Review of Fluid Mechanics Terminology

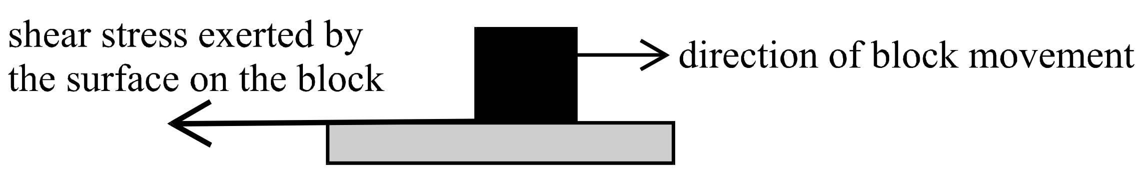
The Continuum Hypothesis: We will regard macroscopic behavior of fluids as if the fluids are perfectly continuous in structure. In reality, the matter of a fluid is divided into fluid molecules, and at sufficiently small (molecular and atomic) length scales fluids cannot be viewed as continuous. However, since we will only consider situations dealing with fluid properties and structure over distances much greater than the average spacing between fluid molecules, we will regard a fluid as a continuous medium whose properties (density, pressure etc.) vary from point to point in a continuous way. For the problems that we will be interested in, the microscopic details of fluid structure will not be needed and the continuum approximation will be appropriate. However, there are situations when molecular level details are important; for instance when the dimensions of a channel that the fluid is flowing through become comparable to the mean free paths of the fluid molecules or to the molecule size. In such instances, the continuum hypothesis does not apply.

Fluid: a substance that will deform continuously in response to a shear stress no matter how small the stress may be.

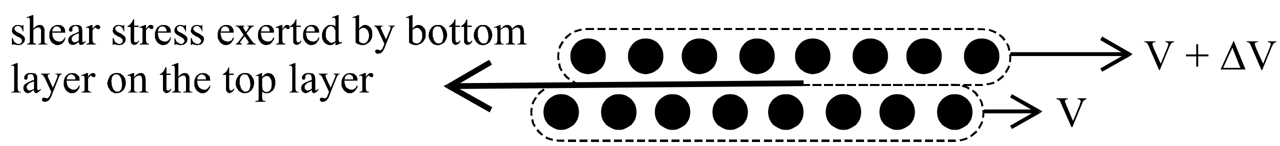
Shear Stress: Force per unit area that is exerted parallel to the surface on which it acts.

Shear stress units: Force/Area, ex. N/m^2. Usual symbols: σ_{ij}, τ_{ij} ($i \neq j$).

Example 1: shear stress between a block and a surface:



Example 2: A simplified picture of the shear stress between two laminas (layers) in a flowing liquid. The top layer moves relative to the bottom one by a velocity ΔV, and collision interactions between the molecules of the two layers give rise to shear stress. Note that the shear stress acts parallel to the surface on which it is exerted.

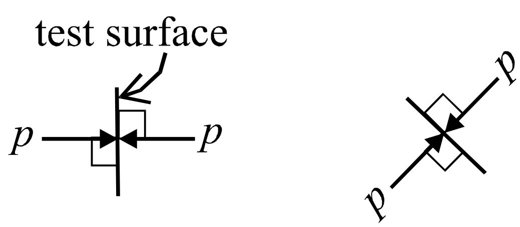


Normal Stress: Force per unit area that is exerted normal to the surface on which it acts. Pressure is a normal stress.

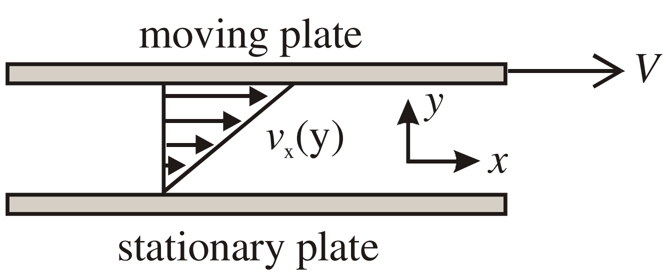
Normal stress units: Force/Area, ex. N/m^2. Usual symbols: σ_{ii}, τ_{ii}.

Pressure: A normal, compressive stress that acts on a surface immersed in a fluid. If we have an infinitesimal "test surface" in a fluid, no matter how we orient the test surface, we would measure the same pressure on it as long as the surface is at rest with respect to the fluid around it. Because the pressure does not depend on the orientation of the test surface, we say that it is "isotropic" (ie. independent of direction). An example of a quantity that is *not* isotropic is gravitational force, since gravitational force acts along a *specific* direction.

Pressure units: Force/Area, ex. N/m^2. Usual symbol: p.



Shear Strain Rate (Velocity Gradient): Imagine that we have a velocity v_x(y) as shown below. Then the shear strain rate is given by



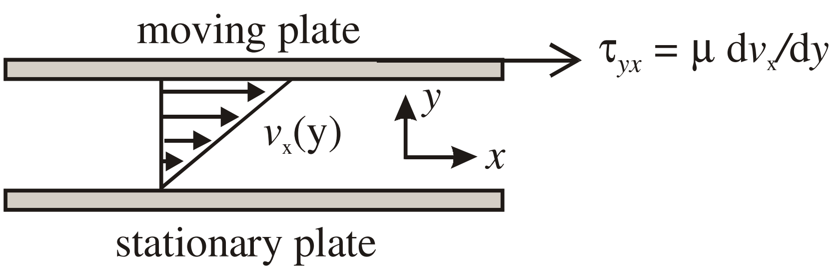
$$\text{Shear Strain Rate} = \frac{dv_x}{dy}$$

Shear strain rate units: 1/Time, ex. 1/s.
Usual symbols for velocity x-component: v_x, u; y-component: v_y, v; z-component: v_z, w.

Note that the direction in which the velocity changes (the y direction), is perpendicular to the direction of the velocity (the velocity points along x).

Also, note that usually the velocity of a fluid at solid walls is assumed to be the same as that of the walls (V for the top surface, 0 for the bottom in the figure above). This is known as the "no slip" boundary condition (i.e. the fluid at the fluid/solid surface moves along with the solid surface and *does not* "slip" relative to the surface).

Viscosity: Viscosity (μ) is a fluid property that measures the fluid's resistance to shear stress. For a "Newtonian fluid", viscosity is a proportionality constant between shear stress and the velocity gradient, as in the following expression:



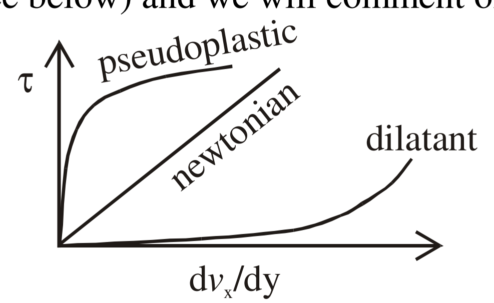
$$\tau_{yx} = \mu\,(dv_x/dy)$$

The higher μ is, the greater the shear stress that results from a given velocity gradient in a fluid. Viewed another way, the higher μ is, the greater the shear stress needed to maintain a given velocity gradient within a fluid. Shear stresses contribute to the viscous dissipation of mechanical energy to heat.

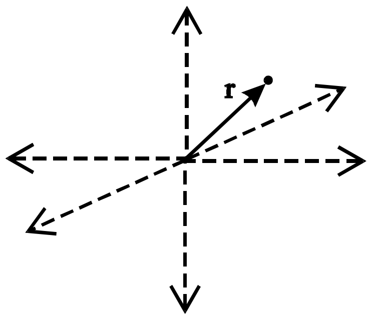
Viscosity units: Force Time/Area, ex. N s / m^2. Often, viscosity is given in "poise", where 1 poise = 1 dyne s / cm^2 = 0.1 N s / m^2, or in centipoise (cp) where 1 cp = 0.01 poise. Usual symbol for viscosity: μ.

The viscosity of liquids typically decreases with an increase in temperature, while that of low density gases will typically increase with an increase in temperature. Viscosities in general increase with an increase in pressure, though the dependence tends to be weak (unless the pressure is near or above the fluid's critical pressure).

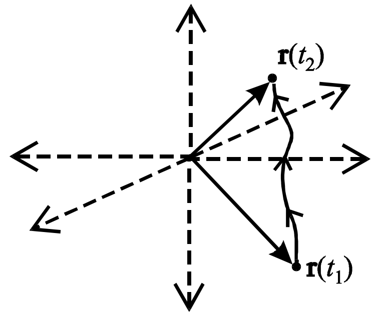
This course will be predominantly concerned with Newtonian fluids, for which the relationship between shear stress and strain rate is linear (see above). However, other fluid behaviors are also known (see below) and we will comment on these as well.



Mathematical Description of Fluid Flow: Fluid mechanics answers questions such as "How do fluid velocity, density, pressure etc. depend on the position **r** and time *t*?" This involves determination of $\mathbf{v}(\mathbf{r},t)$, $\rho(\mathbf{r},t)$, $p(\mathbf{r},t)$ etc., where **r** specifies a point in space with respect to the origin. When **r** simply refers to a fixed point in space, the problem is said to be formulated in the "Eulerian" representation.



Eulerian representation



Lagrangian representation

Another representation is "Lagrangian", where $\mathbf{r} = \mathbf{r}(t)$ is the position of a moving object. Then the velocity of the object is $d\mathbf{r}/dt$. In keeping with the most common usage, we will mostly use the Eulerian representation. In summary, when we use **r** we understand it to simply refer to a position in space (Eulerian representation), and *not* to the changing position of some object such as a fluid element. Note that in the Eulerian representation, taking derivatives of **r** with respect to time has no physical meaning.

Units:

Dimension	English System	SI System
Mass	slug	kilogram (kg)
Time	second (sec)	second (s)
Length	foot (ft)	meter (m)
Force	pound (lb or lb_f) (= slug ft/sec^2)	newton (N) (N = kg m/s^2)
Viscosity	lb sec / ft^2	N s / m^2
Absolute Temperature	degree Rankin (^{o}R)	degree Kelvin (^{o}K)
Density	slug / ft^3	kg / m^3

Caution*:* The "slug" is the unit of mass in the English system. Since the gravitational acceleration g is $g = 32.174$ ft/sec^2, one slug of mass is acted upon by (1 slug)(32.174 ft/sec^2) = 32.174 lb force in Earth's standard gravitational field. The often used "pound mass", abbreviated as lb_m, is that amount of mass that gives rise to 1 lb force in standard gravitational field. From this, it can be deduced that 1 slug = 32.174 lb_m. If you are using lb_m to calculate forces instead of slugs, you must remember to include the conversion factor g_c:

$$F(lb_f) = m(lb_m)\; a(ft/sec^2) \,/\, g_c$$

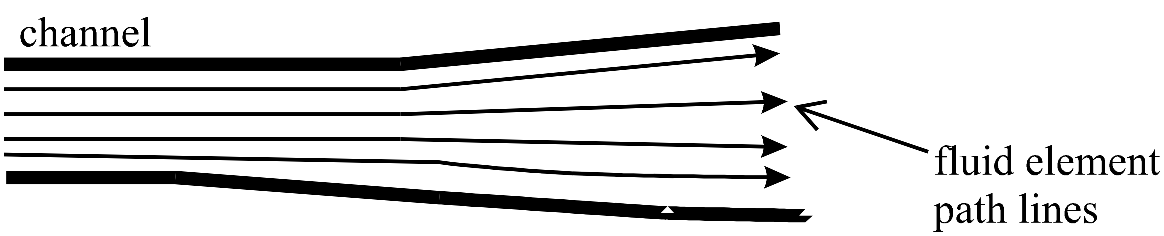
where $g_c = 32.174\ lb_m\ ft/(lb_f\ sec^2) = 32.174\ lb_m/\text{slug}$.

Classifications of Fluid Flow

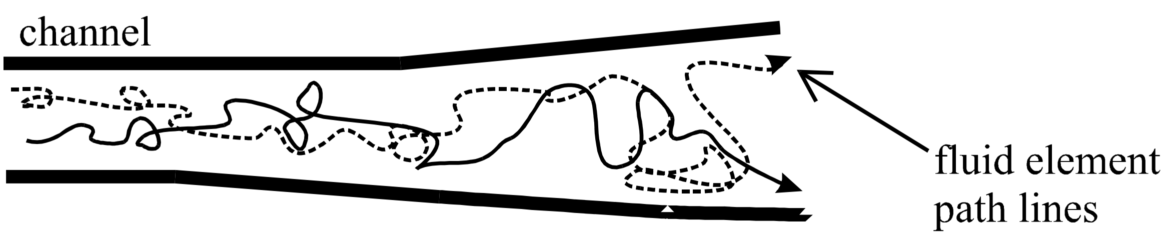
<u>*Steady Flow:*</u> A steady flow is one for which all time derivatives are zero. In other words, $\partial \mathbf{v}/\partial t = 0$, $\partial p/\partial t = 0$, $\partial \rho/\partial t = 0$ etc. Steady flow *does not* mean that acceleration of the fluid is zero, it only means that the conditions at a given point in space do not change with time. For instance, let's say that acceleration at the point $\mathbf{r}_1$ at time t_1 is 5 cm/s^2 and the velocity is 10 cm/s. If the flow is steady then for all later times, even as new particles of fluid pass through $\mathbf{r}_1$, the acceleration at $\mathbf{r}_1$ remains at 5 cm/s^2 and the velocity at 10 cm/s.

<u>*Ideal Flow:*</u> A flow in which the dissipation of mechanical energy to heat (internal energy) is zero. Ideal flow is a good approximation for many real flows in which the dissipation of mechanical energy is low.

<u>*Laminar Flow:*</u> Flow that occurs in laminas (layers). In qualitative terms, the flow is smooth and not chaotic. Laminar flow can be steady or dynamic (changing with time). In laminar flow, the path lines are layered.



<u>*Turbulent Flow:*</u> A flow that is characterized by the presence of apparently random velocity fluctuations. Turbulent flow is chaotic, and can only be dynamic since the velocity at a point fluctuates, and therefore changes, with time. In other words, if you observe the velocity at a point $\mathbf{r}$ as a function of time, you would see it change continuously in an apparently unpredictable manner.

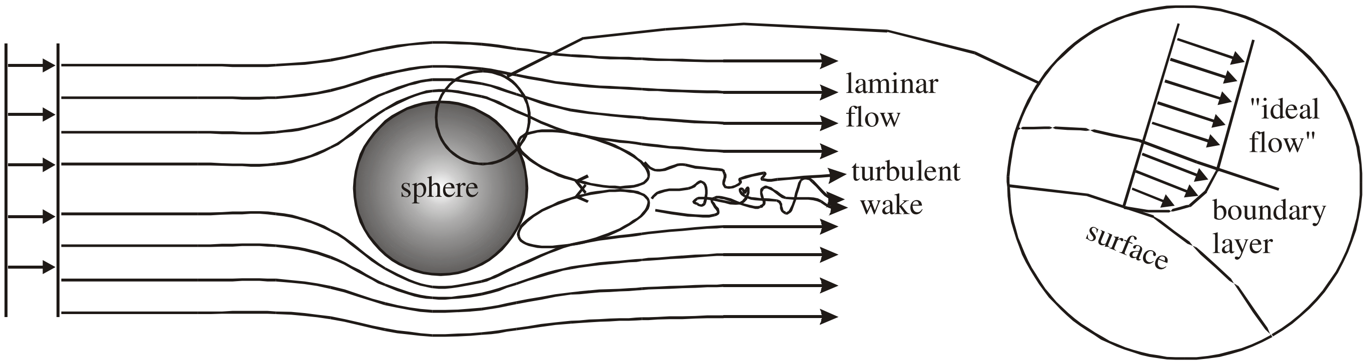


Compressible Flow: Flow in which the fluid density varies appreciably with position or time, as is the case for many gas flows.

Incompressible Flow: Flow in which the fluid density is constant. Incompressibility is often a good approximation for liquid flows.

Subsonic/supersonic flow: Flow in which the fluid velocity remains below the speed of sound (subsonic), or one in which the speed of sound is exceeded (supersonic).

External Flow: Flow around objects. An example is illustrated below.



Internal Flow: Flow in conduits and channels, for example in a pipe or in a river bed. In internal flow, the fluid is confined by walls. An example is illustrated below.