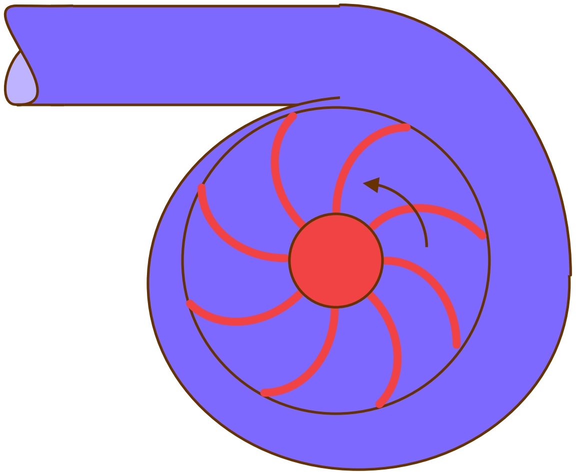
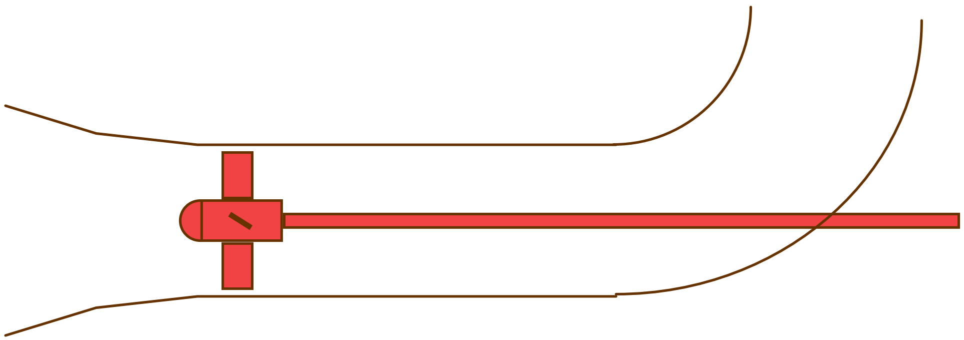
Hydraulic Machinery





Pumps, Turbines...

Hydraulic Machinery Overview

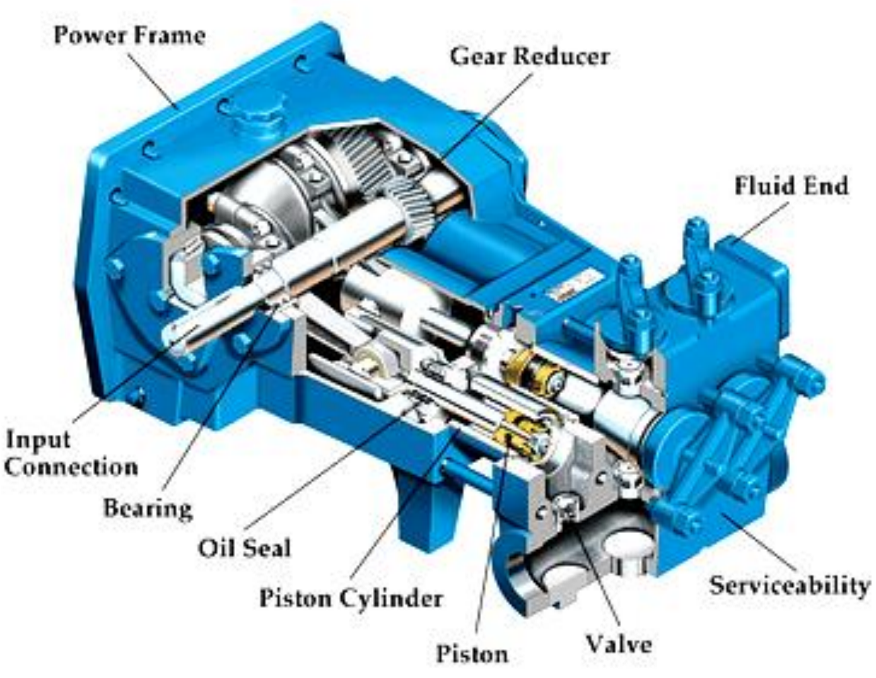
- Types of Pumps
- Dimensionless Parameters for Turbomachines
- Power requirements
- Head-discharge curves
- Pump Issues
  - Cavitation
  - NPSH
  - Priming
- Pump selection

Types of Pumps

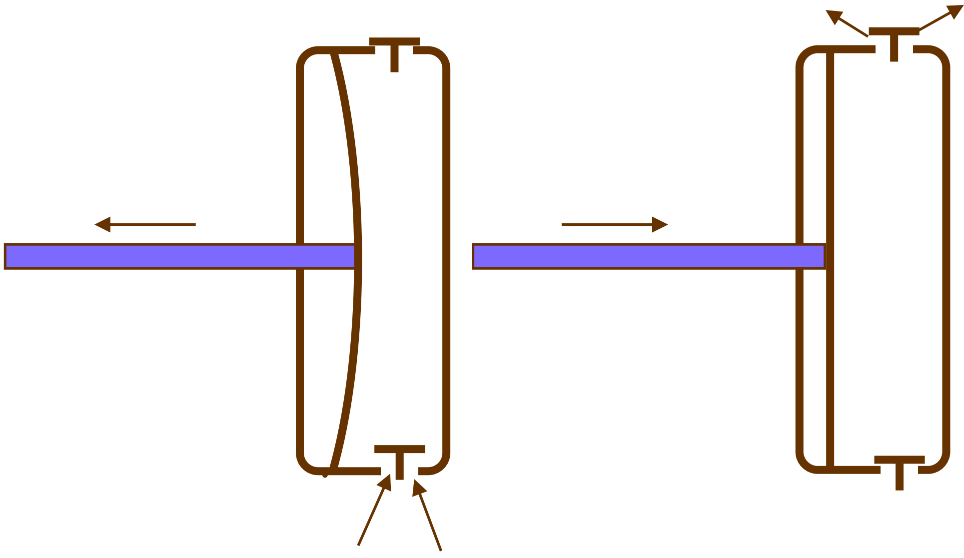
- Positive displacement
  - piston pump
  - Diaphragm pump
  - peristaltic pump
  - Rotary pumps
    - gear pump
    - two-lobe rotary pump
    - screw pump
- Jet pumps
- Turbomachines
  - axial-flow (propeller pump)
  - radial-flow (centrifugal pump)
  - mixed-flow (both axial and radial flow)

Reciprocating action pumps

- Piston pump
  - can produce very high pressures
  - hydraulic fluid pump
  - high pressure water washers

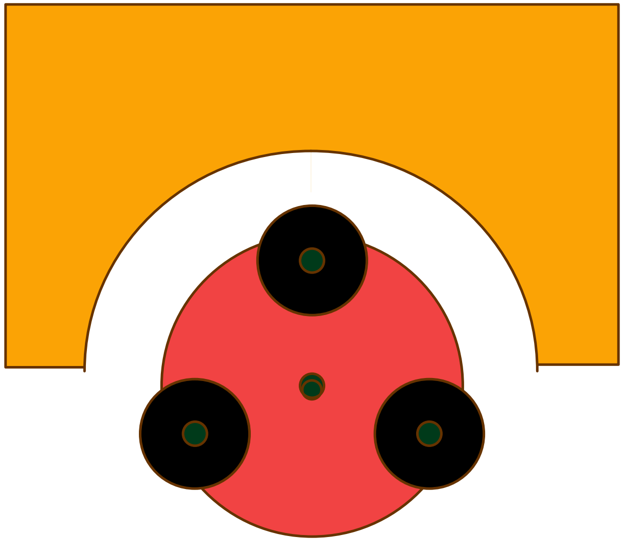


diaphragm pump

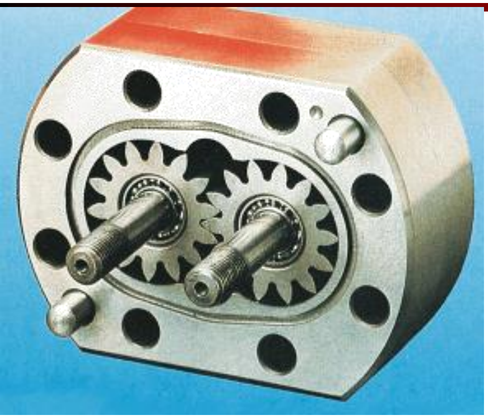


Peristaltic Pump

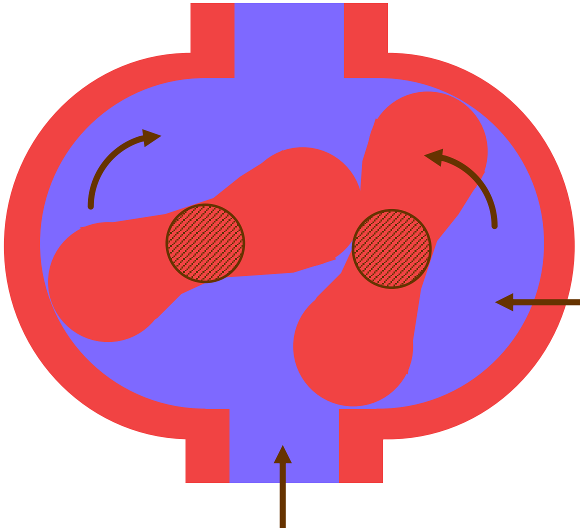
- Fluid only contacts tubing
- Tubing _ID_ and roller _velocity_ with respect to the tubing determine flow rate
- Tubing eventually fails from fatigue and abrasion
- Fluid may leak past roller at high pressures
- Viscous fluids may be pumped more slowly



Rotary Pumps



- Gear Pump
  - fluid is trapped between gear teeth and the housing
- Two-lobe Rotary Pump
  - (gear pump with two “teeth” on each gear)
  - same principle as gear pump
  - fewer chambers - more extreme pulsation



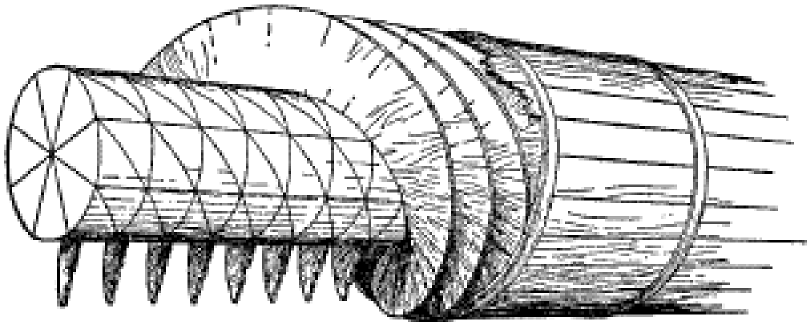
trapped fluid

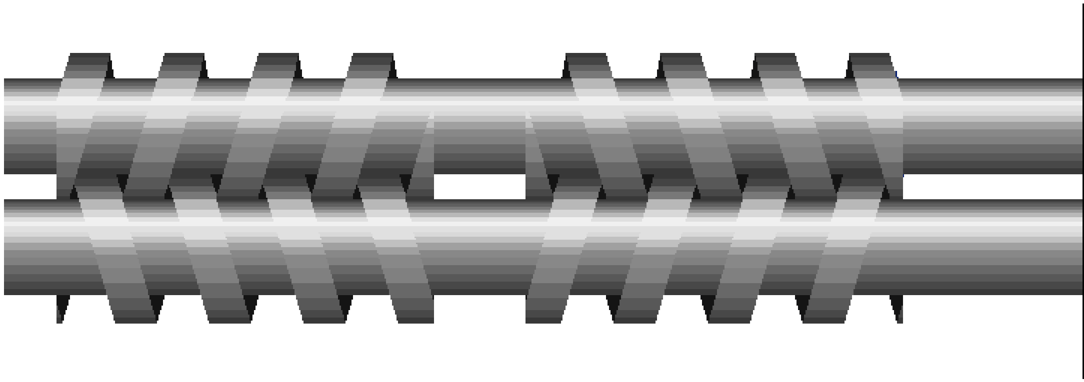
Rotary Pumps

- Disadvantages
  - precise machining
  - abrasives wear surfaces rapidly
  - pulsating output
- Uses
  - vacuum pumps
  - air compressors
  - hydraulic fluid pumps
  - food handling

Screw Pump

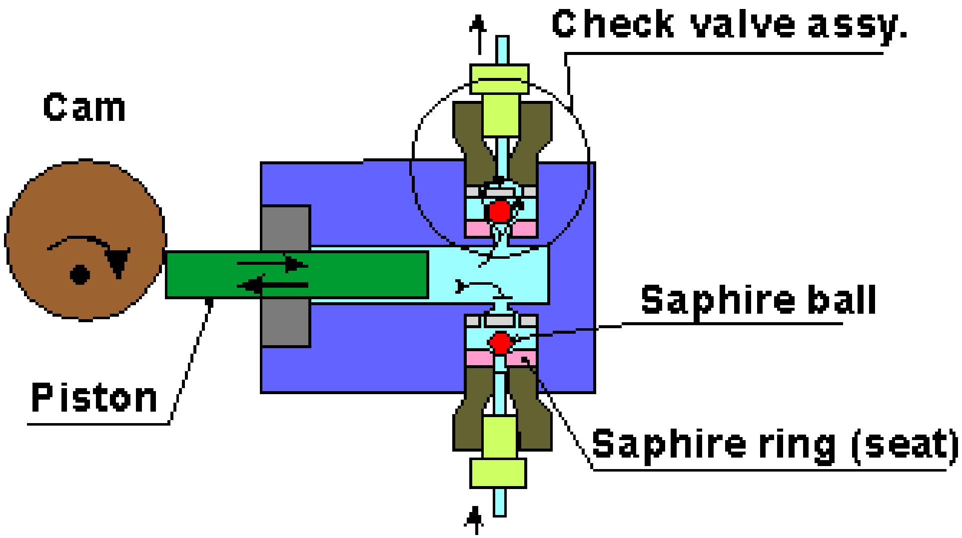
- Can handle debris
- Used to raise the level of wastewater
- Abrasive material will damage the seal between screw and the housing
- Grain augers use the same principle

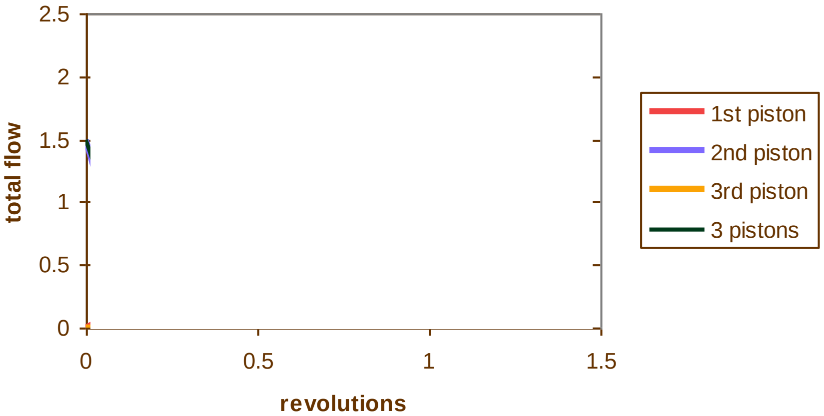




Positive Displacement Pumps

- What happens if you close a valve on the effluent side of a positive displacement pump?
- What does flow rate vs. time look like for a piston pump?





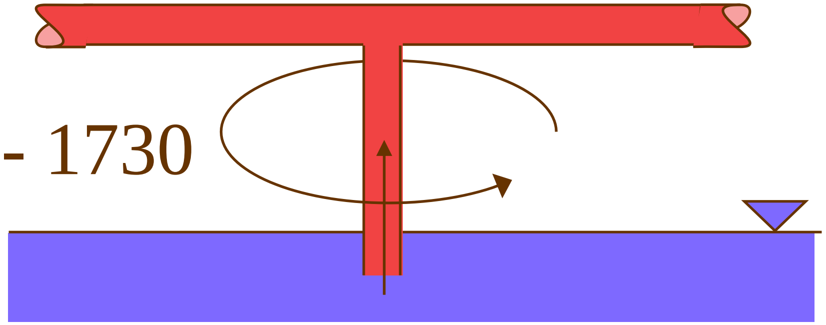
Thirsty Refugees

Jet Pump
“eductor”

- A high pressure, high velocity jet discharge is used to pump a larger volume of fluid.
- Advantages
  - no moving parts
  - self priming
  - handles solids easily
- Disadvantage
  - inefficient
- Uses
  - deep well pumping
  - pumping water mixed with solids

http://spaceflight.nasa.gov/shuttle/upgrades/ojp.html

Turbomachines



- Demour's centrifugal pump - 1730
- Theory
  - conservation of angular momentum
  - conversion of kinetic energy to potential energy in flow expansion _(inefficient process)_
- Pump components
  - rotating element - _impeller_
  - encloses the rotating element and seals the pressurized liquid inside - _casing_ or _housing_

$$T_z = \rho Q\left[\left(r_2 V_{t_2}\right) - \left(r_1 V_{t_1}\right)\right]$$

Pressure Developed by Centrifugal Pumps

- Centrifugal pumps accelerate a liquid
- The maximum velocity reached is the velocity of the periphery of the impeller
- The kinetic energy is converted into potential energy as the fluid leaves the pump
- The potential energy developed is approximately equal to the velocity head at the periphery of the impeller

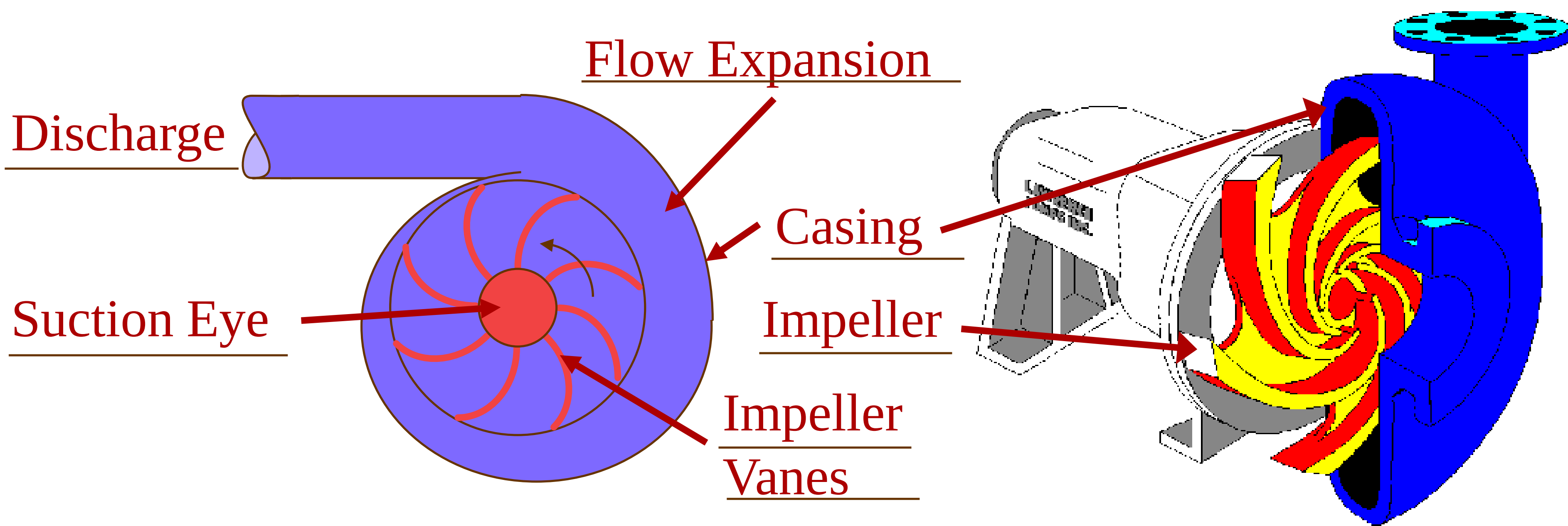
$$h_p = \frac{V^2}{2g}$$

- A given pump with a given impeller diameter and speed will raise a fluid to a certain height regardless of the fluid density

Radial Pumps

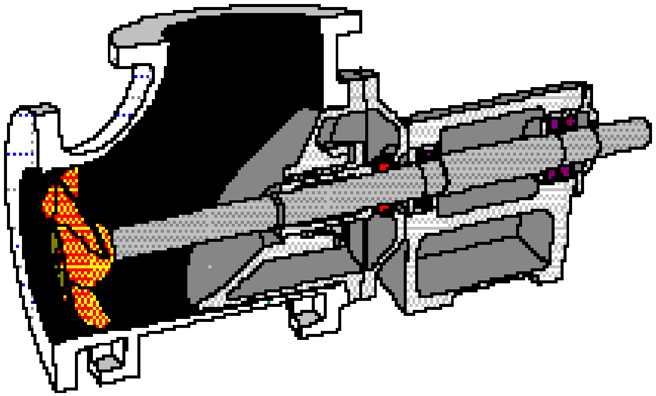
- also called _centrifugal_ pumps
- broad range of applicable flows and heads
- higher heads can be achieved by increasing the diameter or the _rotational speed_ of the impeller

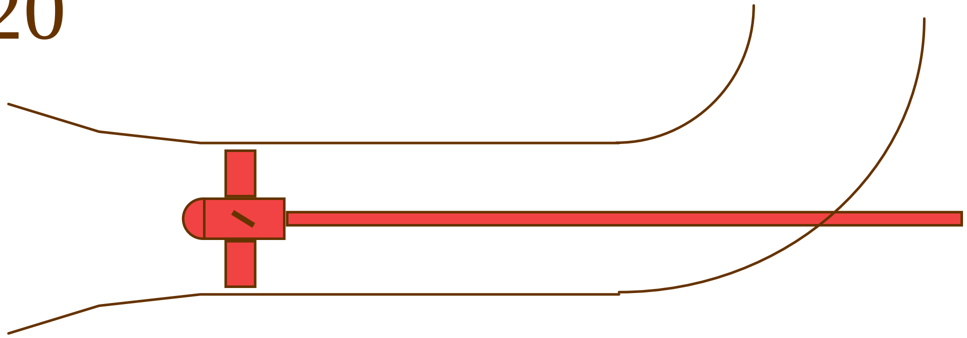
$$h_p = \frac{V^2}{2g}$$



Axial Flow

- also known as propeller______ pumps
- low head (less than 12 m)
- high flows (above 20 L/s)





Dimensionless Parameters for Turbomachines

- We would like to be able to compare pumps with similar geometry. Dimensional analysis to the rescue...
- To use the laws of similitude to compare performance of two pumps we need
  - exact geometric similitude
    - all linear dimensions must be scaled identically
    - roughness must scale
    - homologous - streamlines are similar → same $\frac{Q}{\omega D^3}$
  - constant ratio of dynamic pressures at corresponding points
    - also known as kinematic similitude

Kinematic Similitude: Constant Force Ratio

- Reynolds $\frac{VD\rho}{\mu}$
  - ratio of inertial to viscous forces
- Froude $\frac{V^2}{gl}$ $\frac{V}{\sqrt{gl}}$
  - ratio of inertial to gravity force
- Weber $\frac{V^2 l\rho}{\sigma}$
  - ratio of inertial to surface-tension forces
- Mach $\frac{V}{c}$
  - ratio of inertial to elastic forces

Turbomachinery Parameters

$$C_p = f\left(Re, \cancel{F}, \cancel{W}, \cancel{M}, \frac{D_{flow}}{D_{impeller}}, \frac{\varepsilon}{D_{flow}}, \frac{Q}{\omega D_{flow}^3} \right)$$

Where is the fluid?

$$C_p = \frac{-2\Delta p}{\rho V^2} \qquad C_H = \frac{h_p g}{V^2} \qquad V = \omega D_{impeller} \qquad C_H = \frac{h_p g}{\omega^2 D_{impeller}^2}$$

head, shape, roughness, discharge

$$\frac{h_p g}{\omega^2 D_{impeller}^2} = C_H = f\left(Re, \frac{D_{flow}}{D_{impeller}}, \frac{\varepsilon}{D_{flow}}, \frac{Q}{\omega D_{flow}^3} \right)$$

flow → impeller

(Impeller is better defined)

Shape Factor

- Related to the ratio of flow passage diameter to impeller diameter
- Defined for the point of best efficiency
- What determines the ideal shape for a pump?

$$S = f(\omega, Q, \Delta p, \rho)$$

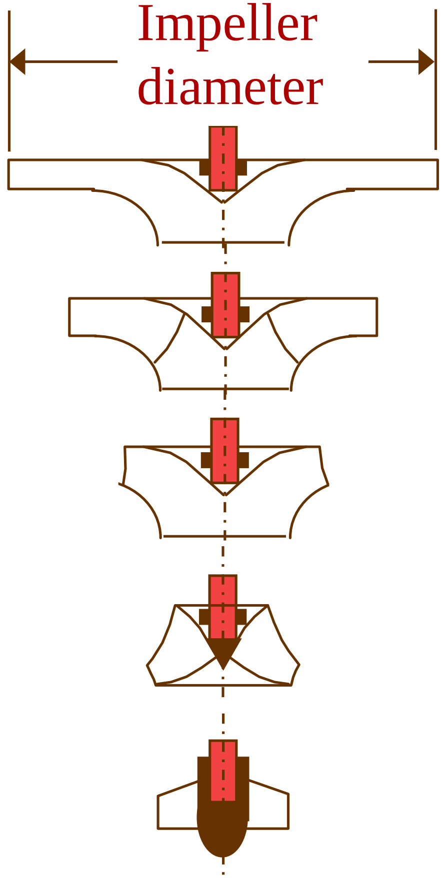
Exercise

Impeller Geometry: Shape Factor

$$N_{sp} = \frac{N\sqrt{Q}}{\left(h_p\right)^{3/4}}^{*}$$

$$S = \frac{w\sqrt{Q}}{\left(gh_p\right)^{3/4}}$$

N	S	
500	0.18	Radial: high pressure, low flow
1000	0.37	radial
3400	1.25	mixed
6400	2.33	mixed
10000	3.67	axial: high flow, low pressure



*N in rpm, Q in gpm, H in ft

$N_{sp} = 2732S$

Use of Shape Factor: Specific Speed

$$S = \frac{w\sqrt{Q}}{\left(gh_p\right)^{3/4}}$$

- The maximum efficiencies for all pumps occurs when the Shape Factor is close to 1!
  - Flow passage dimension is close to impeller diameter!
  - Low expansion losses!
- There must be an optimal shape factor given a discharge and a head.
- Shape factor defined for specific cases
  - Double suction
    - Treat like two pumps in parallel
  - Multistage (pumps in series)
    - Use Q and H for each stage

Why multistage?

Additional Dimensionless Parameters

$$C_H = \frac{h_p g}{w^2 D^2}$$

D is the impeller diameter

$$C_Q = \frac{Q}{\omega D^3}$$

$$P_w = gQh_p$$

$$C_P = \frac{P}{\rho \omega^3 D^5}$$

P is the power

$$S = \frac{C_Q^{1/2}}{C_H^{3/4}}$$

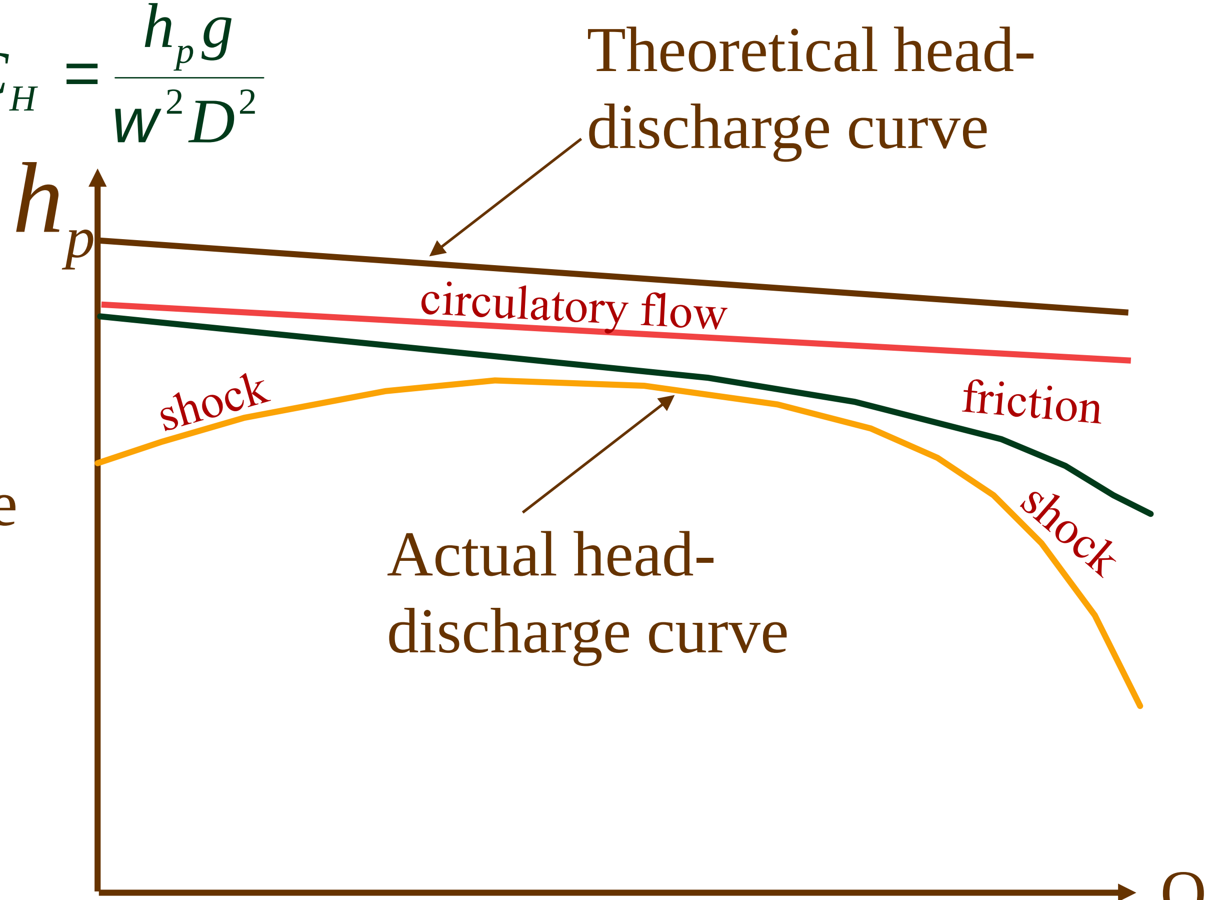
Alternate equivalent way to calculate S.

(defined at max efficiency)

Head-Discharge Curve

- circulatory flow - inability of finite number of blades to guide flow
- friction - $\underline{\quad V^2}$
- shock - incorrect angle of blade inlet $\underline{\quad \Delta V^2}$
- other losses
  - bearing friction
  - packing friction
  - disk friction
  - internal leakage

$$C_H = \frac{h_p g}{w^2 D^2}$$



$$C_Q = \frac{Q}{\omega D^3}$$

Pump Power Requirements

$$P_w = gQh_p$$

Water power

$$e_P = \frac{P_w}{P_s}$$

$$e_m = \frac{P_s}{P_m}$$

$$P_m = \frac{gQh_p}{e_P e_m}$$

Subscripts

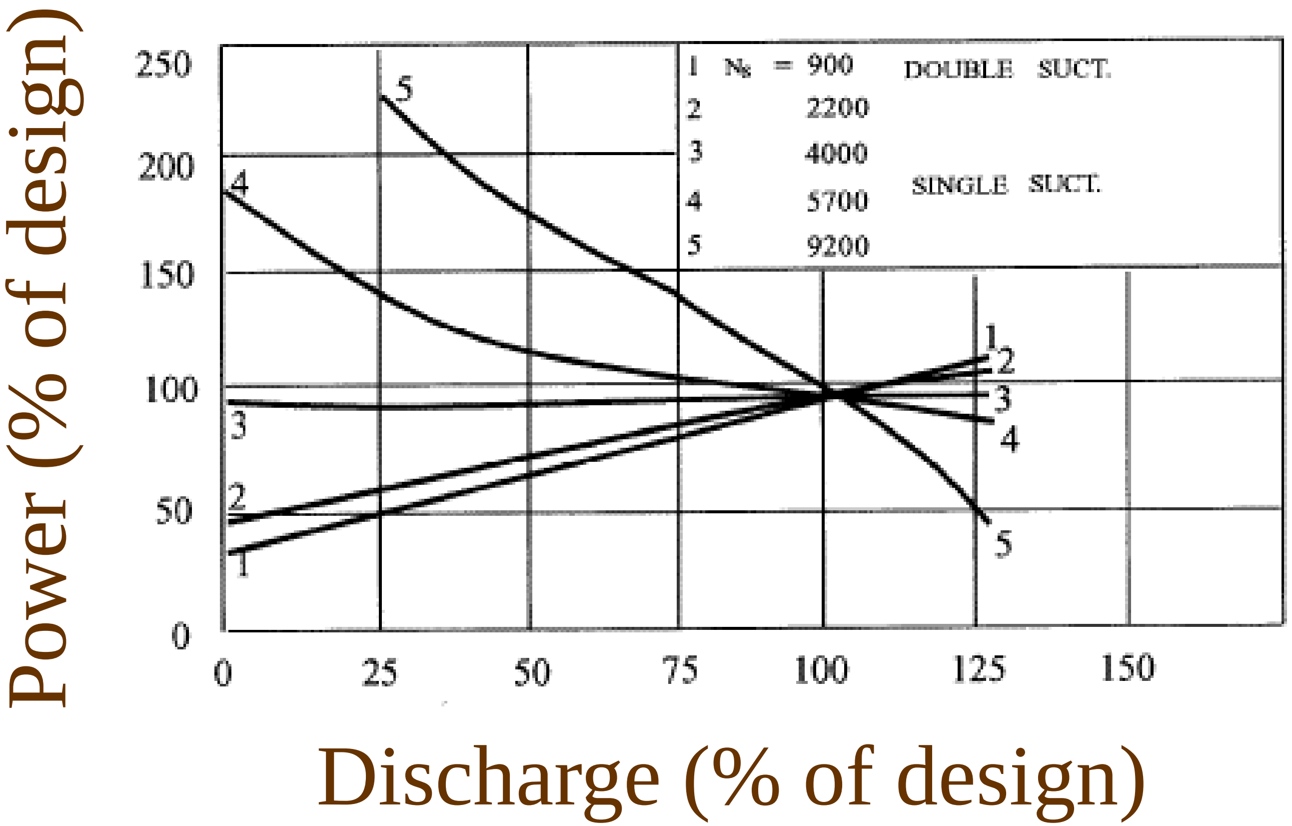
w = water

p = pump

s = shaft

m = motor

Impeller Shape vs. Power Curves



	S
radial	1 - O.33
	2 - 0.81
	3 - 1.5
	4 - 2.1
axial	5 - 3.4

http://www.mcnallyinstitute.com/

Implications

Affinity Laws

homologous

$C_Q =$ held constant

- With diameter, D, held constant:

$$P = \gamma Q \Delta H$$

$$C_Q = \frac{Q}{\omega D^3} \quad\quad C_H = \frac{h_p g}{w^2 D^2} \quad\quad C_P = \frac{P}{\rho \omega^3 D^5}$$

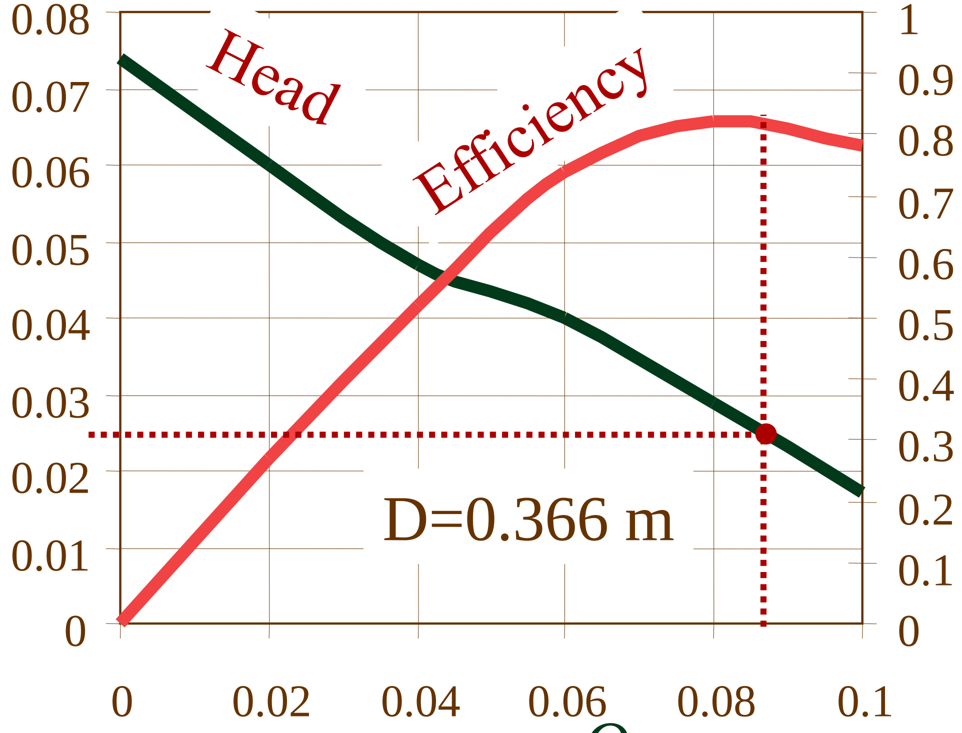
$$\frac{Q_1}{Q_2} = \frac{\omega_1}{\omega_2} \quad\quad \frac{h_{p1}}{h_{p2}} = \left(\frac{w_1}{w_2}\right)^2 \quad\quad \frac{P_1}{P_2} = \left(\frac{\omega_1}{\omega_2}\right)^3$$

- With speed, ω, held constant:

$$\frac{Q_1}{Q_2} = \left(\frac{D_1}{D_2}\right)^3 \quad\quad \frac{h_{p1}}{h_{p2}} = \left(\frac{D_1}{D_2}\right)^2 \quad\quad \frac{P_1}{P_2} = \left(\frac{D_1}{D_2}\right)^5$$

Dimensionless Performance Curves

$$C_H = \frac{h_p g}{w^2 D^2}$$



Efficiency

$$C_Q = \frac{Q}{\omega D^3}$$

shape

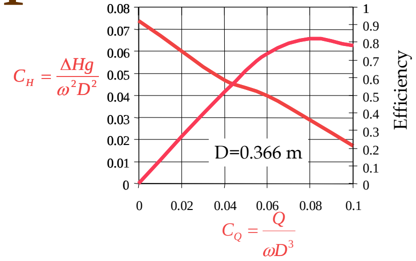
$$S = \frac{C_Q^{1/2}}{C_H^{3/4}} \quad \frac{(0.087)^{0.5}}{(0.026)^{0.75}} = 4.57$$

(defined at max efficiency)

- Curves for a particular pump
- Independent of the fluid!

Pump Example

- Given a pump with shape factor of 4.57, a diameter of 366 mm, a 2-m head, a speed of 600 rpm, and dimensionless performance curves (previous slide).

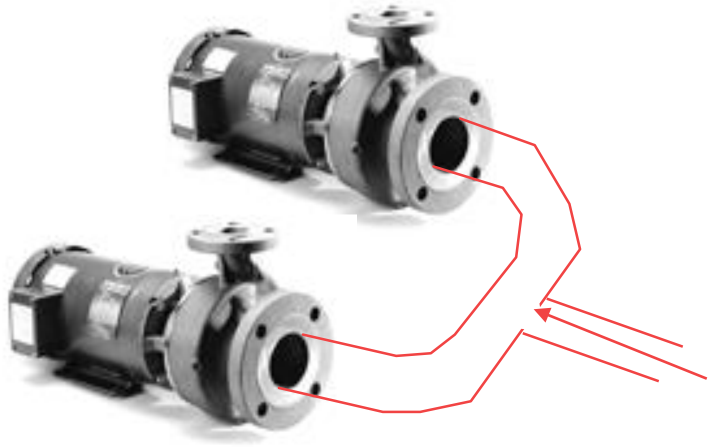


- What will the discharge be?
- How large a motor will be needed if motor efficiency is 95%?

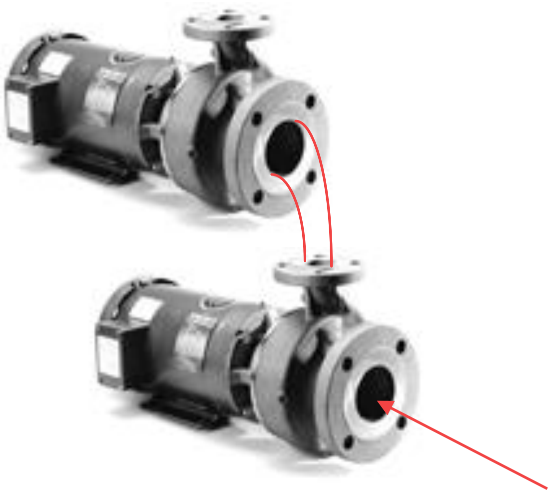
Exercise

Pumps in Parallel or in Series

- Parallel
  - Flow ___adds___
  - Head ___same___



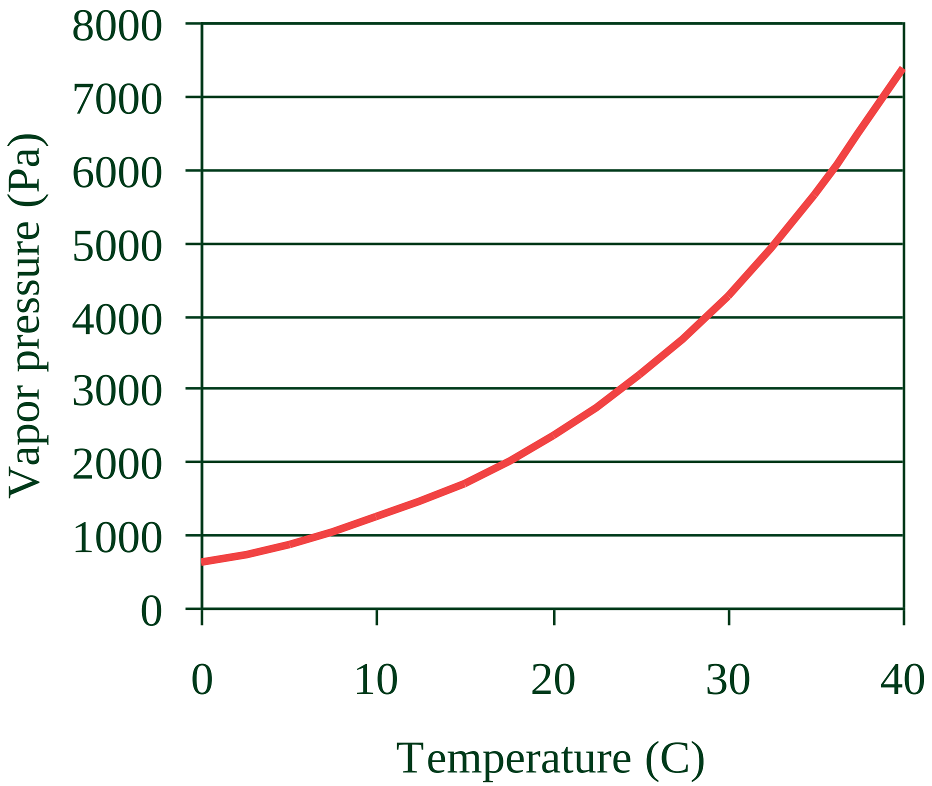
- Series
  - Flow ___same___
  - Head ___adds___



- Multistage

Cavitation in Water Pumps

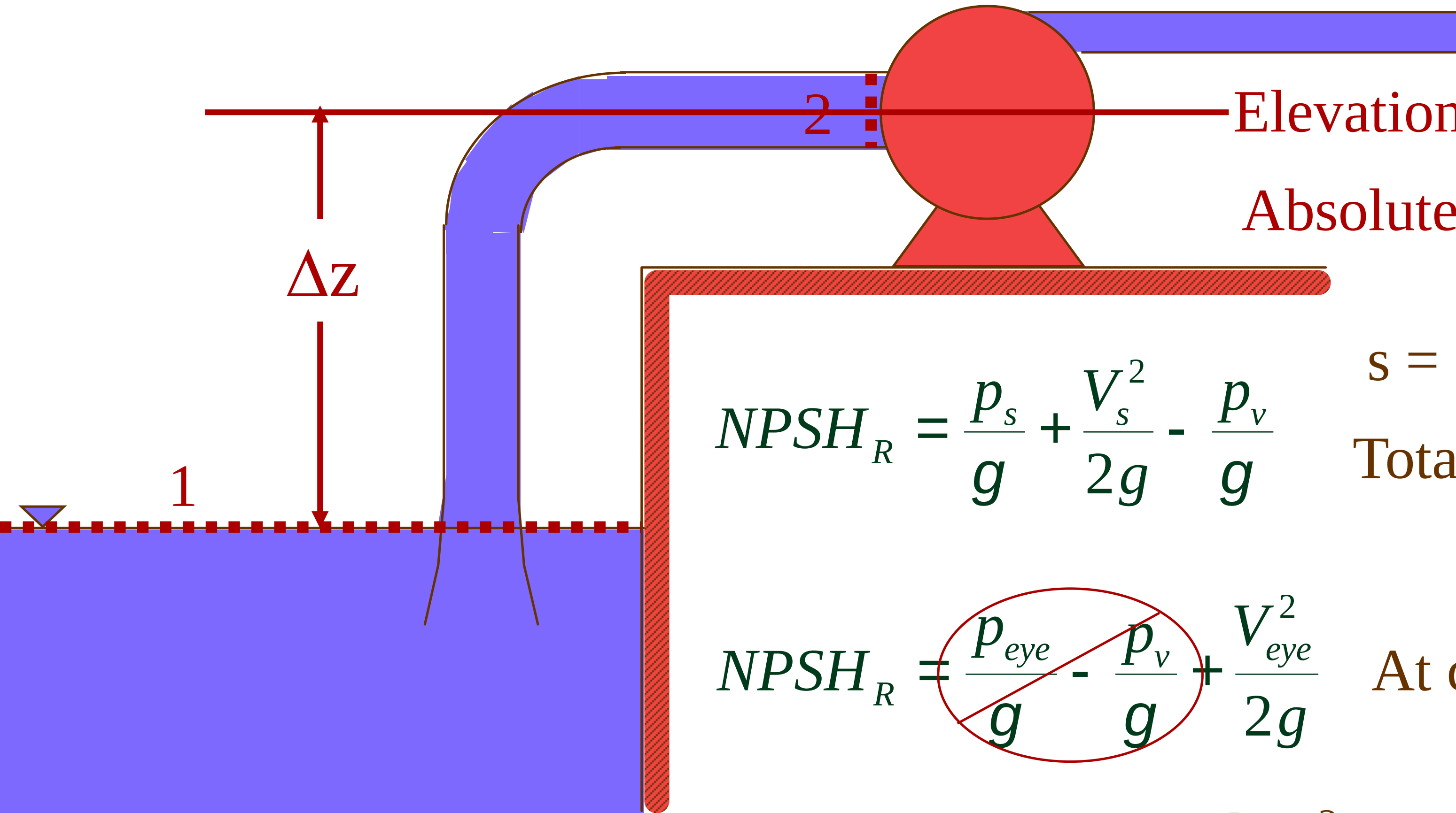
- water vapor bubbles form when the pressure is less than the vapor pressure of water
- very high pressures (800 MPa or 115,000 psi) develop when the vapor bubbles collapse



Net Positive Suction Head

- $NPSH_R$ - absolute pressure in excess of vapor pressure **required** at pump inlet to prevent cavitation
  - given by pump manufacturer
  - determined by the water velocity at the entrance to the pump impeller
- $NPSH_A$ - pressure in excess of vapor pressure **available** at pump inlet
  - determined by pump installation (elevation above reservoir, frictional losses, water temperature)
- If $NPSH_A$ is less than $NPSH_R$ cavitation will occur

Net Positive Suction Head



Absolute pressure

$$NPSH_R = \frac{p_s}{g} + \frac{V_s^2}{2g} - \frac{p_v}{g}$$

s = suction

Total head $-p_v$!

$$NPSH_R = \frac{p_{eye}}{g} - \frac{p_v}{g} + \frac{V_{eye}^2}{2g}$$

At cavitation!

$NPSH_R$ increases with Q^2!

How much total head in excess of vapor pressure is available?

NPSH$_A$

$$\frac{p_1}{\gamma} + \cancel{\frac{V_1^2}{2g}} + z_1 = \frac{p_2}{\gamma} + \frac{V_2^2}{2g} + \cancel{z_2} + h_L$$

$$\frac{p_{atm}}{\gamma} + z_{reservoir} = \frac{p_s}{\gamma} + \frac{V_s^2}{2g} + h_L$$

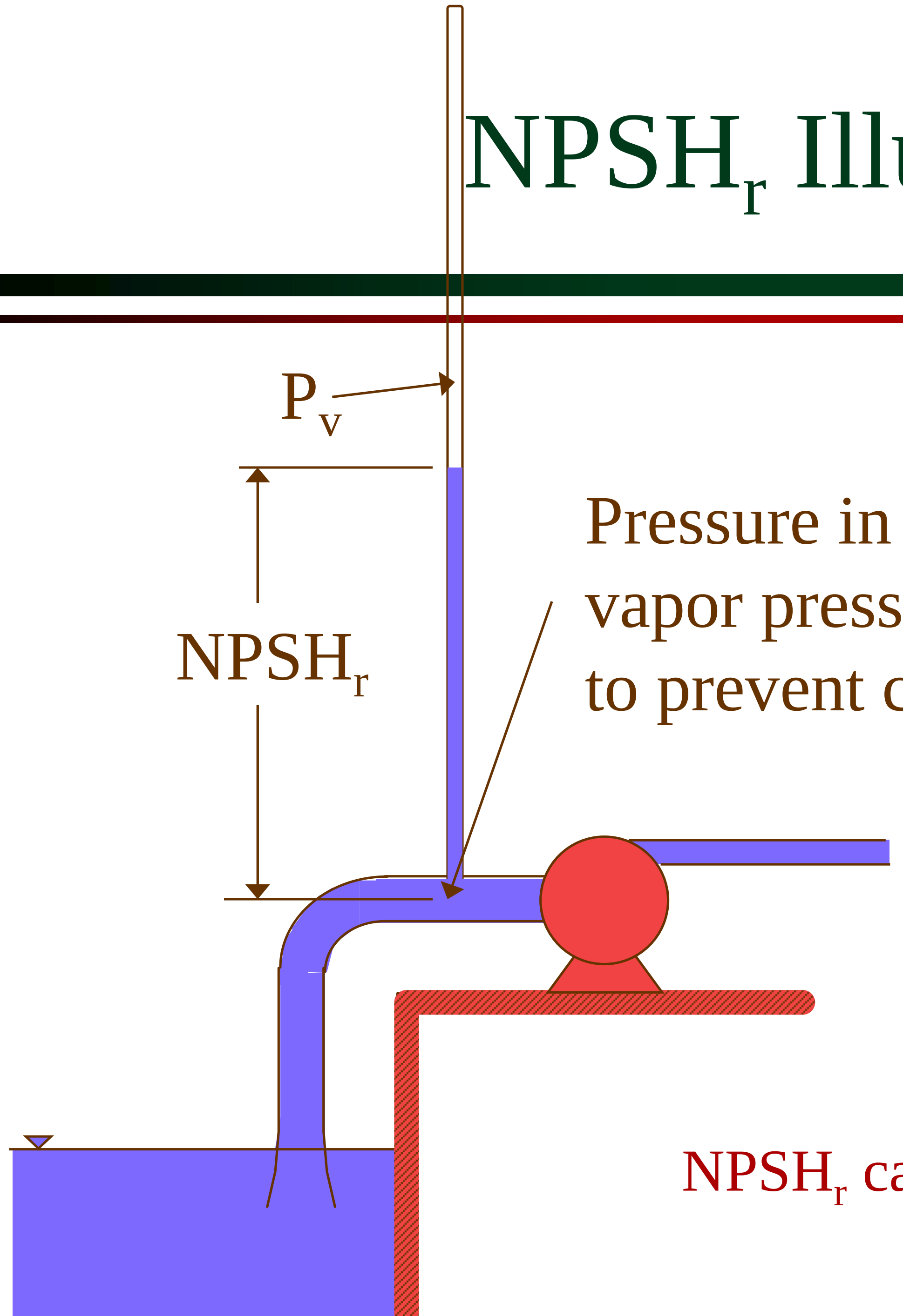
$$\frac{p_{atm}}{\gamma} - \Delta z - h_L = \frac{p_s}{\gamma} + \frac{V_s^2}{2g}$$

$$\frac{p_{atm}}{\gamma} - \Delta z - h_L - \frac{p_v}{\gamma} = \frac{p_s}{\gamma} + \frac{V_s^2}{2g} - \frac{p_v}{\gamma}$$

Subtract vapor pressure

$$\frac{p_{atm}}{\gamma} - \Delta z - h_L - \frac{p_v}{\gamma} = NPSH_A$$

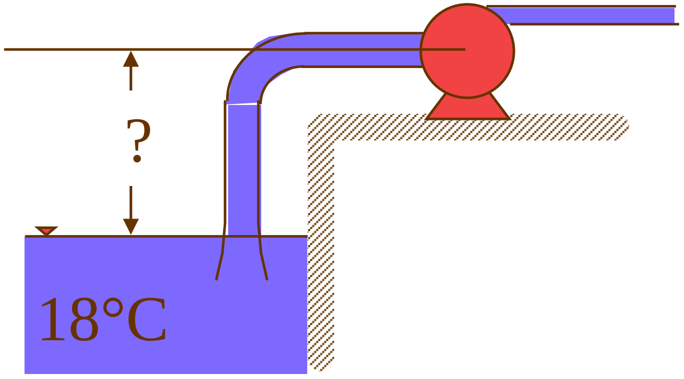
$NPSH_r$ Illustrated



$NPSH_r$ can exceed atmospheric pressure!

NPSH problem

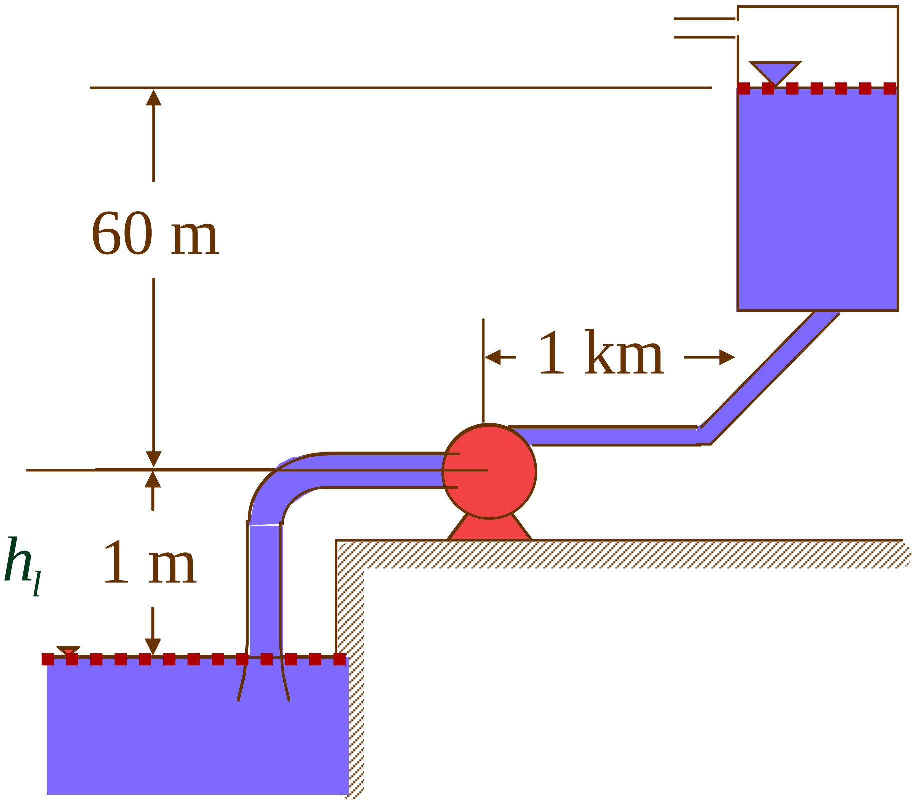
Determine the minimum reservoir level relative to the pump centerline that will be acceptable. The $NPSH_r$ for the pump is 2.5 m. Assume you have applied the energy equation and found a head loss of 0.5 m.



Exercise

Pumps in Pipe Systems

Pipe diameter is 0.4 m and friction factor is 0.015. What is the pump discharge?

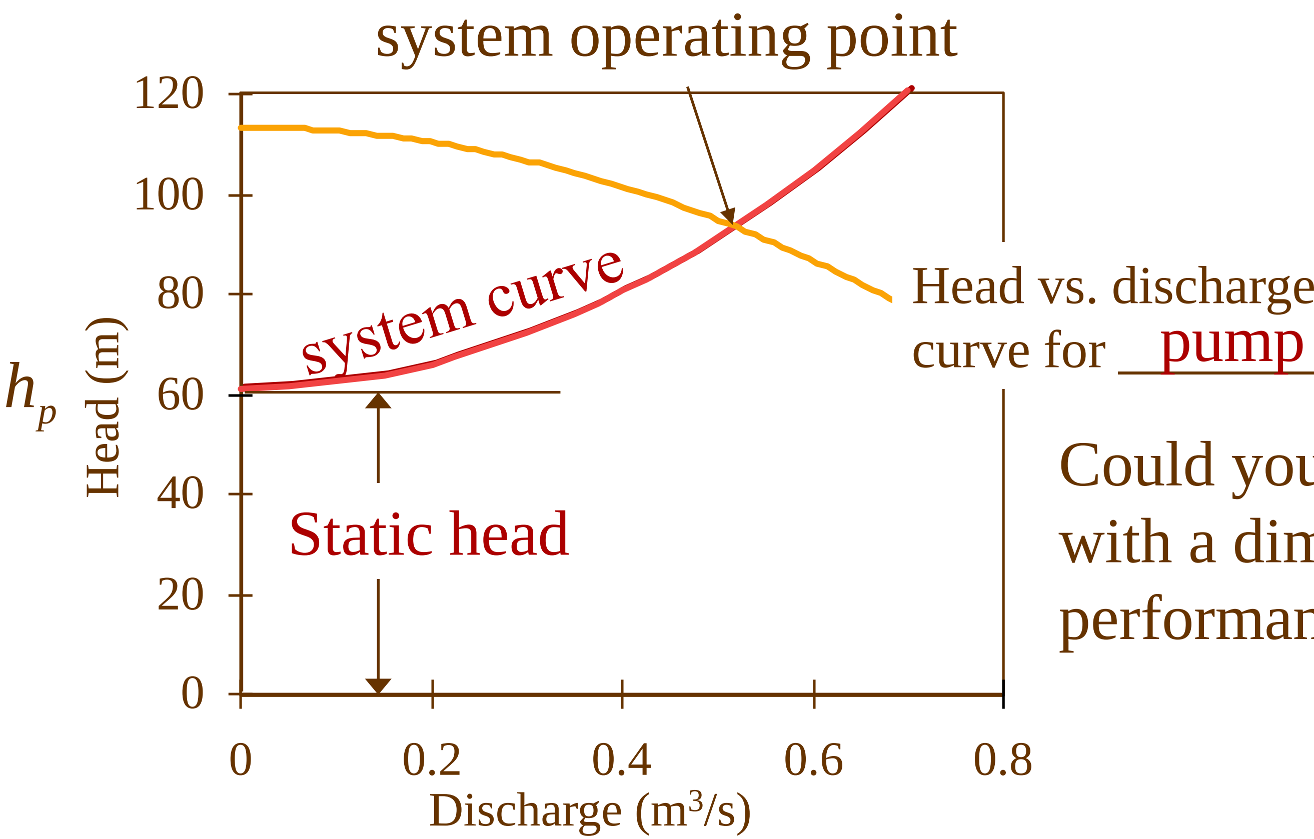


$$\frac{p_1}{\gamma} + \frac{V_1^2}{2g} + z_1 + h_p = \frac{p_2}{\gamma} + \frac{V_2^2}{2g} + z_2 + h_l$$

$$h_p = z_2 - z_1 + h_l$$

$h_p = f(Q)$ often expressed as $h_p = a - bQ^2$

Pumps in Pipe Systems



Could you solve this with a dimensionless performance curve?

$$C_H = \frac{h_p g}{w^2 D^2}$$

What happens as the static head changes (a tank fills)?

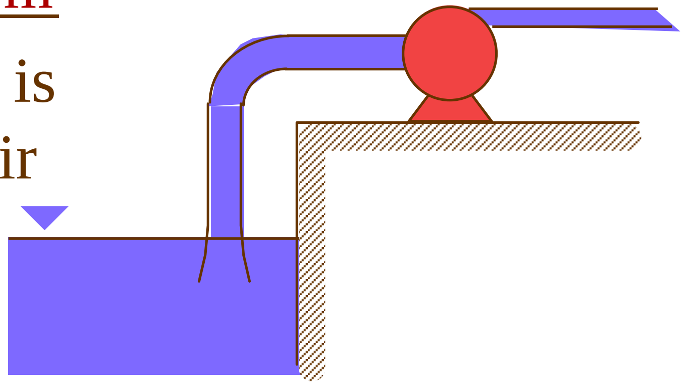
Priming

- The pressure increase created is proportional to the _density_ of the fluid being pumped.
- A pump designed for water will be unable to produce much pressure increase when pumping air
  - Density of air at sea level is _1.225 kg/m³_
  - Change in pressure produced by pump is about 0.1% of design when pumping air rather than water!

$$C_H = \frac{h_p g}{w^2 D^2}$$

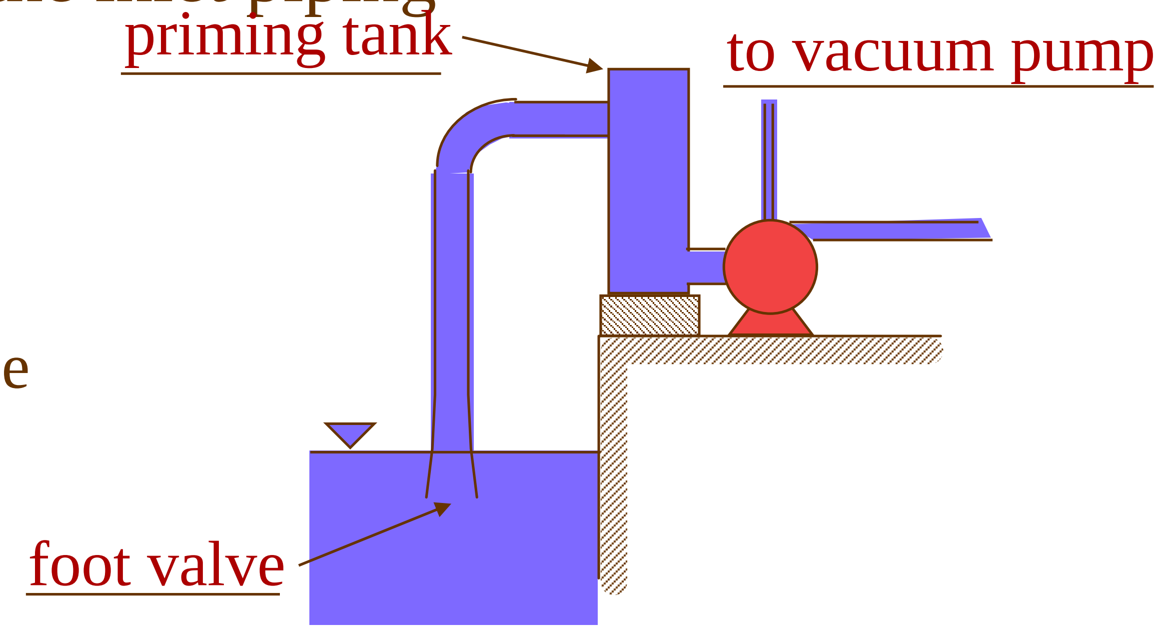
$$C_H = \frac{\Delta p}{\rho \omega^2 D^2}$$

$$\Delta p = C_H \rho \omega^2 D^2$$



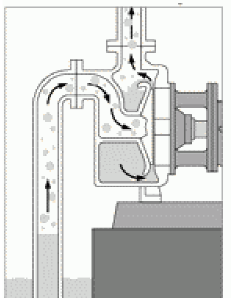
Priming Solutions

- Applications with water at less than atmospheric pressure on the suction side of the pump require a method to remove the air from the pump and the inlet piping
- Solutions
  - foot valve
  - priming tank
  - vacuum source
  - self priming



Self-Priming Centrifugal Pumps

- Require a small volume of liquid in the pump
- Recirculate this liquid and entrain air from the suction side of the pump
- The entrained air is separated from the liquid and discharged in the pressure side of the pump



Variable Flows?

- How can you obtain a wide range of flows?
  - **Valve**
  - **Multiple pumps (same size)**
  - **Multiple pumps (different sizes)**
  - **Variable speed motor**
  - **Storage tank**
- Why is the flow from two identical pumps usually less than the 2x the flow from one pump?

RPM for Pumps

- 60 cycle
- Other options
  - variable speed
  - belt drive

number of poles	sync	full load	rad/sec
2	3600	3500	367
4	1800	1750	183
6	1200	1167	122
8	900	875	92
10	720	700	73
12	600	583	61
14	514	500	52
16	450	438	46
18	400	389	41
20	360	350	37
22	327	318	33
24	300	292	31
26	277	269	28
28	257	250	26
30	240	233	24

Estimate of Pump rpm

- The best efficiency is obtained when S=1
- Given a desired flow and head the approximate pump rpm can be estimated!

$$S = \frac{w\sqrt{Q}}{\left(gh_p\right)^{3/4}} \qquad w \approx \frac{\left(gh_p\right)^{3/4}}{\sqrt{Q}}$$

Pump for flume in DeFrees Teaching Lab…

$Q = 0.1\ m^3/s$, $h_p = 4$ m.

Therefore $\omega = 50$ rads/s = 470 rpm

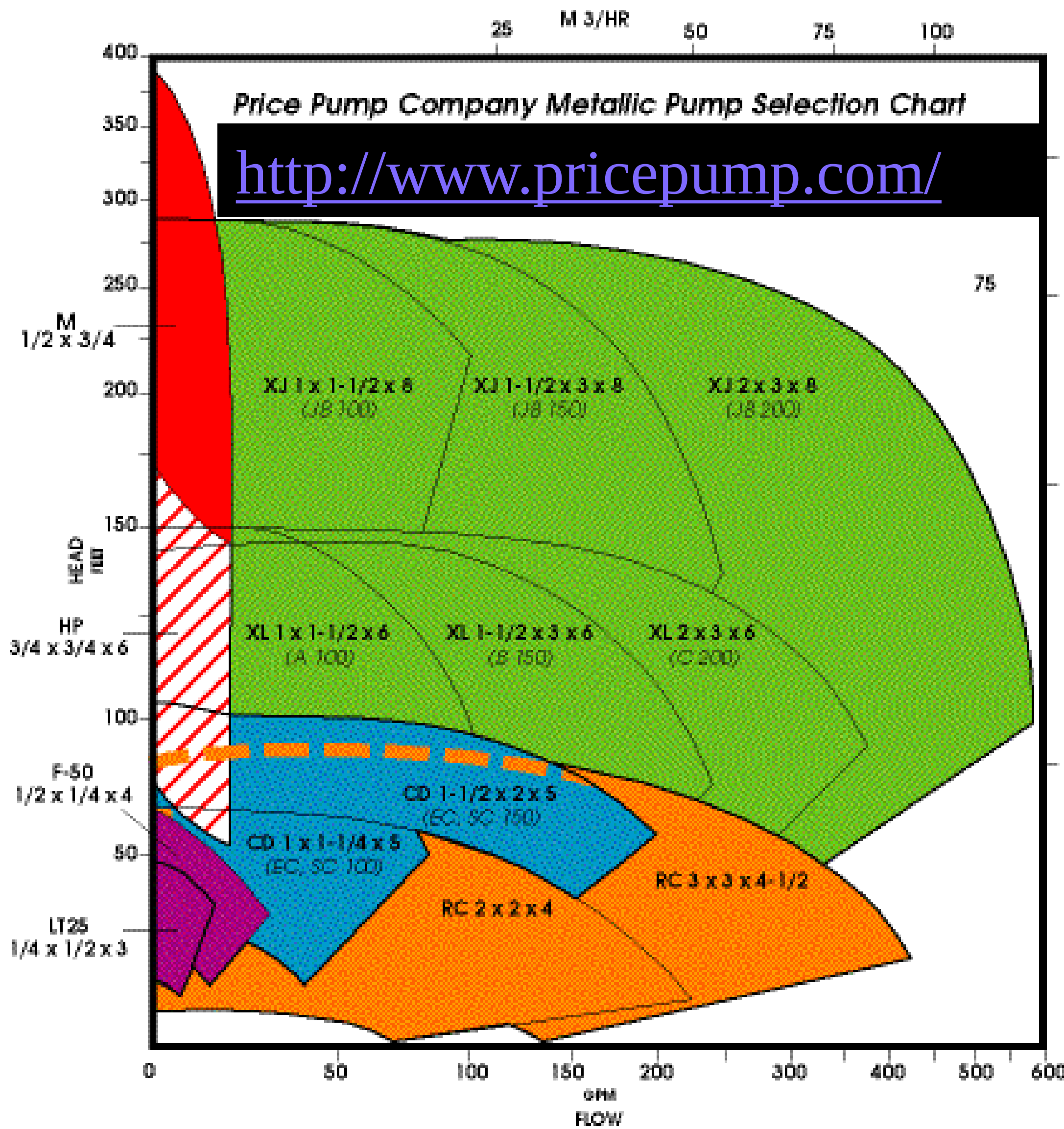
Actual maximum rpm is 600!

Pump Selection

- Material Compatibility
- Solids
- Flow
- Head
- $NPSH_a$
- Pump Selection software
- A finite number of pumps will come close to meeting the specifications!

Pump Selection Chart

Model M



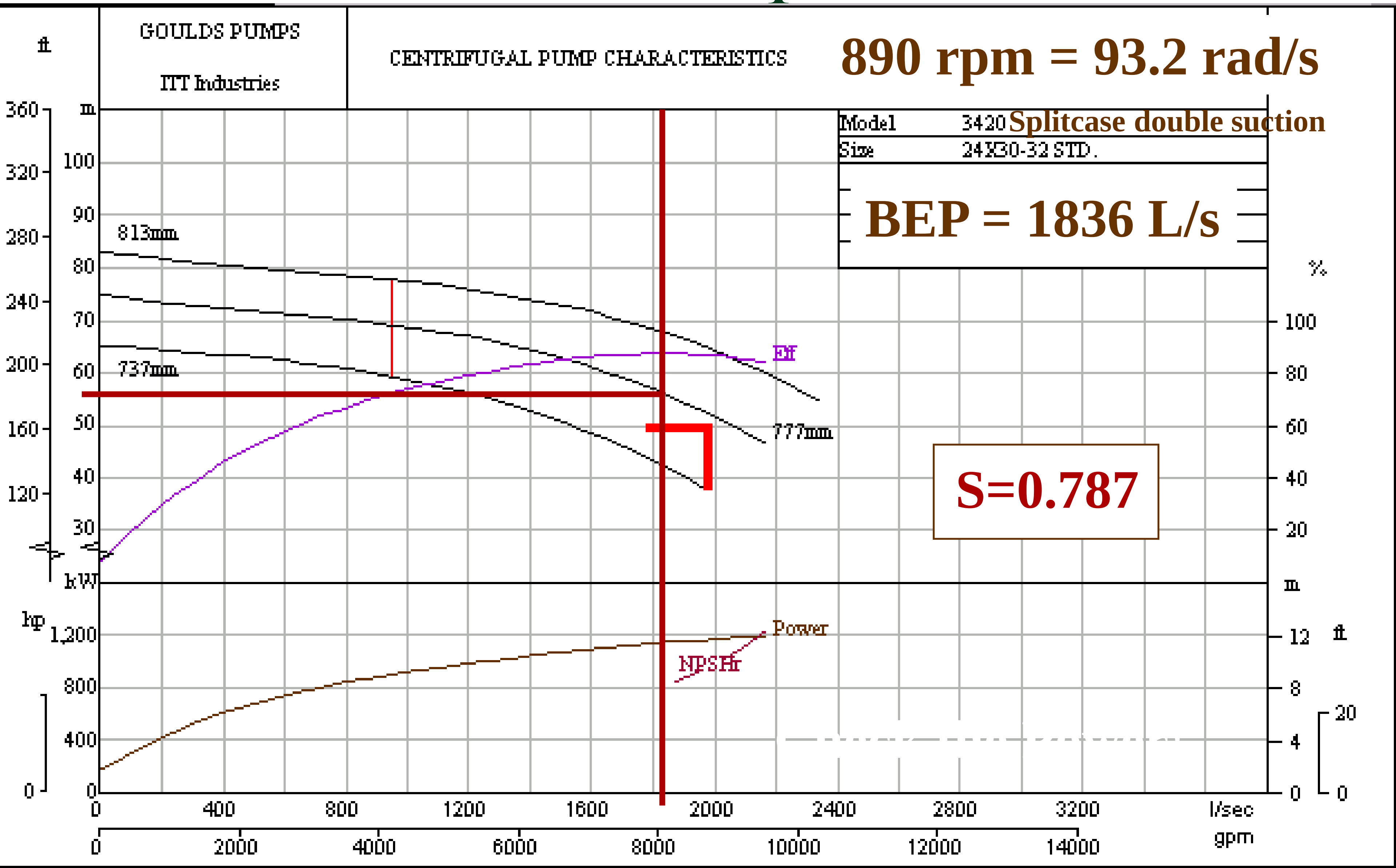
Model X

End of Curve Operation

- Right of the BEP (Best Efficiency Point)
  - is sufficient NPSH available for the pump to operate properly?
  - fluid velocities through the suction and discharge nozzles of the pump could be extremely high, resulting in increased pump and system noise (and wear)
- Left of BEP operation
  - high thrust loads on the pump bearings and mechanical face seals result in premature failure.
  - The pump is oversized, resulting in lower efficiency and higher operating and capital costs.

Gould's Pump Curves

$$S = \frac{w\sqrt{Q}}{\left(gh_p\right)^{3/4}}$$



Pump Installation Design

- Why not use one big pump?
- Can the system handle a power failure?
- Can the pump be shut down for maintenance?
- How is the pump primed?
- Are there enough valves so the pump can be removed for service without disabling the system?

Pump Summary

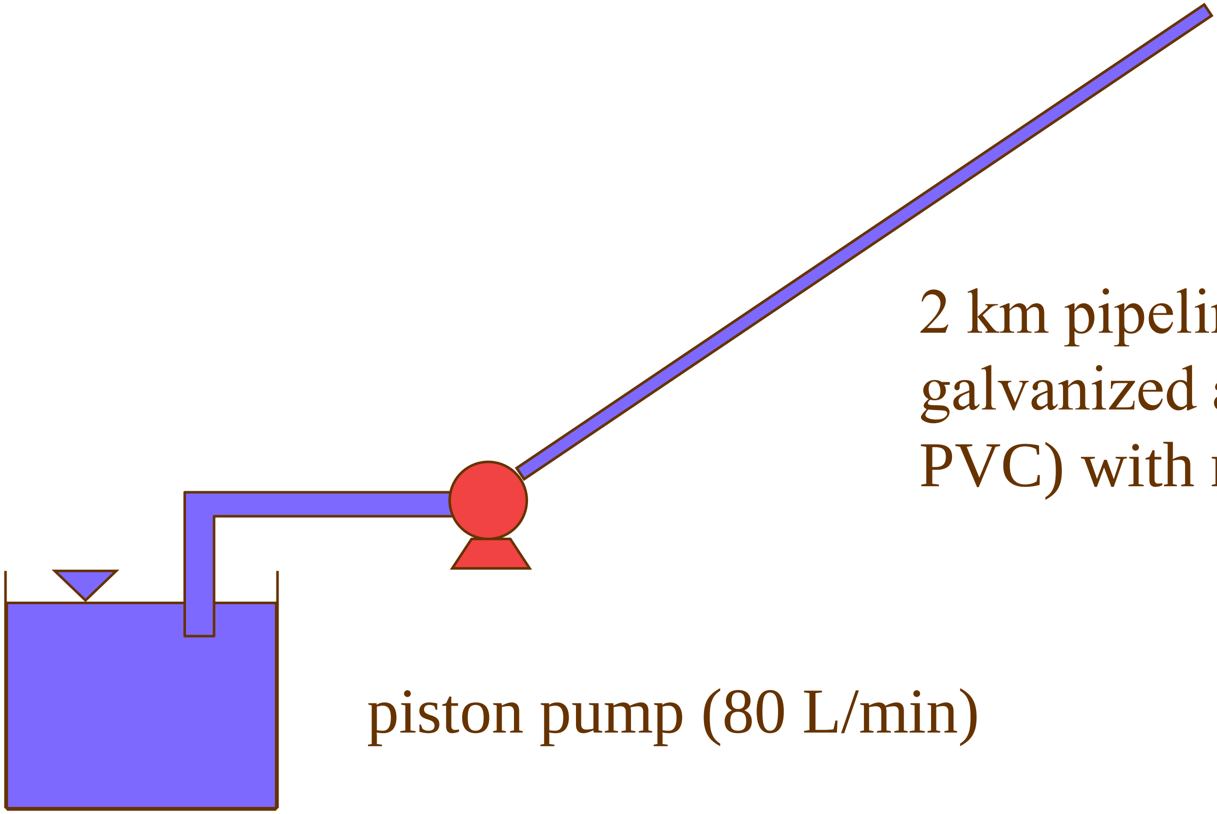
- Positive displacement vs. turbomachines
- Dimensional analysis
  - Useful for scaling
  - Useful for characterizing full range of pump performance from relatively few data points
- Turbomachines convert shaft work into increased pressure (or vice versa for turbines)
- The operating point is determined by where the pump and system curves intersect
- NPSH

Water problem?

Early in my college days I took a break and spent 17 months in Salvadoran refugee camps in Honduras. The refugee camps were located high in the mountains and for several of the camps the only sources of water large enough to sustain the population of 6-10,000 were located at much lower elevations. So it was necessary to lift water to the camps using pumps.

When I arrived at the camps the pumps were failing frequently and the pipes were bursting frequently. Piston pumps were used. The refugees were complaining because they needed water. The Honduran army battalion was nervous because they didn't want any refugees leaving the camp. There was only one set of spare parts (valve springs and valves) for the pump and the last set of parts only lasted a few days. The pump repair crew didn't want to start using the pump until the real cause of the problem was fixed because spare parts have to be flown in from Miami.

Water problem: proposed solutions?



2 km pipeline (2” galvanized and then 3” PVC) with rise of 100 m

piston pump (80 L/min)

Shape Factor Solution

- Create a dimensionless grouping

$$S = f(\omega, Q, \Delta p, \rho)$$

$$\frac{\Delta p}{\rho}$$ Eliminate mass $$\frac{\left[\frac{M}{T^2}\frac{L}{L^2}\right]}{\left[\frac{M}{L^3}\right]} = \left[\frac{L^2}{T^2}\right]$$

$$\frac{\Delta p}{\rho Q^{2/3}}$$ Eliminate length $$\left[\frac{L^2}{T^2}\frac{T^{2/3}}{\left(L^3\right)^{2/3}}\right] = \left[\frac{1}{T^{4/3}}\right]$$

$$\frac{\Delta p}{\rho Q^{2/3}\omega^{4/3}}$$ Eliminate time

$$S = \frac{\omega\sqrt{Q}}{\left(\frac{\Delta p}{\rho}\right)^{3/4}}$$

$$S = \frac{w\sqrt{Q}}{\left(gh_p\right)^{3/4}}$$

Pump Curve Solution

$$\omega = \left(\frac{600 rev}{\min}\right) \cdot \left(\frac{1 \min}{60 s}\right) \cdot \left(\frac{2\pi}{rev}\right) = 62.8 / s$$

$$C_H = \frac{h_p g}{w^2 D^2} \qquad C_H = \frac{(2m)(9.8 m/s^2)}{(62.8/s)^2 (0.366 m)^2} = 0.037$$

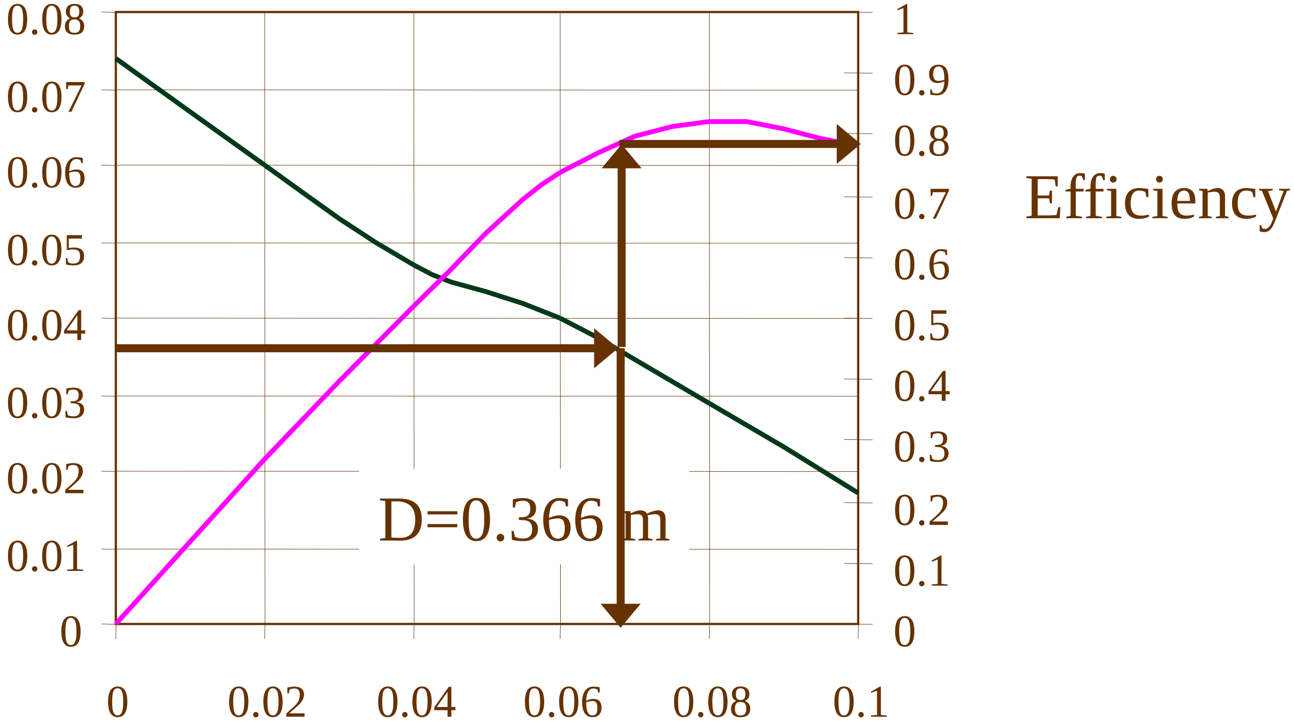
$$C_Q = \frac{Q}{\omega D^3} \qquad C_Q = 0.068$$

$$Q = C_Q \omega D^3 \qquad Q = (0.068)(62.8/s)(0.366 m)^3 = 0.21 m^3/s$$

$$P_m = \frac{g Q h_p}{e_P e_m} \qquad P = \frac{(9800 N/m^3)(0.21 m^3/s)(2m)}{(0.78)(0.95)} = 5.55 kW$$

Pump Curve Solution

$$C_H = \frac{h_p g}{w^2 D^2}$$



$$C_Q = \frac{Q}{\omega D^3}$$

NPSH solution

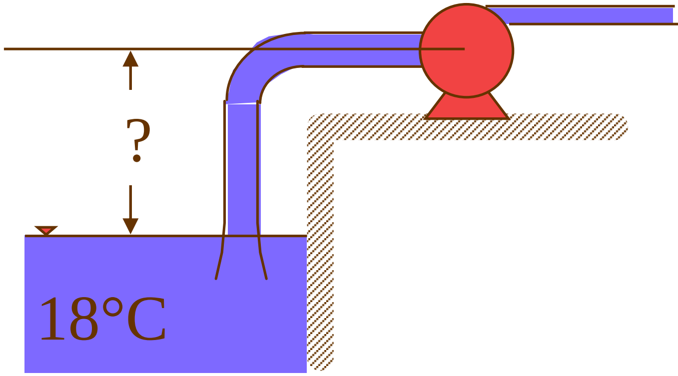
$$NPSH_A = NPSH_R$$

$$NPSH_A = \frac{p_{atm} - p_v}{\gamma} - \Delta z - h_L$$

$$\Delta z = \frac{p_{atm} - p_v}{\gamma} - h_l - NPSH_R$$

$$\Delta z = \frac{(101300Pa)-(2000Pa)}{9789N/m^3} - 0.5m - 2.5m$$

$$\Delta z = 7.14m$$



$$p_v = 2000Pa$$

$$p_{atm} = 101300Pa$$

$$\gamma = 9789N/m^3$$

Implications of Power Curves

- You are going to start a radial flow pump powered by an electric motor. You want to reduce the starting load on the motor. What can you do? Close the effluent valve
- What would you do if you were starting an axial flow pump? Open the effluent valve
- How could reducing the head on a radial flow pump result in motor failure?

An effluent pipe break would increase the flow and increase the power requirement

Find Q

$$T_z = \rho Q\left[\left(r_2 V_{t_2}\right) - \left(r_1 V_{t_1}\right)\right]$$

Let A = 10 cm^2

$$T_z = \rho Q V_{t_2} r_2$$

$$T_z \omega = \rho Q \omega V_{t_2} r_2$$

work

$$h_p = \frac{T_z \omega}{\gamma Q} = \frac{\omega V_{t_2} r_2}{g} \qquad \frac{T_z \omega}{\gamma V A} = \frac{\omega V_{t_2} r_2}{g}$$

Dimensional analysis

$$\frac{p_1}{\gamma} + \frac{V_1^2}{2g} + z_1 + h_p = \frac{p_2}{\gamma} + \frac{V_2^2}{2g} + z_2 + h_l$$

Datum is reservoir level

$$\frac{\omega V_{t_2} r_2}{g} = \frac{V_2^2}{2g} + z_2$$

Neglect head loss

How could we lift water more efficiently?

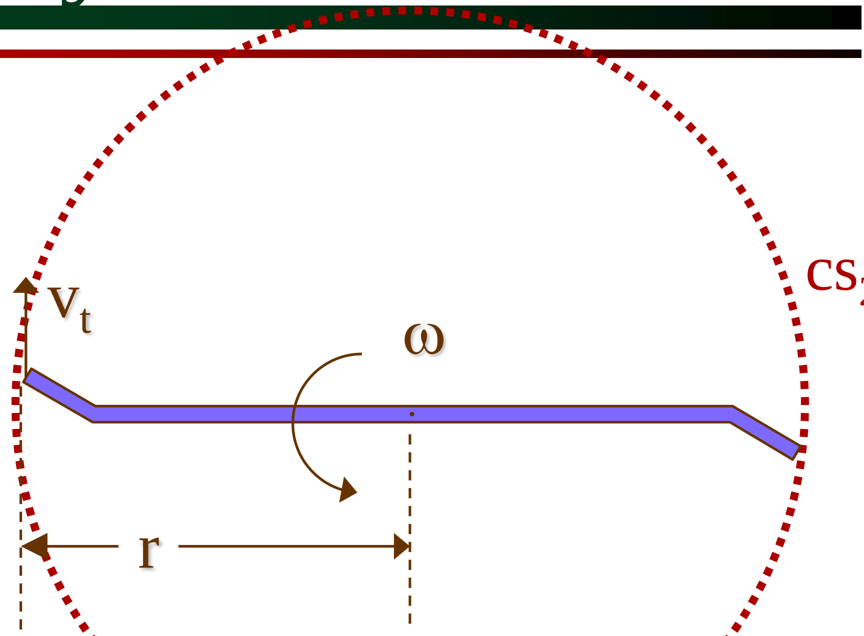
Shaft work added

Kinetic energy

Potential energy

$$\frac{\omega V_{t_2} r_2}{g} = \frac{V_2^2}{2g} + \Delta z$$

Solve for Q=AV



$$T_z \omega = \rho Q \omega V_{t_2} r_2$$

$$Q = A\sqrt{2\omega V_{t_2} r_2 - 2g\Delta z} = AV_2$$

Decrease V without decreasing Q! (

$$\frac{h_p}{\Delta z} = \frac{T_z \omega}{\gamma Q \Delta z}$$

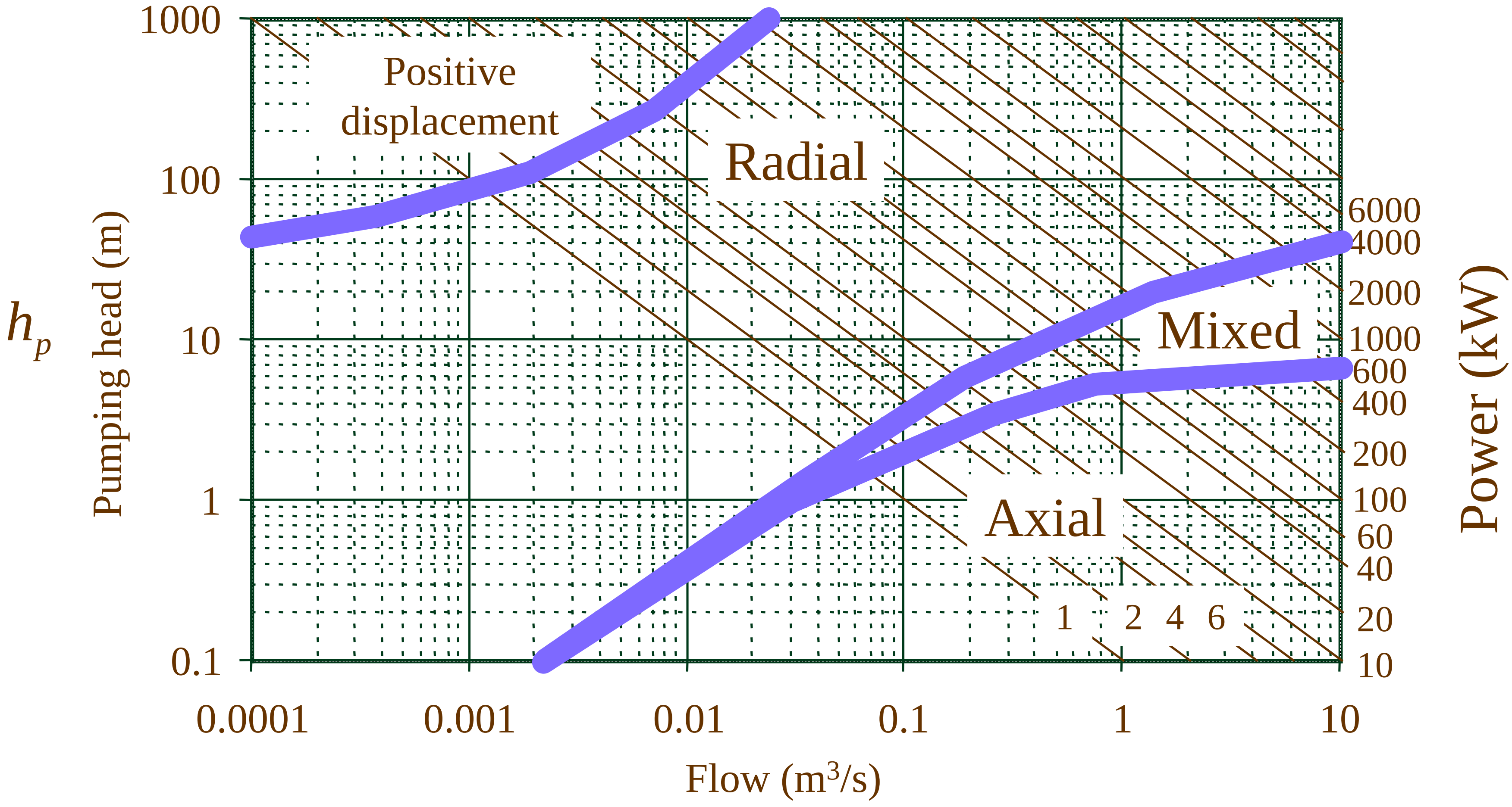
$$\frac{\Delta z}{h_p} = \frac{\gamma A \Delta z \sqrt{2\omega V_{t_2} r_2 - 2g\Delta z}}{T_z \omega}$$

Lost energy

$$\frac{wV_{t_2} r_2}{g} = \frac{V_2^2}{2g} + Dz$$

$$\frac{wV_{t_2} r_2}{g} = \frac{V_2^2}{2g} + Dz$$

Selection of Pump Type



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