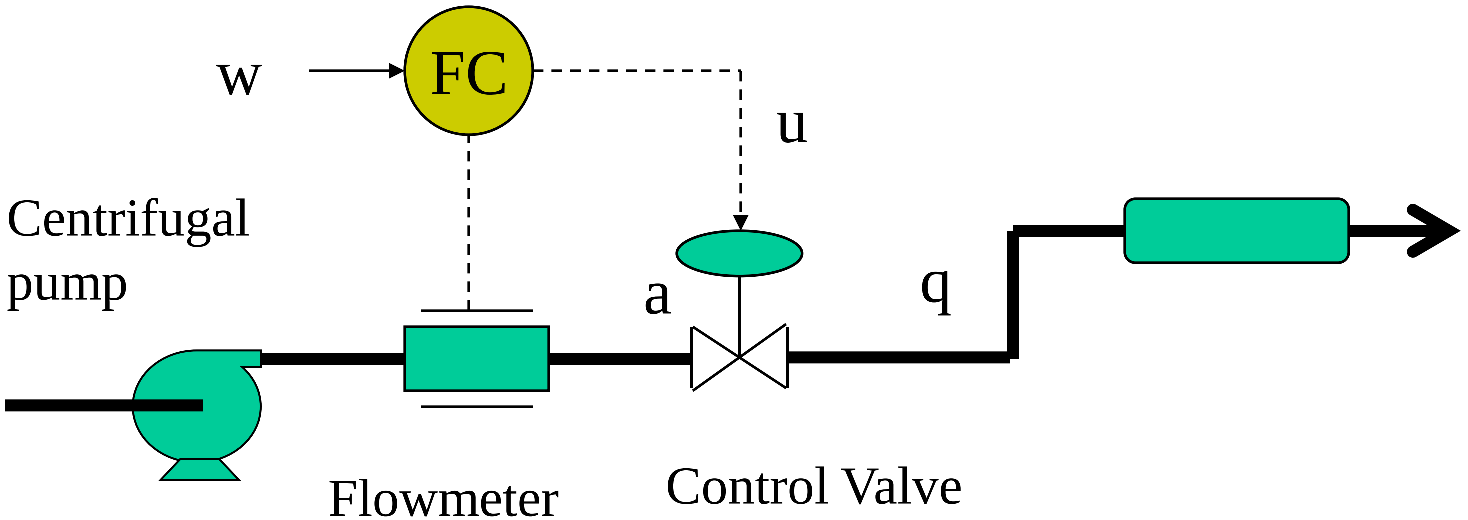
Some typical control loops

Prof. Cesar de Prada
Dpt. Systems Engineering and Automatic Control
Univ. of Valladolid

Outline

- Flow control
- Level Control
- Pressure control
- Temperature control

Flow control



Important element:
valve selection

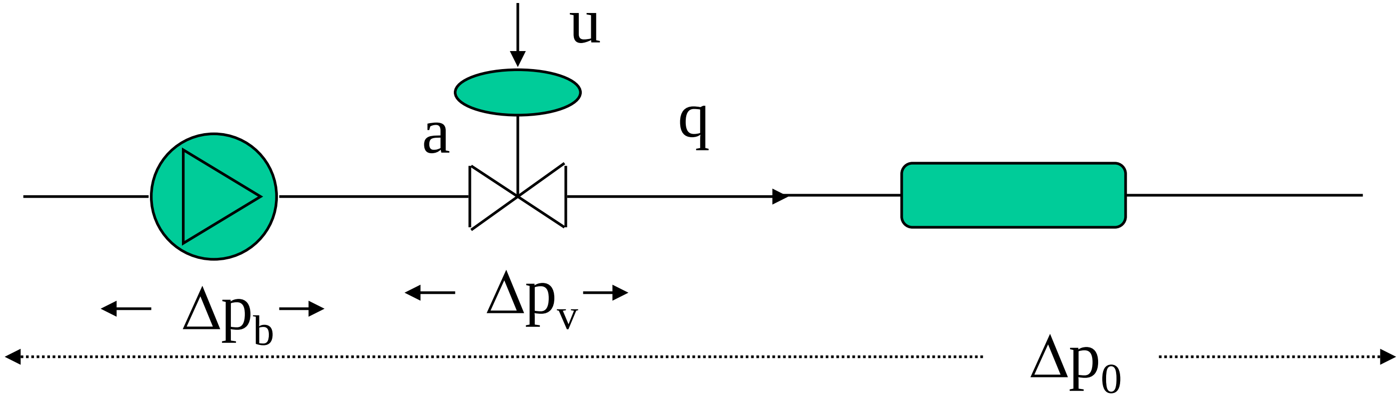
Pump, valve: sizing, placement

Flowmeter: Type, range

Right order: Pump, flowmeter, valve

Sizing

From a design point of view, control valves with a large C_v should be chosen, as they present a lower pressure drops, allowing the use of smaller pumps. Nevertheless, the use of smaller control valves gives wider flow changes making the process more controllable.



Example

Design specifications

Flow: $q_s = 100$ gpm

Pressure drop in the line $\Delta p_L = 40$ psi

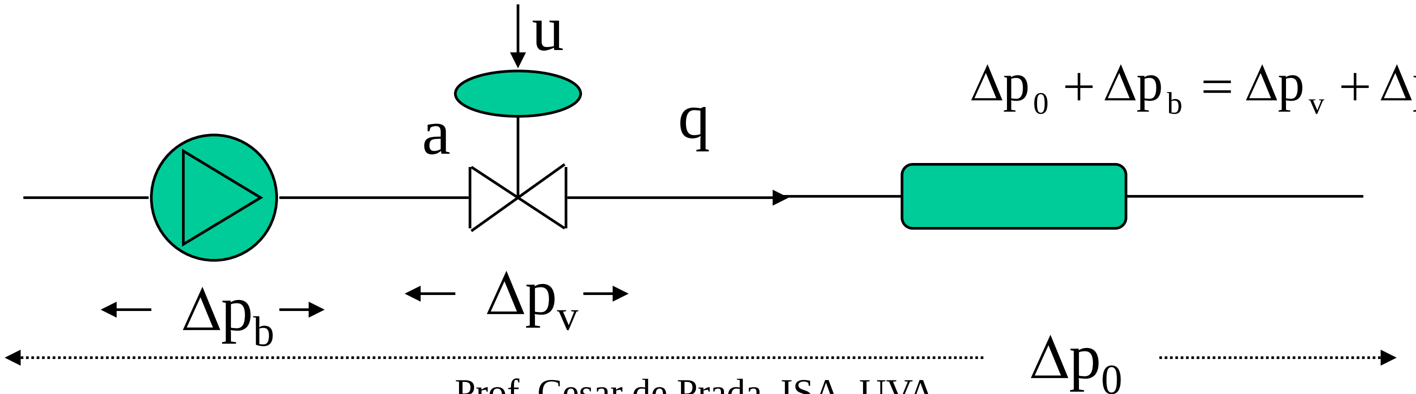
Total Pressure difference $\Delta p_0 = -150$ psi

density = 1   desired valve opening = 50%

Higher pressure in the line end

Case 1: $\Delta p_v = 20$ psi   Case 2: $\Delta p_v = 80$ psi

$$\Delta p_0 + \Delta p_b = \Delta p_v + \Delta p_L$$



Example

Case 1: $\Delta p_v = 20$ psi

$\Delta p_b = 150+40+20 = 210$

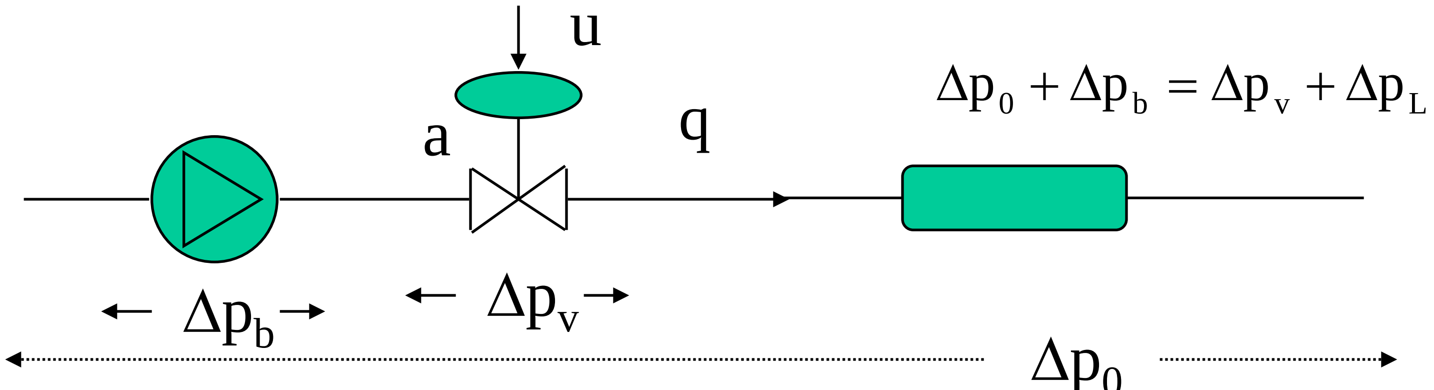
Case 2: $\Delta p_v = 80$ psi

$\Delta p_b = 150+40+80 = 270$

$$q_s = aC_v\sqrt{\frac{\Delta p_v}{\rho}}$$

$$100 = 0.5C_{v1}\sqrt{20} \qquad 100 = 0.5C_{v2}\sqrt{80}$$

$$C_{v1} = 44.72 \qquad C_{v2} = 22.36$$



Range of operation

Assuming that Δp_b is constant

Case 1: a=1 , a=0.1

$$\Delta p_v = \Delta p_0 + \Delta p_b - \Delta p_L$$

$$\Delta p_b + \Delta p_0 = 210 - 150 = 60$$

$$q_{max1} = 1C_{v1}\sqrt{60 - 40\left(\frac{q_{max1}}{100}\right)^2}$$

$$q_{max1} = 115\text{gpm}$$

$$q_{min1} = 0.1C_{v1}\sqrt{60 - 40\left(\frac{q_{min1}}{100}\right)^2}$$

$$q_{min1} = 33.3\text{gpm}$$

Case 2: a=1, a=0.1

$$q = aC_v\sqrt{\frac{\Delta p_v}{\rho}}$$

$$\Delta p_b + \Delta p_0 = 270 - 150 = 120$$

$$q_{max2} = 1C_{v2}\sqrt{120 - 40\left(\frac{q_{max2}}{100}\right)^2}$$

$$q_{max2} = 141\text{gpm}$$

$$q_{min2} = 0.1C_{v2}\sqrt{120 - 40\left(\frac{q_{min2}}{100}\right)^2}$$

$$q_{min2} = 24.2\text{gpm}$$

The smaller valve provides a wider range of operation in q

Design

Size the pump (Δp_b) and valve C_v as a function of the maximum and minimum flows required for the operation of the process, taking into account the design flow q_s and pressures Δp_0, Δp_{Ls} solving:

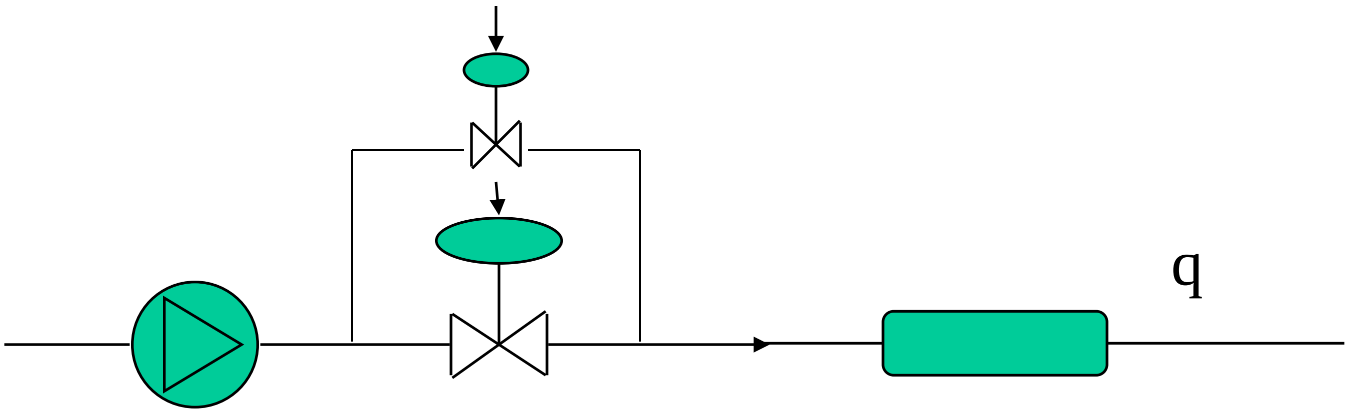
$$q_{max} = 1 \;\; C_v \sqrt{\Delta p_0 + \Delta p_b - \Delta p_{Ls}\left(\frac{q_{max}}{q_s}\right)^2}$$

$$q_{min} = a_{min} C_v \sqrt{\Delta p_0 + \Delta p_b - \Delta p_{Ls}\left(\frac{q_{min}}{q_s}\right)^2}$$

Design

A solution exists for this equations if $\frac{a_{min} q_{max}}{q_{min}} < 1$

Otherwise, use a split range control structure

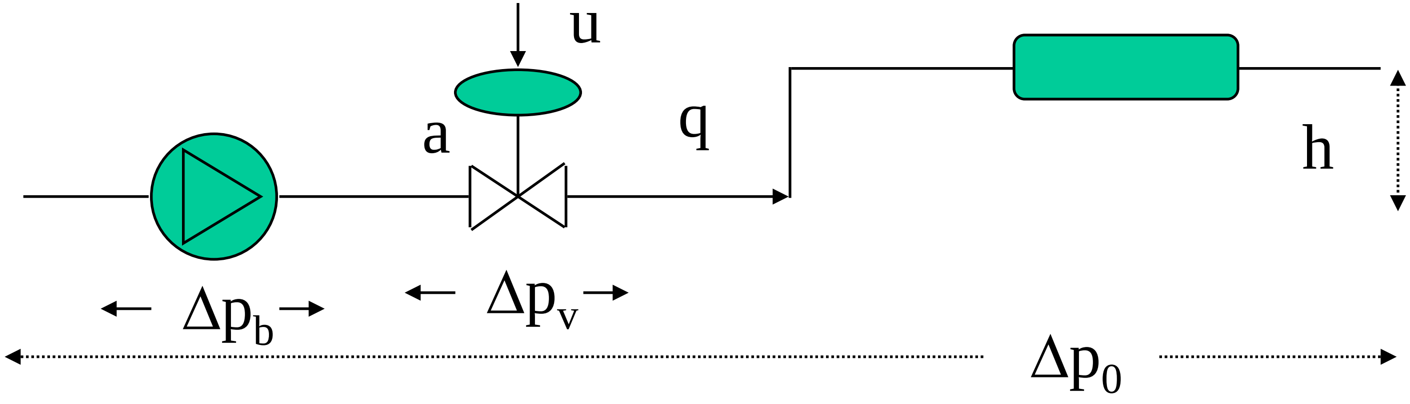


Flow control

$$\frac{d\,mv}{d\,t} = A(\Delta p_0 + \Delta p_b) - A\Delta p_v - AfL\rho v^2 - Ah\rho g$$

$$\Delta p_v = \frac{1}{a^2 C_v^2}\rho q^2 \qquad m = AL\rho \qquad q = Av \qquad \Delta p_b = \rho(\alpha\omega^2 - \beta q^2)$$

$$\frac{d\,q}{d\,t} = \frac{A}{L}\left[\frac{\Delta p_0}{\rho} + \alpha\omega^2 - \left(\beta + \frac{1}{a^2 C_v^2} + \frac{fL}{A^2}\right)q^2 - gh\right]$$



Linearized model

$$\frac{dq}{dt} = \frac{A}{L}\left[\frac{\Delta p_0}{\rho} + \alpha\omega^2 - \left(\beta + \frac{1}{a^2 C_v^2} + \frac{fL}{A^2}\right) q^2 - gh\right]$$

$$\frac{d\Delta q}{dt} = \frac{A}{L}\left[\frac{\Delta(\Delta p_0)}{\rho} - \left\{\left(\beta + \frac{1}{a^2 C_v^2} + \frac{fL}{A^2}\right)2q\right\}_0 \Delta q + \left\{\frac{2}{a^3 C_v^2} q^2\right\}_0 \Delta a\right]$$

$$\frac{1}{\left\{\frac{A}{L}\left(\beta + \frac{1}{a^2 C_v^2} + \frac{fL}{A^2}\right)2q\right\}_0} \frac{d\Delta q}{dt} + \Delta q =$$

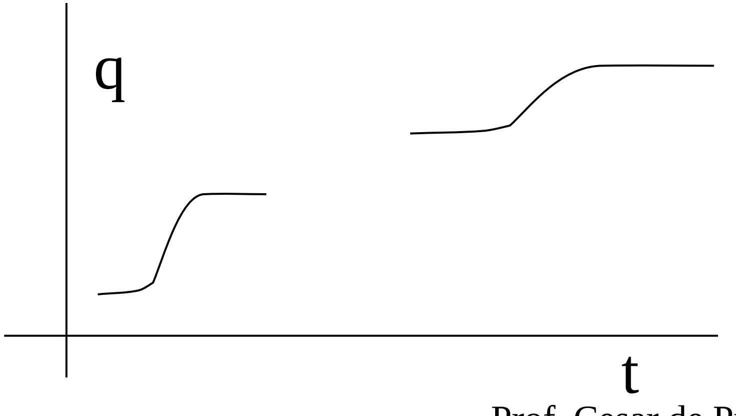
$$= \frac{1}{\left\{\rho\left(\beta + \frac{1}{a^2 C_v^2} + \frac{fL}{A^2}\right)2q\right\}_0}\left[\Delta(\Delta p_0) + \left\{\frac{2}{a^3 C_v^2}\rho q^2\right\}_0 \Delta a\right]$$

$$\tau \frac{d\Delta q}{dt} + \Delta q = K_1 \Delta(\Delta p_0) + K_2 \Delta a$$

Changes in the operating point

$$\tau \frac{d\,\Delta q}{d\,t} + \Delta q = K_1 \Delta(\Delta p_0) + K_2 \Delta a$$

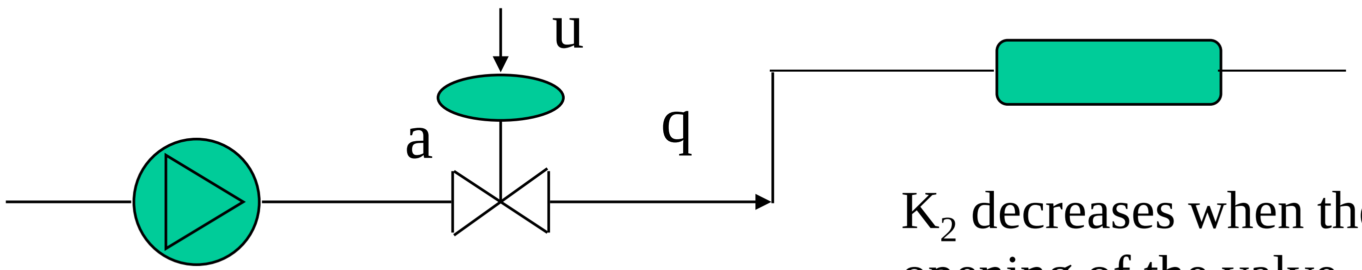
$$\tau = \frac{1}{\left\{ \frac{A}{L}(\beta + \frac{1}{a^2 C_v^2} + \frac{fL}{A^2})2q \right\}_0} \qquad K_2 = \left\{ \frac{q}{a(\beta a^2 C_v^2 + 1 + \frac{fLa^2 C_v^2}{A^2})} \right\}_0$$



τ grows when the opening of the valve increases

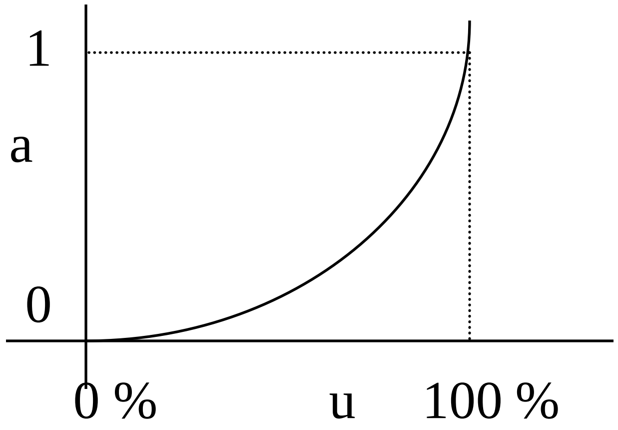
K_2 decreases when the opening of the valve increases

Linearized model



A equal percentage valve compensates the change in gain

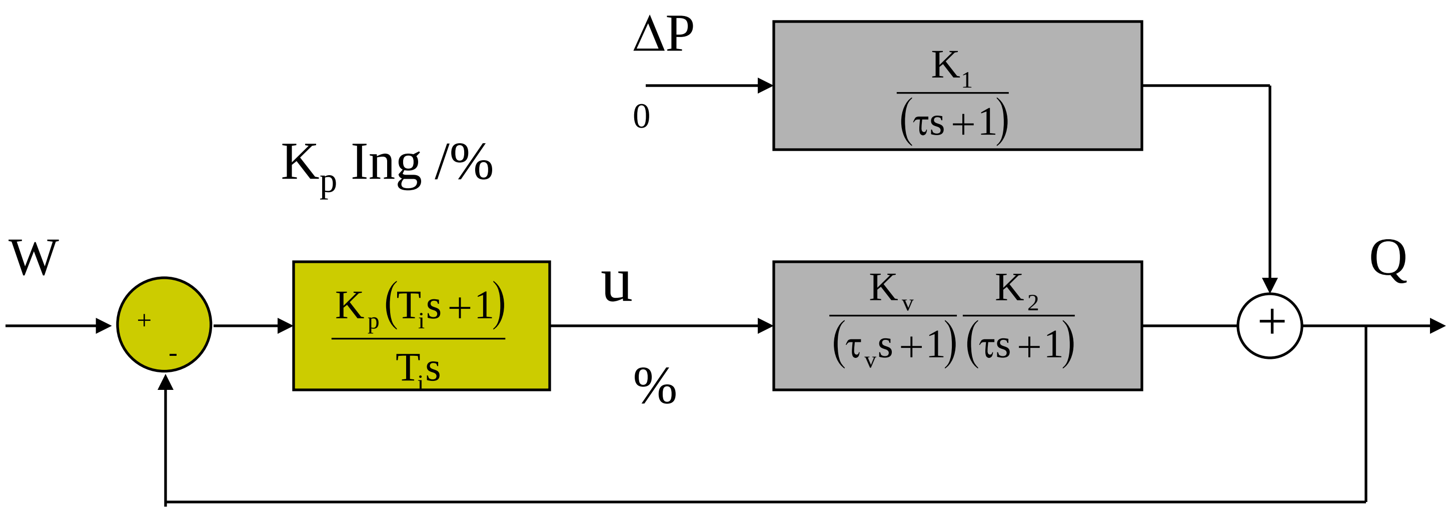
K_2 decreases when the opening of the valve increases



Valve dynamics must be taken into account very often. Let's assume that it is approximated by:

$$\tau_v \frac{d\Delta a}{dt} + \Delta a = K_v \Delta u$$

Block diagram

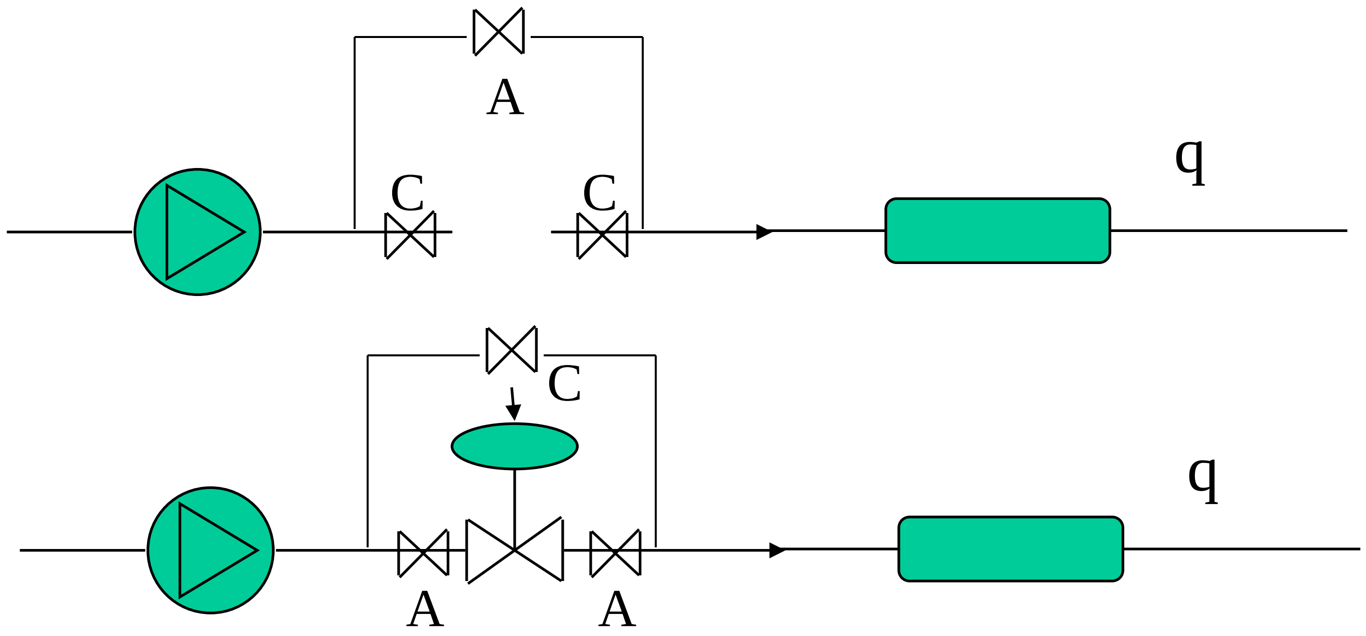


The transmitter dynamic can be neglected

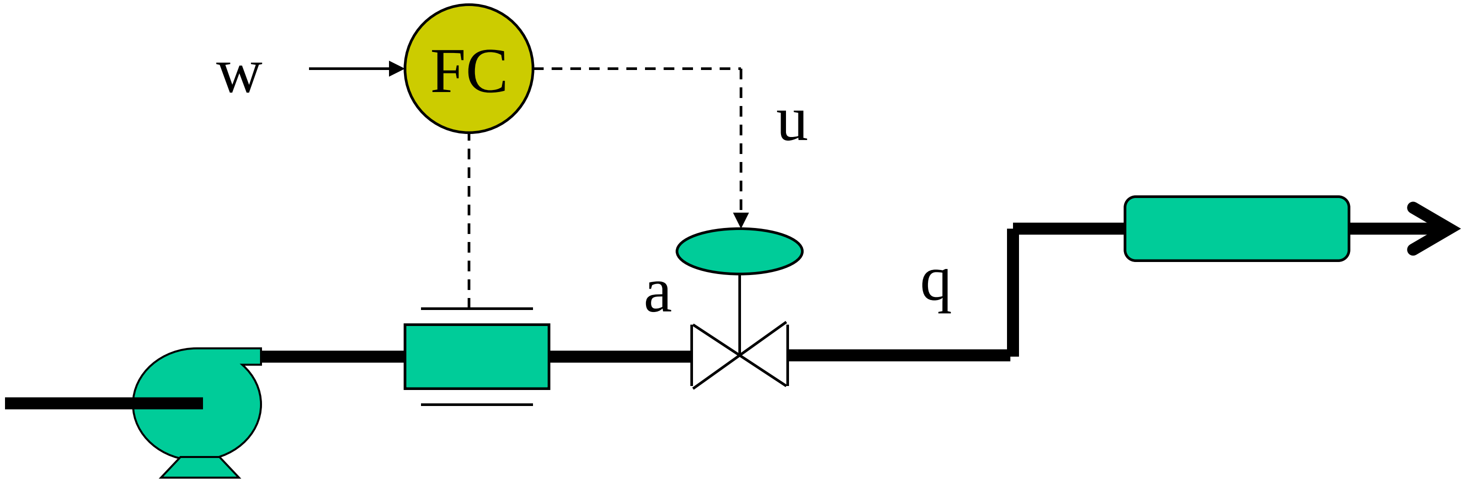
Choose the transmitter gain according to the maximum admissible flow

Field installation

The use of the manual valves allows to remove the control valve for repair without stopping the flow to the process



Flow control



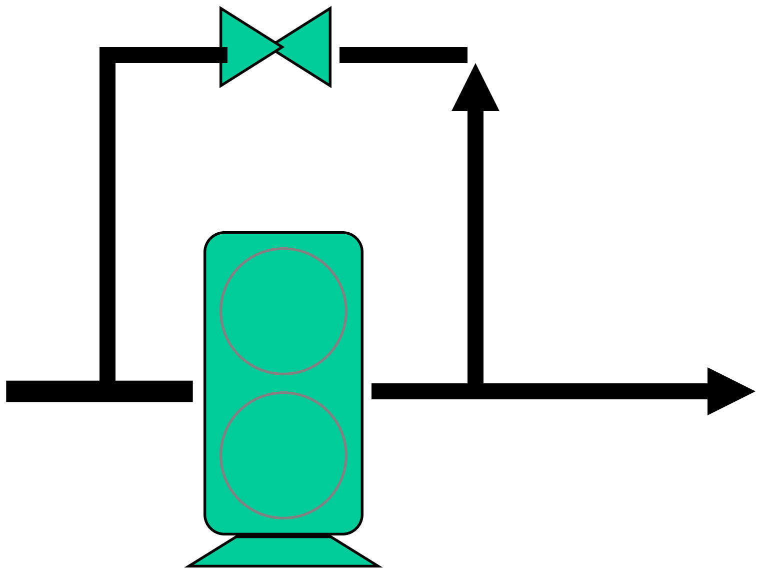
PI Fast and noisy process

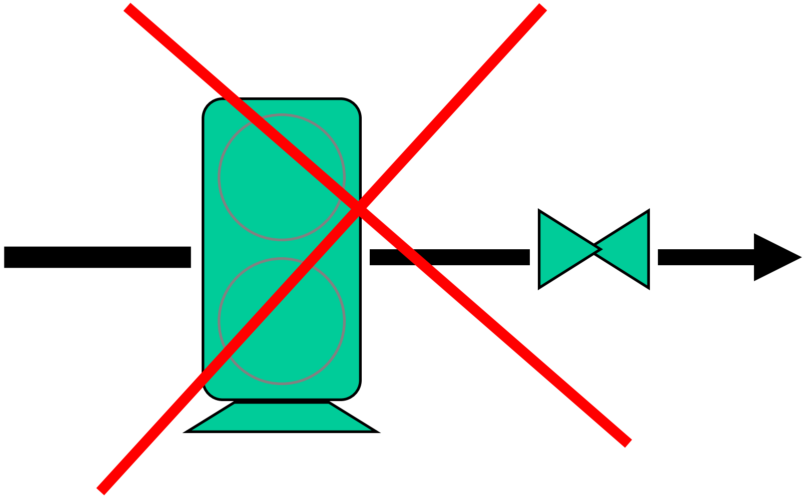
Low K_p to decrease the noise effect (0.6 %/%)

Low T_i to cancel soon the steady state error (0.1 min)

Positive Displacement pumps

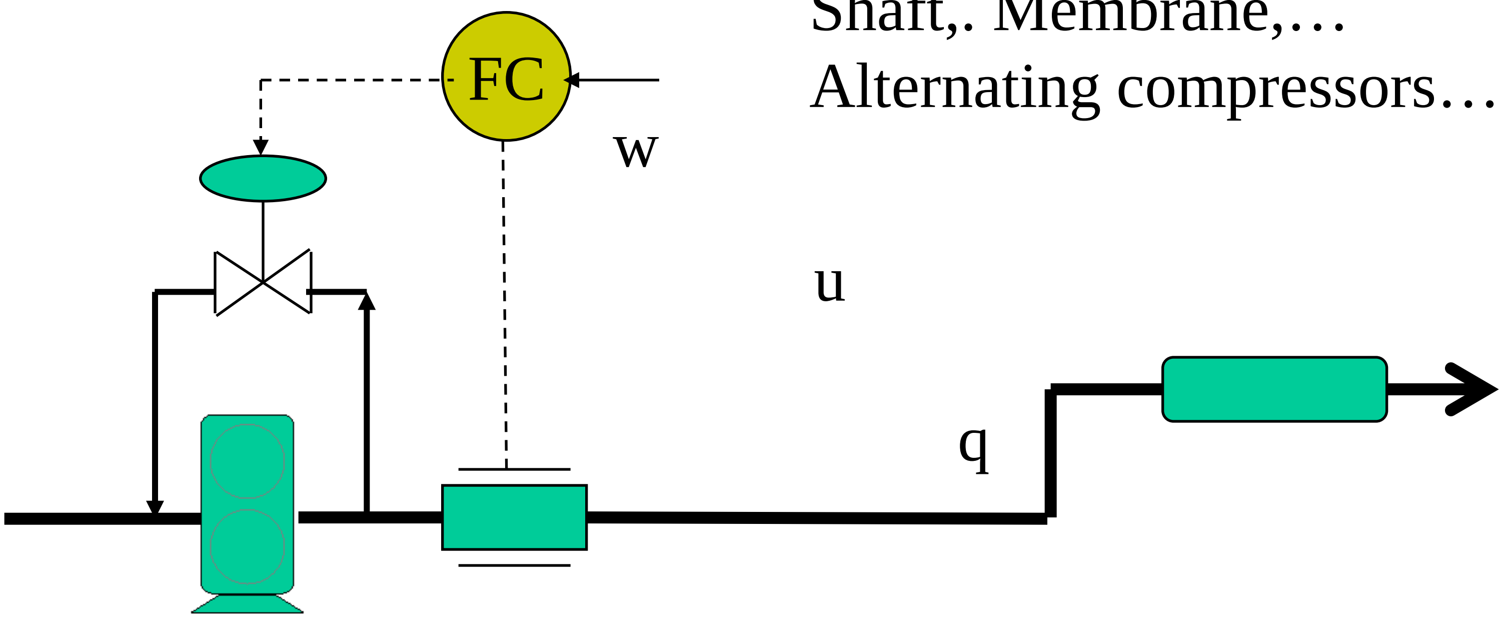
Shaft,. Membrane,…
Alternating compressors…



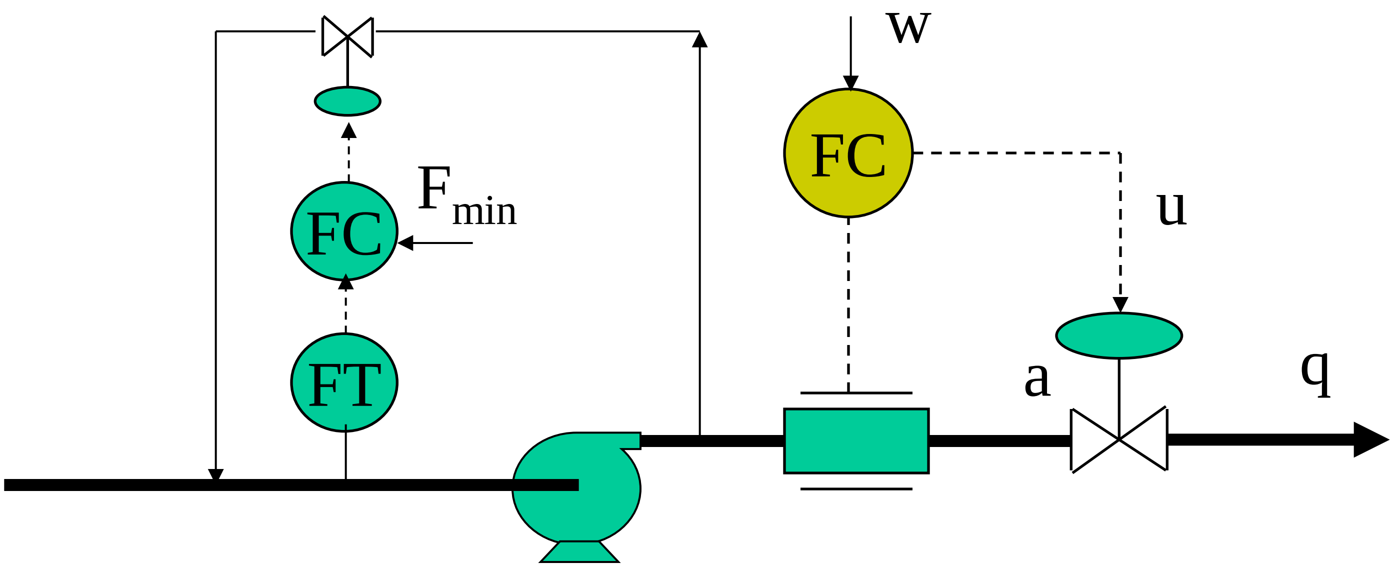


Positive Displacement pumps

Shaft,. Membrane,…
Alternating compressors…

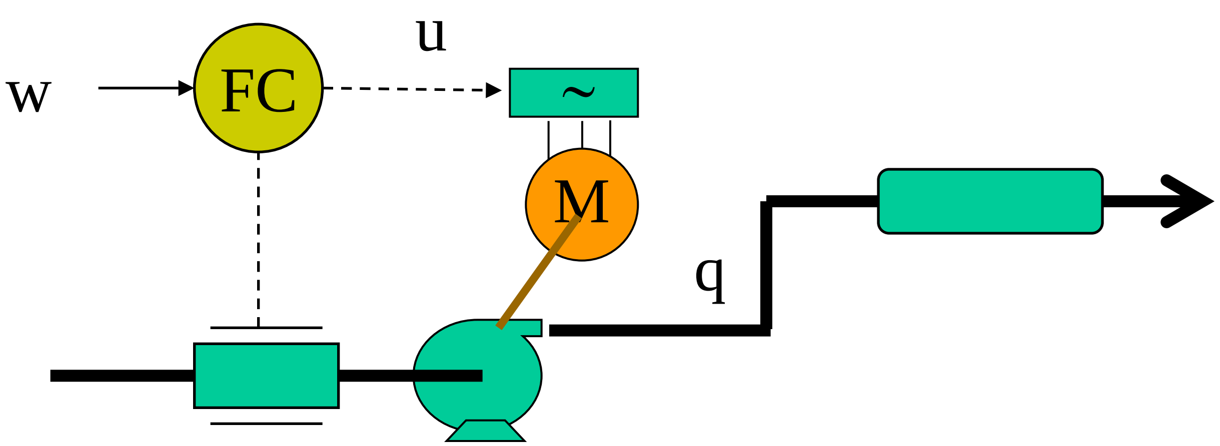


Minimum flow in the pump



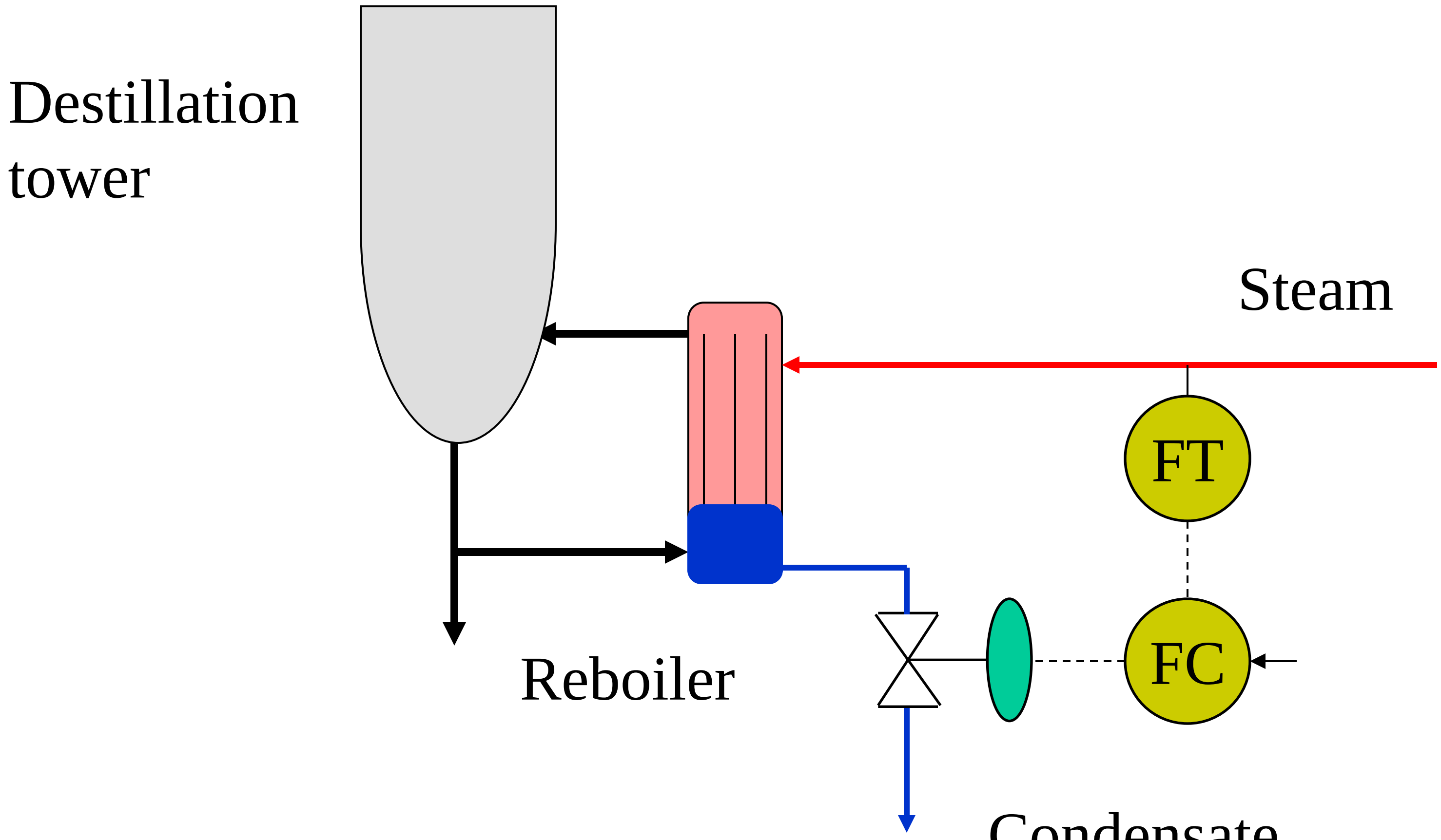
Sometimes, in order to guarantee a minimum flow through the pump, an extra flow loop is added. When $w > F_{min}$ the recirculation valve is closed, but if $w < F_{min}$ then the extra flow loop opens the recycle to maintain the required flow

Flow control

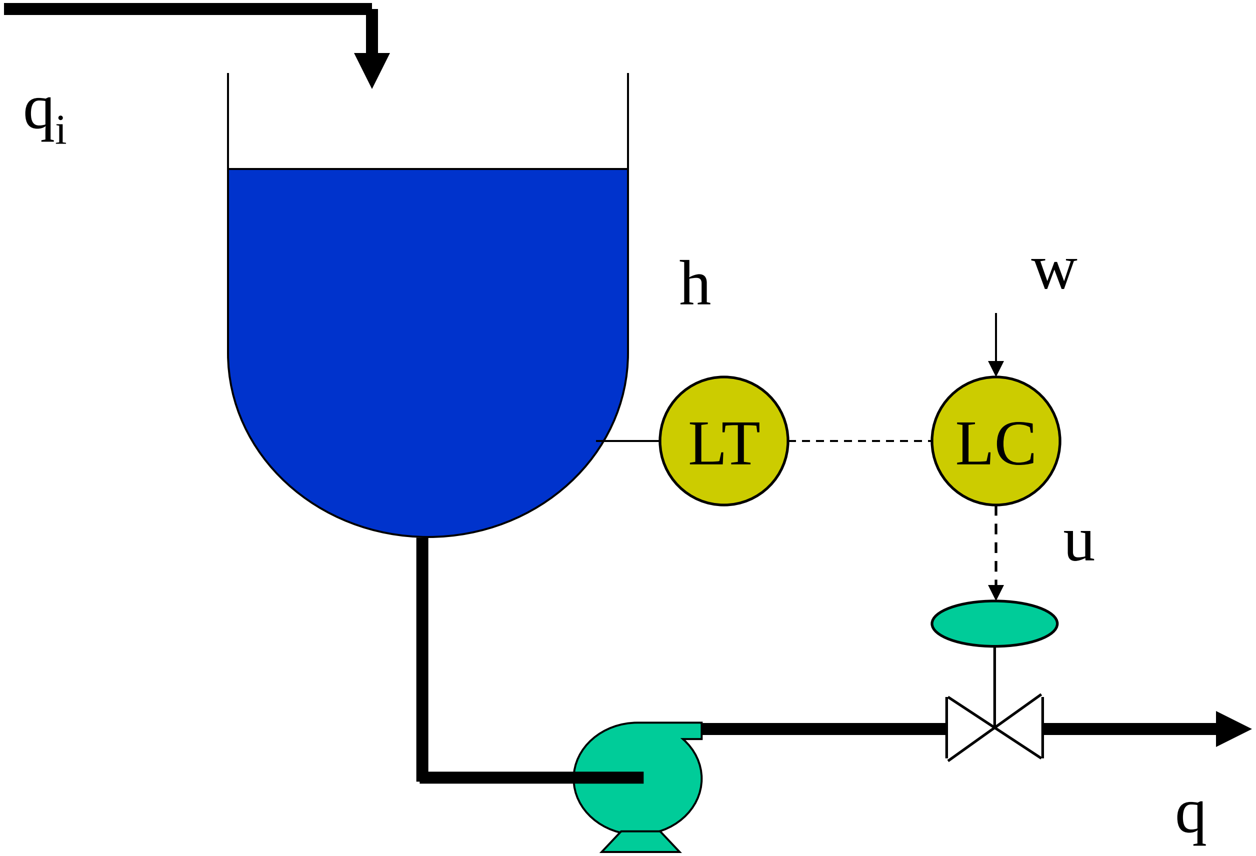


When the flow is high, instead of control valves, variable speed pumps are a sensible alternative that allows to save energy. A frequency converter (o similar device) connected to the pump asynchronous motor is required

Flow control



Level Control



Different alternatives for the level transmitter

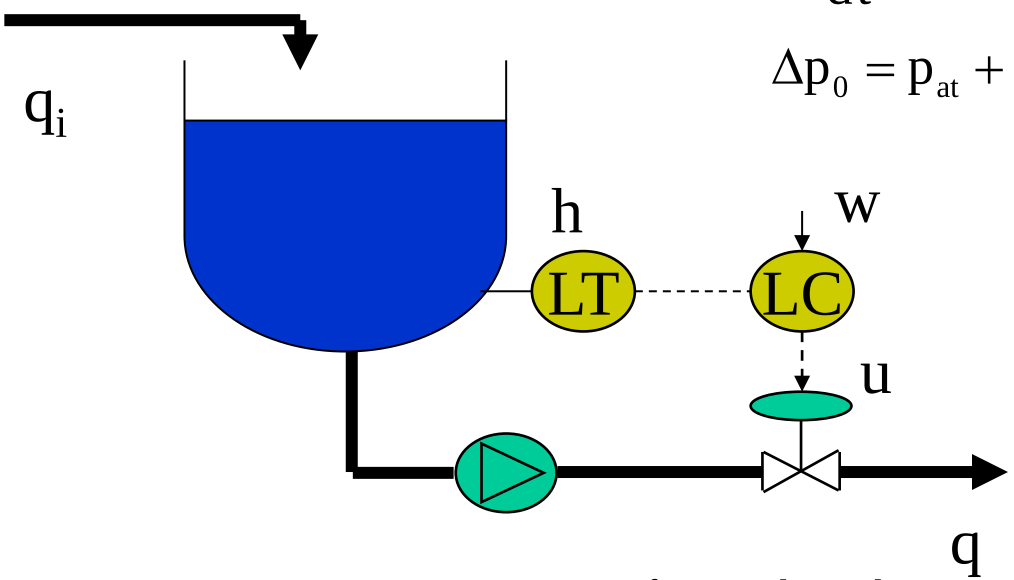
Level Control

$$\frac{dm}{dt} = q_i \rho - q\rho \qquad m = Ah\rho$$

$$A\frac{dh}{dt} = q_i - q \qquad A\frac{d\Delta h}{dt} = \Delta q_i - \Delta q$$

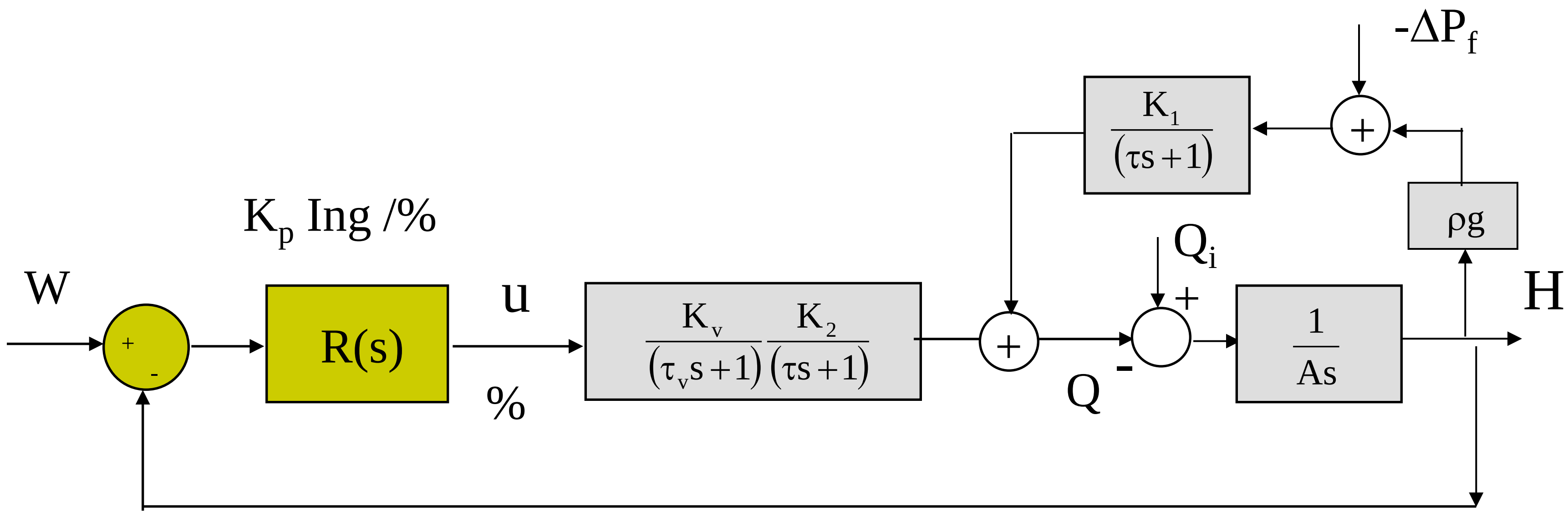
$$\tau \frac{d\Delta q}{dt} + \Delta q = K_1 \Delta(\Delta p_0) + K_2 \Delta a$$

$$\Delta p_0 = p_{at} + \rho g h - p_f \qquad \Delta(\Delta p_0) = \rho g \Delta h - \Delta p_f$$

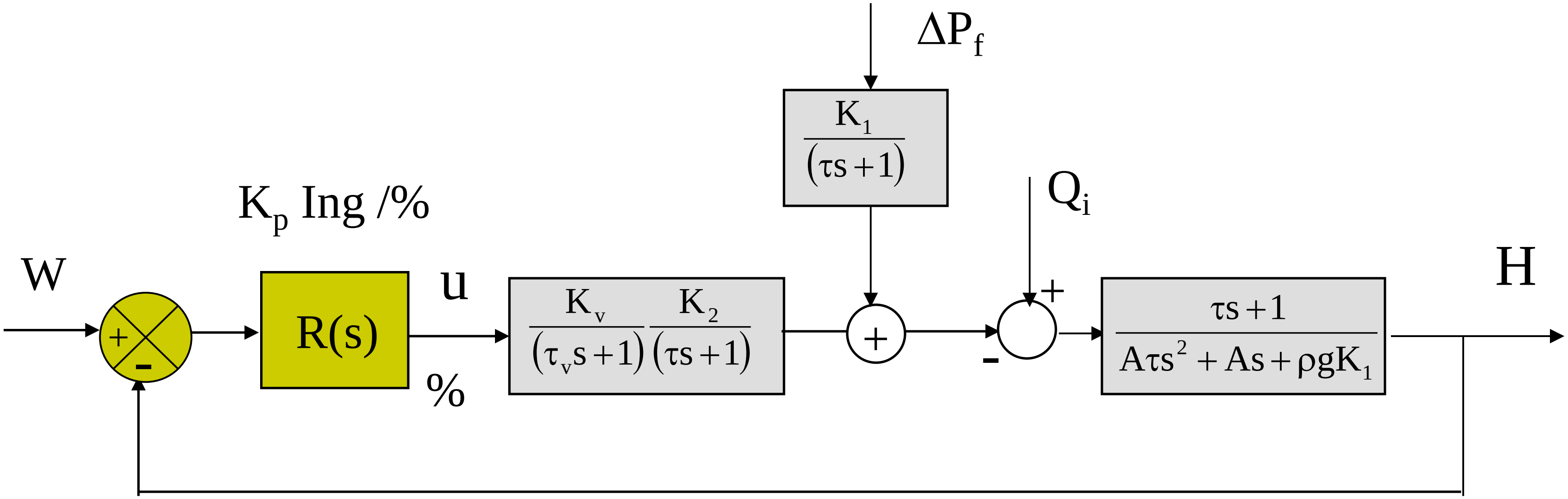


$$\tau_v \frac{d\Delta a}{dt} + \Delta a = K_v \Delta u$$

Block diagram



Block diagram



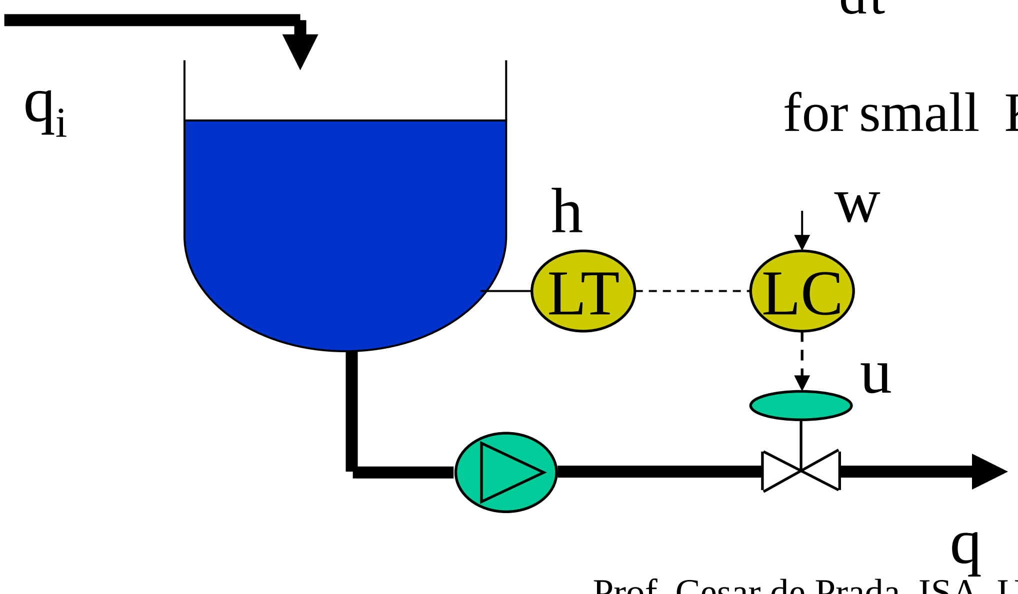
Level Control

$$\frac{dm}{dt} = q_i\rho - q\rho \qquad m = Ah\rho$$

$$A\frac{dh}{dt} = q_i - q \qquad A\frac{d\Delta h}{dt} = \Delta q_i - \Delta q$$

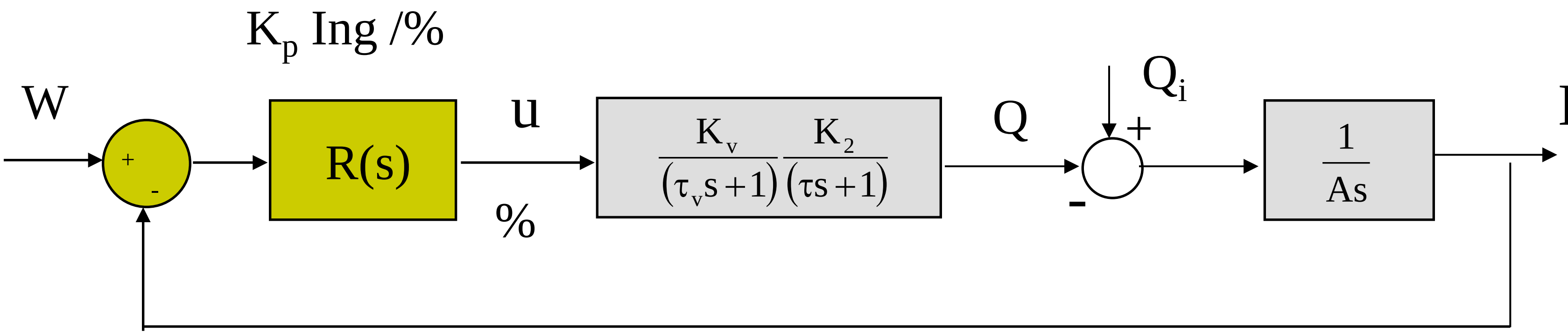
$$\tau\frac{d\Delta q}{dt} + \Delta q = K_1\Delta(\Delta p_0) + K_2\Delta a$$

$$\text{for small } K_1 : \tau\frac{d\Delta q}{dt} + \Delta q = K_2\Delta a$$



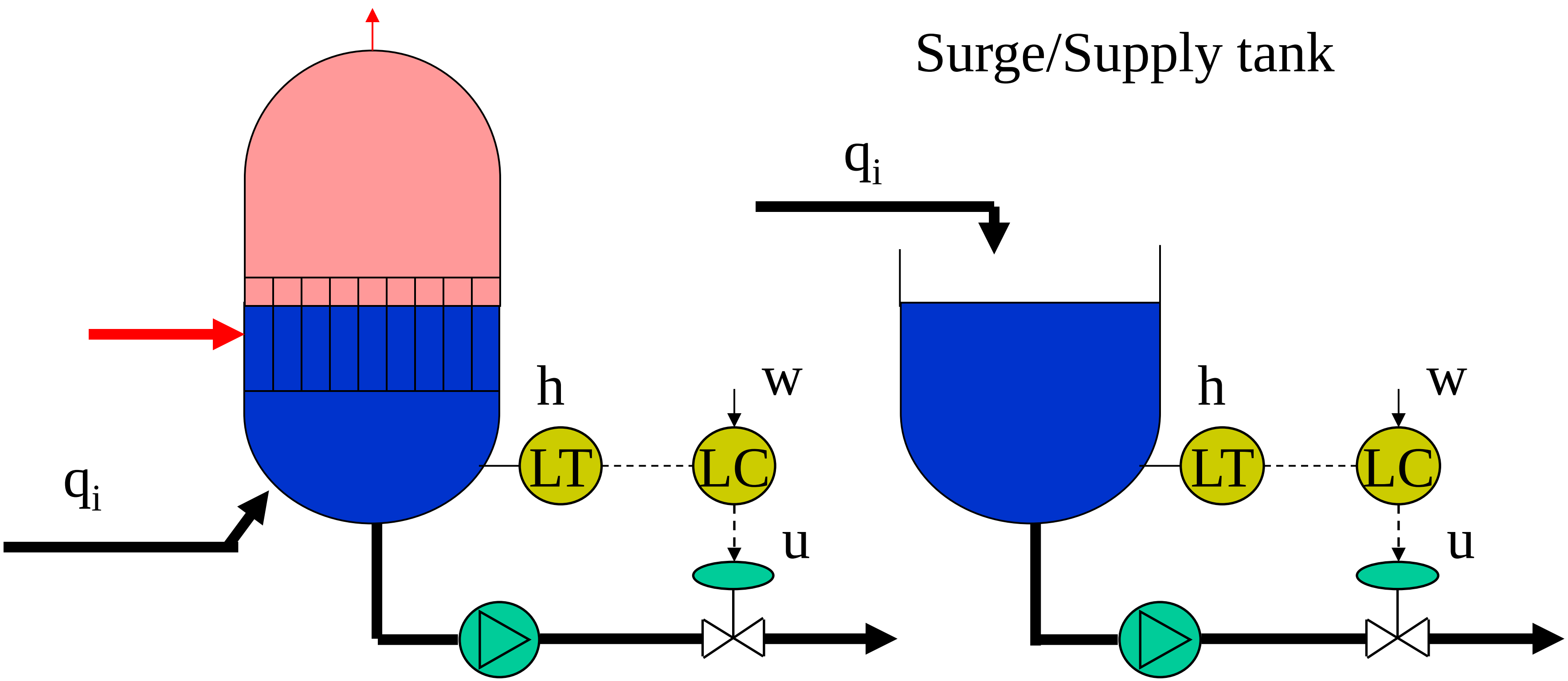
$$\tau_v\frac{d\Delta a}{dt} + \Delta a = K_v\Delta u$$

Block diagram



In practice it behaves as a process with an integrator

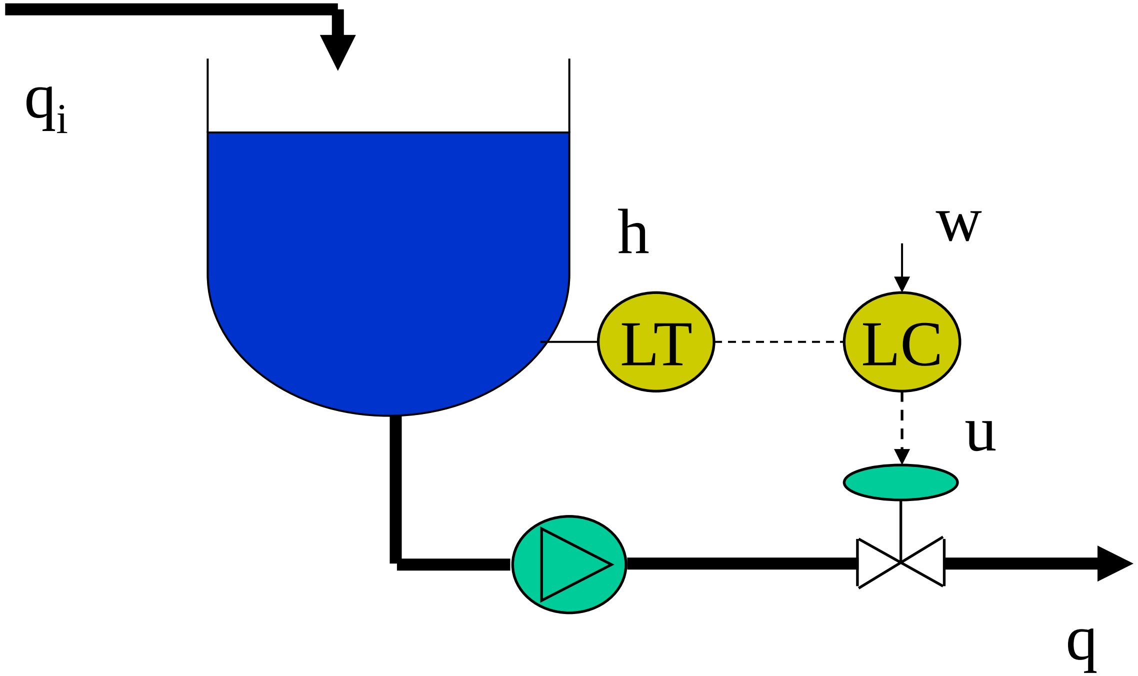
Tight /Average control



The level must be maintained tightly: PI with “active” tuning

Store liquid + smooth changes in q_i : P with “loose” tuning

Average Control



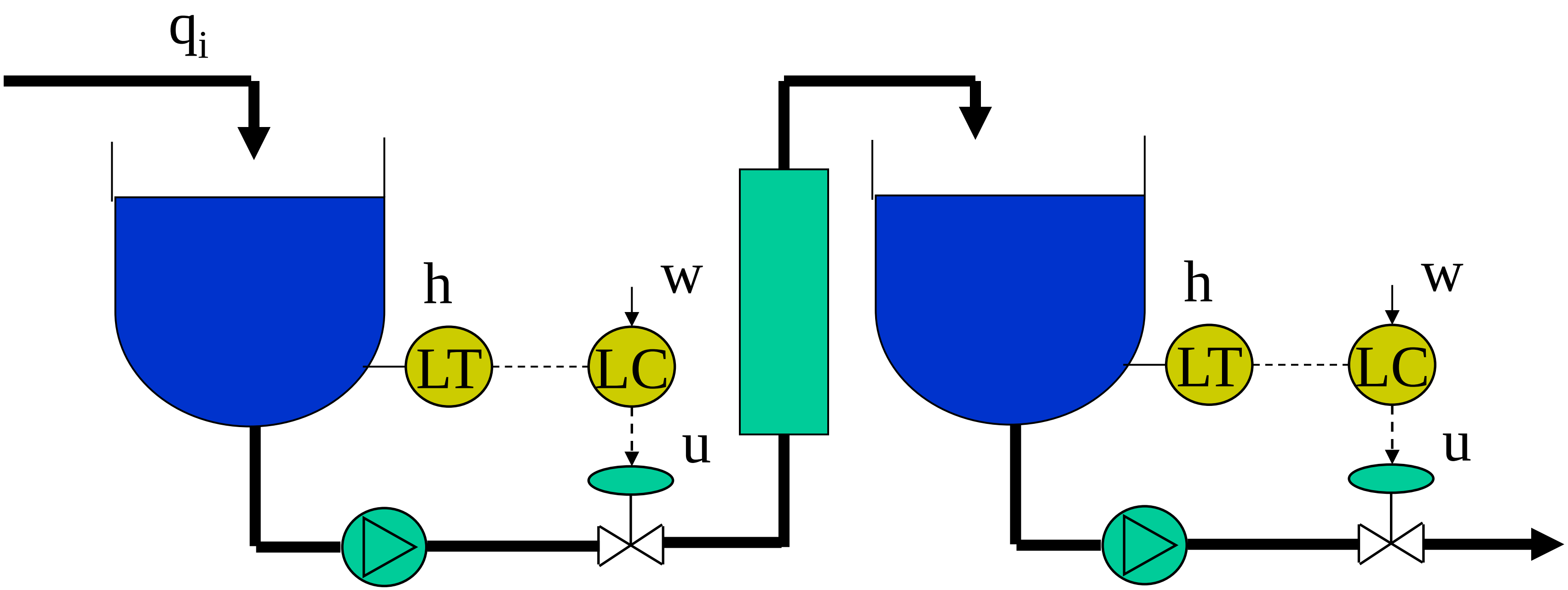
Smooth disturbances

P control with low K_p: The level oscillates and there is steady state error but q changes smoothly

$$u = K_p e + \text{bias}$$

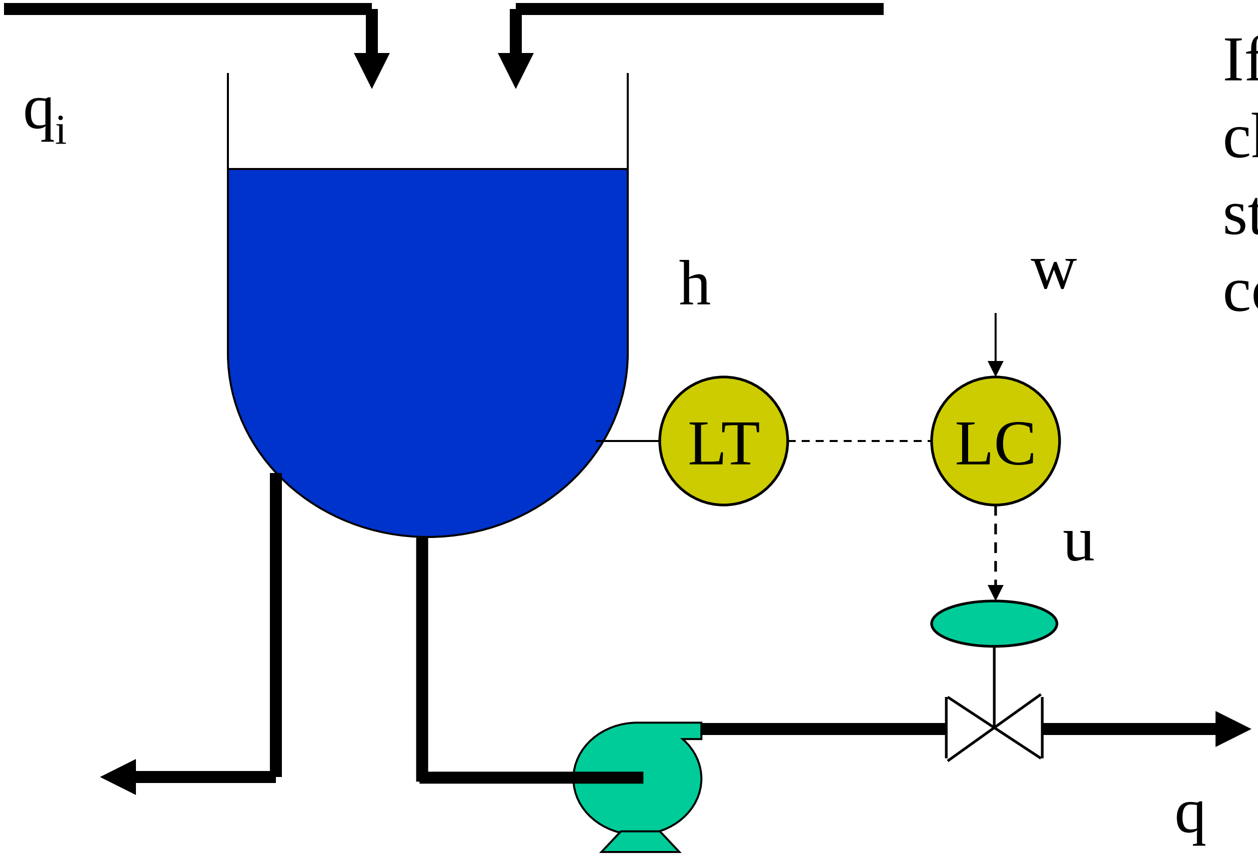
If w = 50%, $K_p = 1$ and bias = 50%, then u = 100 if h = 100%, u = 0 if h = 0

Units in series



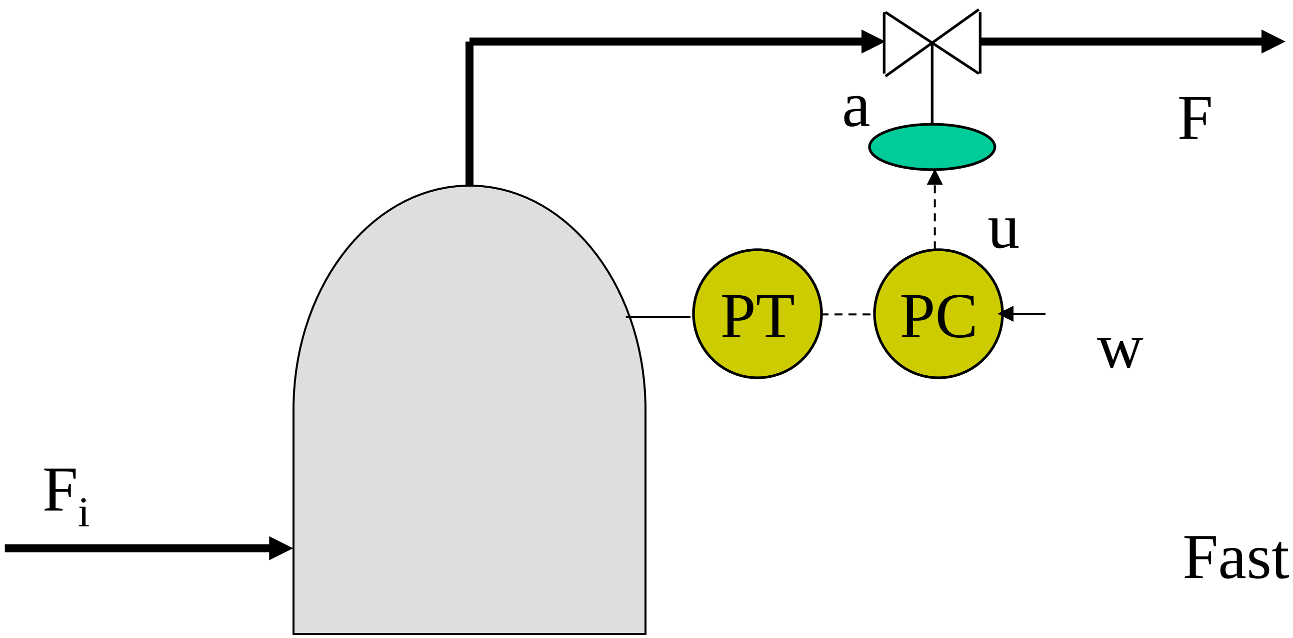
All level control must be placed in the same direction

Several streams



If possible, then choose the larger stream for control

Pressure control

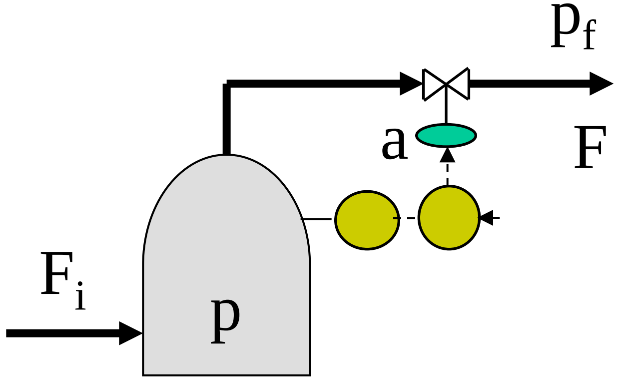


Fast process

PI with “tight” tuning

Many different dynamics and aims

Pressure control



$$\frac{dm}{dt} = F_i - F = F_i - aC_v\sqrt{p^2 - p_f^2}$$

$$m = V\rho \qquad p = \frac{\rho}{M}RT \qquad \text{isothermal tank}$$

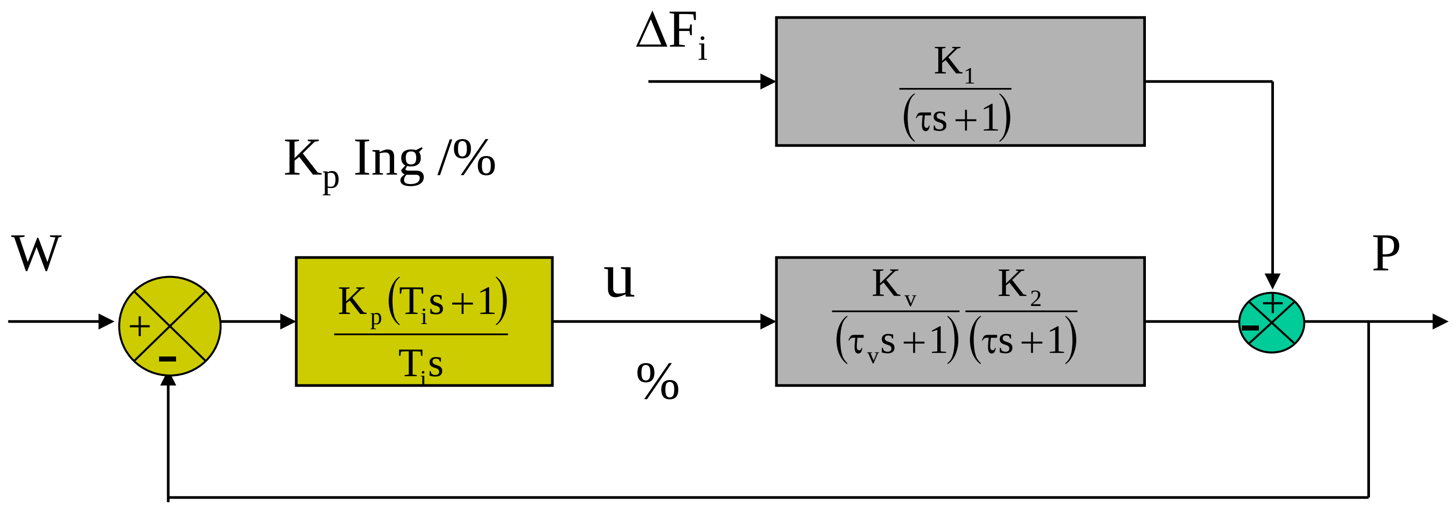
$$\frac{VM}{RT}\frac{dp}{dt} = F_i - aC_v\sqrt{p^2 - p_f^2}$$

$$\left\{\frac{VM}{RT}\right\}_0 \frac{d\Delta p}{dt} = \Delta F_i - \left\{C_v\sqrt{p^2 - p_f^2}\right\}_0 \Delta a - \left\{aC_v \frac{p}{\sqrt{p^2 - p_f^2}}\right\}_0 \Delta p$$

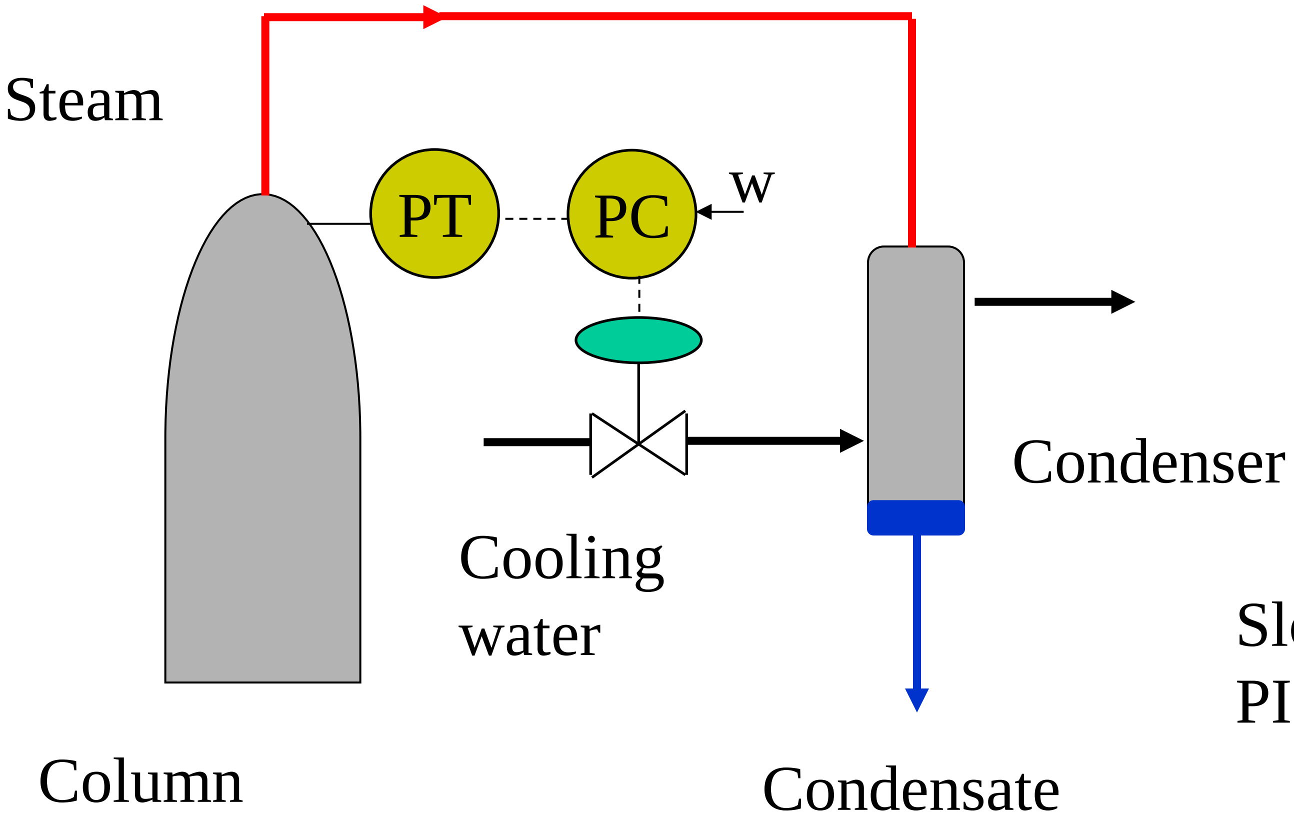
$$\left\{\frac{VM\sqrt{p^2 - p_f^2}}{RTaC_v p}\right\}_0 \frac{d\Delta p}{dt} + \Delta p = \left\{\frac{\sqrt{p^2 - p_f^2}}{aC_v p}\right\}_0 \Delta F_i - \left\{\frac{p^2 - p_f^2}{ap}\right\}_0 \Delta a$$

$$\tau\frac{d\Delta p}{dt} + \Delta p = K_1\Delta F_i - K_2\Delta a \qquad \text{Valve:} \qquad \tau_v\frac{d\,\Delta a}{d\,t} + \Delta a = K_v\Delta u$$

Block diagram

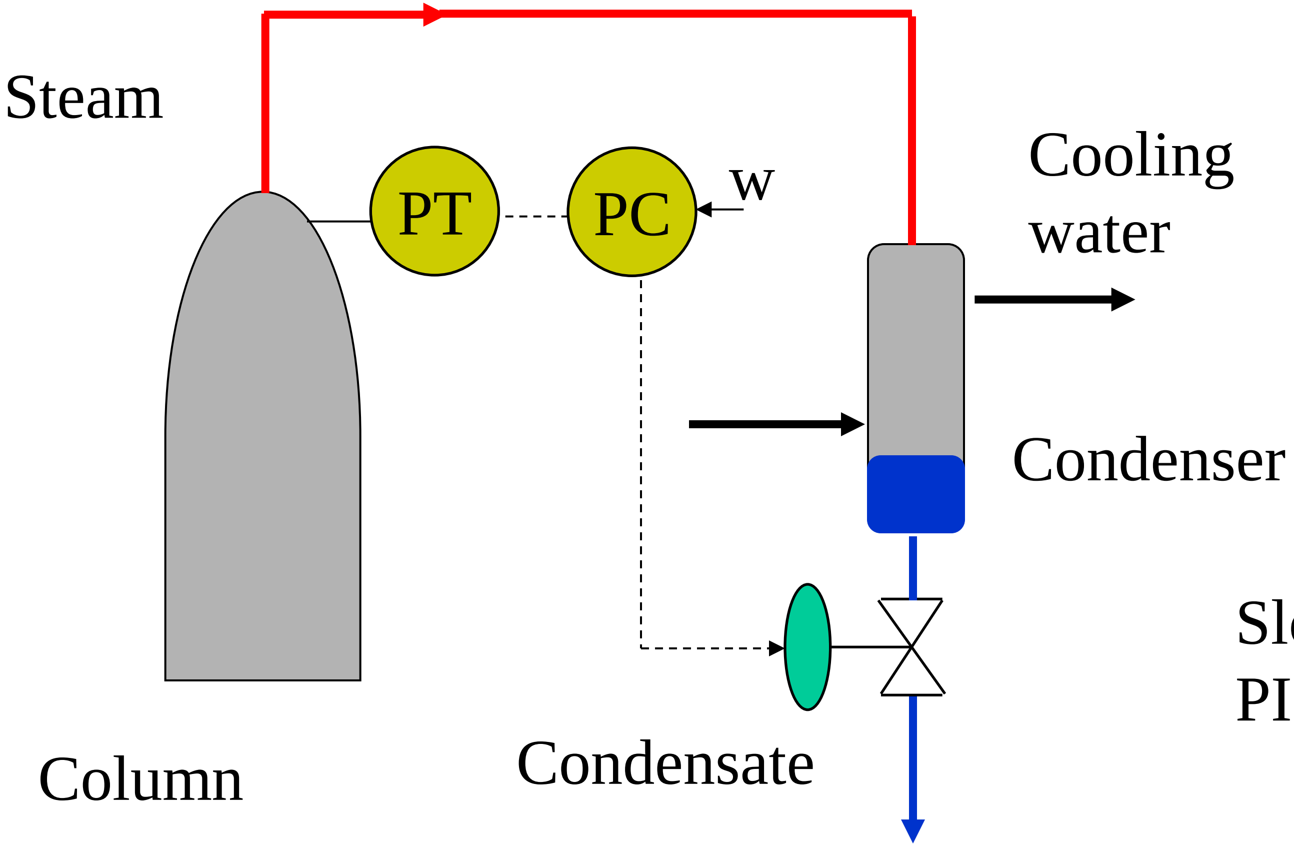


Pressure control



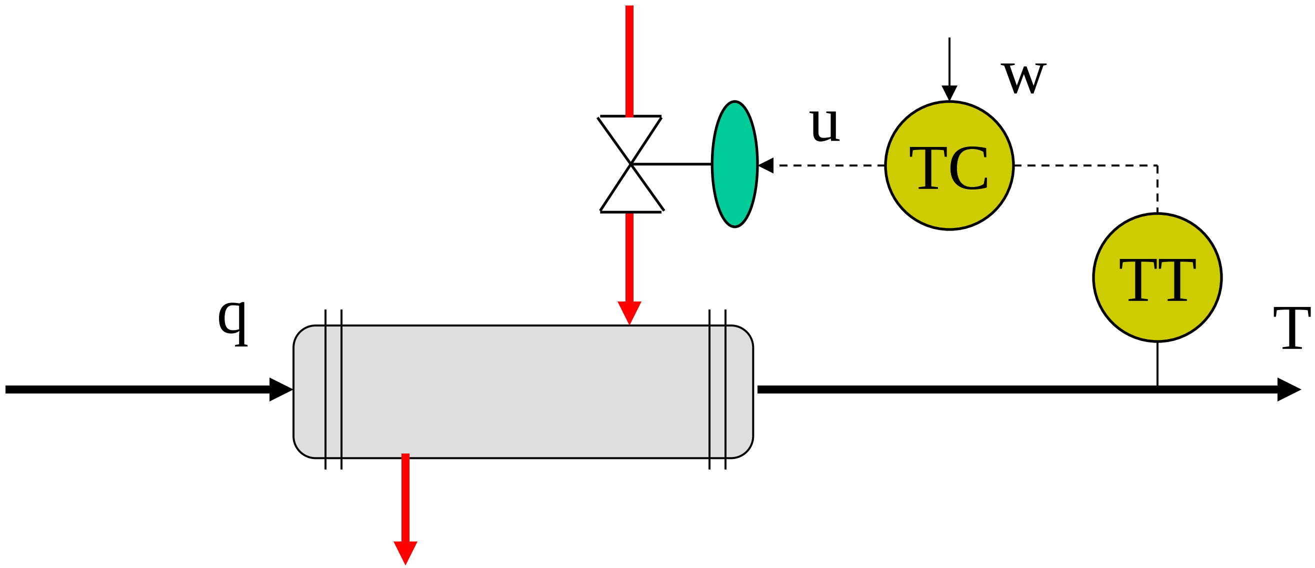
Slow process,
PI / PID

Pressure control



Slow process,
PI / PID

Temperature Control



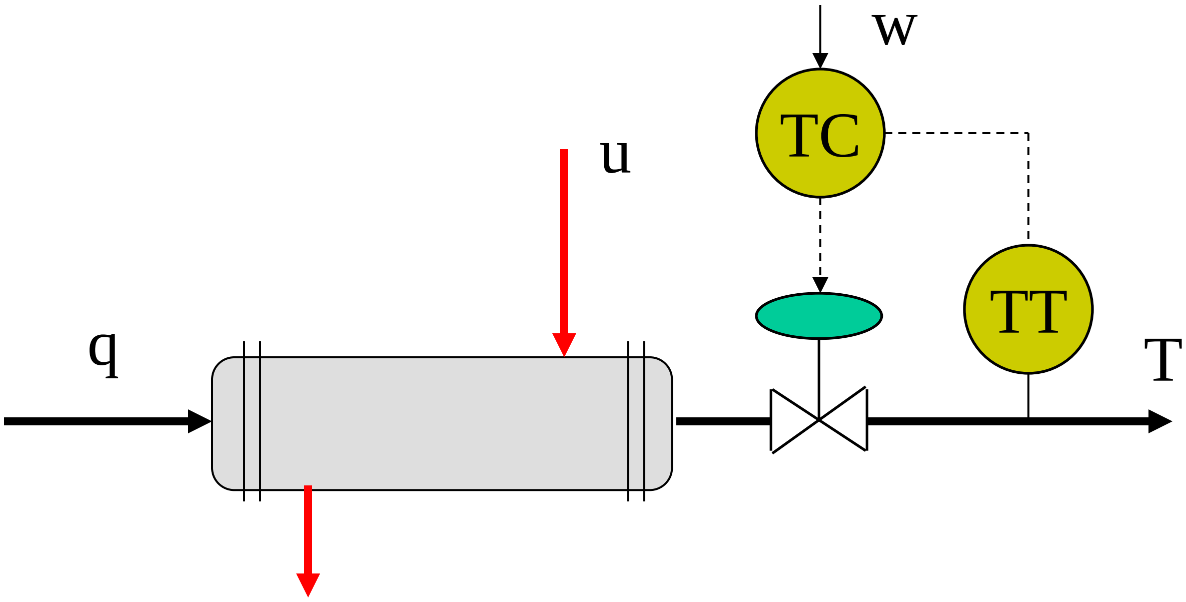
Many architectures / processes

Slow process PID

Transmitter dynamics can be significant

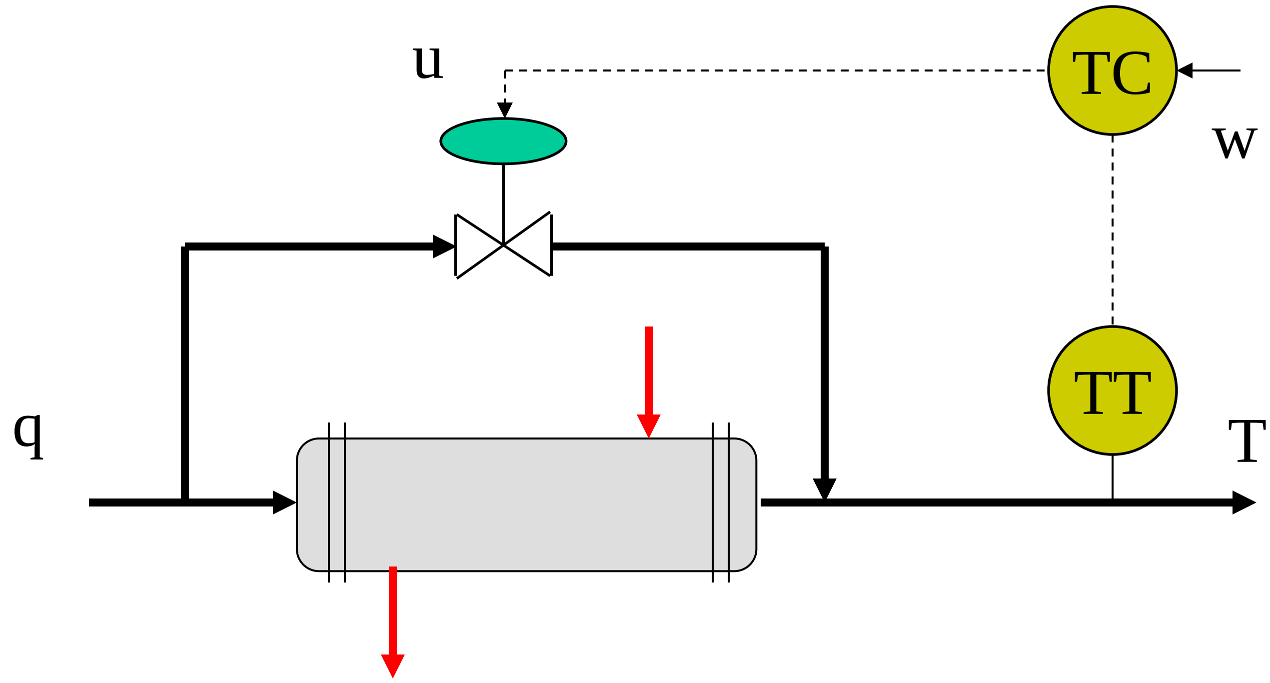
Be careful with the placement of the transmitter in order to avoid transport delays

Temperature Control



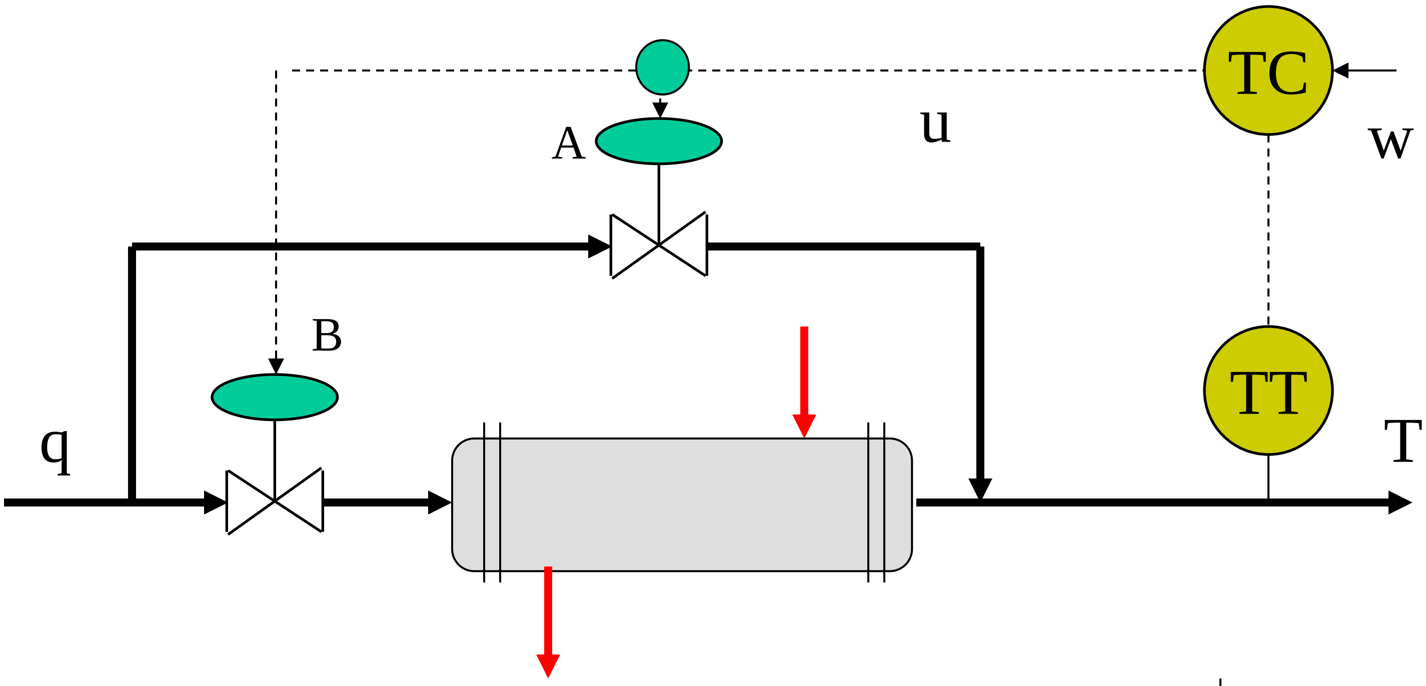
The product flow cannot be changed independently

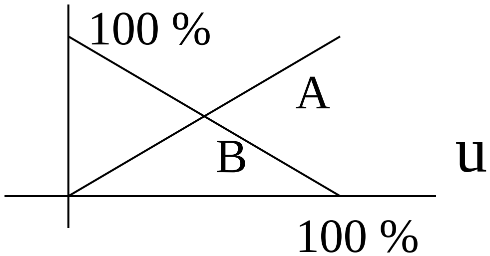
Temperature Control



Product by-pass
Fast dynamics, low range of control

Temperature Control

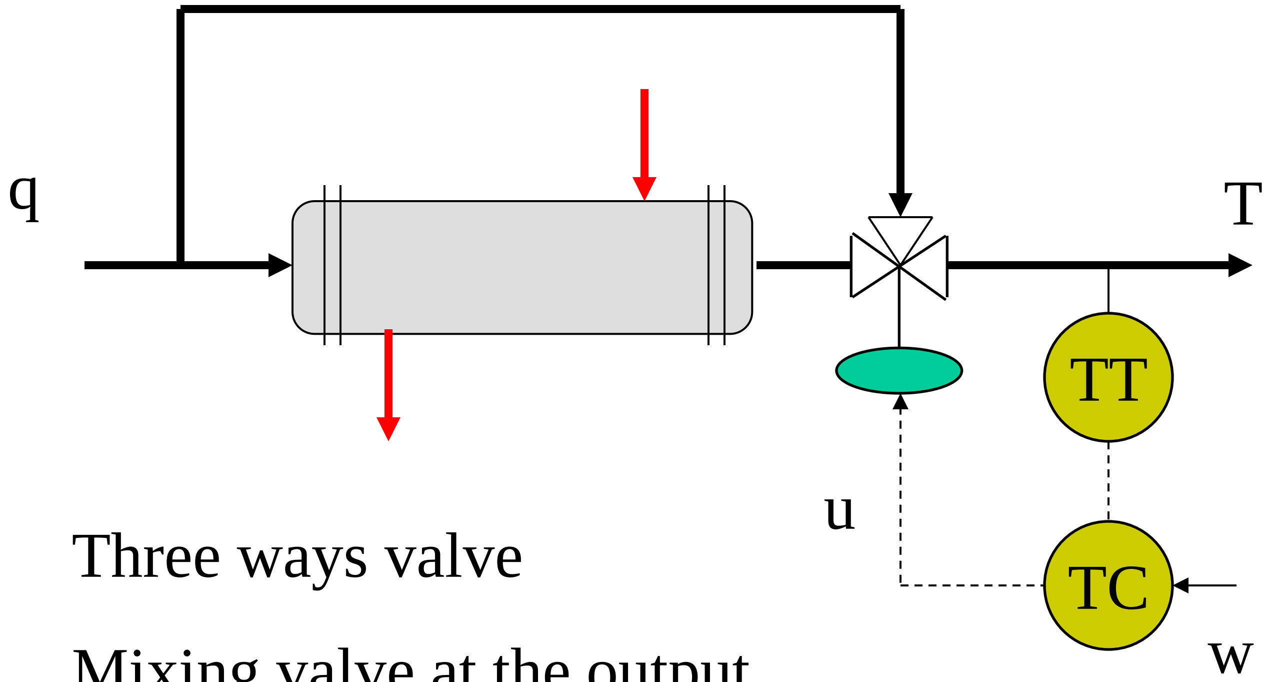




The valves operate in opposition, one is air-open and the other one air-close

The total product flow is not changed

Temperature Control

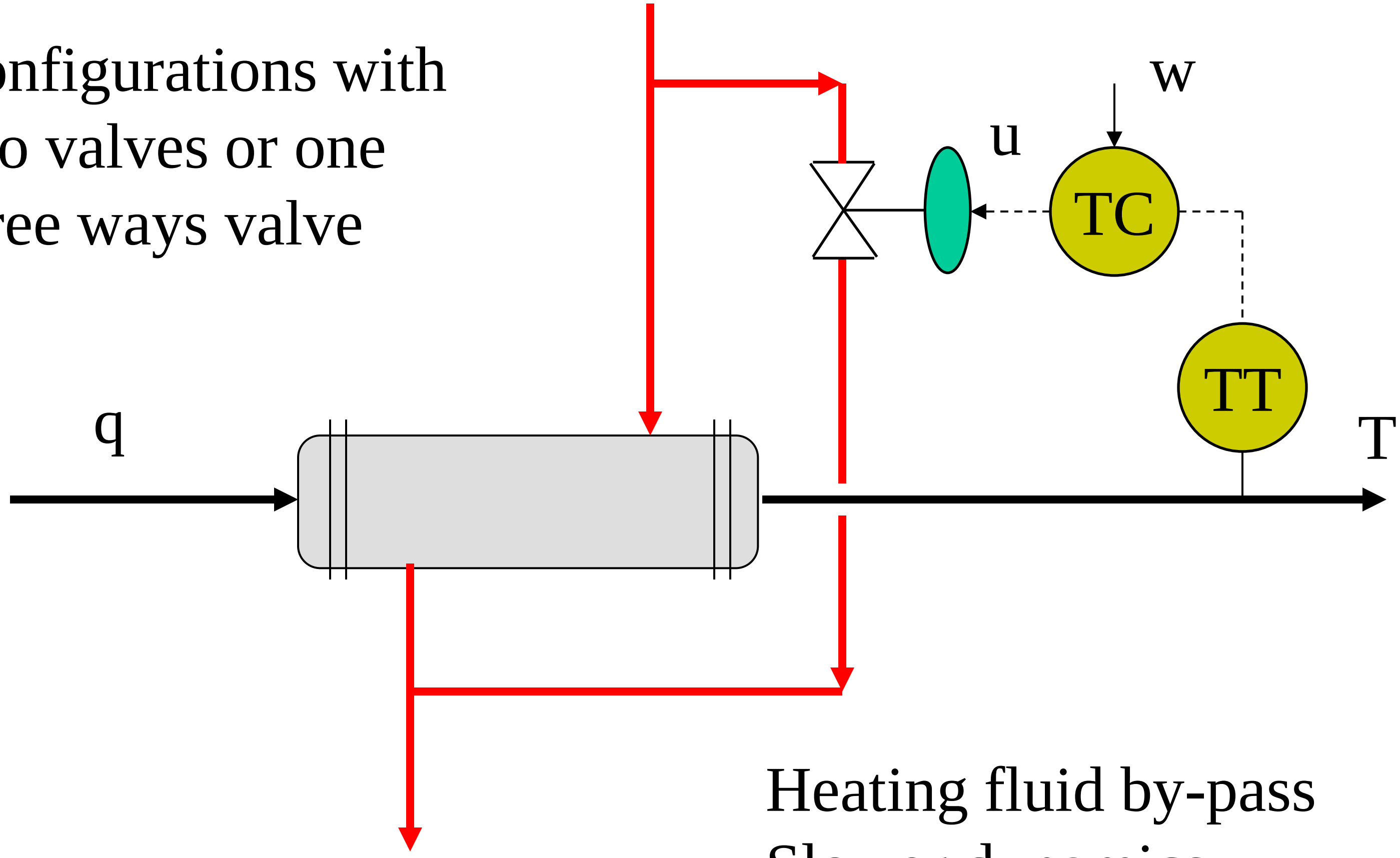


Three ways valve

Mixing valve at the output or splitting valve at the input

Temperature Control

Configurations with
two valves or one
three ways valve



Heating fluid by-pass
Slower dynamics

Temperature Control