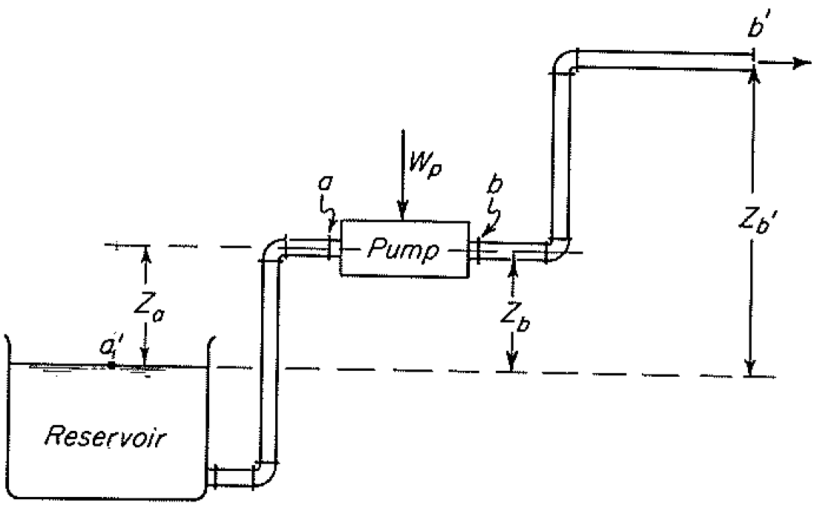
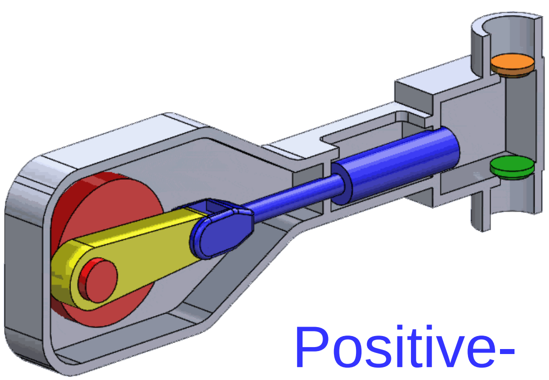
Transportation of fluids

- In this part, we will introduce pumps and compressors that used for transporting fluids.
- Pumps are used for liquid flow, and compressors are usually used for gas.
- It's cheaper to transport fluid than solid, thus solid is usually suspended in liquid or high-velocity gas stream.

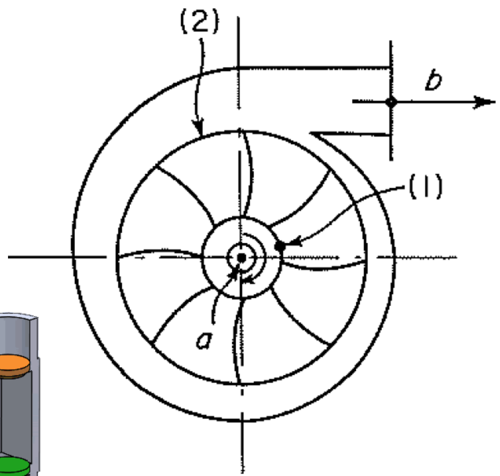


Power of the pump required?

***NPSH*?**

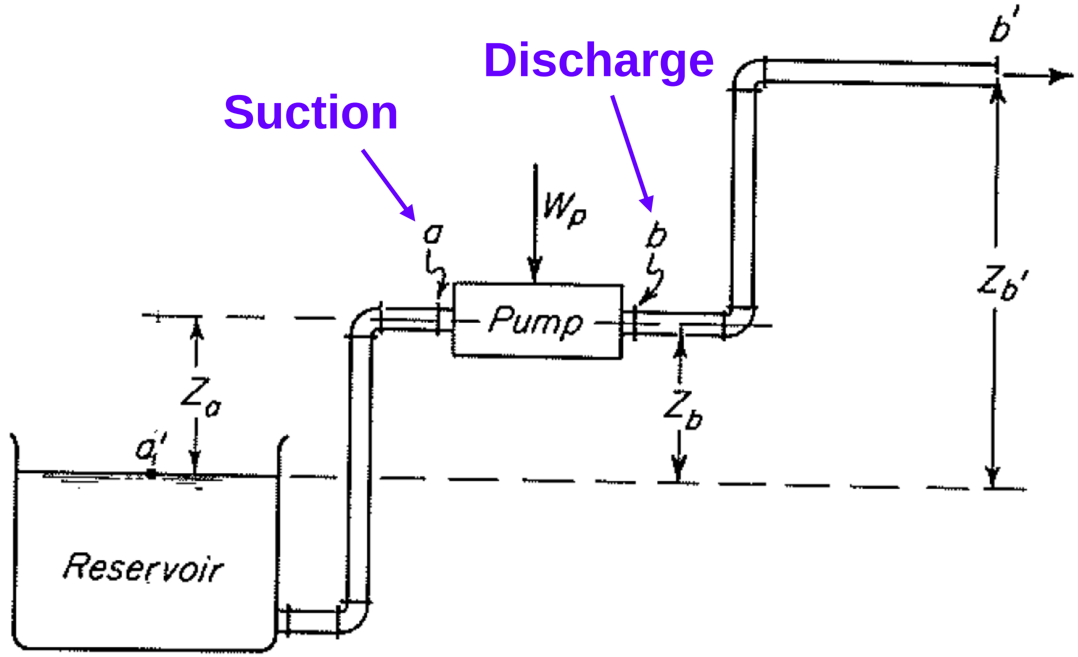


Positive-displacement pump



Centrifugal pump

Power and virtual head of a pump



Pump efficiency (η):

Effect from friction loss

Recall:

$$\boxed{\rho A v[F + \Delta(\frac{P}{\rho}) + \frac{1}{2}\Delta(\alpha v^2) + g\Delta z] = Power\ required(W_P)}$$

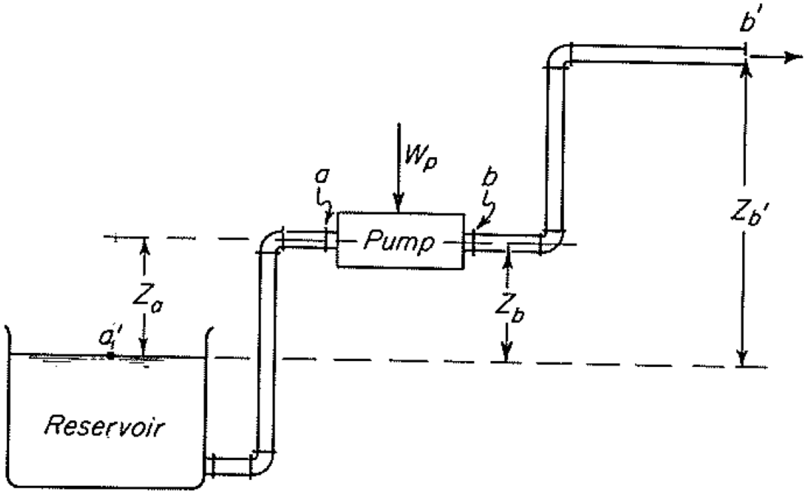
- Let's define the system **from "a" to "b"**: $(\rho A v = G\ \text{(mass flow rate)})$

$$\rho A v[(\frac{P_b - P_a}{\rho}) + \frac{\alpha_b v_b^2 - \alpha_a v_a^2}{2} + g(z_b - z_a)] = \eta W_P$$

$$\left(\frac{P_b - P_a}{\rho g}\right) + \frac{\alpha_b v_b^2 - \alpha_a v_a^2}{2g} + (z_b - z_a) = virtual\ head\ of\ a\ pump\ [m]$$

Net Positive Suction Head (NPSH)

- The suction pressure of a pump needs to be higher than the vapor pressure of the fluid. If not, the liquid may be vaporized inside the pump, a process called "**cavitation**", which may damage the pump!



- Let's define the system **from *a'* to *a***:

No velocity at a'

$$\frac{F}{g} + \Delta\left(\frac{P}{\rho g}\right) + \frac{1}{2g}\Delta(\alpha v^2) + \Delta z = 0; \quad h_f + \frac{P_a - P_{a'}}{\rho g} + \frac{\alpha_a v_a^2 - \cancel{\alpha_{a'} v_{a'}^2}}{2g} + Z_a = 0$$

H_f: friction head loss between a' and a **[m]**

$$\longrightarrow \underline{\frac{P_a}{\rho g} + \frac{\alpha_a v_a^2}{2g} - \frac{P_v}{\rho g}} = \frac{P_{a'}}{\rho g} - h_f - \Delta z - \frac{P_v}{\rho g} \equiv NPSH_{Available}$$

Suction pressure − vapor pressure must be > 0

P_v: vapor pressure of the fluid

Net Positive Suction Head (NPSH)

To prevent cavitation in a pump:

$$\boxed{NPSH_{Available} \equiv \frac{P_{a'}}{\rho g} - h_f - \Delta z - \frac{P_v}{\rho g} > 0}$$

- In reality, the friction loss within the pump also needs to be considered. Thus, the "**$\text{NPSH}_{\text{required}}$**" (or "**NPSHR**") is provided by the pump manufacturers for each pump. The value is around 2-3 m for small pump and can be up to 15 m for large pumps.

$$\boxed{NPSH_{Available} > NPSHR}$$

- To get high-enough $NPSH_{Available}$, a common strategy is to have a large enough negative Δz (by lifting the reservoir above the pump).

Example 8.1

Benzene at 37.8 ^oC is pumped through the system at the rate of 9.09 m^3/h. The reservoir is at atmospheric pressure. The gauge pressure at the end of the discharge line is 345 kN/m^2. The discharge is 10 ft, and the pump suction is 4 ft above the level in the reservoir. The pipe has an inside diameter of 1.61 inch. The friction in the suction line is 3.45 kN/m^2, and that in the discharge line is 37.9 kN/m^2. The mechanical efficiency of the pump is 0.60. The density of benzene is 865 kg/m^3, and its vapor pressure is 26.2 kN/m^2 at 37.8 ^oC.

Find: (a) The total power input.

(b) If the NPSHR of the pump is 3.05 m, will the pump be suitable for this process?

Solution:

Some notes:

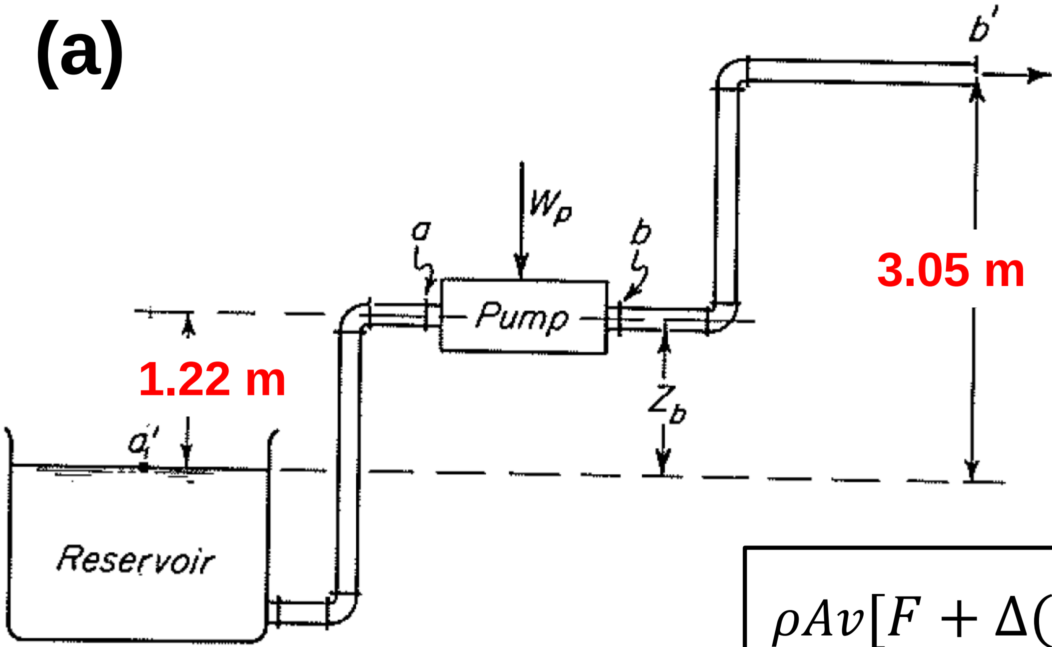
(1) Absolute pressure = Gauge pressure + Atmospheric pressure

(2) The unit of friction here is “kPa” → **$F\rho$**

(3) Plot the process first!

Example 8.1

(a)



$$G = \rho A v = \frac{9.09 \times 865}{3600} = 2.18\ (kg/s)$$

$$v = \frac{2.18}{865(0.25\pi(0.041)^2)} = 1.91\ (\frac{m}{s})$$

$$v_{a'} = 0$$

$$P_{b'} - P_{a'} = 345000\ (Pa)$$

$$\boxed{\rho A v[F + \Delta(\frac{P}{\rho}) + \frac{1}{2}\Delta(\alpha v^2) + g\Delta z] = \eta W_P}$$

- Let's define the system ***from a' to b'***:

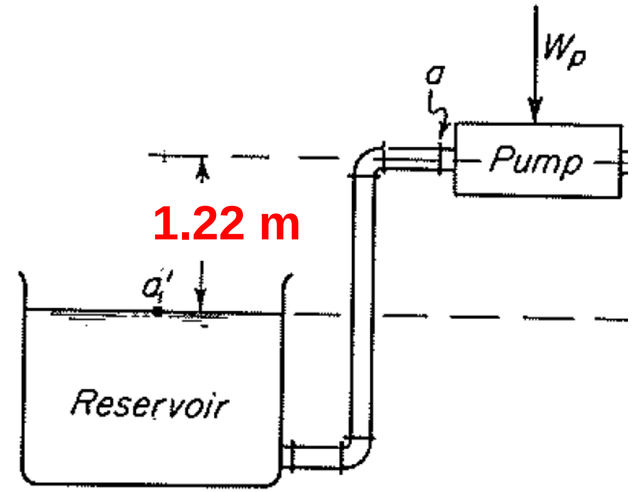
$$2.18(\frac{3450 + 37900}{865} + \frac{345000}{865} + \frac{1(1.91)^2 - 0}{2} + 9.8 \times 3.05] = 0.6 W_P$$

$$W_P = 1740\ W$$

Example 8.1

(b)

$$\boxed{NPSH_{Available} = \frac{P_{a'}}{\rho g} - h_f - \Delta z - \frac{P_v}{\rho g}}$$



$$NPSH_{Available} = \frac{101325}{865 \times 9.8} - \frac{3450}{865 \times 9.8} - 1.22 - \frac{26200}{865 \times 9.8} = 7.24\ (m)$$

$(7.24\ m > 3.05\ \mathrm{m})$

Types of pumps

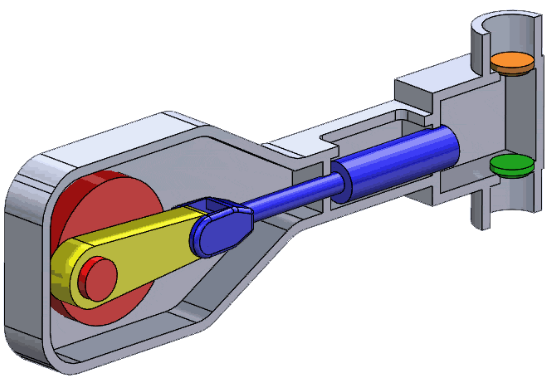
- Pumps can be classified into two categories:

  (1) **Positive-displacement pumps**

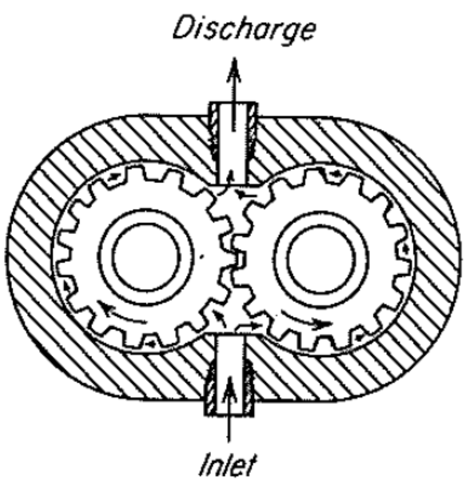
  (2) **Centrifugal pumps**

- <u>Positive-displacement pumps</u>:

(1) Reciprocating pumps:

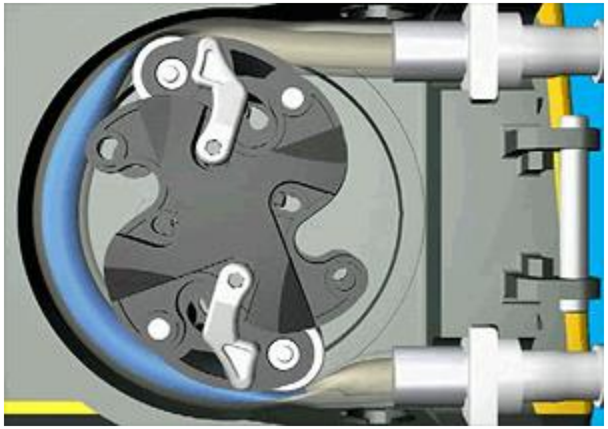


(2) Rotary pumps:



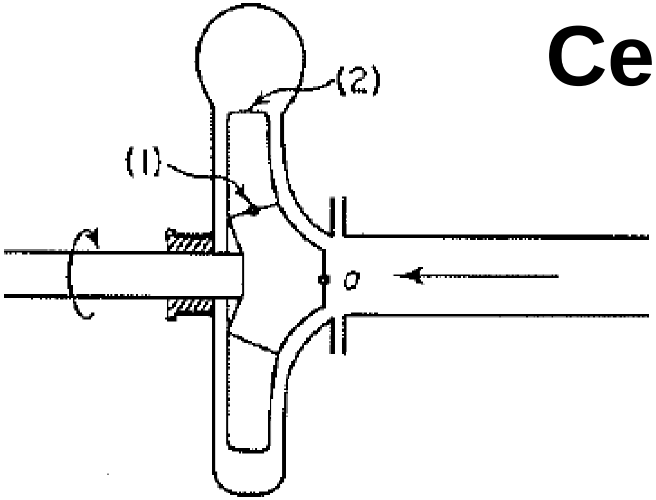
(Gear pump for viscous fluid)

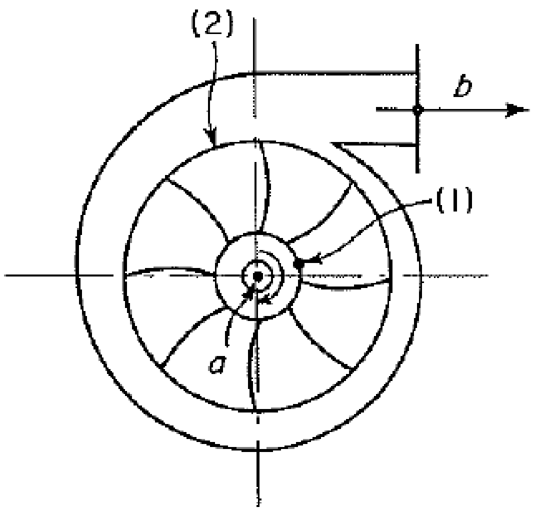
(3) Peristaltic pumps:

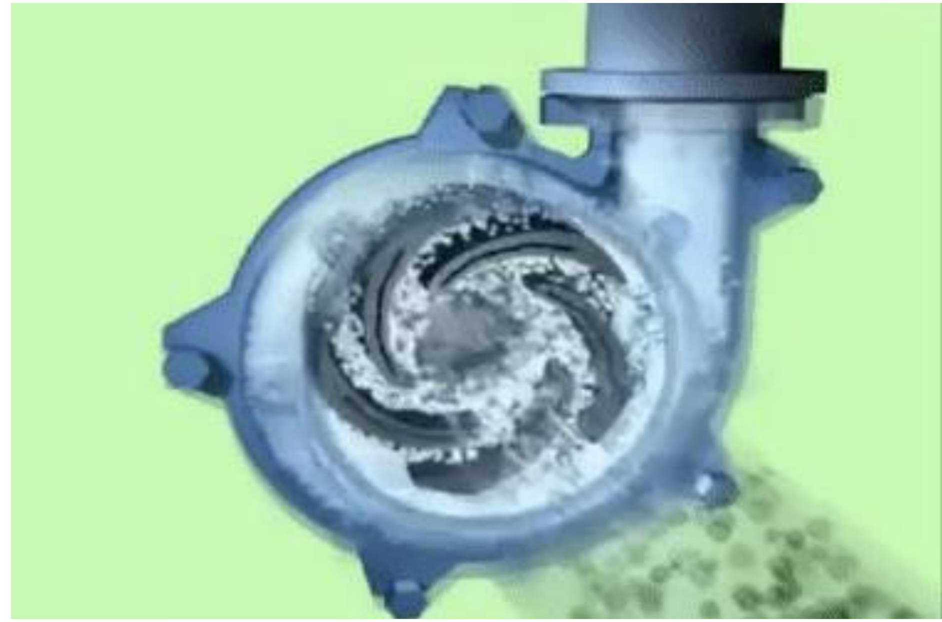


- Common for biochemicals that are not allowed to expose to air
- Only for small flow rates

Centrifugal pumps





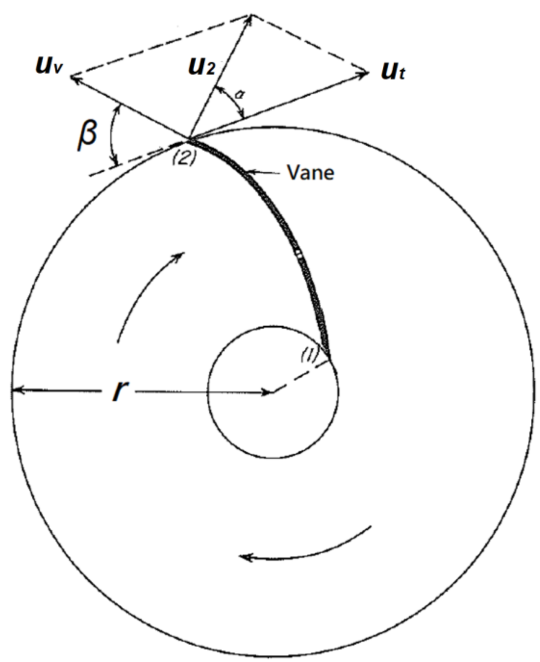


- For unit mass of fluid:

$$W_p = \omega r_2 (u_t - \frac{Q}{A_p tan\beta})$$

“1”: Inlet

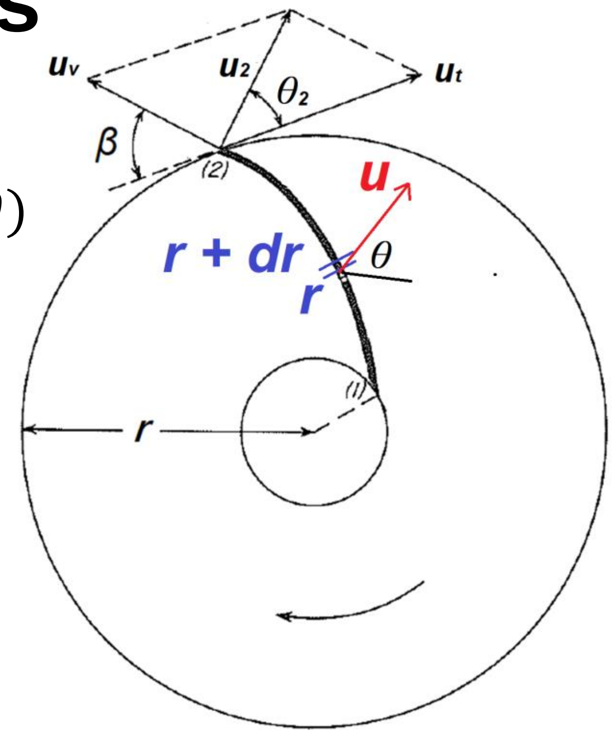
“2”: At the tip of the vane



Centrifugal pumps

Torque

$$d\tau = d(force \times r) = \frac{\partial[dm(ucos\theta)r]}{\partial t} = Q\rho \times d(urcos\theta)$$



$$\tau = Q\rho(u_2 r_2 cos\theta_2 - u_1 r_1 cos\theta_1)$$

$$Power = \tau\omega = \omega Q\rho(u_2 r_2 cos\theta_2 - u_1 r_1 cos\theta_1)$$

[ML²/t²] [1/t]

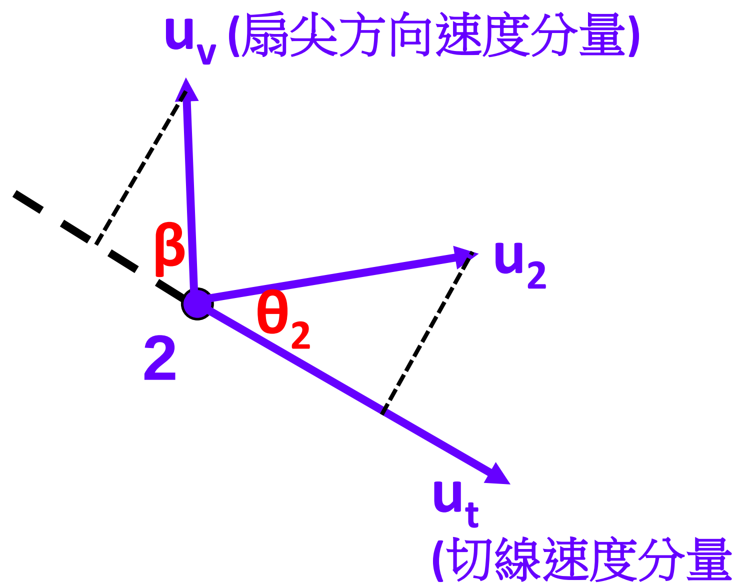
"1" is at the center (~0)

$$Power = \omega Q\rho u_2 r_2 cos\theta_2 \quad (1)$$

$$u_t = u_2 cos\theta_2 + u_v cos\beta \quad (2)$$

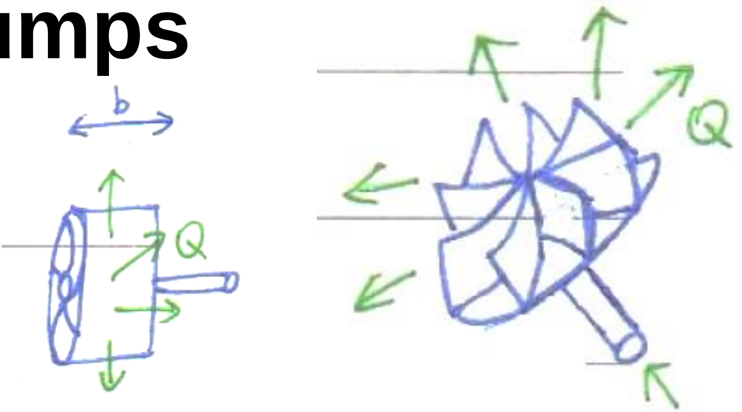
$$u_t = \omega r_2 \quad (3)$$

$$u_2 sin\theta_2 = u_v sin\beta \quad (4)$$



Centrifugal pumps

$$Q = 2\pi r_2 b u_2 sin\theta_2 \quad \textbf{(5)}$$



- **From (1) to (5)…**

$$Power\ (W_p) = Q\rho\omega u_2 r_2 cos\theta_2 = Q\rho\omega r_2 (u_t - u_v cos\beta)$$

$$= Q\rho\omega r_2 \left(\omega r_2 - \frac{u_2 sin\theta_2}{sin\beta} cos\beta\right) = Q\rho\omega r_2 \left(\omega r_2 - \frac{Q}{2\pi r_2 b tan\beta}\right)$$

$$= \underline{Q\rho}\left(\omega^2 r_2^2 - \frac{\omega Q}{2\pi b tan\beta}\right)$$

Mass flow rate

- **Note:**
  $\omega = 2\pi f$;
  f = revolution per second
  (60f = RPM)

$$h \equiv \frac{W_p}{Q\rho g} = \frac{\omega^2 r_2^2}{g} - \frac{\omega Q}{2\pi b g tan\beta}$$

"Virtual head developed by the pump"

Centrifugal pumps – Key findings

$$\boxed{\textit{Power delivered by the pump } (W_p) = Q\rho\left(\omega^2 r_2^2 - \frac{\omega Q}{2\pi b \tan\beta}\right)}$$ **(J/s)**

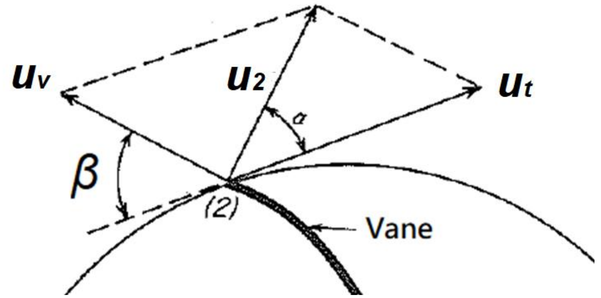
$$\boxed{\textit{Head developed by the pump } (h) = \frac{\omega^2 r_2^2}{g} - \frac{\omega Q}{2\pi b g \tan\beta}}$$ **(m)**

(1) The effect of β:

$\beta < 90^o$ → Backward blades → **Q↑, h↓**

$\beta = 90^o$ → Radical blades → **h ≠ f(Q)**

$\beta > 90^o$ → Forward blades → **Q↑, h↑**



Backward blades are commonly used; forward blades cause unstable flow!

(2) For the same pump:

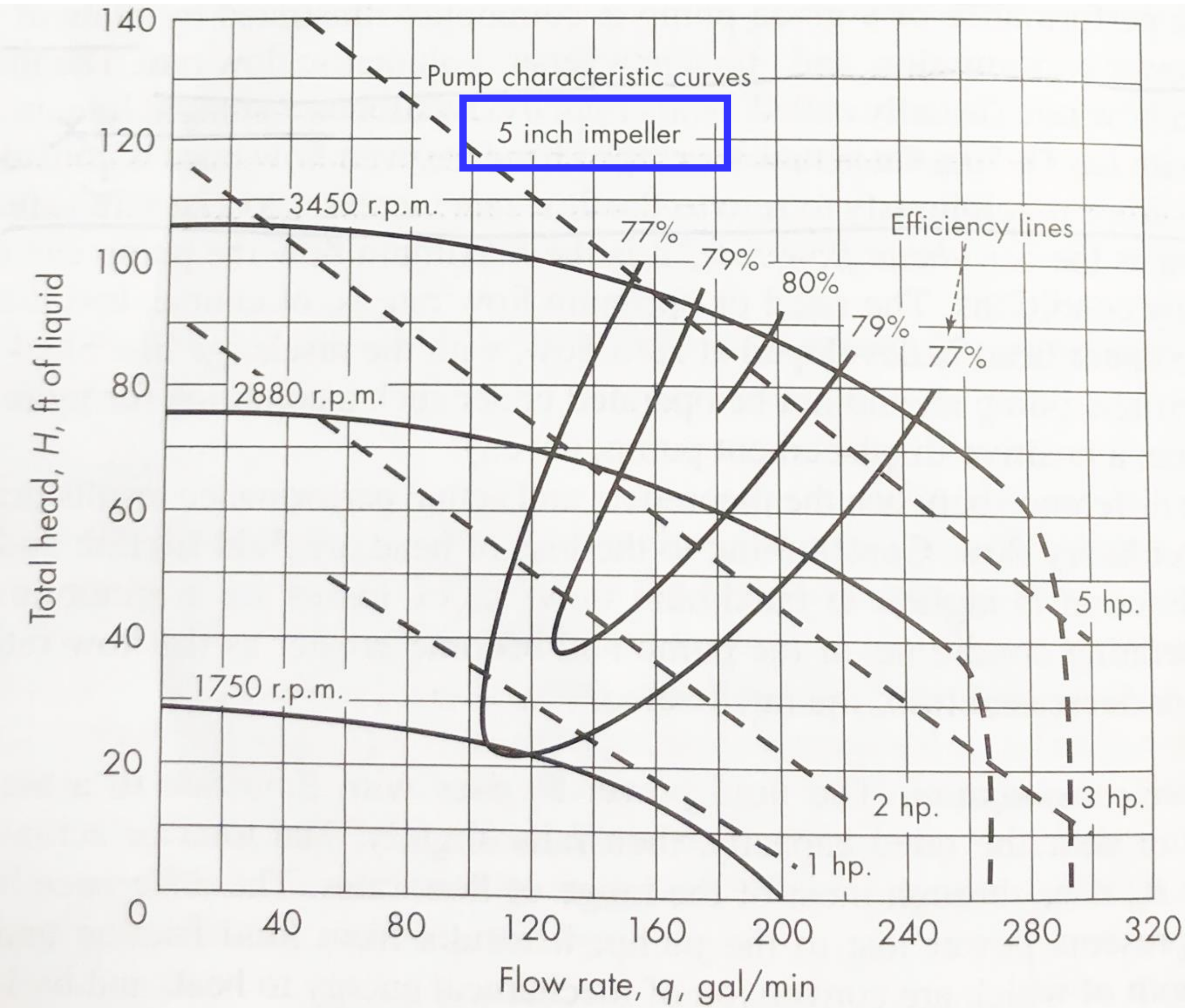
$Q \propto \omega$

$h \propto \omega^2$

$W_p \propto \omega^3$

Centrifugal pumps – The efficiency

- The ideal pump head (h) plotted with volumetric flow rate (Q) should be a straight line, but in practice the head decreases a lot when Q is too large.



- Ex:

At 3450 rpm, the optimized Q is 200 gal/min, the total head is 88 ft, the power required is 5.5 hp, and the efficiency is 80%.

"Duty Point"

For gas transportation…

1. Fans: Low-velocity transportation of air; generated pressure < 0.04 atm
2. Blowers: The maximum pressure is about 2 atm.
3. Compressors: Above 2 atm

- **Constant pressure** can be assumed for centrifugal fans.

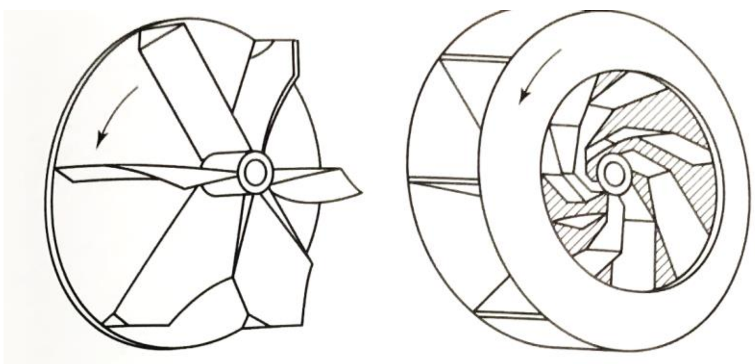


FIGURE 8.11
Impellers for centrifugal fans.

- For blowers and compressors, the thermodynamics of compressible fluids are necessary…

$$PV^{\frac{C_P}{C_V}} \equiv PV^{\gamma} = constant$$

Example 8.2

Question: A centrifugal fan is used to take flue gas at rest at 737 mmHg at 366 K and discharge it at 765 mmHg with a velocity of 45.7 m/s. Calculate the power needed to move 16990 std m^3/h of gas. Use 101.32 kPa and 273 K as the standard conditions. The efficiency of the fan is 65%, and the molecular weight of the gas is 31.3.

Solution:

$$\rho_{in} = \frac{31.3 \times 10^{-3} \times P}{RT} = \frac{0.0313 \times 98260}{8.3145 \times 366} = 1.01\ kg/m^3$$

$$\rho_{out} = \frac{31.3 \times 10^{-3} \times P}{RT} = \frac{0.0313 \times 101990}{8.3145 \times 366} = 1.05\ kg/m^3$$

$$Assume:\ \rho = 1.03\ kg/m^3$$

$$\boxed{G[\cancel{F} + \Delta(\frac{P}{\rho}) + \frac{1}{2}\Delta(\alpha v_{avg}^2) + g\cancel{\Delta z}] = Power\ required}$$

Example 8.2

$$G = \rho_{std}\mathrm{Q} = \frac{P(0.0313)}{RT}Q = \left(\frac{101325 \times 0.0313}{8.3145 \times 273}\right)\left(\frac{16990}{3600}\right) = 6.594\ (\frac{kg}{s})$$

$$Power\ required = G\left[\left(\frac{101990 - 98260}{\rho}\right) + \frac{1}{2}(45.7)^2\right]$$
$$= 30770\ (J/s)$$

$$\frac{33770}{0.65} = 47340\ \left(\frac{J}{s}\right) = 47.34\ kW$$

Scaling laws for pumps/fans (WRF CH14)

Variable	Symbol	Dimensions
Head x g	gh	L^2/t^2
Viscosity	μ	M/Lt
Density	ρ	M/L^3
Flow rate	Q	L^3/t
Shaft speed	ω	$1/t$
Impeller diameter	D	L
Power	W	ML^2/t^3

- Let's choose D, ω, and ρ *as the recurring set:*

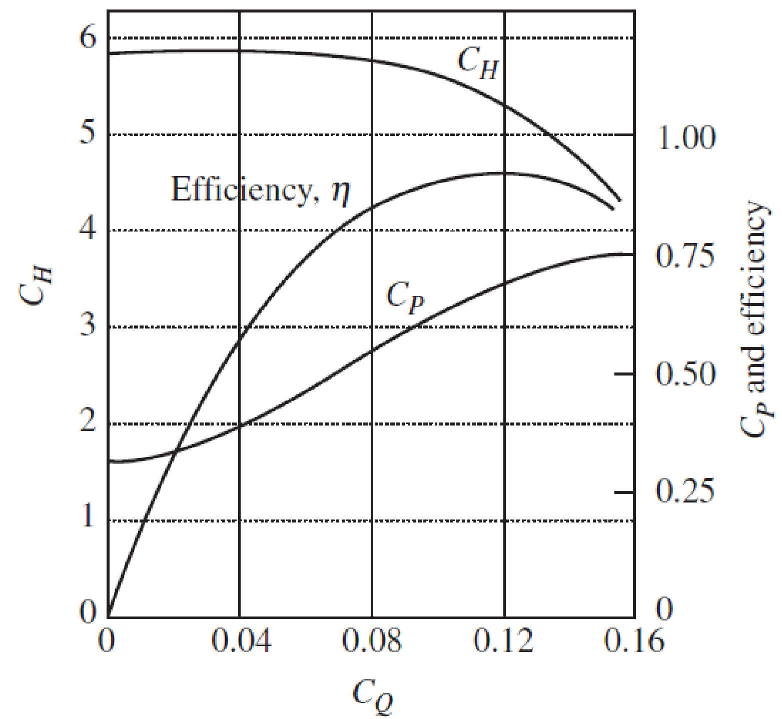
$$\longrightarrow \quad \underline{D1 = \frac{gh}{D^2\omega^2}} \qquad \underline{D2 = \frac{Q}{\omega D^3}} \qquad \underline{D3 = \frac{W}{\rho\omega^3 D^5}} \qquad \boxed{D4 = \frac{\mu}{D^2\omega\rho}}$$

Re^{-1}

Head coefficient (C_H) **Flow coefficient (C_Q)** **Power coefficient (C_P)**

Scaling laws for pumps/fans (WRF CH14)

$$\underline{\eta = \frac{C_H C_Q}{C_P}} = \frac{gh}{D^2\omega^2}\frac{Q}{\omega D^3}\frac{\rho\omega^3 D^5}{W} = \frac{\rho g h Q}{W}$$



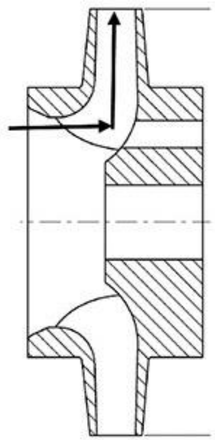
- To scale up the pumps/fans with the same geometry:

$\boxed{C_{H1} = C_{H2}}$ $\boxed{C_{Q1} = C_{Q2}}$ $\boxed{C_{P1} = C_{P2}}$

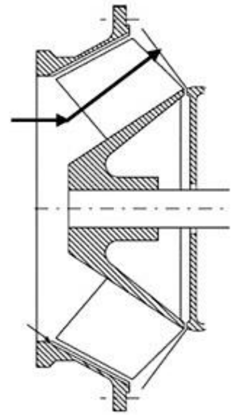
$$\frac{h_1}{D_1^2\omega_1^2} = \frac{h_2}{D_2^2\omega_2^2} \qquad \frac{Q_1}{\omega_1 D_1^3} = \frac{Q_2}{\omega_2 D_2^3} \qquad \frac{W_1}{\rho_1\omega_1^3 D_1^5} = \frac{W_2}{\rho_2\omega_2^3 D_2^5}$$

(See details in Example 3 in section 14.2)

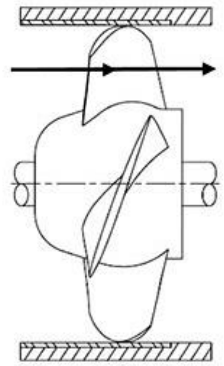
Selection of pumps with maximized efficiency



Centrifugal pump



Mixed-flow pump



Axial pump

$$N_S \equiv \frac{C_Q^{0.5}}{C_H^{0.75}} = \frac{\omega Q^{0.5}}{(gh)^{0.75}}$$

"Specific speed"

- High flow rate & low head

  → Axial pump

- Large head & low flow rate

  → Centrifugal pump