Thermal Fluid Engineering
ENMC4411
Chapter 6 Pumps-Fans- Compressors

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Outline Part I Pumps

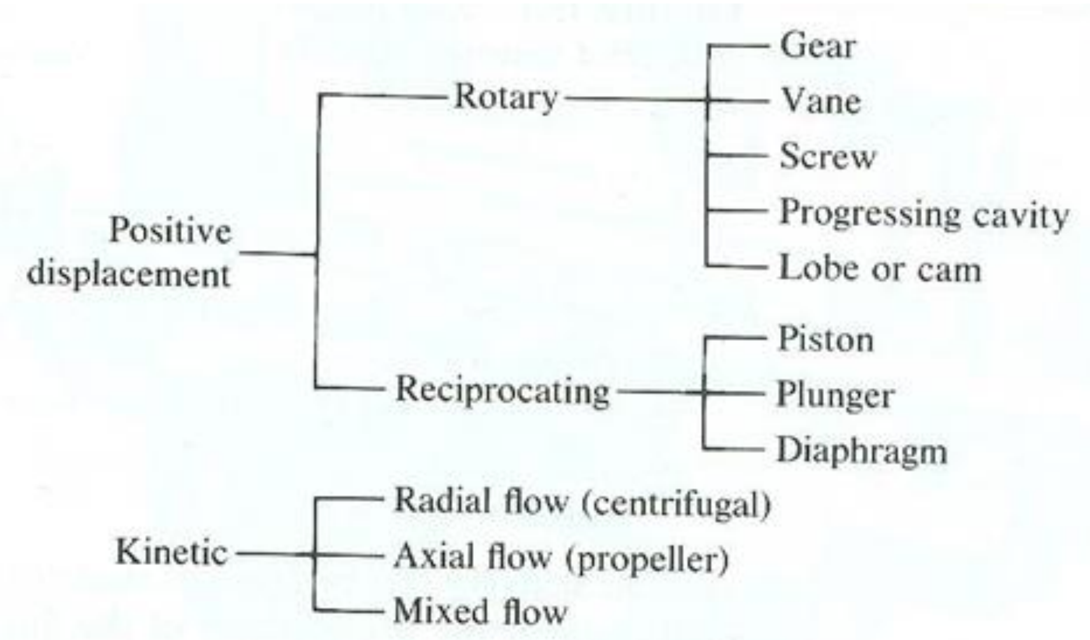
- Pump types
- Specifications
- Performance curves
- Operating point
- Pump selection
- Connecting pumps

Function

- Function: Fluids are moved by pumps, fans, blowers, and compressors. These use work to increase the mechanical energy of a fluid, which in turn can increase the flow rate (velocity), pressure, or elevation of the fluid.
- Liquids are typically moved by pumps. Gases are moved by fans (large volume, small pressure difference), blowers (large volume, moderate pressure difference), or compressors (large pressure differences). Specialized equipment is also used to produce vacuums in process systems.

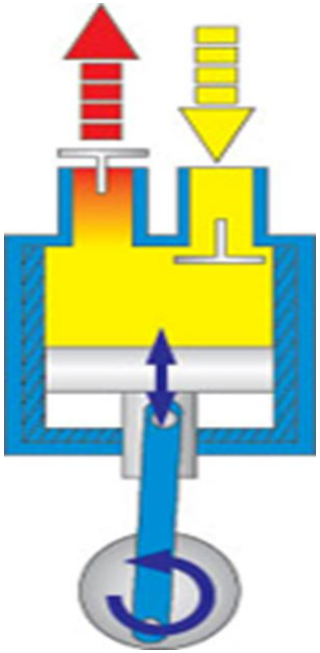
Pumps types

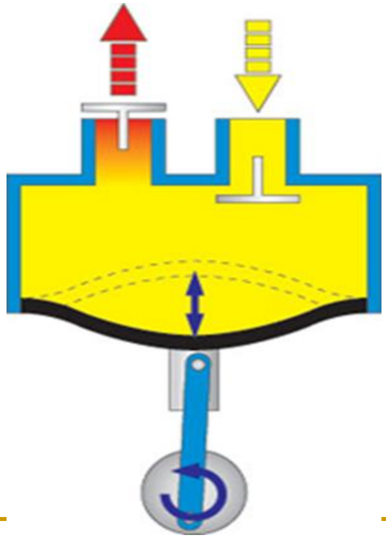
- Pumps are classified into
  - positive displacement
  - kinetic pumps.
- Positive displacements are divided into
  - rotary and
  - reciprocating;
- Rotary pumps includes
  - gear pumps,
  - vane pumps,
  - screw pumps,
  - lobe and cam pumps.
- Kinetic pumps include
  - Radial or centrifugal,
  - axial flow and
  - mixed flow pumps.



Reciprocating pumps

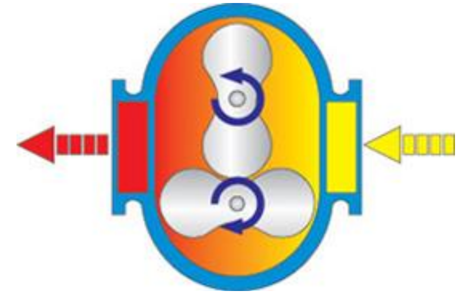
- Positive displacement pumps operate by trapping a fixed volume of liquid then releasing it to a higher pressure by means of a piston or rotary gear.
- *Reciprocating pumps* use a piston, plunger, or diaphragm to raise the pressure of a liquid.
- The pumping chambers are surrounded by one-way valves so that liquid can only move in from the low pressure side and out from the high pressure side.
- Reciprocating pumps are best for low volume, high head applications (up to 50000 psi). They cannot be used when pulsating flow is a problem.
- Their chief advantage is that the fluid being pumped never comes in contact with the mechanism and eliminates leakage; thus they are good for toxic or very expensive liquids.

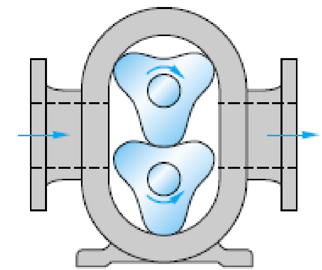


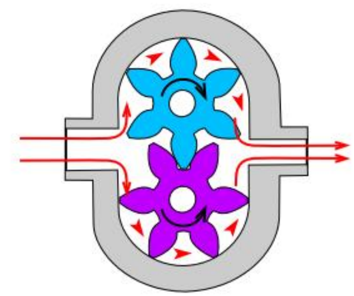


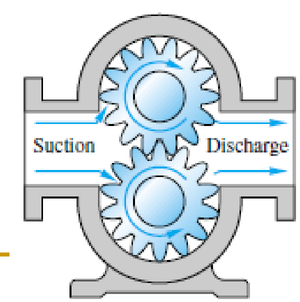
Rotary pumps

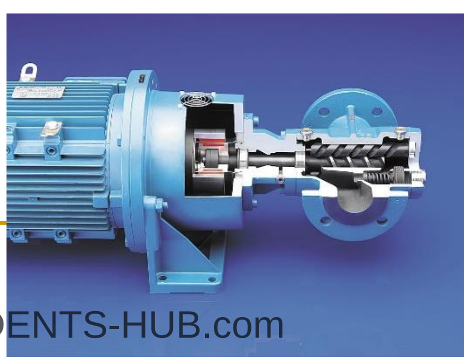
- Rotary pumps use a gear, lobe, screw, cam, or vane to compress liquid.
- Liquid enters through a gap between the rotating element and pump wall at a low pressure where it is trapped.
- Then, as the element rotates, it squeezes the liquid out through a one-way valve on the opposite side of the casing.
- Typically, rotary pumps are used in high head, low flow applications. They are good for high viscosity and low vapor pressure fluids.
- The fluid pumped must be "lubricating"; s cannot be present.



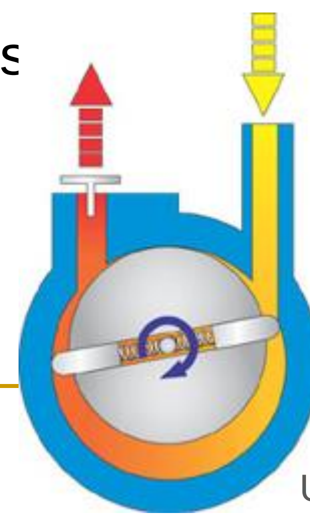








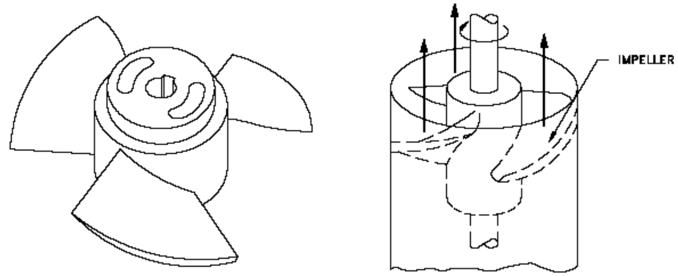
Scroll pump



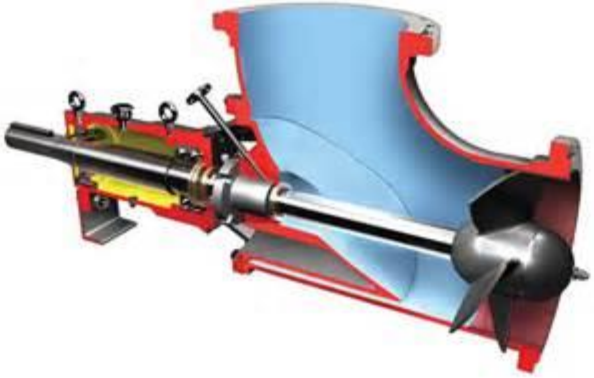
Kinetic energy pumps

Axial pump

- Axial flow fluid enters and exits along the same direction parallel to the rotating shaft. Axial flow pumps operate at much lower pressures and higher flow rates than radial flow pumps.

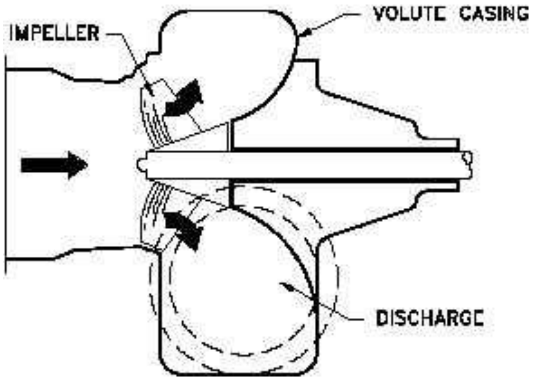


Axial pump



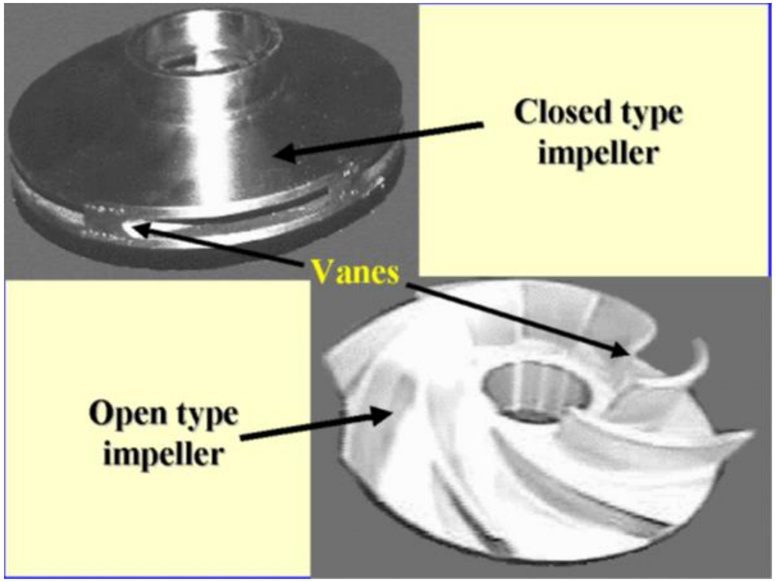
Mixed flow pumps

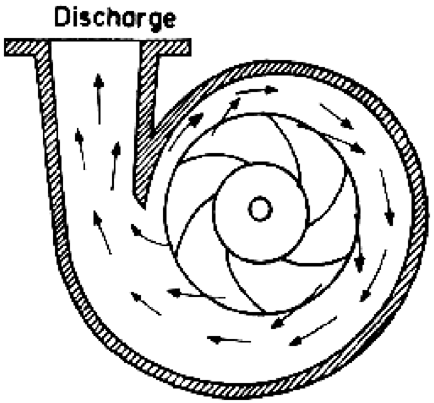
- Mixed flow pumps, a compromise between radial and axial flow pumps, the fluid exits the impeller somewhere between 0-90 degrees from the axial direction.
- Mixed flow pumps operate at higher pressures than axial flow pumps while delivering higher discharges than radial flow pumps



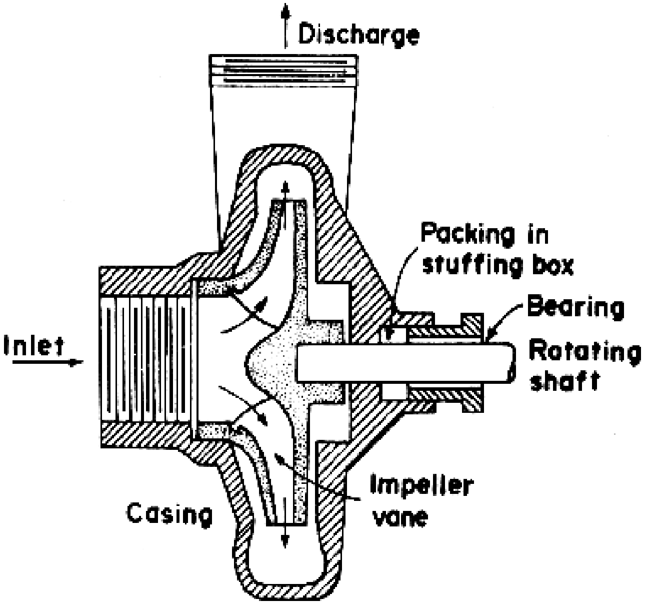
Centrifugal pump

- Liquid enters at the center of the impeller, is accelerated by the rotating impeller vanes, and leaves through the side of the pump casing.





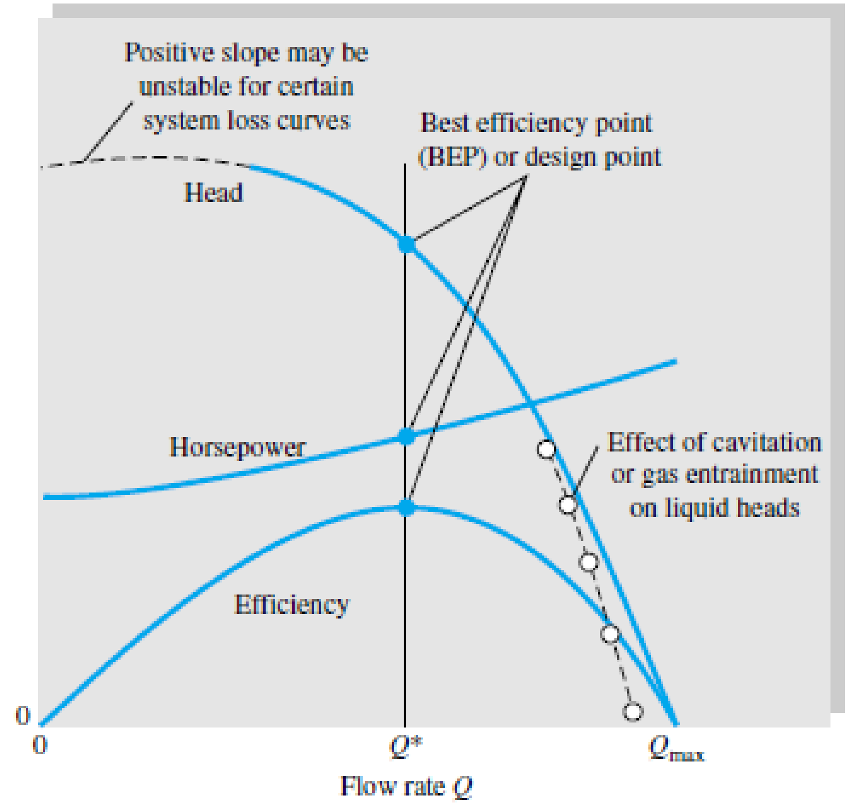
a. Volute centrifugal pump cross section



b. Horizontal centrifugal pump cross section

Pumps Specifications

- Pumps are commonly rated by horsepower, flow rate, outlet pressure in feet (or metres) of head, inlet suction in suction feet (or metres) of head.
- The performance of a centrifugal pump can be shown graphically on a characteristic curve. A typical characteristic curve shows the total dynamic head, and brake horsepower, efficiency, all plotted over the capacity range of the pump.



Friction head, capacity, power

- Friction Head (h_f) is the head required to overcome the resistance to flow in the pipe and fittings. $h_f = (L/d)(V^2 /g)\ f$
- Capacity means the flow rate Q with which liquid is moved or pushed by the pump to the desired point in the process.
- It is commonly measured in either gallons per minute (gpm) or cubic meters per hour (m^3/hr), or liter per minute (l/min).
- The power added to the fluid flow by the pump (*Po*),

$$Po = \rho g Q hp = \gamma Q hp$$

Po is the output power of the pump (W)

ρ is the fluid density (kg/m^3)

g is the gravitational constant (9.81 m/s^2)

hp is the energy Head added to the flow (m)

Q is the flow rate (m^3/s)

- Pump efficiency is defined as the ratio of the power imparted on the fluid by the pump in relation to the power supplied to drive the pump

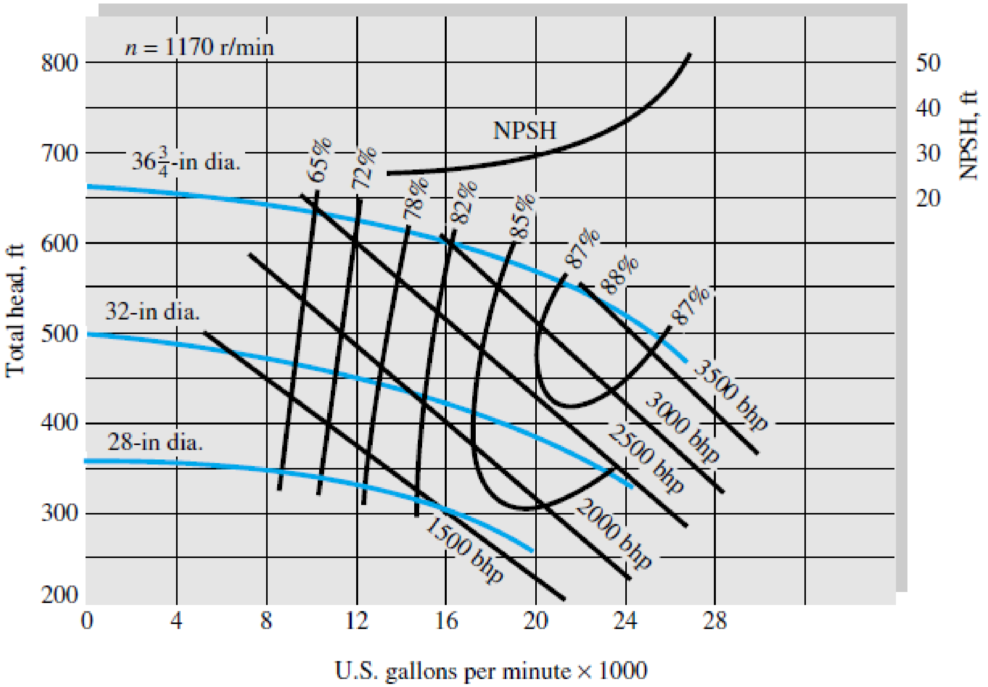
Net Positive Suction Head

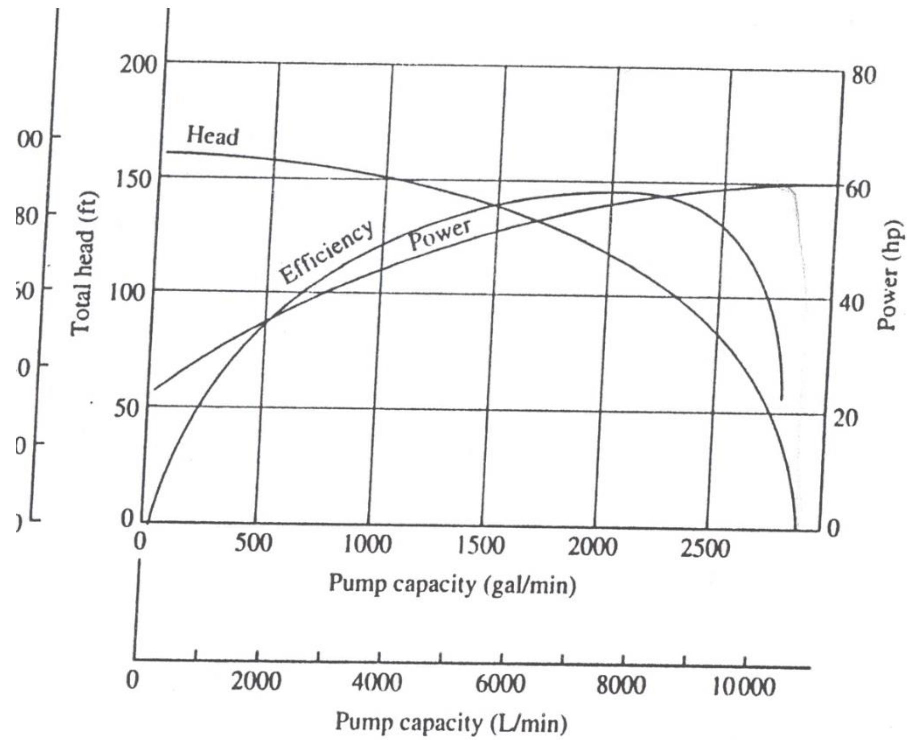
- Net Positive Suction Head Available is a function of the system in which the pump operates.
- It is the excess pressure of the liquid in feet absolute over its vapor pressure as it arrives at the pump suction,
- to be sure that the pump selected does not cavitate. It is calculated based on system or process conditions.
- The Net Positive Suction Head - NPSH - can be expressed as the difference between the Suction Head, and the Liquids Vapor Head as

$NPSH = h_s - h_v$

To avoid cavitation NPSH should be greater than zero

Typical centrifugal pump curves





Operating point

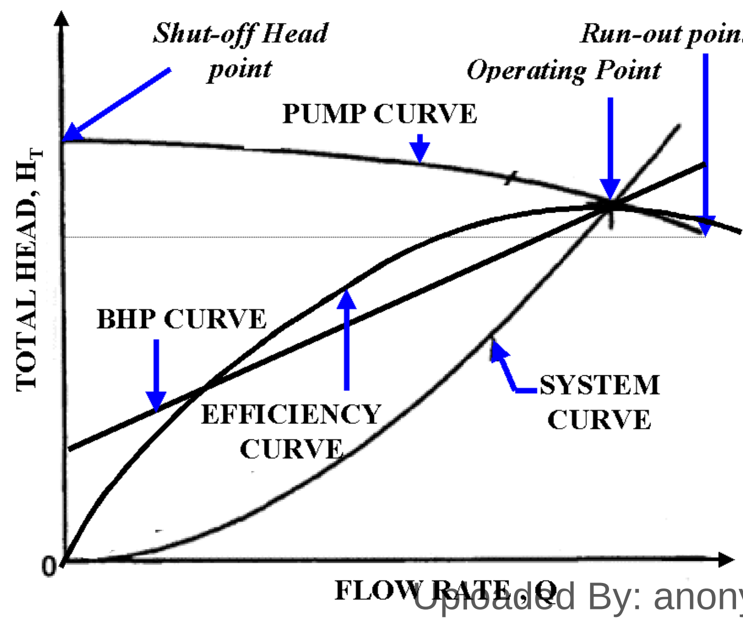
- The operating point is at the intersection of the system curve and pump curve.
- The point where the pump operates on its curve is dependent upon the characteristics of the system in which it is operating, commonly called the System Head Curve
- This representation is in a graphic form and, since friction losses vary as a square of the flow rate, the system curve is parabolic in shape;

$(P1/\gamma) + z1 + (V_1^2/2g) = (P_B/\gamma) + z_B + (V_B^2/2g) + h_f + h_{minor} + hp$

If P1 =P2 = Atmospheric and V1 =V2

$$H_{sys} = (z_2 - z_1) + \frac{V^2}{2g}\left(\sum \frac{fL}{D} + \sum K\right)$$

- $h_p = \Delta z + C1\, V^2/2g$
- Since $V = 4\, Q/d^2 * \pi$
- $h_p = \Delta z + C2\, Q^2$



EXAMPLE 11.6

- We want to use the 32-in pump of Fig. 11.7*a* at 1170 r/min to pump water at 60°F from one reservoir to another 120 ft higher through 1500 ft of 16-in-ID pipe with friction factor *f* = 0.030.
- (*a*) What will the operating point and efficiency be?
- For reservoirs the initial and final velocities are zero; thus the system head is

$$H_s = z_2 - z_1 + \frac{V^2}{2g}\frac{fL}{D} = 120 \text{ ft} + \frac{V^2}{2g}\frac{0.030(1500 \text{ ft})}{\frac{16}{12} \text{ ft}}$$

$$V = Q/A = Q/[\tfrac{1}{4}\pi(\tfrac{16}{12} \text{ ft})^2]$$

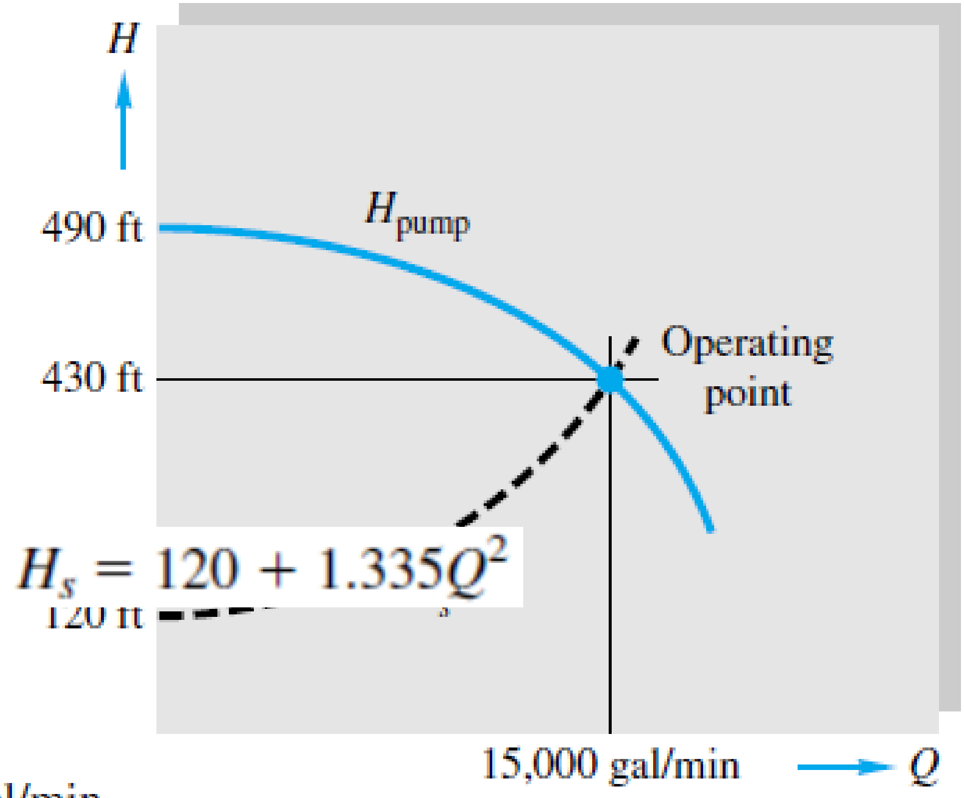
$$H_s = 120 + 0.269Q^2 \qquad Q \text{ in ft}^3/\text{s}$$

$$H_s = 120 + 1.335Q^2 \qquad Q \text{ in } 10^3 \text{ gal/min}$$

EXAMPLE 11.6

- plot Eq. (2) on Fig. 11.7*a* and see where it intersects the 32-in pump-head curve, as in Fig. E11.6. A graphical solution gives approximately

H= 430 ft , Q= 15,000 gal/min



An analytic solution is possible if we fit the pump-head curve to a parabola;

$$H_{pump} \approx 490 - 0.26Q^2$$

at the operating point

$$490 - 0.26Q^2 = 120 + 1.335Q^2$$

$$Q^2 = \frac{490 - 120}{0.26 + 1.335} = 232$$

$$Q = 15.2 \times 10^3 \text{ gal/min} = 15{,}200 \text{ gal/min}$$

$$H = 490 - 0.26(15.2)^2 = 430 \text{ ft}$$

Selecting a pump

When selecting a pump, consider the following factors;

- Nature of liquid (viscosity, toxicity, slurry containing solids etc)
- Required capacity (flow , discharge or Q)
- Required total head , hp
- Suction conditions
- Discharge conditions
- Types of power supply (electricity AC/DC, mechanical ,)
- Cost of pump and operation.

Selecting a pump

- Pump is selected for specific application based on the pump head, hp; the flow rate, Q and taken into consideration NPSH

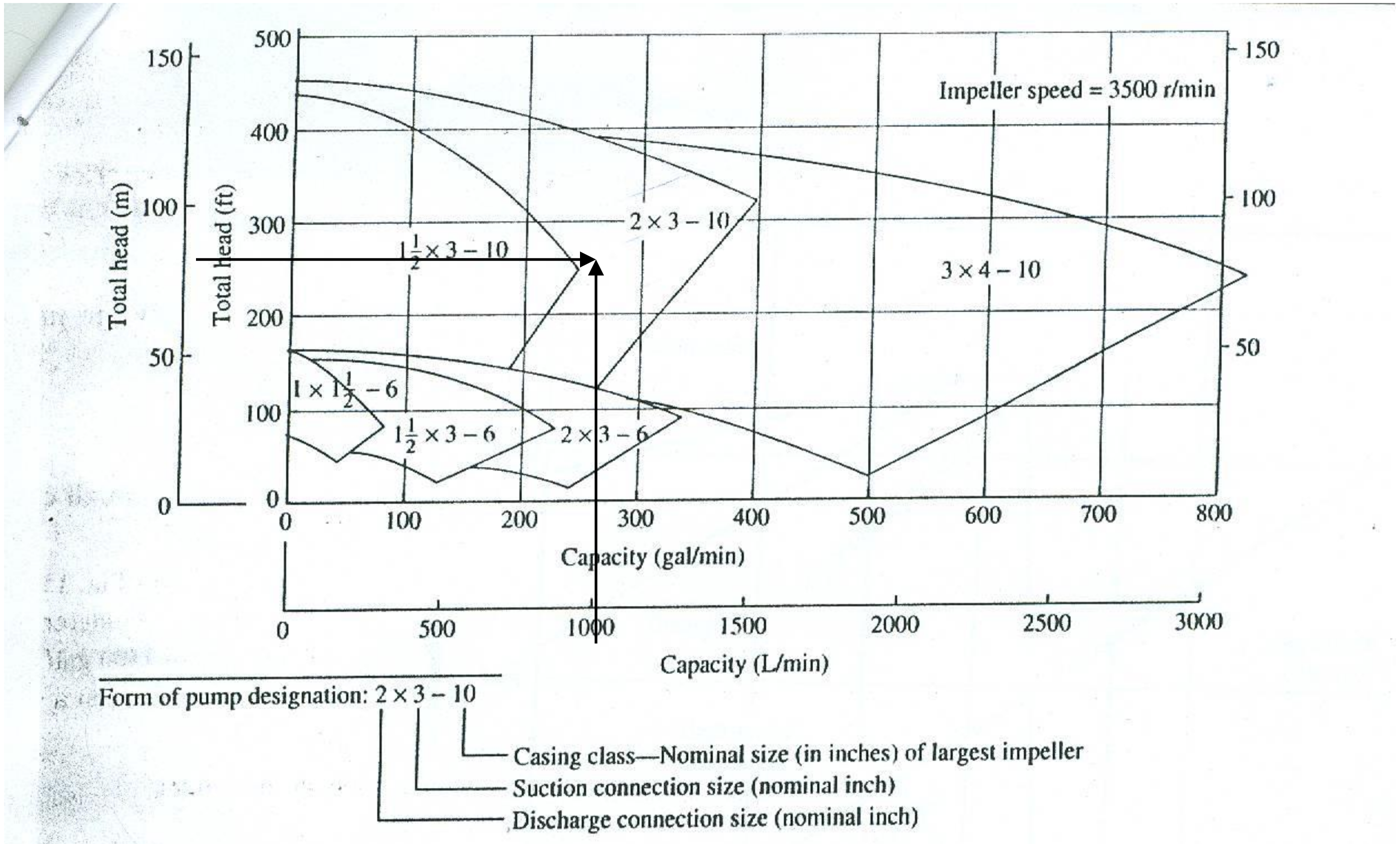
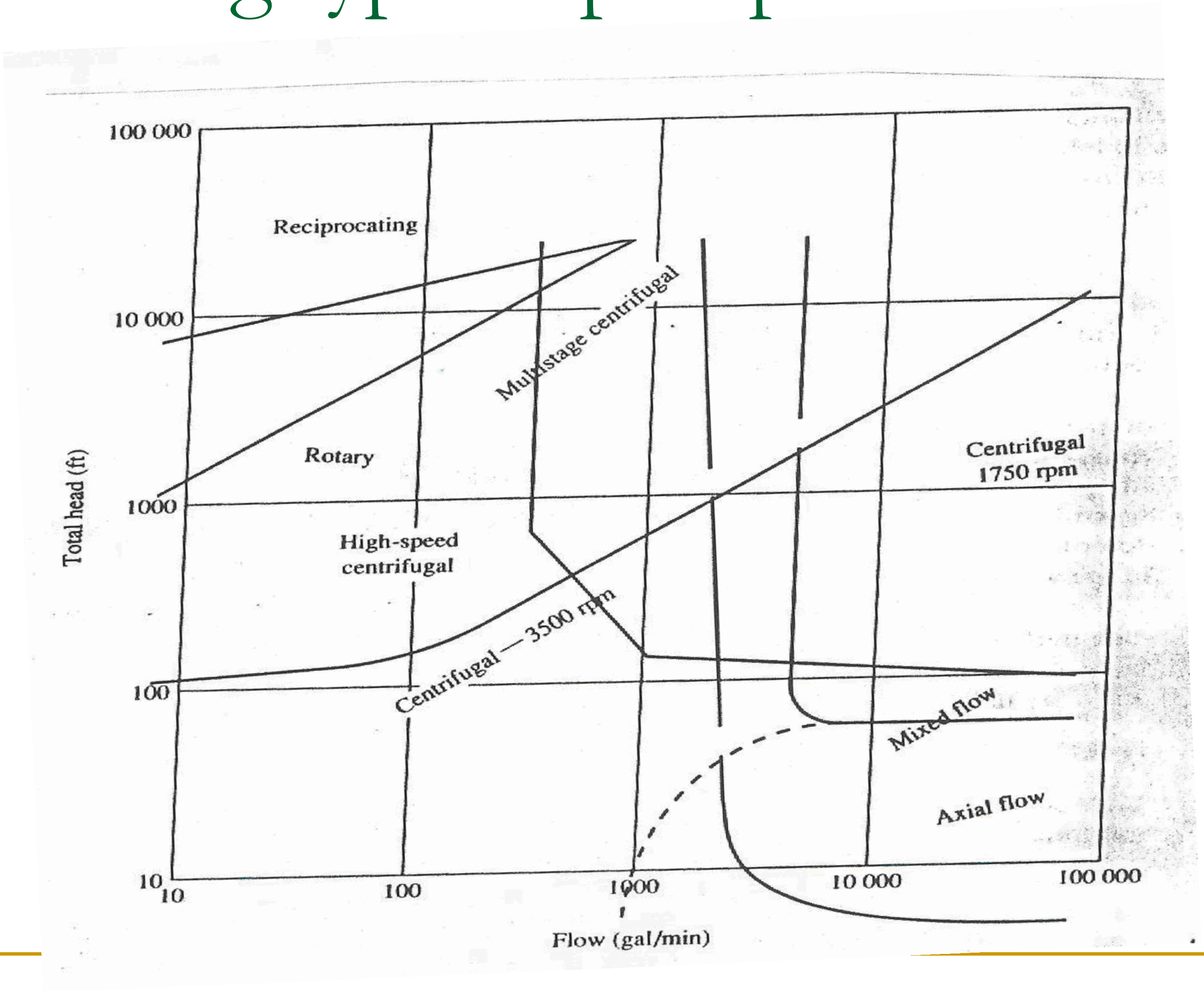


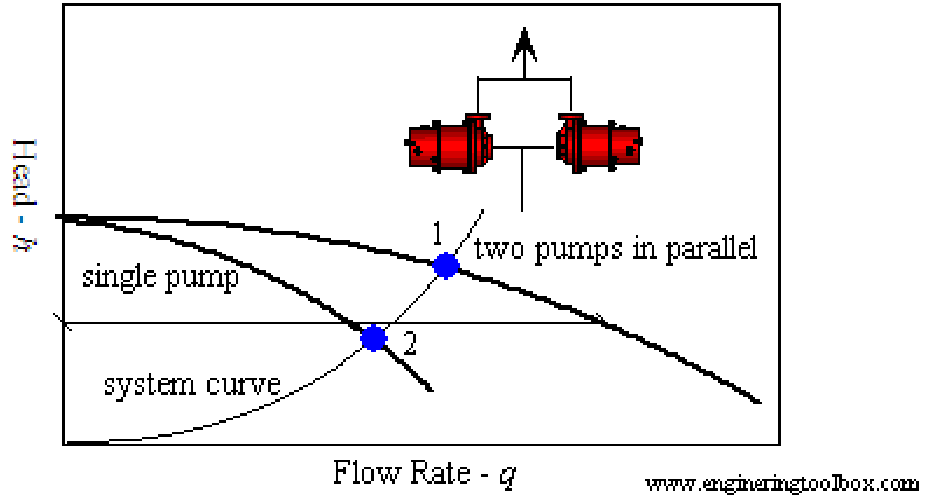
FIGURE 15.17 Composite rating chart for a line of centrifugal pumps.

Selecting type of pump

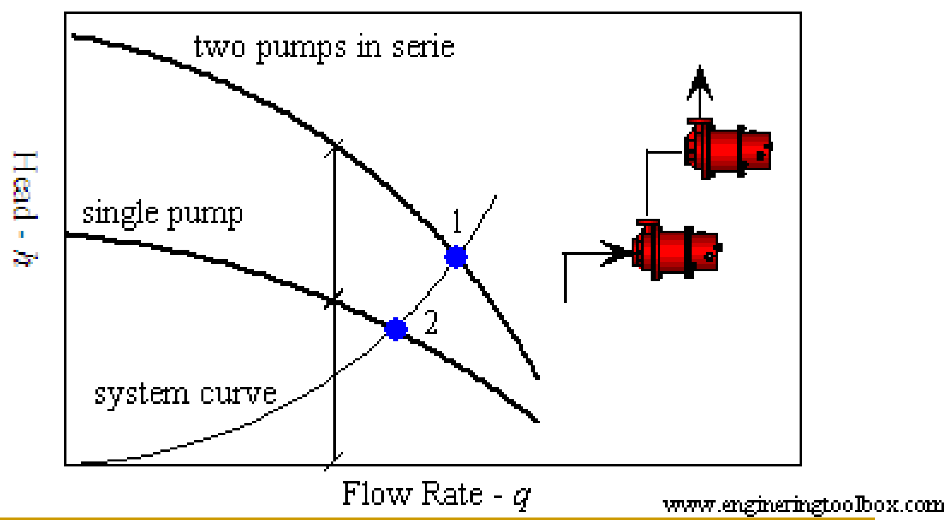


Connecting Pumps

- In parallel; Two or more pumps are arranged in parallel, their resulting performance curve is obtained by adding their flowrates at the same head.



- In series: Two (or more) pumps are arranged in serial, their resulting pump performance curve is obtained by adding heads at the same flow rate.



Affinity laws

Affinity laws apply to all types of centrifugal and axial flow pumps.

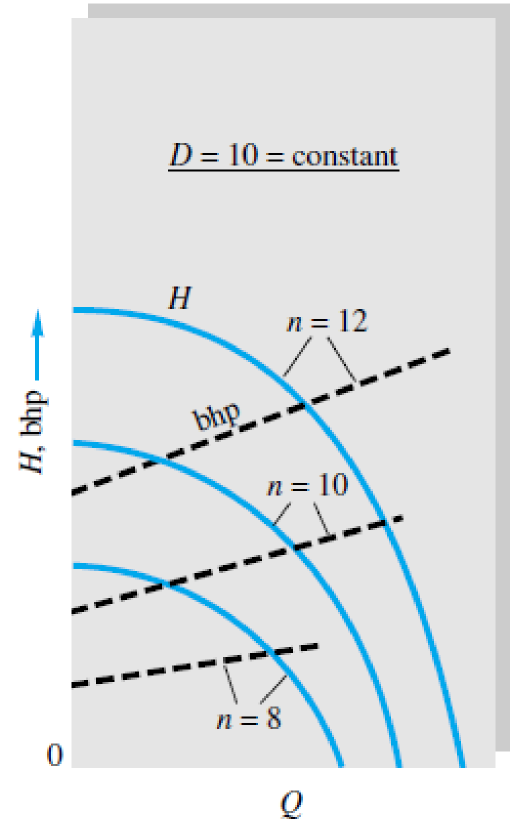
- With impeller diameter D held constant and N varied:

Where: Q = Capacity, GPM
H = Total Head, Feet
BHP = Brake Horsepower
N = Pump Speed, RPM

A. $\frac{Q_1}{Q_2} = \frac{N_1}{N_2}$

B. $\frac{H_1}{H_2} = \left(\frac{N_1}{N_2}\right)^2$

C. $\frac{BHP_1}{BHP_2} = \left(\frac{N_1}{N_2}\right)^3$

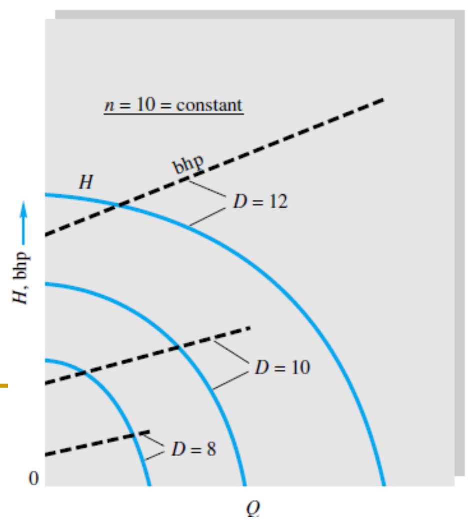


- With speed N held constant, D is varied

A. $\frac{Q_1}{Q_2} = \frac{D_1}{D_2}$

B. $\frac{H_1}{H_2} = \left(\frac{D_1}{D_2}\right)^2$

C. $\frac{BHP_1}{BHP_2} = \left(\frac{D_1}{D_2}\right)^3$



Outline Part II Fans

- Function of fan
- Applications of fans
- Performance & characteristics
- Types of fans

Fans & compressors

- As per American Society of Mechanical Engineers (ASME);
  - the specific ratio - the ratio of the discharge pressure over the suction pressure - is used for defining the fans, blowers and compressors .

$$R_{com} = \frac{p_{dis}}{p_{suc}}$$

where Pdis = discharge pressure at outlet of compressor or fan
Psuc = suction pressure at inlet of compressor or fan

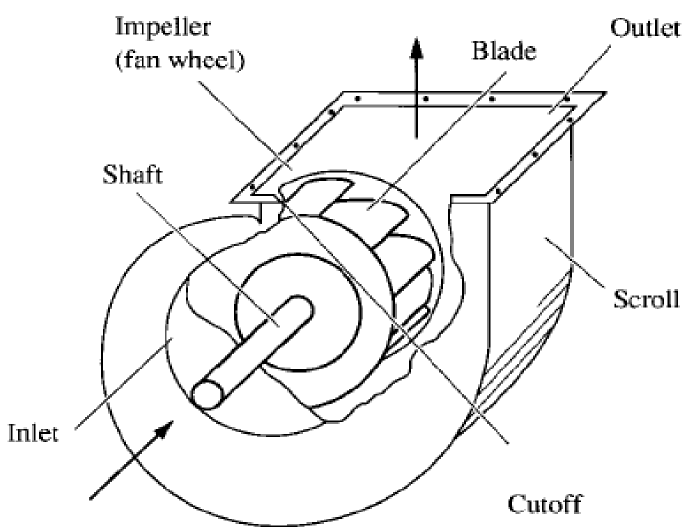
Equipment	Specific Ratio	Pressure rise (mmWg)
Fans	Up to 1.11	1136
Blowers	1.11 to 1.20	1136 – 2066
Compressors	more than 1.20	-

Functions of Fans

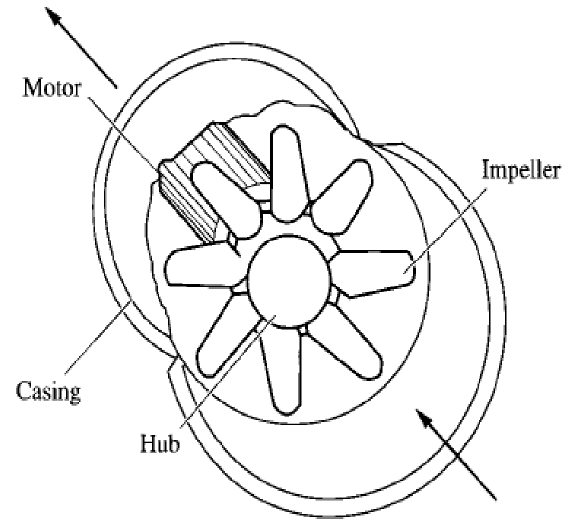
- A fan is the prime mover of an air system or ventilation system.
- It moves the air and provides continuous airflow so that the conditioned air, space air, exhausts air, or outdoor air can be transported from one location to another through air ducts or other air passages.
- Fans are widely used in air conditioning and ventilation systems. In air conditioning systems, fans are often installed in air-handling units, packaged units, or other air conditioning equipment.
- Fans can be mounted individually as ventilating equipment to provide outdoor air or air movement inside a building.
- They can also transport air containing dust particles or material from one place to another via air duct systems

Fan types

- In centrifugal fans, air is radially discharged from the impeller, also known as the fan wheel—air turns 90° from its inlet to its outlet.
- In an axial fan, the direction of airflow is parallel to the axle of the fan



(a)



(b)

Fan capacity

- Fan capacity or the fan volume flow rate , in cfm or cms, (m^3 / s), is defined as the rate of volume flow measured at the inlet of the fan, corresponding to a specific fan total pressure.
- It is usually determined by the product of the duct velocity and the area of the duct connected to the fan inlet.
- Fan volume flow rate is normally rated at standard air conditions, i.e., dry air at an atmospheric pressure of 14.696 psia (101,325 Pa abs.), a temperature of 70°F (21.1°C), and a density of 0.075 lb / ft^3 (1.2 kg /m^3).

Fan total pressure

- Fan total pressure ΔP_{tf} , expressed in inches of height of water column (inches WC or Pa), is the total pressure rise of a fan.
- i.e., the pressure difference between the total pressure at the fan outlet *Pto* and the total pressure at the fan inlet *Pti*, both in in. WG (Pag), or

$$\Delta p_{tf} = p_{to} - p_{ti}$$

Fan static pressure

- Fan static pressure Δpsf, in in. WC (Pa), is the difference between static pressure at fan outlet, *pso*, in. WG (Pa) and the total pressure at the fan inlet *Pti*

$$\Delta p_{sf} = p_{so} - p_{ti}$$

$$\Delta p_{sf} = \Delta p_{tf} - p_{vf} = p_{to} - p_{ti} - p_{vo} = p_{so} - p_{ti}$$

Fan air power

- Air power *P*air, in hp (W), is the work done in moving the air along a conduit against a fan total pressure Δ*ptf*, in in. WC (Pa), at a fan volume flow rate of in cfm (m^3/s).
- Air power =ΔPtf*Vf
- *P*air in hp

$$P_{air} = \frac{\Delta p_{tf} \times 5.192 \times \dot{V}_f}{33{,}000} = \frac{\Delta p_{tf} \dot{V}_f}{6356}$$

1 hp = 33,000 ft . lbf / min, and 1 in. WC = 5.192 lbf /ft^2

Brake horsepower

- The fan power input on the fan shaft, often called the brake horsepower *Pf* , can be calculated as

$$P_f = \frac{\Delta p_{tf} \dot{V}_f}{\eta_t} = \frac{\Delta p_{tf} \dot{V}_f}{\eta_t}$$

$$P_f = \frac{\Delta p_{tf} \dot{V}_f}{C \eta_t} = \frac{\Delta p_{tf} \dot{V}_f}{6356 \eta_t}$$

Fan total efficiency

- Mechanical efficiency (sometimes called the total efficiency)
- It measures how well the fan converts break horsepower into flow and pressure.
- fan total efficiency ηt is the ratio of air power *P*air to fan power input *Pf* on the fan shaft.

$$\eta_t = P_{air}/P_{mech}$$

Fan static efficiency

- Fan static efficiency η*s* is defined as the ratio of the product of the fan static pressure Δ*psf*,, and the fan volume flow rate to the fan power input.

- If pressure difference in inch water.

$$\eta_s = \frac{\Delta p_{sf} \dot{V}_f}{P_f}$$

$$\eta_s = \frac{\Delta p_{sf} \dot{V}_f}{6356 P_f}$$

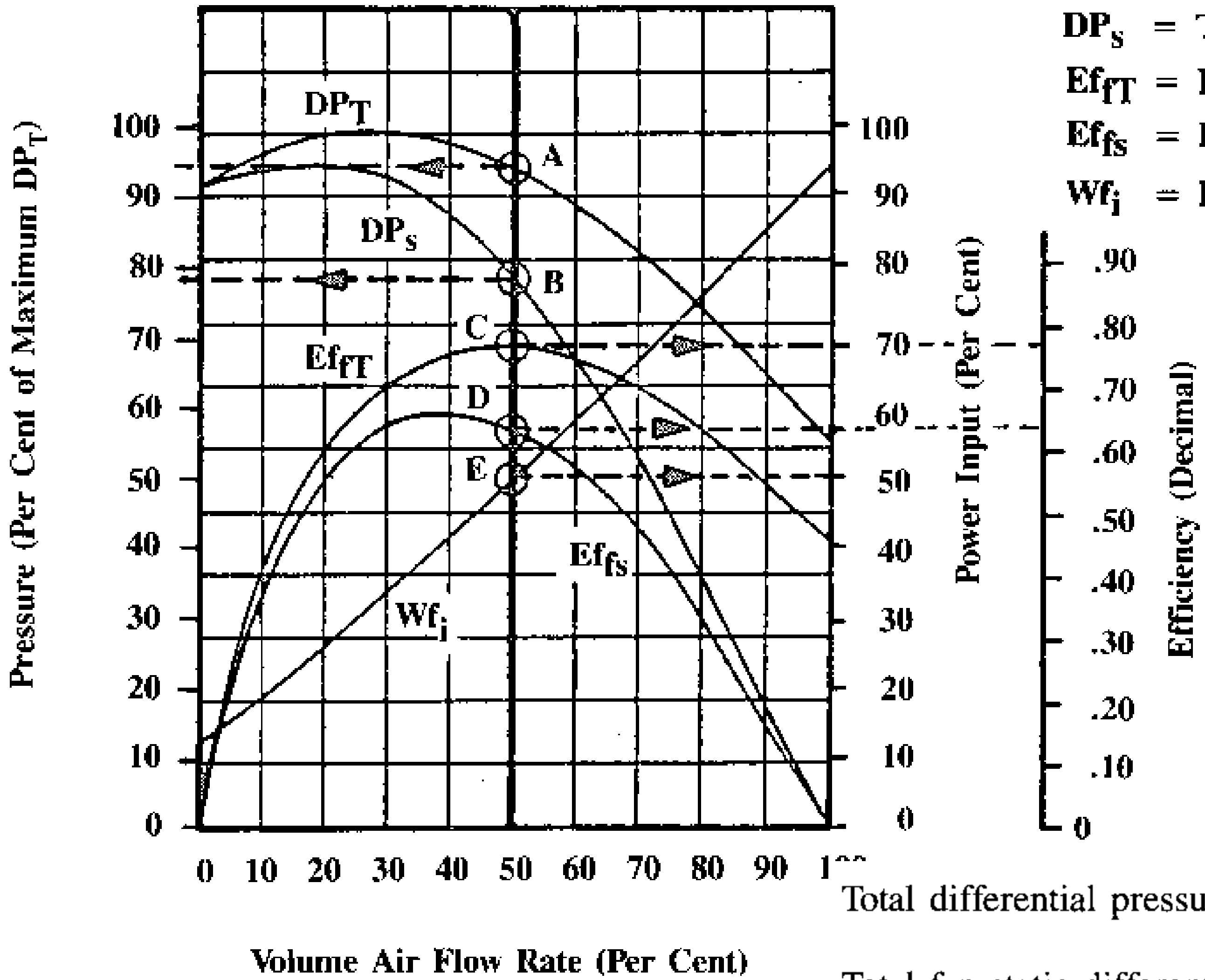
DP_T = Total Differential Pressure

DP_s = Total Fan Static Differential

Ef_{fT} = Fan Total Efficiency

Ef_{fs} = Fan Static Efficiency

Wf_i = Power Input To The Fan Shaft



Total differential pressure, DP_T	94% (Point A)
Total fan static differential pressure, DP_S	79% (Point B)
Fan total efficiency, Ef_{fT}	0.76 (Point C)
Fan static efficiency, Ef_{fS}	0.63 (Point D)
Power input to the fan shaft, Wf_i	50% (Point E)

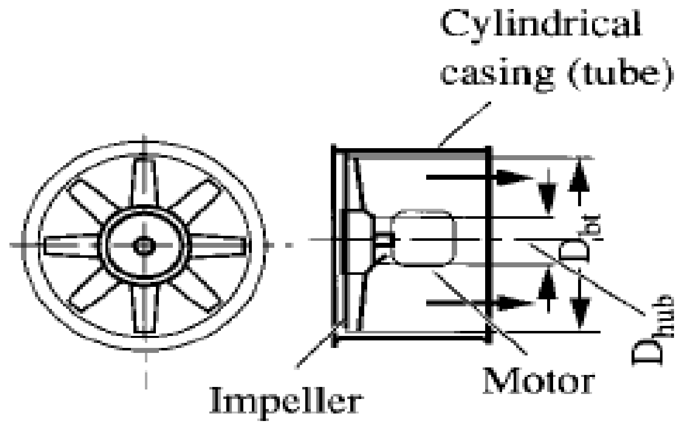
Air Temperature Increase through Fan

- Relationship between fan power input and the air temperature increase.
- $\Delta Tf = \Delta ptf/[\rho_a \, C_{pa} \, \eta_t]$
- when it flows through the fan ΔTf, in °F, is given as If air density ρa = 0.075 lb/ ft^3, the specific heat of air Cpa = 0.243 Btu/ lb.°F, and 1 hp = 42.41 Btu/min

$$\Delta T_f = \frac{0.00667 \Delta p_{tf}}{\rho_a c_{pa} \eta_t} = \frac{0.37 \Delta p_{tf}}{\eta_t}$$

Types of Axial Fans

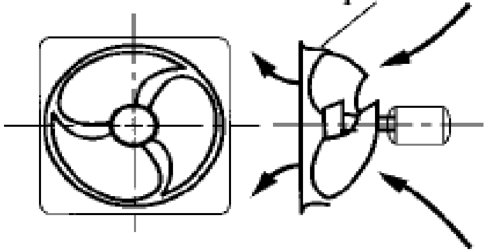
- The capacity and fan total pressure of axial fans can be increased by raising their rotating speed or through the adjustment of the blade pitch angle to a higher value.
- This characteristic is important for axial fans that are driven directly by motor, without belts.



(b)

Propeller Fans

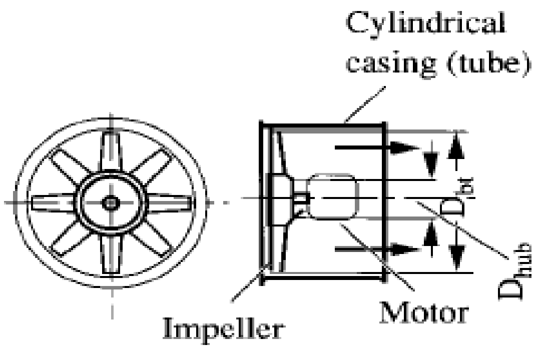
- The blades are generally made of steel or molded plastic and sometimes may increase in width at the blade tip.
- If the impeller is mounted inside an orifice plate, the direction of airflow at the blade tip will not be parallel to the axle. Eddies may form at the blade tips.
- Propeller fans are usually operated at very low static pressure with large volume flow. They often have a hub ratio $R_{hub} \leq 0.15$.



(a)

Tube-Axial Fans

- The impeller of a tube-axial fan usually has 6 to 9 blades.
- It is mounted within a cylindrical casing. The blades can be airfoil blades or curved sheet metal

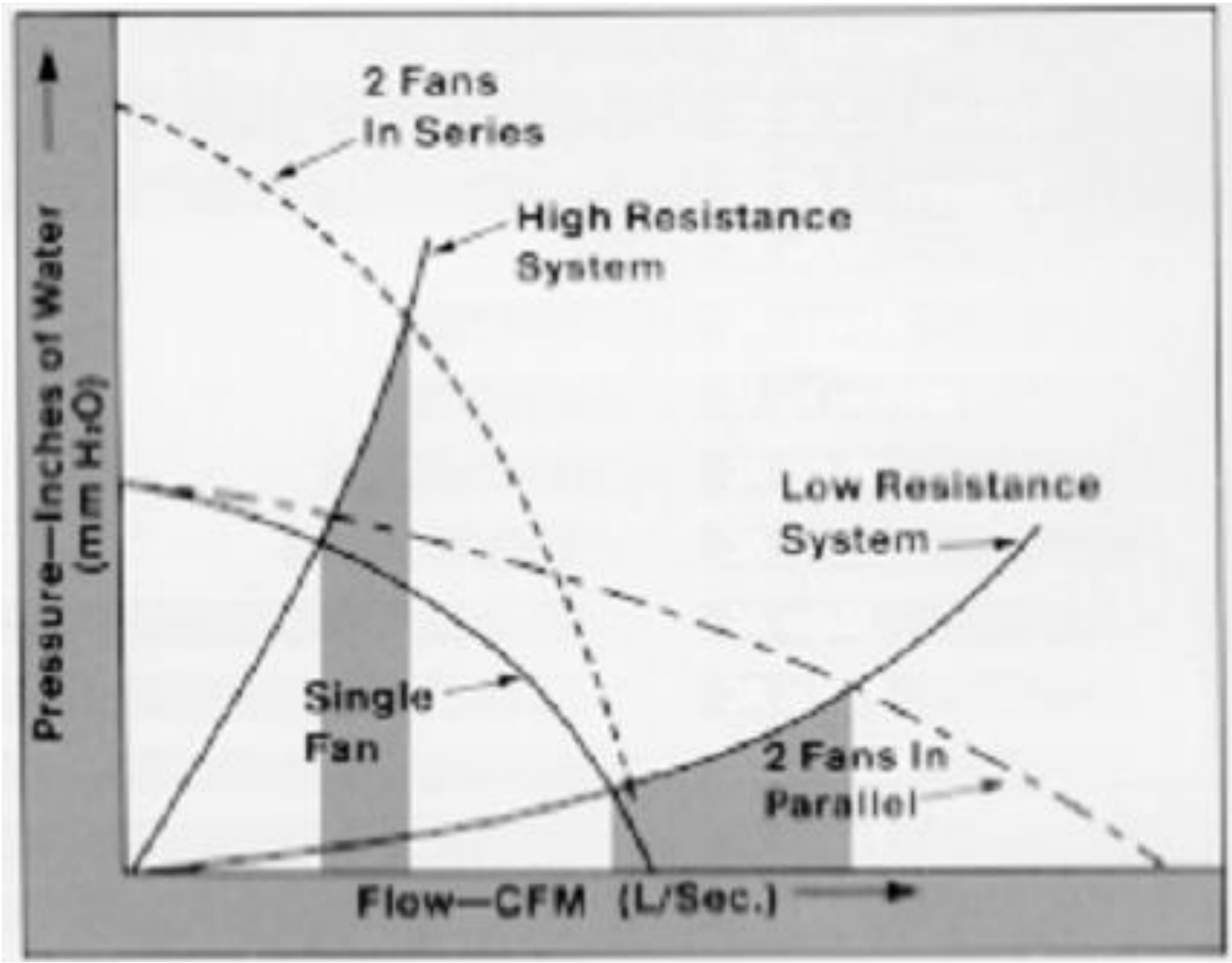


(b)

Fan capacity modulation

- In a variable-air-volume (VAV) air system, more than 90 percent of its running hours operate at airflow less than the design volume flow rate.
- Modulating the fan capacity by providing a new curve with lower volume flow and fan total pressure not only corresponds with load reduction in the conditioned space, but also allows significant energy savings at part-load operation.
- Most widely used, variable-speed drives (VSDs) for fans and pumps are adjustable-frequency VSDs. These VSDs modulate the speed of the ac motor by supplying a variable-frequency and variable-voltage power source.

Series & parallel fans



Fan selection factors to be considered

- *Pressure-volume flow operating characteristics*. Selecting a fan to provide the required volume flow rate and total pressure loss for an air system or a ventilating system is of prime importance.
- An undersized fan results in an uncontrolled indoor environment. An oversized fan wastes energy and money.
- *Fan capacity modulation*. A variable-air-volume system operates at a reduced volume flow rate during part-load operation. Effective and economical fan capacity modulation is an important factor that affects the operation of an air system.
- *Fan efficiency.* Fan efficiency is closely related to the energy consumption of an air system. Fans should be selected so that they can operate at high efficiency during as much of their operation time as possible.

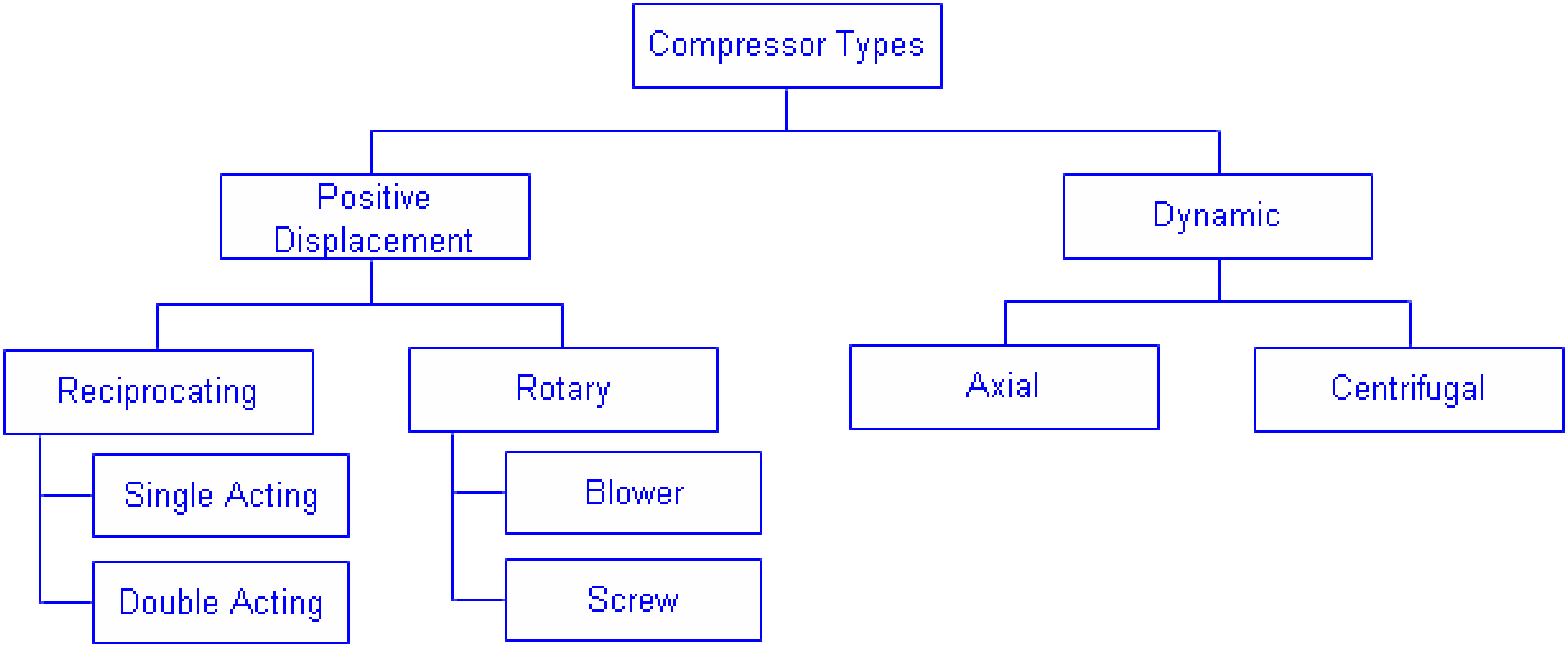
Fan selection factors to be considered

- *Sound power level.* Most commercial and public buildings and many industrial applications need a quiet indoor environment. Fans are the major source of noise in an air system. Usually, the higher the fan total efficiency, the lower the sound power level of the selected fan. A fan with a low sound power level and sound power level at high frequencies is preferable. High-frequency sound is more easily attenuated than low-frequency sound.
- *Airflow direction.* In many applications, a straight-through or in-line flow occupies less space and simplifies layout.
- *Initial cost.* The initial cost of the fan modulation device, sound attenuator(s), and space occupied by a particular type of fan, in addition to the cost of the fan itself, should be considered.

Outline Part III Compressors

- Compressors
  - Reciprocating compressors
  - Vane compressors
  - Axial compressors
  - Centrifugal compressors

Types of compressors

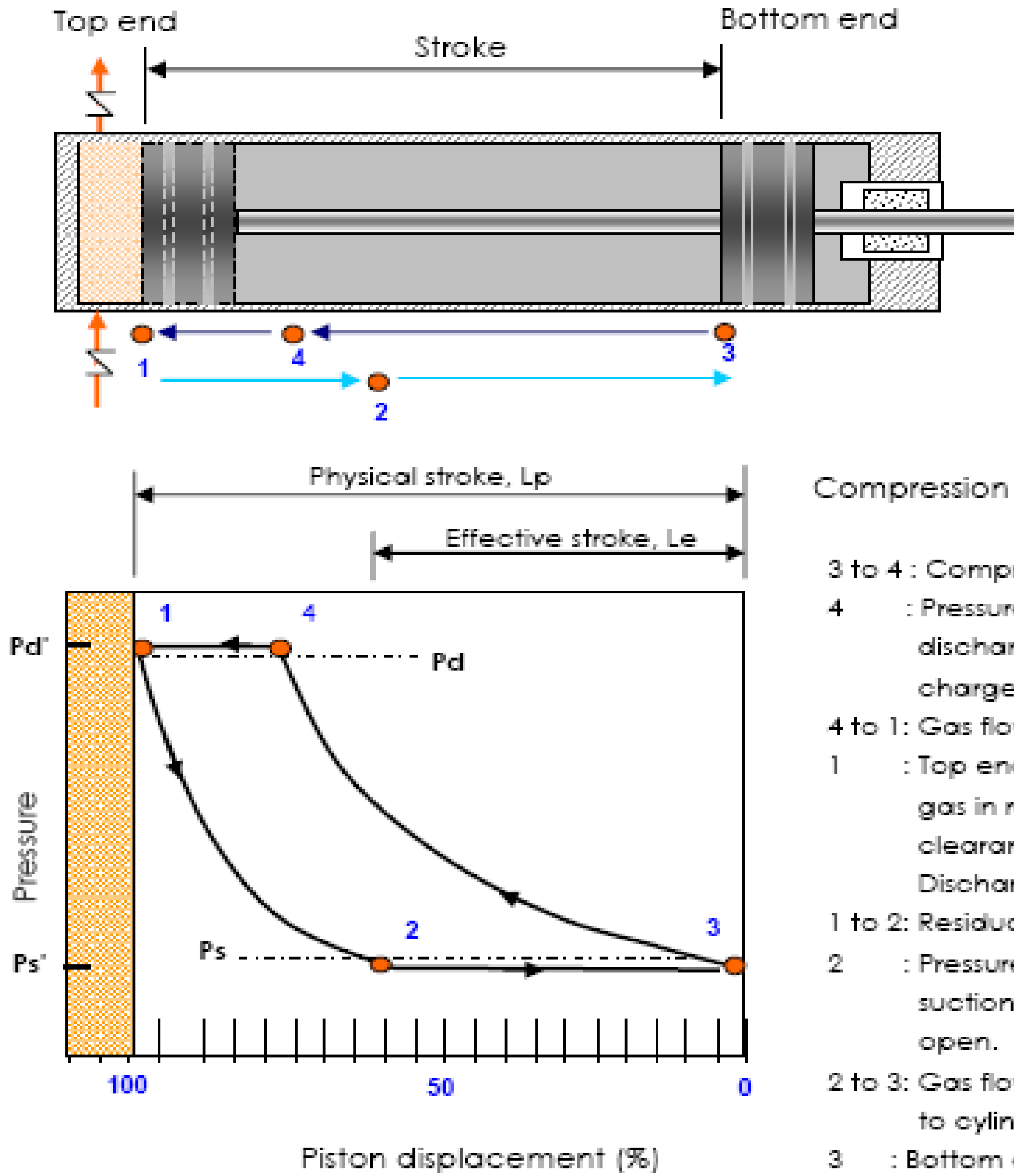


Reciprocating compressors

- Reciprocating compressors are generally classified according to type of drive, motor accessibility, number and arrangement of cylinders, method of lubrication, and capacity control.

- a reciprocating compressor has an external motor it is called an open compressor.
- An open compressor may be belt driven or directly coupled.
- When the motor is directly coupled to the compressor, it is called a direct drive system.
- A reciprocating compressor, driven by a direct drive motor sealed inside the compressor housing, is called a hermetic compressor.

- Multi stage compression -Intercooler is required when compressed gas temperature to the next compression will higher than permitted temperature during or after compression.
- A typical standard give maximum temperature 150 C for any gas based on adiabatic process calculation.



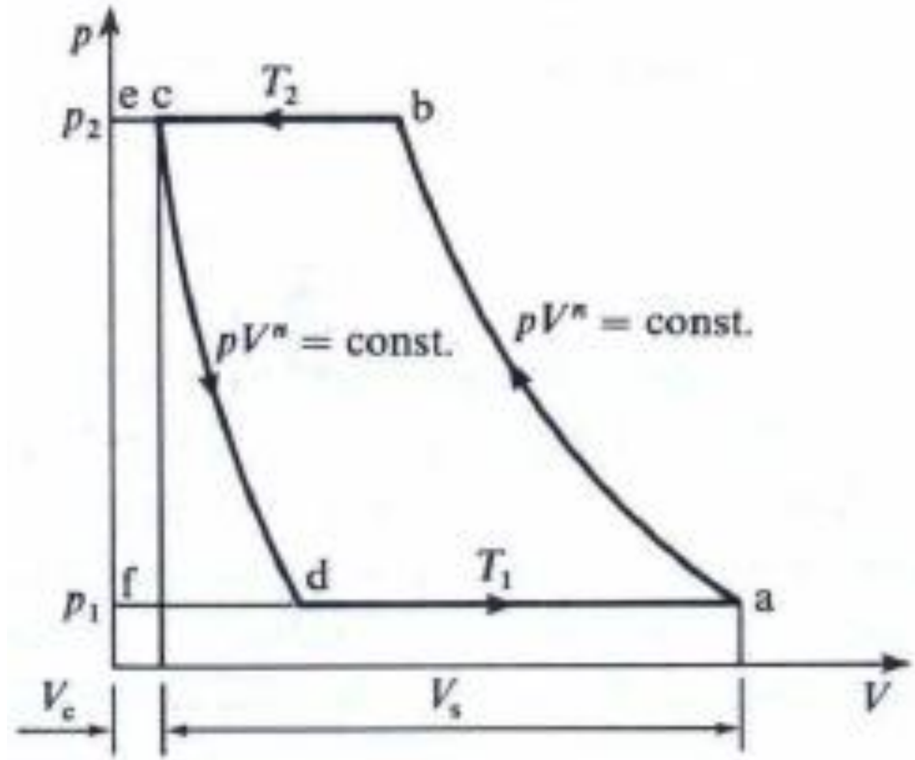
Compression started at point 3

3 to 4 : Compression
4 : Pressure little higher than discharge pressure. Discharge check valve open
4 to 1: Gas flows to discharge side
1 : Top end, but there is still any gas in residual volume + clearance pocket (if any) Discharge check valve close
1 to 2: Residual gas expanded
2 : Pressure little lower than suction side. Inlet check valve open.
2 to 3: Gas flows from suction side to cylinder.
3 : Bottom end. Inlet check valve close.

Ratio of effective stroke (Le) by physical stroke (Lp) called volumetric efficiency.

Clearance volume

- Figure shows the ideal indicator diagram with the clearance volume included. For good quality machines the clearance volume is about 6% of the swept volume, and with a sleeve valve machine it can be as low as 2%, but machines with clearances of 30-35% are also common.



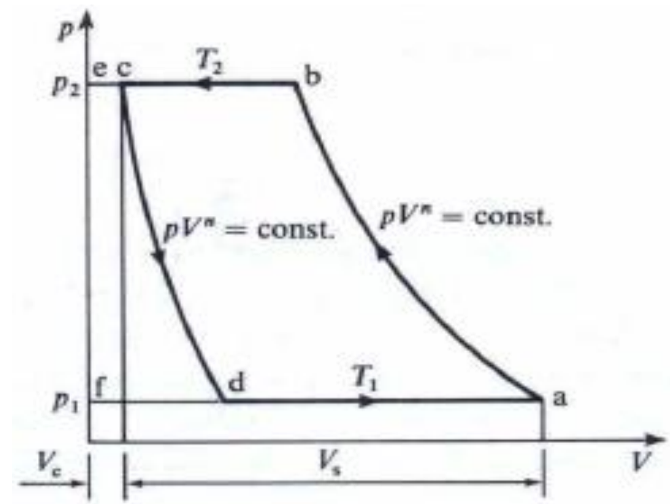
$$\text{Compressor mechanical efficiency } \eta_m = \frac{\text{indicated power}}{\text{shaft power}}$$

Shaft power = indicated power + friction power

$$\text{Indicated power} = \frac{n}{n-1}\dot{m}R(T_2 - T_1) = \frac{n}{n-1}\dot{m}RT_1\left(\frac{T_2}{T_1} - 1\right)$$

$$\text{Indicated power} = \frac{n}{n-1}\dot{m}RT_1\left\{\left(\frac{p_2}{p_1}\right)^{(n-1)/n} - 1\right\}$$

$$\text{Indicated power} = \frac{n}{n-1}p_1\dot{V}\left\{\left(\frac{p_2}{p_1}\right)^{(n-1)/n} - 1\right\}$$



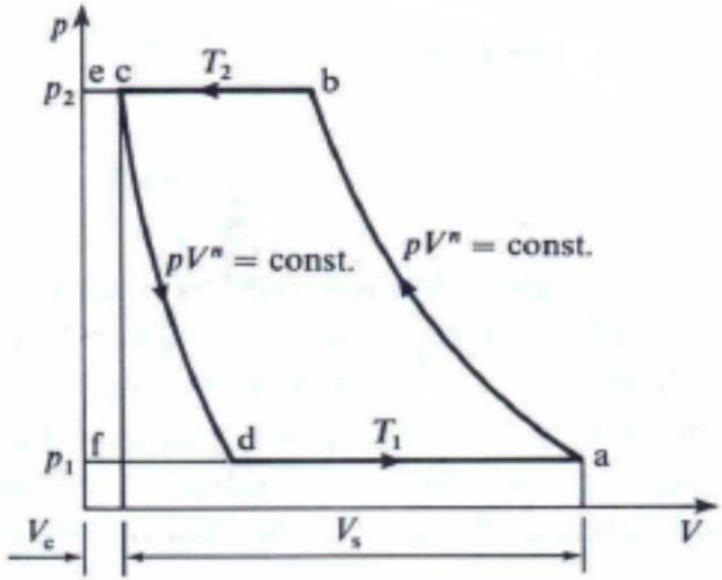
where V is the volume induced per unit time.

Free air delivery

- The volume of air dealt with per unit time by an air compressor is quoted as the free air delivery (FAD), and
- FAD is the rate of volume flow delivered, measured at the pressure and temperature of the atmosphere.

- Volumetric efficiency

η_v = the volume of gas delivered measured at the free air pressure and temperature, divided by the swept volume of the cylinder .



$$\eta_v = 1 - \frac{V_c}{V_s}\left\{\left(\frac{p_2}{p_1}\right)^{1/n} - 1\right\}$$

Rotary Compressor

- Because of the rotary motion of their compressing mechanism, they operate smoother than reciprocating compressors.
- The three general designs of rotary compression mechanisms in common use today are the rolling piston, the rotating vane, and the screw type.
- A scroll compressor consists of two identical spiral scrolls mated face to face,
- The upper scroll is stationary and contains the discharge port. The lower one moves in an orbit around the shaft center of the motor at an amplitude equal to the orbit radius.

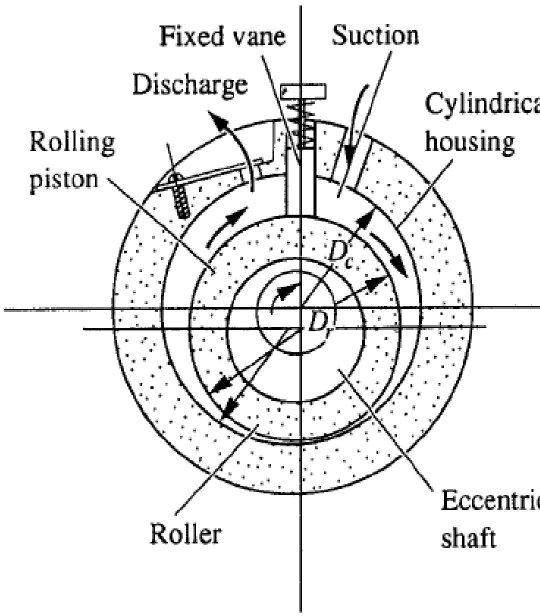
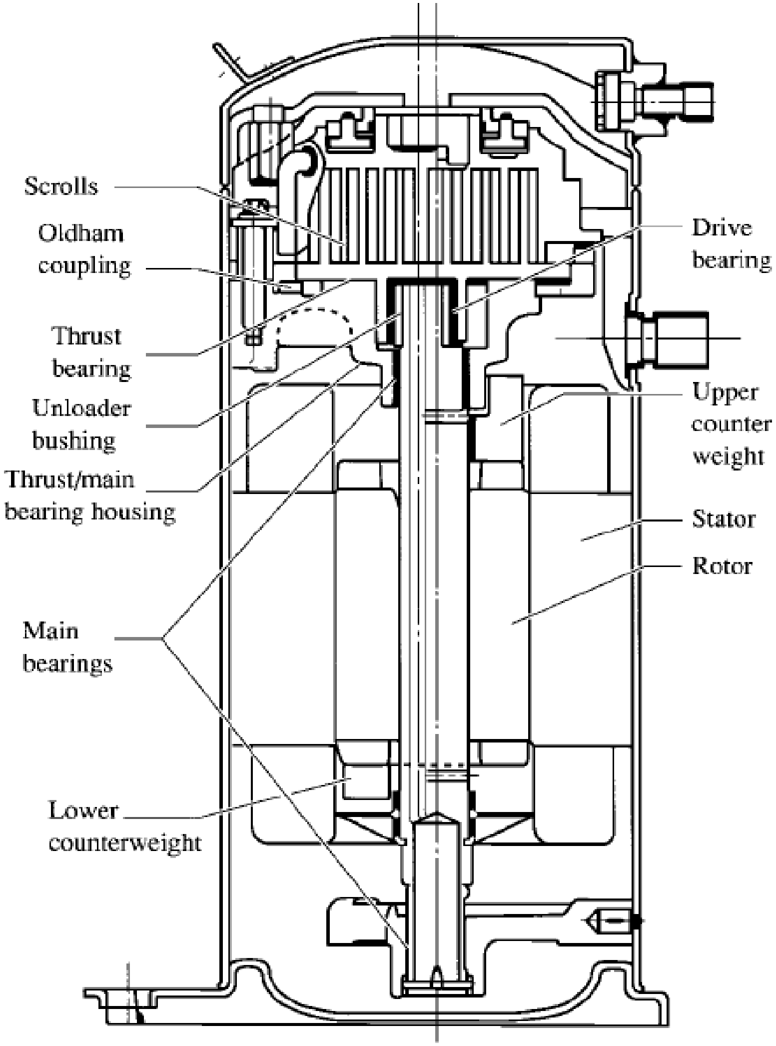
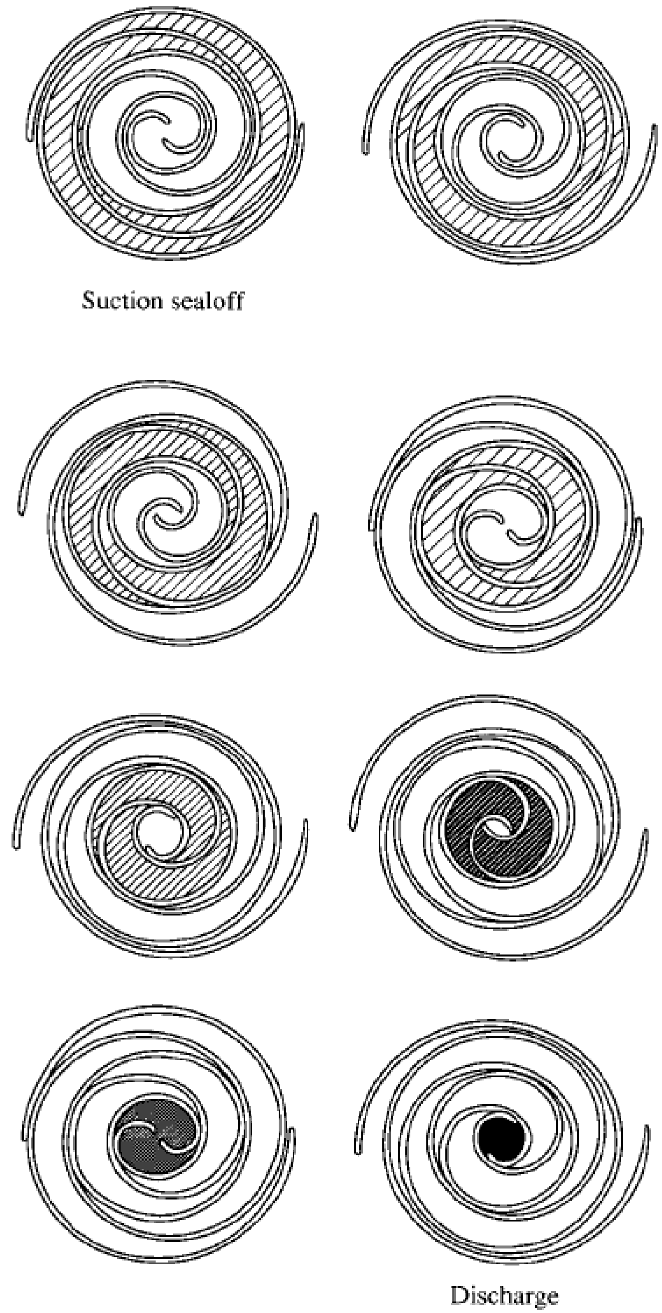


FIGURE 11.24 A rolling-piston rotary compressor.


Scrolls
Oldham coupling
Thrust bearing
Unloader bushing
Thrust/main bearing housing
Main bearings
Lower counterweight
Drive bearing
Upper counter weight
Stator
Rotor

(a)

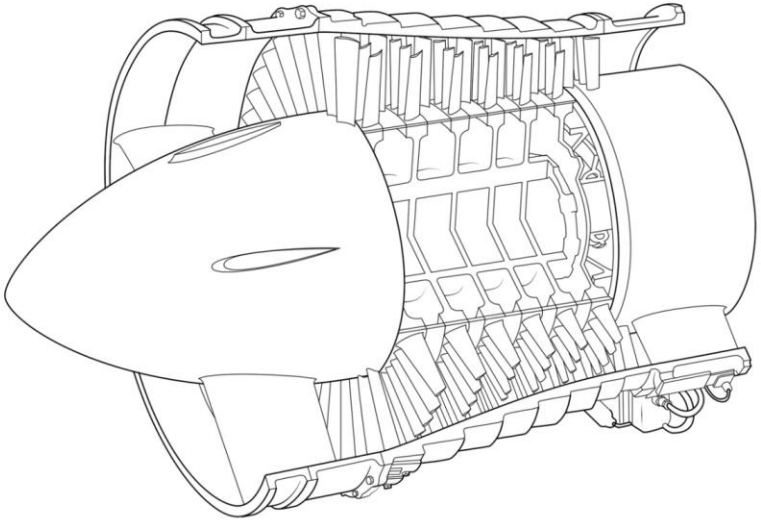

Suction sealoff
Discharge

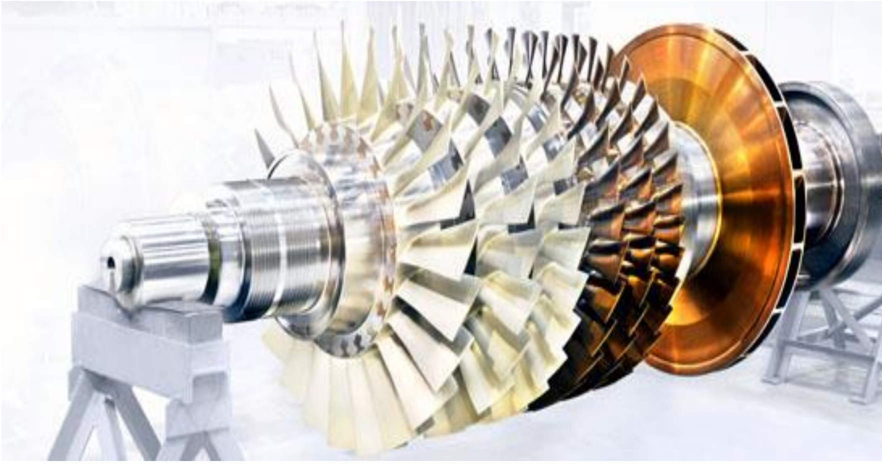
(b)

Axial compressors

It is a rotating, airfoil-based compressor in which the gas or working fluid principally flows parallel to the axis of rotation. Axial flow compressors produce a continuous flow of compressed gas, and have the benefits of high efficiency and large mass flow rate.

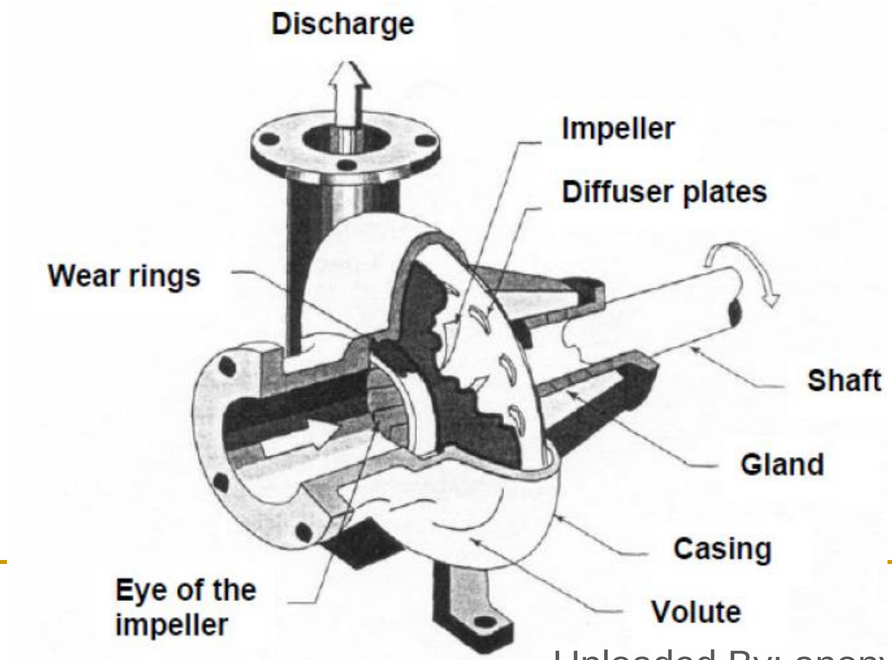
Axial compressors are integral to the design of large gas turbines such as jet engines, high speed ship engines, and small scale power stations.





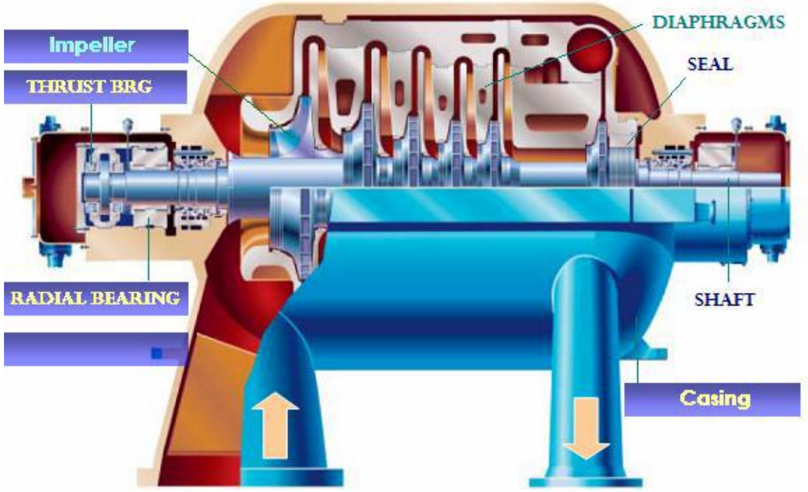
Centrifugal compressors

- Centrifugal compressors, centrifugal fans and centrifugal pumps are all members of the same family of machines where the pumping force is based on impeller size and rotating speed.
- high capacity machines moving large volumes of vapor and can't be economically built for small capacity systems



Operating Principles

- In a centrifugal compressor, low pressure, low temperature and low velocity vapor is drawn into the impeller housing near the center of the compressor, and then enters the inlet of the impeller.
- As the impeller spins, the vapor is discharged at high velocities and higher temperature and pressure to the outside of the housing.



Stages

- Speeds to 25,000 rpm are common. However, centrifugal compressors don’t build up as much pressure as do positive displacement compressors.
- Therefore, several impellers are put in series to increase the pressure of the gas.
- centrifugal compressors will have two, three or four impellers. Each impeller is a stage of compression. After the vapor leaves an impeller, it’s directed into another impeller or into the discharge line.
- The capacity of the compressor, number of stages, and speed all depend on the application

Performance curves

- Like a centrifugal fan, a compressor map includes the volume flow, specific work or power input, efficiency, surge region, and opening of the inlet vanes.
- The centrifugal compressor can be operated either at constant speed or at variable speed.