UCH 1201 Principles of Chemical Engineering

Fluid Mechanics

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June 9, 2021

Contents

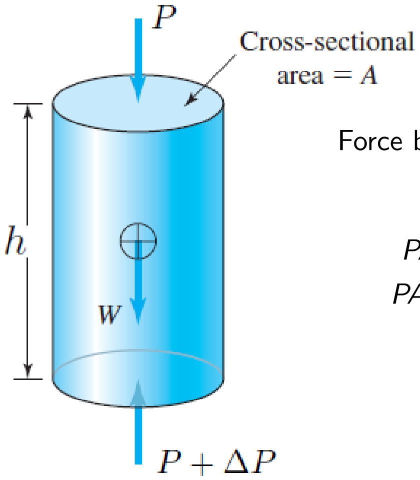
Introduction

- Fluid Mechanics deals with behavior of fluids at rest (fluid statics) or in motion (fluid dynamics).

Fluids

- Fluids refers to gas or liquid.
- Liquid — takes the shape of container and has a free surface. Gas — occupies the entire container, and has no free surface.
- Liquid — hard to compress; Gas — easy to compress. Liquids are called incompressible fluids; gases are called compressible fluids.
- A 'vapor' is a gas whose temperature and pressure are much nearer to its liquid phase. Thus steam is considered a vapor because its state is normally not far from that of water. A 'gas' may be defined as a highly superheated vapor; that is, its state is far away from the liquid phase. Thus air is considered a gas because its state is normally very far from that of liquid-air.
- Fluid Mechanics deals with behavior of fluids at rest (fluid statics) or in motion (fluid dynamics).

Pressure Variation in a Static Fluid



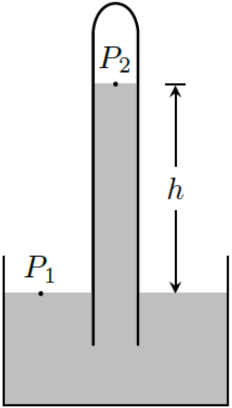
Force balance:

$$
\begin{aligned}
PA + W &= (P + \Delta P)A \\
PA + (V\rho)g &= PA + \Delta PA \\
PA + (Ah\rho)g &= PA + \Delta PA \\
\implies \quad \Delta P &= \rho g h
\end{aligned}
$$

Pressure Measurement

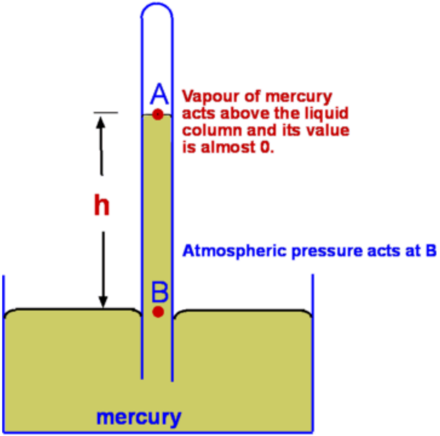
Pressure is proportional to the height of a column of fluid. Manometry exploits this to measure fluid pressure. In other words we measure the height of a column of liquid supported by the pressure (actually the pressure difference). Barometer, piezometer and U-tube Manometer are some of the members of this class.

Barometer



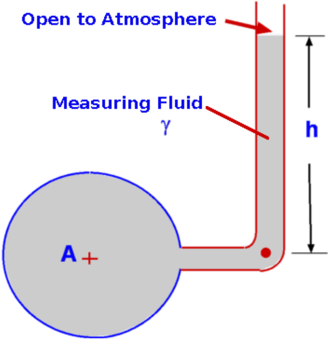
$$
\begin{aligned}
P_1 - P_2 &= \rho g h \\
P_2 &\approx 0. \\
\text{Hence, } h &= \frac{P_1}{\rho g}
\end{aligned}
$$

Barometer (contd..)



Mercury Barometer is the simplest device to measure atmospheric pressure at a location. It consists of a glass tube closed at one end immersed in a container filled with mercury. Because of the atmospheric pressure mercury rises in the tube.

Piezo meter



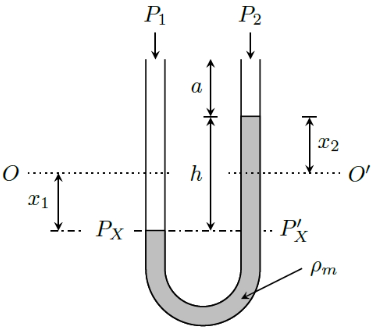
Piezometer tube is perhaps the simplest of the pressure measuring devices and consists of a vertical tube. In its application one end is connected to the pressure to be measured while the other end is open to the atmosphere as shown.

$$P_A - P_{\text{atm}} = \rho g h$$

Manometer

- A manometer is the simplest device to measure pressure differences. A common simple manometer consists of a U shaped tube of glass filled with some liquid.
- Manometric fluids can be colored water, air, oil, carbon tetra chloride, benzenes, bromides, and mercury.
- Manometer principle: pressure at the same level in a continuous body of fluid are equal.

Manometer (contd..)



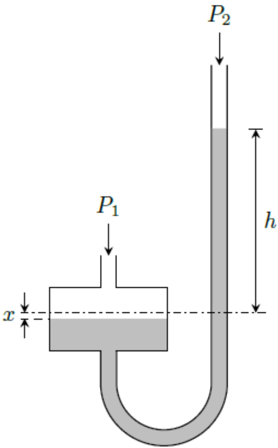
Making pressure balance at XX',

$$P_X = P'_X$$

$$P_1 + \rho g a + \rho g h = P_2 + \rho g a + \rho_m g h$$

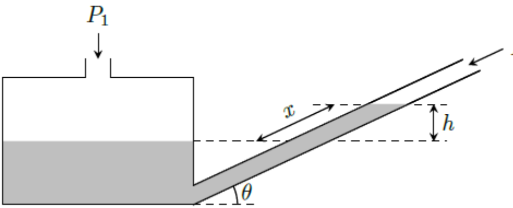
$$P_1 - P_2 = (\rho_m - \rho) g h$$

Manometers (contd..)



$$P_1 - P_2 = \rho_m g h$$

Well-type Manometer

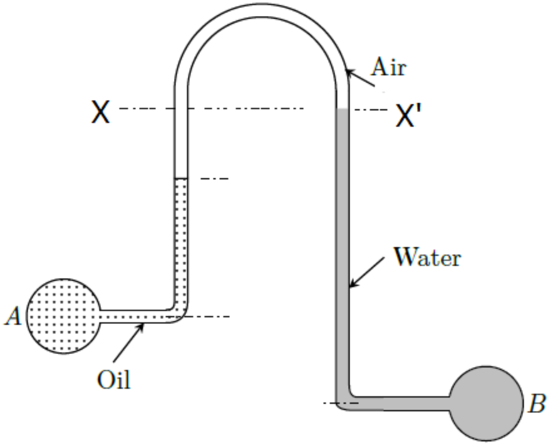


$$P_1 - P_2 = \rho_m g h = \rho_m g (x \sin$$

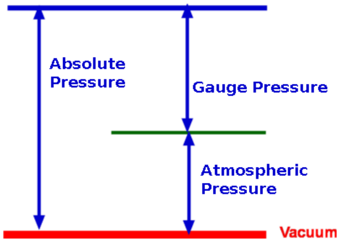
Inclined Manometer

Manometers (contd..)

Inverted U-tube



Absolute and Gauge Pressures



- Pressure is always measured as a difference or with respect to a datum or reference.
- Absolute pressure is measured relative to a perfect vacuum, whereas gauge pressure is measured relative to atmospheric pressure.
- Absolute pressure is the sum of atmospheric pressure and the gauge pressure.

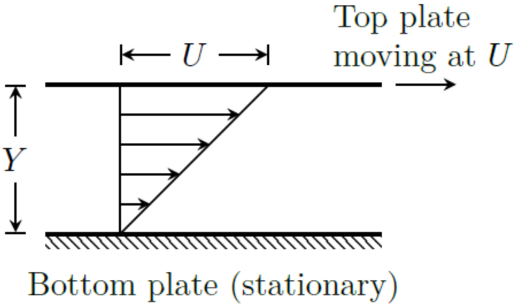
Viscosity

- *Viscosity* of a fluid is a measure of its resistance to shear or angular deformation.
- Lubricating oil, for example, has high viscosity and resistance to shear, is cohesive, and feels sticky, whereas gasoline has low viscosity.
- Lesser the viscosity of the fluid, the greater is its ease of movement (fluidity). The reciprocal of viscosity is *fluidity*.
- All real fluids have some resistance to stress and therefore are viscous, but a fluid which has no resistance to shear stress is known as an ideal fluid or inviscid fluid.

Viscosity (contd..)

- Poise (P) is the unit of viscosity. $1\ \text{P} = 1\ \text{g}/(\text{cm.s})$ $1\ \text{cP} = 1 \times 10^{-2}\ \text{P} = 0.01\ \text{g}/(\text{cm.s})$
$= 0.01 \times 10^{-3}\ \text{kg}/(10^{-2}\text{m.s}) = 0.001\ \text{kg}/(\text{m.s})$
- Viscosity of water at $20^{\circ}\mathrm{C} = 1$ cP.
- Viscosity of air is roughly 50 times smaller than the viscosity of water at the same temperature.
- Viscosity of honey $= 2000 - 10000$ cP

Viscosity



$$\tau = \frac{F}{A} = \mu \frac{U}{Y}$$

τ	$=$	shear stress
F	$=$	force applied to the top plate
A	$=$	surface area of top plate
μ	$=$	viscosity of fluid

Newton's Law of Viscosity

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

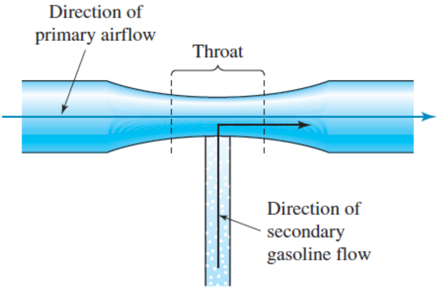
Newton's law of viscosity and states that the shear stress between adjacent fluid layers is proportional to the negative value of the velocity gradient between the two layers

Energy Balance for a Moving Fluid

Bernoulli equation:

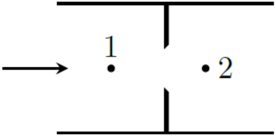
$$\left[P + \frac{\rho v^2}{2} + \rho g h\right]_1 = \left[P + \frac{\rho v^2}{2} + \rho g h\right]_2$$

Pressure Variation in a Moving Fluid (contd..)

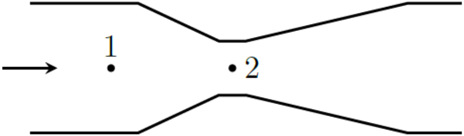


The flow through the venturi tube can be used to induce the flow of a second fluid. e.g.: In carburetor, the primary airflow draws gasoline into the engine. As the air moves through the throat (the region of reduced cross-sectional area), its velocity increases and its pressure decreases. The drop in pressure provides suction, which draws gasoline into the throat and out through the exit of the venturi.

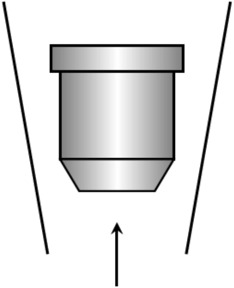
Flow Measurement using Bernoulli Equation



Orifice meter



Venturi meter



Rota meter

Flow Measurement using Bernoulli Equation (contd..)

By using Bernoulli and mass balance equations, velocity at the point 2 (v_2) is obtained as

$$v_2 = \frac{1}{\sqrt{1-\beta^4}}\sqrt{\frac{2(P_1 - P_2)}{\rho}}$$

where $\beta = D_2/D_1$. The above equation applies strictly to the frictionless flow of non-compressible fluids. To account for the small friction loss between locations 1 and 2, the above equation is corrected by introducing an empirical factor C_f, known as the *flow coefficient*.

Flow Measurement using Bernoulli Equation (contd..)

Rotameter

This meter may thus be considered as an orifice meter with a variable aperture, and the formula derived for orifice meter / venturi meter are applicable.

The pressure drop over the float ΔP, is given by:

$$\Delta P = \frac{V_f(\rho_f - \rho)g}{A_f}$$

where V_f is the volume of the float, ρ_f is the density of the float material, and A_f is the maximum cross sectional area of the float in a horizontal plane.

Because of rotameter relies on gravity, it must be installed vertically (with the flowtube perpendicular to the floor).

Comparison of Flow Meters

$$v_2 = \frac{1}{\sqrt{1-(D_2/D_1)^4}}\sqrt{\frac{2(P_1-P_2)}{\rho}}$$

$P_1 - P_2$ is variable with orifice and venturi meters; and,
$D_2/D_1 = \beta$ is a variable with rotameter.
Orifice and venturimeters are also known as variable head meters (or, constant area meters); and, rotameter is a variable area meter (or, constant head meter).

Frictional Losses

When a liquid flows through a pipeline, shear stresses develop between the liquid and the pipe wall. This shear stress is a result of friction, and its magnitude is dependent upon the properties of the fluid, the speed at which it is moving, the internal roughness of the pipe, the length and diameter of pipe.

Reynolds Number (Re)

$$\mathrm{Re} = \frac{Dv\rho}{\mu} = \frac{\text{inertial force}}{\text{viscous force}}$$

where

$$\text{inertial force} = ma = \rho V \frac{dv}{dt}$$

$$\text{viscous force} = \tau A = \mu A \frac{dv}{dy}$$

Hence,

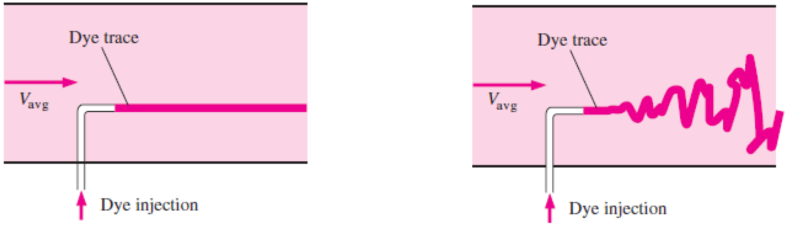
$$\mathrm{Re} = \frac{\rho V \frac{dv}{dt}}{\mu A \frac{dv}{dy}} = \frac{\rho V dy}{\mu A dt} = \frac{Dv\rho}{\mu}$$

Laminar and Turbulent Flows

- Laminar Flow — characterized by smooth streamlines and highly ordered motion.
- Turbulent Flow — characterized by velocity fluctuations and highly disordered motion.

Most flows encountered in practice are turbulent. Laminar flow is encountered when highly viscous fluids such as oils flow in small pipes or narrow passages.

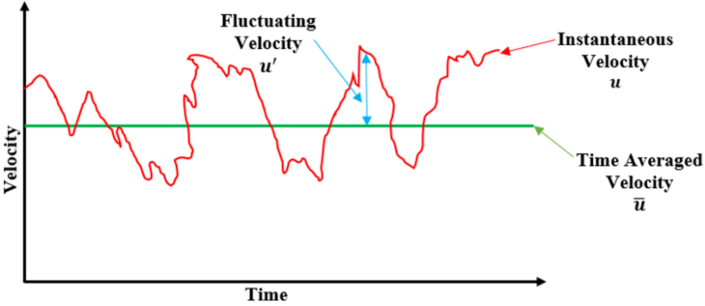
Laminar and Turbulent Flows



(*a*) Laminar flow (*b*) Turbulent flow

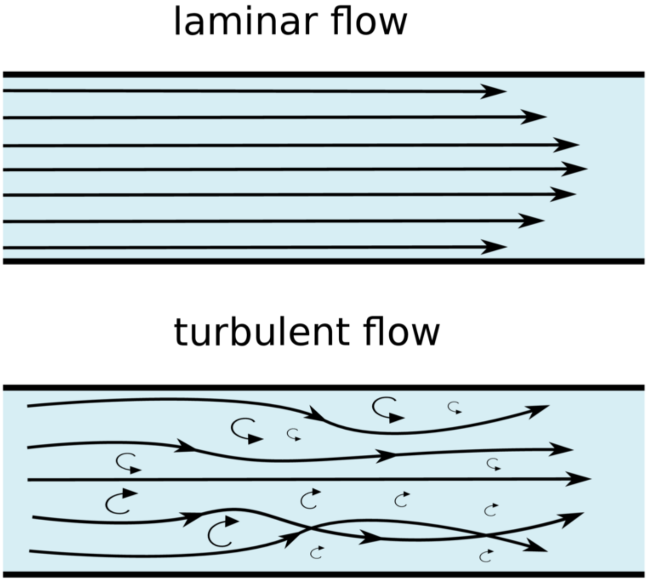
The intense mixing of the fluid in the turbulent flow as a result of rapid fluctuations enhances momentum transfer between fluid particles, which increases the friction force on the surface and thus the required pumping power.

Turbulent Flow - Velocity at a Point



The velocity varies in a chaotic manner around a mean velocity.

Flow Streamlines

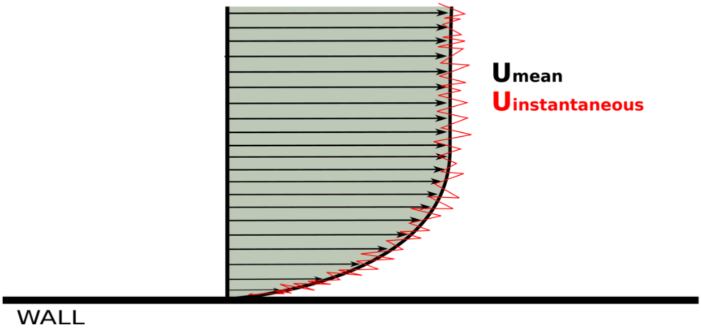


Flow Streamlines (contd..)

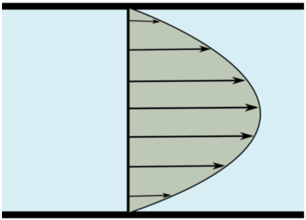
- If a fluid is flowing over a horizontal surface with a steady flow and moves in the form of layers of different velocities which do not mix with each other, then the flow of fluid is called laminar flow. The laminar flow is also known as streamlined flow.
- In a turbulent flow, the path and the velocity of the particles of fluid change continuously and haphazardly with time from point to point.

Turbulent Flow

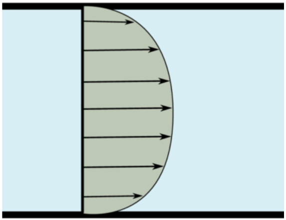
Mean Velocity and Instantaneous Fluctuations



Velocity Profiles



Laminar Flow

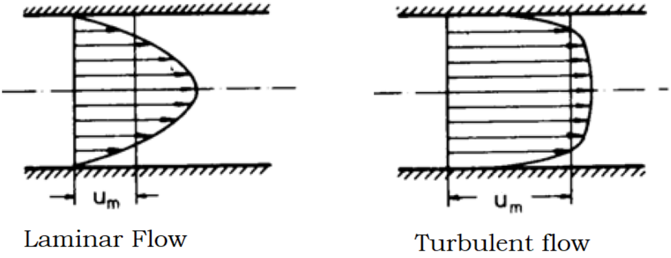


Turbulent Flow

- The nature of velocity profile in a laminar pipe flow is paraboloid with zero at the wall and maximum at the central-line. The maximum velocity in a laminar pipe flow is twice that of average velocity.
- The velocity profile in turbulent flow is flatter in the central part of the pipe (i.e. in the turbulent core) than in laminar flow. The flow velocity drops rapidly extremely close to the walls.

Laminar and Turbulent Flows

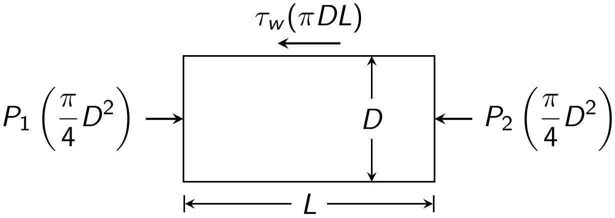
Average Velocities



For laminar flow, average velocity is 0.5 times the maximum velocity. Whereas for turbulent flow, average velocity is 0.8 times the maximum velocity.

Relation between Wall Shear Stress and Pressure Drop

Relation between pressure drop due to friction (ΔP) and wall shear stress (τ_w) for flow through circular pipe:



$$P_1\left(\frac{\pi}{4}D^2\right) - P_2\left(\frac{\pi}{4}D^2\right) = \tau_w(\pi DL) \implies P_1 - P_2 = \Delta P = \frac{4\tau_w L}{D}$$

Pressure Drop due to Friction

Fanning friction factor (f):

$$f = \frac{\tau_w}{\rho v^2/2}$$

Pressure drop (ΔP) due to friction for flow through a pipeline is given by

$$\Delta P = \frac{2fL\rho v^2}{D} \tag{1}$$

D	$=$	diameter of pipe
v	$=$	fluid velocity
L	$=$	length of pipe over which pressure drop is measured
ρ	$=$	density of fluid
f	$=$	friction factor

The above equation is also known as Darcy-Weisbach equation. It should be noted that the 'f' used here is Fanning friction factor.

Pressure Drop due to Friction

Laminar Flow

Hagen-Poiseuille Equation—for laminar flow.

$$\Delta P = \frac{32 L v \mu}{D^2}$$

The above equation can be obtained from Eqn.(**??**) by substituting for $f = 16/\mathrm{Re}$.
One of the use of Hagen-Poiseullie equation is in the experimental measurement of viscosity; by measuring the pressure drop and volumetric flow rate through a capillary tube of known length and diameter.

Pressure Drop due to Friction

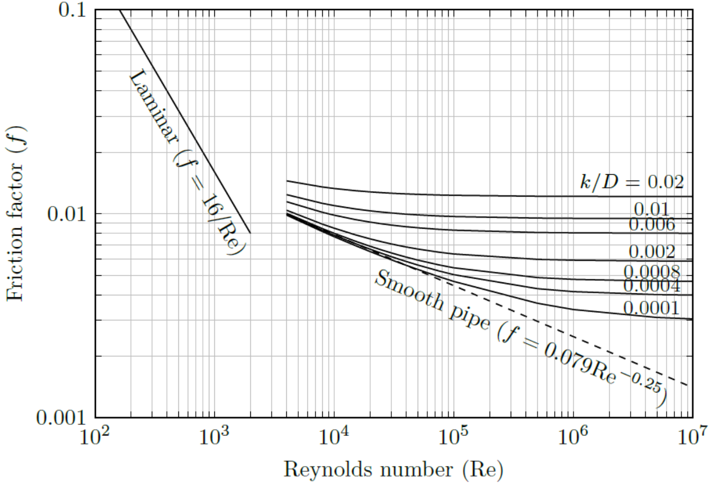
Turbulent Flow

$$f = 0.079 Re^{-0.25}$$

The above equation is valid for flow in a smooth pipe for $3,000 < \mathrm{Re} < 100,000$.

Pressure Drop due to Friction

Friction Factor Chart



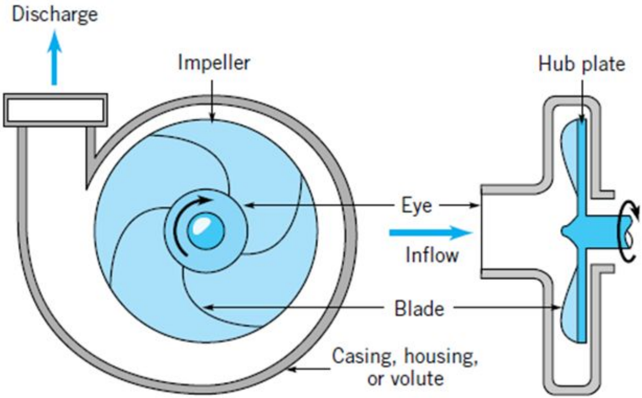
k is the roughness of pipe.

Pumps

Pumps are classified into two major categories—centrifugal pumps, and positive displacement pumps.
Centrifugal pumps are capable of higher flows and can work with lower viscosity liquids. In some chemical plants, 90% of the pumps in use will be centrifugal pumps. However, there are a number of applications for which positive displacement pumps are preferred. For example, they can handle higher viscosity fluids and can operate at high pressures and relatively low flows more efficiently. They are also more accurate when metering is an important consideration.

Pumps (contd..)

Centrifugal Pump

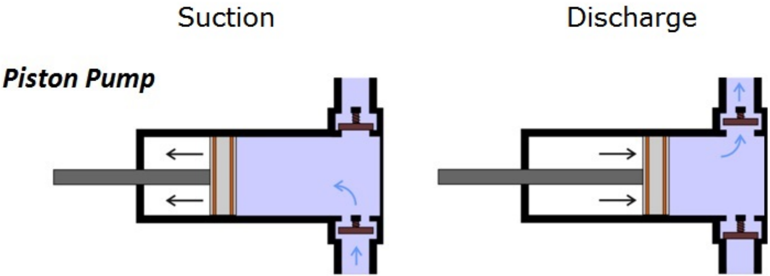


Pumps (contd..)

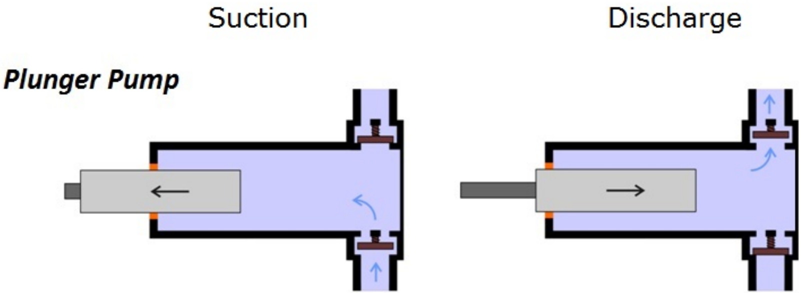
- A positive displacement pump moves a fluid by repeatedly enclosing a fixed volume and moving it mechanically through the system. The pumping action is cyclic and can be driven by pistons, screws, gears, rollers, diaphragms or vanes. Two types of positive displacement pumps—reciprocating and rotary.

Reciprocating Pumps

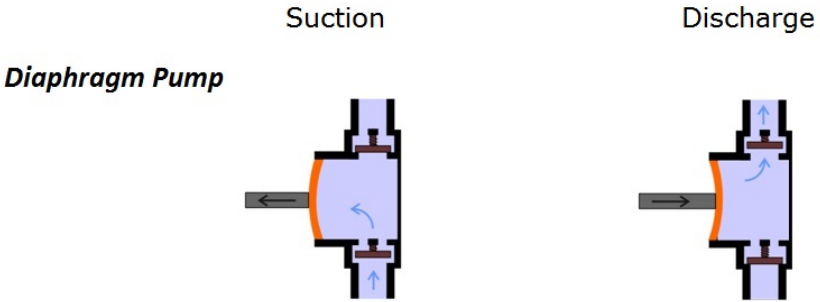
A reciprocating pump works by the repeated back-and-forth movement (strokes) of either a piston, plunger or diaphragm. These cycles are called reciprocation.



Reciprocating Pumps (contd..)

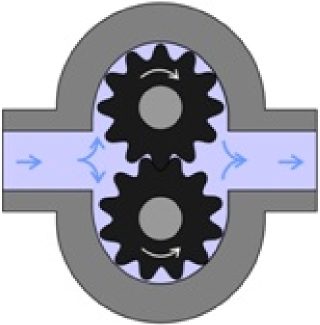


Reciprocating Pumps (contd..)



Rotary Pumps

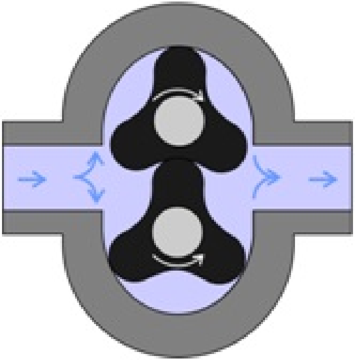
External Gear Pump



An external gear pump consists of two interlocking gears supported by separate shafts. Rotation of the gears traps the fluid between the teeth moving it from the inlet, to the discharge, around the casing. No fluid is transferred back through the centre, between the gears, because they are interlocked.

Rotary Pumps

Lobe Pump



In the case of the lobe pump, the rotating elements are lobes instead of gears. The great advantage of this design is that the lobes do not come into contact with each other during the pumping action, reducing wear, contamination and fluid shear.

Cavitation

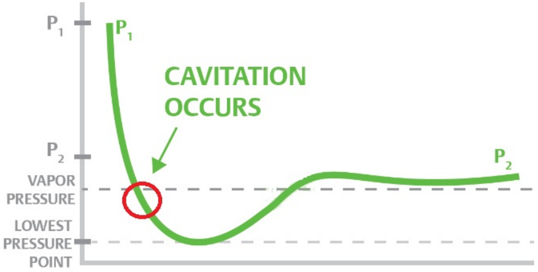
Cavitation is the formation and abrupt collapse of vapour-filled bubbles. This process takes place at points inside the pump where the pressure falls below the vapour pressure of the pumped medium.

Cavitation occurs in fluid flow systems where the local static pressure is below vapor pressure.

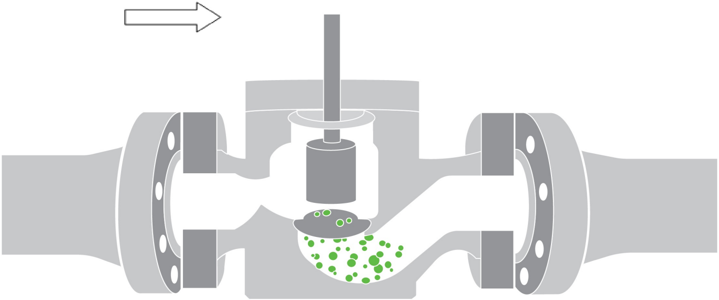
In order to avoid cavitation, it must be ensured that the pressure at the suction port is always greater than the vapour pressure of the liquid at a given temperature of the medium.

Cavitation (contd..)

Cavitation in control valves occurs only with liquid flows; gases cannot cavitate.



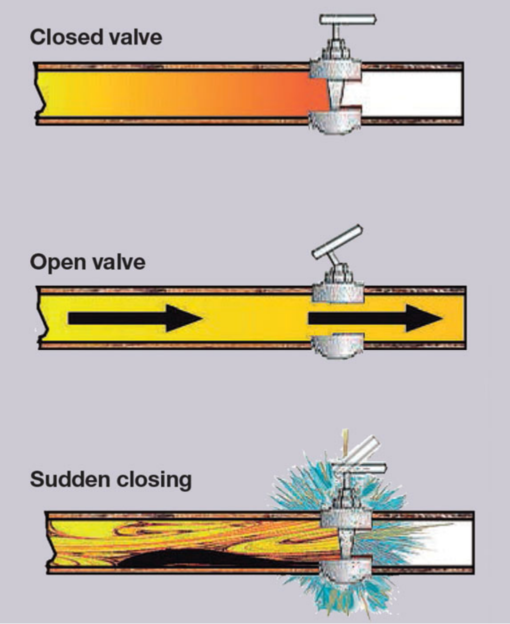
Cavitation (contd..)



Water Hammer

- Water hammer is a pressure surge caused when a fluid (usually a liquid but sometimes also a gas) in motion is forced to stop or change direction suddenly (momentum change).
- Presence of water hammer can be easily detected by the noise it makes.
- Water hammer is also known as hydraulic shock.
- Water hammer has multiple adverse effects on steam systems. Water hammer can damage equipments like flow meters which are installed on the steam network. Instances of rupture and disruption of piping on account of water hammer are also quite common.

Water Hammer (contd..)



Water Hammer (contd..)

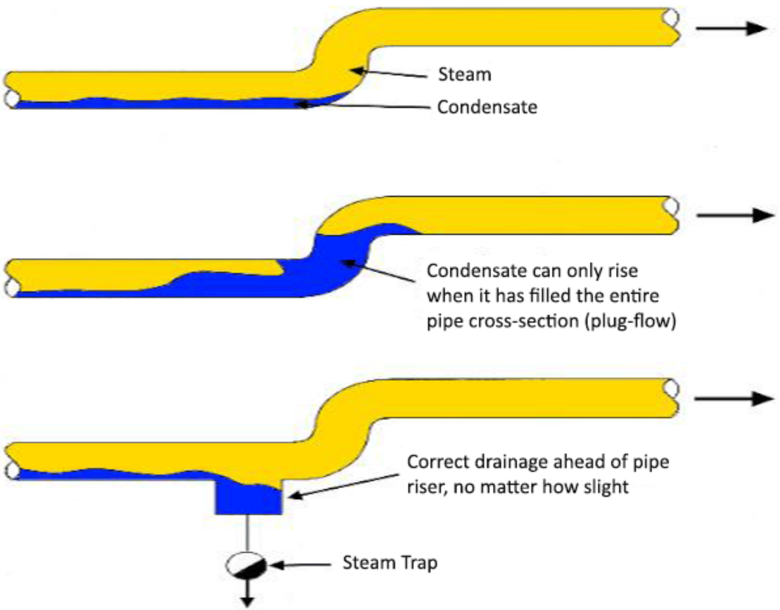
Formation in Steam-lines

As soon as steam leaves the boiler, it starts losing heat. As a result, steam stats condensing inside the pipe work. The rate of condensate formation is high particularly during the start-ups when the system is cold. As a result of the condensation, the droplets of water are formed. After condensate is formed, the flow inside the pipe has two components, steam and the condensate. The flow velocity of steam is much higher than that of the condensate. During such dual phase flow, the heavy condensate which flows at the bottom of the pipe is pulled by high speed steam. This results in formation of water slug which is much denser than steam travelling with the velocity of steam. When this slug is stopped by any abruption like a bend or equipment, the kinetic energy of the slug will be suddenly converted into pressure energy which will create a shock wave in the entire pipework. The pipework will keep on vibrating until this energy is dissipated in the structure.

The destructive nature of water hammer can be realized through the following illustration:
Recommended velocity of saturated steam in pipe network = 20–35 m/s
Recommended velocity of water in pipe network= 2–3 m/s
In case of water hammers, condensate is dragged by steam and hence, the water slug travels with velocity equal to that of steam which is around ten times more than the ideal water velocity. As a result, the total pressure impact exerted by water hammer is very high.

Best Practices to Reduce Water Hammer Effects with Steam-lines

- Steam lines should always be installed with a gradual slope (gradient) in direction of flow.
- Installing steam traps at regular intervals and also at the low points. This ensures removal of condensate from the steam system as soon as it is formed.
- Sagging of pipes should be avoided by providing proper support. Sagging pipes can form pool of condensate in the pipework, increasing the chances of water hammer.



Steam
Condensate
Condensate can only rise when it has filled the entire pipe cross-section (plug-flow)
Correct drainage ahead of pipe riser, no matter how slight
Steam Trap