CIVIL-312: Hydraulic Engineering and Infrastructures

Instructor: Prof. Dr. Mirko Musa
Sustainable River Engineering, Energy, & Morphodynamics (STREEM)
GC G1 517 (Bâtiment GC)
E-mail: mirko.musa@epfl.ch

Fall 2025

Announcement

- Tomorrow workshop on EPANET software—will be used in HW1

- First HW will be assigned tomorrow after the workshop and will be due on November 7th (3 weeks *of class* of time)
  - 1 exercise on hydrostatics
  - 1 exercise on pipes
  - 1 simple EPANET application

- Next week you will have time during the exercise session to work on the HW and ask us question—no other exercises will be given that week

Student Quick Feedback

Indicative Feedback on Teaching

This is a preliminary feedback opportunity. The in-depth evaluation will take place at the end of the course, but your feedback now can help identify areas for improvement while the class is still ongoing.

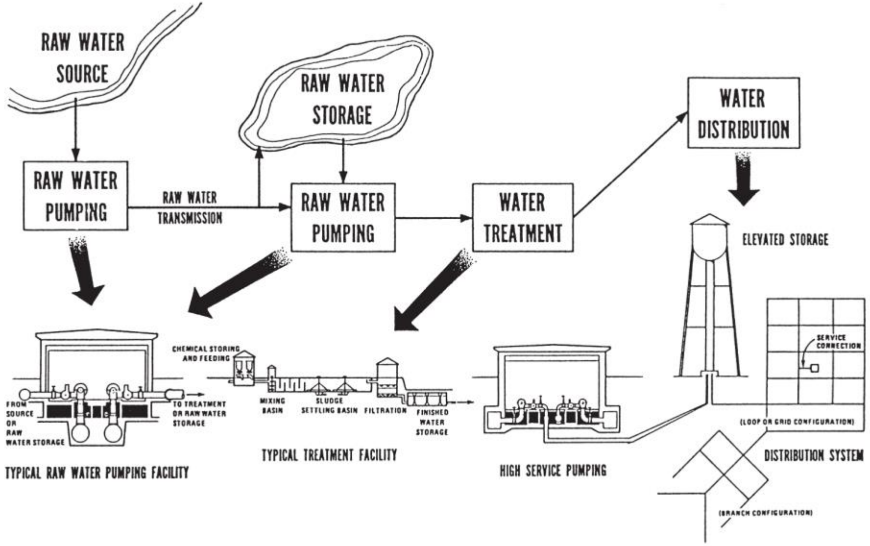
If you wish, please take **5 minutes now** to fill it out.

Otherwise, you can complete it **any time before Sunday, October 12**.

Your input is very much appreciated!

Intro to Pumps

- Water distribution systems have three major components:
  - *Pumping stations*: increase the energy in a water distribution system
  - *Distribution storage*: closely associated with water tanks (either at the ground or in elevation), they i) equalized pump discharge near an efficient point operation point in spite of varying demands, ii) provide supply during high system demands or emergencies, iii) dampen hydraulic transients (oscillations), etc.
  - *Distribution piping*: the pipes that constitute the networks and carry water.

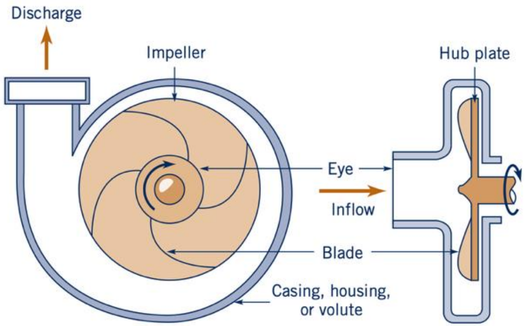


Example of functional components of a water utility

Note: the MSc course **"Water resources engineering and management"** (CIVIL-466, Prof Perona), focuses on designing and managing water systems to ensure sustainable use for both human and environmental needs.

Intro to Pumps

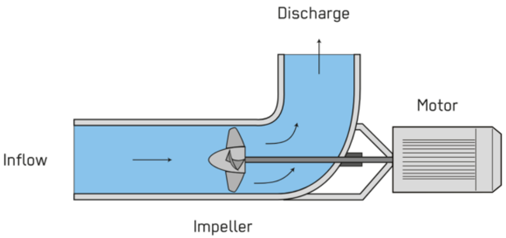
- The most commonly used are *centrifugal pumps*
  - consist of a **stationary casing** and an **impeller** mounted on a rotating shaft. The casing provides a pressure boundary for the pump and contains channels to properly direct the suction and discharge flow. The impeller consists of a number of blades (usually curved)
  - **The impeller energizes the flow, providing HEAD**.



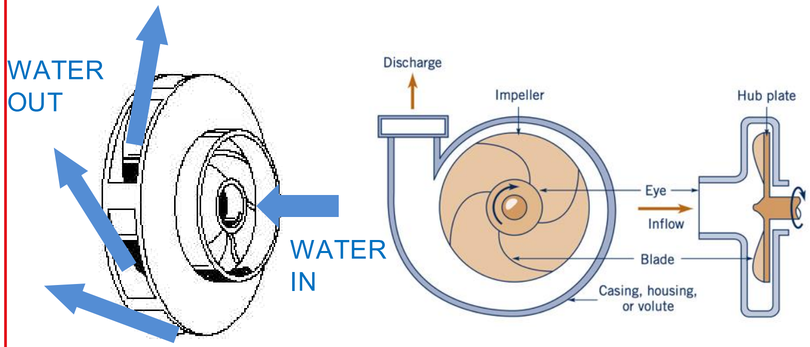
- Three types of centrifugal pumps:

Most common!

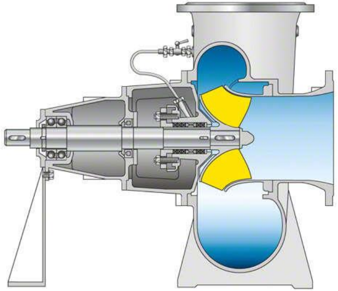
1) *Axial-Flow pumps (or propeller pumps)* – displaces fluid axially in the pump



2) *Radial-flow pumps* -- pump displaces fluid radially (does not scoop water

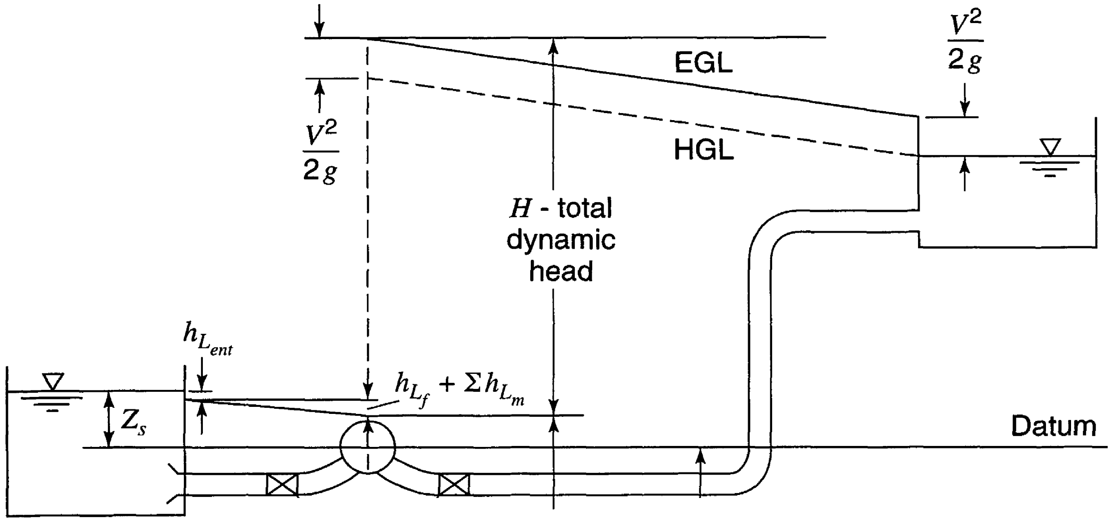


3) *Mixed-flow pumps* -- borrow characteristics from both radial flow and axial flow pumps



Some useful definitions

- *Pump capacity*: flow rate or discharge (Q) of the pump in m³/s
- The *head* is a measure of the **energy per unit weight of fluid** that the pump adds to the flow, or, **how high the pump can raise the fluid** (always accounting for the losses)



System and Pump Performance Curves

- A pump operates against a system: **A system** is the collection of pipes and fittings through which water is being discharged (i.e., the network).

- A system generates flow resistance. The greater the resistance of the system, the lower the discharge rate from the pump.

- For a given length of pipe, *L*, of constant diameter, *D*, the total energy loss is:

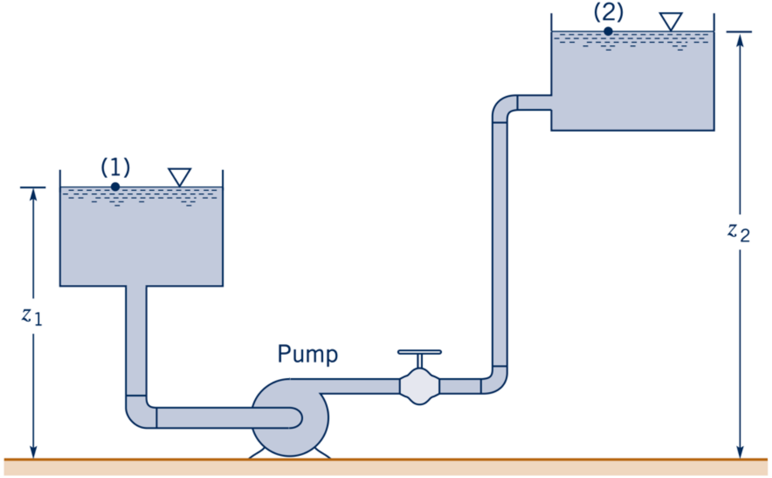
$$h_f = \frac{\mathrm{V}^2}{2\mathrm{g}}\left(\frac{\mathrm{fL}}{\mathrm{D}} + \sum K\right)$$

System and Pump Performance Curves

- **The system characteristic curve**

For a a characteristic system, the pump is used to win the resistances in the flow. Through the energy equation we can find an expression for the energy of the system.

Applying energy balance to this simple system here for example:



$$\frac{P_1}{\gamma} + \frac{V_1^2}{2g} + z_1 + h_p = \frac{P_2}{\gamma} + \frac{V_2^2}{2g} + z_2 + \sum h_f$$

$$z_1 + h_p = +z_2 + \sum h_f$$

The terms other than the pump head is the energy that the system will gain from the pump

$$h_{sys} = z_2 - z_1 + \sum h_f$$

System and Pump Performance Curves

- **The system characteristic curve**

$$h_{sys} = z_2 - z_1 + \sum h_f$$

We know from last week that $h_f \propto Q^2$, so:

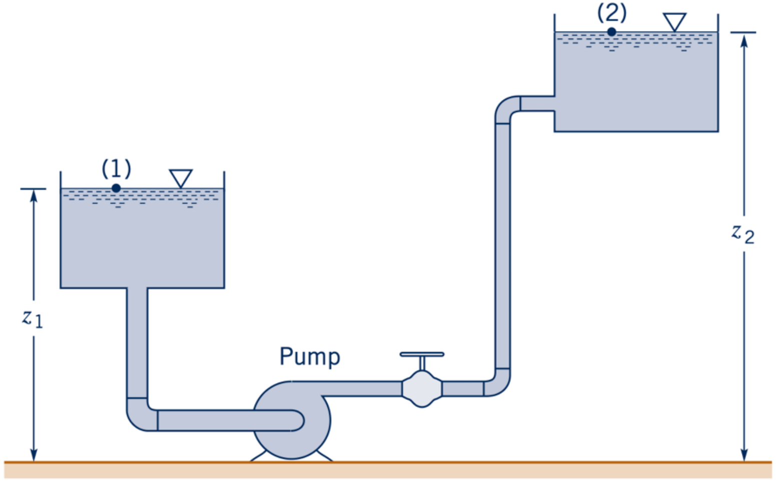
$$h_{sys} = z_2 - z_1 + KQ^2$$

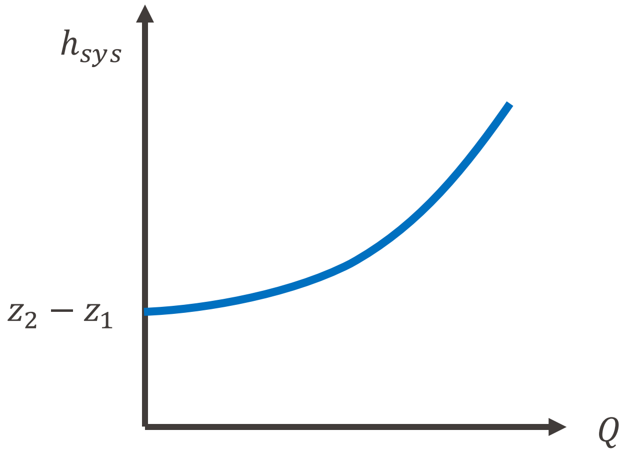
where K depends on the pipe sizes and lengths, friction factors, and minor loss coefficients.

For a given system, z and K are going to be constants so you can see that the *system equation* ha a quadratic form

$$h_{sys} = a + bQ^2$$

Each flow system has its own specific system equation.





System and Pump Performance Curves

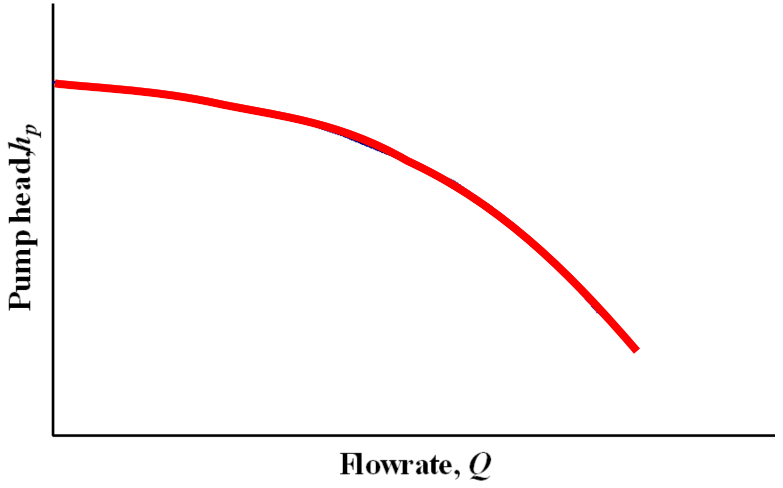
- **Pump performance curve** (also referred to as pump characteristic curve)

The pump has its own unique relationship between the actual pump head gained by the fluid and the flowrate, which is governed by the pump design.

Therefore it is independent from the the *system* and it only depends on the characteristics of the pump (type and geometry.)

Equations for **pump characteristic curves** are generally second order polynomials of the form:

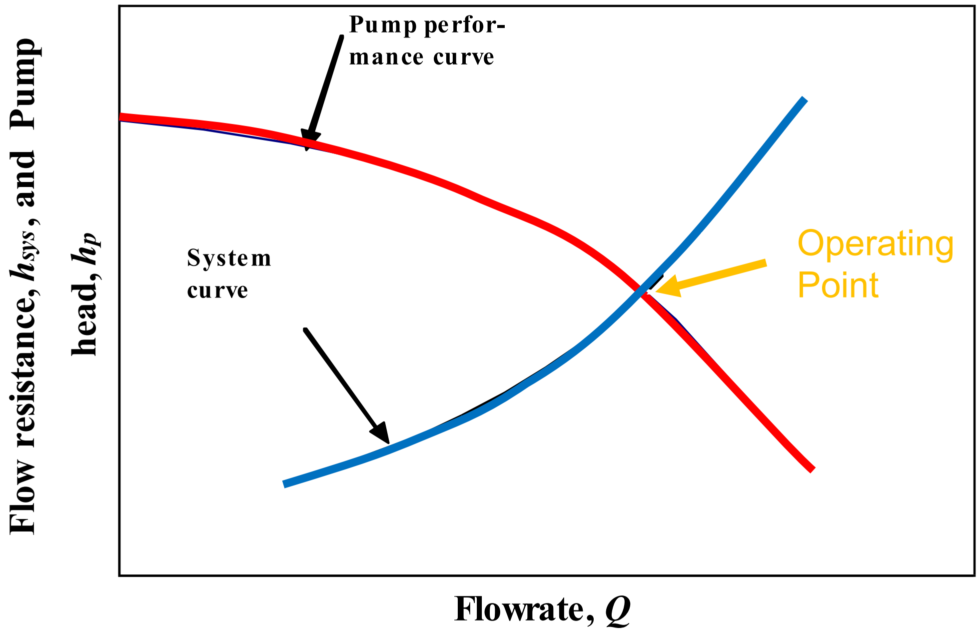
$$h_p = c - dQ - eQ^2$$



where *c, d* and *e* are constants for the pump in question. Pump performance curves are derived experimentally by pump manufactures.

System and Pump Performance Curves

So a typical pump performance curve along with the system curve looks like this:

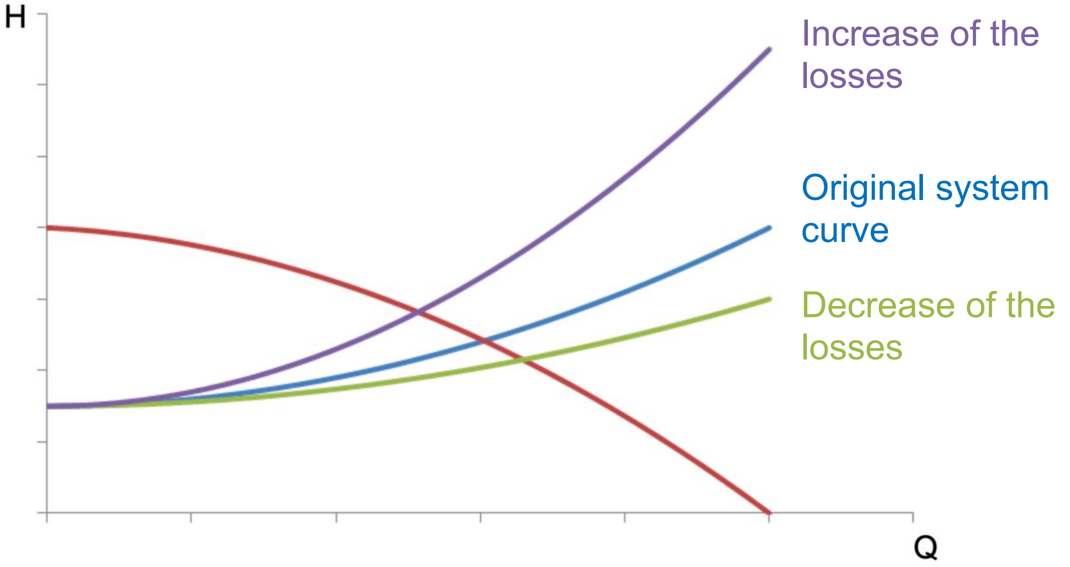


The point at which the two curves intersect is called the "**operating point**."

The operating point tells us what the discharge through a prescribed system will be if the pump represented by the pump performance curve is used in the system.

System and Pump Performance Curves

If something changes in the system, like the losses increase or decrease, the system curve changes accordingly:

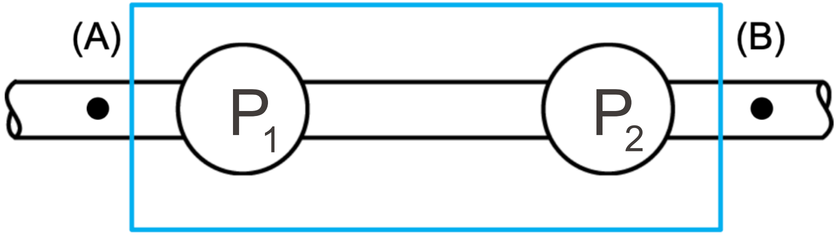


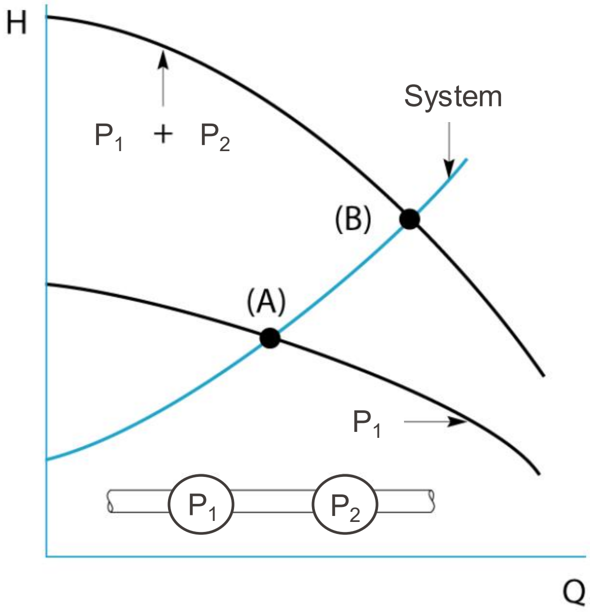
Pumps in Series and Parallel

For situations with a range of H and Q requirements, one pump might not be enough and so multiple pumps are staged in series or parallel!

- **Pumps in series**

Pumps are used in series when we need a lot of height (height head demand)





- Continuity: same flow rate Q through both

$$Q = Q_1 = Q_2$$

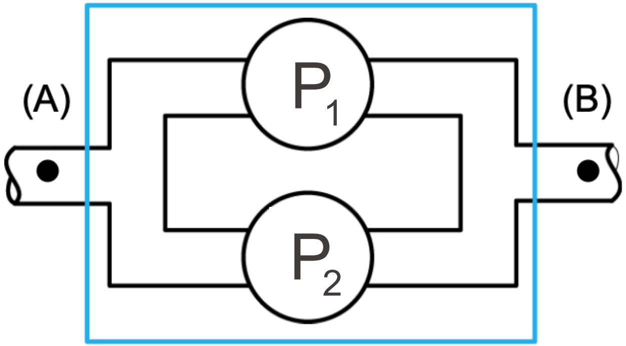
- Energy: the head provided is the sum of the two heads

$$H_{tot} = h_{p_1} + h_{p_2}$$

(very similar concept to pipes in series)

Pumps in Series and Parallel

- **Pumps in parallel**



Pumps are used in parallel when we a large variation in flow demand is required. Pumps are turned on individually to meet the required flow demand and to attain higher operation efficiency

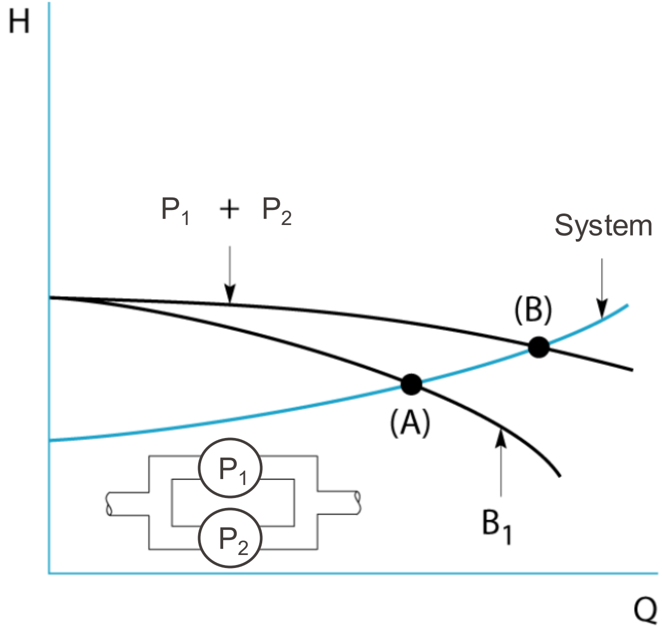
- Continuity: same flow rate Q through both

$$Q = Q_1 + Q_2$$

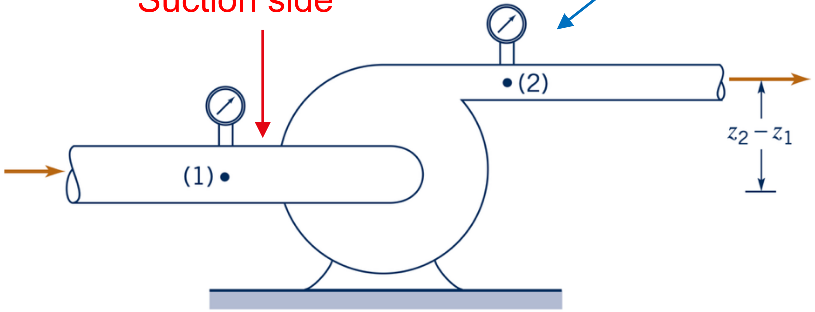
- Energy: the head provided is the sum of the two heads

$$H_{tot} = h_{p_1} = h_{p_2}$$

(again very similar concept to pipes in series)



Pump Performance Curves (continue)



$$\frac{P_1}{\gamma} + \frac{V_1^2}{2g} + z_1 + h_p = \frac{P_2}{\gamma} + \frac{V_2^2}{2g} + z_2 + h_L$$

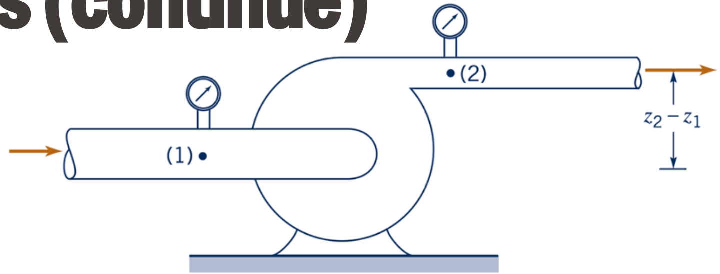
$$h_p - h_L = \frac{P_2 - P_1}{\gamma} + \frac{V_2^2 - V_1^2}{2g} + z_2 - z_1$$

Actual head rise, namely the head of the pump minus the pump head loss

The change in elevation $(z_2 - z_1)$ and velocity $(V_2^2 - V_1^2)$ within the pump are very small, so that the actual head rise corresponds basically to a change in pressure

$$h_a \approx \frac{P_2 - P_1}{\gamma}$$

Pump Performance Curves (continue)



Actual head is

$$h_a \approx h_p - h_L$$

so the **power gained by the fluid** is:

$$P_f = \gamma Q h_a$$

while the power delivered to the impeller (or, the shaft power driving the pump), often referred to as **break power** is given by:

$$P_s = \omega T$$

where ω is the angular velocity of the impeller and T the torque.

If there were no losses, the power of the shaft/impeller P_s would be the equal to the power received by the fluid P_f. Since $P_f < P_s$ due to losses, we then define the efficiency of the turbine as:

$$\eta_P = \frac{P_f}{P_s} = \frac{\gamma Q h_a}{\omega T}$$

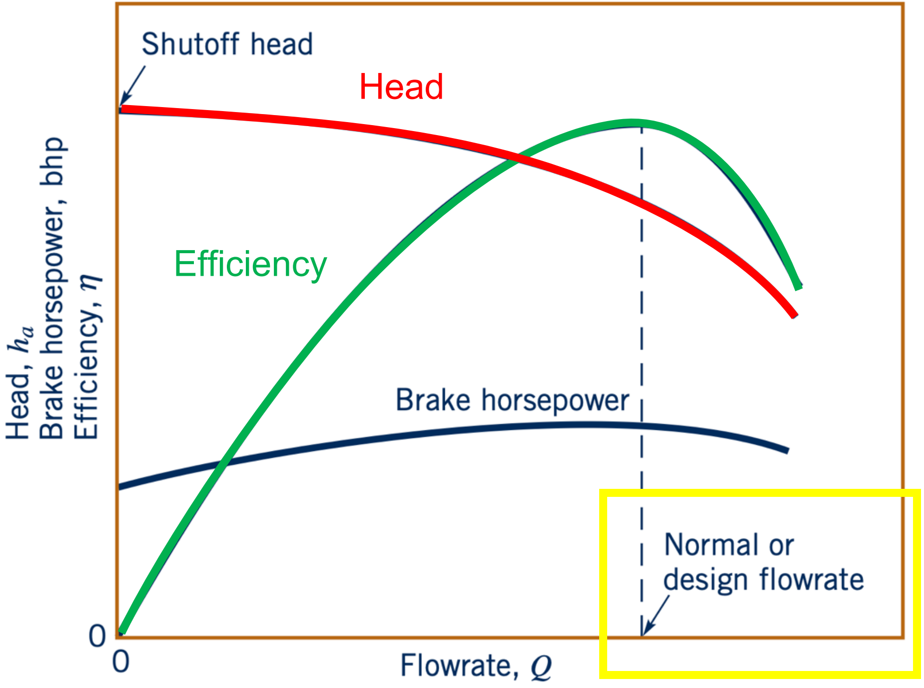
Overall, the efficiency is affected by the hydraulic losses in the pump η_h, the mechanical losses of the machine (bearings, seals, etc.) η_m, and the volumetric losses (i.e., the leakages) η_v

$$\eta_P = \eta_h \eta_m \eta_v$$

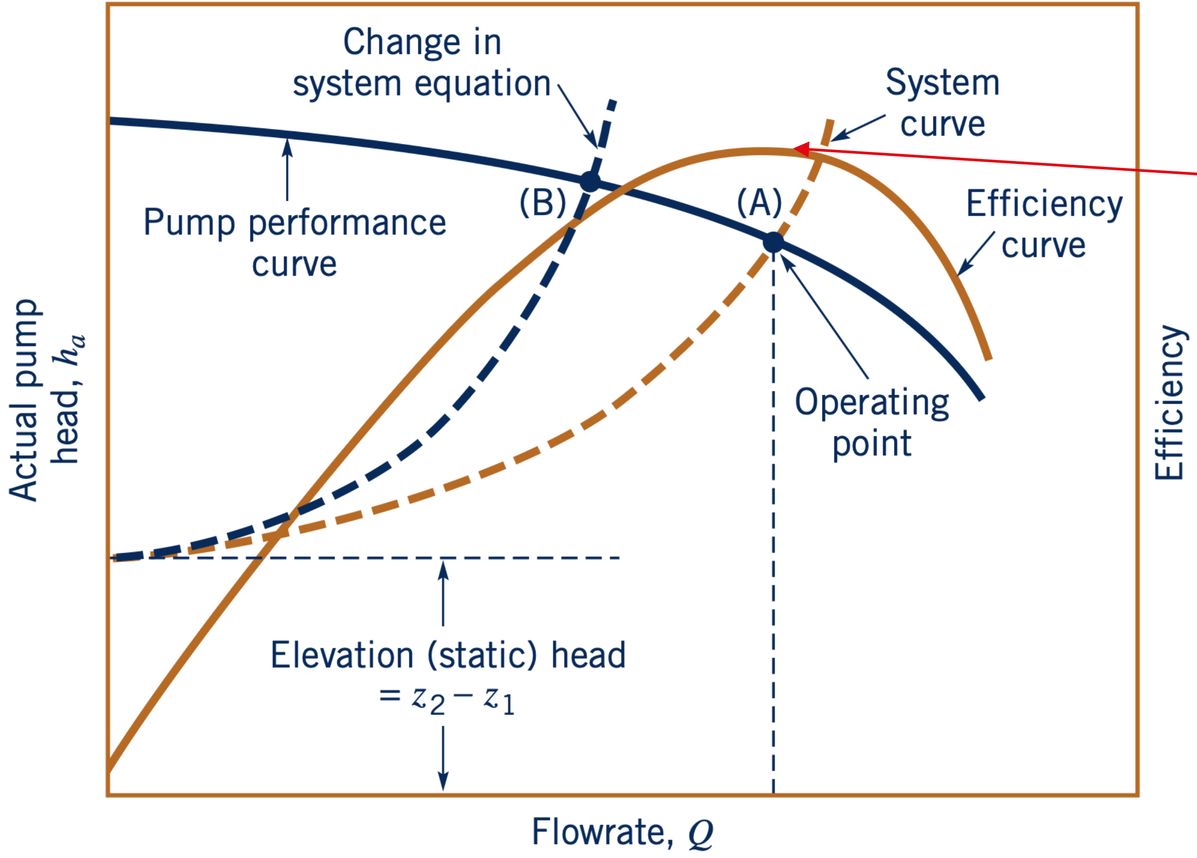
Pump Performance Curves (continue)

Putting together all the characteristic performance curves of a pump:

- H – Q curve: relation between the head and the flow of a pump
- P – Q curve: relation between the power of the pump, or break horsepower, and the flowrate
- η – Q curve: relation between the flow rate and the efficiency of the pump

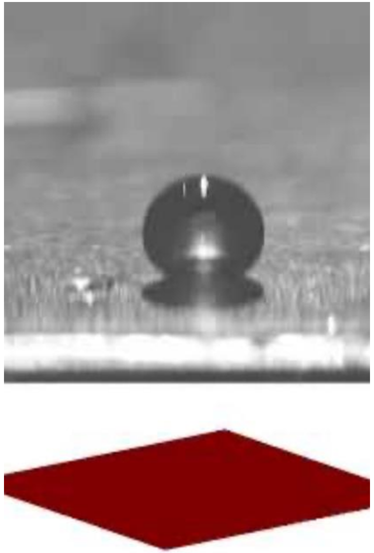


*break horsepower is another way to call the power applied to the shaft of the pump



You typically want the operating point to be closest to the maximum efficiency of the pump

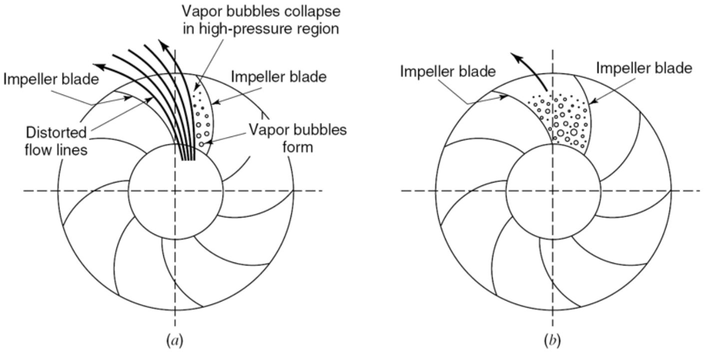
Cavitation and the Net Positive Suction Head



On the suction side of a pump, low pressures are commonly encountered, with the concomitant possibility of cavitation occurring within the pump.

Cavitation occurs when the liquid pressure at a given location is reduced to the vapor pressure of the liquid. When this occurs, vapor bubbles form (the liquid starts to “boil”) and then collapse (condense).

This phenomenon can cause a loss in efficiency as well as structural damage to the pump.



Cavitation and the Net Positive Suction Head

The **Net Positive Suction Head (NPSH)** is the difference between the total head on the suction side of the pump, near the impeller inlet $P_s/\gamma + \frac{V_s}{2g} + z_s$ and the liquid vapor pressure head $\frac{P_v}{\gamma} + z_s$

In other words, the NPSH available at the suction side of a pump ($NPSH_A$) is the difference between the head in the fluid at that point and the head at which vapor cavities begin to form in liquid water (cavitation)

$$NPSH_A = \left(\frac{P_s}{\gamma} + \frac{V_s}{2g} + z_s\right) - \left(\frac{P_v}{\gamma} + z_s\right)$$

Available positive suction head — Head at the suction side of the pump — Head at which vapor cavities begin to form in liquid water

$$NPSH = \frac{P_s}{\gamma} + \frac{V_s}{2g} - \frac{P_v}{\gamma}$$

Note: the pressure used for computing NPSH is typically **absolute** because P_v is given as absolute pressure, meaning that we can't neglect P_{atm} as we usually do!!

P_v is the saturation vapor pressure of water at the temperature of the fluid (tabulated)

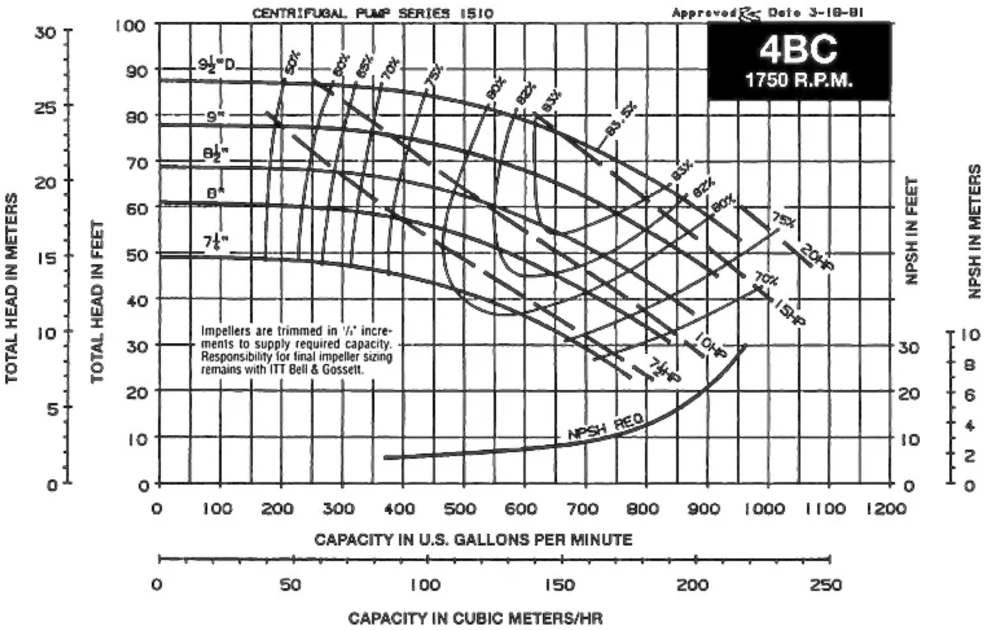
Cavitation and the Net Positive Suction Head

Each pump has a *required* NPSH, or **$NPSH_R$**, which is determined experimentally and provided by manufacturers.

This is the value of net positive suction head that **must be maintained or exceeded** at the suction side for the pump to work and so that cavitation will not occur.

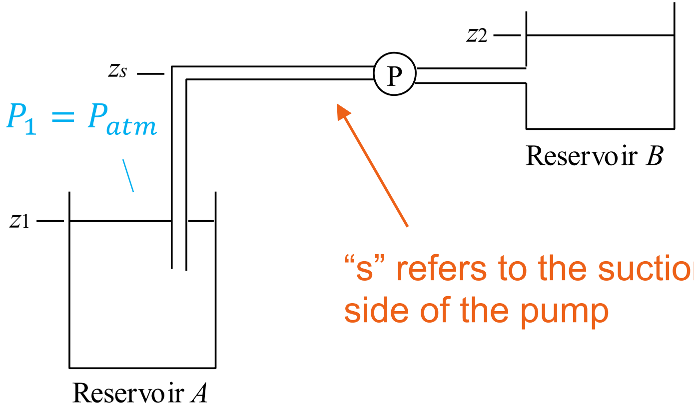
$$NPSH_A \geq NPSH_R$$

1750 RPM PUMP CURVES



Cavitation and the Net Positive Suction Head

Typical example to determine $NPSH_A$:



"s" refers to the suction side of the pump

To get to the head at the suction point (hence to get $NPSH_A$), we apply energy conservation between the first reservoir and the impeller plane:

$$\frac{P_1}{\gamma} + z_1 + \frac{V_1^2}{2g} = \left(\frac{P_s}{\gamma} + \frac{V_s^2}{2g} + z_s\right) + \sum h_{L,1\rightarrow s}$$

$$\left(\frac{P_s}{\gamma} + \frac{V_s^2}{2g} + z_s\right) = \frac{P_1}{\gamma} + z_1 + \frac{V_1^2}{2g} - \sum h_{L,1\rightarrow s}$$

$$NPSH_A = \left(\frac{P_s}{\gamma} + \frac{V_s}{2g} + z_s\right) - \left(\frac{P_v}{\gamma} + z_s\right)$$

$$NPSH_A = \frac{P_1}{\gamma} + z_1 + \frac{V_1^2}{2g} - \sum h_{L,1\rightarrow s} - \left(\frac{P_v}{\gamma} + z_s\right)$$

$$NPSH_A = \frac{P_1 - P_v}{\gamma} + \frac{V_1^2}{2g} + (z_1 - z_s) - \sum h_{L,1\rightarrow s}$$

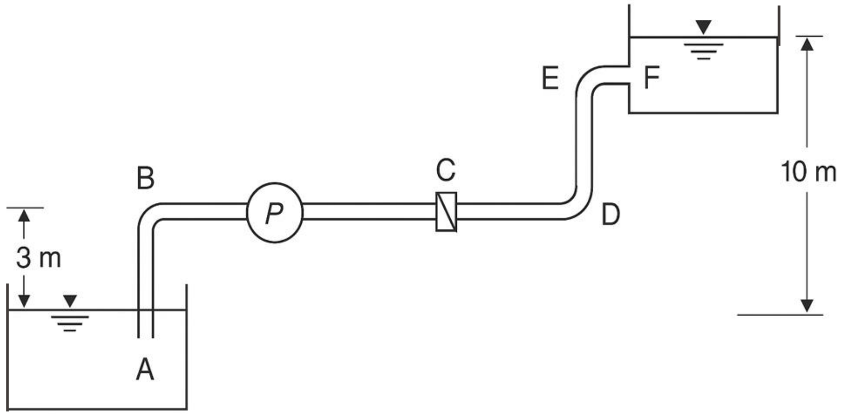
$P_1 = P_{atm} \neq 0$ since we must use the absolute pressure!

Typically = 0

For no cavitation: $NPSH_A \geq NPSH_R$

EPFL

Example



Water ($\nu = 1.00e-6\ m^2/s,\ \gamma = 9789\ N/m^3$) is being pumped from reservoir A to reservoir F through a 30-m-long PVC pipe ($\epsilon = 0$) of diameter 150 mm.

There is an open gate valve ($k_{gv} = 0.2$) located at C; 90° bends (threaded) located at B, D, and E ($k_{bend} = 0.9$); $k_{entr} = 1.0$; $k_{exit} = 1.0$; and the pump performance curve is given by:

$$h_p = 20 - 4713Q^2$$

where h_p is the head added by the pump in meters and Q is the flowrate in m^3/s.
The pump manufacturer has provided a NPSH_R = 2.0 m.

1. Write the energy equation between the upper and lower reservoirs in terms of h_{sys}, f, and Q.
2. Calculate the flowrate and velocity in the pipe. Use the C&W equation to estimate f.
3. What is the net positive suction head if the suction pipe has a length of 10 m? Will cavitation occur in the pump? It's $20°$ C outside. Explain your answer.