Chapter 6

Pumps

Engr. Khurram Sheraz

Assistant Professor

Department of Electrical Engineering

University of Engineering & Technology Peshawar

Contents

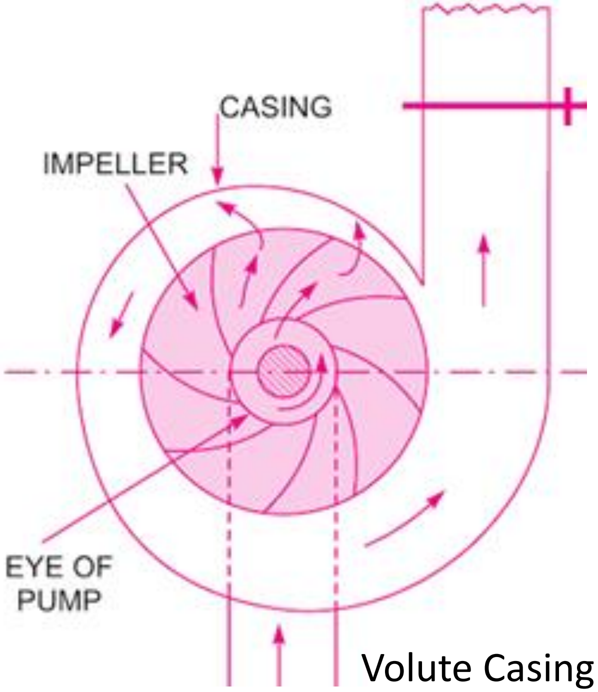
- Centrifugal Pump
- Work Done by a Centrifugal Pump
- Manometric Head Developed by a Centrifugal Pump
- Efficiencies of a Centrifugal Pump
- Power Required to Drive a Centrifugal Pump
- Performance Characteristics
- Specific Speed
- Selection of Pump
- Pump Installations

Classification of Pump

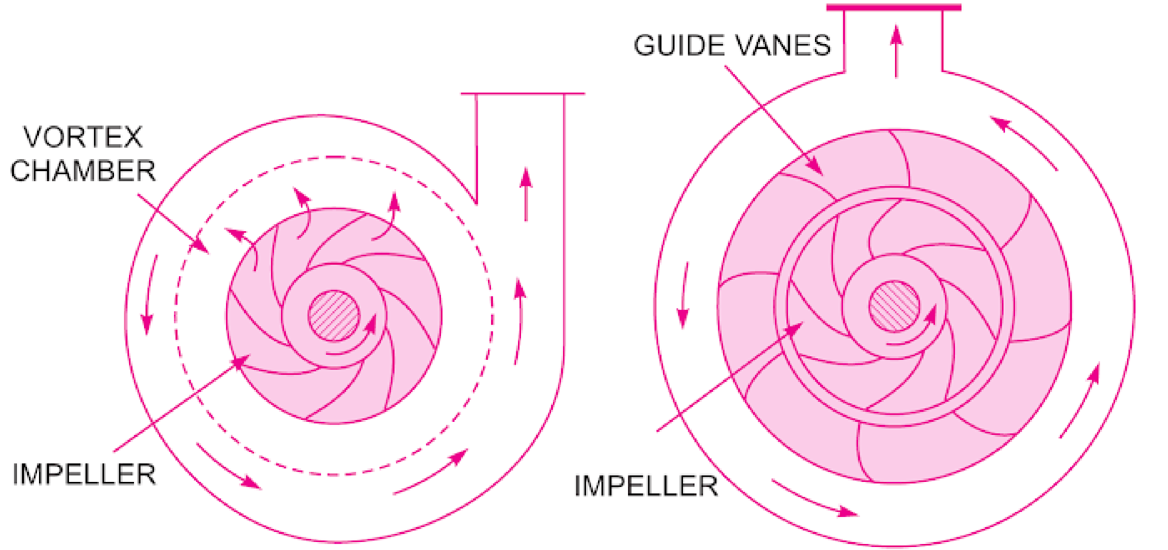
- Pumps
  - Dynamic
    - Centrifugal
      - Axial Flow
      - Mixed Flow
      - Peripheral
    - Special Effect
      - Jet
      - Electromagnetic
  - Postive Displacement
    - Reciprocating
      - Piston, Plunger
      - Diaphragm
    - Rotary
      - Single Rotor
      - Multiple Rotor

Centrifugal Pump

- A pump is a hydraulic machine which converts mechanical energy into hydraulic energy.
- The hydraulic energy is in the form of pressure energy.
- A centrifugal pump is also known as a rotodynamic pump or dynamic pressure pump.
- It works on the principle of centrifugal force.
- The main parts are impeller rotating within a casing, suction pipe with a foot valve and a strainer, and delivery pipe.
- Fluid enters the impeller in the central portion , called the eye, flows radially outward, and is discharged around the entire circumference into a casing.
- During flow through the rotating impellor the fluid receives energy from the vanes, resulting in an increase in both pressure and absolute velocity.
- Since a large part of the energy of the fluid leaving the impeller is kinetic, it is necessary to reduce the absolute velocity and transform the larger portion of this velocity head into pressure head.
- This is accomplished in the volute casing surrounding the impeller or in flow through diffuser vanes.



Volute Casing



(a) VORTEX CASING

(b) CASING WITH GUIDE BLADES

In volute pumps the impeller is surrounded by a spiral case, the outer boundary of which may be a curve called a volute.

The absolute velocity of the fluid leaving the impeller is reduced in the volute casing, with a resultant increase in pressure

The efficiency of pump increases slightly as a large amount of energy is lost due to formation of eddies in this type of casing.

In the diffuser (doughnut-shaped) pump the impeller is surrounded by diffuser vanes which provide gradually enlarging passages to effect a gradual reduction in velocity.

Because of the superficial resemblance to a reaction turbine, this is often called a turbine pump.

The diffusion vanes are usually fixed or immovable but in a very few instances they have been pivoted like the guide vanes in a turbine in order that the angle might be changed to conform to conditions with different rates of flow.

Work Done by a Centrifugal Pump

- In centrifugal pump work is done by the impellor on water.
- It is found out by drawing velocity triangles at inlet and outlet of the impellor in the same way as for a turbine.
- The water enters the impeller radially and at inlet for best efficiency of the pump, which means the absolute velocity (V_1) of water at inlet makes 90^o with the direction of motion of the impeller at inlet, hence, $\alpha = 90^o$, $V_{w_1} = 0$, and $V_{f_1} = V_1$.

N = speed of the impeller in rpm

D_1 = diameter of the impeller at inlet

D_2 = diameter of the impeller at outlet

u_1 = tangential velocity of the impeller at inlet = $\pi D_1 N/60$

u_2 = tangential velocity of the impeller at outlet = $\pi D_2 N/60$

V_1 =absolute velocity of the liquid at inlet

V_2 = absolute velocity of the liquid at outlet.

V_{f_1} & V_{f_2} = velocities of flow at inlet and outlet, respectively

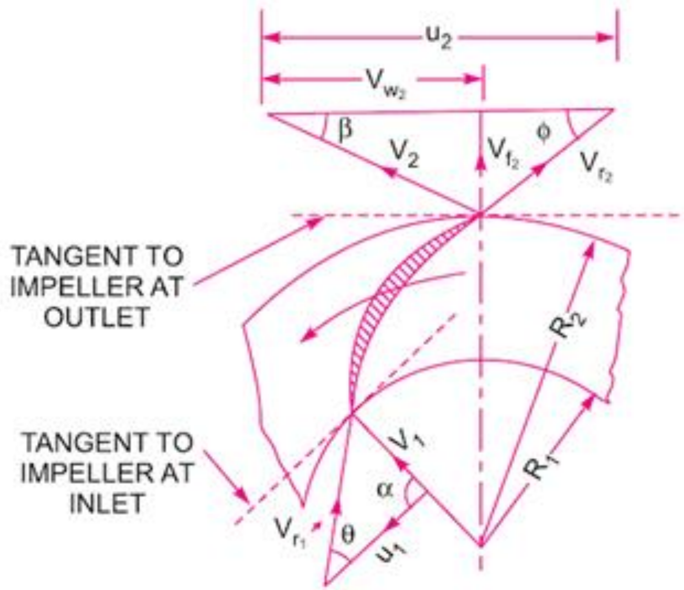
V_{r_1} & V_{r_2} = relative velocities at inlet and outlet, respectively

V_{w_1} = whirl velocity at inlet = $V_1 \cos 90 = 0$ (radial flow, $\alpha = 90^o$)

V_{w_2} = whirl velocity at outlet

α & β = angles between absolute velocities and direction of motion of vane at inlet and outlet, respectively

θ & ϕ = vane angles at inlet and outlet, respectively



Velocity triangles at inlet and outlet.

Work Done by a Centrifugal Pump

- A centrifugal pump is the reverse of a radially inward flow reaction turbine.
- For a series of curved vanes the force exerted can be determined using the impulse-momentum equation:
- The work done/sec/weight of the liquid striking the vane:

$$\text{WD/s/}W = -[\textit{work done in case of radial flow rection turbine})$$

$$\text{WD/s/}W = -\frac{1}{g}\left(V_{\omega_1}u_1 - V_{\omega_2}u_2\right) = \frac{1}{g}\left(V_{\omega_2}u_2 - V_{\omega_1}u_1\right) \qquad \text{since, } V_{\omega_1} = 0$$

$$\text{WD / s / } W = \frac{1}{g}\left(V_{\omega_2}u_2\right)$$

$$\text{WD / s} = \frac{W}{g}\left(V_{\omega_2}u_2\right)$$

Weight (W) = $\gamma Q = \gamma a V$

$$Q = AV$$

$$Q = \pi D_1 B_1 V_{f_1} = \pi D_2 B_2 V_{f_2}$$

also from velocity triangles,

$$\text{WD/s/W} = \frac{V_2^2 - V_1^2}{2g} + \frac{u_2^2 - u_1^2}{2g} + \frac{V_{r1}^2 - V_{r2}^2}{2g}$$

- where B_1 and B_2 are the widths of impeller at inlet and outlet, respectively.

- The equation of work done/s/W gives the head imparted to the water by the impeller or energy given by the impeller to water.

Manometric Head Developed by a Centrifugal Pump

- The head of a centrifugal pump may be expressed in the following ways:

  (1) Static head (2) Manometric head

1. **Static Head:** The sum of suction head and delivery head is known as static head (H_s), mathematically,

$$H_s = h_d - (-h_s)$$

$$H_s = h_d + h_s$$

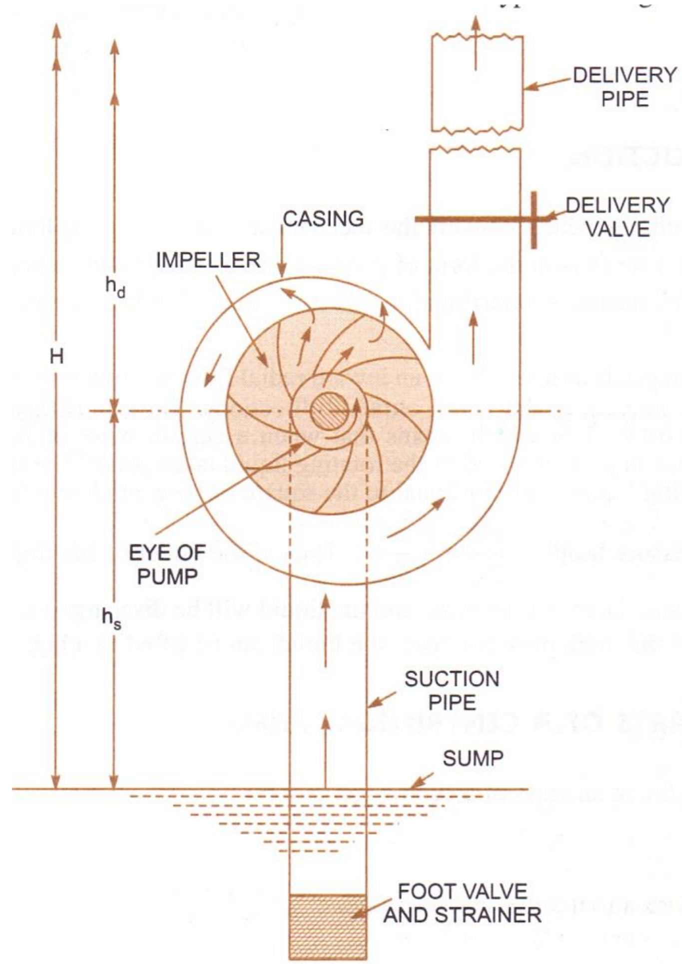


Fig. 19.1 *Main parts of a centrifugal pump.*

i. **Suction Head:**

- It is the vertical height of the centerline of the pump above the water surface in the tank/pump from which water is to be lifted.
- It is also called suction lift and denoted by $-h_s$.

ii. **Delivery Head:**

- The vertical distance between the centerline of the pump and the water surface in the tank to which water is delivered (h_d).

Manometric Head Developed by a Centrifugal Pump

2. Manometric Head:

- The head against which a centrifugal pump has to work is known as the manometric head.
- The official code defines this head on the pump as the difference in total energy heads at the suction and delivery flanges
- It is given by the following expressions:

a) $\mathbf{H_m} = \boldsymbol{head\ imparted\ by\ the\ impeller\ to\ water - loss\ of\ head\ in\ the\ pump}$

$$\mathrm{H_m} = \frac{V_{\omega_2} u_2}{g} - loss\ of\ head\ in\ impeller\ and\ casing$$

$$\mathrm{H_m} = \frac{V_{\omega_2} u_2}{g}$$ if loss of pump is zero

b) $\mathbf{H_m} = \boldsymbol{total\ head\ at\ outlet\ of\ pump - total\ head\ at\ inlet\ of\ pump}$

$$\mathrm{H_m} = \left[\frac{p_o}{\gamma} + \frac{V_o^2}{2g} + Z_o\right] - \left[\frac{p_i}{\gamma} + \frac{V_i^2}{2g} + Z_i\right]$$

c) $$\mathrm{H_m} = [h_s + h_d] + [h_{f_s} + h_{f_d}] + \frac{V_d^2}{2g}$$ (total, gross, or effective head)

Efficiencies of a Centrifugal Pump

- In case of centrifugal pump, the power is transmitted from the shaft of the electric motor to the shaft of the pump and then to the impeller.
- Form the impeller, the power is given to the water.
- Thus, power is decreasing form the shaft of the pump to the impeller and then to the water.
- The following are the most important efficiencies of a centrifugal pump:

  (a) Manometric efficiency (η_{man}) (b) Mechanical efficiency (η_m)

  (c) Overall efficiency (η_o)

a) Manometric efficiency (η_{man}): (60 – 90%)

- The ratio of the manometric head to the head imparted by the impeller to the water is known as manometric efficiency, mathematically,

$$\eta_{man} = \frac{Manometric\ head}{Head\ imparted\ by\ impeller\ to\ water} = \frac{H_m}{\frac{V_{\omega 2} u_2}{g}} = \frac{g H_m}{V_{\omega 2} u_2}$$

- Also, the ratio of the power given to water at outlet of the pump to the power available at the impeller is known as manometric efficiency.

$$The\ power\ given\ to\ water\ at\ outlet\ of\ pump\ (kW) = \frac{W H_m}{1000}$$

$$The\ power\ at\ the\ impeller (kW) = \frac{Work\ done\ by\ impeller\ per\ second}{1000} = \frac{W}{g} \times \frac{V_{\omega 2} u_2}{1000}$$

Efficiencies of a Centrifugal Pump

a) Manometric efficiency (η_{man}):

$$\eta_{man} = \frac{Power\ given\ to\ water\ at\ outlet\ of\ pump}{Power\ at\ the\ impeller} = \frac{\frac{WH_m}{1000}}{\frac{W}{g} \times \frac{V_{\omega 2} u_2}{1000}} = \frac{gH_m}{V_{\omega 2} u_2}$$

b) Mechanical efficiency (η_m): (95 – 98%)

- The ratio of the power available at the impeller to the power at the shaft of pump is known as mechanical efficiency, written as,

$$\eta_{man} = \frac{Power\ at\ the\ impeller}{Power\ at\ the\ shaft\ (brake\ or\ shaft\ power)} = \frac{\frac{W}{g} \times \frac{V_{\omega 2} u_2}{1000}}{\mathrm{T}\,\omega}$$

- where, T is the torque exerted on the shaft of the pump by the motor that drives the pump, and ω is the rate of rotation of the shaft.

c) Overall efficiency (η_o): (70 – 75%)

- It is defined as the ratio of power output of the pump to the power input to the pump by the motor, mathematically,

$$\eta_o = \frac{Power\ output\ of\ the\ pump\ (water\ power)}{Power\ input\ to\ the\ pump\ (shaft\ power)} = \frac{\frac{WH_m}{1000}}{\mathrm{T}\,\omega}$$

- Also, $\eta_o = \eta_{man} \times \eta_m$

15.1 *The diameter of the discharge side of a pump is 100 mm, and that of the intake pipe is 120 mm (Fig. P15.1). The pressure gage at discharge reads 240 kPa and the pressure gage at intake reads 60 kPa. If Q = 45 L/s of water and the pump efficiency is 0.82, find the power delivered to the pump by the drive shaft. The intake of the pump is 350 mm below the discharge side. Neglect the effects of pre-rotation in the entry pipe and assume smooth flow at discharge from the pump.*

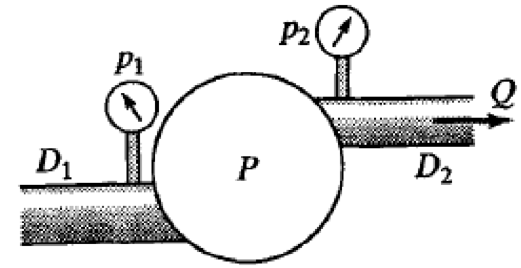


Figure P15.1

SI

$V_s = Q/A_s = (0.045\ \text{m}^3/\text{s})/(\pi 0.120^2/4) = 3.98\ \text{m/s}$

$V_d = V_s(120/100)^2 = 5.73\ \text{m/s}$

Eq. 15.1: $h = (p_d/\gamma + V_d^2/2g + z_d) - (p_s/\gamma + V_s^2/2g + z_s)$

$$h = \left(\frac{240\ \text{kN/m}^2}{9.81\ \text{kN/m}^3} + \frac{5.73^2}{2(9.81)} + 0.35\right) - \left(\frac{60\ \text{kN/m}^2}{9.81\ \text{kN/m}^3} + \frac{3.98^2}{2(9.81)} + 0\right) = 19.56\ \text{m}$$

Eq. 15.2: $P = \gamma Q h/\eta = 9.81(0.045)19.56/0.82 = 10.53\ \text{kW}$ ◄

Power Required to Drive a Centrifugal Pump

- The power required to drive a centrifugal pump may be found out by either of the following two methods:

1. The power required to drive the pump from the manometric head is called the shaft power or the brake power, may be found out by the relation,

$$P = \frac{\gamma\, Q\, H_m}{\eta_o} \text{ (kW)} \qquad \text{also, } P = T\omega$$

H_m = Manometric head of water in (m)

Q = Discharge of the pump (m^3/sec)

η_o = Overall efficiency of the pump

2. The power required to drive the pump from the velocity triangles may be found out by the relation,

$$P = \frac{\gamma\, Q\, V_{\omega_2}\, u_2}{g} \text{ (kW)}$$

V_{ω_2} = velocity of whirl at outlet

u_2 = tangential velocity of impeller at outlet

15.6 *A pump delivers 1000 L/s of water at a head of 8.5 m. If the efficiency of the pump is 68%, what is the shaft power?*

$$\eta = \frac{WP}{P}$$

$$\eta = \frac{\gamma\ Q\ H}{P}$$

$$P = \frac{\gamma\ Q\ H}{\eta}$$

$$P = \frac{9.81 \times 1 \times 8.5}{0.68}$$

$$P = 122.63\ kW$$

Minimum Starting Speed of a Centrifugal Pump

- When the pump is switched on, the flow of water will not take until the rise in pressure through the impeller is large enough to overcome the manometric head.
- At the time of start, the fluid velocities are zero, and head due to change of kinetic energy into pressure energy is not available.
- As a centrifugal head (kinetic) caused by the centrifugal force on the rotating water will be $\frac{u_2^2 - u_1^2}{2g}$ (rise in pressure head).
- In other words, there will be flow of liquid only when the speed of the pump is such that the required centrifugal head is sufficient to overcome the manometric head H_m, hence, flow will commerce only if $\frac{u_2^2 - u_1^2}{2g} \geq H_m$

For minimum speed we must have, $\frac{u_2^2 - u_1^2}{2g} = H_m$

$$\because \eta_{man} = \frac{gH_m}{V_{w_2} u_2} \qquad \therefore H_m = \eta_{man} \times \frac{V_{w_2} u_2}{g}$$

$$\frac{u_2^2 - u_1^2}{2g} = \eta_{man} \times \frac{V_{w_2} u_2}{g} \qquad \because u_2 = \frac{\pi D_2 N}{60} \text{ and } u_1 = \frac{\pi D_1 N}{60}$$

Minimum Starting Speed of a Centrifugal Pump

$$\frac{1}{2g}\left[\left(\frac{\pi D_2 N}{60}\right)^2 - \left(\frac{\pi D_1 N}{60}\right)^2\right] = \eta_{man} \times \frac{V_{w_2}}{g} \times \left(\frac{\pi D_2 N}{60}\right)$$

- Now, dividing by $\frac{\pi N}{60}$

$$\frac{\pi N}{120}\left(D_2^2 - D_1^2\right) = \eta_{man} \times \left(V_{w_2} \times D_2\right)$$

$$N_{\min} = \frac{120 \times \eta_{man} \times V_{w_2} \times D_2}{\pi\left(D_2^2 - D_1^2\right)}$$

- The above equation gives the minimum starting speed of a centrifugal pump.

Specific Speed [on the basis of unit quantity]

- The specific speed (N_s) of a centrifugal pump is defined as the speed of a geometrically similar pump which would deliver unit quantity (one cubic meter of liquid per second) against a unit head (one meter).
- The specific speed is a characteristic of a pumps which can be used as a basis for comparing the performance of different pumps.
- The discharge through impeller is given by, Q = Area x Velocity of flow

$$Q = \pi D_1 B_1 V_{f_1} = \pi D_2 B_2 V_{f_2}$$

$Q \propto DBV_f$ or $\boldsymbol{Q \propto D^2 V_f}$ as $B \propto D$

- The tangential speed of impeller is given by

$u = \frac{\pi DN}{60}$ $\quad$ $\boldsymbol{u \propto DN}$

As, $u = K_u\sqrt{2gH_m}$ $\quad$ $V_f = K_f\sqrt{2gH_m}$ $\quad$ $\boldsymbol{u \propto V_f \propto \sqrt{H_m}}$

$DN \propto \sqrt{H_m}$ $\quad$ $D \propto \frac{\sqrt{H_m}}{N}$

$Q \propto \left(\frac{\sqrt{H_m}}{N}\right)^2 \sqrt{H_m}$ $\quad$ $Q \propto \frac{(H_m)^{\frac{3}{2}}}{N^2}$ $\quad$ $N^2 \propto \frac{(H_m)^{3/2}}{Q}$

$N = C\frac{(H_m)^{3/4}}{\sqrt{Q}}$ where C is a constant of proportionality

- When Q = 1 m^3/s, H_m= 1 m then C = N which is known as specific speed N_s.

$$N_s = \frac{N\sqrt{Q}}{(H_m)^{3/4}}$$

15.8.5 *A pump is to discharge 0.8 m^3/s at a head of 40 m when running at 300 rpm. What type of pump will be required?*

SI

Eq. 15.8*b*: $(N_s)_{SI} = \omega\sqrt{Q}/(gh)^{3/4}$ where $\omega = 2\pi n/60$ (ω rad/s, n rev/min)

$(N_s)_{SI} = 2\pi(300/60)\sqrt{0.8}/(9.81 \times 40)^{3/4} = 0.318$

Sec. 15.8 and Fig. 15.11: This is a radial-flow centrifugal pump. ◀

15.24 *A pump is to deliver 2.0 m^3/s against a head of 160 m when operating at 300 rpm. What type of pump will be required?*

SI

300 rpm $= 2\pi(300)/60 = 31.4$ rad/s $= \omega_e$

Eq. 15.9*b*: $(N_s)_{SI} = \omega_e\sqrt{Q}/(gh)^{3/4} = 31.4\sqrt{2}/(9.81 \times 160)^{3/4} = 0.178$

Fig. 15.11 indicates that this is a radial-flow pump with a low specific speed (outside the range of most radial-flow centrifugal pumps). It is not very desirable because of low efficiency. ◀

15.25 *At its optimum point of operation, a given centrifugal pump with an impeller diameter of 500 mm delivers 3.2 m^3/s of water against a head of 25 m when rotating at 1450 rpm. (a) If its efficiency is 82%, what is the brake power of the drive shaft? (b) If a homologous pump with a diameter of 800 mm is rotating at 1200 rpm, what would be the discharge, head, and shaft power? Assume both pumps operate at the same efficiency. (c) Compute the specific speed of both pumps.*

SI

(*a*) Brake power $= \gamma Qh/\eta = 9.81(3.2)25/0.82 = 957$ kW ◀

(*b*) Eq. 15.4: $Q \propto nD^3$, $Q = 3.2(1200/1450)(800/500)^3 = 10.85\ m^3/s$ ◀

Eq. 15.5: $h \propto n^2D^2$, $h = 25(1200/1450)^2(800/500)^2 = 43.8$ m ◀

Eq. 15.6: $P \propto n^3D^5$, $P = 957(1200/1450)^3(800/500)^5 = 5687$ kW ◀

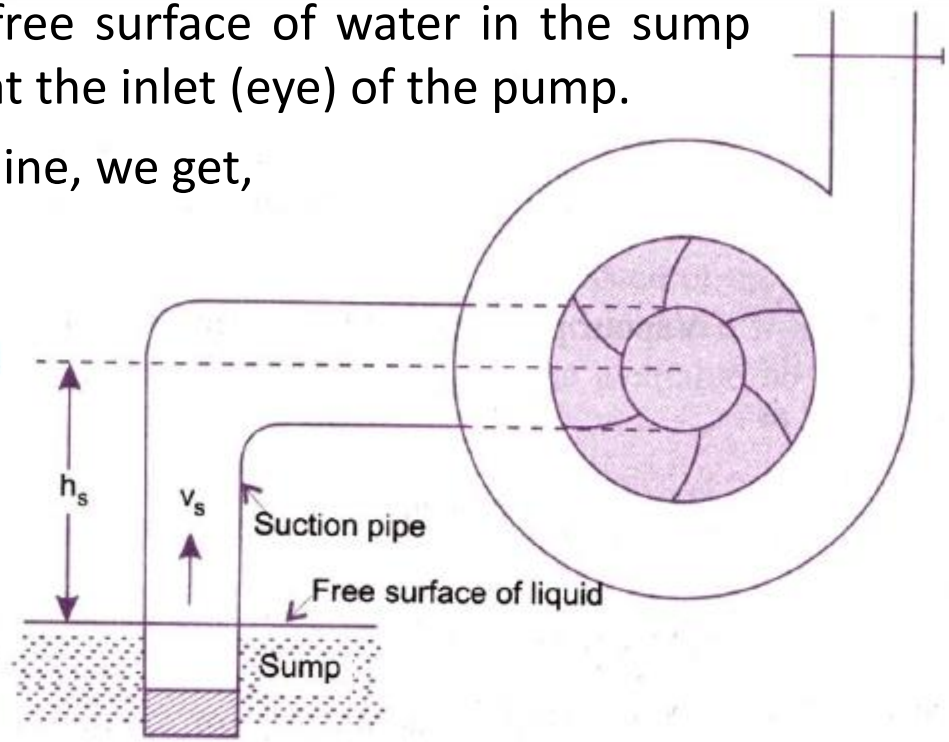
(*c*) For $n = 1450$ rpm, $\omega = 2\pi n/60 = 151.8$ rad/s ; $(N_s)_{SI} = 151.8(3.2)^{1/2}/(9.81 \times 25)^{3/4} = 4.38$ ◀

For $n = 1200$ rpm, $\omega = 2\pi(1200)/60 = 125.6$ rad/s

$(N_s)_{SI} = 125.6(10.85)^{1/2}/(9.81 \times 43.8)^{3/4} = 4.38$ ◀ This is an axial-flow pump.

Maximum Suction Lift or Suction Height

- Consider the following centrifugal pump that lifts water from a sump.
- The free surface of the water is at a depth of h_s below the pump axis.
- The water is flowing with a velocity V_s in the suction pipe.
- Applying Bernoulli's equation at the free surface of water in the sump and Section-1 in the suction pipe just at the inlet (eye) of the pump.
- Taking free surface of water as datum line, we get,



- $\frac{P_a}{\rho g} + \frac{V_a^2}{2g} + z_a = \frac{P_1}{\rho g} + \frac{V_1^2}{2g} + z_1 + h_L$
- $\frac{P_a}{\rho g} + 0 + 0 = \frac{P_1}{\rho g} + \frac{V_s^2}{2g} + h_s + h_{fs}$
- $\frac{P_a}{\rho g} = \frac{P_1}{\rho g} + \frac{V_s^2}{2g} + h_s + h_{fs}$
- $\frac{P_1}{\rho g} = \frac{P_a}{\rho g} - \left(\frac{V_s^2}{2g} + h_s + h_{fs}\right)$

p_a = Atmospheric pressure on the free surface of liquid
V_a = Velocity of liquid at the free surface of liquid $\simeq 0$
Z_a = Height of free surface from datum line = 0
p_1 = Absolute pressure at the inlet of pump
V_1 = Velocity of liquid through suction pipe = v_s
Z_1 = Height of inlet of pump from datum line = h_s
h_L = Loss of head in the foot valve, strainer and suction pipe = h_{fs}

Maximum Suction Lift or Suction Height

- For finding the maximum suction lift, the pressure at the inlet of the pump should not be less than the vapor pressure of the water.
- Hence, taking minimum pressure at the inlet of the pump equal to the vapor pressure of the water, we get,
- $P_1 = P_v$ where P_v = absolute vapor pressure
- $\frac{P_v}{\rho g} = \frac{P_a}{\rho g} - \left(\frac{V_s^2}{2g} + h_s + h_{fs}\right)$
- $h_s = \frac{P_a}{\rho g} - \frac{P_v}{\rho g} - \frac{V_s^2}{2g} - h_{fs}$
- $h_s = H_a - H_v - \frac{V_s^2}{2g} - h_{fs}$
- The above equation gives the value for maximum suction lift (or suction height) for a centrifugal pump.
- If the suction height of the pump is greater than that computed from the above equation, then vaporization of liquid at the inlet of the pump will take place and there will be a possibility of cavitation.

Net Positive Suction Head (NPSH)

- The term NPSH is commonly used in pump industry because the minimum suction conditions are specified in terms of NPSH.
- Net positive suction head is defined as "*the absolute pressure head at the inlet to the pump minus the vapor pressure head (absolute) plus the velocity head".*
- Or "*the difference between the net inlet head and the head corresponding to the vapor pressure of the water."*
- Or "*the net head (m of water that is required to make the liquid flow through the suction from the sump to the impeller*".
- $NPSH = \frac{P_1}{\rho g} - \frac{P_v}{\rho g} - \frac{V_s^2}{2g}$
- $\frac{P_1}{\rho g} = \frac{P_a}{\rho g} - \left(\frac{V_s^2}{2g} + h_s + h_{fs}\right)$
- $NPSH = \frac{P_a}{\rho g} - \left(\frac{V_s^2}{2g} + h_s + h_{fs}\right) - \frac{P_v}{\rho g} - \frac{V_s^2}{2g}$
- $NPSH = \frac{P_a}{\rho g} - \frac{P_v}{\rho g} - h_s - h_{fs}$
- $NPSH = (H_a - h_s - h_{fs}) - H_v$

Net Positive Suction Head (NPSH)

- Hence, NPSH is equal to the total suction head.
- For any pump installation, a distinction is made between required NPSH and the available NPSH.
- The value of required NPSH is given by manufacturer, which can also be determined experimentally.
- For determining its value, the pump is tested and minimum value of h_s is obtained at which the pump gives maximum efficiency without any objectionable noise (i.e. cavitation free).
- The required NPSH varies with the design, speed and capacity of the pump.
- When the pump is installed , the available NPSH is calculated from,
- $NPSHA = (H_a - h_s - h_{fs}) - H_v$
- In order to have cavitation free operation of centrifugal pump,

NPSHA > NPSHR