Pumping of liquids

Topic 4.1

Types of pumps

What you've done so far

One of your classmates recently bought a house that is on top of a hill. She is installing a sprinkler system in order to water her yard. She wants to pull the water from a pond that is located at the bottom of the hill.

She knows the sprinkler system requires 100 liters per minute of water.

Being an awesome engineer, she has designed a piping system to transfer the water from the pond to her house.

But how will she get the water from the bottom of the hill…?

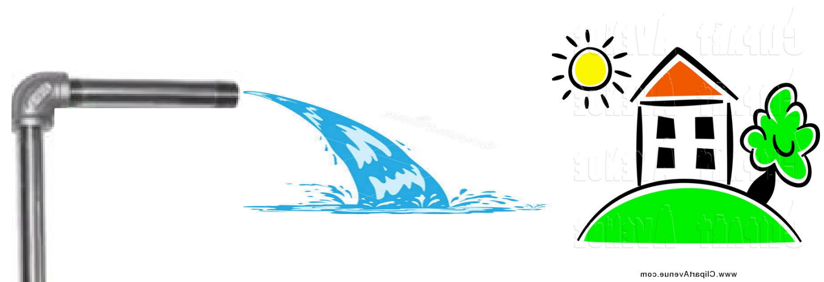
What you've done so far

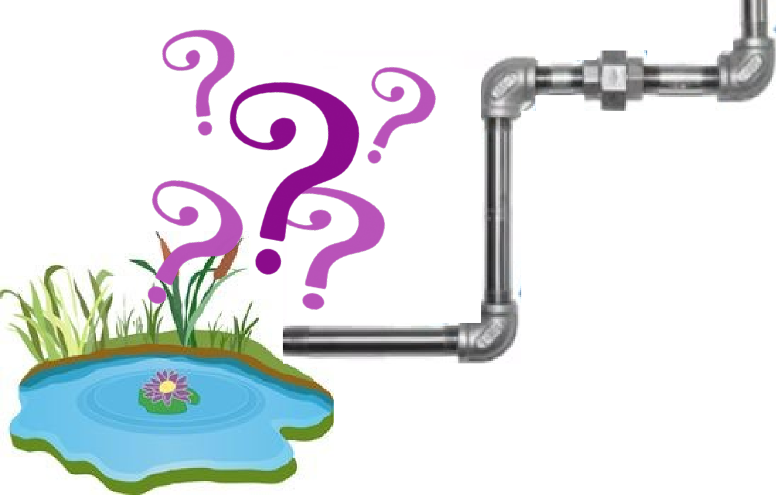
At this point in class, she can draw a piping system that will transfer the fluid. It will have pipes with a certain roughness, it will have elbows, it will have fittings, etc.

Additionally, she know the desired volumetric flow rate (Q) the pipes need to deliver

She also knows how to calculate the head loss of the system. This head loss will be due to friction with the pipes, losses in elbows, etc.

What she doesn't know is how to get the water from the pond to the house





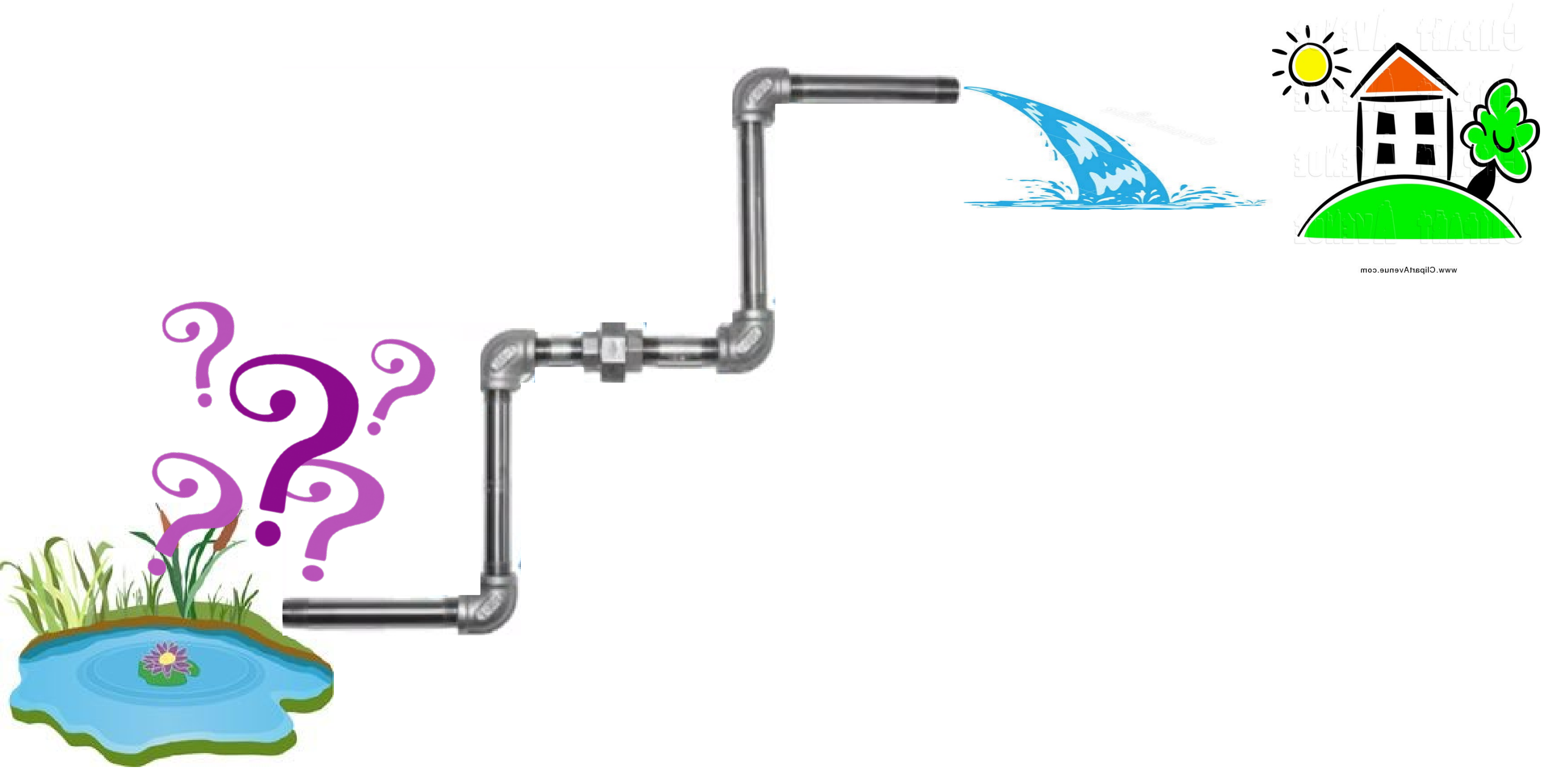
If only there was a device she could use to push the water against gravity and against friction within the system…

What you’ve done so far

She’s even written the mechanical energy balance for the system

$$\frac{\Delta P}{\rho}+\frac{\Delta \overline{V}^2}{2\alpha}+g\Delta z+W_s+F=0$$

If only there was a device she could use to add mechanical energy to the system so that she could transfer fluid from the pond to her yard…



Pumps increase the head of a liquid stream

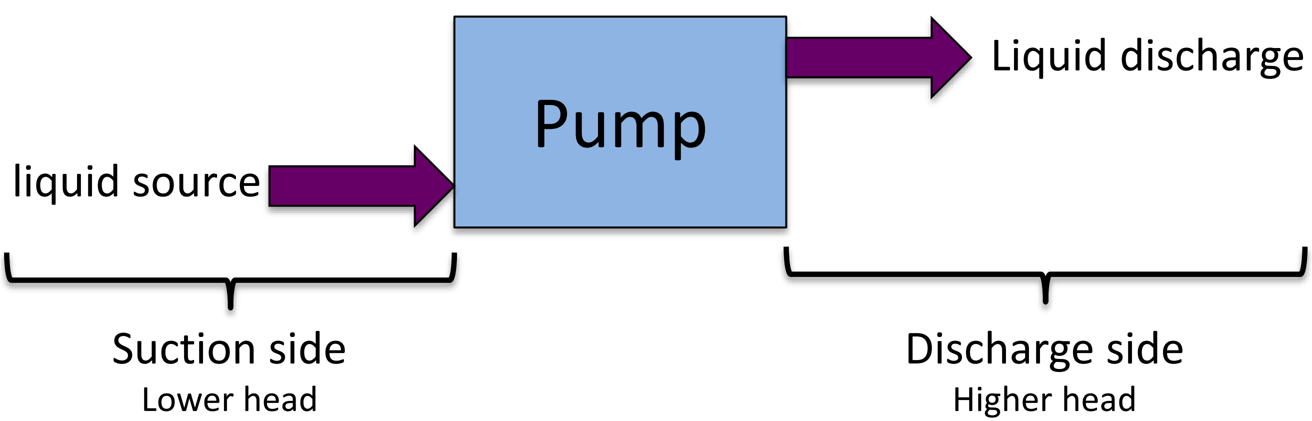
In industrial settings **pressure driven flow** is the most common method of moving a fluid from one point to another

However, this requires a device that can push/pull a fluid in order to initiate and maintain flow

- For liquids, such a device is called a **pump**
- For gases, such a device is called a **compressor**

We are discussing liquid flow, so this conversation will be about **pumps**

There are many pump types but all have the same basic setup



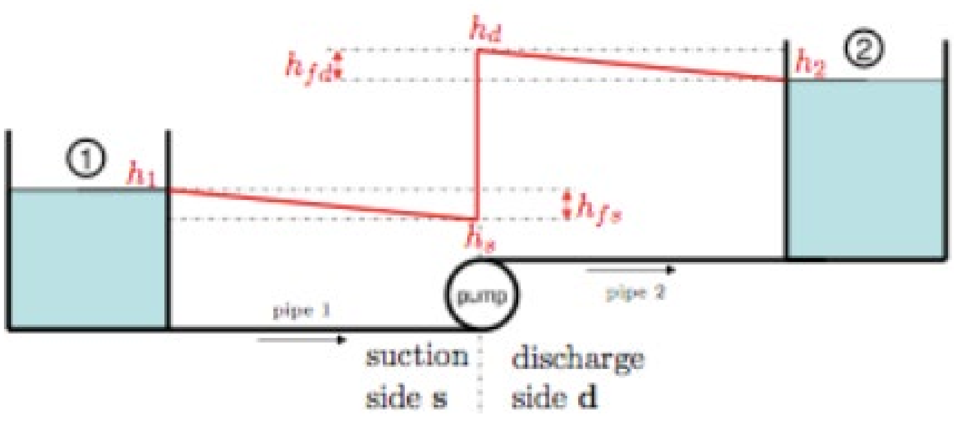
Pumps increase the head of a liquid stream

In this lecture we will discuss many different types of pumps

However, regardless of their configuration, they all have one job:

To increase the head (mechanical energy) of the flow

Specifically, they will allow you to introduce enough head to your system to overcome frictional losses and to work against gravity



Incorporating pump head into the M.E.B.

The shaft work term is how we quantify the impact of pumps on the system

$$\frac{\Delta P}{\rho}+\frac{\Delta \overline{V}^2}{2\alpha}+g\Delta z+W_s+F=0$$

Written in terms of head

$$\frac{\Delta P}{\rho g}+\frac{\Delta \overline{V}^2}{2\alpha g}+\Delta z+\frac{W_s}{g}+\frac{F}{g}=0$$

Define pump head: $h_p=-\frac{W_s}{g}$

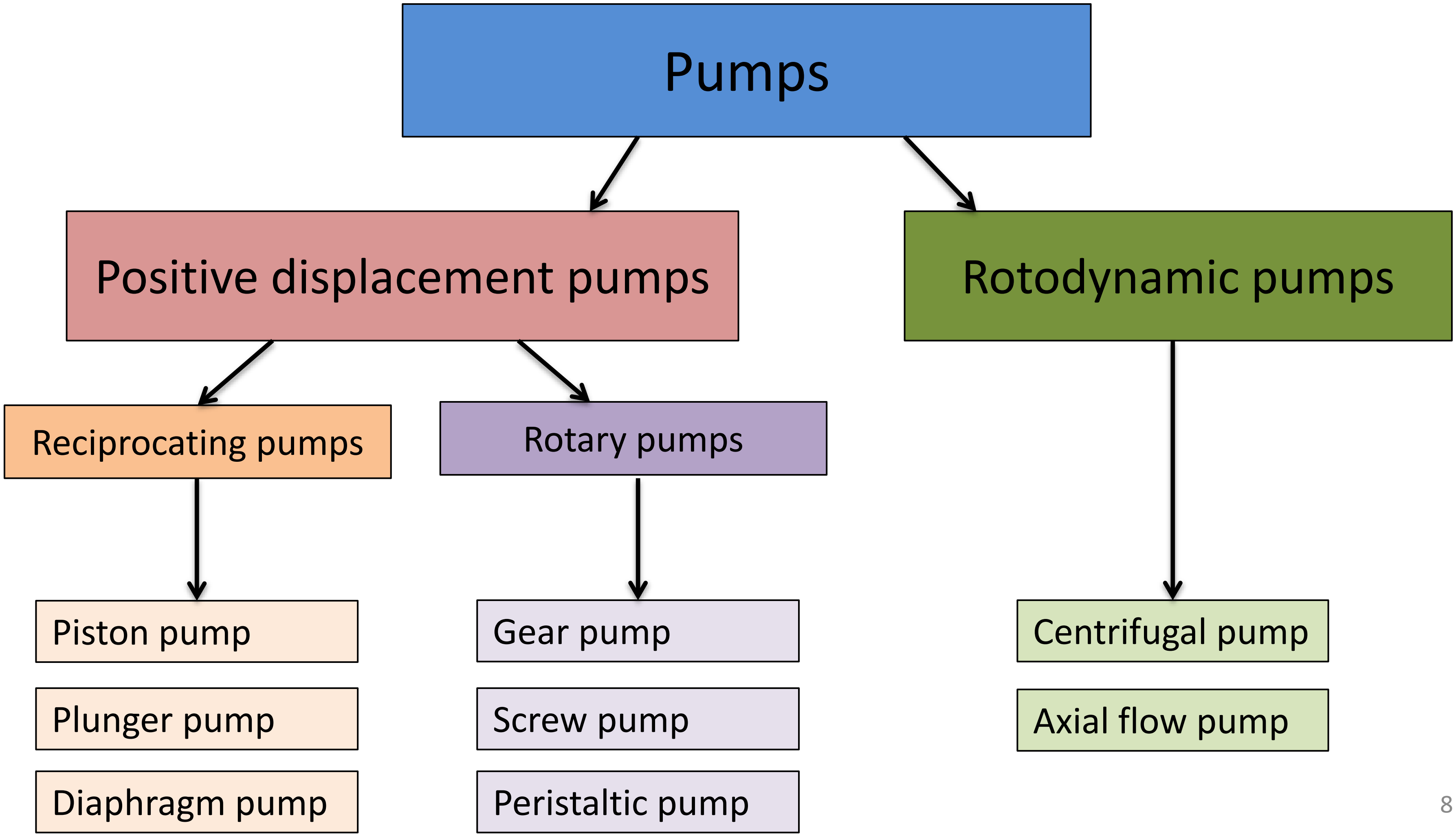
Include friction head: $h_f=\frac{F}{g}$

$$\frac{\Delta P}{\rho g}+\frac{\Delta \overline{V}^2}{2\alpha g}+\Delta z=h_p-h_f$$

The difference between mechanical energy at points 1 and 2 is due to energy lost from the flow due to friction and energy added to the flow due to shaft work from the pump

The big world of pumps

Before we begin solving problems with pumps, we'll look at the different varieties of pumps in the market



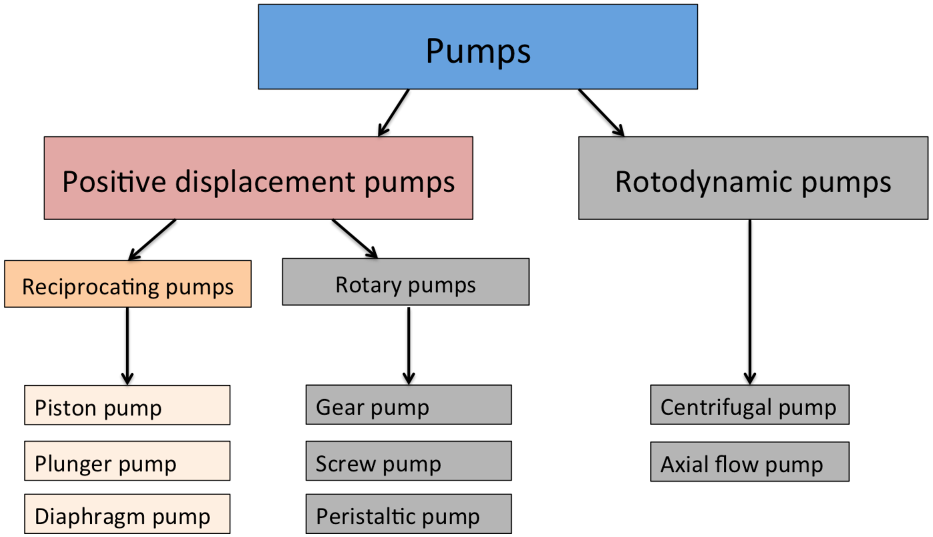
Reciprocating positive displacement pumps

Positive displacement pumps move fluid via a volume change or by displacing a volume of fluid

Reciprocating pumps work by displacing volume through the forward/reverse motion of a moving part

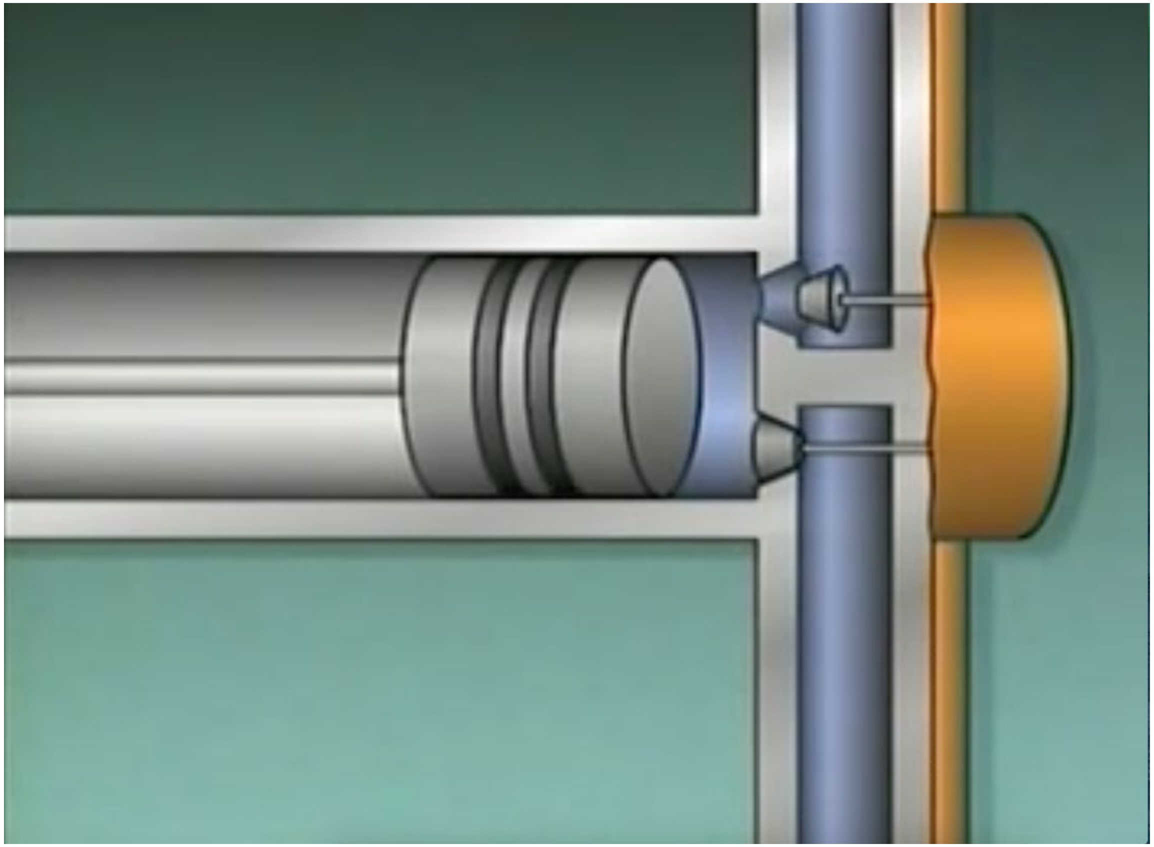
- Examples that are near and dear include your **heart** and your **lungs**

- Industrial examples include **piston pumps**, **plunger pumps**, **diaphragm pumps**, etc.



Reciprocating positive displacement pumps

Here is a video that shows how a piston pump works

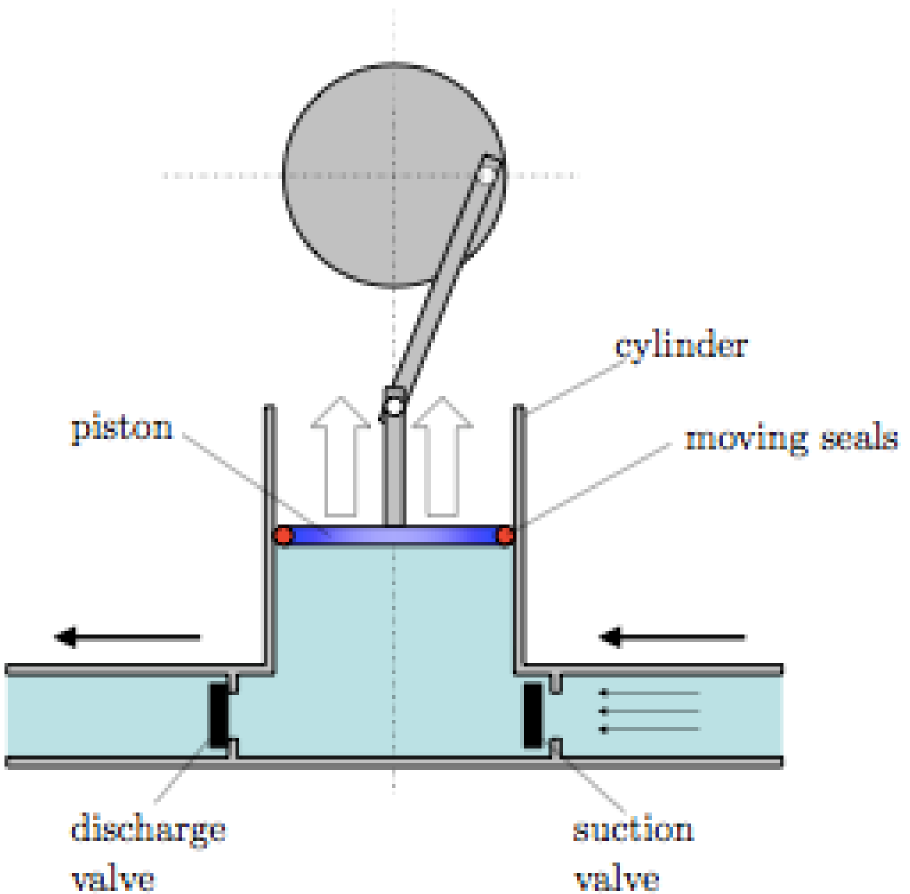


https://www.youtube.com/watch?v=kKpESDDJQso

Reciprocating positive displacement pumps

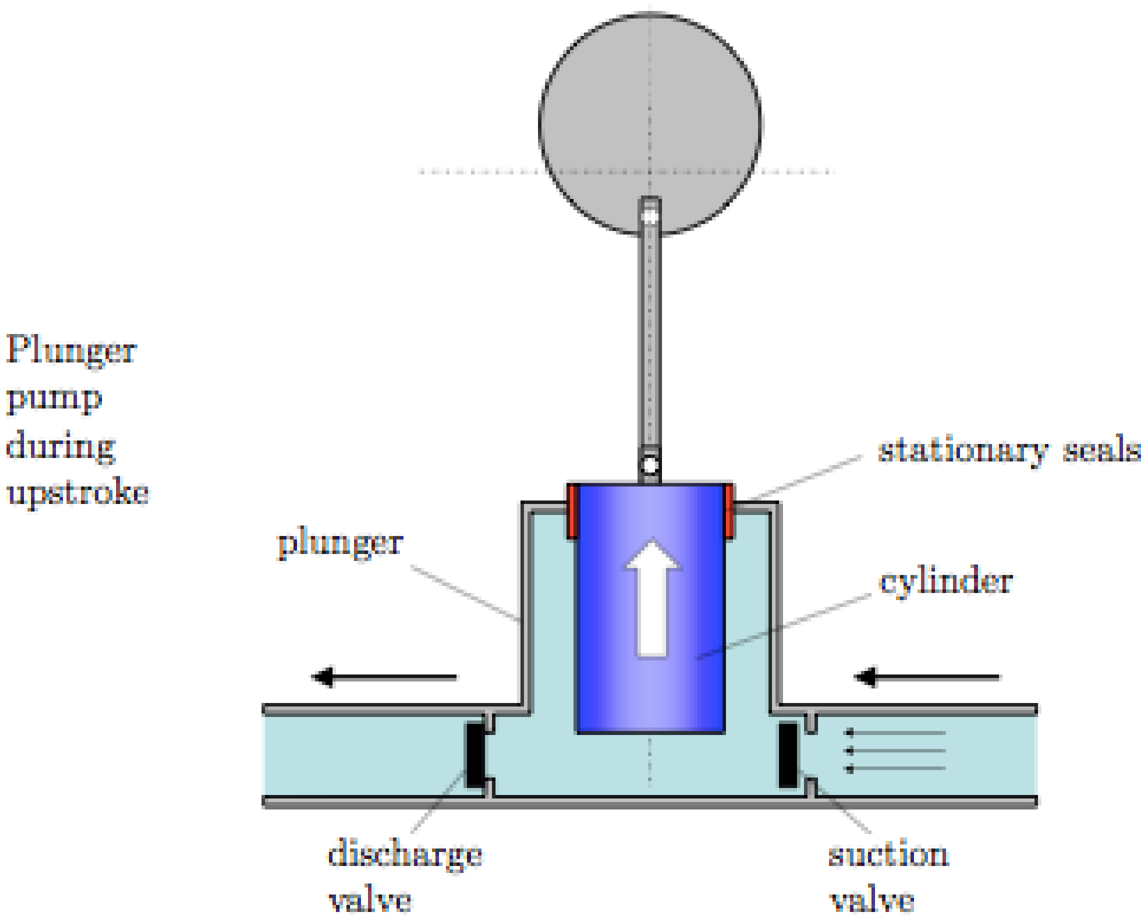
Piston pumps move fluid by using the forward/reverse motion of a piston and two valves

Piston pump during upstroke



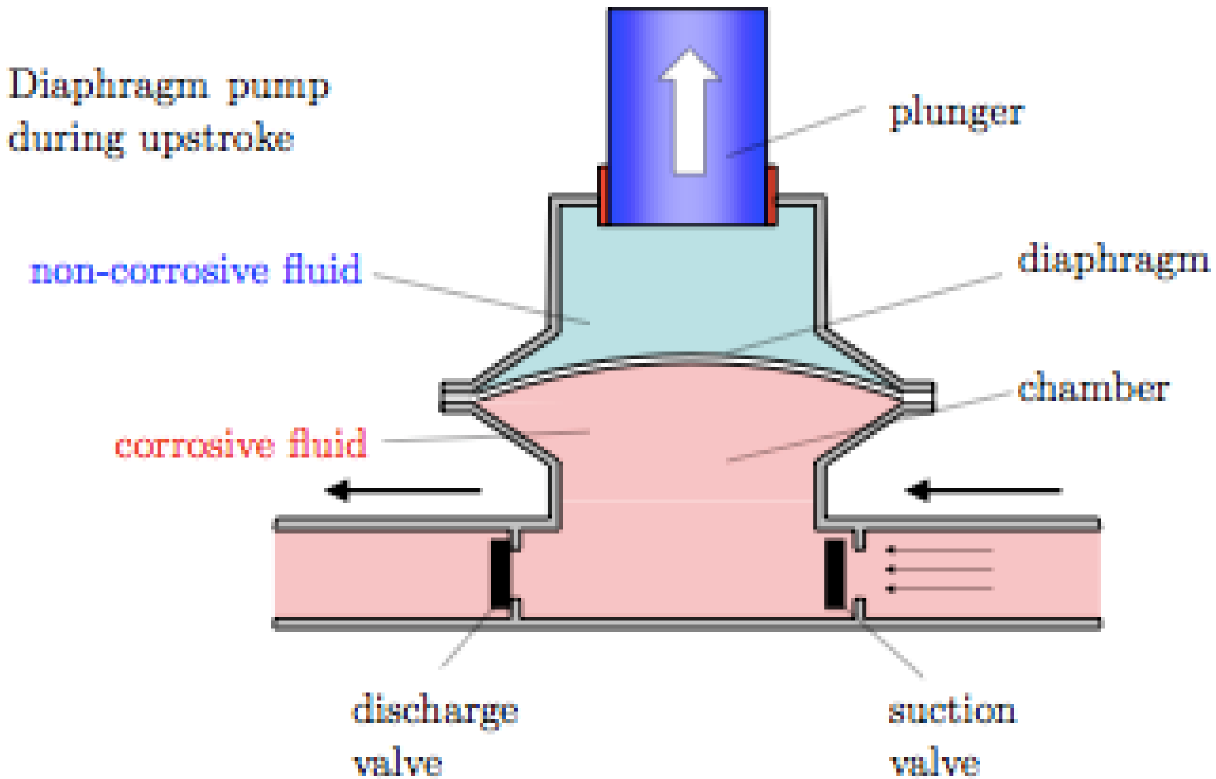
Reciprocating positive displacement pumps

Plunger pumps move fluid by using the forward/reverse motion of a plunger and two valves



Reciprocating positive displacement pumps

Diaphragm pumps move fluid by using the forward/reverse motion of a diaphragm and two valves

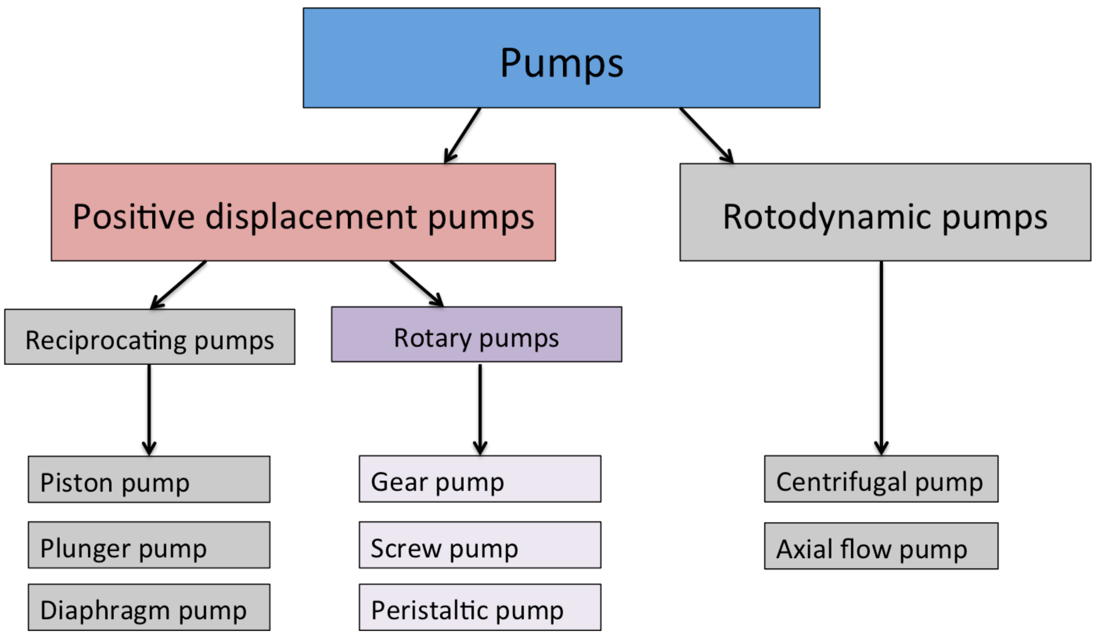


Rotating positive displacement pumps

Positive displacement pumps move fluid via a volume change or by displacing a volume of fluid

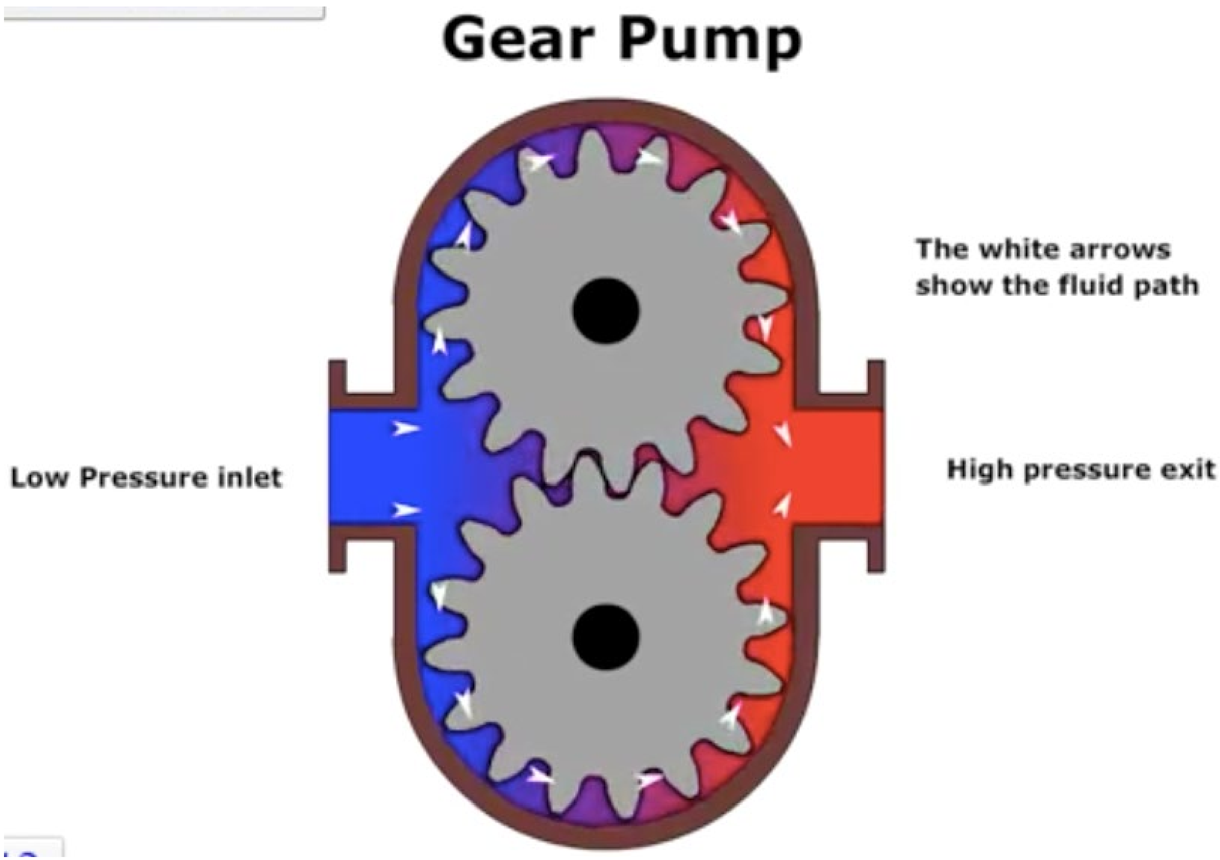
Rotating pumps work by displacing through the circular motion of a moving part

- Industrial examples include **gear pumps**, **lobe pumps** **screw pumps**, **peristaltic pumps**, etc.



Rotary positive displacement pumps

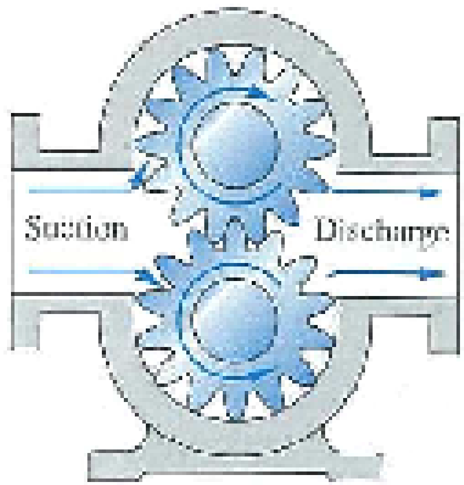
Here is a video that shows how a gear pump works



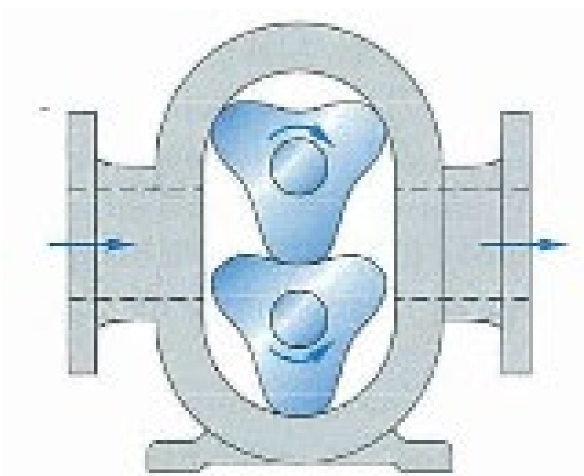
https://www.youtube.com/watch?v=c6gwU7IHtlo

Rotating positive displacement pumps

Gear pumps move fluid by using the rotation of gears



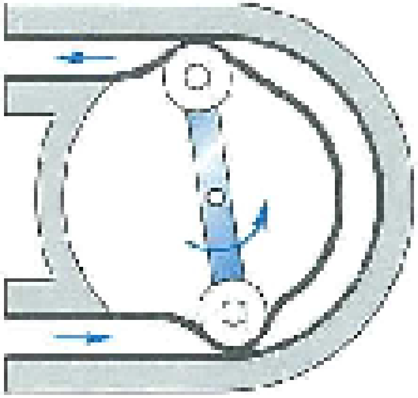
Lobe pumps move fluid by using the rotation of lobed wheels



Rotating positive displacement pumps

Screw pumps move fluid by using the rotation of a screw

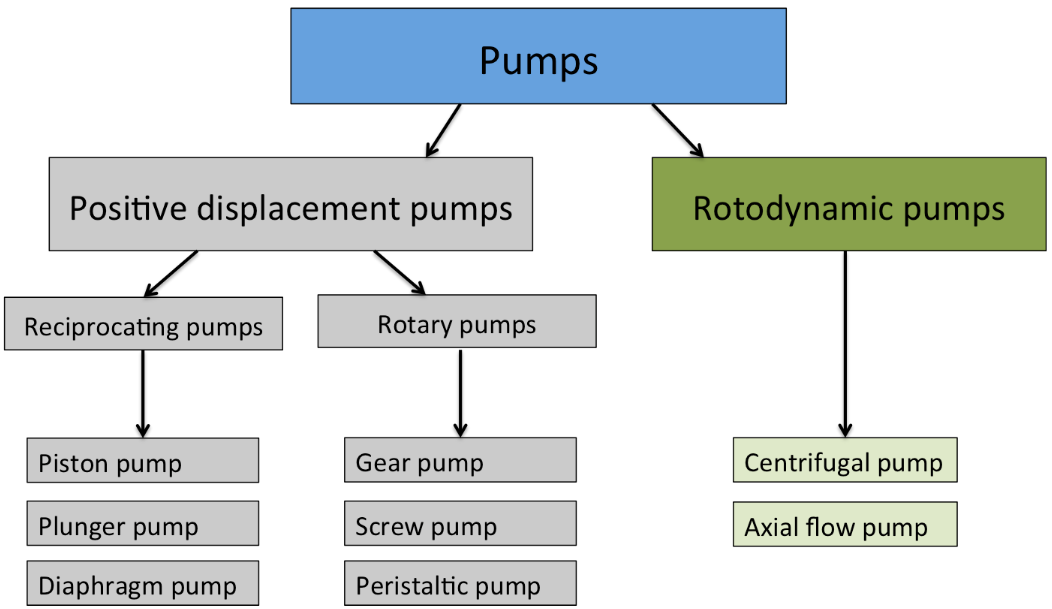
Peristaltic pumps move fluid through flexible tubing by using the rotation of a lobed wheel



Rotodynamic pumps

Rotodynamic pumps work by providing the fluid with energy from the motion of rotating blades or vanes

- Industrial examples include **Centrifugal pumps**, **axial flow pumps**, etc.



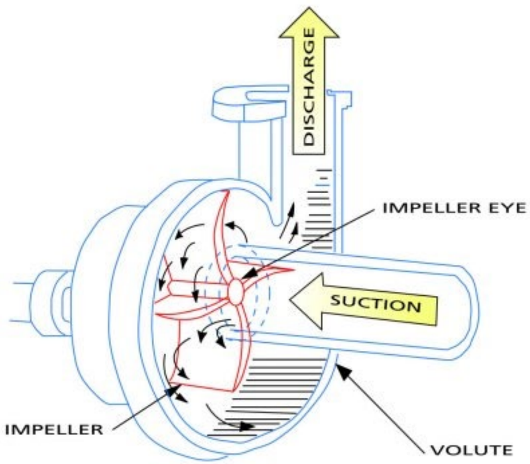
Rotodynamic pumps

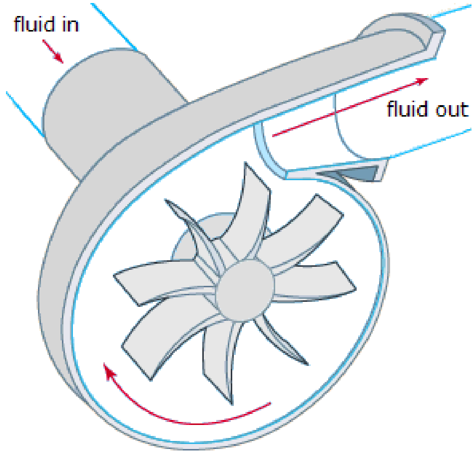
Here is a video that show how a centrifugal pump works

https://www.youtube.com/watch?v=BaEHVpKc-1Q

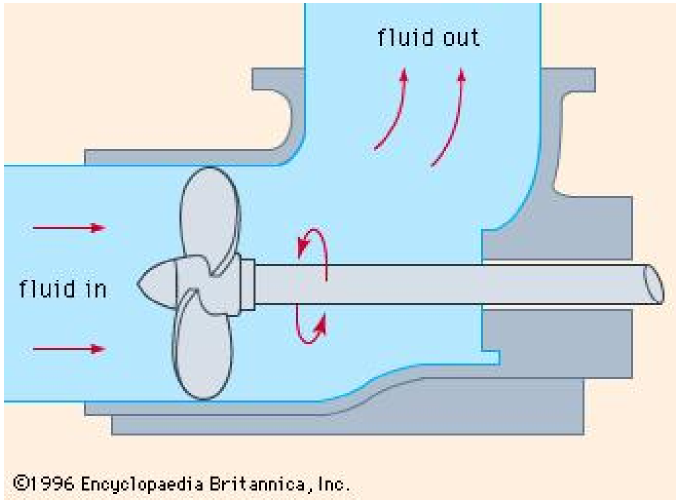
Rotodynamic pumps

Centrifugal pumps move fluid by using a rotating impeller





Axial flow pumps move fluid by using a rotating impeller

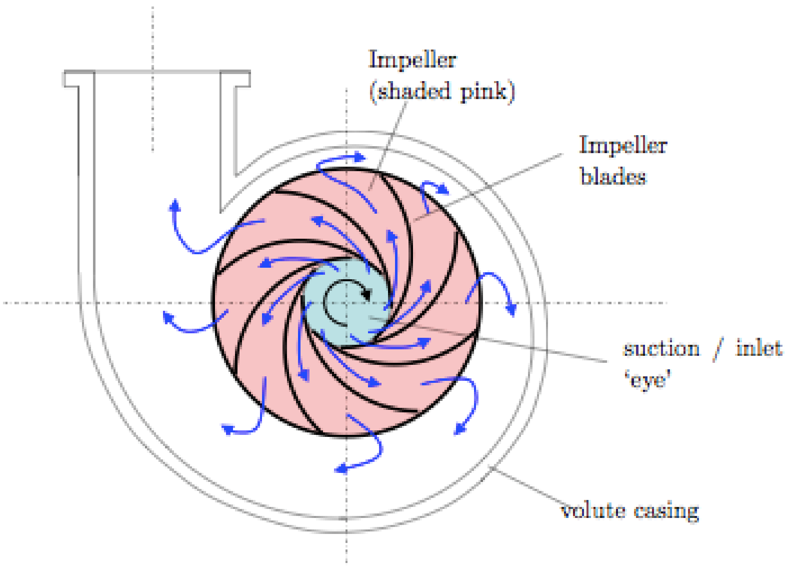


Centrifugal pumps

The **centrifugal pump** is the most widely used type of pump as it can pump a variety of liquids and can produce high flow rate for its size

Mode of operation

- Energy provided to impeller by a motor
- Liquid enters axially through the eye
- Impeller blades transfers energy to the fluid resulting in an increase in pressure
- The cross sectional area of the volute increases to accommodate increasing amounts of fluid



Why so many different types of pumps?

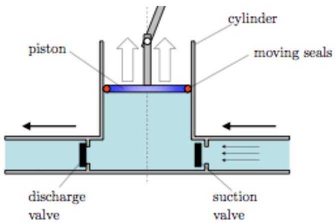
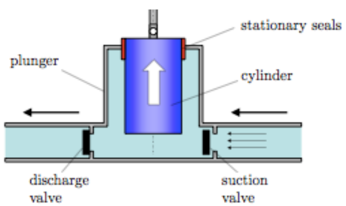
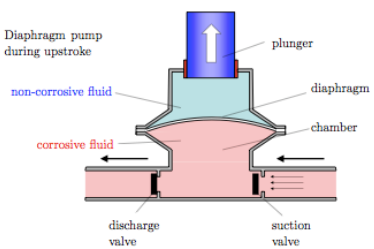
As you can see, there are a huge number of pump types to choose from

The choice of pump depends on many aspects of your pumping system

- Fluid properties: viscosity, corrosiveness, suspensions
- Required flow rate
- Other operational considerations: cost, efficiency, maintenance, etc

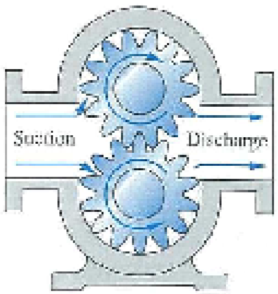
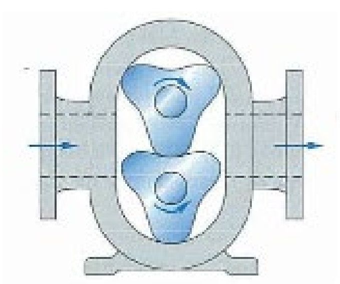
Choosing your pump

When is a **reciprocating positive displacement pump** useful?

Pump type	**Pros**	**Cons**
Piston pump 	Can produce high discharge head	Limited by mechanical strength of the seal
Plunger pump 	Can produce high discharge head	Can only handle small flow rates
Diaphragm pump 	Designed to handle corrosive/abrasive liquids	Requires periodic replacement of diaphragm

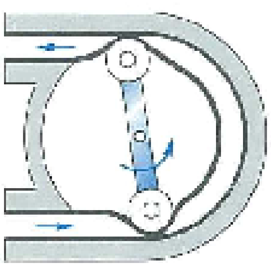
Choosing your pump

When is a **rotary positive displacement pump** useful?

Pump type	**Pros**	**Cons**
Gear pump 	Good for high viscosity fluids (ex. oils)	Limited flow rate
Lobe pump 	Good for high viscosity fluids or dense suspensions. Often used in food processing	Limited flow rate

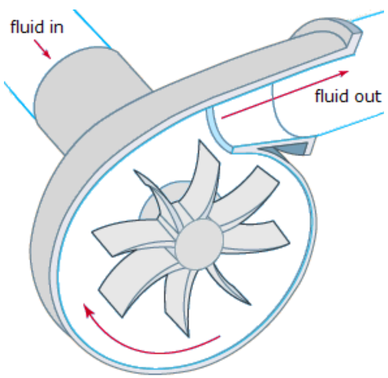
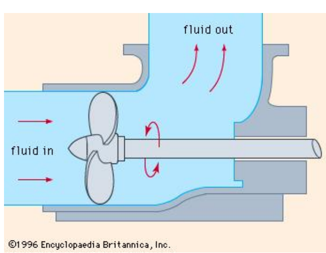
Choosing your pump

When is a **rotary positive displacement pump** useful?

Pump type	**Pros**	**Cons**
Screw pump 	Good for high viscosity fluids. Often used in polymer or food processing	Complicated design and parts
Peristaltic pump 	Often used for sensitive biological fluids as fluid never touches pump components	Limited flow rate

Choosing your pump

When is a **rotodynamic pump** useful?

Pump type	**Pros**	**Cons**
Centrifucal pump 	Can pump a wide variety of liquids Small and compact Provides high flow rates for its size	Operates at lower flow rates than axial flow pumps Best for low viscosity fluids
Axial flow pump 	Operates at higher flow rates than centrifugal	Operates at lower pressures than centrifugal Best for low viscosity fluids

Centrifugal pumps

Since centrifugal pumps are the most widely used, that is what we will pay the most attention to in the coming days

Additional pros and cons of centrifugal pumps

Pros

- Simple construction
- Relatively compact
- No valves
- Steady delivery of fluid
- Can handle suspensions/slurries
- Low maintenance
- A variety of construction materials

Cons

- Head rise in a single stage pump is limited to 30-60m
- Conditions for high efficiency are limited
- Not usually self priming
- Not efficient for highly viscous fluids

Pumping of liquids

Topic 4.2

Pump curves

Performance indicators

Regardless of the type of pump you're working with, there are three main performance indicators

1. **Capacity** or **flow rate** (**Q**)
2. **Efficiency** (η)
   - Mechanical efficiency
   - Hydraulic efficiency
3. **Pump head** (h_p)

Best efficiency point

1. Capacity (flow rate, Q)

Capacity – or **flow rate** (**Q**) – is the simplest of the pump performance indicators

It is the volumetric flow rate of fluid that is being generated by the pump

Usually this is a design criteria. You know the desired flow rate you want, and you must design the pumping system to meet this need

2. Efficiency

Power is required in order to run the pump and meet the desired flow rate. Electricity powers a motor, which turns the drive shaft, which turns the impeller, which pushes the fluid

Unfortunately, pumps are not 100% efficient, so not all of this power will be transferred to the fluid

In fact, we have two efficiencies when discussing pumps

- Mechanical efficiency
- Hydraulic efficiency

2.1. Mechanical efficiency

As the pump runs, there is internal friction between parts of the pump rubbing against one another

The energy lost due to this friction is accounted for by the **mechanical efficiency** of the pump

- The total power supplied to the pump is called the **brake power** (**P_B**)
- The power that is actually transferred to the fluid is called the **fluid power** (**P_F**)

$$Mechanical Efficiency = \frac{P_F}{P_B} < 1$$

2.1. Mechanical efficiency

Break power is usually a known value, you can measure how much power you are supplying to the pump

Fluid power is more difficult, you have to know the actual flow rate of the fluid in order to calculate the fluid power

$$P_F = -W_s G = h_p g \rho Q$$

This means you actually have to run the pump to know what is the fluid power (and thus the pump efficiency)

2.2. Hydraulic efficiency

Pumps provide fluid with mechanical energy in the form of pressure energy, and this energy is measured as head

Theoretical pump head is always greater than *actual pump head* because of additional inefficiencies related to the transfer of energy from the pump to the fluid

This is quantified as the **hydraulic efficiency** (η)

$$\eta = \frac{h_{actual}}{h_{theoretical}}$$

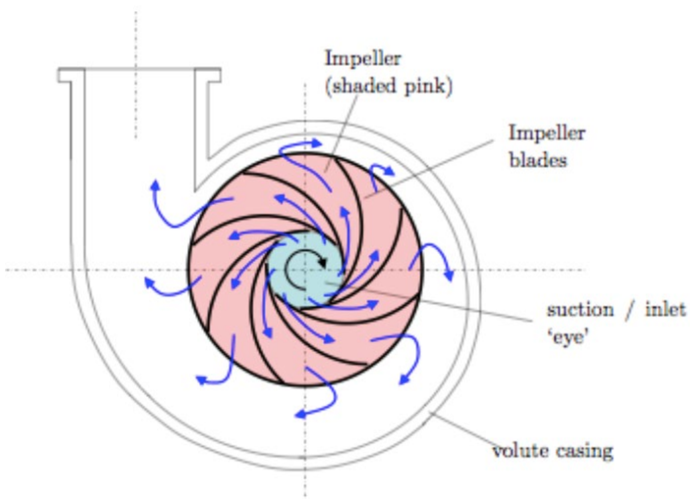
2.2. Hydraulic efficiency

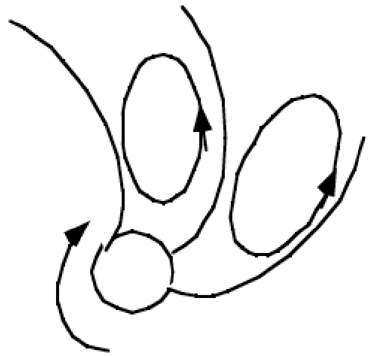
What causes these losses in efficiency?

- **Shock losses**. Losses due to turbulence due to sudden changes in the direction at the impeller eye and tip

- **Leakage**. This can be significant, especially at low throughputs

- **Circulatory flow**. Circulation in the space between the blades

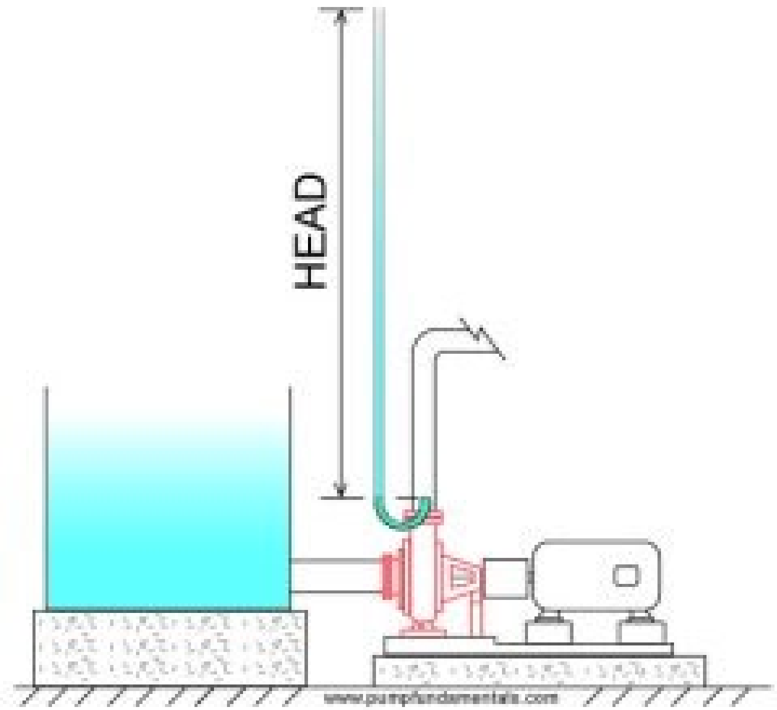




3. Pump head

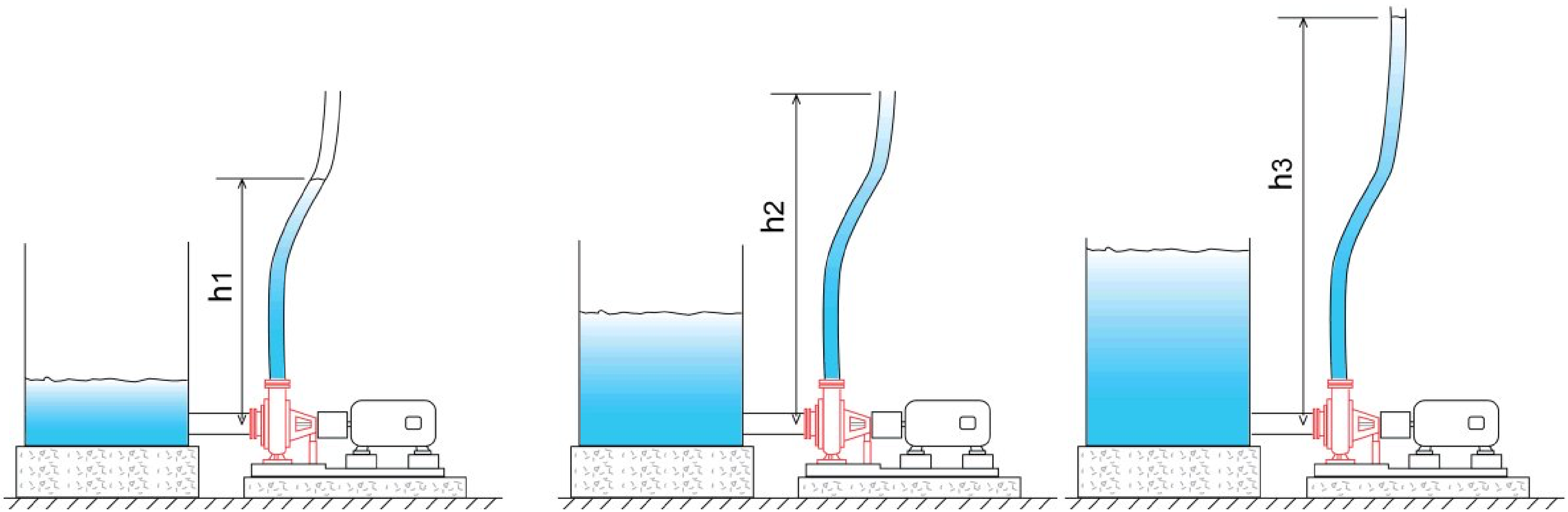
Assume you have a pump where the discharge pipe is extended vertically into the air

Pump head is the height at which a pump can raise a fluid



3. Pump head

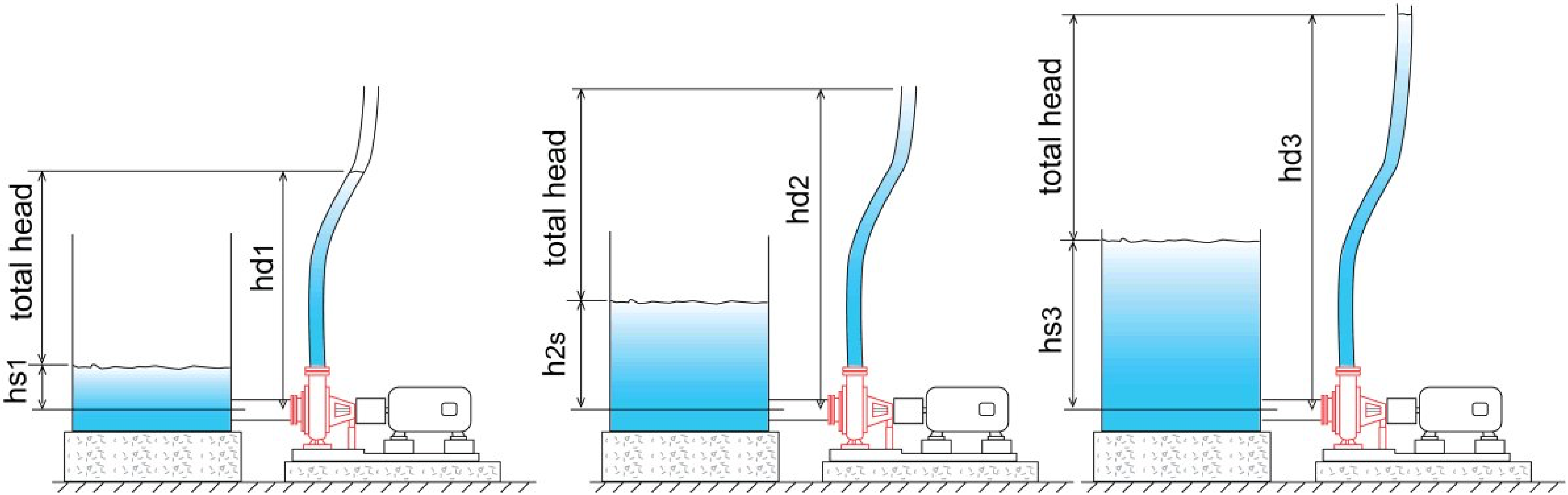
What will happen if the level of the head in the suction tank increase?



3. Pump head

Some new vocabulary

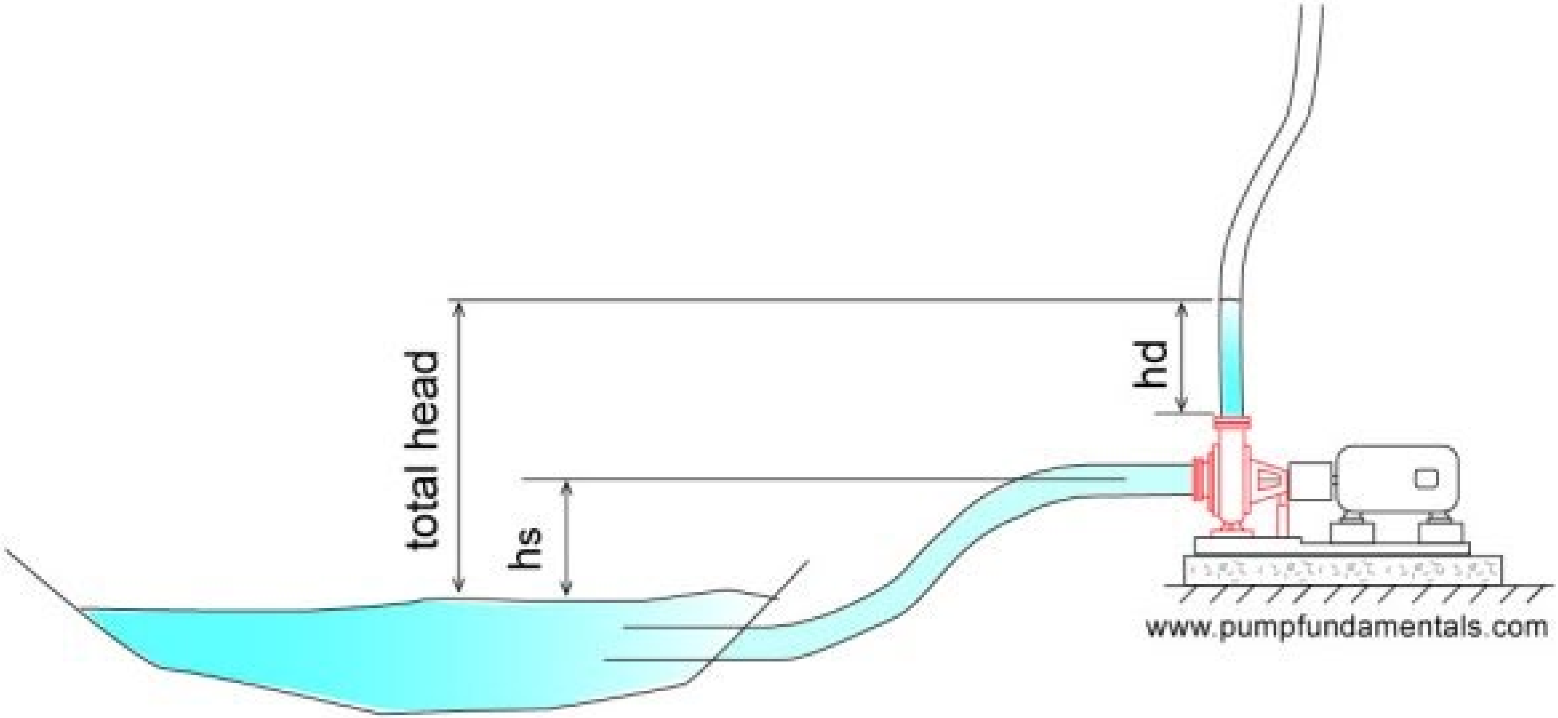
- **Discharge head** (**h_d**) – on the previous two slides, we've been discussing discharge head, the height to which the pump can push water vertically in the discharge pipe
- **Suction head** (h_s) – the head (height of fluid) that is available on the suction side of the pupm
- **Total head** (**h_p**) – the difference between the discharge head and the suction head. This is the value that is used in the M.E.B.



3. Pump head

What if the fluid level is below the level of the pump?

Total head is still calculated the same way



Can pump head be calculated?

So on the previous slides, we **measured** the *actual* pump head.

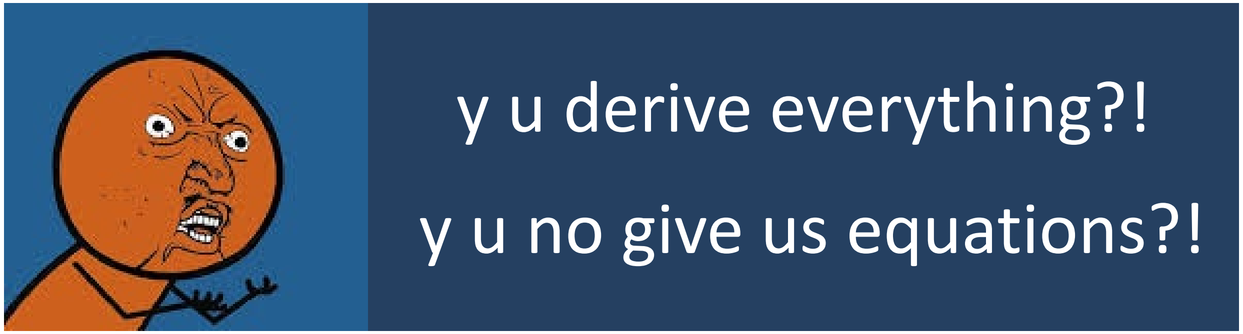
Can it be calculated?

Unfortunately, the *actual pump head* cannot be calculated, it can only be measured

However, the **theoretical pump head** can be calculated

Often pumps are characterized by their **theoretical pump head** and their **efficiency**. With these two parameters, the actual pump head can be determined

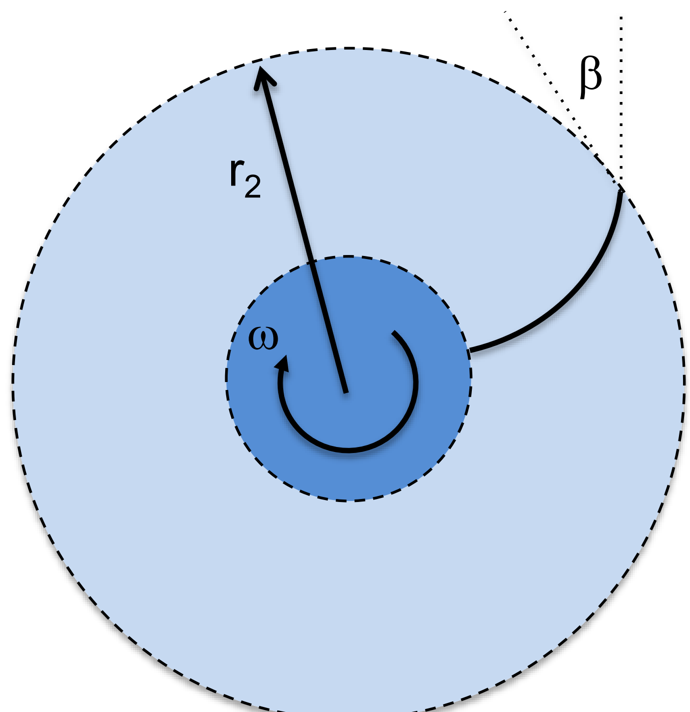
Theoretical pump head



So we won't derive the equation for the theoretical efficiency of a centrifugal pump, we'll just give it to you

$$\boxed{h_p = \frac{\omega^2 r_2^2}{g} - \frac{Q\omega}{2\pi b g \tan\beta}}$$

Variable	Physical meaning
ω	Angular velocity (rads/s)
r_2	Outer radius of vanes
g	Acceleration due to gravity
Q	Volumetric flow rate
b	Width of vanes
β	Angle with outside radius



Theoretical pump performance curves

For a centrifugal pump, we can see that at a given angular velocity the theoretical relationship between **pump head** and **flow rate** is linear

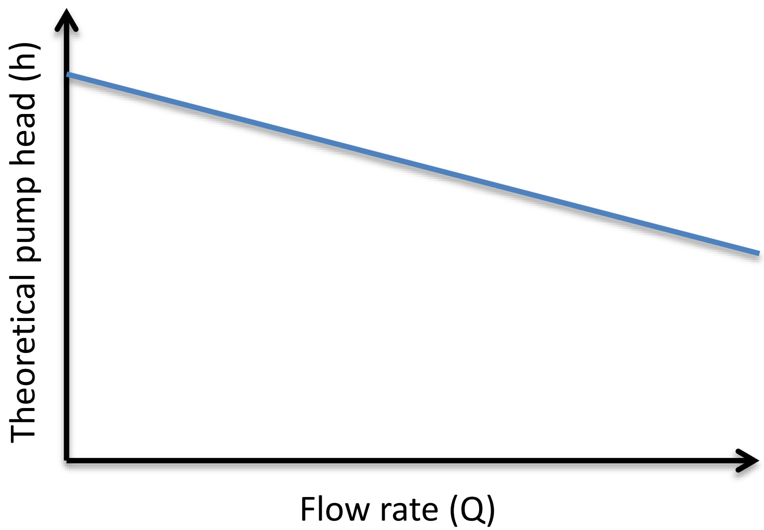
The curve depends on the geometric features of the pump components including impeller diameter, impeller angle, and vane width

$$\boxed{h_p = \frac{\omega^2 r_2^2}{g} - \frac{Q\omega}{2\pi b g \tan\beta}}$$

We can plot a relationship between pump head and flow rate on a **pump curve**

3. Theoretical pump curves

A basic theoretical pump curve for a centrifugal pump



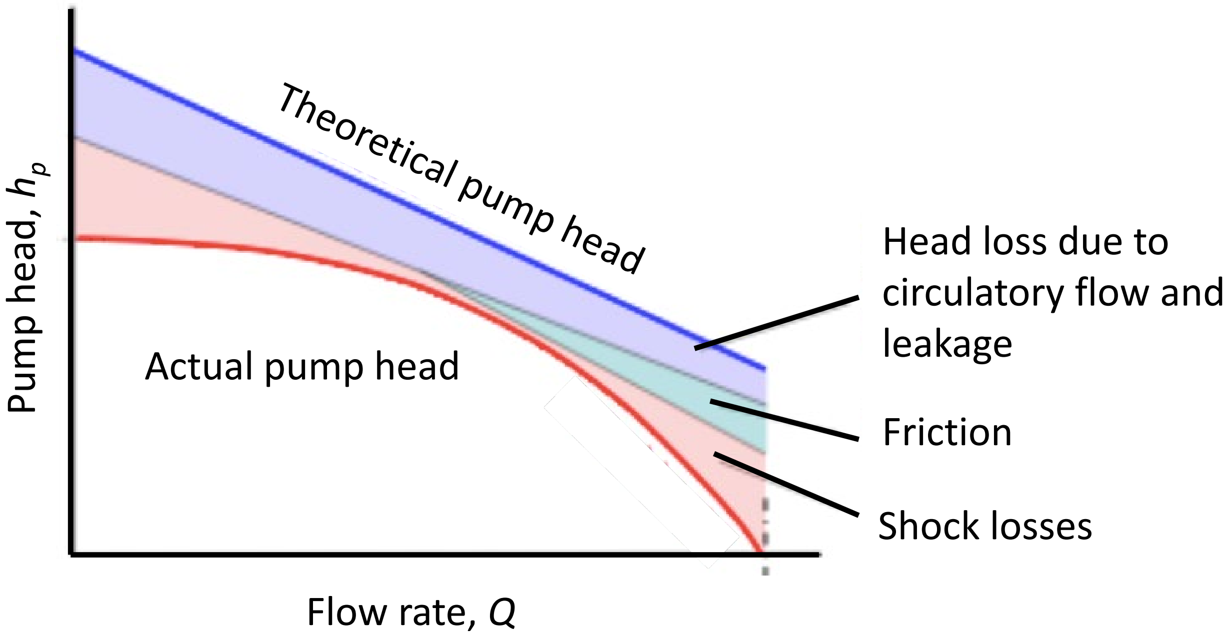
$$h_p = \frac{\omega^2 r_2^2}{g} - \frac{Q\omega}{2\pi b g \tan\beta}$$

These plots illustrate that there is a strong relationship between the head that the pump can produce and the flow rate

For a given angular velocity (ω), this pump can theoretically produce combinations of Q and h_p that fall on this line

Actual versus theoretical pump curves

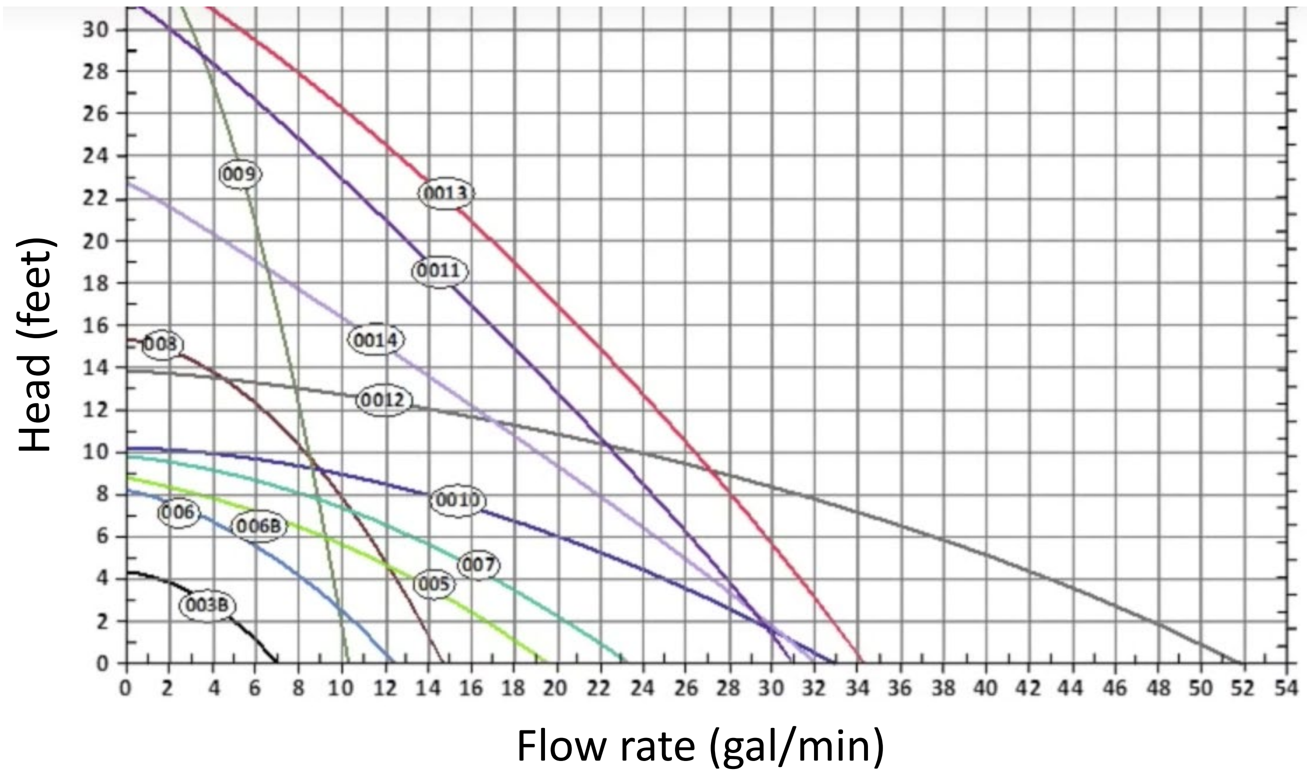
Actual pump curves are always less than theoretical due to losses



A company will usually produce a variety of different pumps, develop the pump curves for each of these pumps, and the customer then uses these curves to select the appropriate pump

Pump curves

Here are pump curves for a variety of pumps produced by the American company Taco Comfort Solutions

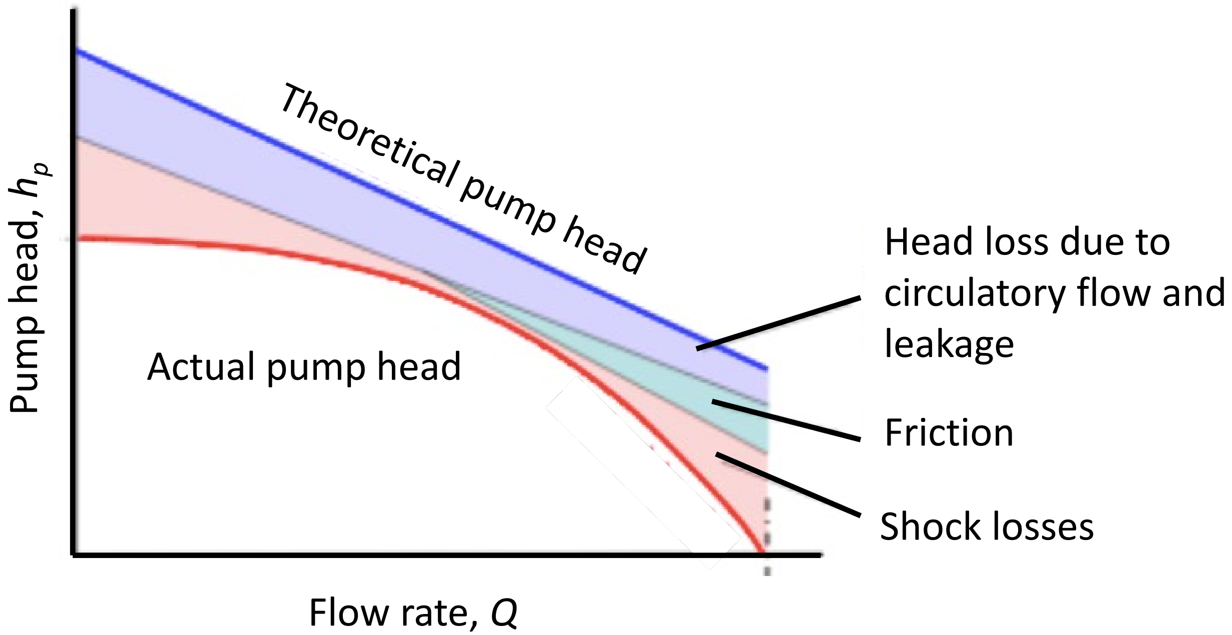


The shape of the pump performance curve depends on a wide variety of pump characteristics including the power of the pump and the size and shape of the impeller

Best efficiency point

The magnitude of each type of loss can vary with flow rate

- Head loss due to circulatory flow/leakage is relatively constant
- Friction increases with higher flow rates due to more viscous losses
- Shock losses have a minimum

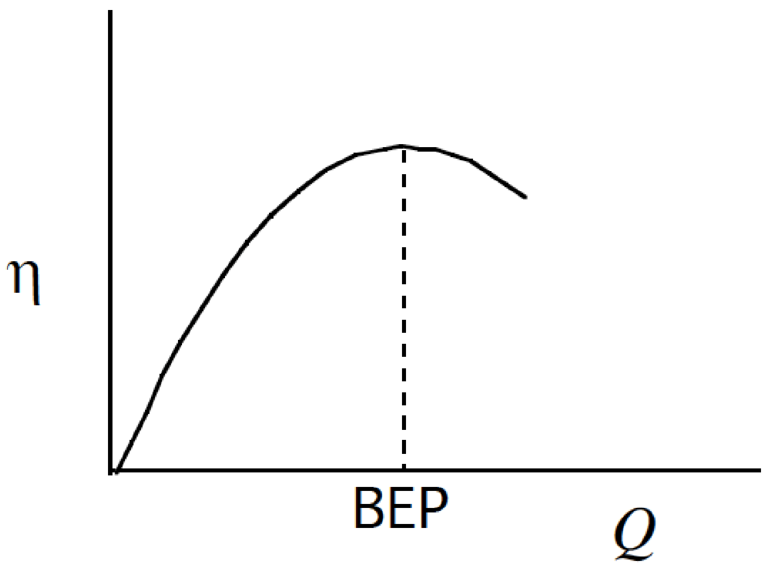


The overall efficiency of the pump varies with flow rate

There is a flow rate that corresponds to the highest efficiency of the pump

Best efficiency point

The efficiency of the pump (η) is a function of flow rate (Q) and there is a maximum in this curve known as the **best efficiency point (BEP)**



For monetary reasons, it is desirable to select a pump that operates near the BEP at the desired operating conditions, else you are **wasting money**

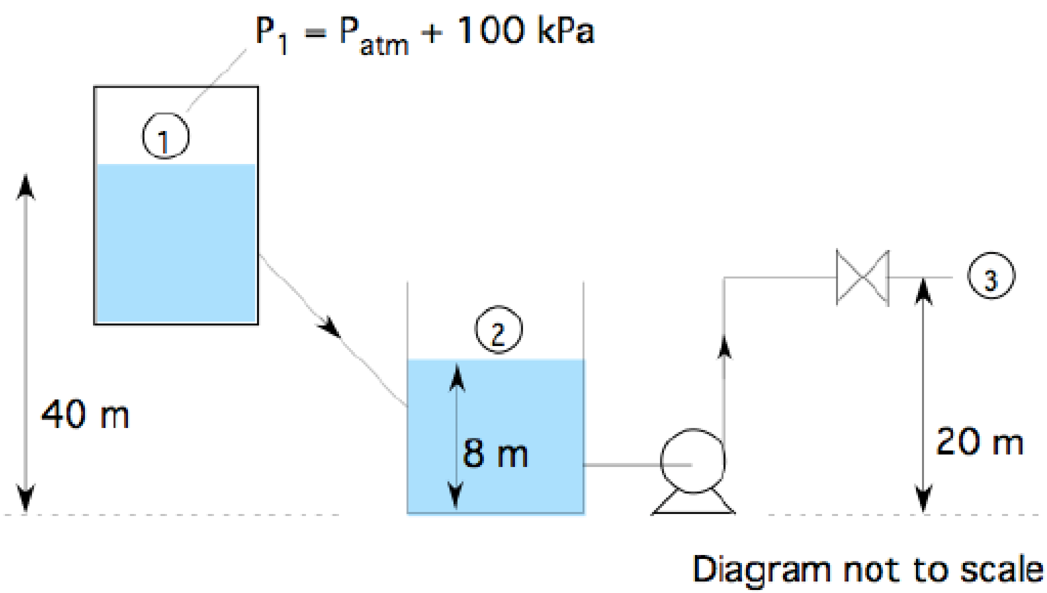
As with the pump performance curve, the efficiency curve must be provided by the supplier

Example problem 4.1

You are using a pump to drain a series of tanks as shown below. The system is operating at steady state.

A. Find the velocity in the pipe between tanks 1 & 2

B. Find the power required by the pump



Pipe 1 → 2 information

L = 100 m (includes minor losses)

D = 10 cm

e = 0.03 mm

Pipe 2 → 3 information

L = 60 m

D = 15 cm

e = 0.015 cm

$K_{valve} = 0.15$

$L_{eq,elbow} = 35D$

Fluid property data

ρ = 1000 kg/m3

μ = 0.001 Pa s

Pumping of liquids

Topic 4.3

Determining operating conditions

Remembering the M.E.B

The shaft work term is how we quantify the impact of pumps on the system

$$\frac{\Delta P}{\rho}+\frac{\Delta \overline{V}^2}{2\alpha}+g\Delta z+W_s+F=0$$

Written in terms of head

$$\frac{\Delta P}{\rho g}+\frac{\Delta \overline{V}^2}{2\alpha g}+\Delta z+\frac{W_s}{g}+\frac{F}{g}=0$$

Define pump head: $h_p=-\frac{W_s}{g}$

Include friction head: $h_f=\frac{F}{g}$

$$\frac{\Delta P}{\rho g}+\frac{\Delta \overline{V}^2}{2\alpha g}+\Delta z-h_p+h_f=0$$

Re-writing the mechanical energy balance

Let’s add pump head from both sides of the equation

$$\frac{\Delta P}{\rho g}+\frac{\Delta \overline{V}^2}{2\alpha g}+\Delta z+h_f=h_p$$

Label left hand side as system head, h_{sys}

$$h_{sys}=h_p$$

For any flow system, the **system head is equal to the pump head**

System head vs. flow rate

If the tanks are large, how does the system head vary with the volumetric flow rate between points 1 and 2 for the system below?

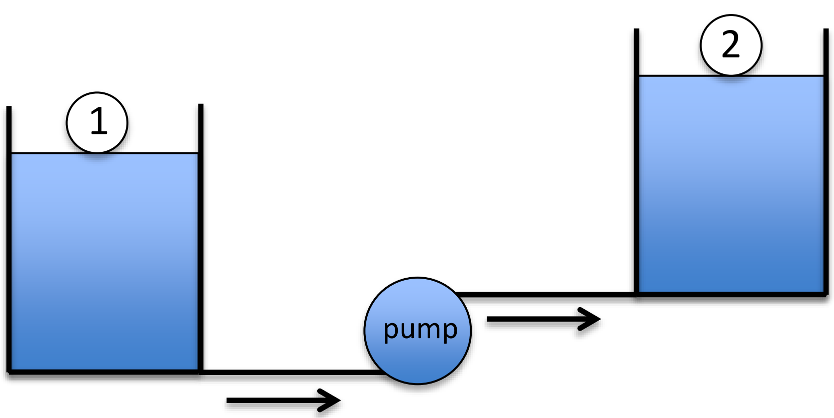
$$h_{sys} = \frac{\Delta P}{\rho g} + \frac{\Delta \bar{V}^2}{2\alpha g} + \Delta z + h_f$$

- Pressure head:

- Velocity head:

- Gravitational head:

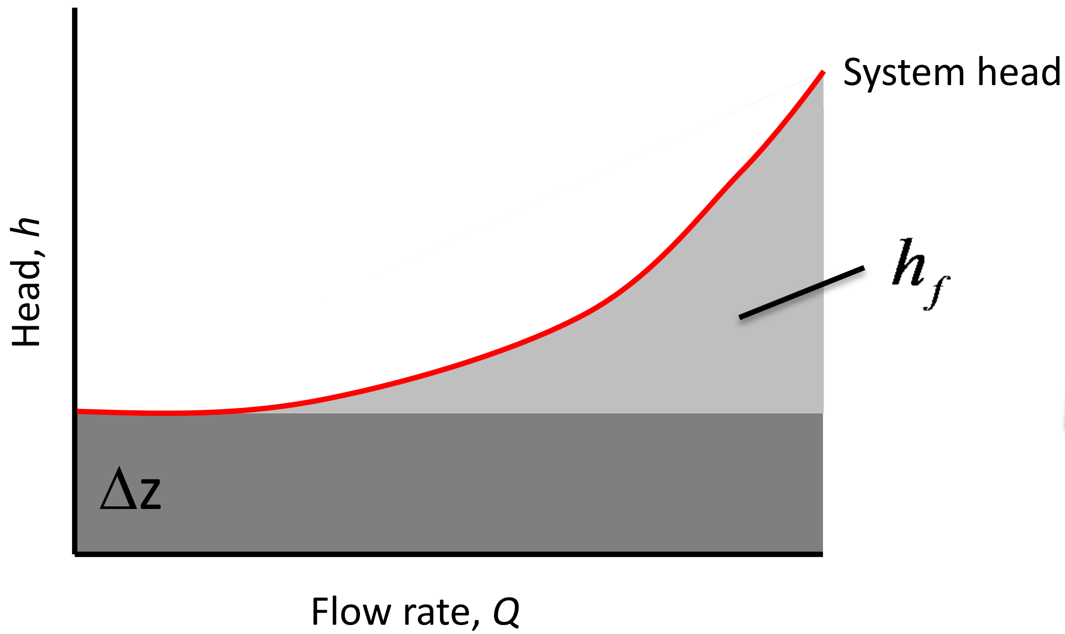
- Frictional losses:



System head vs. flow rate

As the volumetric flow rate through the system increases, the system head will also increase

This increase in head is largely due to increase in frictional losses which arise at higher velocities

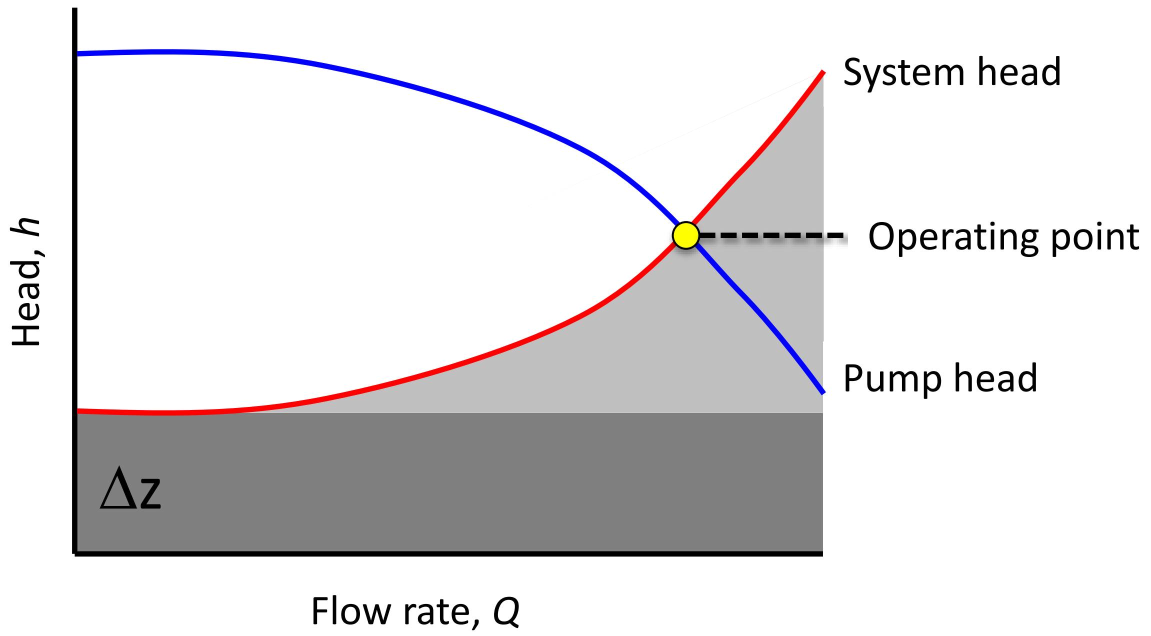


Velocity head is not present in this diagram since the velocity at each of the free surfaces is zero. Pressure is not present as both tanks are open to atmosphere

Determining the operating point

As we've already seen in the pump curves, the head of the pump decreases with increasing flow rate

Since the system head and the pump head have to be equal, the operating point of a flow system is where these two lines intersect



Determining the operating point

Remember that each pump comes with its own unique pump curve

Therefore, you must select a pump that crosses the system head curve at as close to the desired flow rate as possible

However, it is unlikely you will get an exact match

For systems where the exact flow rate is not necessary, this is OK

But what do you do if the necessary flow rate is critical?

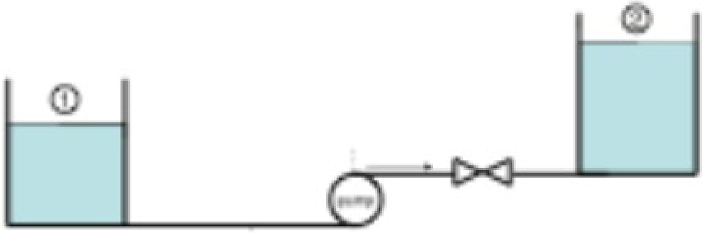
Throttling the pump

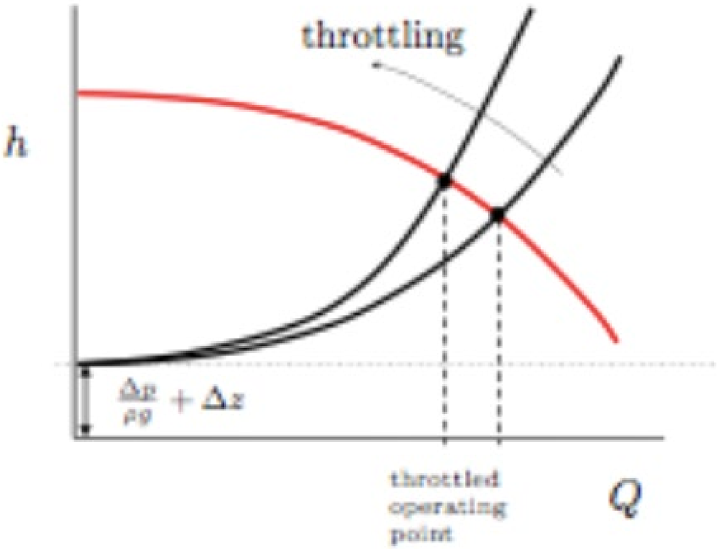
If you require an exact flow rate, you can throttle the pump

In this scenario you add additional frictional losses into the system (usually by means of a valve)

By adjusting how open the valve is, you adjust the minor losses in the system

This enables you to achieve the desired flow rate





Summary

The operation point of a flow system occurs when the system head is equal to the pump head

- The system head is determined by the mechanical energy balance
- The pump head is provided to you in the form of a pump curve

A pump curve is a plot of pump head (mechanical energy imparted to the fluid) versus volumetric flow rate

By selecting the appropriate pump (and potentially throttling the pump) you can achieve the desired flow rate for your system

It is often best to select a pump that is also operating near its best efficiency point at the desired flow rate of the system

Pumping of liquids

Topic 4.4

Cavitation &

Net positive suction head

Boiling point and elevation

Why does water boil at lower temperatures at higher elevations?

- At sea level, water boils at 100°C
- In Denver, Colorado (a city that is 2 kilometers above sea level), water boils at 95°C

My water boils at 95°C!

Denver, Colorado, USA

My water boils at 100°C!

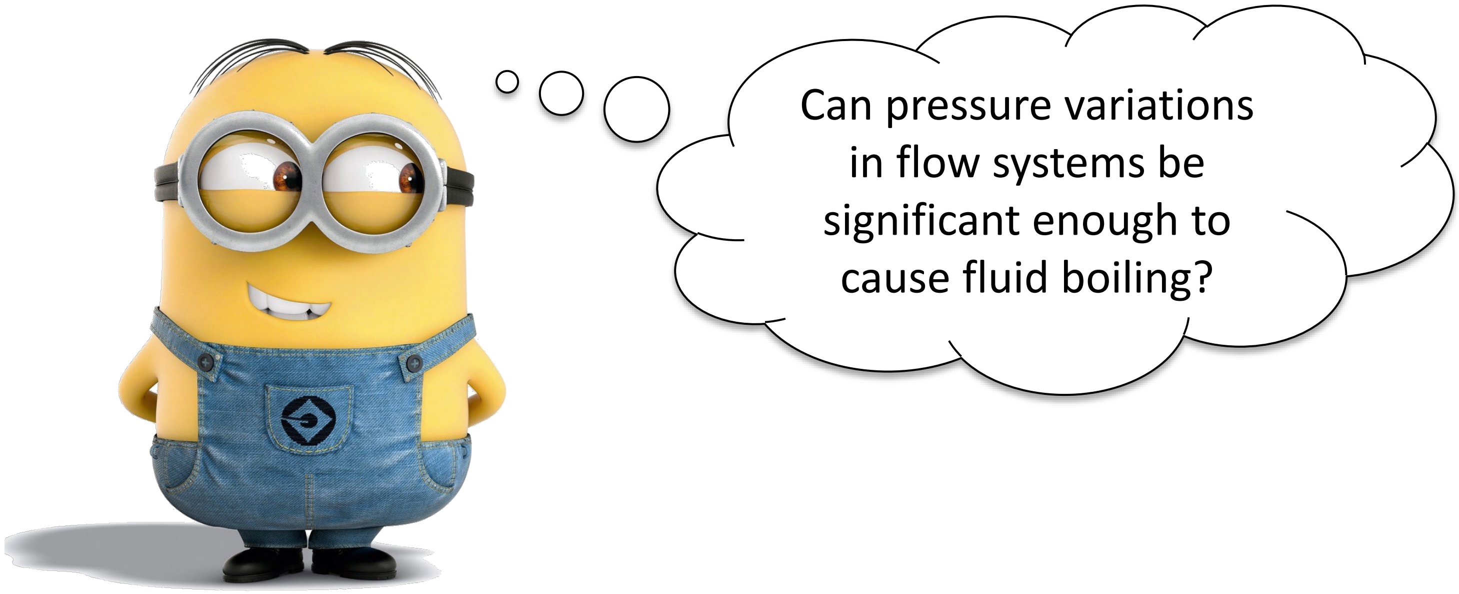
Sea level

Boiling point and pressure

A strong relationship exists between vapour pressure and boiling point

As the pressure decreases, a fluid boils at lower temperatures

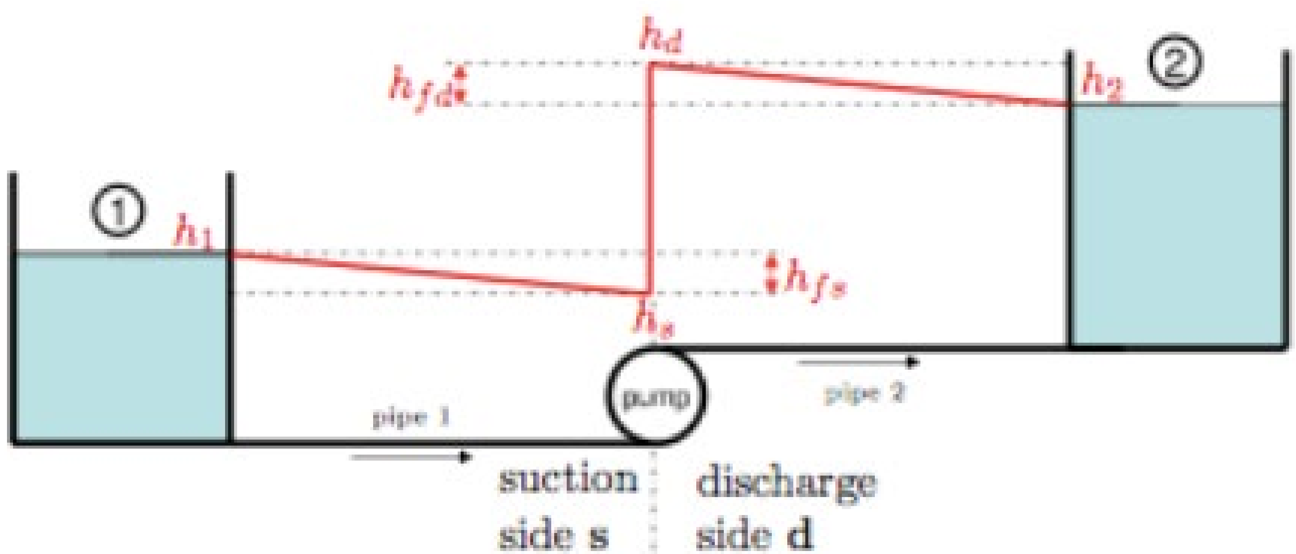
In pumping systems, we can have significant variations in pressure along the length of the pipe



Cavitation

A pump creates a pressure differential in a system, and the minimum pressure will be located at the suction side of the pump

If the pressure goes too low (below the vapor pressure of the fluid) the liquid you are pumping will boil and create bubbles



Cavitation

This occurrence is called **cavitation**

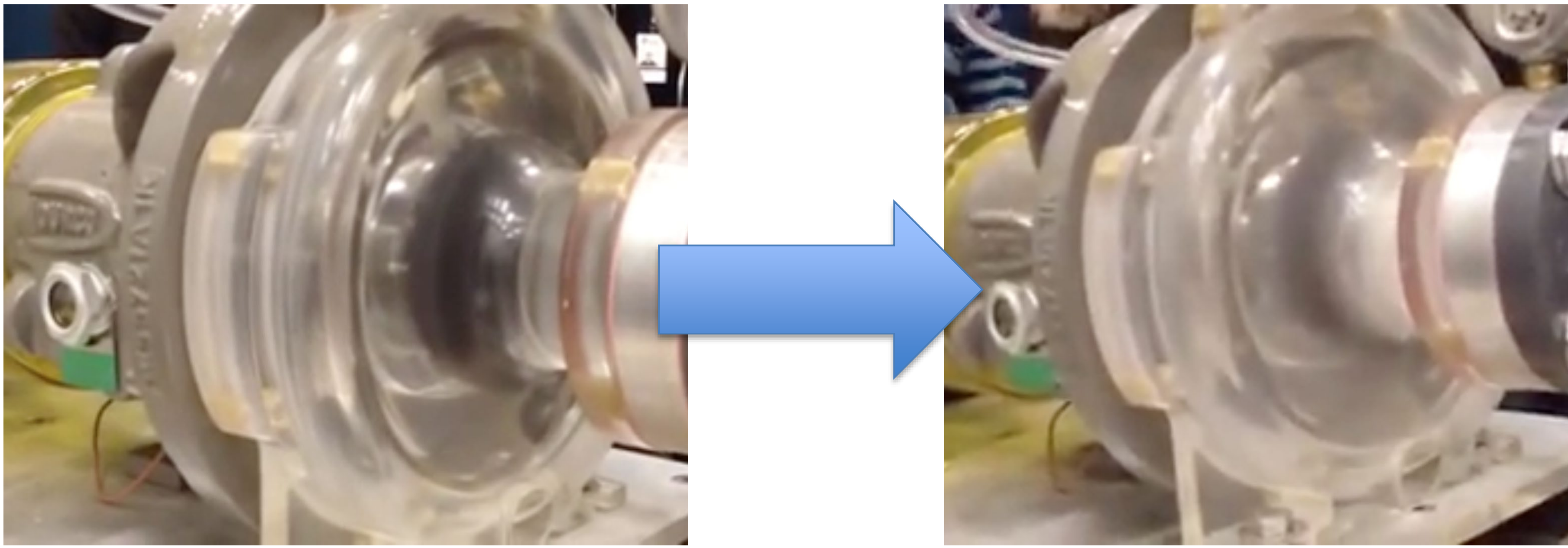
Cavitation has several unwanted consequences

- Creates sudden and unwanted noise and vibration in the system
- Results in loss of head and efficiency
- The formation and collapse of the bubble cause pressure waves in the system that result in mechanical damage to the pump

Cavitation is expensive and dangerous. The pumping system must be designed to avoid cavitation

Cavitation

Here is a video that shows cavitation happening in a variable speed centrifugal pump

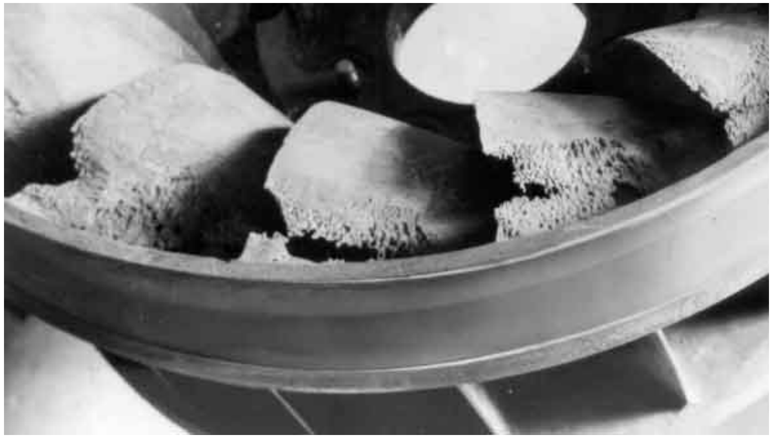


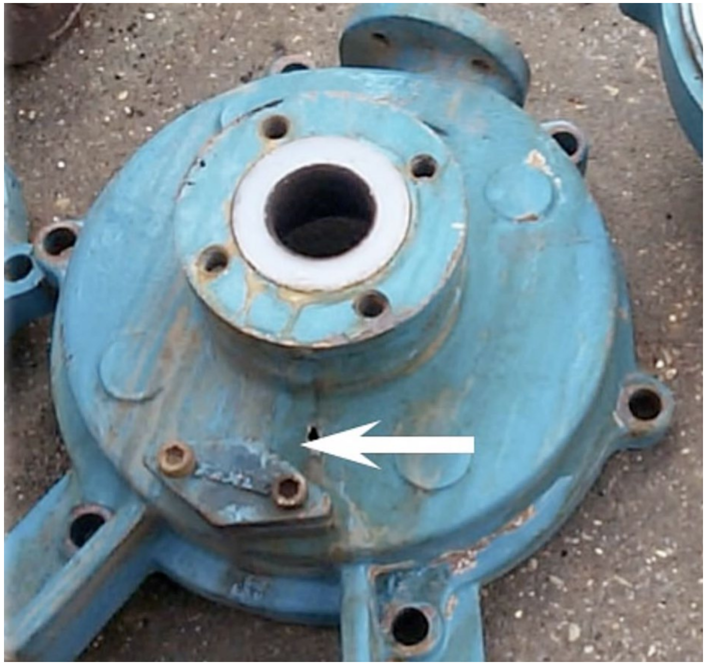
$P_{system} > P_{vp}$ $\qquad$ $P_{system} < P_{vp}$

https://www.youtube.com/watch?v=7vp78sE-AcI

Cavitation

Impeller damage due to cavitation in centrifugal pumps





Pump casing damage due to damage to pump lining. This allowed the acidic fluid being pumped to contact the metal of the casing and eat through it

How do we prevent cavitation?

In order to ensure that cavitation does not occur we must make sure that the pressure on the suction side of the pump is greater than the vapour pressure of the fluid, at the operating temperature

$$\boxed{P_{suction\ side} > P_{vapour\ pressure}}$$

But how do we do that…?

Suction head

Generally, we discuss a fluid's properties in terms of head (or mechanical energy)

- Similarly, when discussing cavitation, we will talk about the fluid in terms of its head
- To avoid cavitation, the fluid head on the suction side of the pump (h_s) must be greater than the vapour pressure head

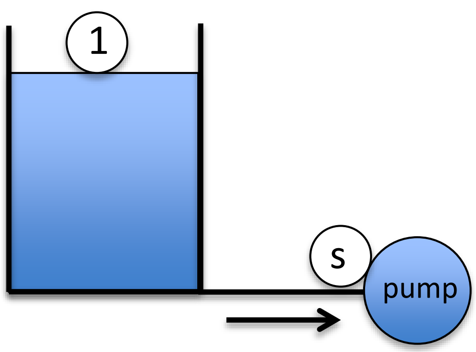
$$\boxed{h_s > \frac{P_{vp}}{\rho g}}$$

Quantifying suction head

We are draining a tank, as shown below

Use the mechanical energy balance to determine the head difference between point 1 and point s, the suction side of the pump

- Point s is located at the centerline of the pump
- Notice the pump is **not** between points 1 & s
- The head at point s (h_s) is equal to the head at point 1 (h_1) minus the head loss of friction on the suction side of the pump (h_{fs})



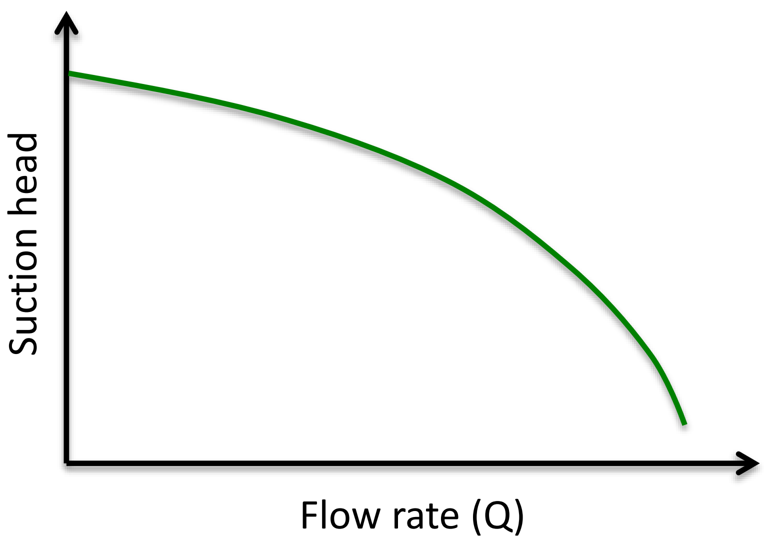
$$h_1 - h_s = h_{fs}$$

$$h_s = \frac{P_1}{\rho g} + z_1 - h_{fs}$$

Suction head vs. Flow rate

The head on the suction side of the pump (h_s) decreases with increasing flow rate

- A lower suction head means you are sucking harder in order to maximize flow rate
  - Think of when you're really thirsty and you suck really hard on a straw to maximize the flow rate of a beverage into your mouth
- This is because the friction on the suction side of the pump increases with flow rate



$$h_s = \frac{P_1}{\rho g} + z_1 - h_{fs}$$

Available net positive suction head

Now we need to compare the vapour pressure head to the suction head to ensure that cavitation will not occur

- The difference between the suction head and the vapour pressure head is called the **net positive suction head**
- More precisely, this is referred to as the **available net positive suction head**

$$NPSH_A = h_s - \frac{P_{vp}}{\rho g}$$

$$\Big\Downarrow \quad h_s = \frac{P_1}{\rho g} + z_1 - h_{fs}$$

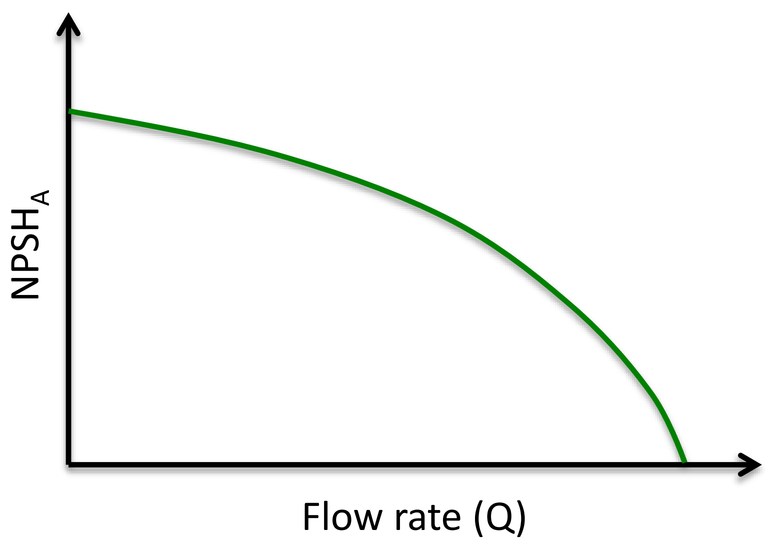
$$NPSH_A = \frac{P_1 - P_{vp}}{\rho g} + z_1 - h_{fs}$$

Available net positive suction head

Available Net Positive Suction Head (**$NPSH_A$**) a measure of how close the fluid at a given point is to cavitation.

You must calculate $NPSH_A$, and it is unique for each pumping system

$NPSH_A$ is calculated by the following equation. Since it is dependent on the vapor pressure, it is a strong function of the fluid you're pumping and the temperature of that fluid



$$NPSH_A = \frac{P - P_{vp}}{\rho g} + z - h_f$$

Net positive suction head

The available net positive suction head is calculated at the inlet of the pump on the suction side

However, the minimum pressure in the system occurs at the pump eye, the centre of the impeller

- The suction head at the impeller eye cannot be calculated
- The suction head at the impeller eye has to be experimentally determined

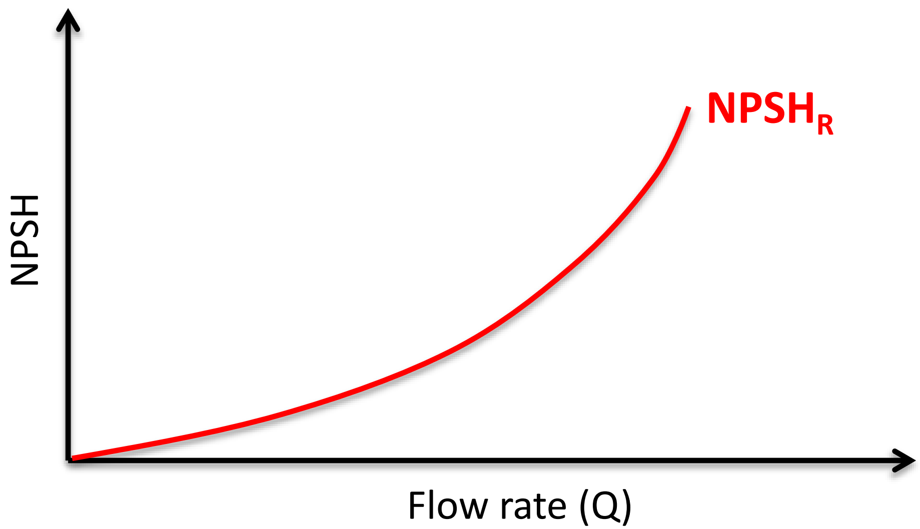
For each pump, the supplier will experimentally measure the suction head at which cavitation occurs, over a range of flow rates

- NPSHA changes with the flow system, while these data are intrinsic to the pump
- The curve generated when these data are plotted are called the **required net positive suction head** (**$NPSH_R$**)

Required net positive suction head

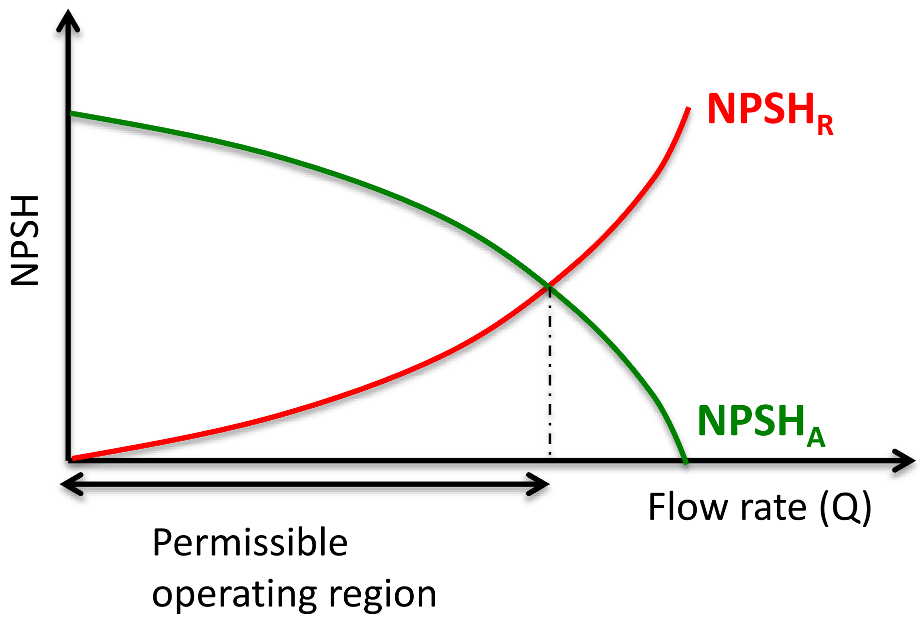
A standard $NPSH_R$ curve has the shape below

Cavitation will occur for combinations of NPSH and Q below the curve



Net positive suction head

By superimposing the **$NPSH_R$** and **$NPSH_A$** graphs, you can determine a **zone of permissible operation**, where $NPSH_A$ is greater than $NPSH_R$



Net positive suction head

Cavitation is avoided by using **Net Positive Suction Head** (**NPSH**)

There are actually two types of net positive suction head:

- **Net positive suction head required** (**$NPSH_R$**)
- **Net positive suction head available** (**$NPSH_A$**)

The available net positive suction head must be greater than the required net positive suction head in order to avoid cavitation

$$\boxed{NPSH_A > NPSH_R}$$

Summary

Pumps are characterized by pump performance curves which plot head versus flow rate

- A fixed speed pump can only operate on that line

When designing a system you will know the desired flow rate of liquid and you can calculate the head loss in the system

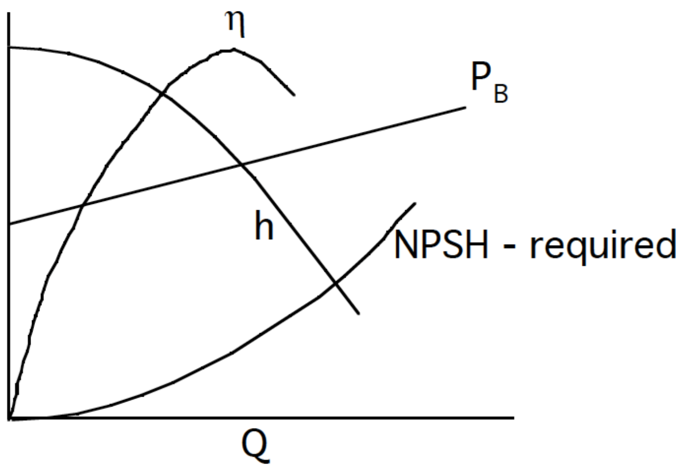
From the pump performance curves you can select a pump that will give you the required flow rate and head to achieve your pumping goals

It is best to choose a pump that operates near its BEP

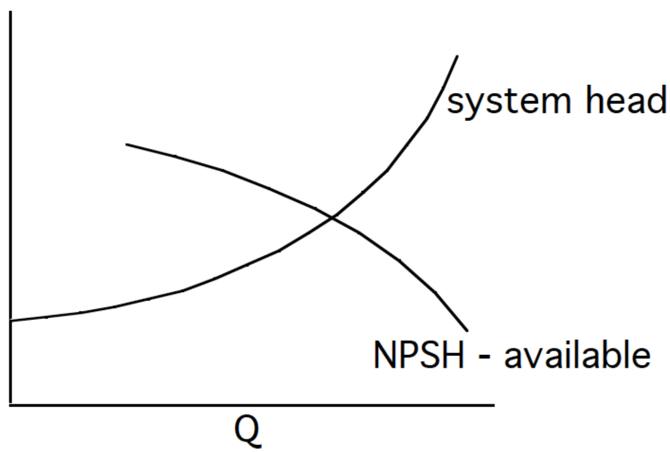
You will also need to calculate the $NPSH_A$ to ensure that cavitation does not occur in your system

Summary

When selecting a pump, a lot of information is provided by the supplier

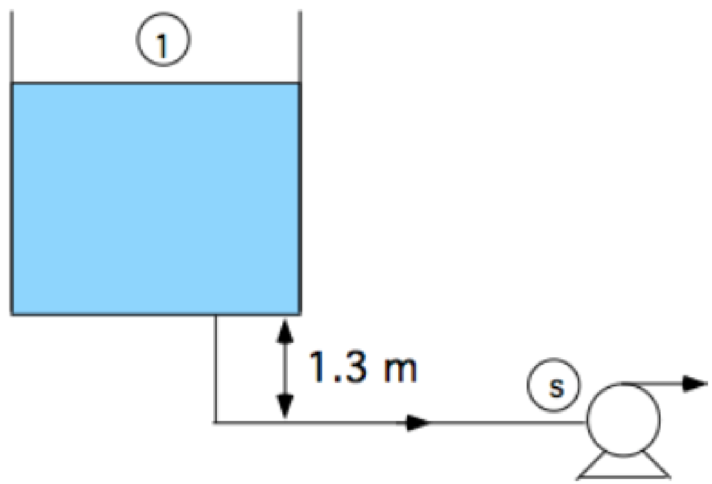


Some information is provided by you, the consumer



Example problem 4.2

You are using a pump to drain a tank, as shown in the sketch below. Find the minimum level of liquid in the tank to prevent cavitation at BEP conditions.



Pipe information

$L = 6$ m (includes minor losses)

$D = 0.05$ m

$e = 0.03$ mm

At BEP

$h_p = 26$ m

$Q = 0.012$ m^3/s

$NPSH_R = 1.4$ m

Fluid property data

$\rho = 1120$ kg/m3

$\mu = 0.0011$ Pa s

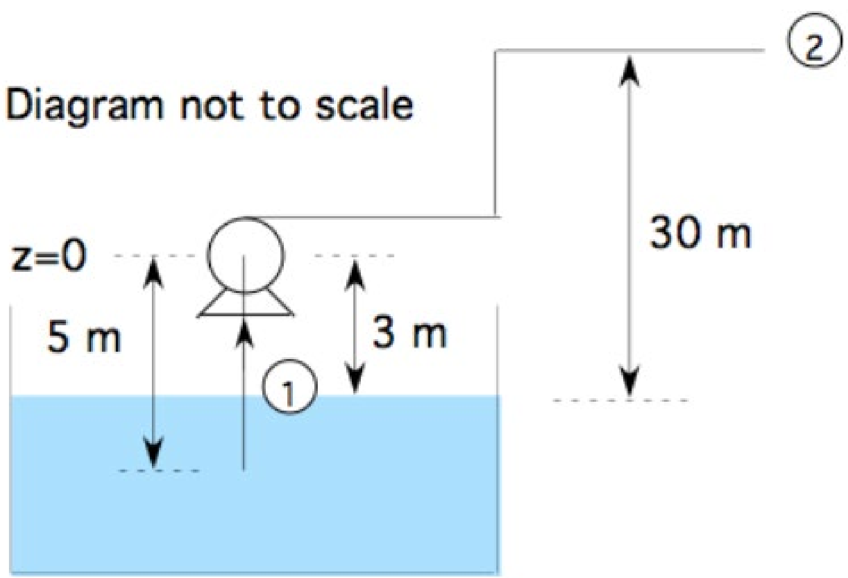
$P_{vap} = 62$ kPa

$P_{atm} = 101$ kPa

Example problem 4.3

You are using a pump to drain a series of tanks as shown below

A. What is the power required to pump at 2 kg/s
B. What is the break power when the mechanical efficiency is 60%
C. What is the gauge pressure at the discharge outlet of the pump
D. What is the system head when the mass flow rate is 2 kg/s
E. What is the available NPSH when the vapour pressure is 13 kPa
F. The pump and suction pipe is to be raised. What is the maximum height of the pump above the liquid surface for no cavitation to occur?



Pipe information

L_d = 100 m

L_s = 5m

D = 5 cm

e = 0.05 mm

K_{elbow} = 0.75

Fluid property data

ρ = 1000 kg/m^3

μ = 0.001 Pa s

P_{atm} = 101.3 kPa