Control Structures
(Advanced Control)

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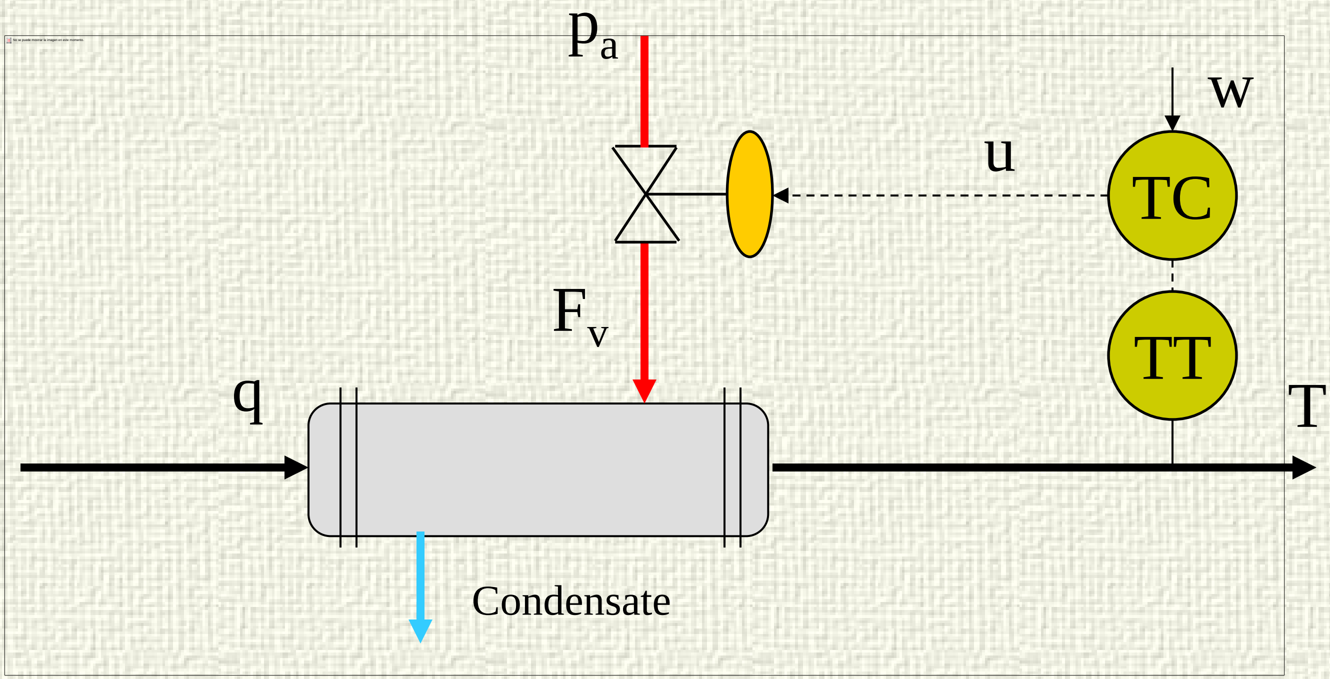
Control Structures

- Changes made in conventional control loops in order to improve:
  - Disturbance rejection
  - Ratio between variables
  - Operation with several competing variables
  - Operation with several controllers
  - Operation with several actuators
  - Etc.

Control structures

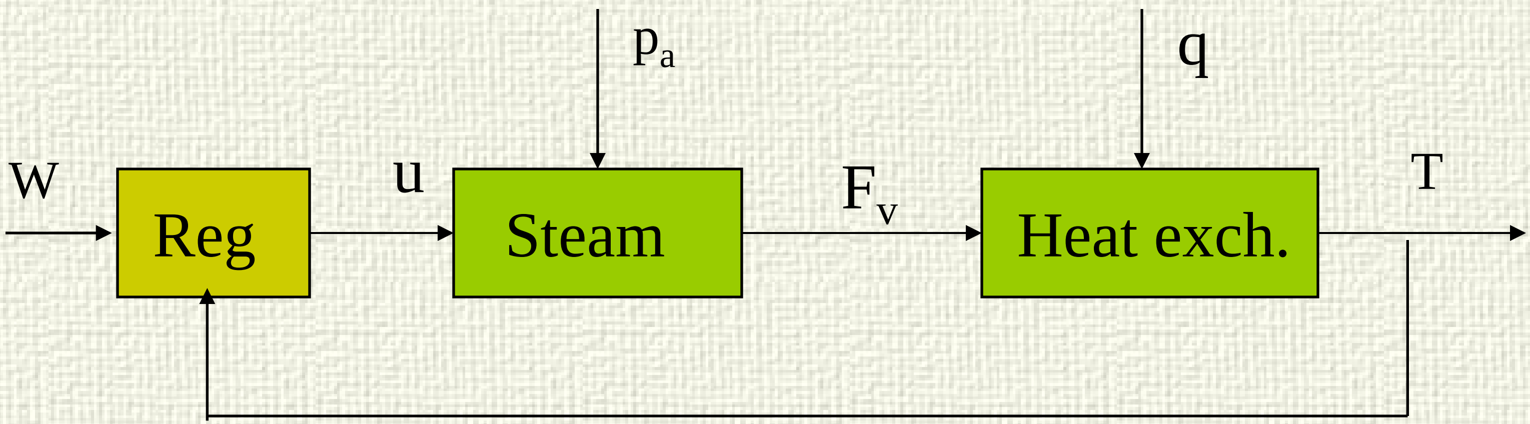
- Cascade loops
- Feedforward compensators
- Ratio controllers
- Selective control
- Override control
- Split range
- Inferential control
- Examples of control of several process units
- Design methodology

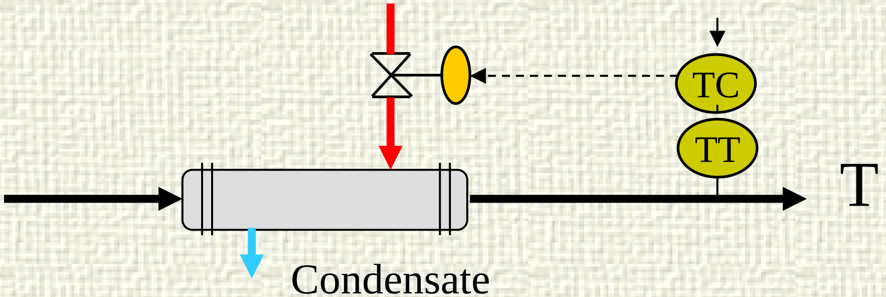
Standard control loop



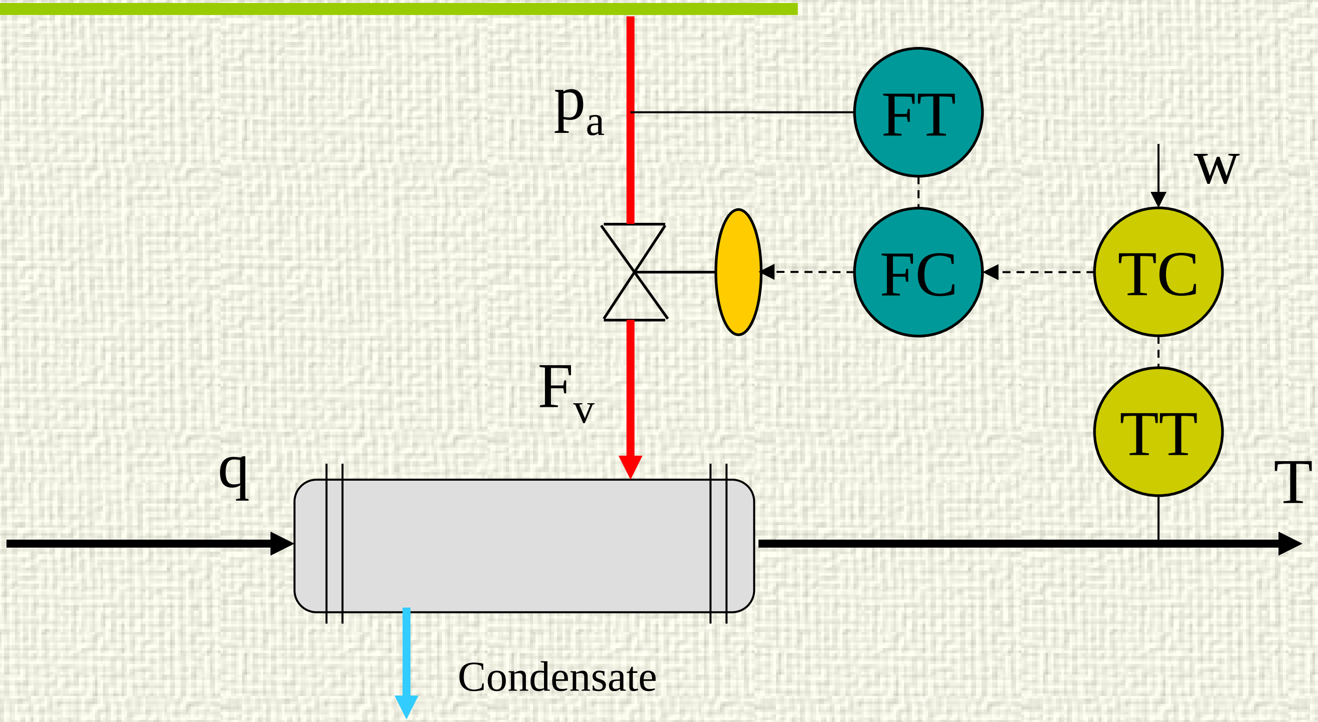
If p_a changes, T will change and the disturbance will be corrected by the controller using the signal u to the valve

Block Diagram



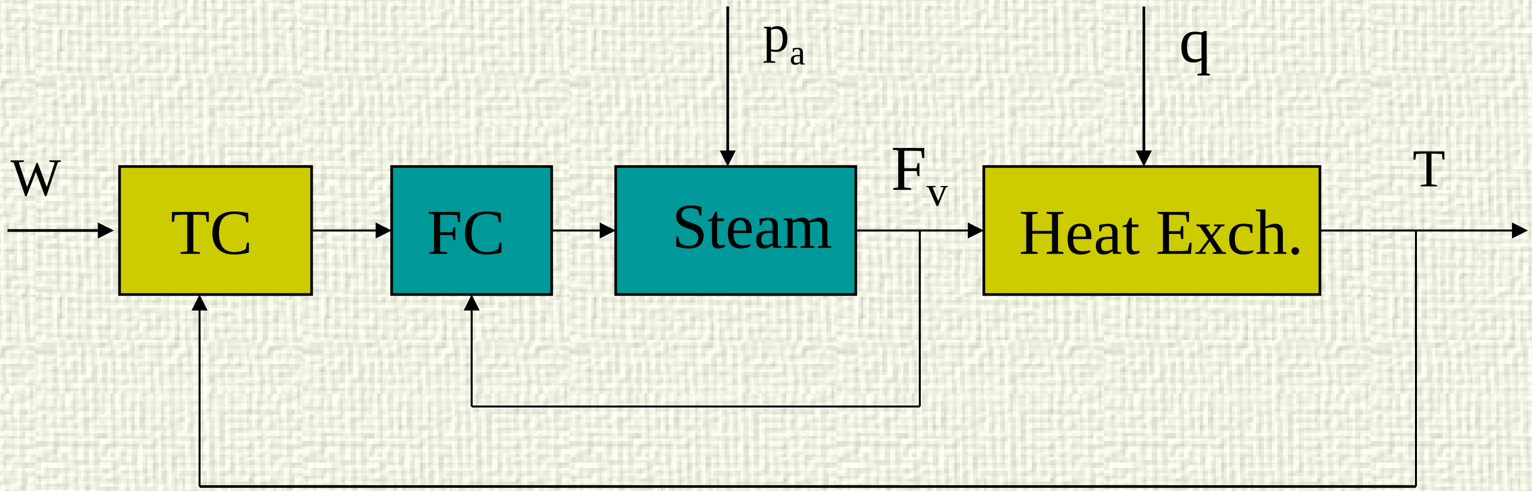


Cascade of controllers



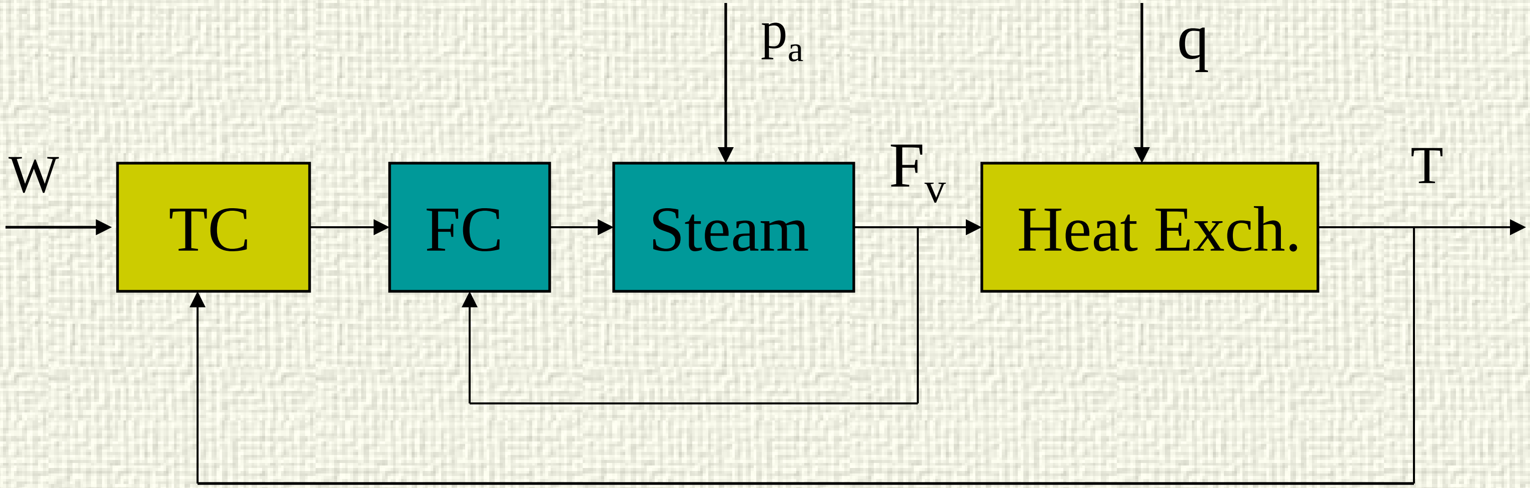
The external regulator (TC) changes the set point of the internal one (FC), which corrects the effect of the pressure change in p_a over F_v before the disturbance affects the heat exchanger in a significant way

Cascade control



The external regulator (TC) changes the set point of the internal one (FC), which corrects the effect of the pressure change in p_a over F_v before the disturbance affects the heat exchanger in a significant way

Cascade Control



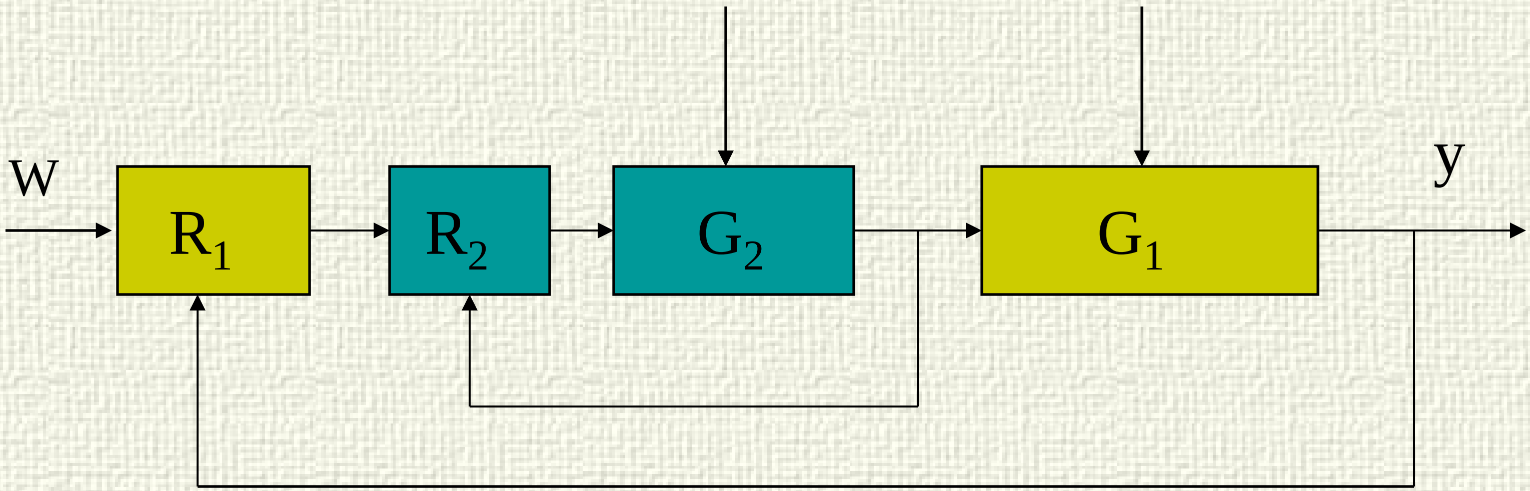
Main process (TC-Heat Exchanger) slow

Secondary process (FC-Steam) fast

Disturbances on the secondary part of the process that can be corrected

More instrumentation

Tuning/Operation

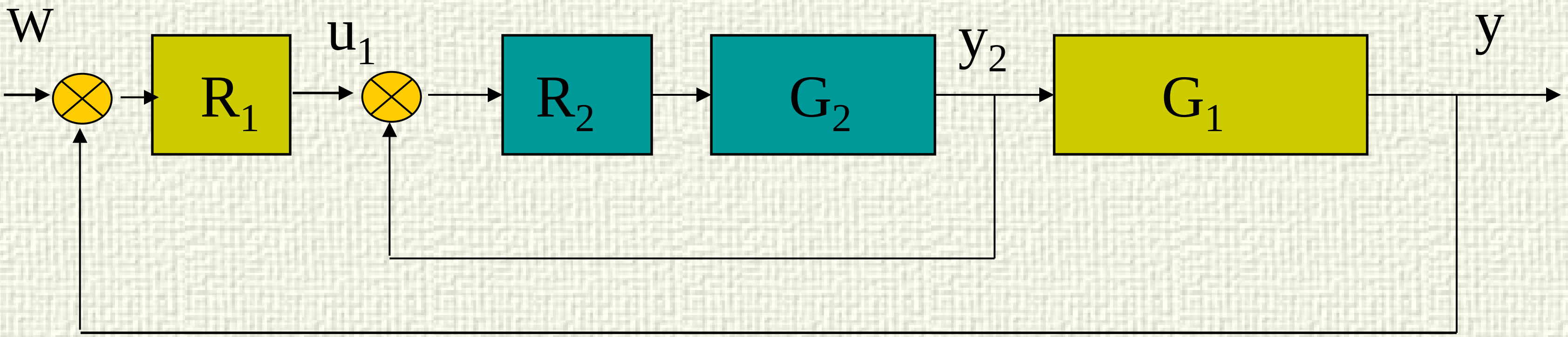


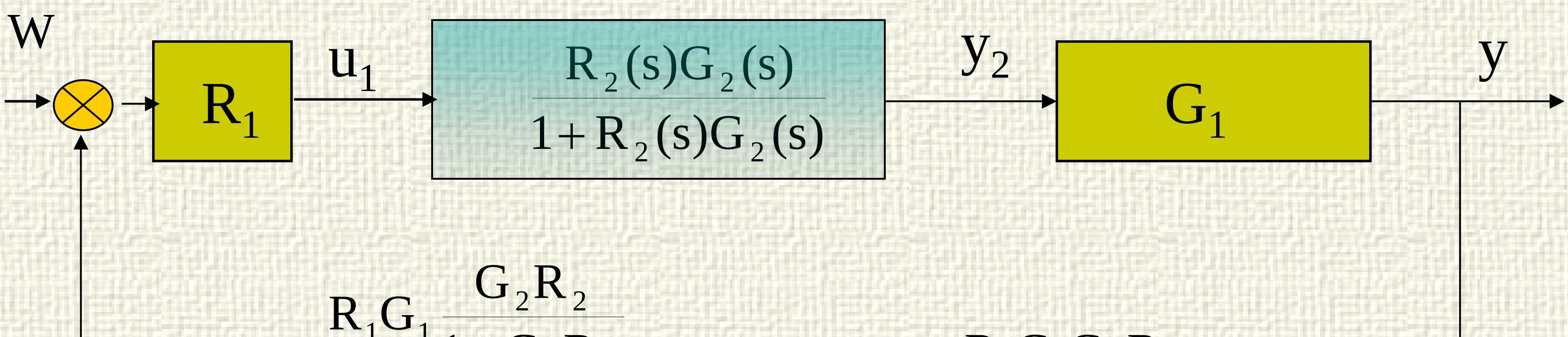
Internal loops must be tuned first, then the external ones

Generally speaking, cascade control is faster than single loop

If a controller is in manual, all loops external to it must be in manual

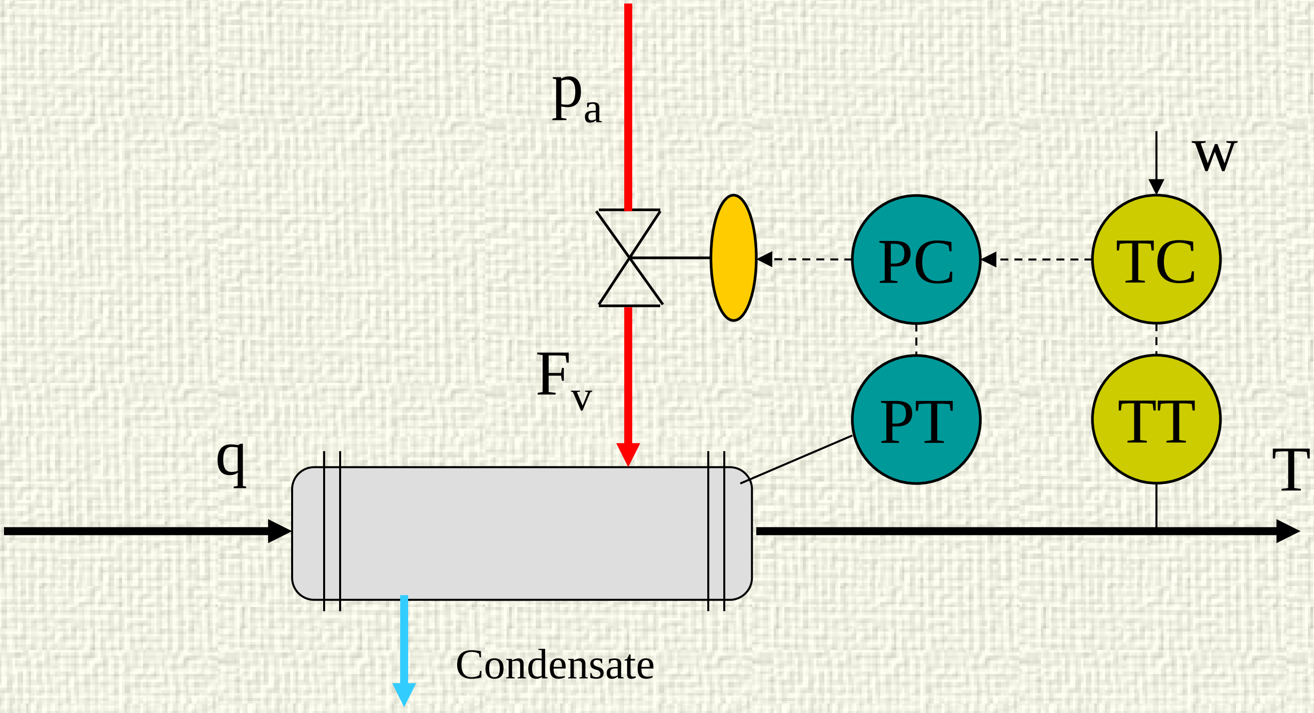
Closed loop TF





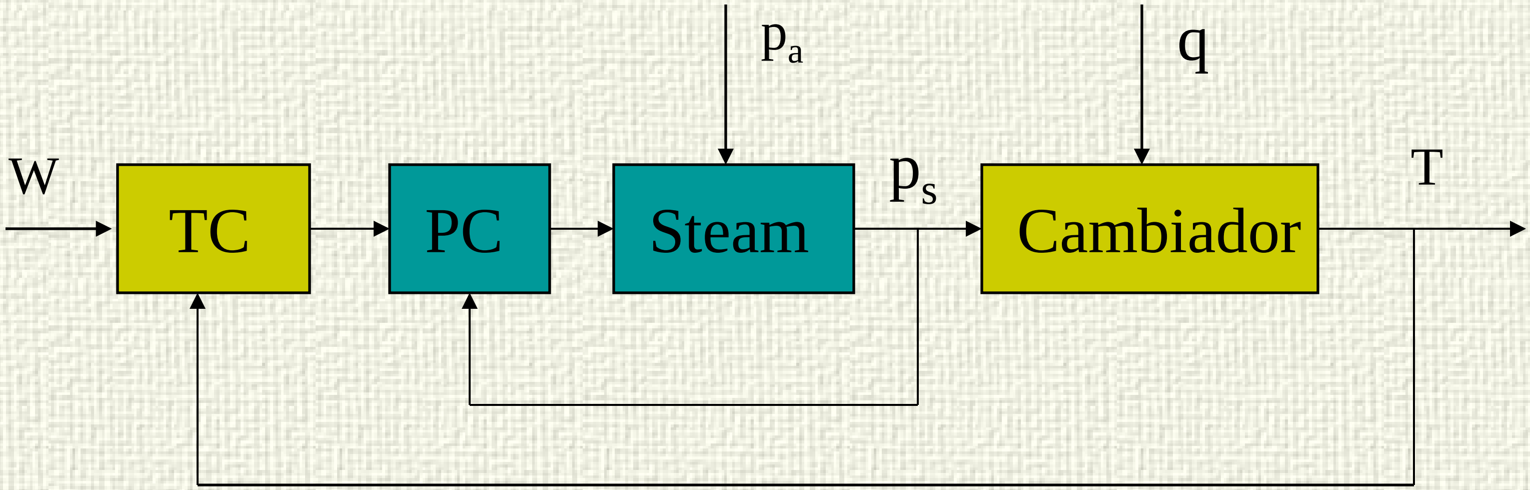
$$Y_1(s) = \frac{R_1 G_1 \dfrac{G_2 R_2}{1+G_2 R_2}}{1+R_1 G_1 \dfrac{G_2 R_2}{1+G_2 R_2}} W_1(s) = \frac{R_1 G_1 G_2 R_2}{(1+G_2 R_2)+R_1 G_1 G_2 R_2} W_1(s)$$

Cascade Temp-Pressure



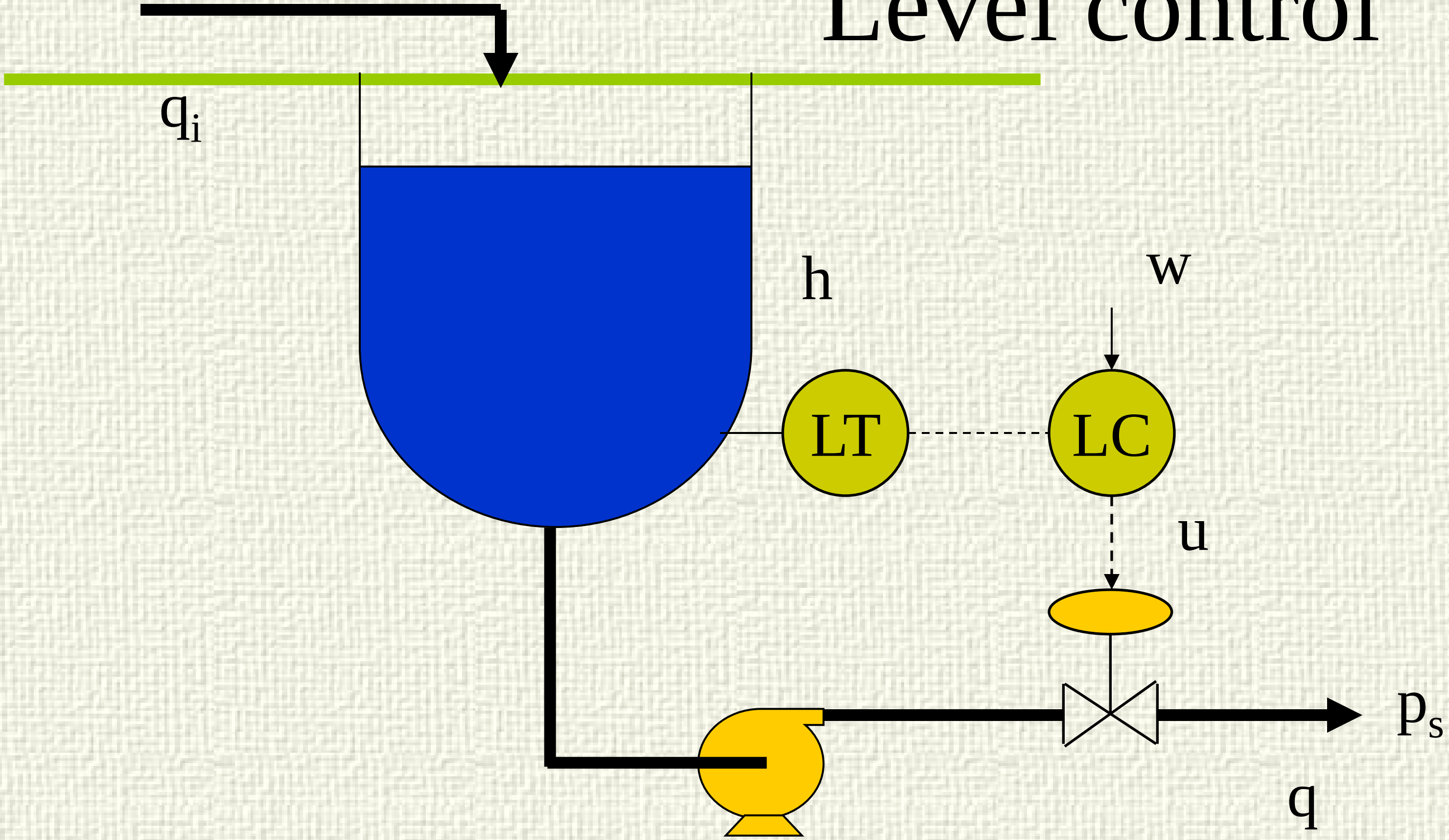
An internal pressure controller (PC) can perform a more efficient operation

Cascade Control



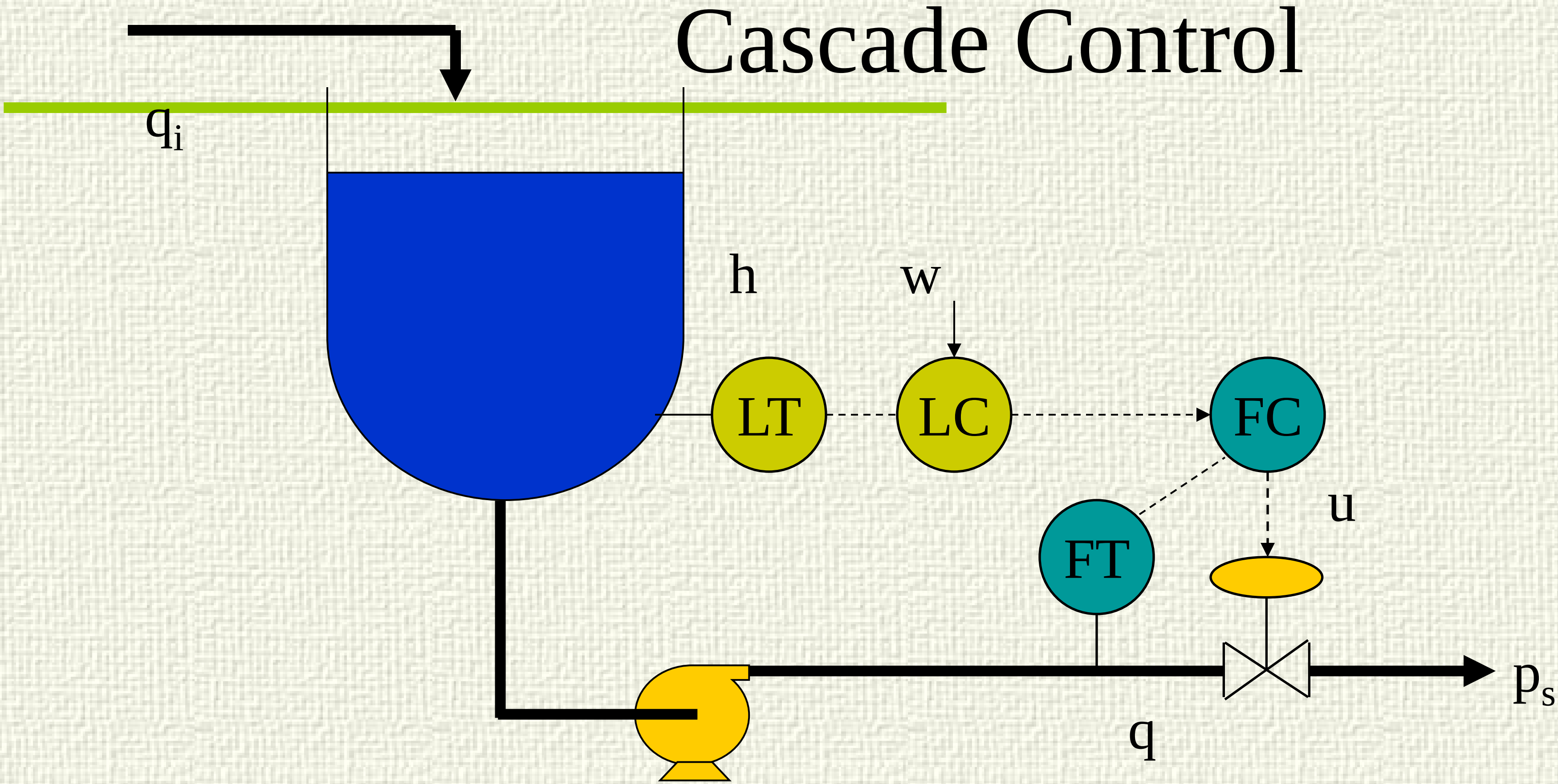
The external controller (TC) commands the SP of the internal one (PC) which corrects the effect of changes in p_a over p_s before they reach the heat exchanger

Level control



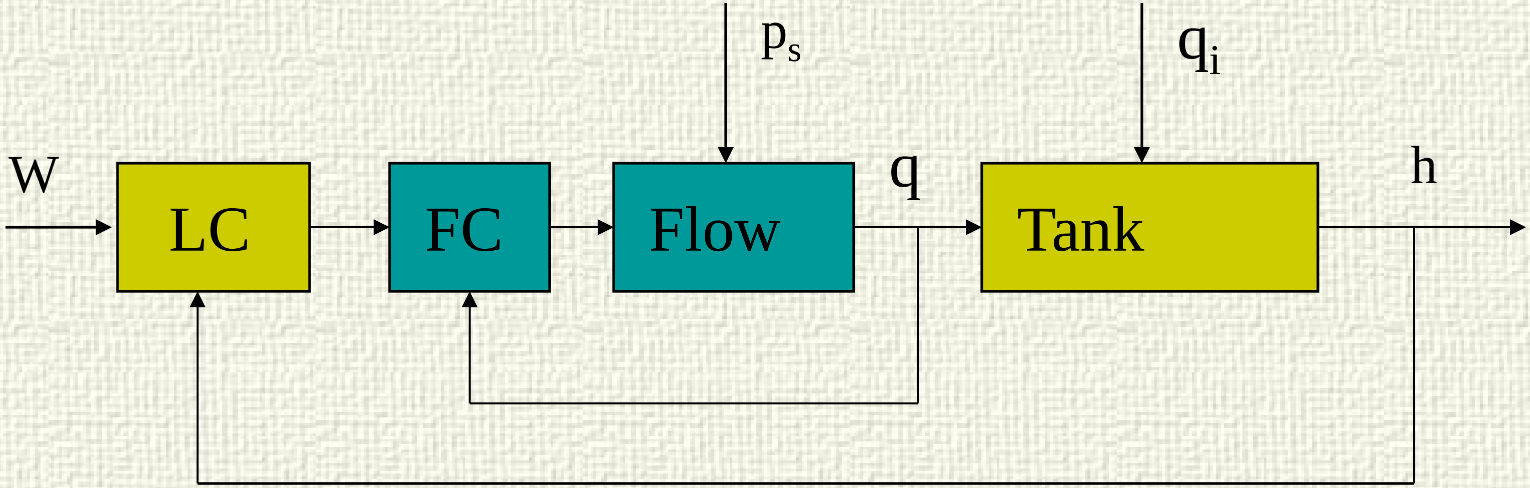
Changes in pressure p_s at the end of the line modify the flow q and the level h. The controller changes u to restore level

Cascade Control



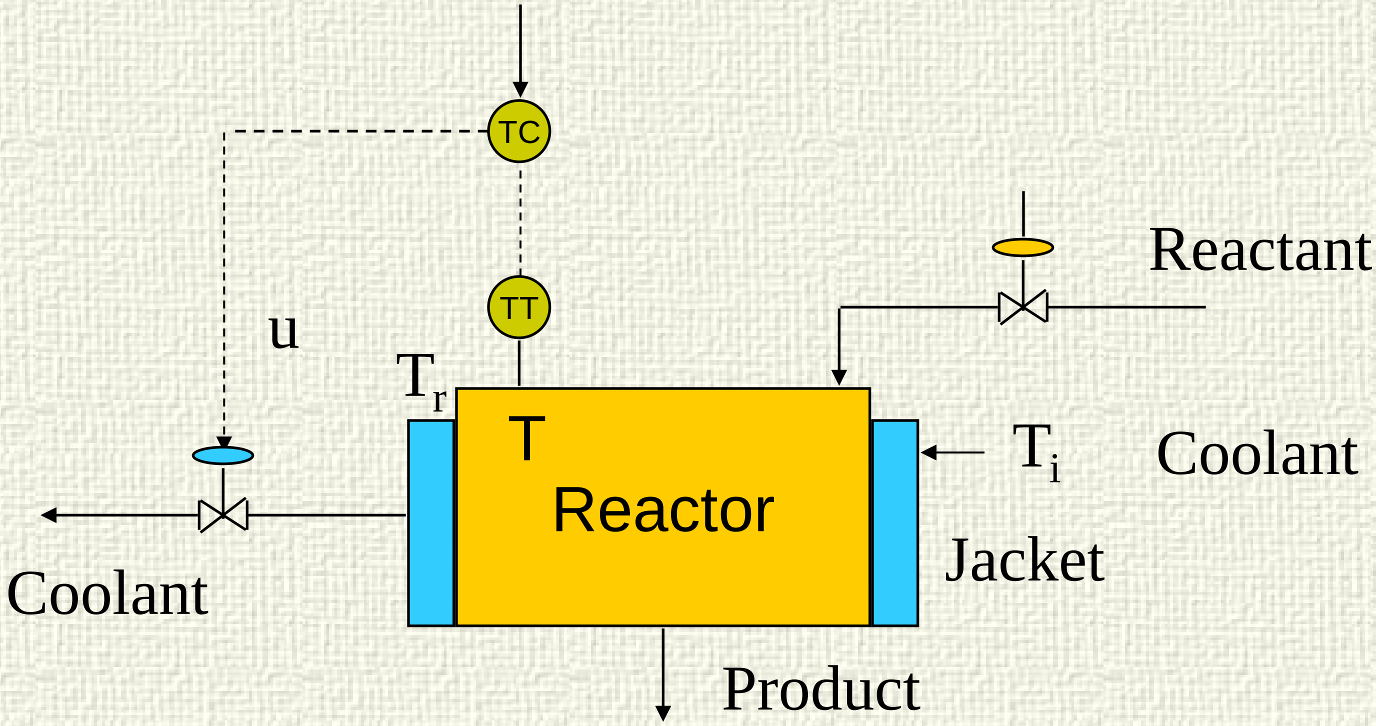
The external regulator (LC) modifies the internal one (FC) SP, which corrects the disturbances on q before they affect in a significant way the tank level h

Cascade Level-Flow



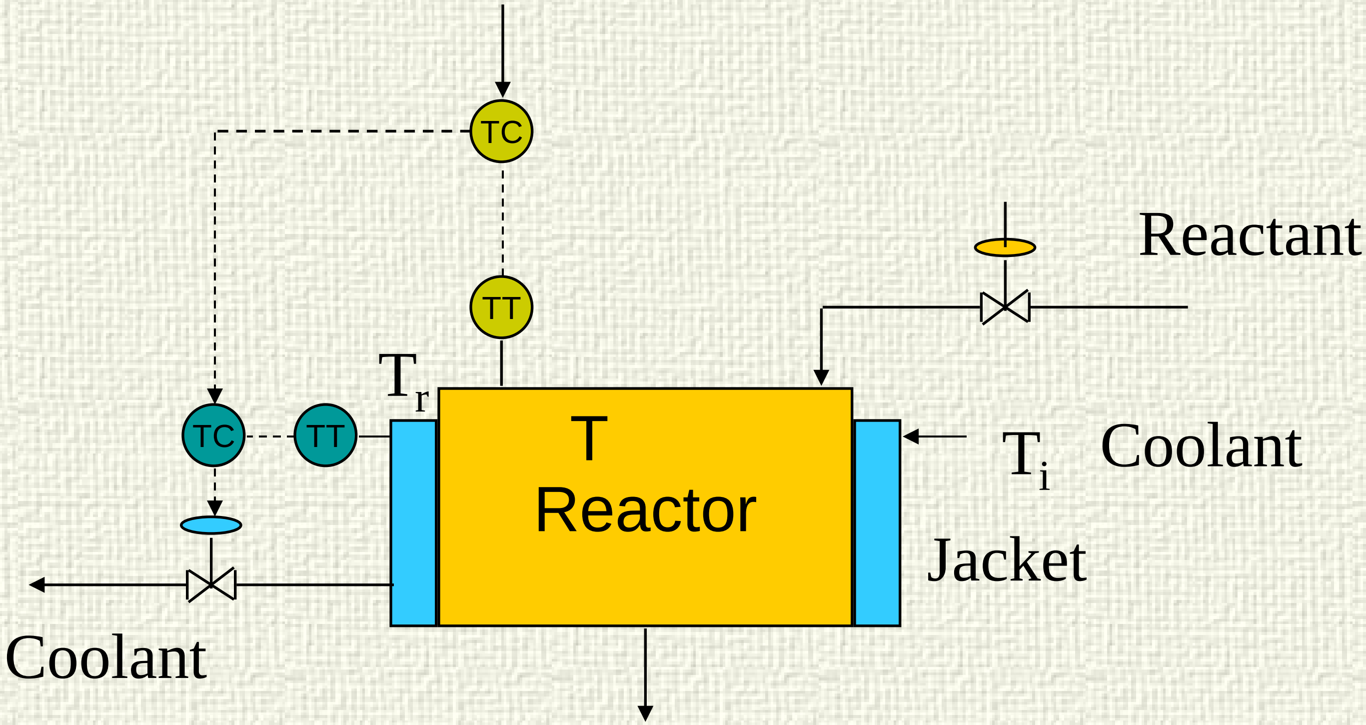
The external regulator (LC) modifies the external one (FC) SP, which corrects the disturbances on q before they affect in a significant way the tank level h

Temperature- Reactor



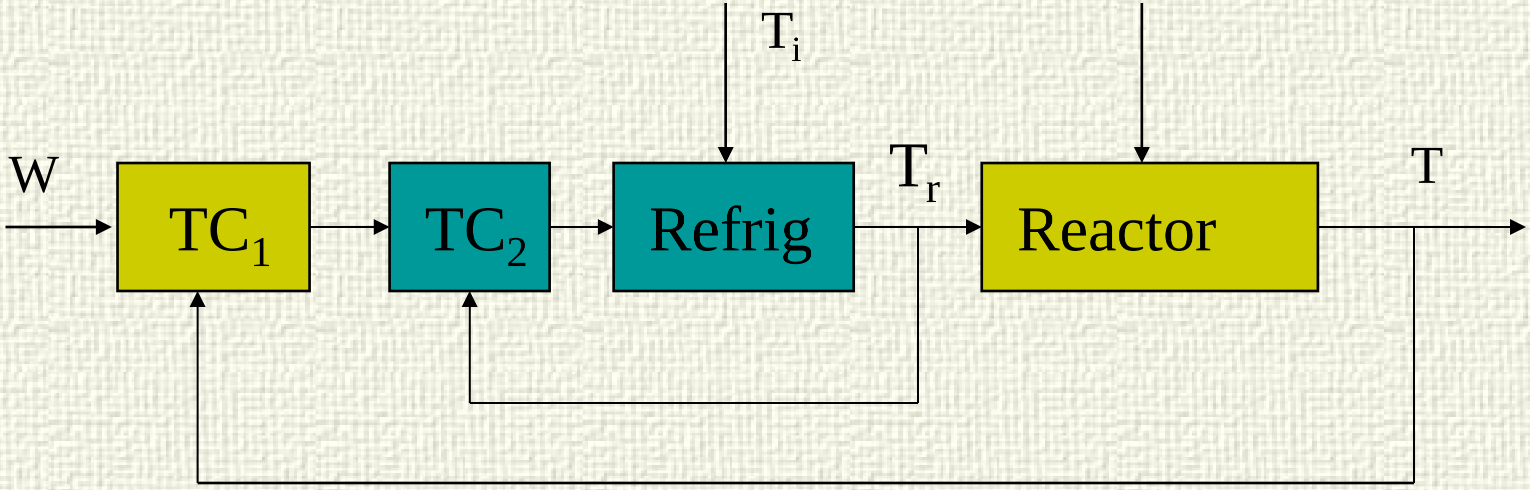
If the input refrigerant temperature T_i changes: T_r and T will change too and the TC controller will correct it by changing the control signal u

Cascade Temp-Temp



The external regulator (TC_1) modifies the internal one (TC_2) SP, which corrects the effect of the disturbance T_i on T_r before they affect T in a significant way

Cascade Temp-Temp



The external regulator (TC_1) modifies the internal one (TC_2) SP, which corrects the effect of the disturbance T_i on T_r before they affect T in a significant way

Temperature reactor control

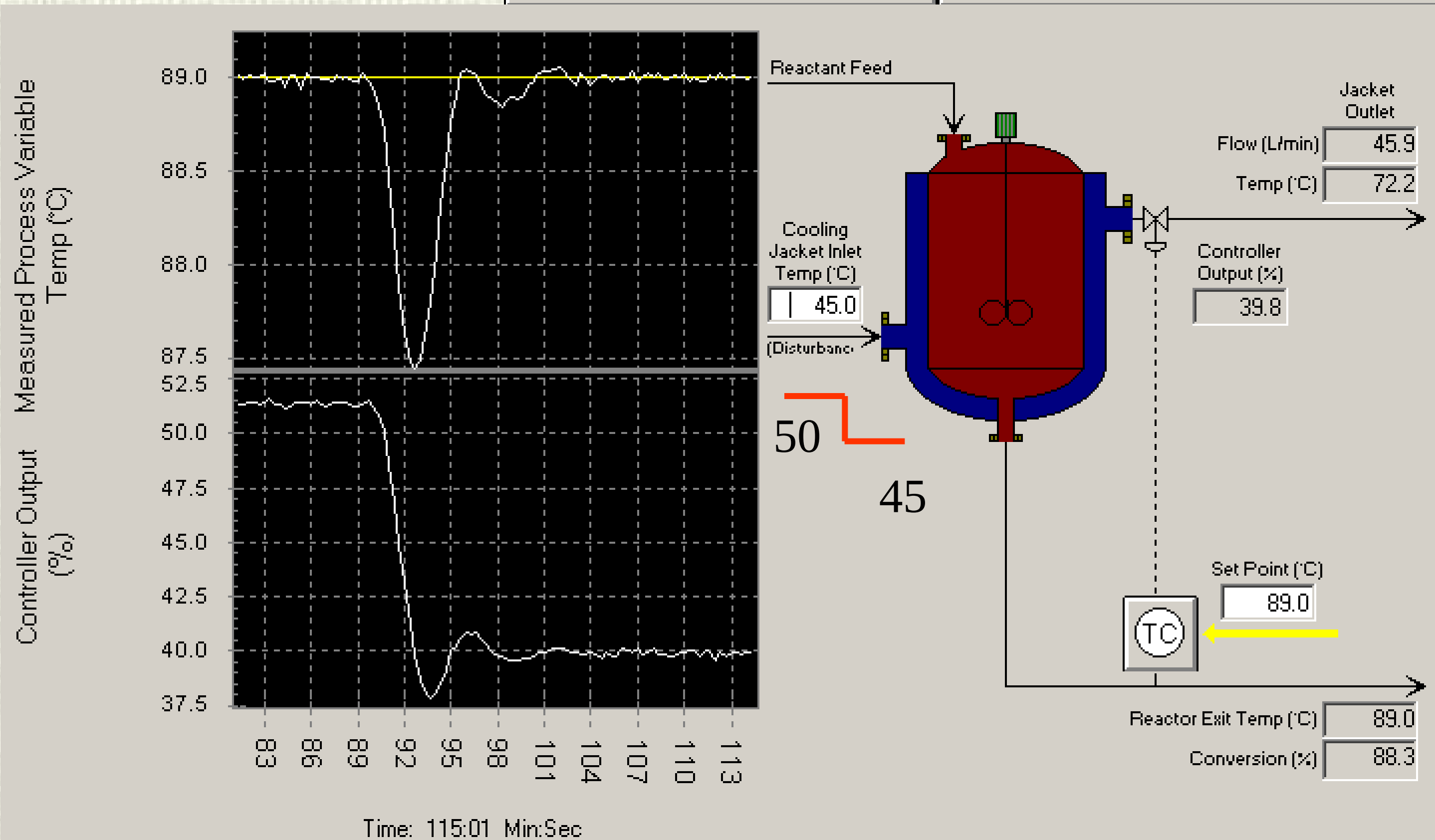
Model Parameters

Process Gain, K	-0.3197
Overall Time Constant, τ	1.79
Dead Time, θ	0.7437
Sum of Squared Error (SSE)	0.2868
Goodness of Fit (R^2)	0.9989

Standard PID | Conservative PID | DMC Tuning

Using IMC (Lambda) Correlations	Kc	τ_I	τ_D	α
P-Only	-1.84			
PI	-4.18	1.79		
PID Ideal (Non-interacting)	-6.99	2.16	0.308	
PID Interacting	-5.79	1.79	0.372	
PID Ideal with Filter	-5.05	2.16	0.308	0.537
PID Interacting with Filter	-4.18	1.79	0.372	0.444

User Specified Closed Loop Time Constant: 0.595



1.5 ºC

10 min.

Jacket temperature reactor control

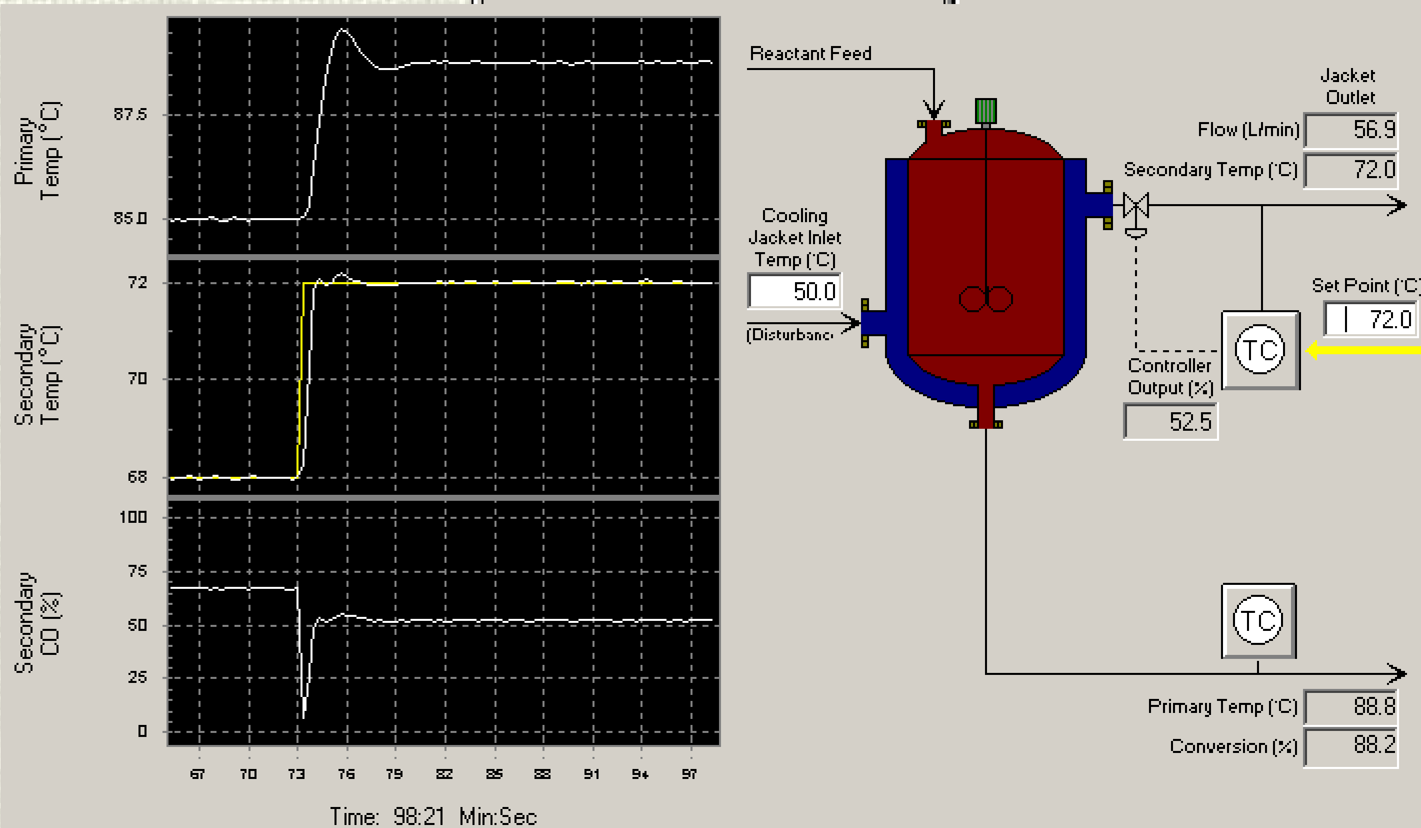
Model Parameters

Process Gain, K	-0.3545
Overall Time Constant, τ	1.85
Dead Time, θ	0.1726
Sum of Squared Error (SSE)	0.1797
Goodness of Fit (R^2)	0.9995

Standard PID | Conservative PID | DMC Tuning

Using IMC (Lambda) Correlations	Kc	τ_I	τ_D	α
P-Only	-10.28			
PI	-14.6	1.85		
PID Ideal (Non-interacting)	-20.14	1.94	0.082	
PID Interacting	-19.24	1.85	0.086	
PID Ideal with Filter	-15.28	1.94	0.082	0.542
PID Interacting with Filter	-14.6	1.85	0.086	0.518

0.1852



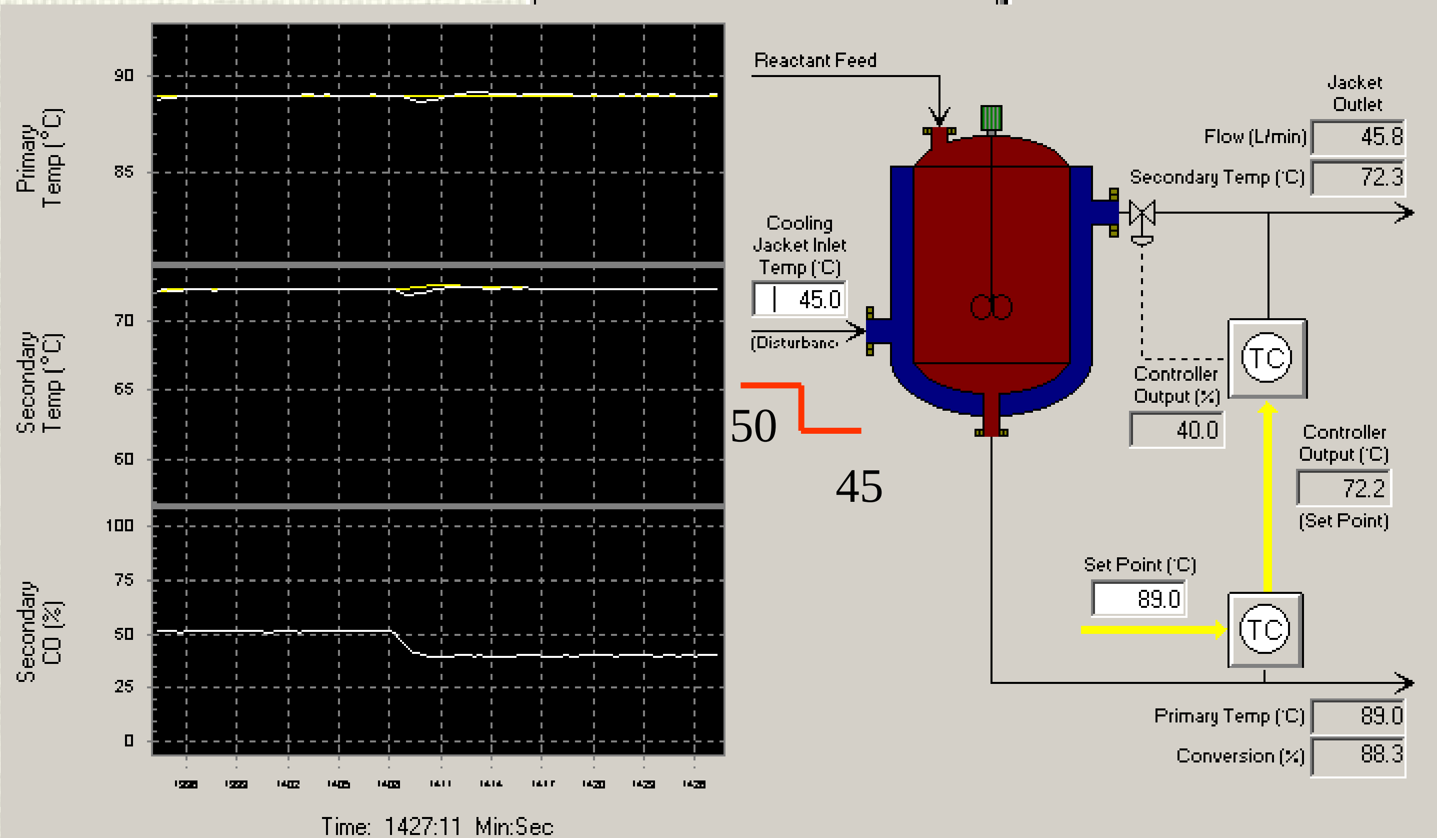
Cascade temp reactor control

Model Parameters	
Process Gain, K	0.9535
Overall Time Constant, τ	0.4492
Dead Time, θ	0.5491
Sum of Squared Error (SSE)	1.40
Goodness of Fit (R^2)	0.9863

Standard PID | Conservative PID | DMC Tuning

Using IMC (Lambda) Correlations	Kc	τ_I	τ_D	α
P-Only	0.166			
PI	0.477	0.449		
PID Ideal (Non-interacting)	1.06	0.724	0.17	
PID Interacting	0.66	0.449	0.275	
PID Ideal with Filter	0.768	0.724	0.17	0.716
PID Interacting with Filter	0.477	0.449	0.275	0.444

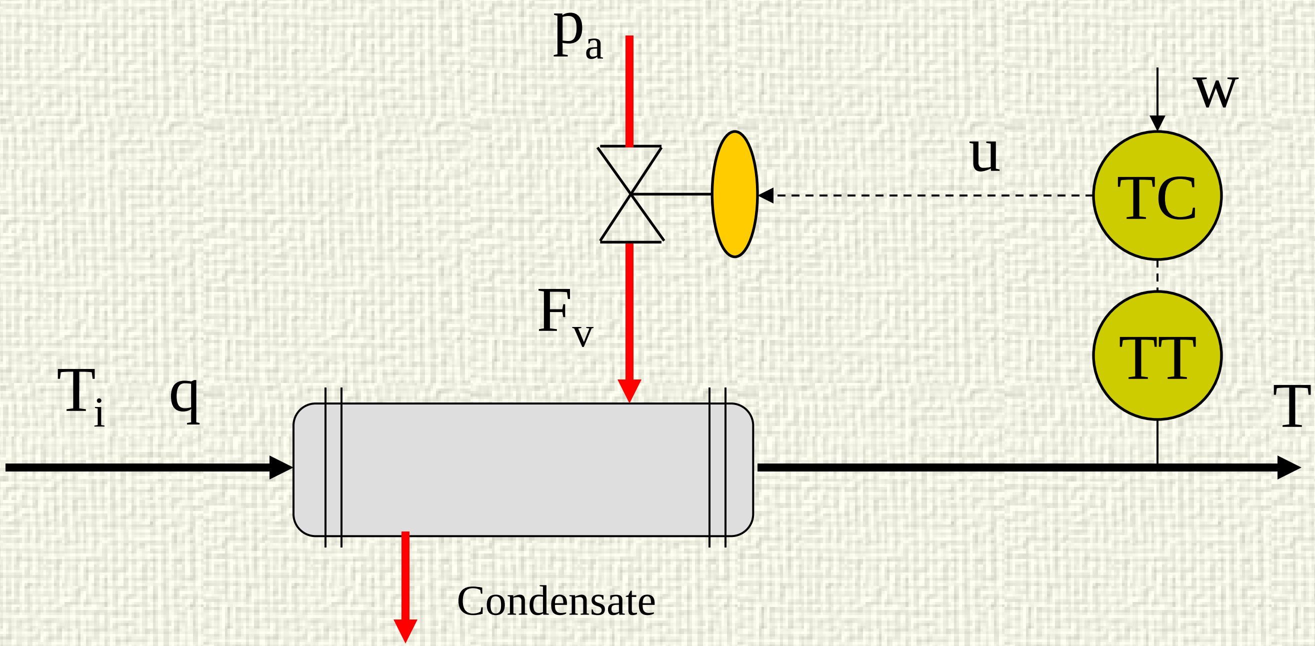
0.4393



0.3 ºC

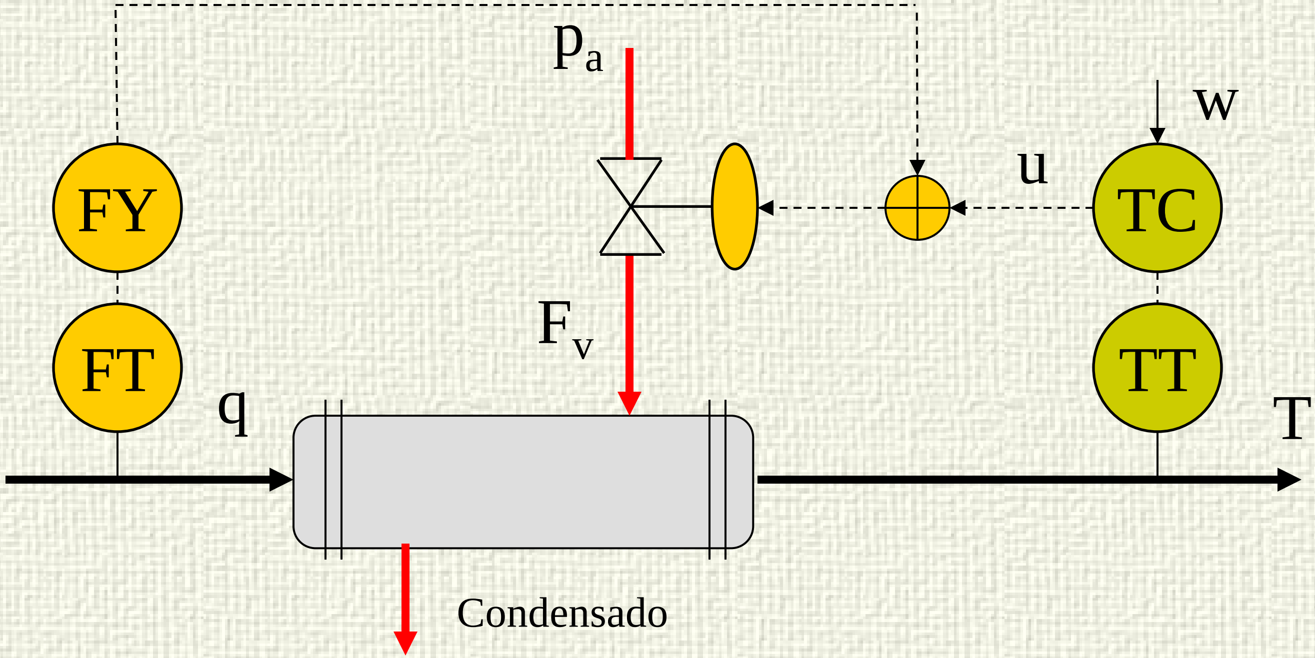
4 min.

Feedforward control



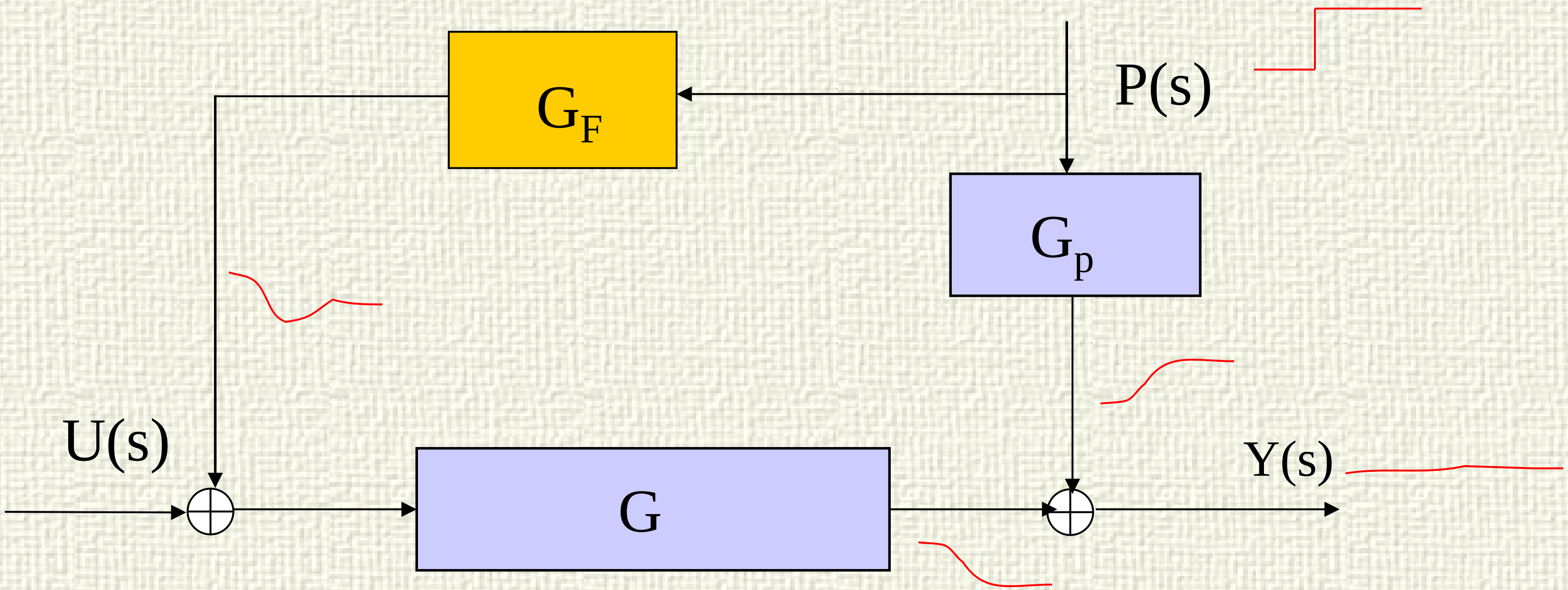
If there are changes in the flow q or in T_i:
The controller only reacts when T has changed

Feedforward



Changes in flow q :
Feedforward compensator will modify the signal to the valve according to the flow changes as soon as they appear

Feedforward

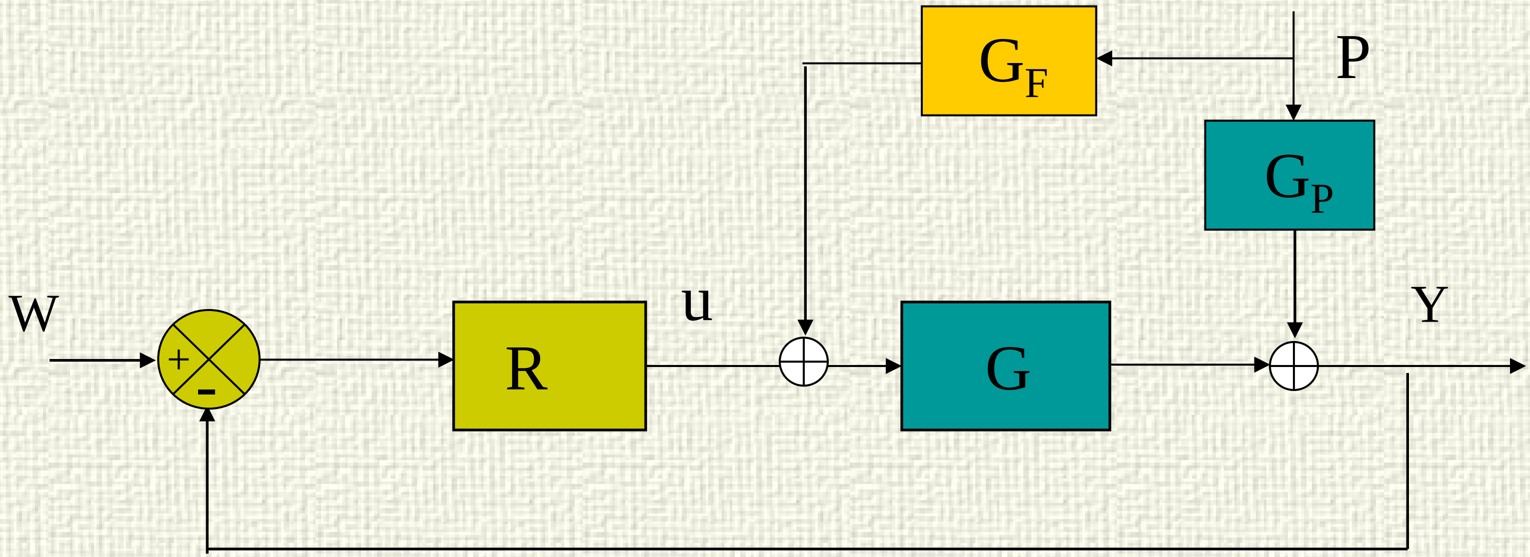


The compensator will implement a change on Y(s) through G_F and G, equal in magnitude and of opposite sign to the one produced by the disturbance P(s) through G_P, in order to compensate it

Feedforward

- ✓ Measurable disturbances that cannot be controlled directly
- ✓ Additional instrumentation and computation is needed
- ✓ G_P should be slower than G
- ✓ It is an open loop compensation. It must be used in addition to closed loop control

Block Diagram

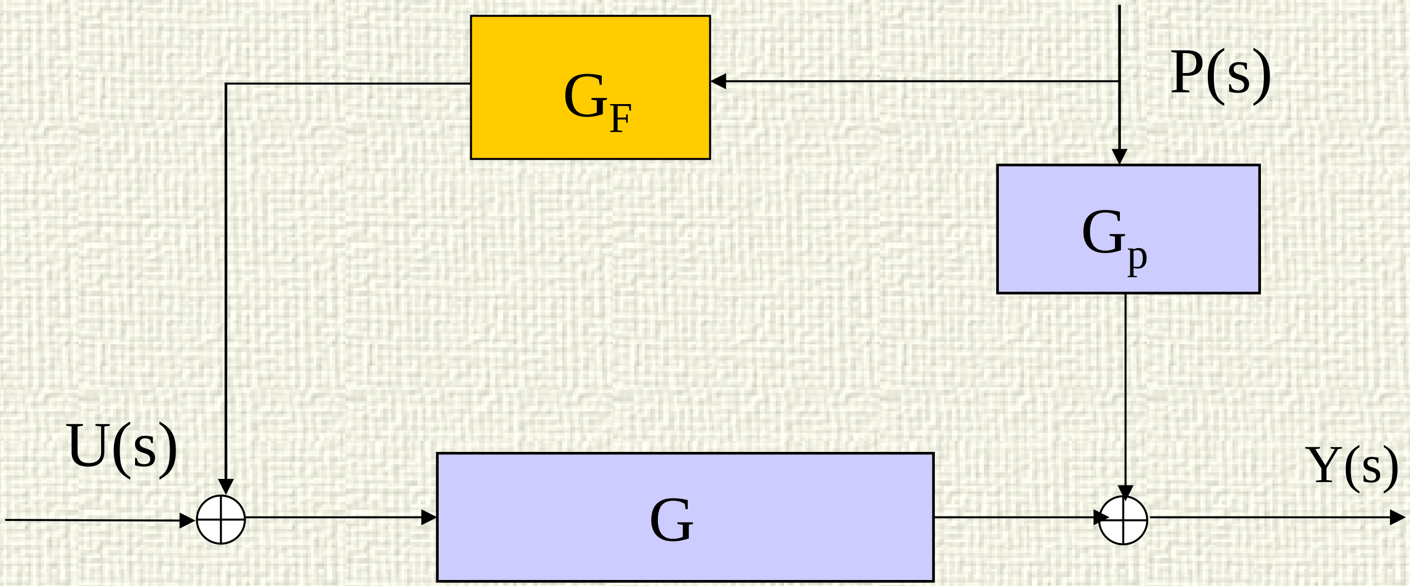


Closed loop dynamics does not change

$$Y(s) = G(s)\left[U(s) + G_F(s)P(s)\right] + G_P(s)P(s) =$$
$$= G(s)R(s)\left[W(s) - Y(s)\right] + \left[G(s)G_F(s) + G_P(s)\right]P(s)$$

$$Y(s) = \frac{G(s)R(s)}{1 + G(s)R(s)}W(s) + \frac{G(s)G_F(s) + G_P}{1 + G(s)R(s)}P(s)$$

How to compute G_F?



$$Y(s) = G(s)\left[U(s) + G_F(s)P(s)\right] + G_P(s)P(s) =$$
$$= G(s)U(s) + \left[G(s)G_F(s) + G_P(s)\right]P(s)$$
$$0 = G(s)G_F(s) + G_P(s)$$

$$G_F = -\frac{G_P(s)}{G(s)}$$

Practical G_F

$$G_F = -\frac{G_P(s)}{G(s)}$$

Realizability not assured
Can be high order
Linear approach: range of validity (G_P and G)

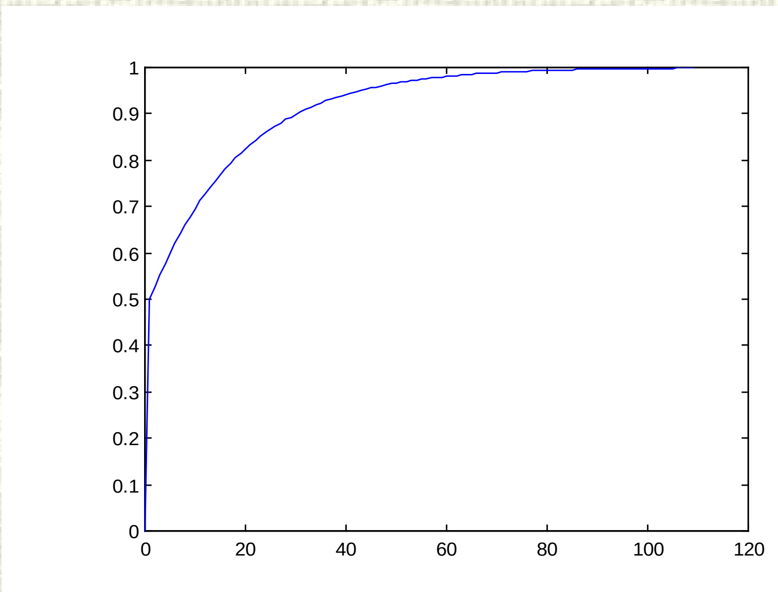
Practical G_F :

$$G_F = -\frac{K_F(bs+1)}{(as+1)} \qquad K_F = \frac{K_P}{K}$$

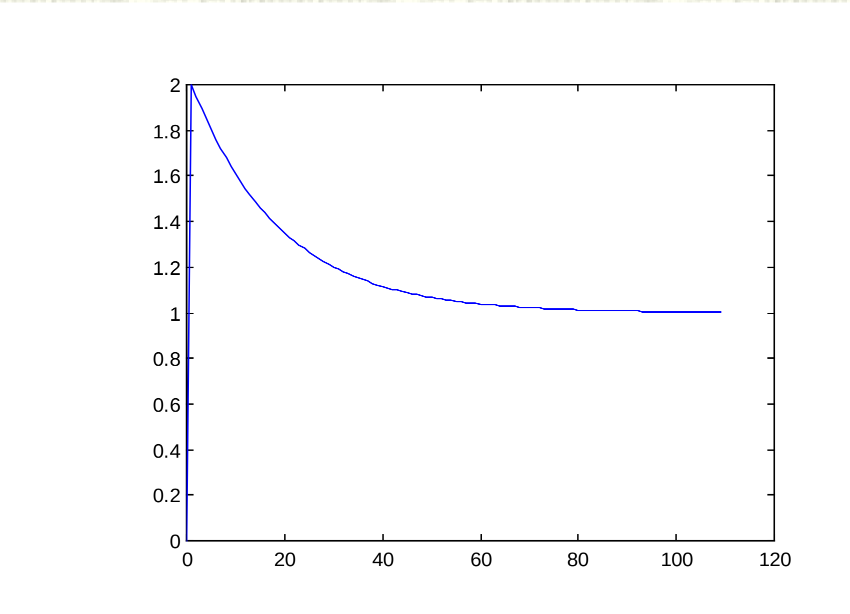
Lead/Lag

$$G_F = -\frac{K_F(bs+1)}{(as+1)}$$

b < a



b > a



Heat exchanger- disturbance

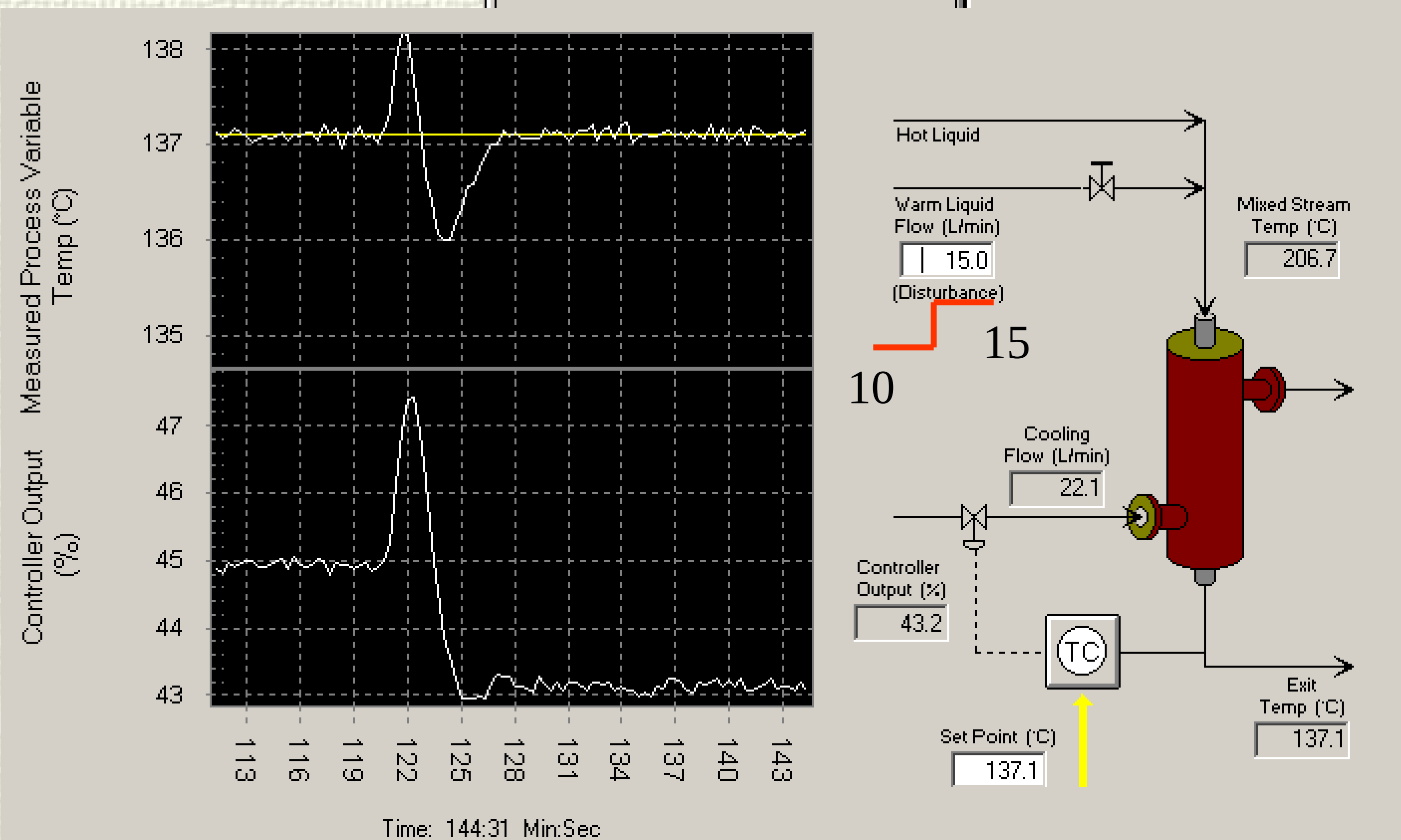
Model Parameters

Process Gain, K	-0.4605
Overall Time Constant, τ	0.9582
Dead Time, θ	0.8781
Sum of Squared Error (SSE)	1.19
Goodness of Fit (R^2)	0.9977

Standard PID | Conservative PID | DMC Tuning

Using IMC (Lambda) Correlations	Kc	τ_I	τ_D	α
P-Only	-0.488			
PI	-1.32	0.958		
PID Ideal (Non-interacting)	-2.66	1.40	0.301	
PID Interacting	-1.82	0.958	0.439	
PID Ideal with Filter	-1.92	1.40	0.301	0.648
PID Interacting with Filter	-1.32	0.958	0.439	0.444

0.7025

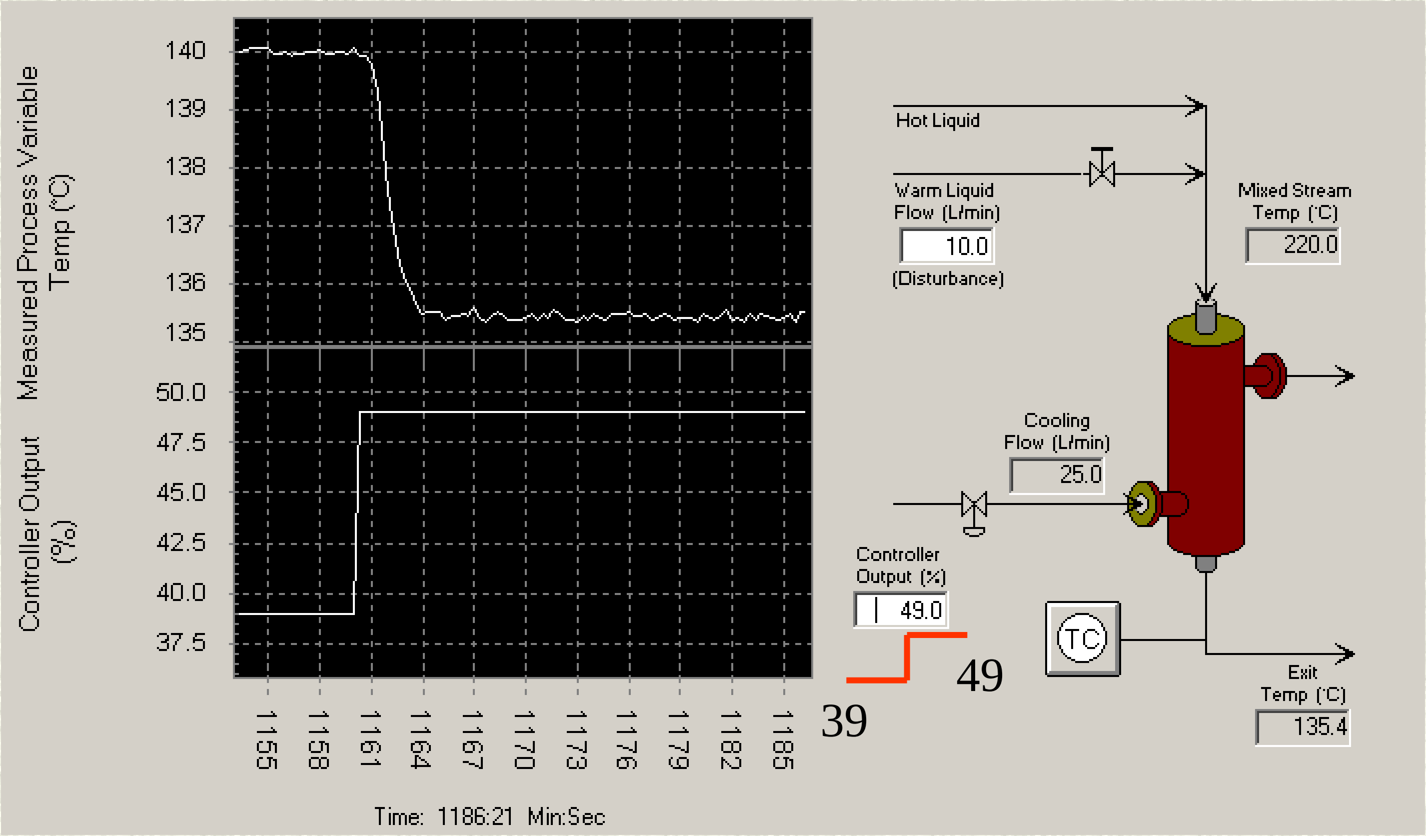


2 ºC

7 min.

Model Temp - u

Open loop test



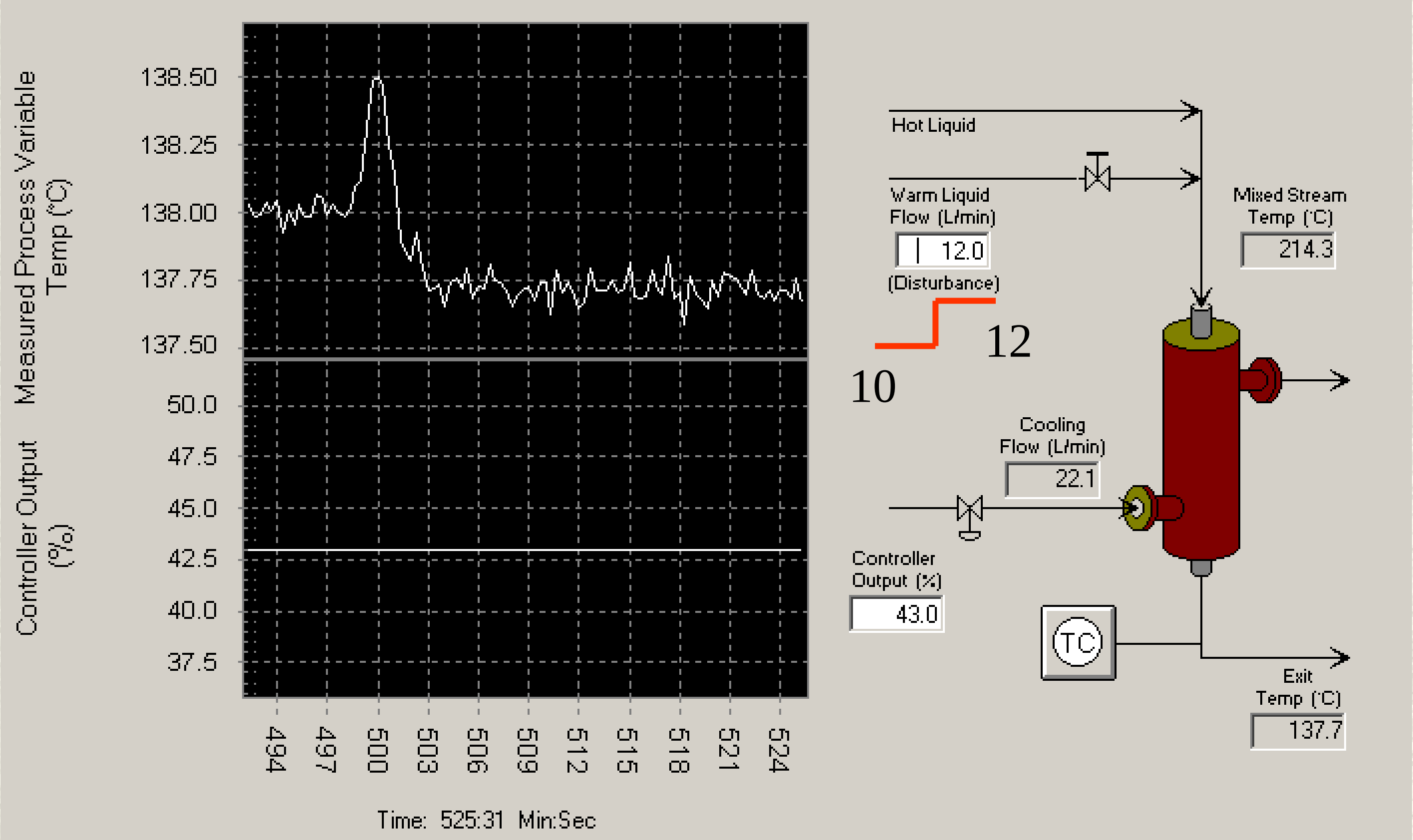
Model Temp - u

$$G(s) = \frac{ke^{-sd}}{(\tau s + 1)}$$

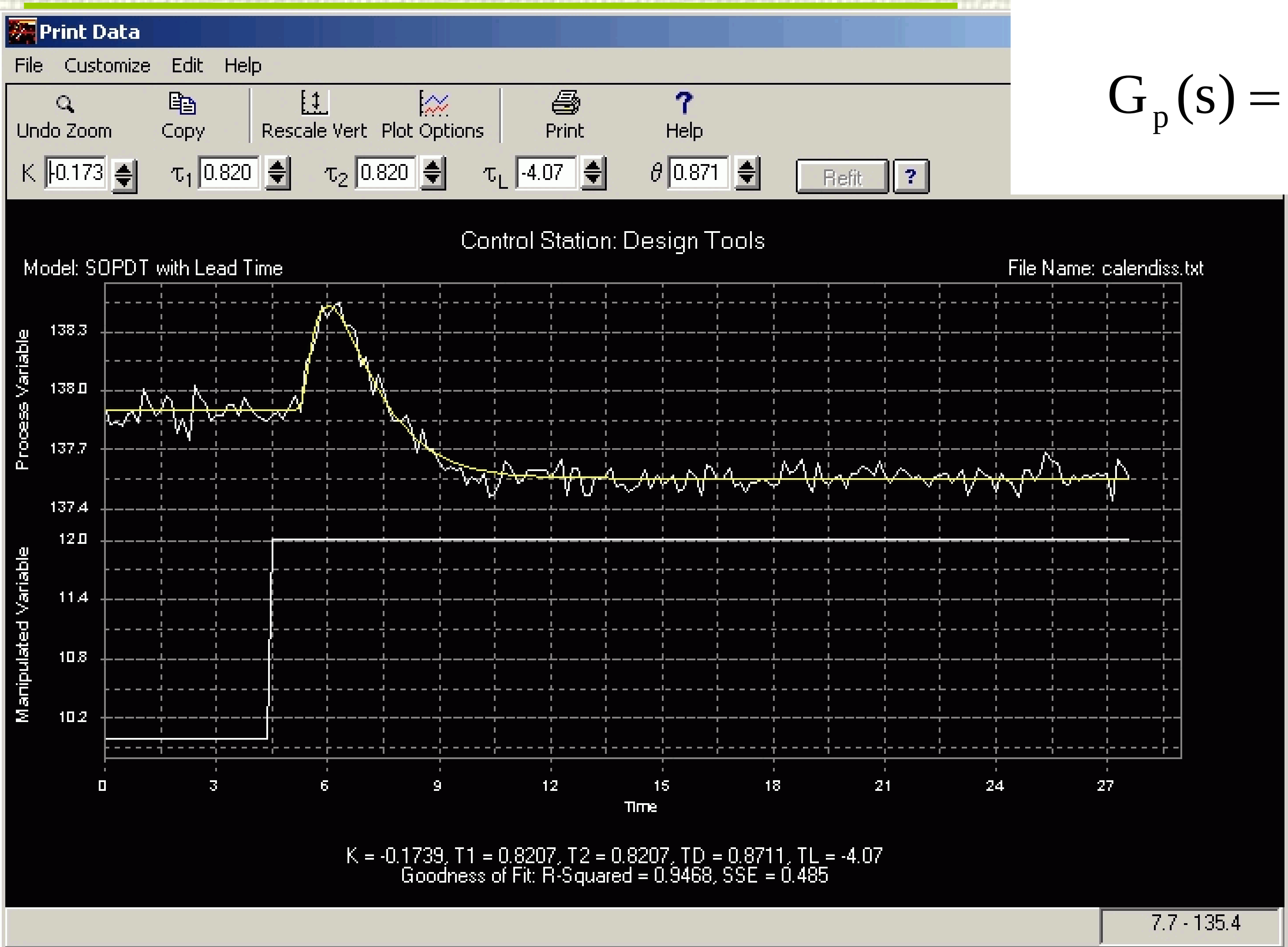
$$= \frac{-0.46e^{-0.87s}}{0.96s + 1}$$

Model temp-warm flow

Open loop test



Model Temp- warm flow



$$G_p(s) = \frac{k(\tau_L s + 1)e^{-sd}}{(\tau_1 s + 1)(\tau_2 s + 1)}$$

$$\frac{-0.17(-4.07s + 1)e^{-0.87s}}{(0.82s + 1)^2}$$

Heat exchanger Feedforward compensator

Model Parameters	
Process Gain, K	-0.4605
Overall Time Constant, τ	0.9582
Dead Time, θ	0.8781
Sum of Squared Error (SSE)	1.19
Goodness of Fit (R^2)	0.9977

Model Parameters	
Process Gain, K	-0.1739
First Time Constant, τ_1	0.8207
Second Time Constant, τ_2	0.8207
Lead Time, τ_L	-4.07
Dead Time, θ	0.8711
Sum of Squared Error (SSE)	0.485
Goodness of Fit (R^2)	0.9468

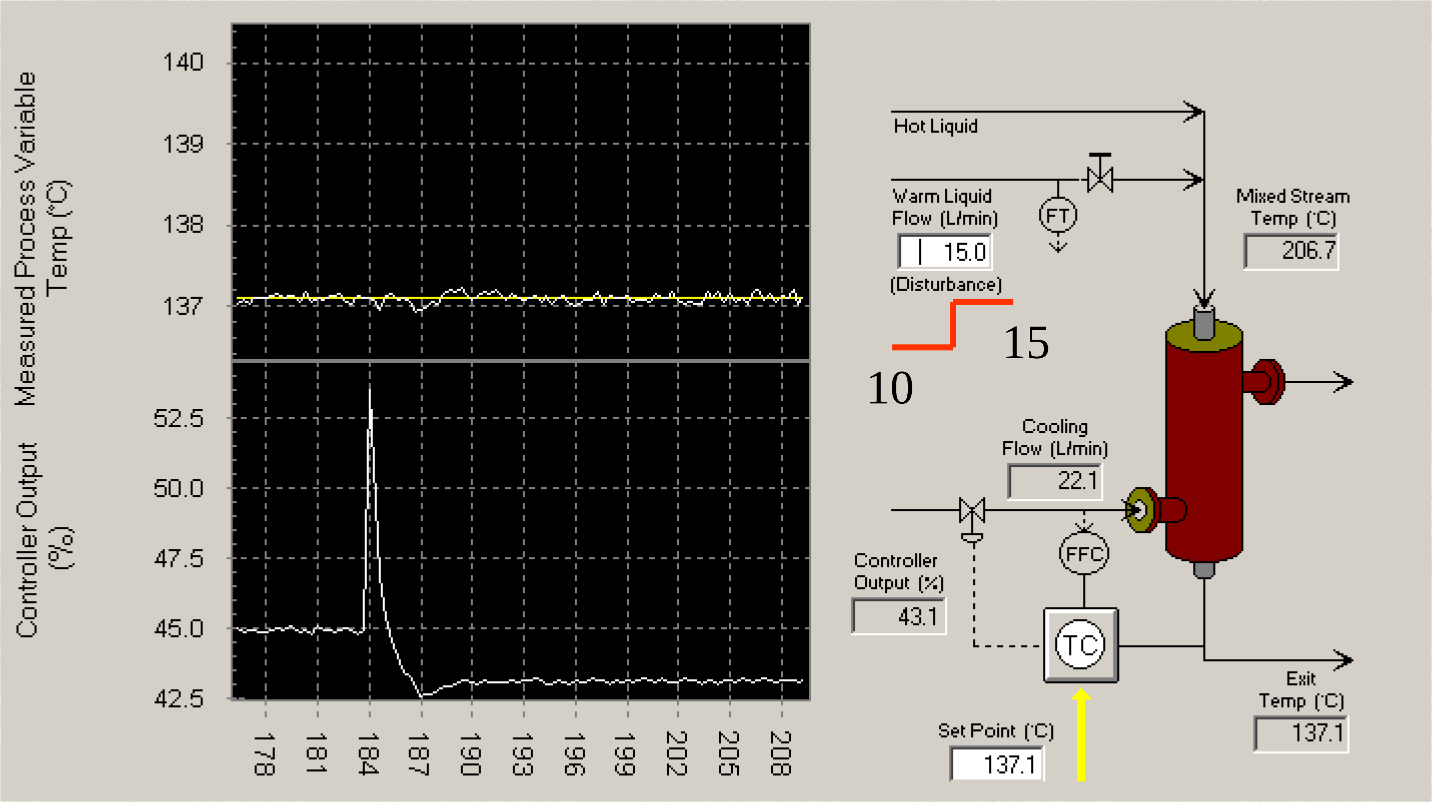
ID | DMC Tuning

τ_I	τ_D	α
0.958		
1.40	0.301	
0.958	0.439	
1.40	0.301	0.648
0.958	0.439	0.444

.7025

$$G_F = -\frac{G_P(s)}{G(s)} = \frac{\dfrac{-0.17(-4s+1)e^{-0.87s}}{(0.82s+1)^2}}{\dfrac{-0.46e^{-0.87s}}{0.96s+1}} = \frac{0.34(0.96s+1)(-4s+1)}{(0.82s+1)^2}$$

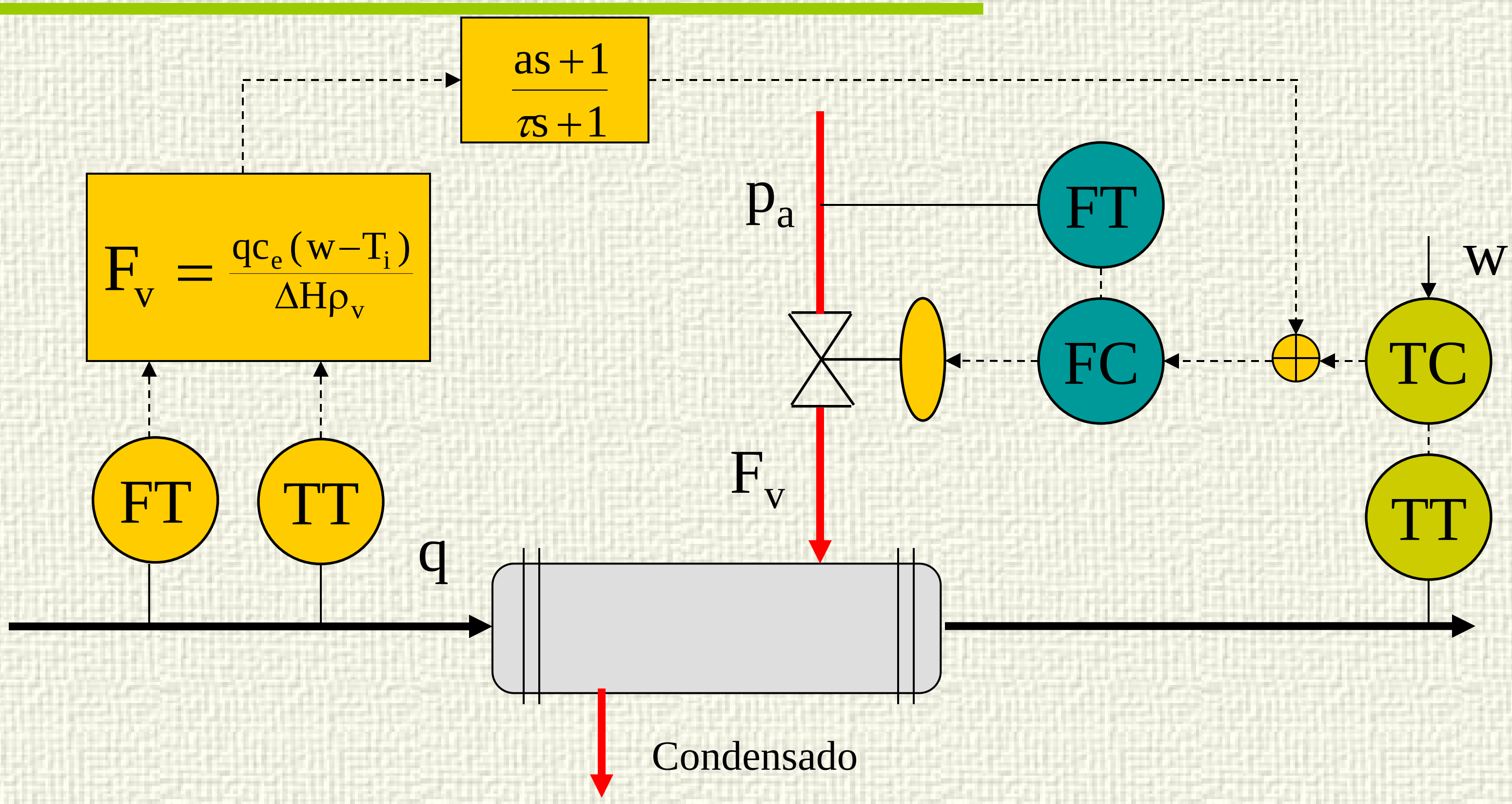
Heat exchanger with feedforward



0.2 ºC

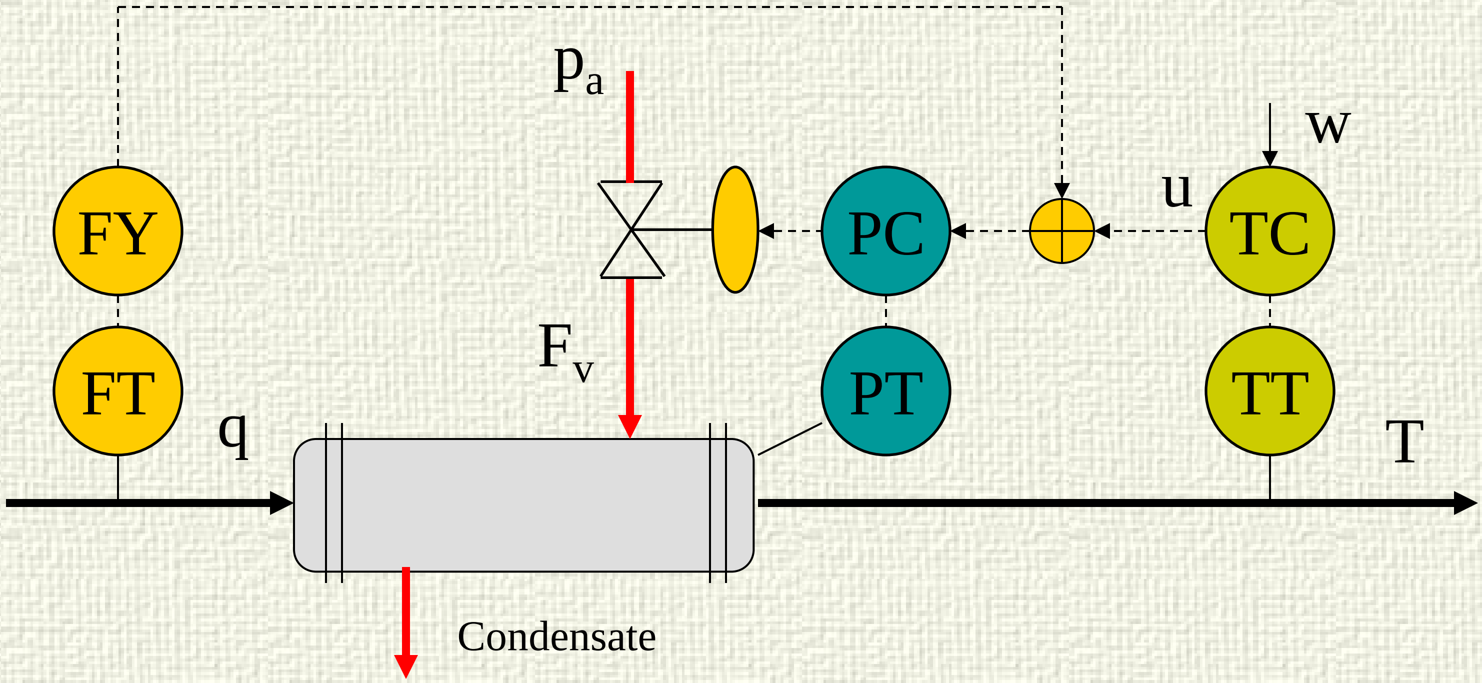
? min.

Static Compensator / model

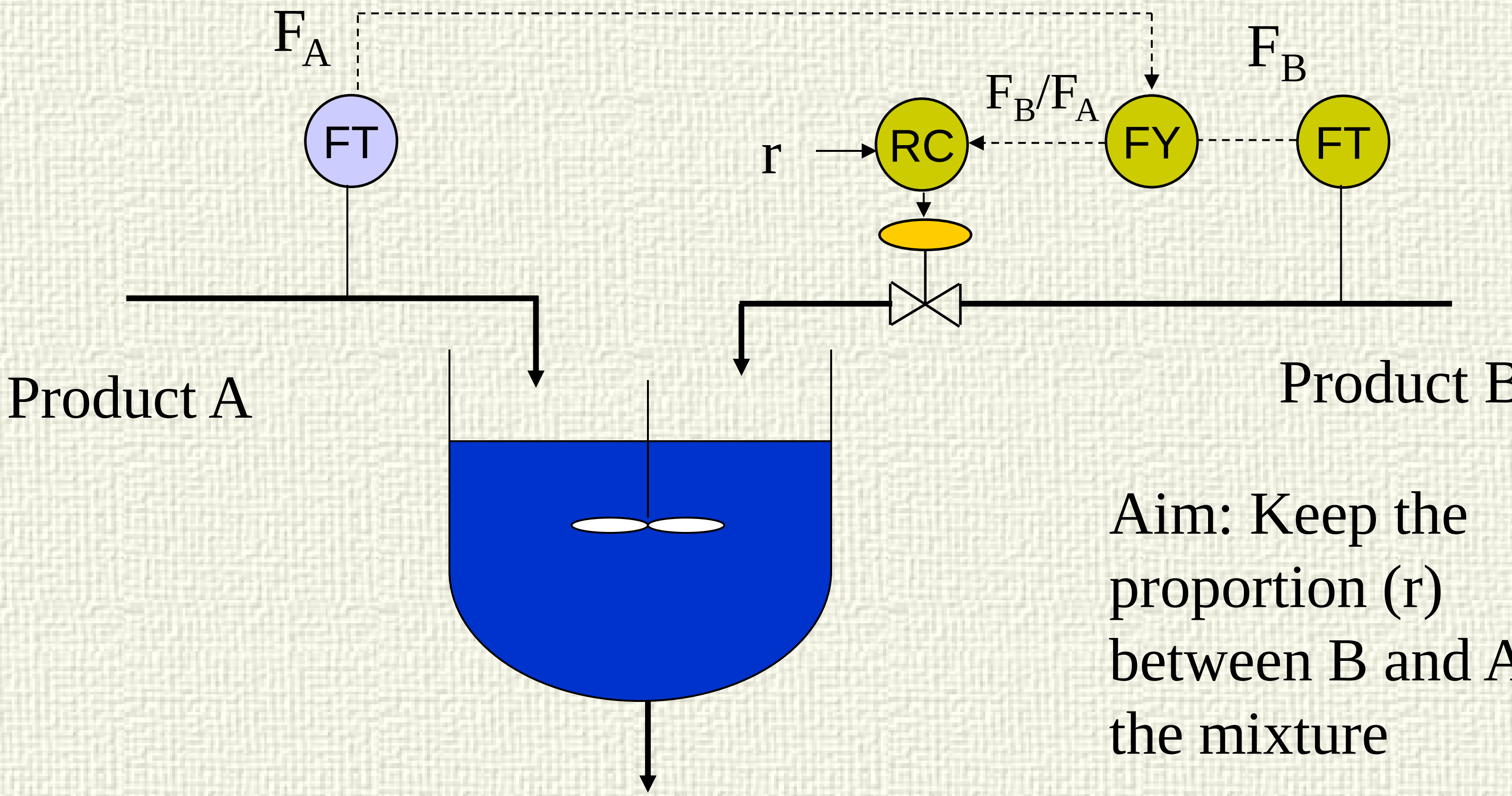


Process dynamics must be included
Static model provides K_F

Cascade+Feedforward

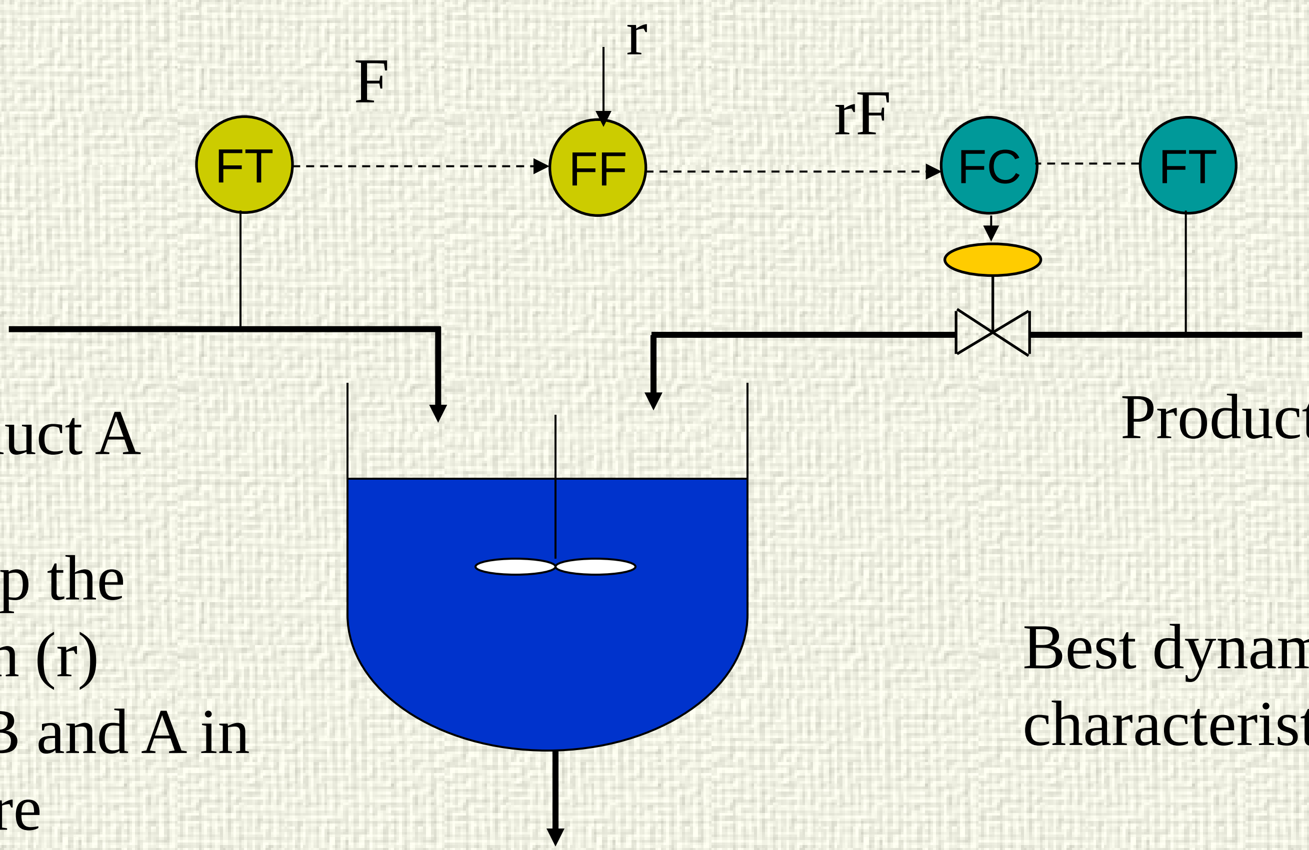


Control of proportions



Aim: Keep the proportion (r) between B and A in the mixture

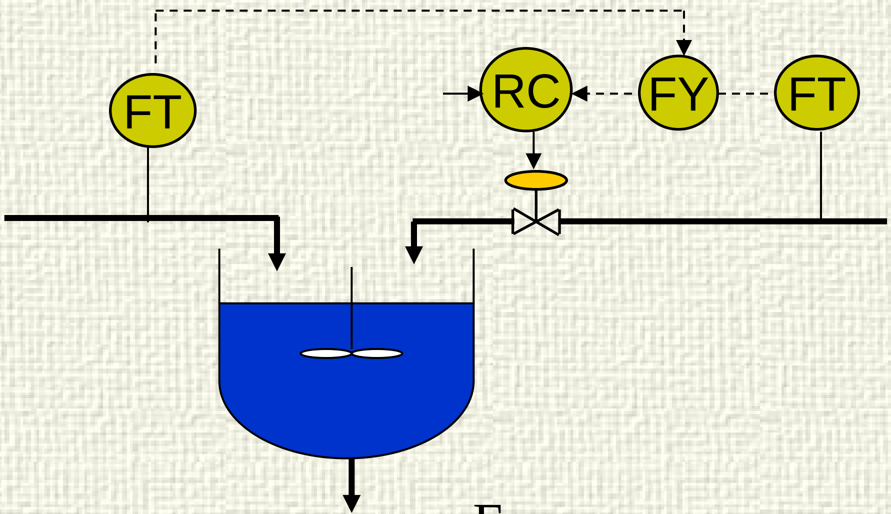
Ratio Control

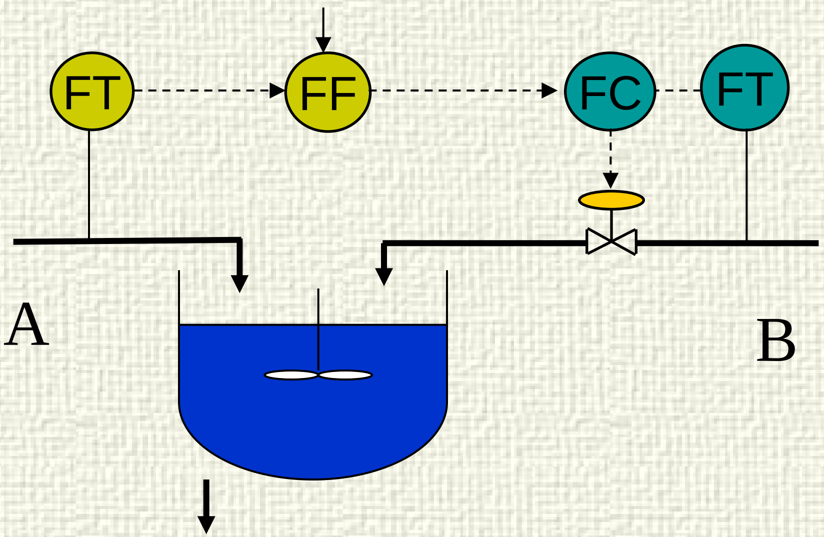


Aim: Keep the proportion (r) between B and A in the mixture

Best dynamic characteristics

Ratio Control





$$r = \frac{F_B}{F_A}$$ Controlled Variable $$F_B = rF_A$$

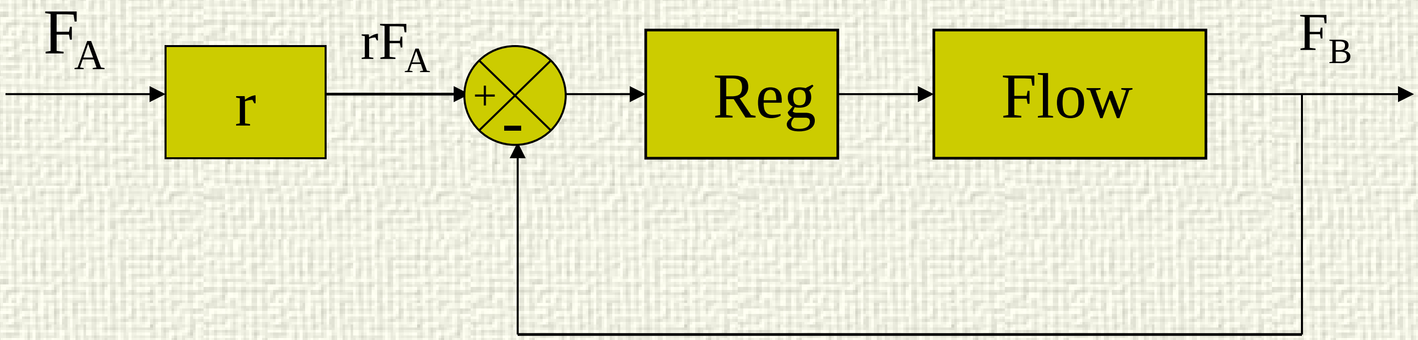
$$\frac{\partial r}{\partial F_A} = -\frac{F_B}{F_A^2}$$ Gain disturbance $$\frac{\partial F_B}{\partial F_A} = r$$

$$\frac{\partial r}{\partial F_B} = \frac{1}{F_A}$$ Gain Manipulated Var. $$\frac{\partial F_B}{\partial F_B} = 1$$

Gain changes

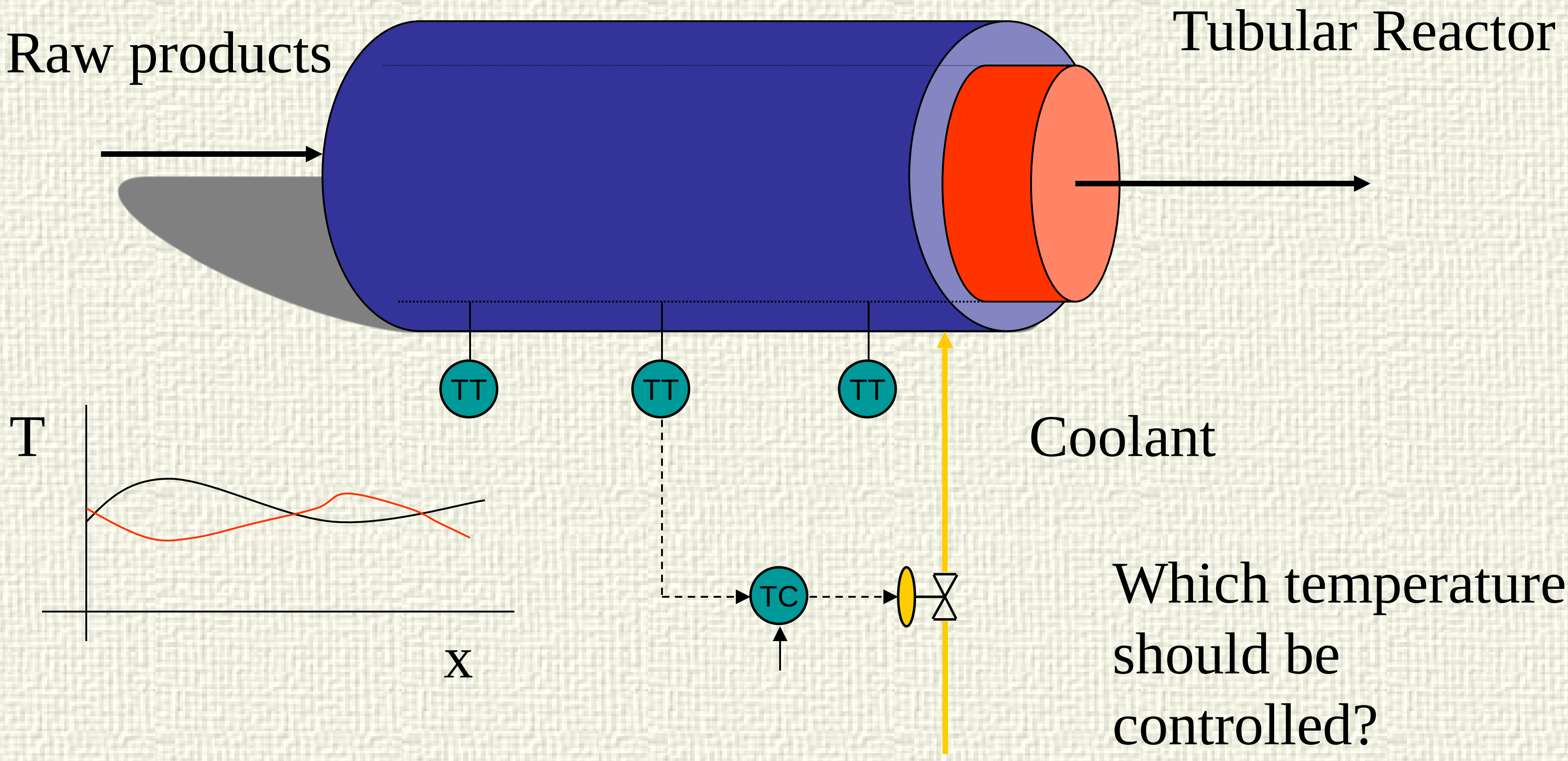
Gain is cte

Block Diagram



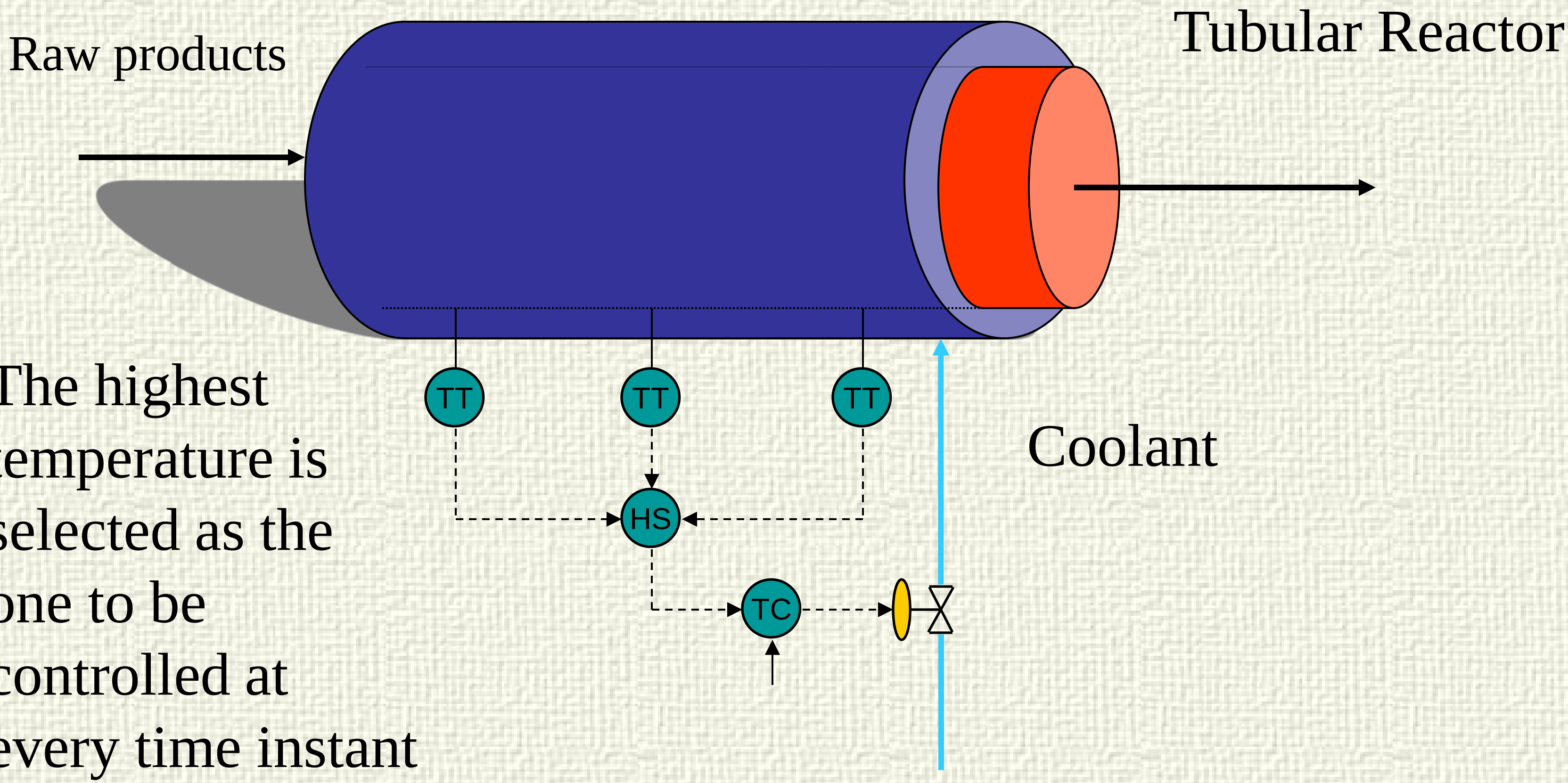
The set point of flow F_B is adjusted continuously as a function of the measured flow F_A

Selective Control



Which temperature should be controlled?

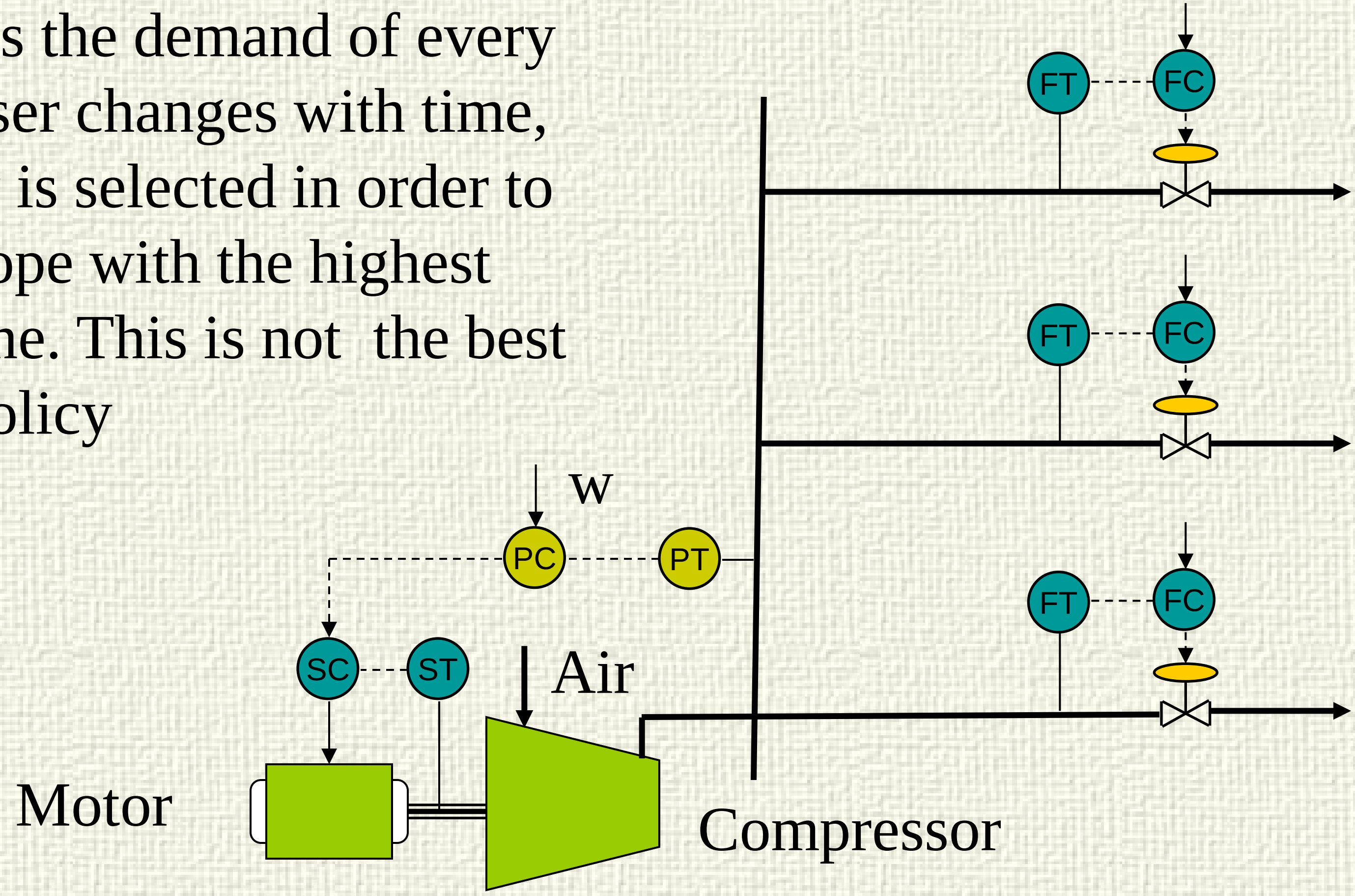
Selective Control



The highest temperature is selected as the one to be controlled at every time instant

Selective Control

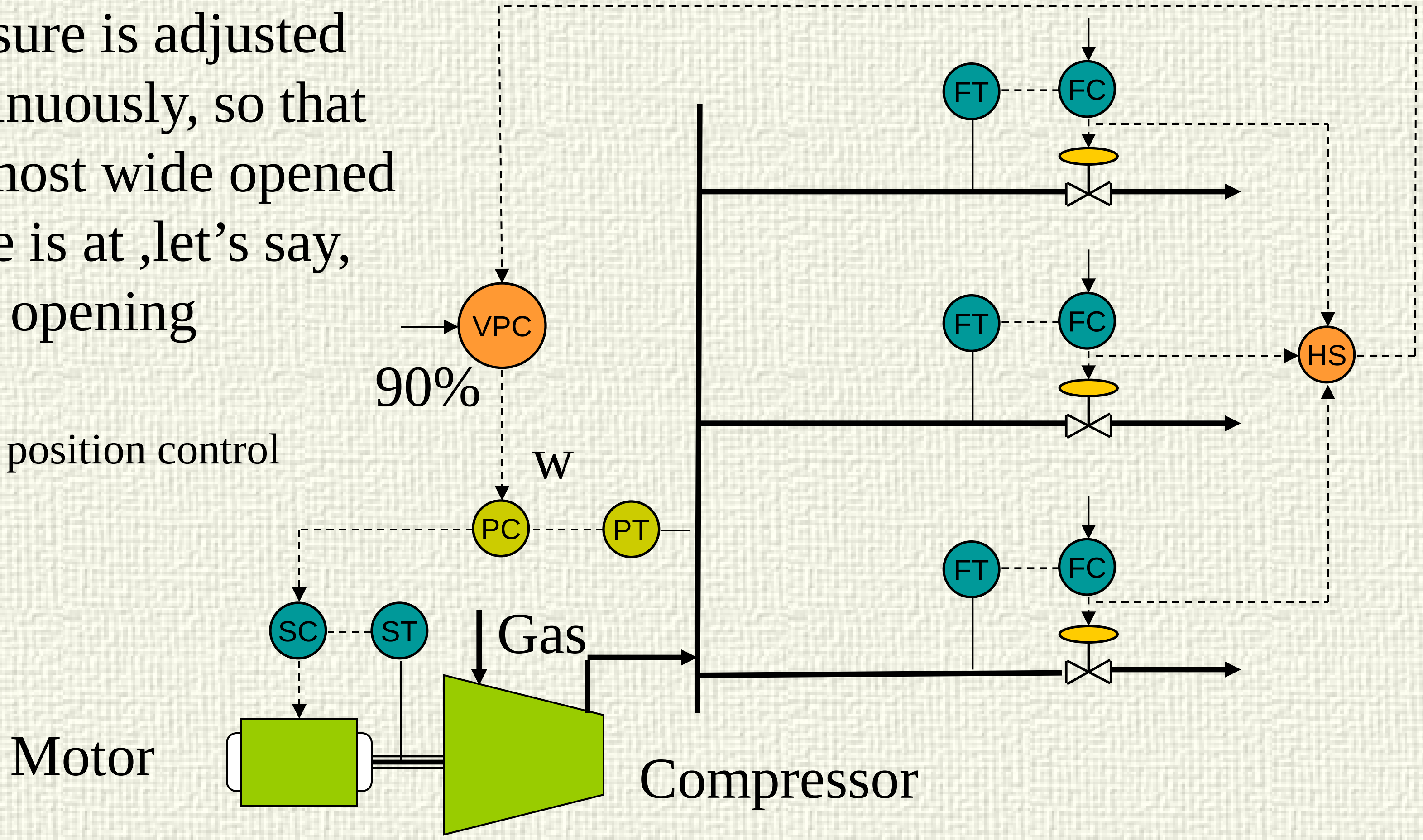
As the demand of every user changes with time, w is selected in order to cope with the highest one. This is not the best policy



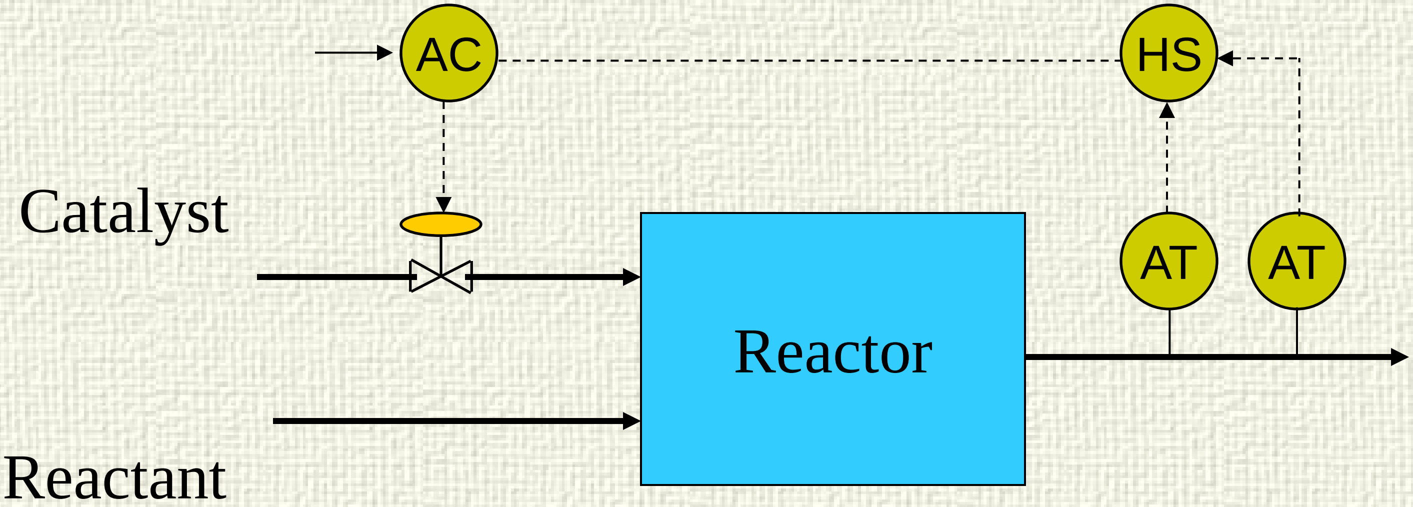
Selective Control / VPC

Pressure is adjusted continuously, so that the most wide opened valve is at ,let's say, 90% opening

VPC:
Valve position control

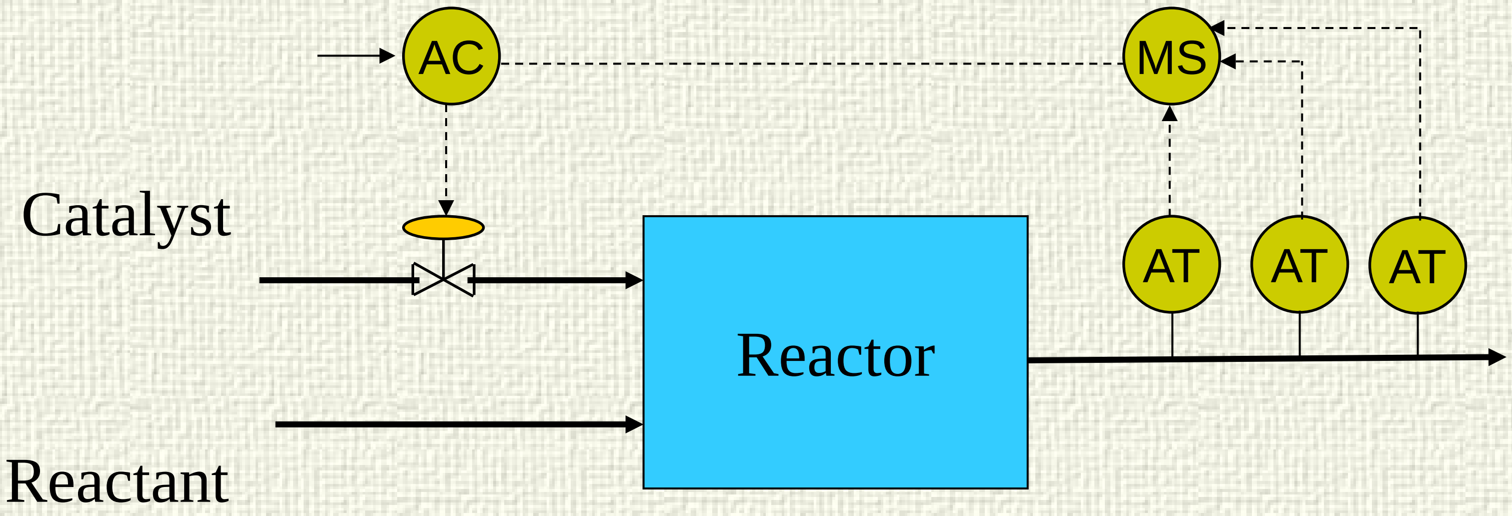


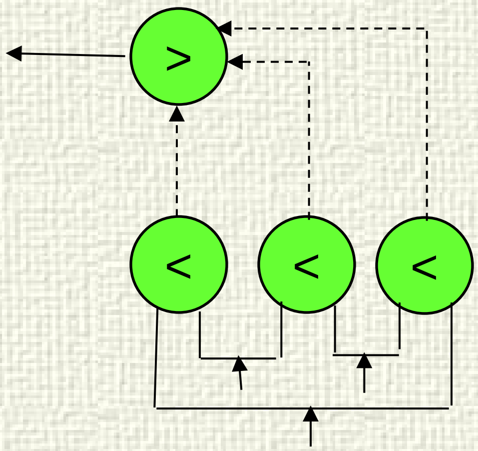
Selective Control / Safety



If a transmitter fails (signal to zero) the selector maintains the reading of the correct one. (but if the failure is signal to 100%, the controller stops the plant)

Selective Control / Safety

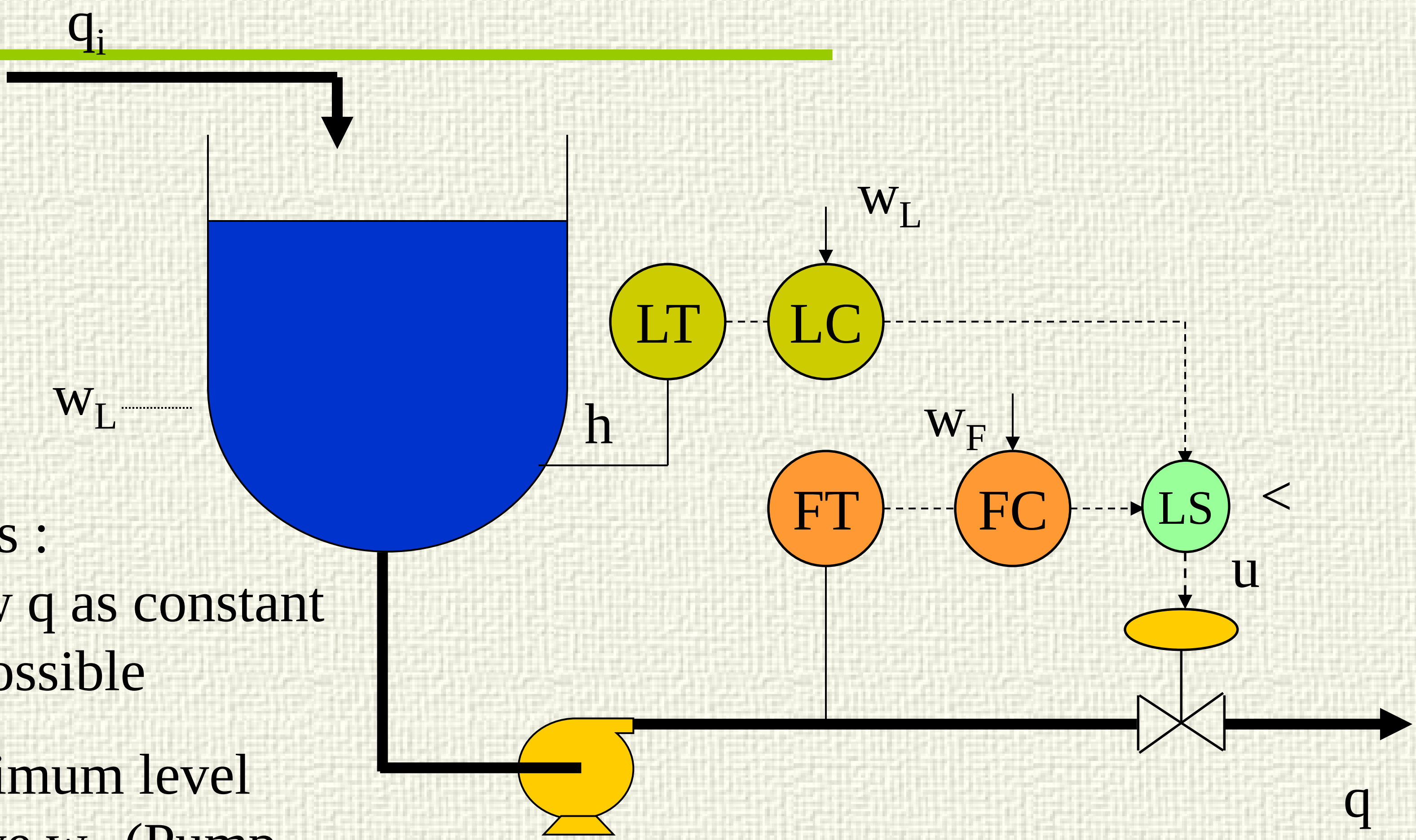




Another option is a two against one policy or a intermedium value selector

Selects the signal in the middle

Override Control



Aims :
Flow q as constant as possible

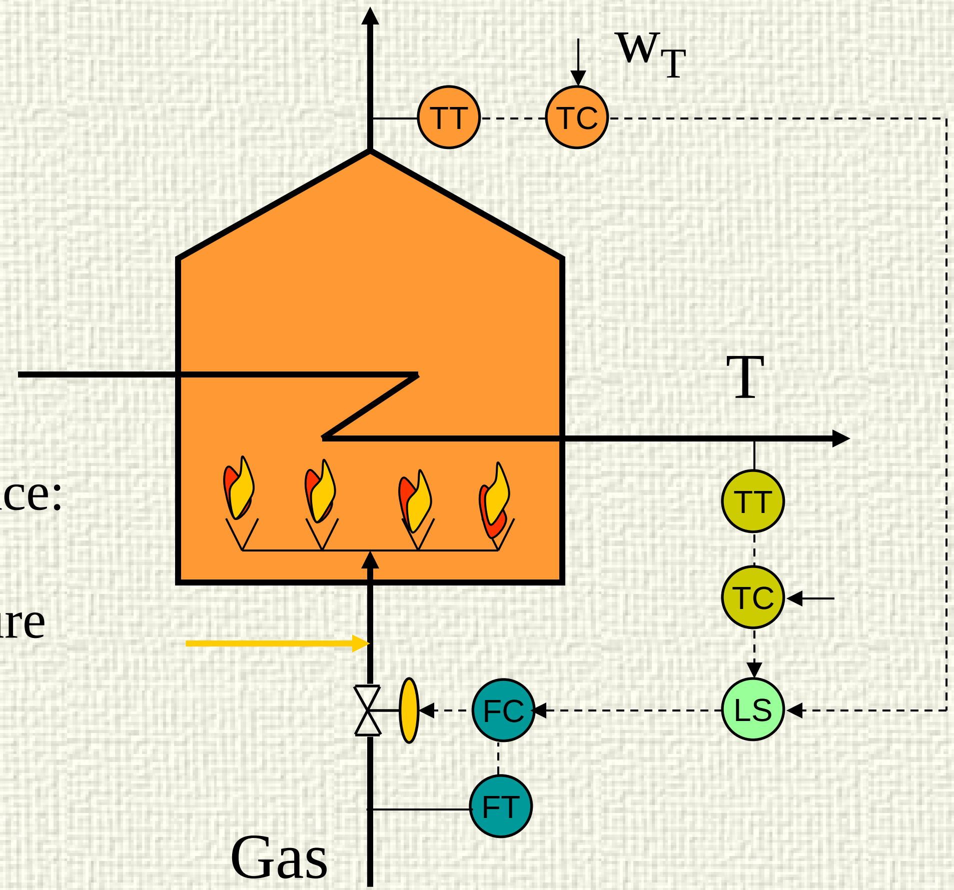
Minimum level above w_L (Pump protection)

Override Control

Aims: Keep T as constant as possible

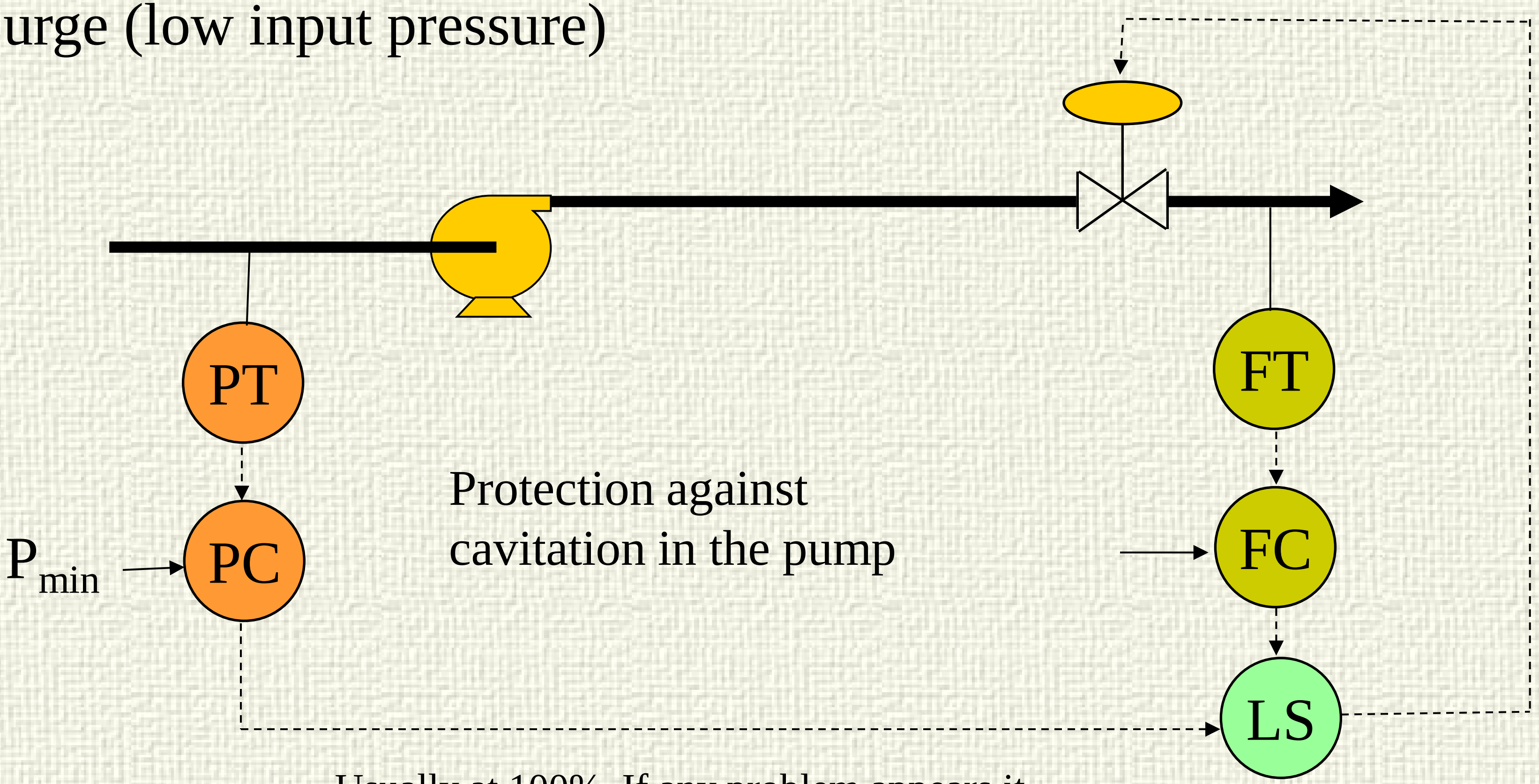
Smoke temperature below w_T

Disturbance: oil input temperature decreases



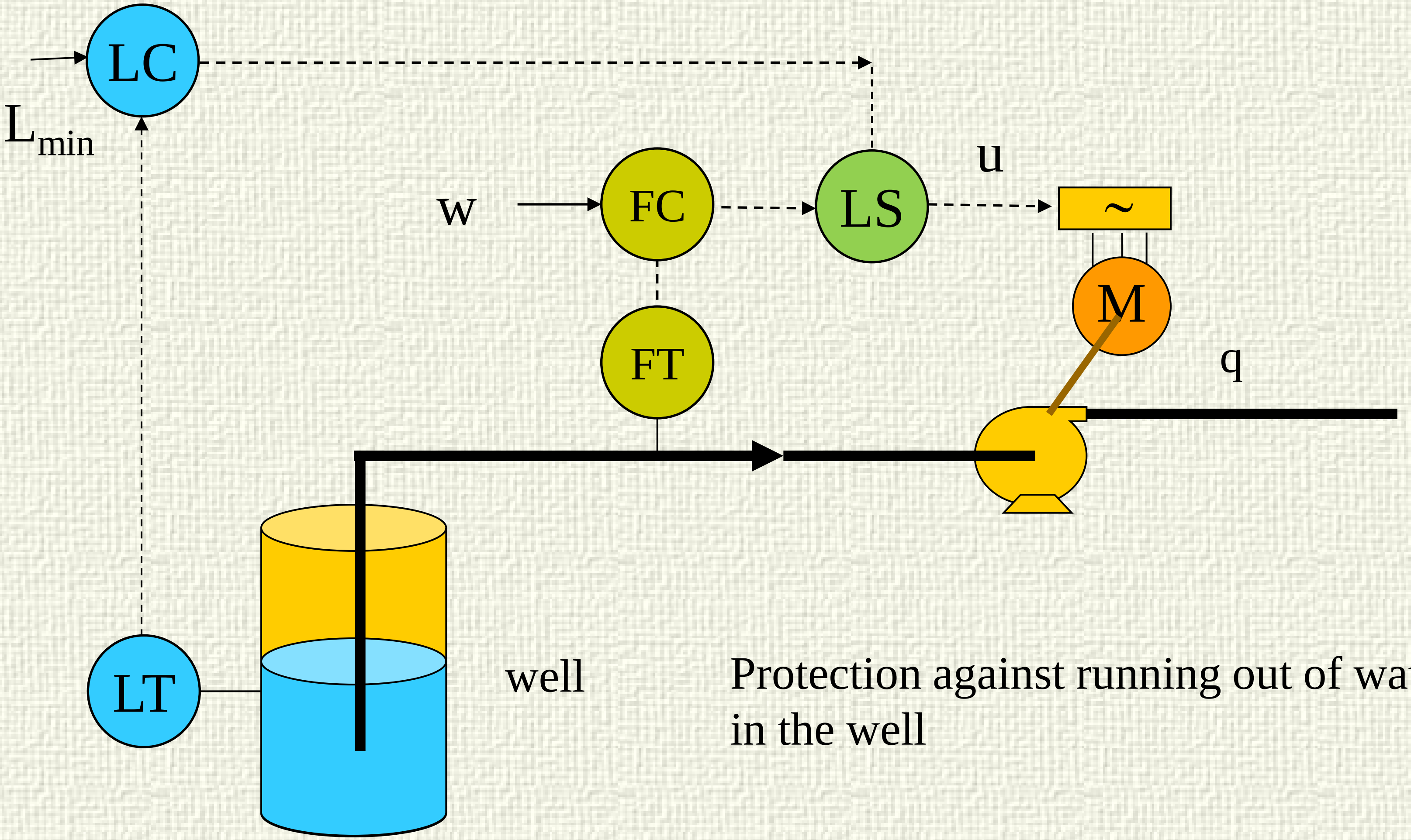
Override Control

Surge (low input pressure)



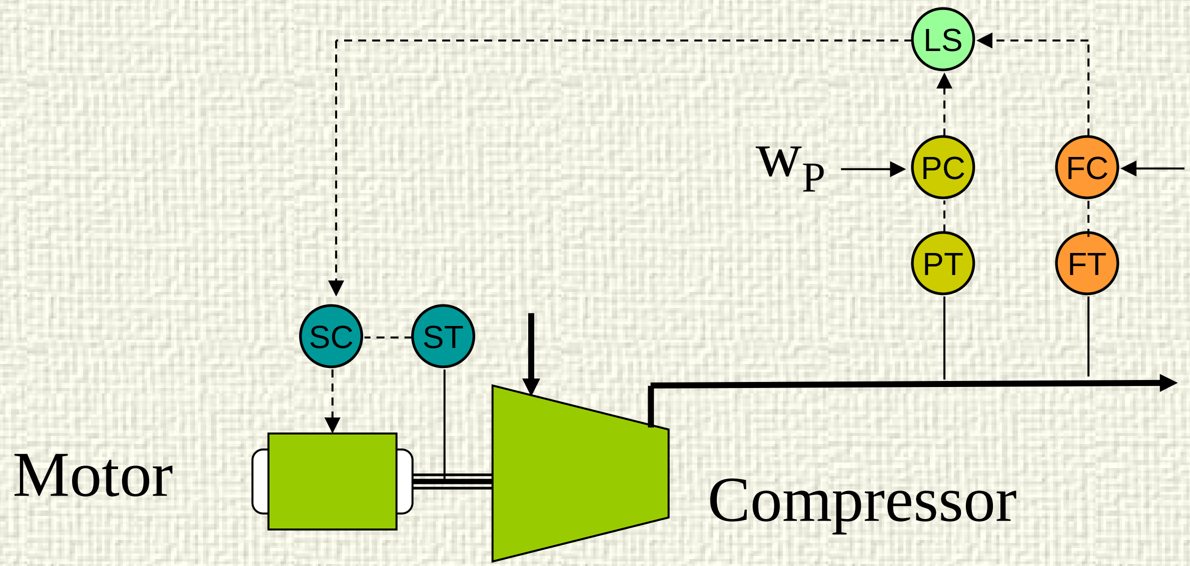
Usually at 100%. If any problem appears it will decrease until the controller overrides the FC

Override control



Protection against running out of water in the well

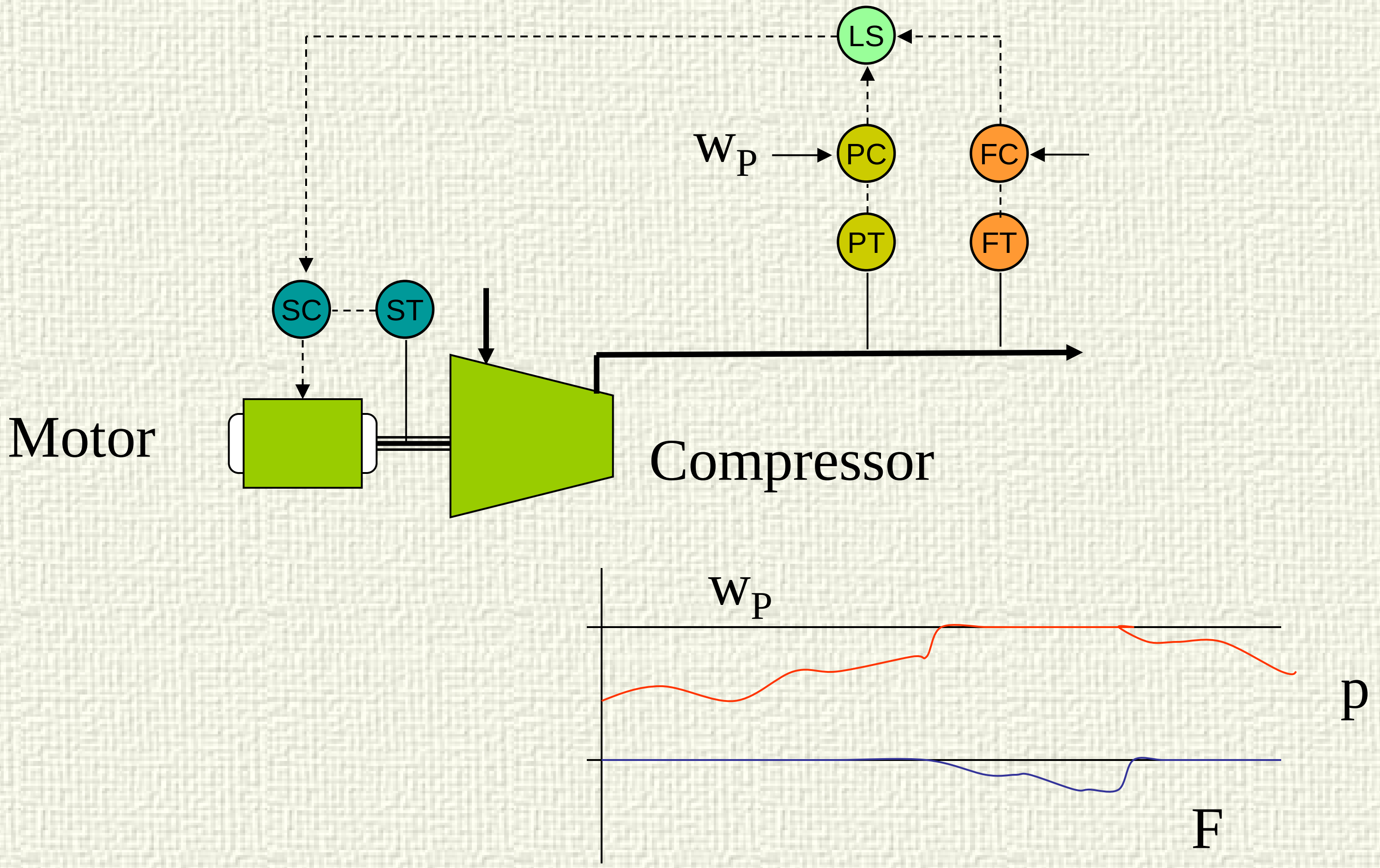
Override Control



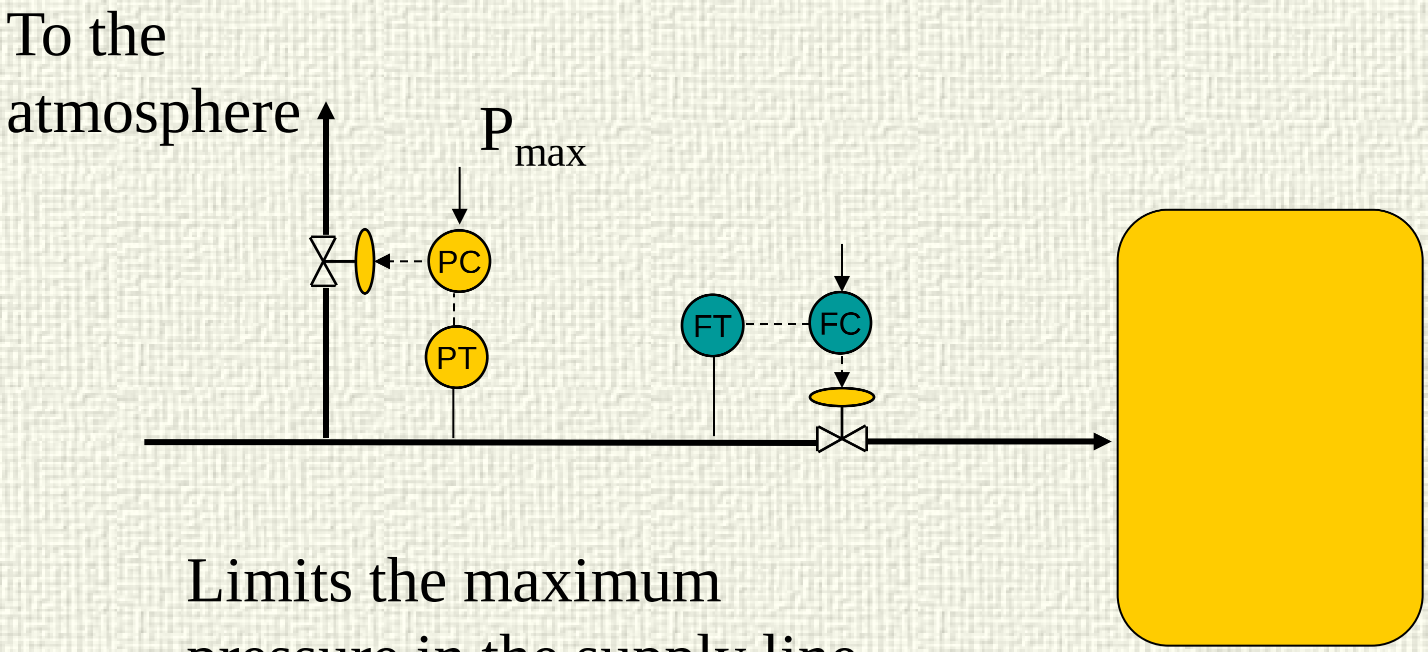
Aims:

- ✓Flow as constant as possible,
- ✓Maximum pressure on the line below w_P in spite of changing demands

Override Control

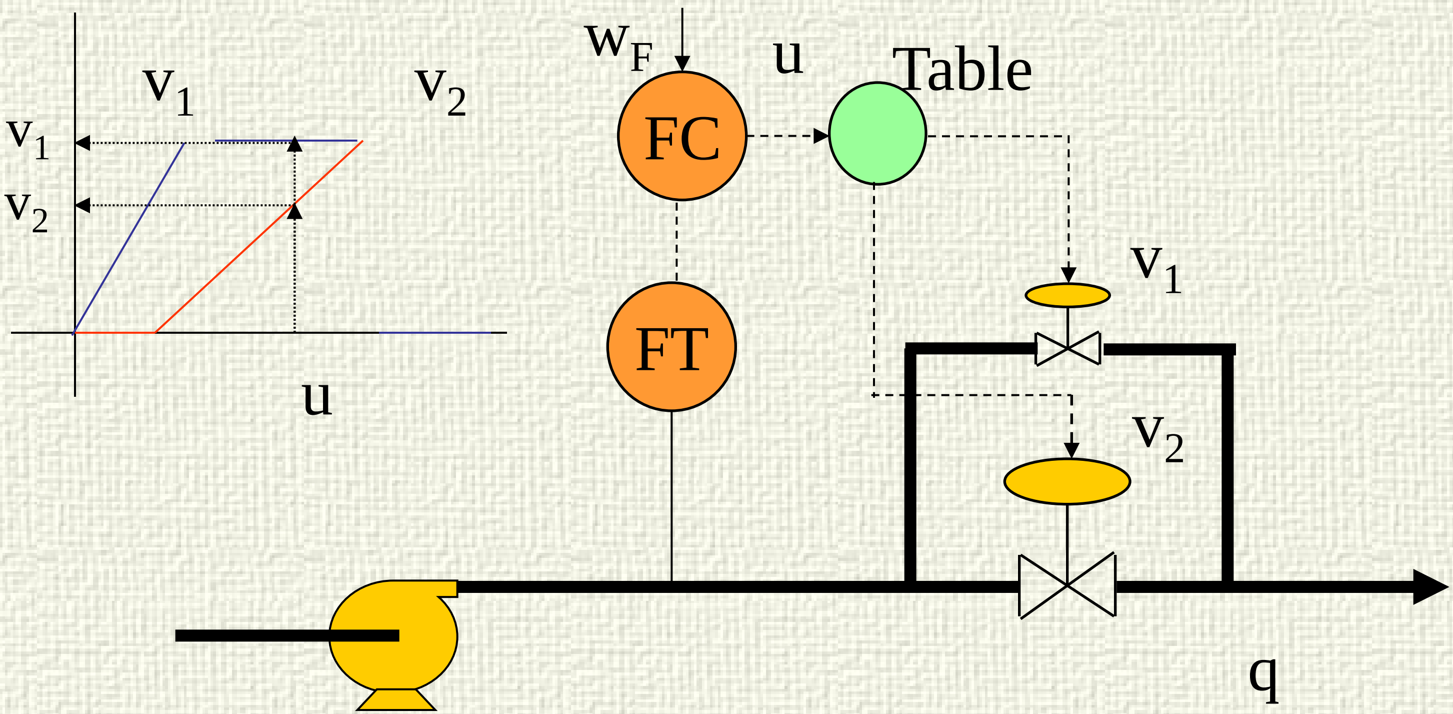


Safety

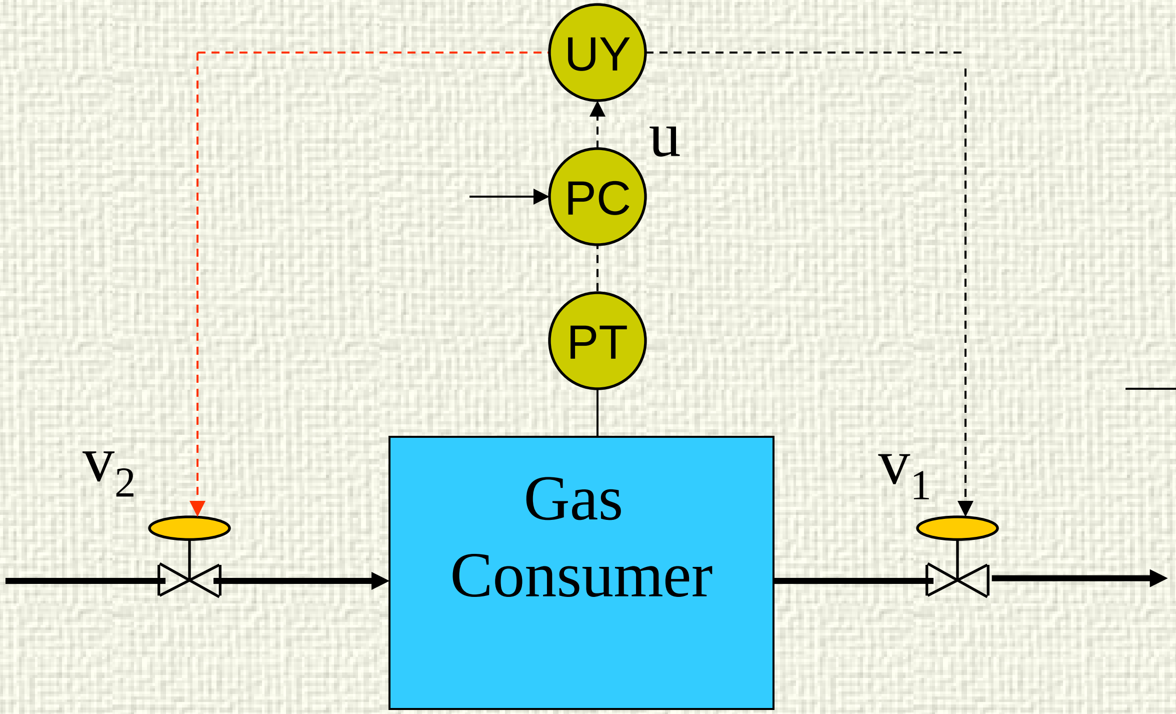


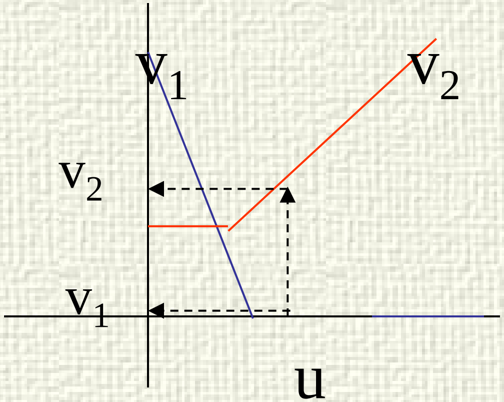
Limits the maximum pressure in the supply line

Split-range Control



Split-range Control

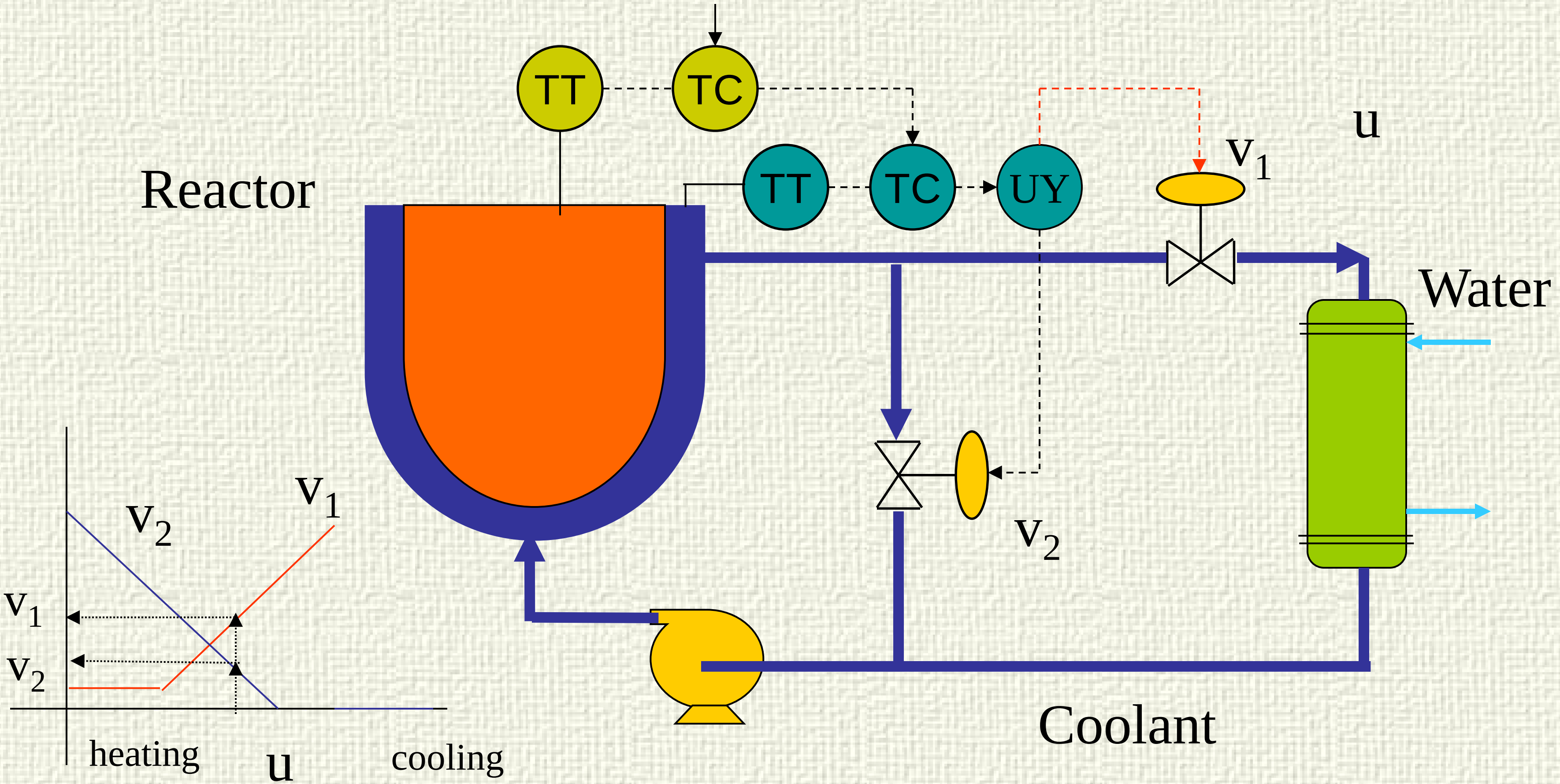




Split range

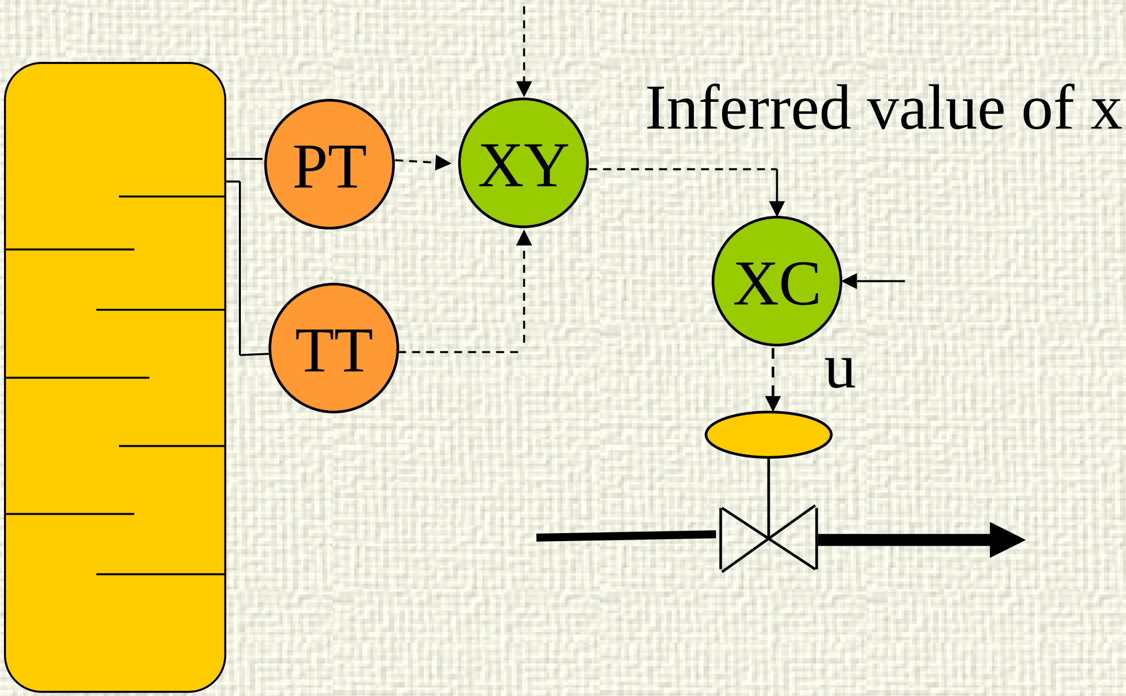
Under normal operating conditions, pressure regulation is performed with V_2, but if it reaches its minimum, then V_1 is used as a release valve

Split range Control

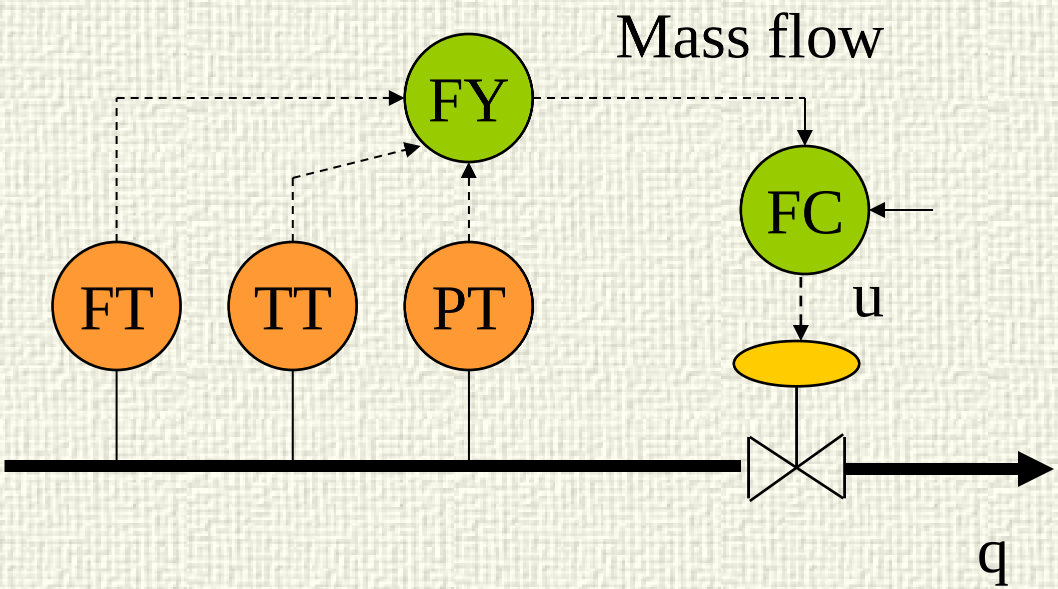


Inferential Control

Very often, we faced variables that are expensive or difficult to measure, or which measurements are unreliable or slow. In these cases, it is possible to substitute the transmitter signal by an estimation made from physical laws, models like NN, inferences, etc.

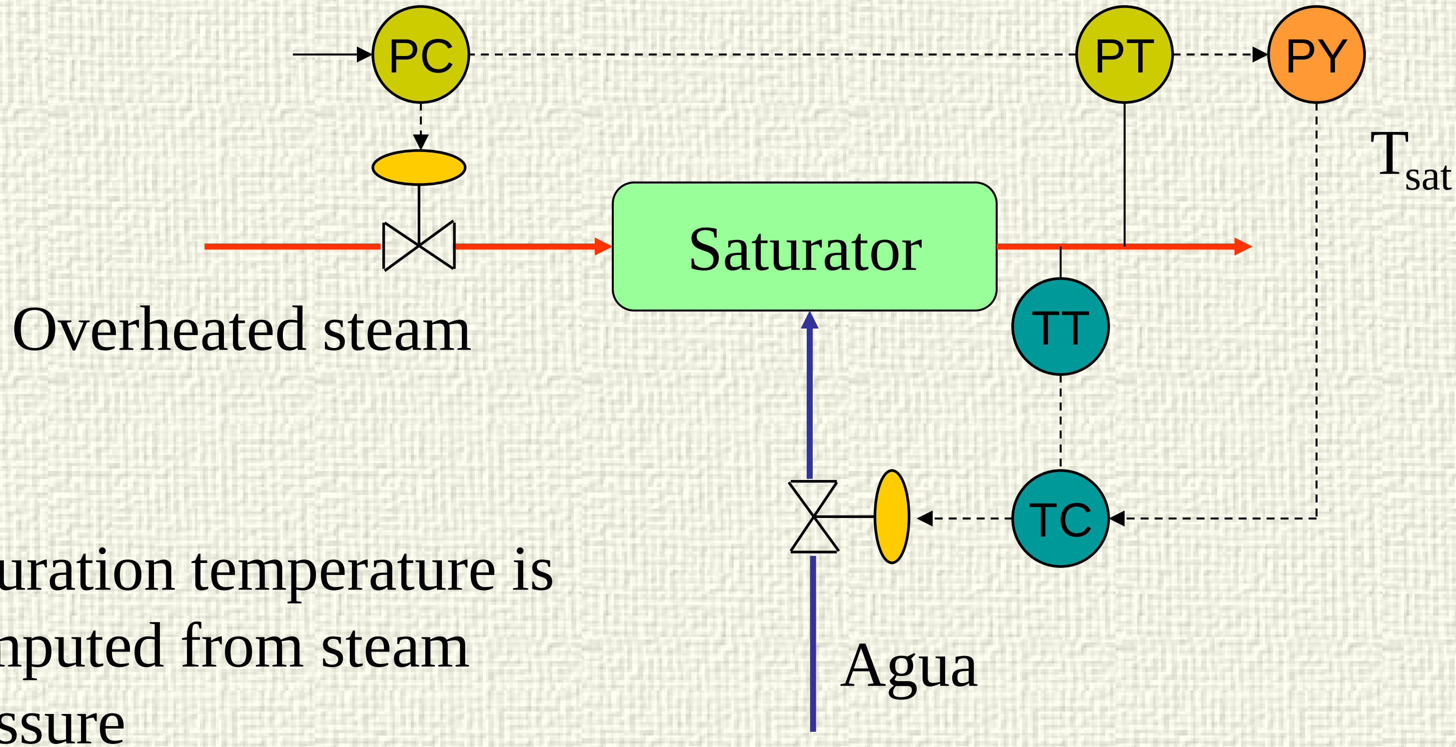


Inferential Control



Compute or estimate a non-measured controlled variable. Compute mass flow from volumetric flow, pressure and temperature

Physical laws



Saturation temperature is computed from steam pressure