Fluid Mechanics Primer

Fluids and Solids: Fundamentals

We normally recognize three states of matter: **solid; liquid and gas**.

However, liquid and gas are both **fluids**: in contrast to solids they lack the ability to resist deformation.

Because a fluid cannot resist deformation force, it moves, or *flows* under the action of the force. Its shape will change continuously as long as the force is applied.

A solid can resist a deformation force while at rest. While a force may cause some displacement, the solid does not move indefinitely.

Introduction to Fluid Mechanics

- Fluid Mechanics is the branch of science that studies the dynamic properties (e.g. motion) of fluids
- A fluid is any substance (gas or liquid) which changes shape uniformly in response to external forces
- The motion of fluids can be characterized by a continuum description (differential eqns.)
- Fluid movement transfers mass, momentum and energy in the flow. The motion of fluids can be described by conservation equations for these quantities: the Navier-Stokes equations.

Some Characteristics of fluids

Pressure: P = force/unit area

Temperature: T = kinetic energy of molecules

Mass: M=the quantity of matter

Molecular Wt: M_w = mass/mole

Density: _ = mass/unit volume

Specific Volume: v = 1/_

Dynamic viscosity: µ = mass/(length•time)

-Dynamic viscosity represents the “stickiness” of the fluid

Important fluid properties -1

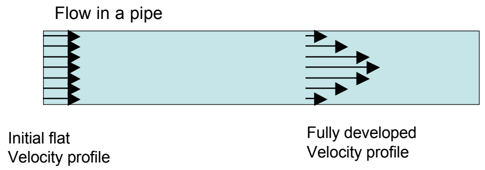
- A fluid does not care how much it is deformed; it is oblivious to its shape
- A fluid does care how fast it is deformed; its resistance to motion depends on the rate of deformation
- The property of a fluid which indicates how much it resists the rate of deformation is the dynamic viscosity

Important fluid properties -2

- If one element of a fluid moves, it tends to carry other elements with it… that is, a fluid tends to stick to itself.
- Dynamic viscosity represents the rate at which motion or momentum can be transferred through the flow.
- Fluids can not have an abrupt discontinuity in velocity. There is always a transition region where the velocity changes continuously.
- Fluids do not slip with respect to solids. They tend to stick to objects such as the walls of an enclosure, so the velocity of the fluid at a solid interface is the same as the velocity of the solid.

Boundary layer

- A consequence of this no-slip condition is the formation of velocity gradients and a boundary layer near a solid interface.



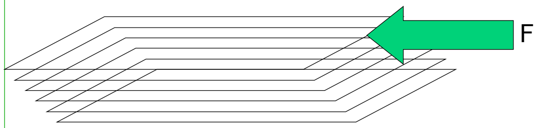
- The existence of a boundary layer helps explain why dust and scale can build up on pipes, because of the low velocity region near the walls

Boundary layer

- The Boundary layer is a consequence of the stickiness of the fluid, so it is always a region where viscous effects dominate the flow.
- The thickness of the boundary layer depends on how strong the viscous effects are relative to the inertial effects working on the flow.

Viscosity

- Consider a stack of copy paper laying on a flat surface. Push horizontally near the top and it will resist your push.



Viscosity

- Think of a fluid as being composed of layers like the individual sheets of paper. When one layer moves relative to another, there is a resisting force.
- This frictional resistance to a shear force and to flow is called viscosity. It is greater for oil, for example, than water.

Typical values

Property	Water	Air
Density ρ (kg/m^3)	1000	1.23
Bulk modulus K (N/m^2)	2×10^9	--------
Viscosity μ (kg/ms)	1.14×10^{-3}	1.78×10^{-5}

Shearing of a solid (a) and a fluid (b)

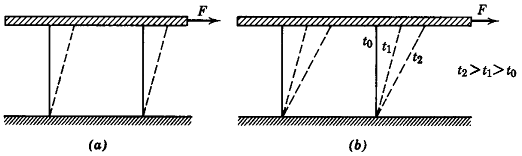


Fig. 1.1 Behavior of (a) solid and (b) fluid, under the action of a constant shear force.

The crosshatching represents (a) solid plates or planes bonded to the solid being sheared and (b) two parallel plates bounding the fluid in (b). The fluid might be a thick oil or glycerin, for example.

Shearing of a solid and a fluid

- Within the elastic limit of the solid, the shear stress τ = F/A where A is the area of the surface in contact with the solid plate.

- However, for the fluid, the top plate does not stop. It continues to move as time t goes on and the fluid continues to deform.

Shearing of a fluid

- Consider a block or plane sliding at constant velocity δu over a well-oiled surface under the influence of a constant force δF_x.
- The oil next to the block sticks to the block and moves at velocity δu. The surface beneath the oil is stationary and the oil there sticks to that surface and has velocity zero.
- **No-slip boundary condition--**The condition of zero velocity at a boundary is known in fluid mechanics as the "no-slip" boundary condition.

Shearing of a fluid (Couette flow model)

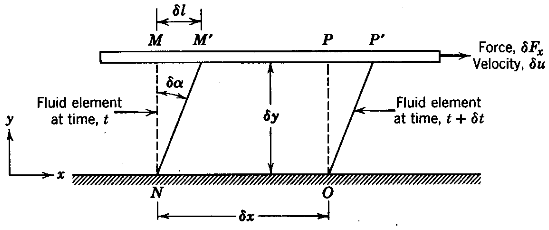


Fig. 2.8 Deformation of a fluid element.

Shearing of a fluid

- It can be shown that the shear stress τ is given by

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

- The term du/dy is known as the velocity gradient and as the rate of shear strain.
- The coefficient is the coefficient of **dynamic** viscosity, μ. (kg/m•s)

Shearing of a fluid

- And we see that for the simple case of two plates separated by distance h, one plate stationary, and the other moving at constant speed *V (gradient is linear)*
- Newton’s law of viscosity:

$$\hat{o} = \grave{i}\,\frac{du}{dy} = \grave{i}\,\frac{V}{h} = \frac{F_u}{Area}$$

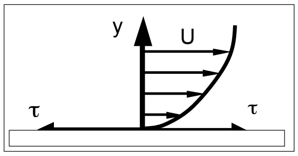
Coefficient of dynamic viscosity

- Intensive property of the fluid.
- Dependent upon both temperature and pressure for a single phase of a pure substance.
- Pressure dependence is usually weak and temperature dependence is important.
- Typical symbol is μ. (mu) in units of: mass length^{-1} time^{-1} (kg/m•s or lbm/ft•s)

Shearing of a fluid

- Fluids are broadly classified in terms of the relation between the shear stress and the rate of deformation of the fluid.
- Fluids for which the shear stress is directly proportional to the rate of deformation are know as *Newtonian* fluids.
- Engineering fluids are mostly Newtonian. Examples are water, refrigerants and hydrocarbon fluids (e.g., propane).
- Examples of non-Newtonian fluids include toothpaste, ketchup, and some paints.

Shear stress in moving fluids



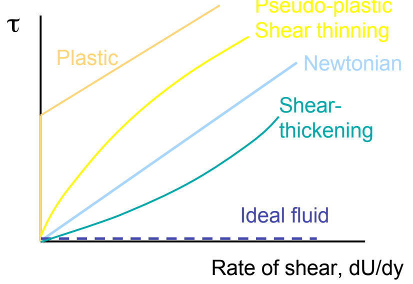
Newtonian fluid

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

_ = (mu)= viscosity (or dynamic viscosity) kg/m s

_ = (nu)= kinematic viscosity m^2/s $\boxed{\nu = \mu / \rho}$

Non-Newtonian Fluids



Viscous forces: F_u

$$\text{ô} = \frac{F_u}{Unit\ Area} = \text{ì}\,\frac{V}{h}$$

$$\tau \approx \frac{F_u}{h^2} = \text{ì}\,\frac{V}{h}$$

$$F_u = \text{ìVh}$$

Reynolds number derivation

Inertial force = F_I

$$F_I = \rho V^2 h^2$$

Viscous force = F_u

$$F_u = \text{ìVh}$$

$$\mathrm{Re} = \frac{F_I}{F_u} = \frac{\rho V^2 h^2}{\text{ì}\,Vh} = \frac{\rho Vh}{\text{ì}}$$

$$\boxed{\mathrm{Re} = \frac{\rho Vh}{\text{ì}}}$$

Re indicates when inertial forces for the fluid flow are large compared to the viscous forces. It is one of the most important non-dimensional numbers in fluid mechanics. Geometrically similar flows with similar Re will have similar boundary layers and other flow structures.

Reynolds number (2)

- Kinematic viscosity = dynamic viscosity/density

$$\boxed{\nu \equiv \frac{\mu}{\rho}}$$

- So Reynolds number becomes:

$$\boxed{\mathrm{Re} = \frac{Vh}{\nu} = \frac{Velocity \bullet Length}{Kinematic\ Vis\cos ity}}$$

- Re described by a velocity, length, and viscosity

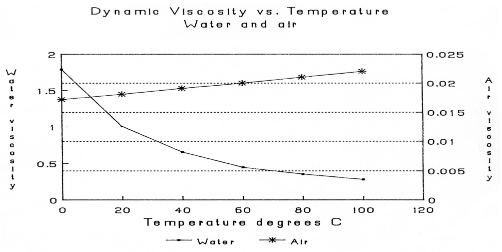
Application of Reynolds number

- The Re is useful to describe when the inertial of the fluid is important relative to the viscosity
  - Inertial forces → keeps things moving
  - Viscous forces → makes things stop
- Re also tells when the flow is smooth (laminar) or chaotic (turbulent)
  - High Inertial forces → large Re → turbulent flow
  - High viscous forces → small Re → laminar flow
- Laminar flow generally for Re < 1000
- Turbulent flow generally for Re > 10,000

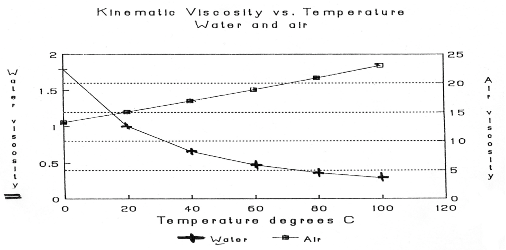
Viscosity changes with Temp

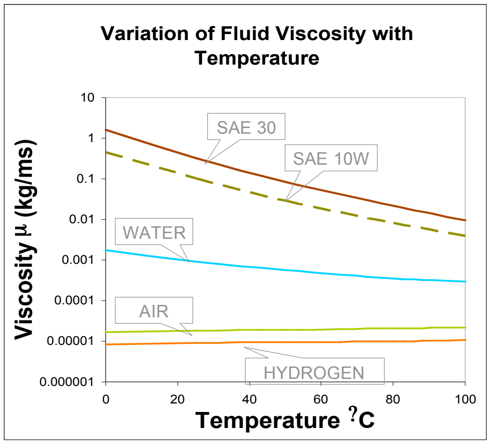
- Fluid properties depend on T (and P somewhat) because of molecular interactions
  - For a liquid, as T increases viscosity decreases
  - For a gas, as T increases viscosity increases
- Gases also change density significantly with T, so the kinematic viscosity increases more rapidly than the dynamic viscosity

Dynamic viscosity



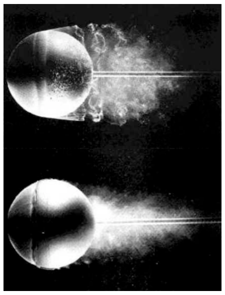
Kinematic Viscosity

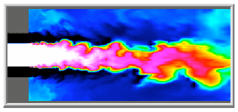




Laminar and Turbulent flow

- UPPER IMAGE: Flow past a sphere at Re =15,000. Boundary layer separating ahead of the equator and remaining laminar ~ one radius, then becomes unstable and turbulent.
- BOTTOM IMAGE: Flow past a sphere at Re =30,000 with a trip wire. Wire hoop ahead of the equator trips the boundary layer, so it separates farther back than if it were laminar. The overall drag is dramatically reduced. This occurs naturally on a smooth sphere only at a Re numbers 10 times as great.
- Flow from a turbulent jet [car exhaust]





Jet: Werle, 1980 (ONERA) Photos from Album of Fluid Motion," by Van Dyke

Flow in a pipe for different Re

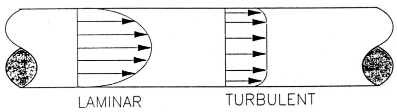
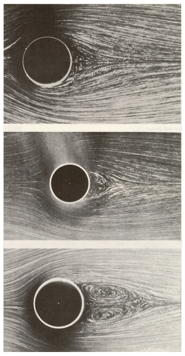


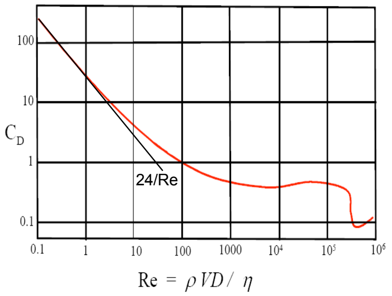
Figure 2.6 Flow-velocity profiles of laminar (Re < 2000) and turbulent (Re > 4000) flow regimes. The turbulent flow profile is nearly uniform across the radius, whereas the laminar profile is more parabolic.

Flow around a sphere



- Re ~ 1
- Re ~ 10
- Re ~ 100

Coefficient of Drag for a Sphere



$$F_D = \left(\frac{1}{2}\rho V^2\right)C_D A_D$$

$$A_D = \pi D^2 / 4$$

Variation of Log (Cd) vs Log(Re) for a smooth sphere

Line shows Cd for stokes region (Re<1)

END HERE Part I

- For smooth spheres Newton's drag law:

$$F_D = C_D \frac{\pi}{8}\rho_G d^2 V^2$$

- Re < 1, Cd = 24/Re
- 1< Re<1000

$$C_D = \frac{24}{Re}\left(1 + \frac{Re^{\frac{2}{3}}}{6}\right)$$

- 1000 < Re < 10^5
  Cd ≈ 0.44 Re