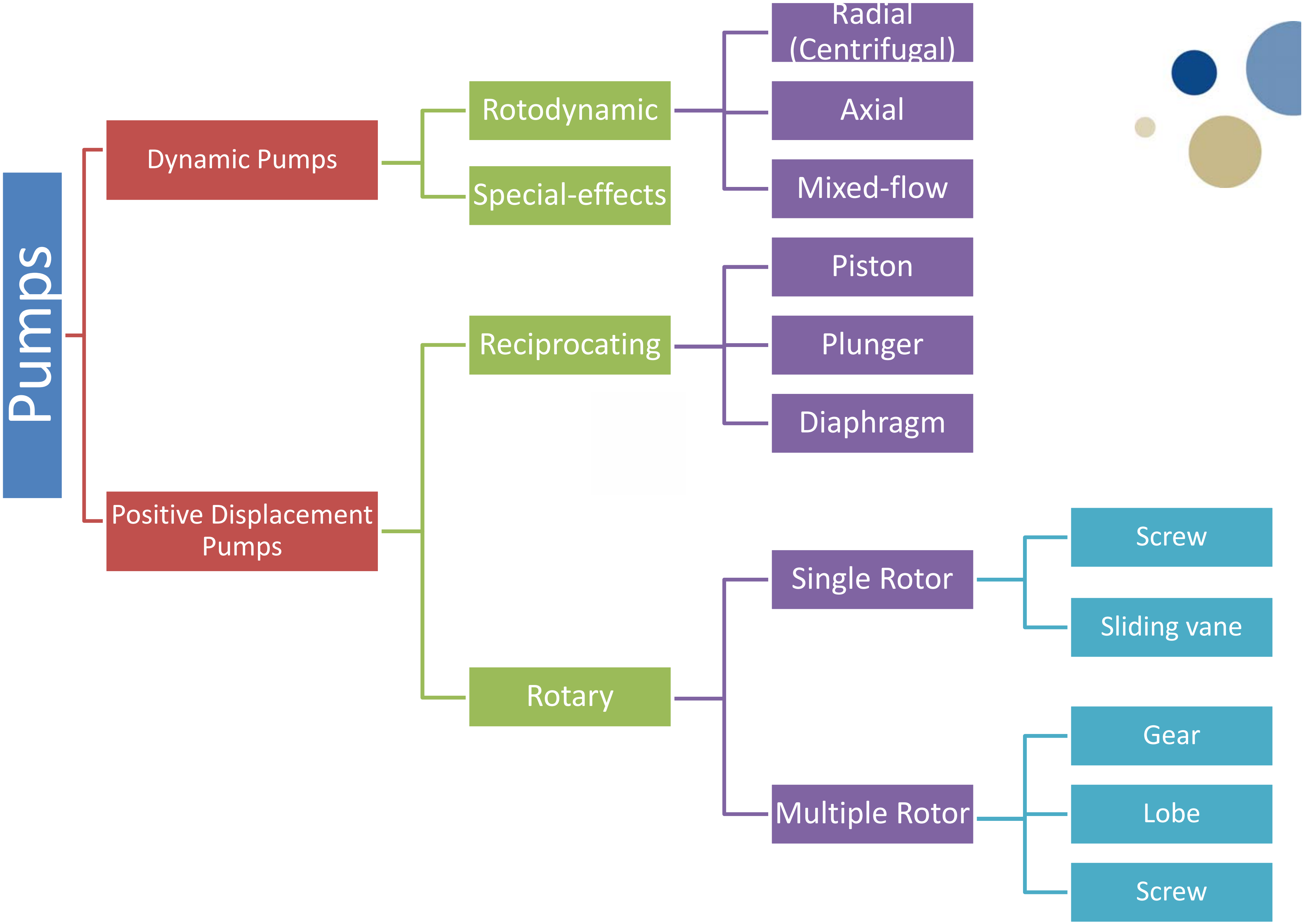
NTNU – Trondheim
Norwegian University of
Science and Technology

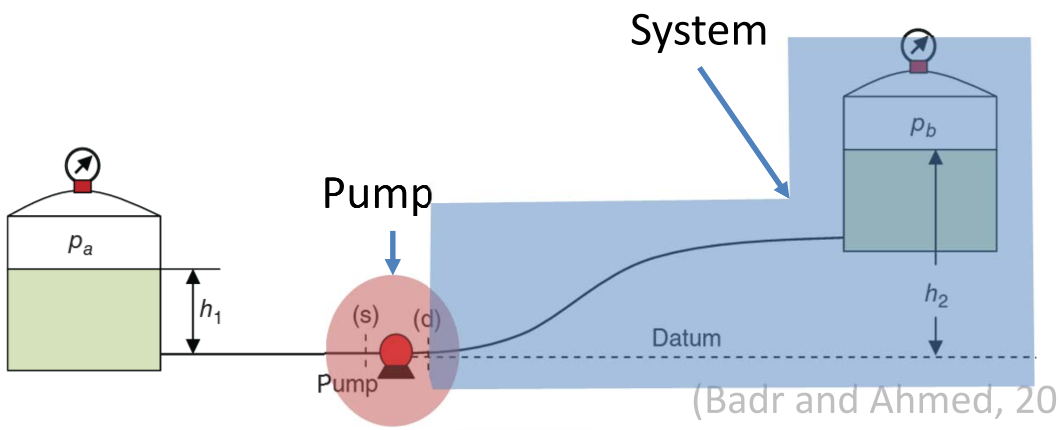
# TPG 4135 Production Technology

## Field Processing and Systems

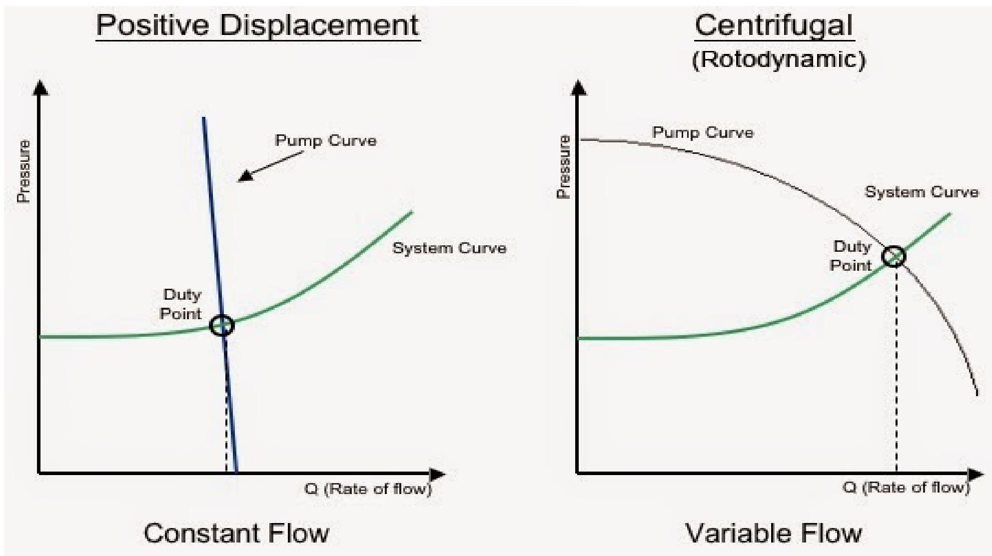
Postdoc Mariana Díaz
03 /26/2019


Pumps
Dynamic Pumps
Positive Displacement Pumps
Rotodynamic
Special-effects
Reciprocating
Rotary
Radial (Centrifugal)
Axial
Mixed-flow
Piston
Plunger
Diaphragm
Single Rotor
Multiple Rotor
Screw
Sliding vane
Gear
Lobe
Screw

# *System characteristic*



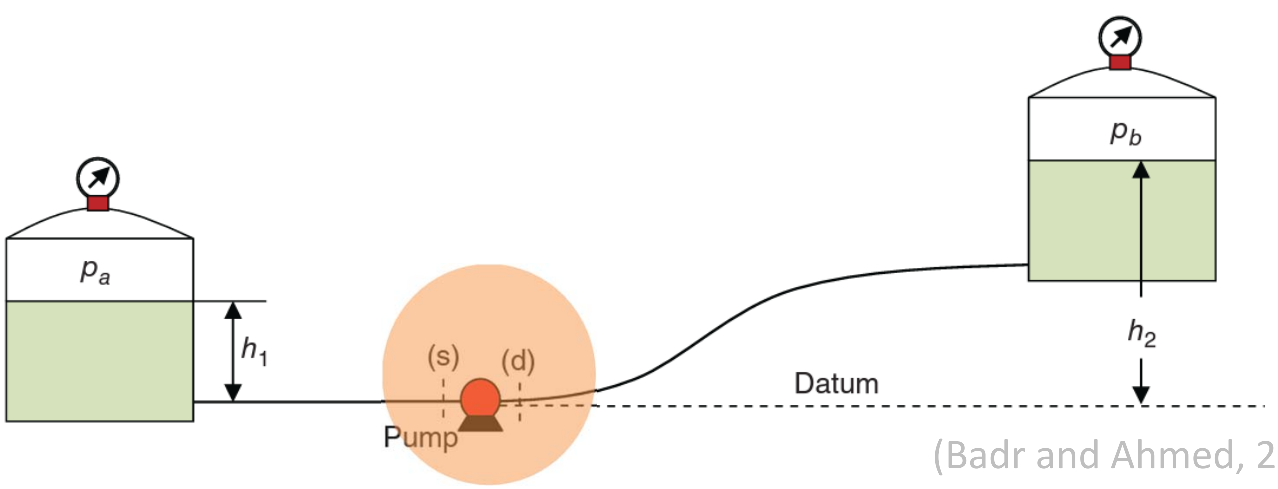

(Badr and Ahmed, 2014)




http://www.hkdivedi.com/2015/05/difference-between-positive-and-non.html

# Definitions and Terminology

2. **Pump Heads**:
   - Pump suction head ($H_s$): pressure head at the pump suction nozzle when the pump is in operating condition
   - Pump delivery head ($H_d$): pressure head at the pump delivery nozzle when the pump is in operating condition
   - Pump total head ($\Delta H$): represents the energy added to the fluid by the pump (between the suction and delivery nozzles) per unit weight of fluid.




(Badr and Ahmed, 2014)

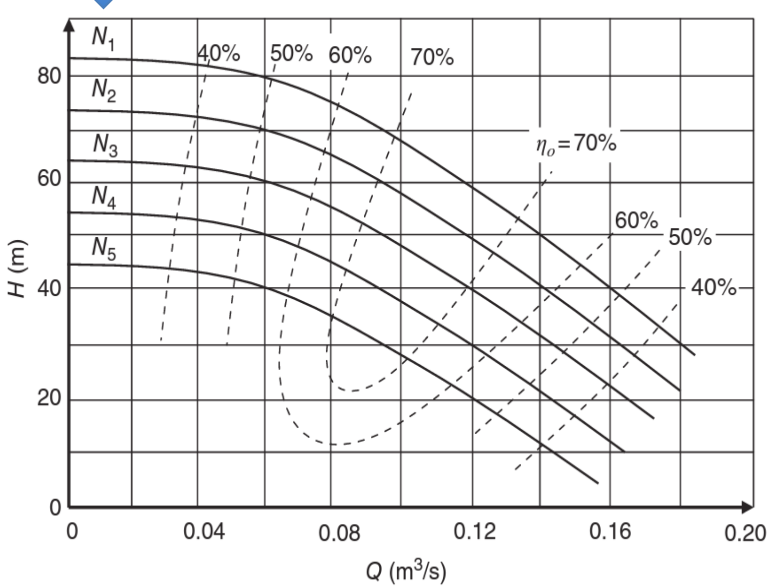
# Definitions and Terminology

## 3. Pump performance characteristics

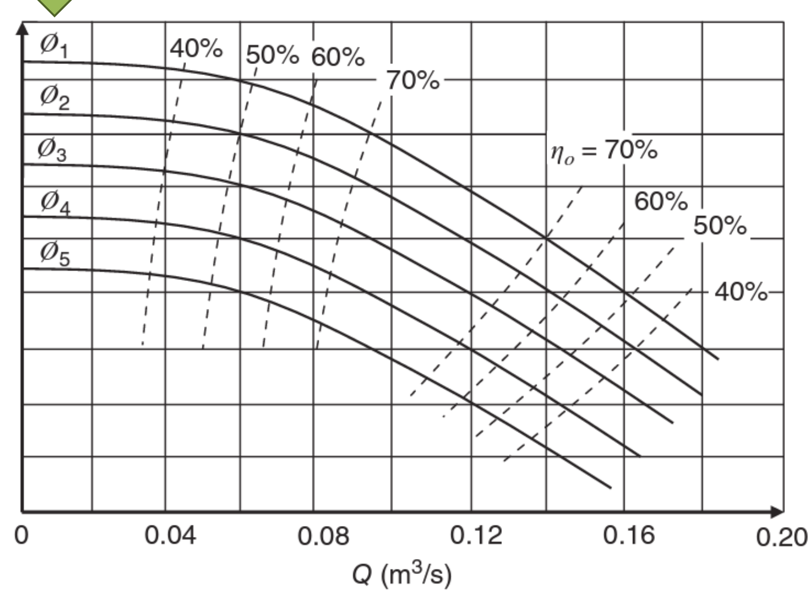
– Presented as a set of **Iso-efficiency curves** at:

- Different speeds
- Different size for geometrically similar pumps at constant speed

*Different speeds*




*Different Impeller Diameter*




*Typical for a radial-type centrifugal pump*

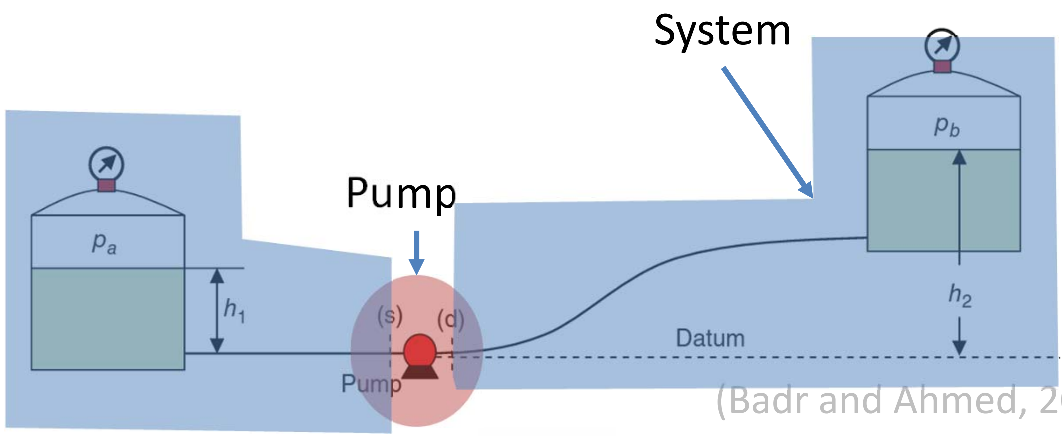


(Badr and Ahmed, 2014)

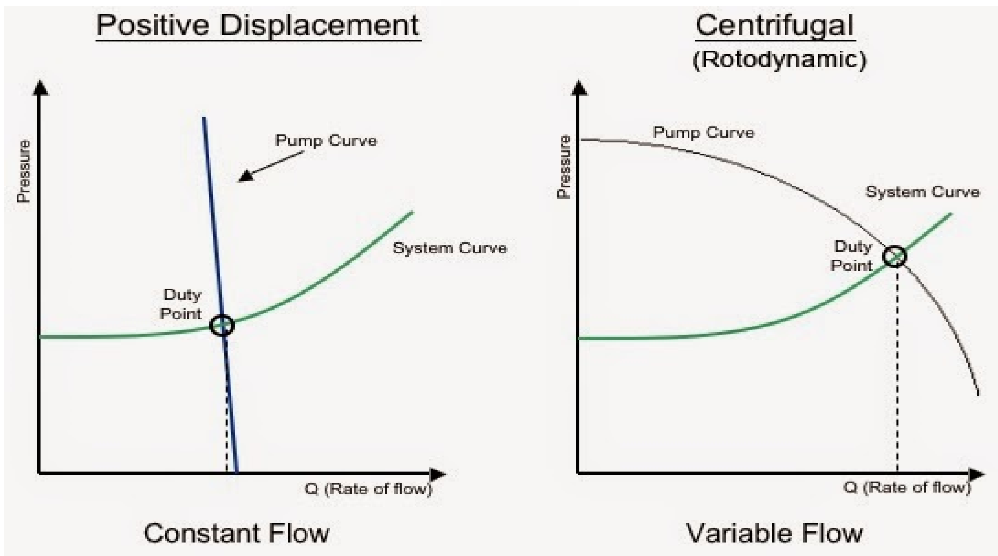
# Definitions and Terminology

4. **Cavitation.** It is the formation of vapor cavities of the liquid being pumped at normal operating temperatures when the static pressure reaches the fluid vapor pressure.
   - **Problems:**
     - Reduces the pump total head and flow rate
     - Reduces the pump overall efficiency
     - Damages impeller and casing walls
     - Creates noise and vibration problems

# System characteristic




(Badr and Ahmed, 2014)




http://www.hkdivedi.com/2015/05/difference-between-positive-and-non.html

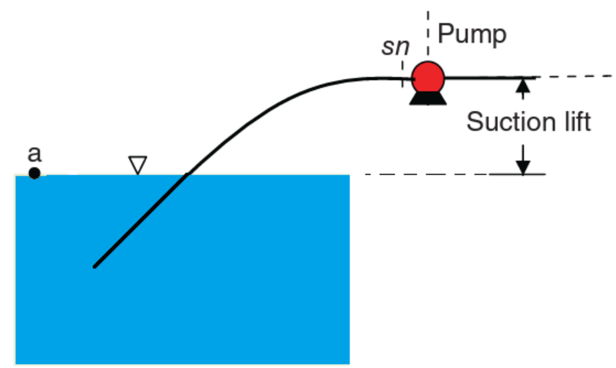
# Definitions and Terminology

5. **Net Positive Suction Head** (NPSHA) **Available**: is the available positive head at the centerline of the pump inlet flange

$$NPSHA = h_{sn} + \frac{V_{sn}^2}{2g} - \frac{P_v}{\rho g}$$

$$h_{sn} + \frac{V_{sn}^2}{2g} = \frac{P_a}{\rho g} - suction\ lift - h_{ls}$$

* sn… inlet of the pump suction nozzle



# Definitions and Terminology

5. **Net Positive Suction Head** (NPSHA) **Available**: is the available positive head at the centerline of the pump inlet flange

$$NPSHA = h_{sn} + \frac{V_{sn}^2}{2g} - \frac{P_v}{\rho g}$$

$$h_{sn} + \frac{V_{sn}^2}{2g} = \frac{P_a}{\rho g} - suction\ lift - h_{ls}$$

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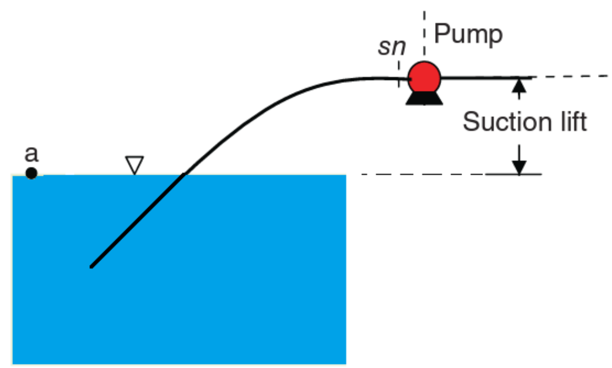
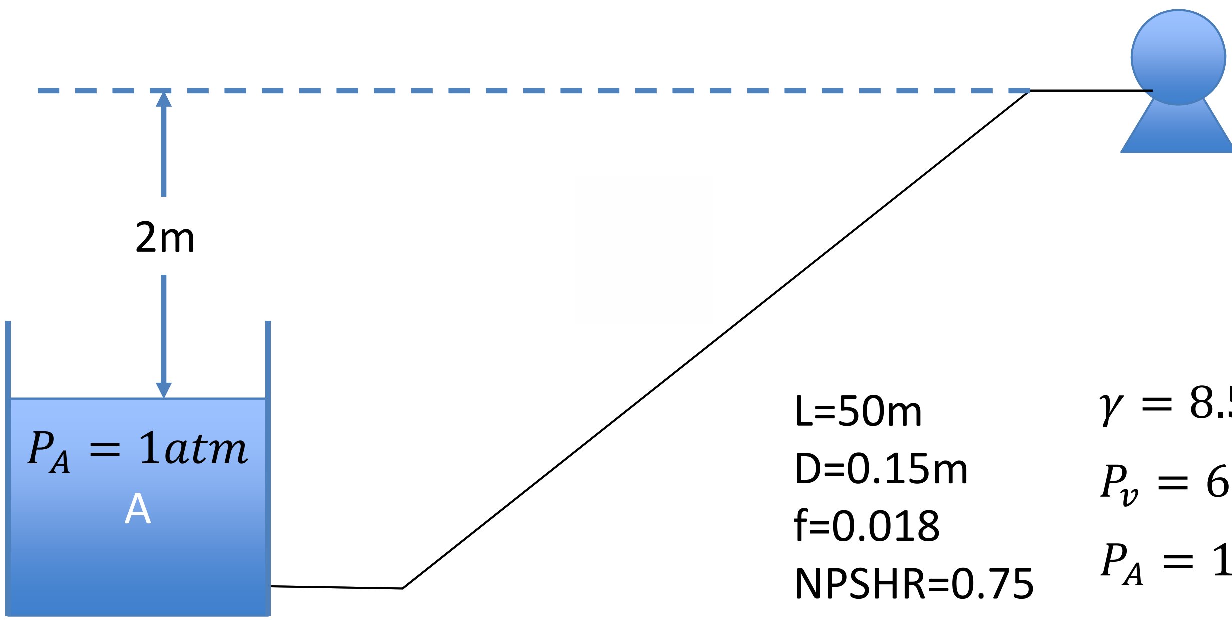



6. **Net Positive Suction Head (NPSHR) Required:** is the positive head specified by a pump manufacturer for proper pump operation.

$$NPSHA > NPSHR \longrightarrow P_{min} > P_v$$

# NPSH Example

$$NPSHA = H_{sn} + \frac{V_{sn}^2}{2g} - \frac{P_v}{\rho g}$$




L=50m
D=0.15m
f=0.018
NPSHR=0.75

$\gamma = 8.5\ kN/m3$

$P_v = 60kPa$

$P_A = 101\ kPa$

$$NPSHA > NPSHR$$

Determine the critical flow

# NPSH Example

$$NPSHA = Hs + \frac{V_{sn}^2}{2g} - \frac{P_v}{\rho g}$$

Calculate the Hs

$$\frac{V_A^2}{2g} + \frac{P_A}{\rho g} + Z_a = \frac{V_s^2}{2g} + \frac{P_s}{\rho g} + Z_s + h_{ls}$$

Hs

$$\frac{V_s^2}{2g} + H_s - \frac{P_v}{\rho g} = \frac{P_A}{\rho g} + (Z_a - Z_s) - h_{ls} - \frac{P_v}{\rho g}$$

$$NPSHA = \frac{P_A}{\rho g} + (Z_a - Z_s) - h_{ls} - \frac{P_v}{\rho g}$$

Calculate the Loss

$$h_{ls} = \frac{fLV^2}{2gD} = \frac{fLQ^2}{2gDA^2} = 979.28Q^2$$

# NPSH Example

$$NPSHA = Hs + \frac{V_{sn}^2}{2g} - \frac{P_v}{\rho g}$$

Calculate NPSHA

$$NPSHA = \frac{P_A}{\rho g} + (Z_a - Z_s) - h_{ls} - \frac{P_v}{\rho g}$$

$$NPSHA = \frac{1kPa}{8.5} + (2m) - 979.28Q^2 - \frac{60kPa}{8.5}$$

$$NPSHA = 2.83 - 979.28Q^2$$

Calculate critical flow

$$NPSHA > NPSHR$$

$$2.83 - 979.28Q^2 > 0.75$$

Critical Flow Rate $Q^2 < 0.046\, m^3/s$

# Definitions and Terminology

7. **Minimum Flow:** the lowest continuous flow at which a manufacturer will guarantee the performance of the pump

8. **Critical Speed:** Speed at which the equipment may vibrate enough to cause damage

# Definitions and Terminology

## 9. Input and Output Power and efficiency:

– Pump input power ($P_m$,BP) is the mechanical power to drive the pump (shaft power or brake power)

$$P_m = BP = Driving\ Torque\ * Angular\ Velocity = T\omega$$

– Pump useful power ($P_u$) represents the shaft power which remains after all losses have been overcome

$$P_u = \dot{m}W = \dot{m}g\Delta H = \rho Q g \Delta H$$

– Hydraulic Power ($P_h$)

$$P_h = P_u = \rho Q g \Delta H$$

(Badr and Ahmed, 2014),
(Nesbitt, 2006)

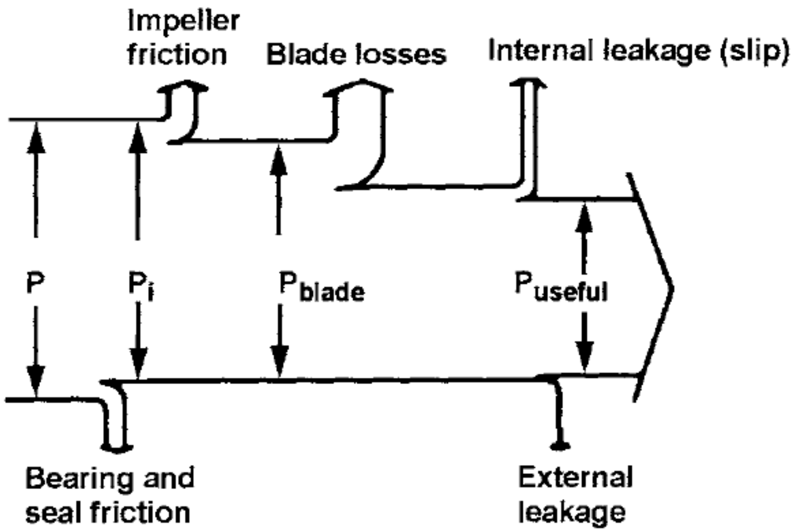
# Definitions and Terminology

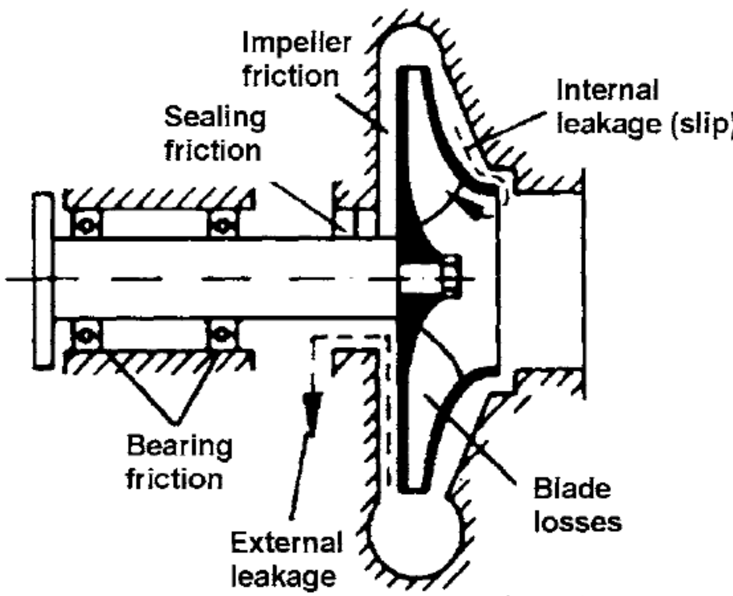
## 6. Input and Output Power and efficiency:

– Pump overall efficiency ($\eta_o$)

$$\eta_o = \frac{P_u}{P_m} = \frac{\rho Q g \Delta H}{BP}$$

$$\eta_o = \eta_m * \eta_i * \eta_c * \eta_v$$




(Nesbitt, 2006)

# Definitions and Terminology

## 6. Input and Output Power and efficiency:

$$\eta_o = \eta_m * \eta_i * \eta_c * \eta_v$$

– Mechanical efficiency ($\eta_m$)

$$\eta_m = \frac{P - P_{jm}}{P}$$

$P_{jm}$…friction resistance in bearings and seals

– Impeller efficiency ($\eta_i$) is a measure of how much of the power available ($P - P_{jm}$) is converted to kinetic energy in the liquid and how much is lost in blade losses and disc friction

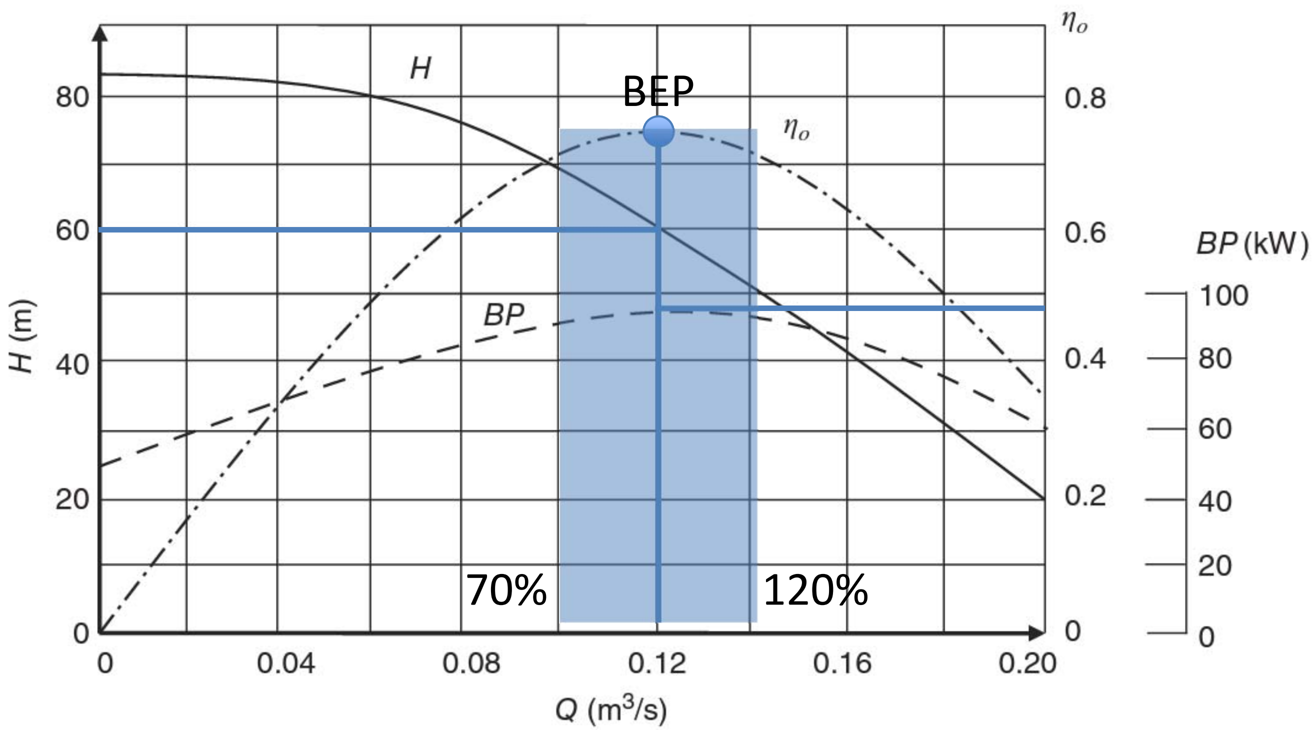
– Casing efficiency ($\eta_c$) is a measure of how much kinetic energy produced by the impeller, is recovery as static pressure rise compared to the losses which appear as temperature increase

– Volumetric efficiency ($\eta_v$) is a measure of how much flow is delivery form the pump discharge compare to the flow through the impeller

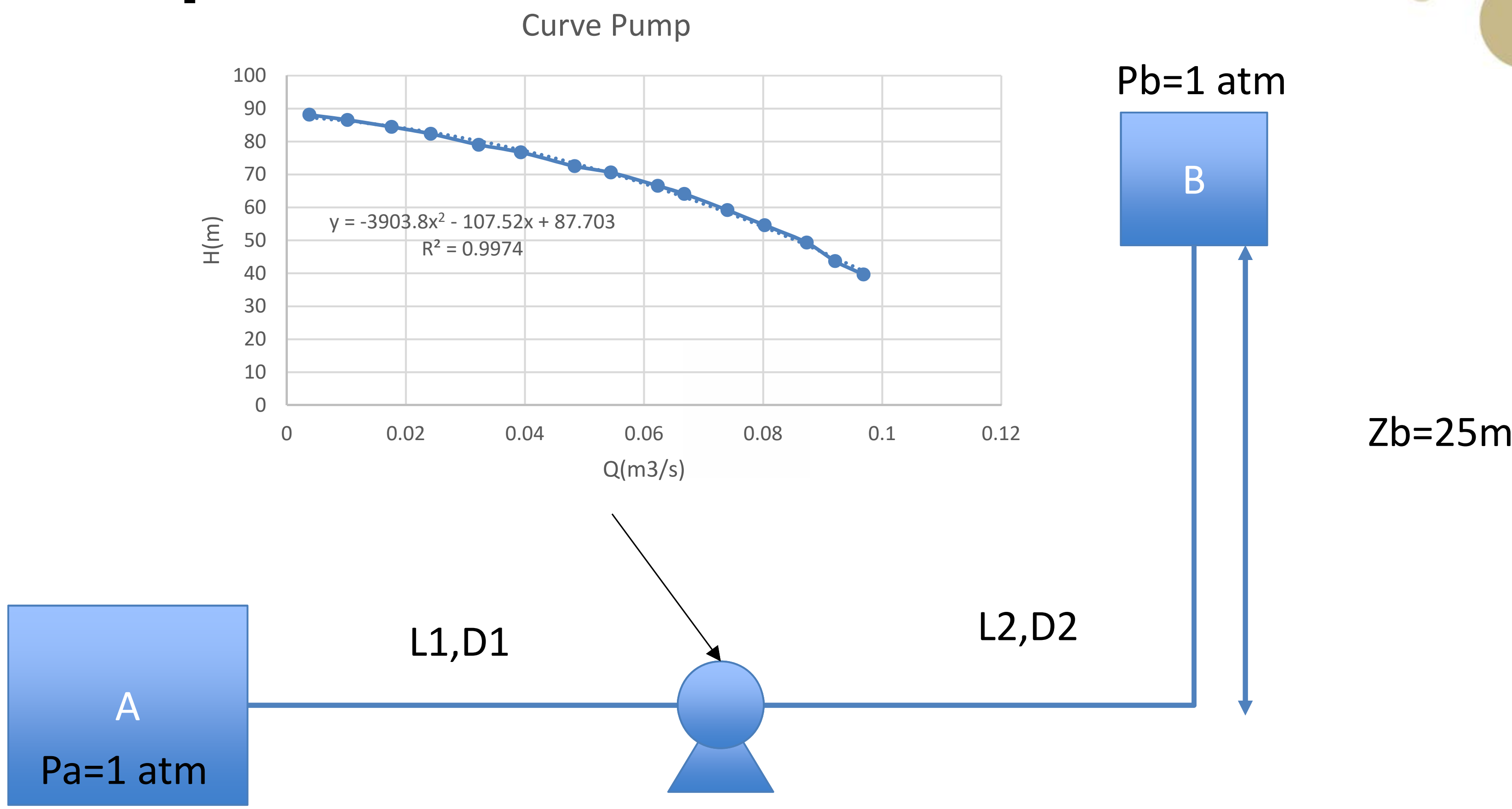


(Nesbitt, 2006)

# The best efficiency point (BEP)



# Output Power and efficiency: Example



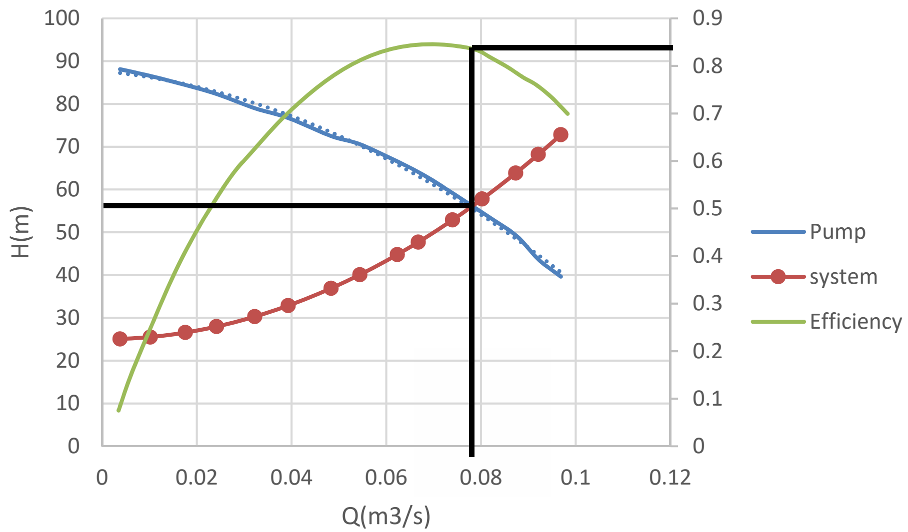

L1=6.7cm
D1=15cm
L2=205m
D2=15cm

$h_{l\,minors} = 5.9m$

f=0.018

operating point??

# Output Power and efficiency: Example




$$Q = 0.077\, m^3/s \qquad \Delta H = 56\, m \qquad \eta_o \approx 84\%$$

$$\gamma = 9.79\ kN/m3$$

$$\eta_o = \frac{P_u}{P_m} = \frac{\rho Q g \Delta H}{BP}$$

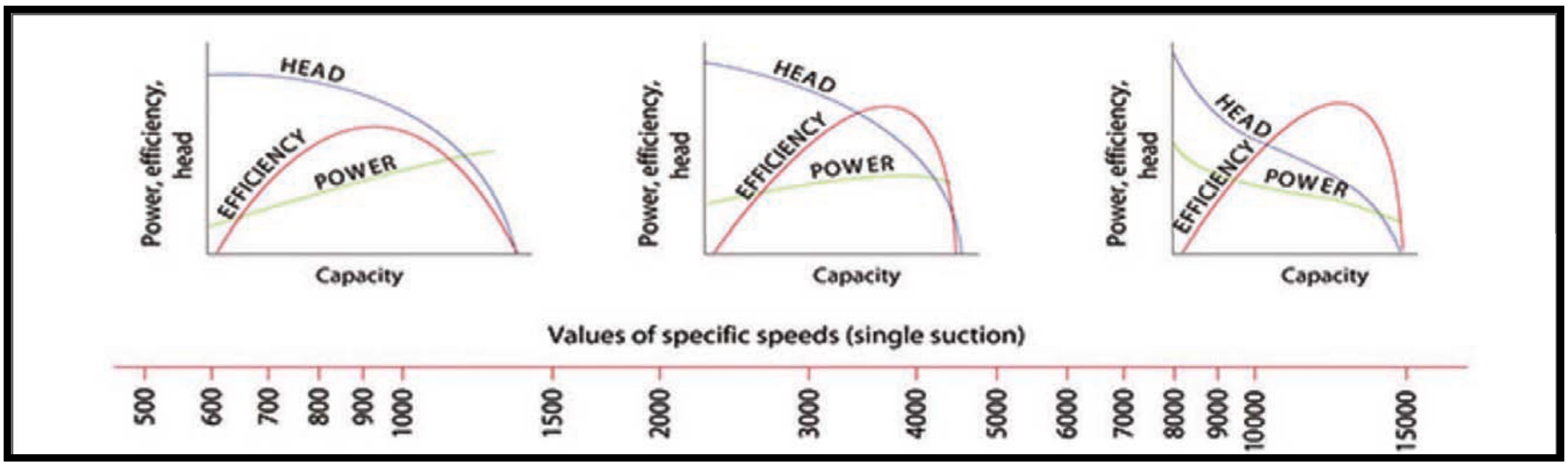
$$P_m = \frac{P_u}{\eta_o} = \frac{\gamma Q \Delta H}{\eta_o} = \frac{(9.79)(0.077)(56)}{0.84} = 50.23\text{kW}$$

# Definitions and Terminology

## 7. Pump Specific Speed

$$N_s = \frac{N\sqrt{Q}}{H^{3/4}}$$

$N$ … *Specific Speed*
$N$… Pump speed (rpm)
$Q$… Flow rates at best efficiency point (L/s)
H… Total dynamic head at best efficiency point (m)

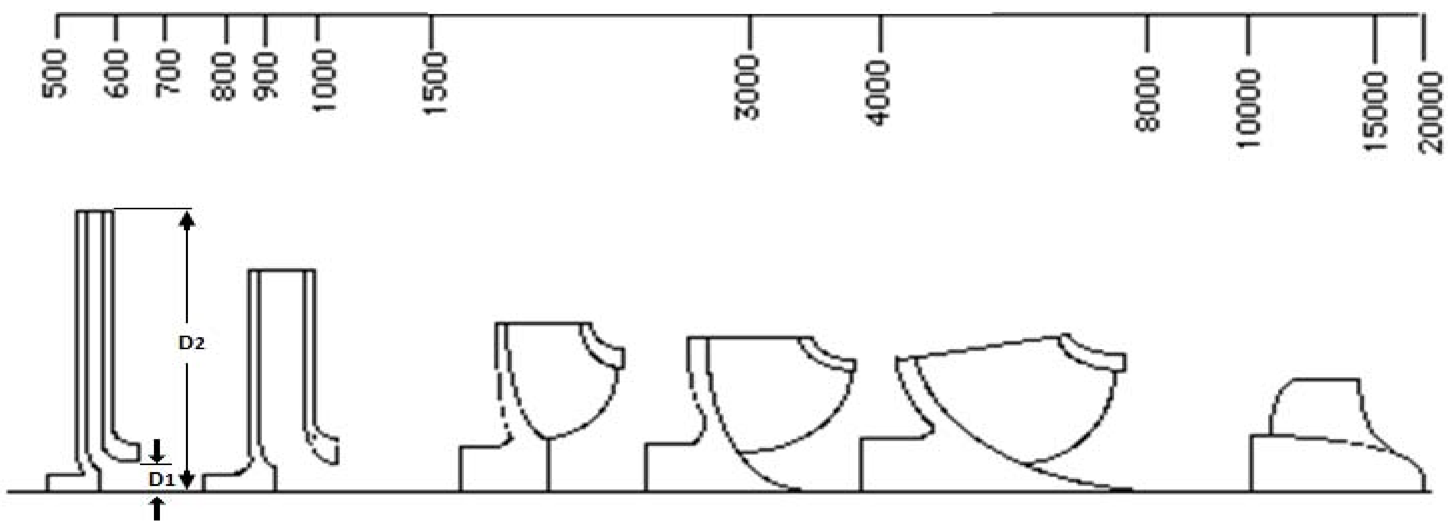



https://waterwelljournal.com/specific-speed/

# Definitions and Terminology

## 10. Pump Specific Speed

Values of Specific Speeds




| Radial Vane | Francis Vane | Mixed Flow | Axial Flow |
|---|---|---|---|
| $\frac{D_2}{D_1} > 2$ | $\frac{D_2}{D_1} = 1.5\ to\ 2$ | $\frac{D_2}{D_1} < 1.5$ | $\frac{D_2}{D_1} = 1$ |

(Asheim and Norges tekniske høgskole Institutt for petroleumsteknologi og anvendt, 1985)

# Definitions and Terminology

## 11. Affinity Law

There are two sets of affinity laws to approximate head, flow and power for different rotation speed and/or diameter:

1. Affinity laws for a **specific pump**
2. Affinity laws for a family of **geometrically similar pumps**

# Definitions and Terminology

1. Affinity laws for a **specific pump**

$\boldsymbol{D_1 = D_2}$

**For the Flows**

$$\frac{Q_1}{Q_2} = \frac{N_1 D_1}{N_2 D_2}$$

$$Q \propto N$$

**For the Head**

$$\frac{H_1}{H_2} = \frac{N_1^2 D_1^2}{N_2^2 D_2^2}$$

$$H \propto N^2$$

**For the Power requirements**

$$\frac{P_1}{P_2} = \frac{N_1^3 D_1^3}{N_2^3 D_2^3}$$

$$P \propto N^3$$

(Nesbitt, 2006)

# Definitions and Terminology

1. Affinity laws for a family of **geometrically similar pumps**

**For the Flows**

$$\frac{Q_1}{Q_2} = \frac{N_1 D_1^3}{N_2 D_2^3}$$

**For the Head**

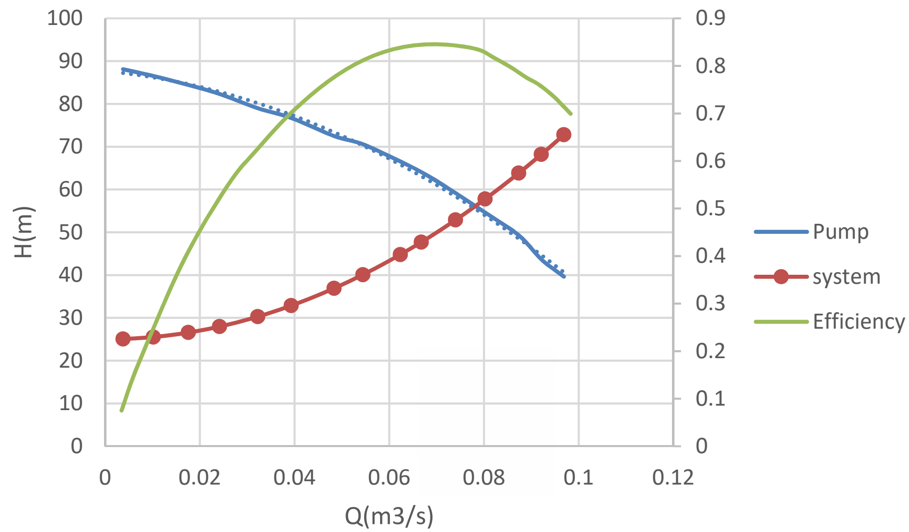
$$\frac{H_1}{H_2} = \frac{N_1^2 D_1^2}{N_2^2 D_2^2}$$

**For the Power requirements**

$$\frac{P_1}{P_2} = \frac{N_1^3 D_1^5}{N_2^3 D_2^5}$$

(Nesbitt, 2006)

# Affinity Example




N=1500rpm $Q = 0.077\, m^3/s \qquad \Delta H = 56\, m \qquad \eta_o \approx 84\% \qquad P_m = 50.23\text{kW}$

N=1800rpm →

$$\frac{Q_1}{Q_2} = \frac{N_1 D_1}{N_2 D_2} \qquad \frac{H_1}{H_2} = \frac{N_1^2 D_1^2}{N_2^2 D_2^2} \qquad \frac{P_{m1}}{P_{m2}} = \frac{N_1^3 D_1^3}{N_2^3 D_2^3}$$

D=Cte →

$$\frac{Q_1}{Q_2} = \frac{N_1}{N_2} \qquad \frac{H_1}{H_2} = \frac{N_1^2}{N_2^2} \qquad \frac{P_{m1}}{Pm_2} = \frac{N_1^3}{N_2^3}$$

# Affinity Example

N=1500rpm → $Q = 0.077\, m^3/s$ $\Delta H = 56\, m$ $\eta_o \approx 84\%$ $P_m = 50.23\text{kW}$

N=1800rpm

D=Cte

→ $\frac{Q_1}{Q_2} = \frac{N_1}{N_2}$ $\frac{H_1}{H_2} = \frac{N_1^2}{N_2^2}$ $\frac{Pm_1}{P_{m2}} = \frac{N_1^3}{N_2^3}$

$$\frac{N_1}{N_2} = r = \frac{1500}{1800} = 0.83$$

$Q_2 = \frac{Q_1}{r}$ $H_2 = \frac{H_1}{r^2}$ $Pm_2 = \frac{Pm_1}{r^3}$

N=1800rpm

$Q_2 = 0.092\, m^3/s$ $H_2 = 80.6\, m$ $P_m = 86.8\text{kW}$

$$\eta_o = \frac{P_u}{P_m} = \frac{\gamma Q \Delta H}{P_m} = \frac{(9.79)(0.092)(80.6)}{86.8} = 0.84$$

# Affinity Example II

| | | |
|---|---|---|
| N1 | 1780 | rpm |
| D | 250 | mm |
| **Q(m3/h)** | **H(m)** | **E(%)** |
| 180 | 380 | 62 |
| 360 | 310 | 82 |
| 420 | 278 | 81 |
| 480 | 235 | 77 |

Operating point:

| Q(m3/h) | H(m) |
|---|---|
| 450 | 300 |

Determine the speed at which the required condition can be achieved

# Affinity Example II

| | | |
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| N1 | 1780 | rpm |
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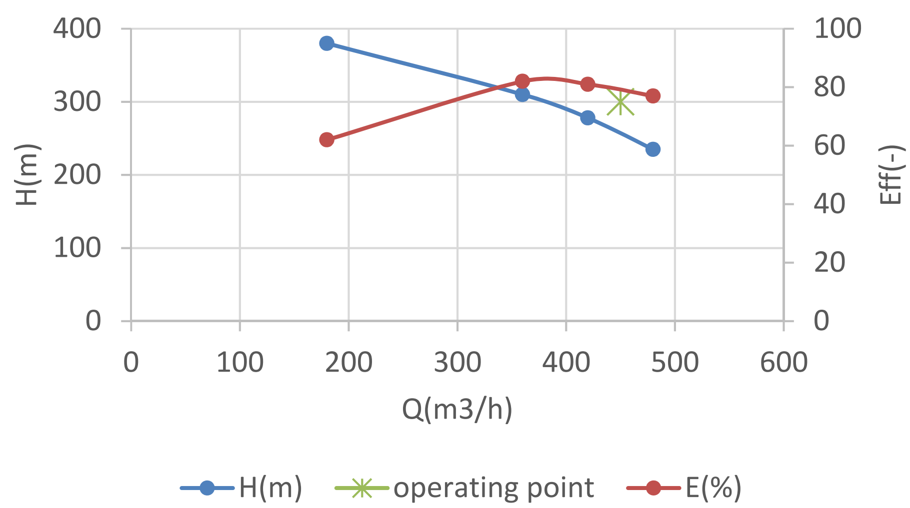

# Affinity Example II

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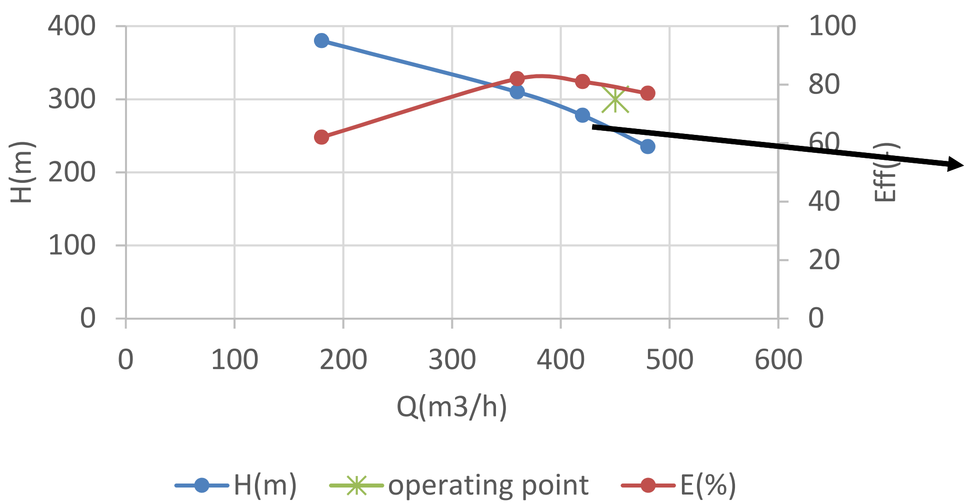
| 180 | 380 | 62 |
| 360 | 310 | 82 |
| 420 | 278 | 81 |
| 480 | 235 | 77 |

Operating point:

| Q(m3/h) | H(m) |
|---|---|
| 450 | 300 |

The pump is fitted with a variable speed drive with a speed range of 1500 rpm to 3000rpm

Determine the speed at which the required condition can be achieved




$$H = -0.00082182Q^2 + 0.061648Q + 395.42$$

# Affinity Example II

| | | |
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| **Q(m3/h)** | **H(m)** | **E(%)** |
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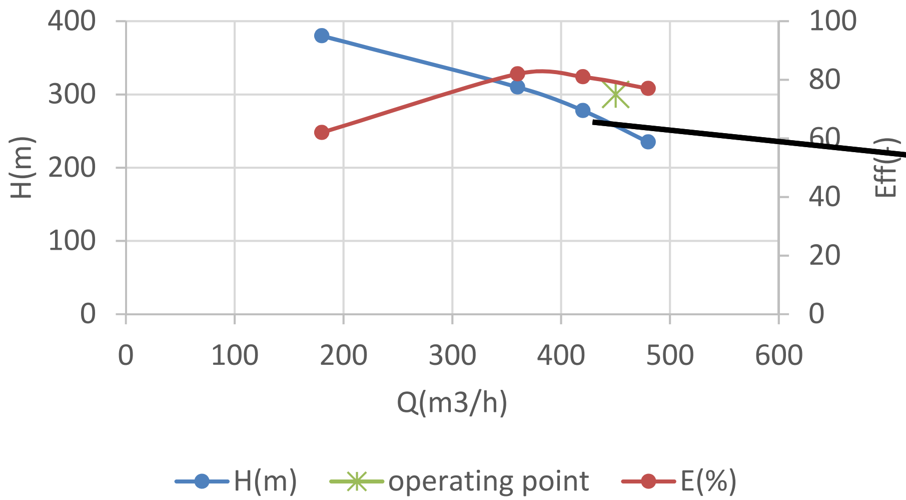



$H = -0.00082182Q^2 + 0.061648Q + 395.42$

$$\frac{Q_1}{Q_2} = \frac{N_1 D_1}{N_2 D_2} \qquad \frac{H_1}{H_2} = \frac{N_1^2 D_1^2}{N_2^2 D_2^2}$$

$$\frac{N_1}{N_2} = r \rightarrow \frac{Q_1}{Q_2} = r \qquad \frac{H_1}{H_2} = r^2$$

# Affinity Example II

| | | |
|---|---|---|
| N1 | 1780 | rpm |
| D | 250 | mm |

| Q(m3/h) | H(m) | E(%) |
|---|---|---|
| 180 | 380 | 62 |
| 360 | 310 | 82 |
| 420 | 278 | 81 |
| 480 | 235 | 77 |

Operating point:

| $Q_2$ | $H_2$ |
|---|---|
| Q(m3/h) | H(m) |
| 450 | 300 |

Determine the speed at which the required condition can be achieved

$$H_1 = -0.00082182Q_1^2 + 0.061648Q_1 + 395.42$$

$$\frac{Q_1}{Q_2} = r \qquad \frac{H_1}{H_2} = r^2$$

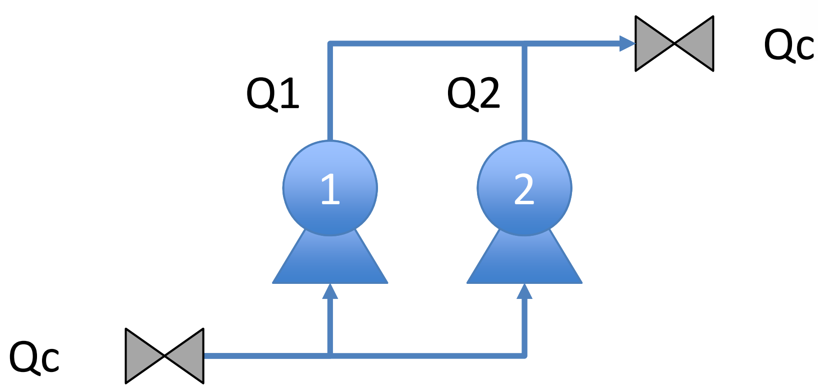
$$r^2 H_2 = -0.00082182(rQ_2)^2 + 0.061648\, rQ_2 + 395.42 \rightarrow r = 0.950 \rightarrow \frac{N_1}{N_2} = r$$

$$N_2 = \frac{N_1}{r} = 1872 \text{ rpm}$$

# Series and parallel

- We can connect several identical or different pumps in series or in parallel in order to increase the system flow rate or to develop the required delivery head (Badr and Ahmed, 2014)

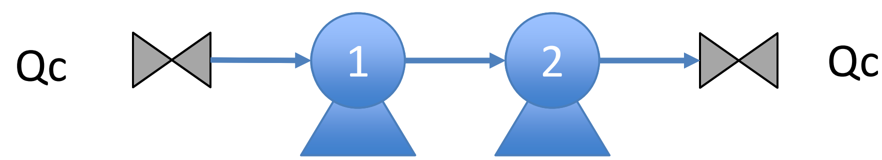
**Parallel**




$$Q_C = Q_1 + Q_2$$

$$H_C = H_1 = H_2$$

**Series**

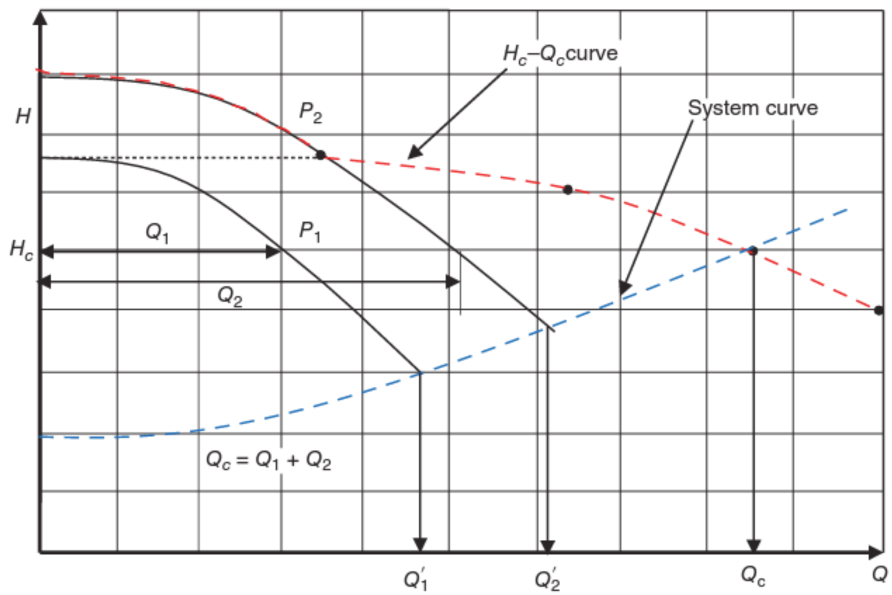



$$Q_C = Q_1 = Q_2$$

$$H_C = H_1 + H_2$$

# Series and parallel

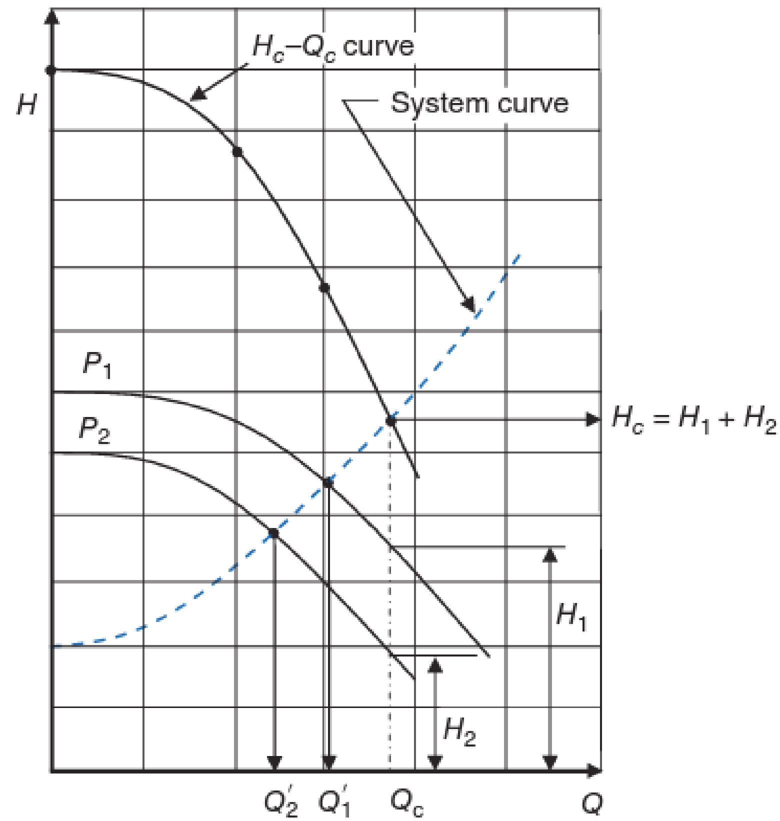
## Parallel




*H-Q curves for two different pumps in parallel*

(Badr and Ahmed, 2014)

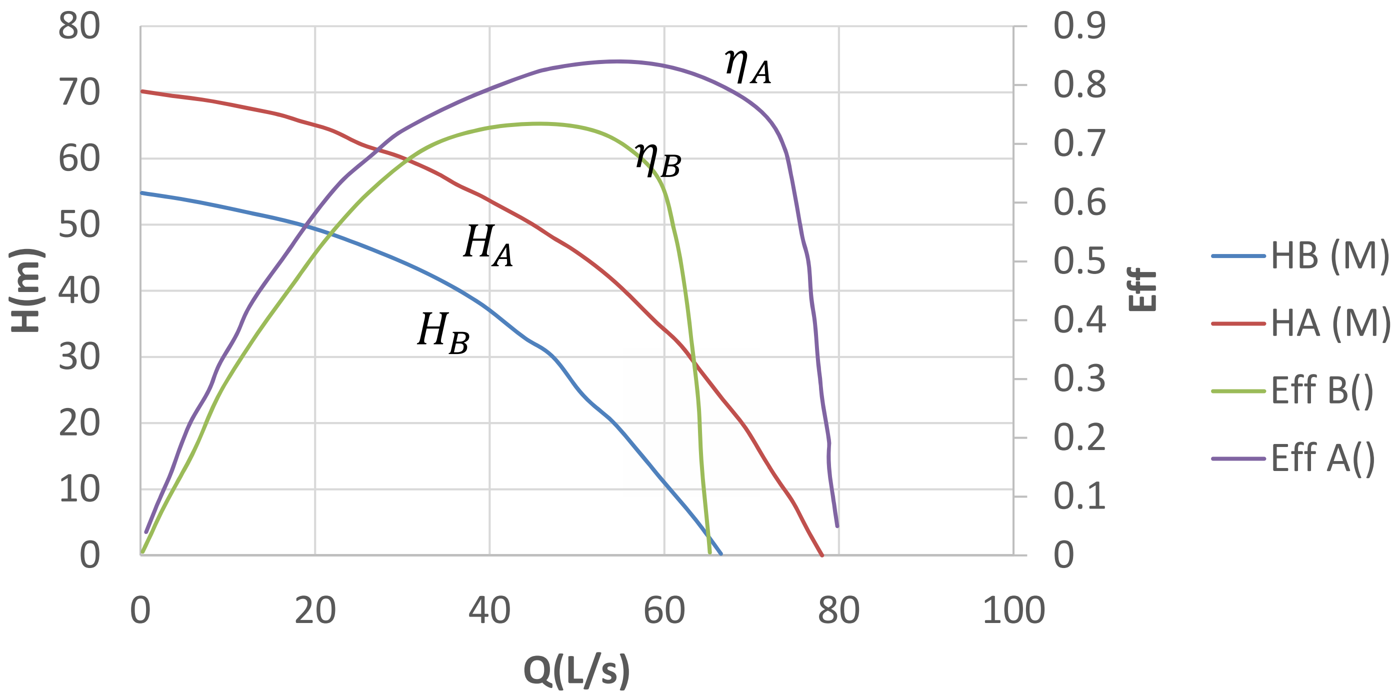
## Series

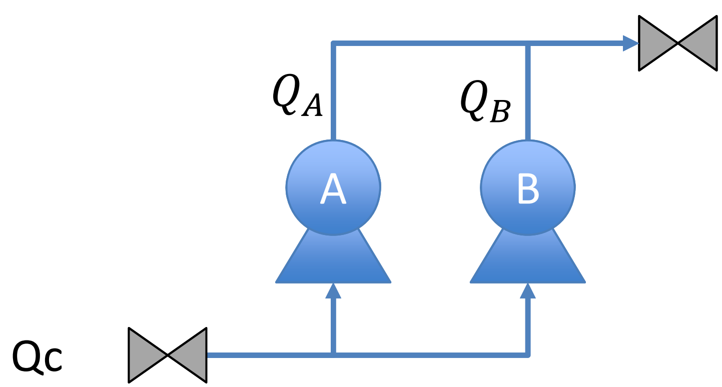



*H-Q curves for two different pumps in series*

(Badr and Ahmed, 2014)

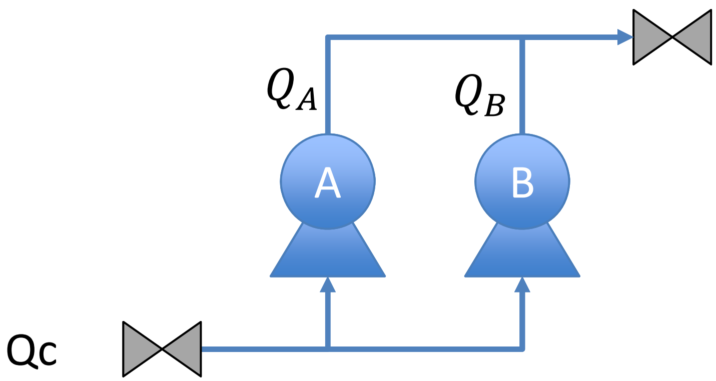
# Series and parallel: example



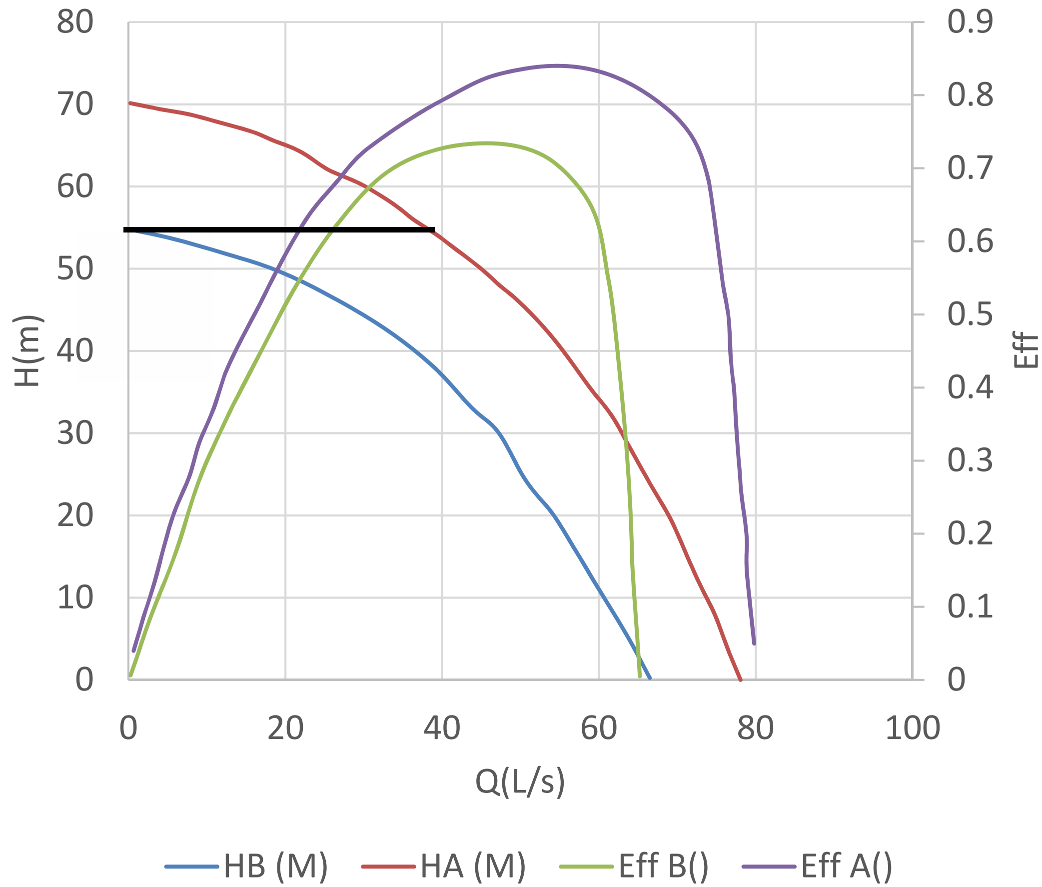

Obtain the combined H-Q, $\eta$-Q

# Series and parallel: example




$$Q_C = Q_1 + Q_2$$

$$H_C = H_1 = H_2$$



# Series and parallel: example

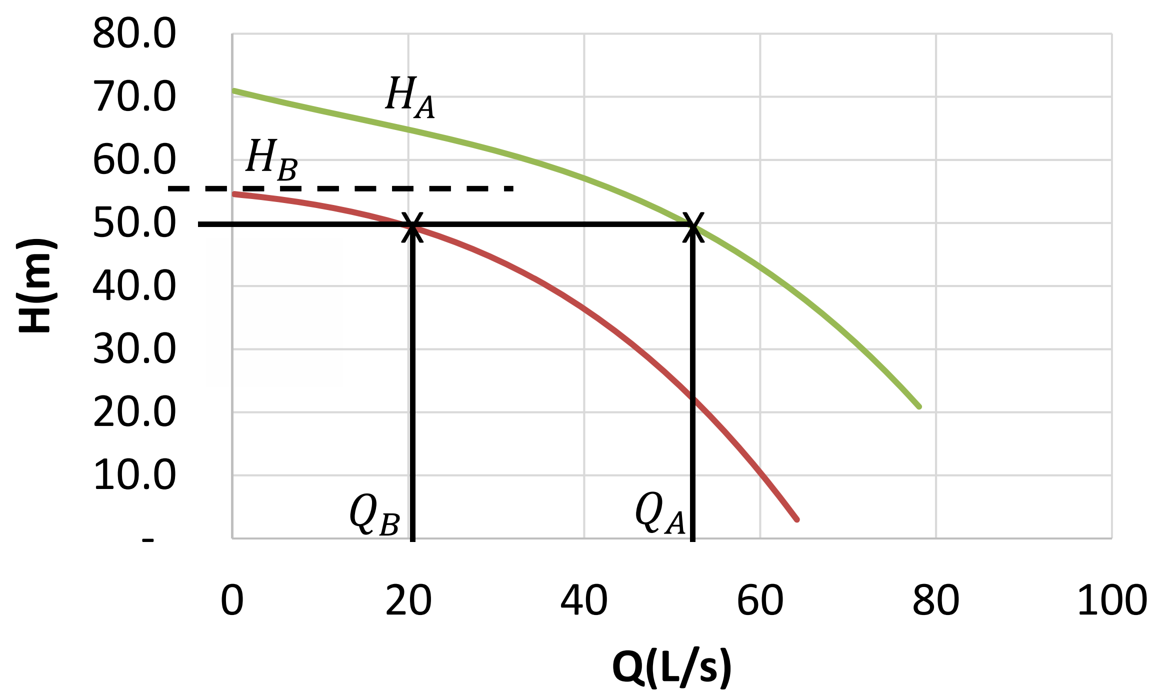
Select a $H$

$$H_C = H_A = H_B = H$$

For each H find $Q_A$ and $Q_B$

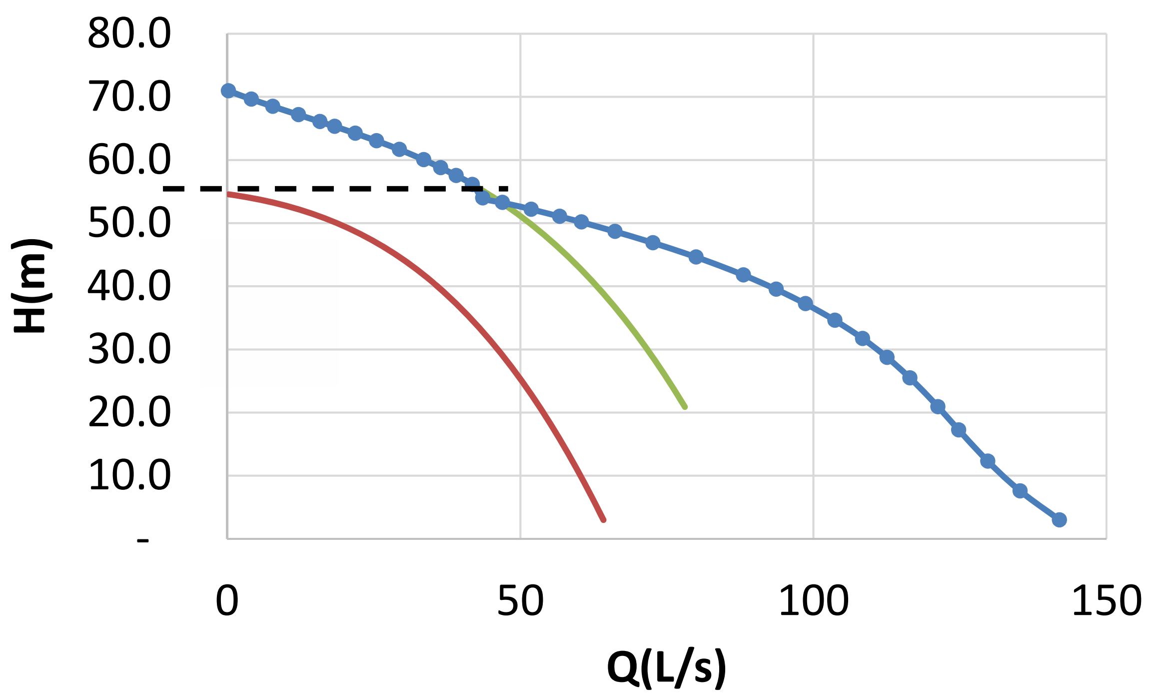
For each H calculate $Q_C$

$$Q_C = Q_A + Q_B$$



# Series and parallel: example

| H | QA | QB | QA+QB |
|---|---|---|---|
| 54.0 | 42.4 | 1.2 | 43.6 |
| 53.3 | 43.4 | 3.6 | 47.0 |
| 52.2 | 44.9 | 7.0 | 51.9 |
| 51.1 | 46.3 | 10.4 | 56.7 |
| 50.1 | 47.5 | 13.0 | 60.5 |
| 48.7 | 49.2 | 17.0 | 66.2 |
| 46.9 | 51.2 | 21.5 | 72.6 |
| 44.6 | 53.4 | 26.6 | 80.0 |
| 41.8 | 56.0 | 32.1 | 88.1 |
| 39.5 | 57.8 | 35.9 | 93.7 |
| 37.2 | 59.4 | 39.3 | 98.7 |



# Series and parallel: example

Calculate the Combined Efficiency

$$\eta_c = \frac{Total\ output\ power}{Total\ input\ power}$$

$$P_u = \rho g H Q$$

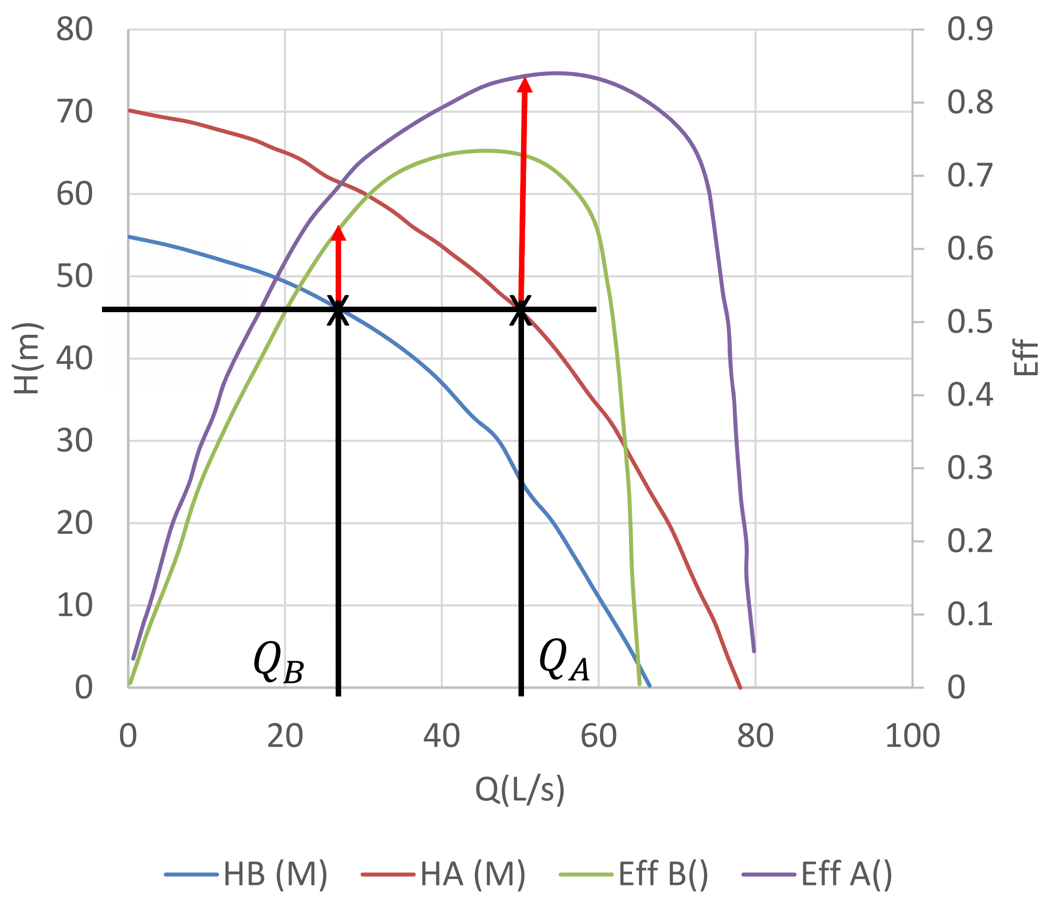
$$P_m = \frac{P_u}{\eta_0}$$

$$\eta_c = \frac{P_u^A + P_u^B}{P_m^A + P_m^B} = \frac{\rho g H_A Q_A + \rho g H_B Q_B}{\frac{\rho g H_A Q_A}{\eta_A} + \frac{\rho g H_B Q_B}{\eta_B}} = \frac{\eta_A \eta_B (Q_A + Q_B)}{\eta_B Q_A + \eta_A Q_B}$$

# Series and parallel: example

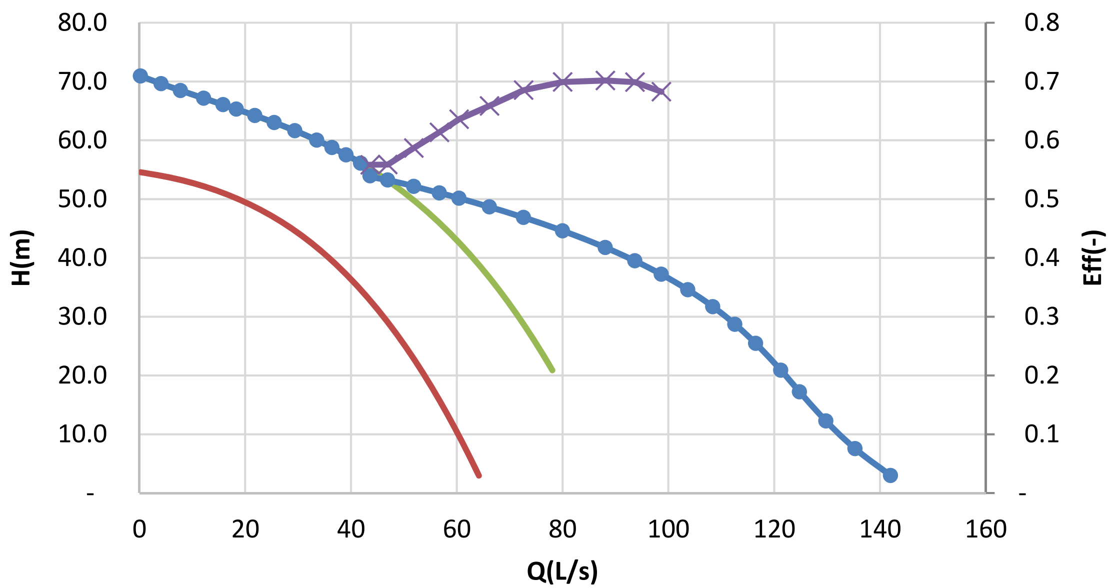
Calculate the Combined Efficiency

$$\eta_c = \frac{\eta_A \eta_B (Q_A + Q_B)}{\eta_B Q_A + \eta_A Q_B}$$



# Series and parallel: example

| HB | QA | Eff A() | QB | Eff B() | QA+QB | Eff C() |
|---|---|---|---|---|---|---|
| 54.0 | 42.4 | 0.7 | 1.2 | 0.1 | 43.6 | 0.6 |
| 53.3 | 43.4 | 0.7 | 3.6 | 0.1 | 47.0 | 0.6 |
| 52.2 | 44.9 | 0.7 | 7.0 | 0.3 | 51.9 | 0.6 |
| 51.1 | 46.3 | 0.7 | 10.4 | 0.4 | 56.7 | 0.6 |
| 50.1 | 47.5 | 0.7 | 13.0 | 0.4 | 60.5 | 0.6 |
| 48.7 | 49.2 | 0.7 | 17.0 | 0.5 | 66.2 | 0.7 |
| 46.9 | 51.2 | 0.7 | 21.5 | 0.6 | 72.6 | 0.7 |
| 44.6 | 53.4 | 0.7 | 26.6 | 0.7 | 80.0 | 0.7 |
| 41.8 | 56.0 | 0.7 | 32.1 | 0.7 | 88.1 | 0.7 |
| 39.5 | 57.8 | 0.7 | 35.9 | 0.8 | 93.7 | 0.7 |
| 37.2 | 59.4 | 0.6 | 39.3 | 0.8 | 98.7 | 0.7 |



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