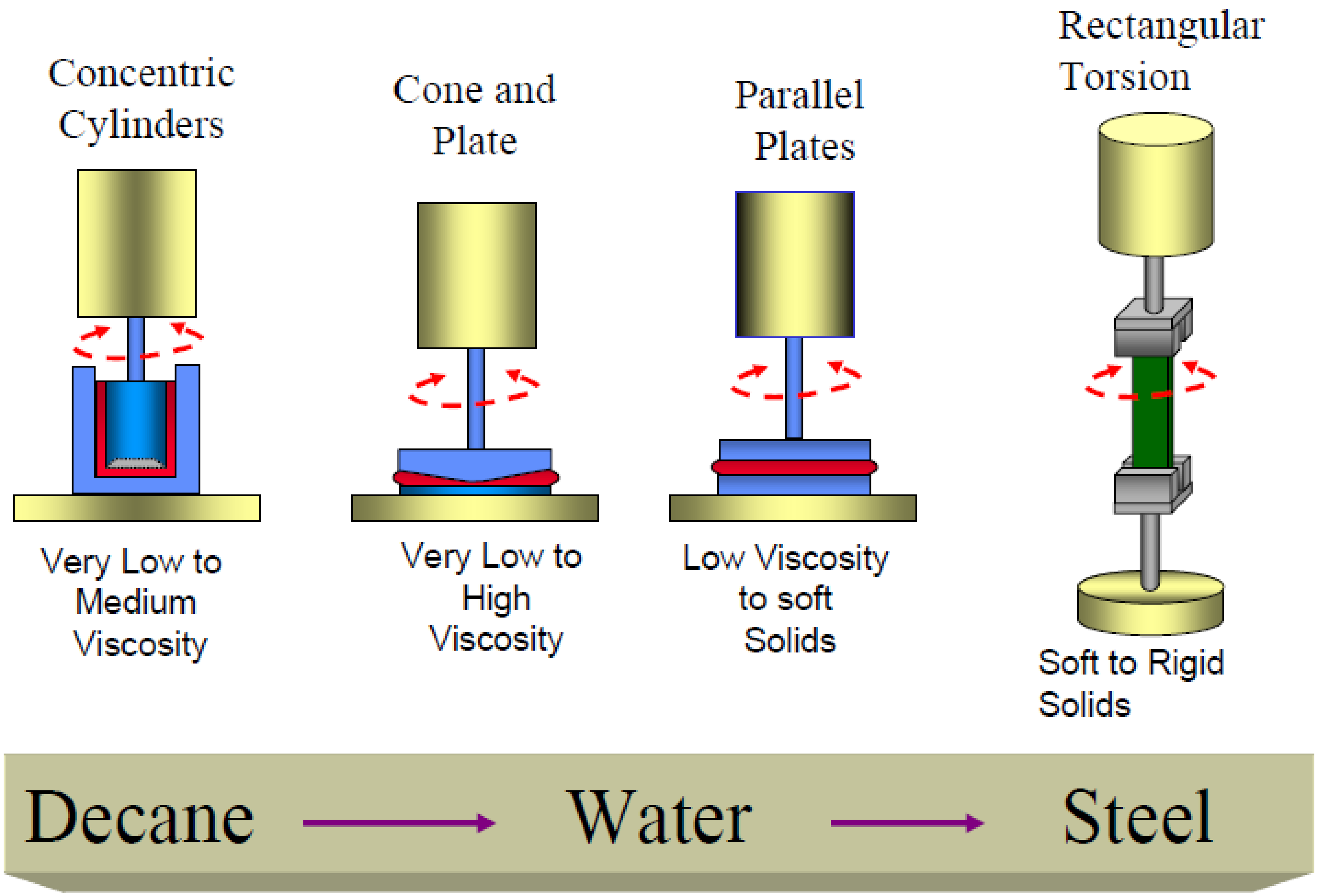
$$\tau = \tau_0 + \mu\dot{\gamma}$$

$$\tau = a\dot{\gamma}^b$$

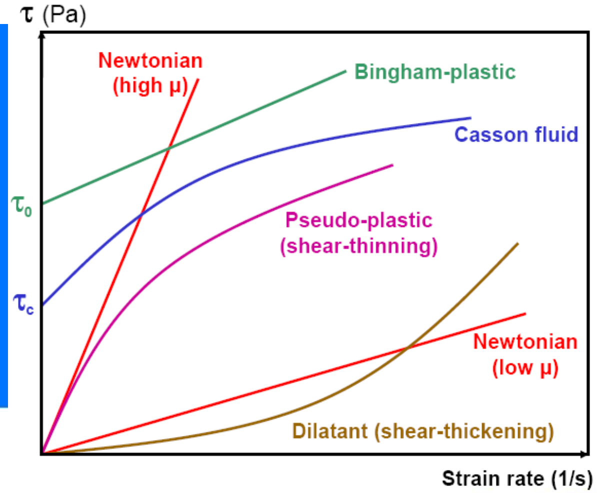
$$\tau = \eta\dot{\gamma}$$

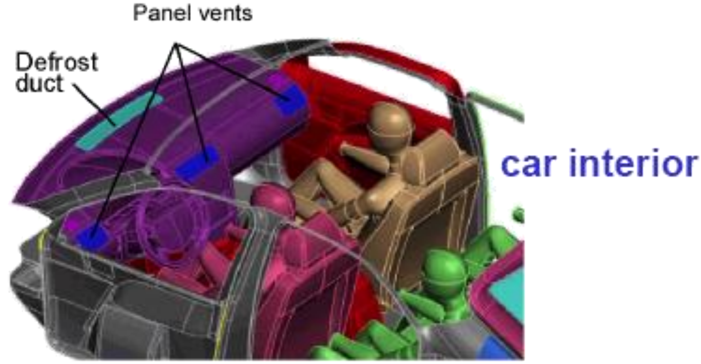
$$\tau = a\dot{\gamma}^b$$

Measuring Systems - Geometries



Classification





- Internal vs. external
- Laminar vs. turbulent
- Compressible vs. incompressible
- Steady vs. unsteady
- Supersonic vs. transonic vs. subsonic
- Single-phase vs. multiphase
- Elliptic vs. parabolic vs. hyperbolic
- Newtonian vs. non-Newtonian

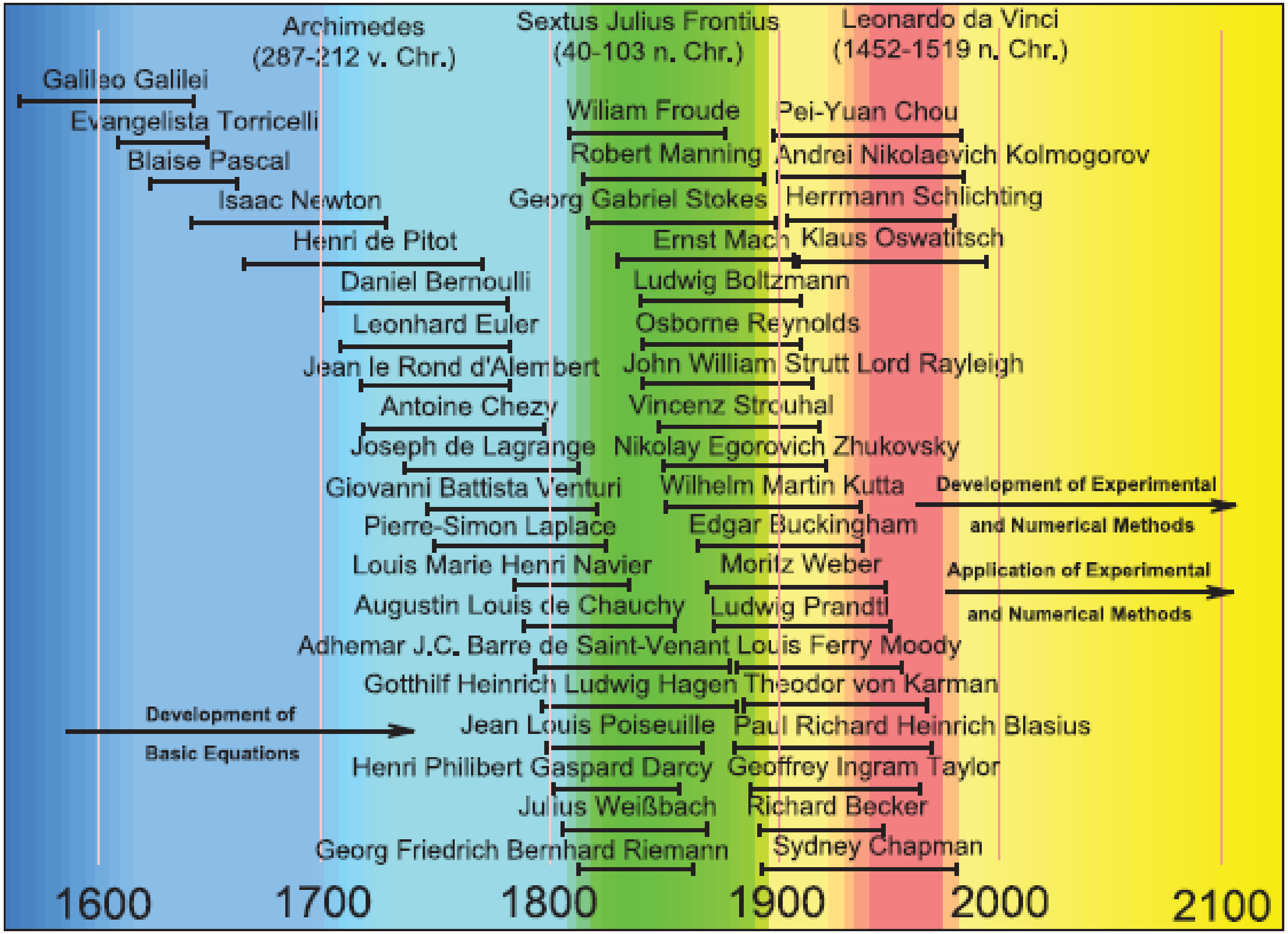


Fig. 1.7 Diagram listing the epochs and scientists contributing to the development of fluid mechanics

History

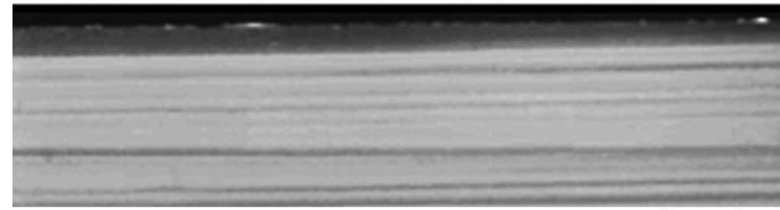
- **Archimedes (285–212 B.C.)** formulated the principles of buoyancy of submerged bodies and determined the gold content of the crown of King Hiero I
- At about the same time, the **Roman engineers** built an extensive network of fresh-water supply
- The development of fluid mechanics continued along two different paths:
  - **mathematicians and physicists developed the theory** and applied it to “idealized” problems that did not have much practical value
  - **engineers developed empirical equations** that could be used in the design of fluid systems in a limited range.
- The **lack of communication** between these two groups hindered the development of fluid mechanics for a long time.

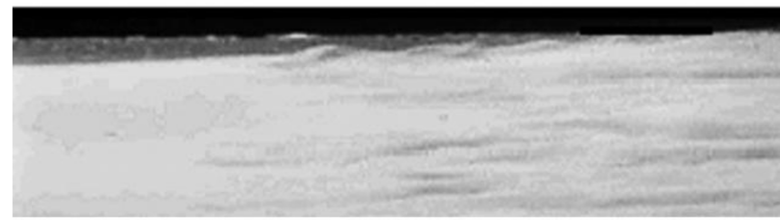
Modern Times

- **Leonardo da Vinci (1459–1519)** conducted several experiments and derived the conservation of mass equation for one-dimensional steady flow
- The development of the **laws of motion by Isaac Newton (1649–1727)** and the linear law of viscosity for the so-called Newtonian fluids set the stage for advances in fluid mechanics.
- **Leonhard Euler (1707–1783) obtained the differential equations for fluid motion** in 1755.
- **Daniel Bernoulli (1700–1782) developed the energy equation** for incompressible flow in 1738.
- **Lord Rayleigh (1849–1919) developed the powerful dimensional analysis technique**.
- **Osborn Reynolds (1849–1912) conducted extensive experiments with pipe flow** and in 1883 came up with the dimensionless number that bears his name.
- The general equations of fluid motion that include the effects of fluid friction, known as the Navier–Stokes equations, were developed by **Claude Louis Marie Navier (1785–1836) in 1827 and independently by George Gabriel Stokes** (1819–1903) in 1845.
- **Ludwig Prandtl (1875–1953) showed that fluid flows can be divided into a layer near the walls, called the boundary layer, where the friction effects** are significant and an outer layer where such effects are negligible, thus the Euler and Bernoulli equations are applicable.
- **Theodore von Karman (1889–1963) and Sir Geoffrey I. Taylor (1886–1975)** also contributed greatly to the development of fluid mechanics in the twentieth century.
- The **availability of high-speed computers in the last decades and the development of numerical methods** have made it possible to solve a variety of real-world fluids problems and to conduct design and optimization studies through numerical simulation.

Laminar vs. Turbulent Flow

- **Laminar**
  - Highly ordered fluid motion with smooth streamlines.
- **Turbulent**
  - Highly disordered fluid motion characterized by velocity fluctuations and eddies.
- **Transitional**
  - A flow that contains both laminar and turbulent regions
- **Reynolds number**
  - **Re = Dρv/μ**, is the key parameter in determining whether or not a flow is laminar or turbulent.


Laminar


Transitional


Turbulent

Governing Equations

- **Conservation laws of physics**
  - **Mass**
  - **Linear Momentum** - Newton's second law: the change of momentum equals the sum of forces on a fluid particle
  - **Angular momentum**
  - **Energy** - First law of thermodynamics: Rate of change of energy equals the sum of rate of heat addition to and work done on fluid particle
  - **Entropy Balance** - Second law of thermodynamics: measure of irreversibility
- **The fluid is treated as a continuum**
  - For length scales of, say, 1 mm and larger, the molecular structure and motions may be ignored

Governing Equations

The conservation of mass

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{U}) = 0$$

Newton's second law of motion

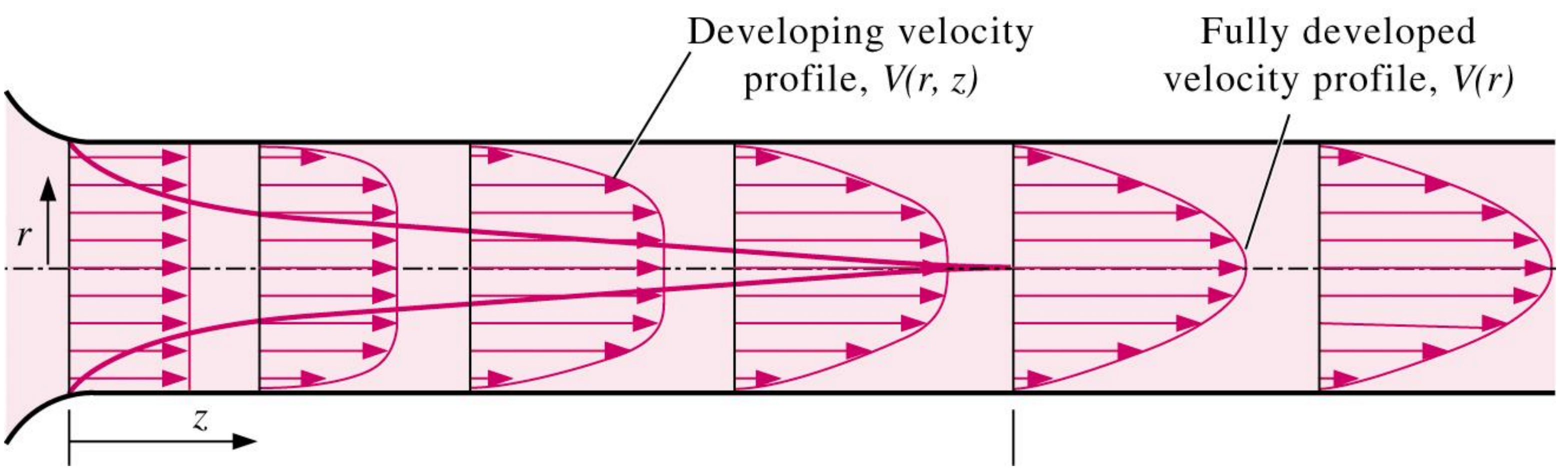
$$\rho \frac{\partial \mathbf{U}}{\partial t} + (\mathbf{U} \cdot \nabla)\,\mathbf{U} = -\nabla p + \rho \mathbf{g} + \mu \nabla^2 \mathbf{U}$$

The principle of angular momentum
The first law of thermodynamics
The second law of thermodynamics

- Internal vs. External
- Viscous vs. Inviscid
- Compressible vs. Incompressible
- Steady vs. Unsteady
- Laminar vs. Turbulent
- One-, Two-, and Three-dimensional flows

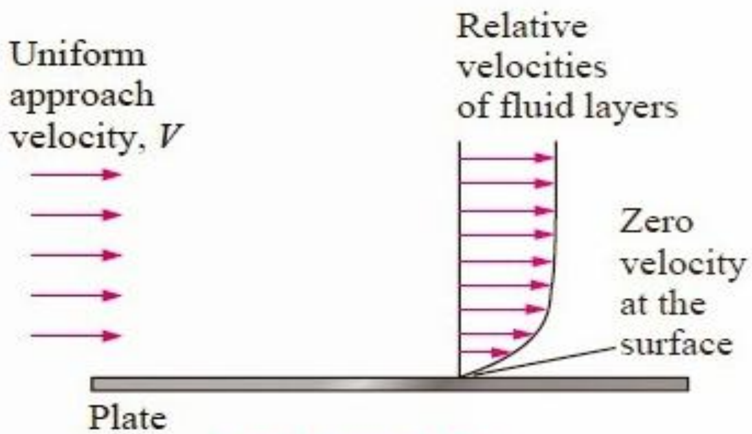
One-, Two-, and Three, Dimensional Flows

- N-S equations are 3D vector equations.
- Velocity vector, $\boldsymbol{U}(x,y,z,t)= [U_x(x,y,z,t),U_y(x,y,z,t),U_z(x,y,z,t)]$
- Lower dimensional flows reduce complexity of analytical and computational solution
- Change in coordinate system (cylindrical, spherical, etc.) may facilitate reduction in order.
- Example: for fully-developed pipe flow, velocity *V(r)* is a function of radius *r* and pressure *p(z)* is a function of distance *z* along the pipe.

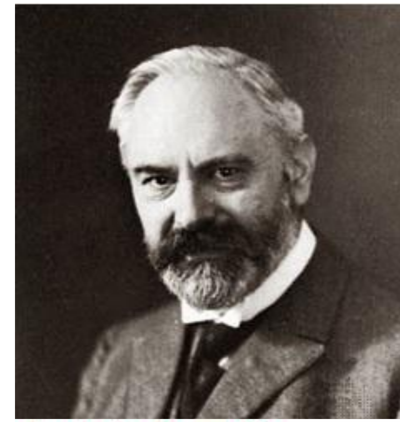


Boundary Conditions

✓Layer of fluid attached to the solid surface sticks to the solid surface
✓Fluid has zero relative velocity with the solid surface
✓Wall shear stress τ_w comes into picture
✓Fluid property responsible for the no-slip condition is **viscosity**



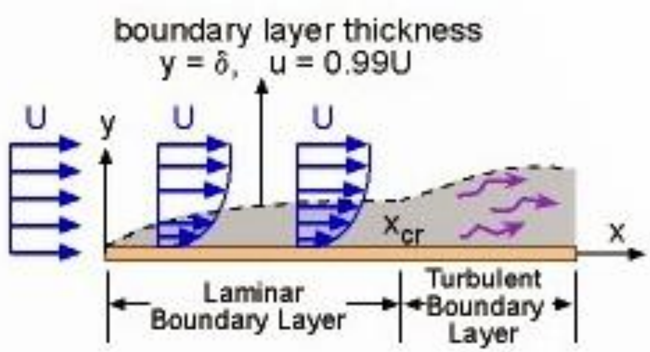
No slip condition



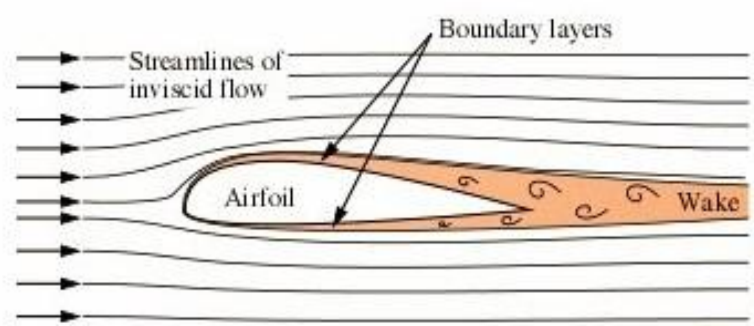
Ludwig Prandtl

German Fluid dynamicst

Introduced boundary layer concept on 1904

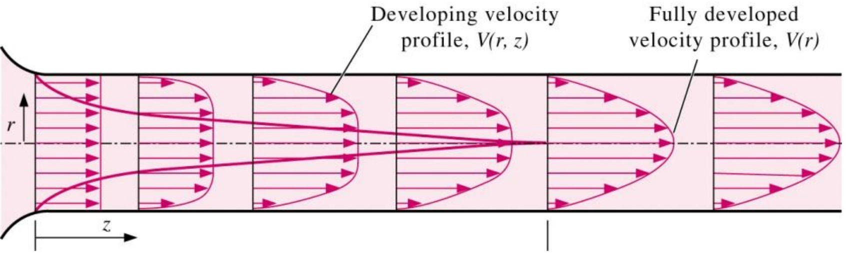


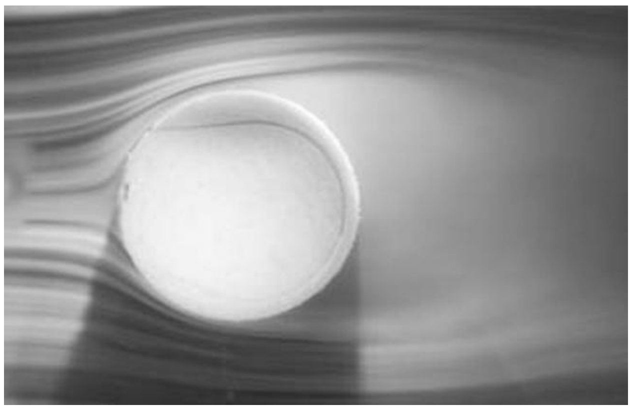
Boundary layer on flat plate



Boundary layer on aerofoil

Internal vs. External & Viscous vs. Inviscid Regions of Flow



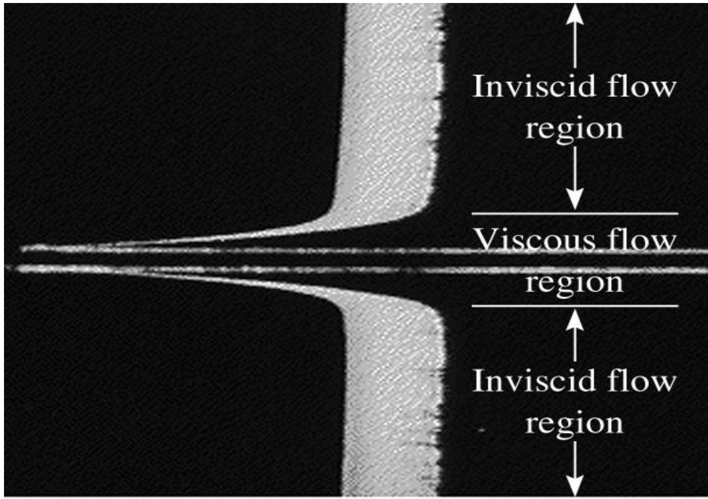


- Frictional effects are significant near boundaries
  - Called viscous regions
- Frictional forces are small away from the boundaries
  - Inertial or pressure forces are called inviscid

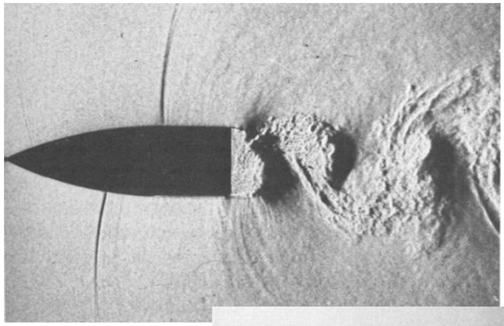
For inviscid flows:

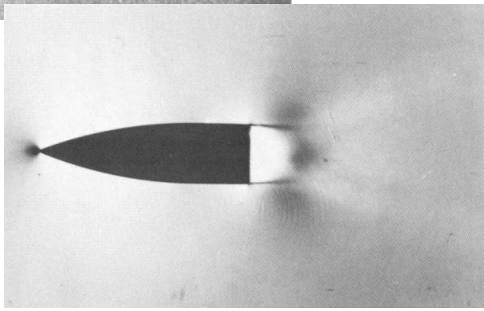
$$\rho \frac{\partial \mathbf{U}}{\partial t} + (\mathbf{U} \cdot \nabla)\,\mathbf{U} = -\nabla p + \rho \mathbf{g} + \cancelto{0}{\mu \nabla^2 \mathbf{U}}$$

- Internal flows are dominated by the influence of viscosity
- For external flows, viscous effects are limited to the boundary layer and wake



Compressible vs. Incompressible & Steady vs. Unsteady Flow

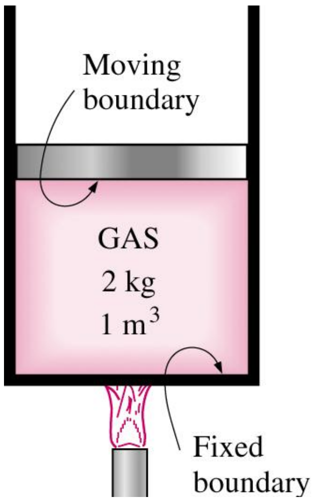


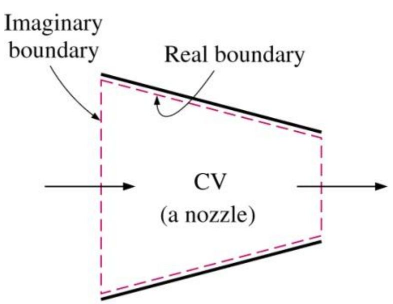


- A flow is classified as incompressible if the density remains nearly constant.
- **Liquid flows** are typically **incompressible**.
- **Gas flows** are often **compressible**, especially for high speeds.
- Mach number, Ma = V/c is a good indicator of whether or not compressibility effects are important.
  - $Ma < 0.3$: Incompressible
  - $Ma < 1$: Subsonic
  - $Ma = 1$: Sonic
  - $Ma > 1$: Supersonic
  - $Ma >> 1$: Hypersonic

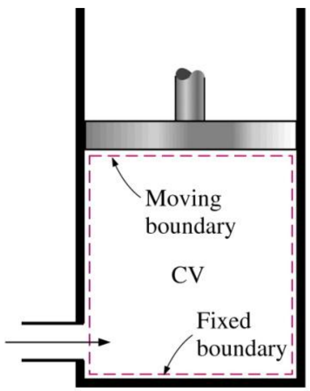
- Steady
  - No change in velocity, pressure at a point with time
  - Transient terms in N-S equations are zero
- Unsteady
  - Change in velocity, pressure at a point with time
- Time-Periodic
  - A flow which oscillates about a mean.
  - Unsteady flows may appear steady if “time-averaged”

System and Control Volume





(*a*) A control volume (CV) with real and imaginary boundaries



(*b*) A control volume (CV) with fixed and moving boundaries

- A system is defined as a quantity of matter or a region in space chosen for study.
- A closed system consists of a fixed amount of mass.
- An open system, or control volume, is a properly selected region in space.
- We'll discuss control volumes in more detail in Chapter 4.

Method of Analysis and Method of Description

- ✓ Differential Approach & Integral approach

✓ LAGRANGIAN APPROACH

- ➢ The time change of any property [p] is denoted as $\frac{Dp}{Dt}$, which is called as **material derivative or substantial derivative**.
- ➢ It reflects time **change in any property of the labelled** /marked/tagged **fluid particles as observed by an observer moving with the fluid**.
- ➢ Also called "**particle based approach**"
- ➢ Recorded properties are associated with the **same fluid particle, but at different locations and at different times**

✓ EULERIAN APPROACH

- ➢ The time change of any property [p] is denoted as $\frac{\partial p}{\partial t}|_{x,y,z}$ which is called as partial **derivative with respect to time**.
- ➢ Observer records the **change in the property at the fixed location (x,y,z)**
- ➢ $\left(\frac{\partial p}{\partial t}\right)$ **also called ``local rate of change of that property"**
- ➢ Recorded properties are associated with the **fixed location in the flow-fluid, having different fluid elements at different times**

Dimensions and Units

- Any physical quantity can be characterized by **dimensions**.
- The magnitudes assigned to dimensions are called **units**.
- **Primary dimensions** include: mass m, length L, time t, and temperature T.
- **Secondary dimensions** can be expressed in terms of primary dimensions and include: velocity V, energy E, and volume V.
- Unit systems include English system and the metric SI (International System). We'll use both.
- **Dimensional homogeneity** is a valuable tool in checking for errors. Make sure every term in an equation has the same units.
- **Unity conversion ratios** are helpful in converting units. Use them.

Accuracy, Precision, and Significant Digits

Engineers must be aware of three principals that govern the proper use of numbers.

1. ***Accuracy error :*** Value of one reading minus the true value. Closeness of the average reading to the true value. Generally associated with repeatable, fixed errors.
2. ***Precision error :*** Value of one reading minus the average of readings. Is a measure of the fineness of resolution and repeatability of the instrument. Generally associated with random errors.
3. ***Significant digits :*** Digits that are relevant and meaningful. When performing calculations, the final result is only as precise as the least precise parameter in the problem.

Summary

- Define and distinguish fluid
- Solid vs. Fluid
- Classification
- Examples
- Governing Laws
- Governing equations & boundary conditions
- Constitutive Relations
- Units and dimensions