Split-range control (contd---)

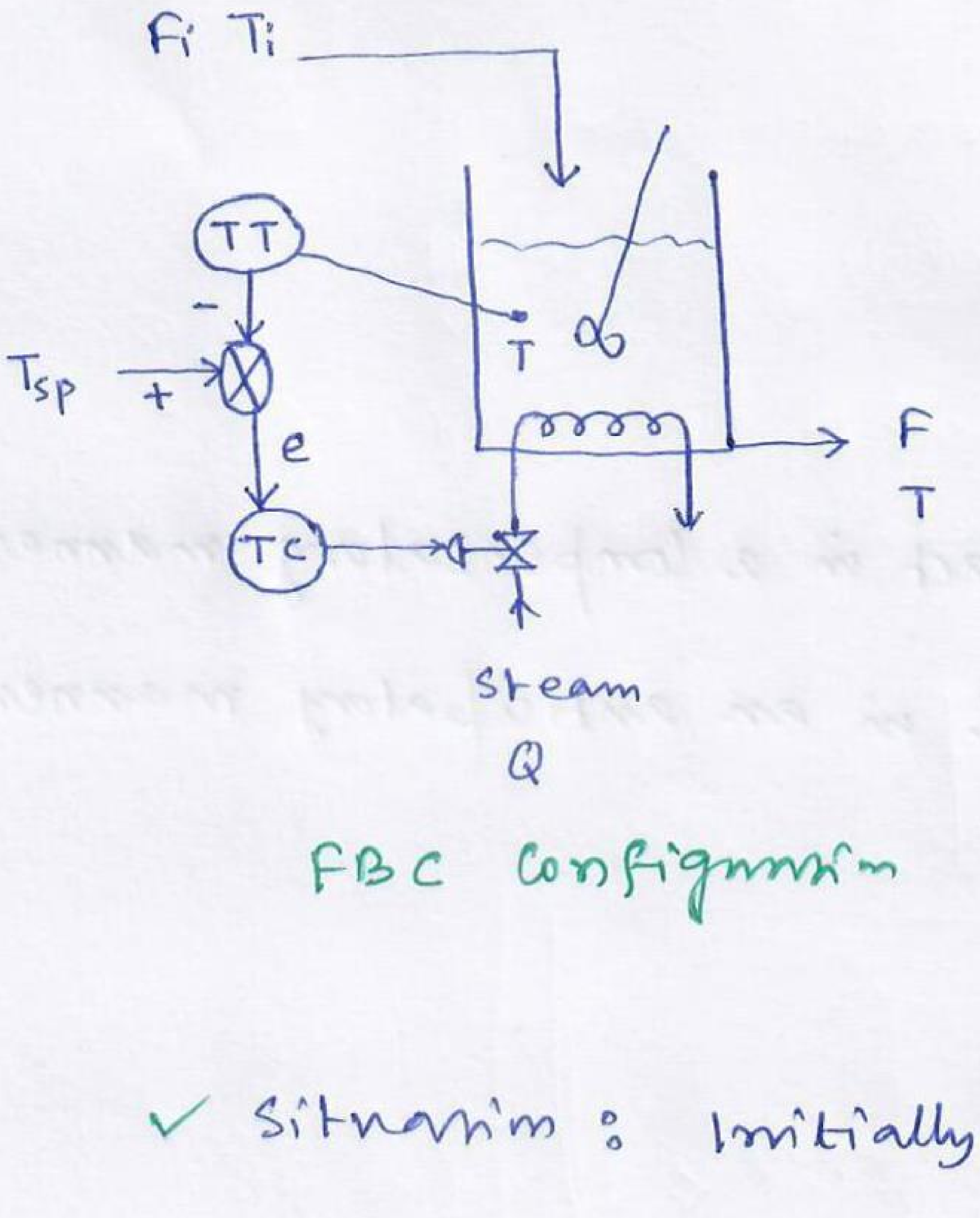
Applications.

- For p^H control in wastewater treatment by the use of both acid and base.
- For year-round heating and cooling of office buildings.

Feedforward control (FFC)

Motivation

Let us first discuss the limitation of FBC.



FBC configuration

- control obj : $T = T_{sp}$

CV	MV
T	Q

- for TC (PI controller)

$$Q = Q_s + K_c e + \frac{K_c}{\tau_i}\int e\,dt$$

$$e = T_{sp} - T \; ; \; Q_s, K_c, \tau_i \rightarrow \text{consts.}$$

- Q changes only if T changes (i.e., e chgs) so a FBC takes action only when T change is detected.

✓ Situation : Initially the process is at SS ($T_s = 50°c$).

- There is an increase in T_i
- It leads to increase T ($\epsilon \downarrow$)
- controller takes action $Q \downarrow$

Controller takes action after the effect of disturbance has been felt by the process through T.

So, perfect control can never be achieved by FBC scheme "theoretically".

Perfect control action we can achieve only if:

= Controller takes "perfect" action "before" the disturbance affects the process.

FFC
- For this, we need to measure the disturbance
- The controller should act before the effect of disturbance is felt by the process.

Note

Feedback controller acts after the fact in a compensatory manner

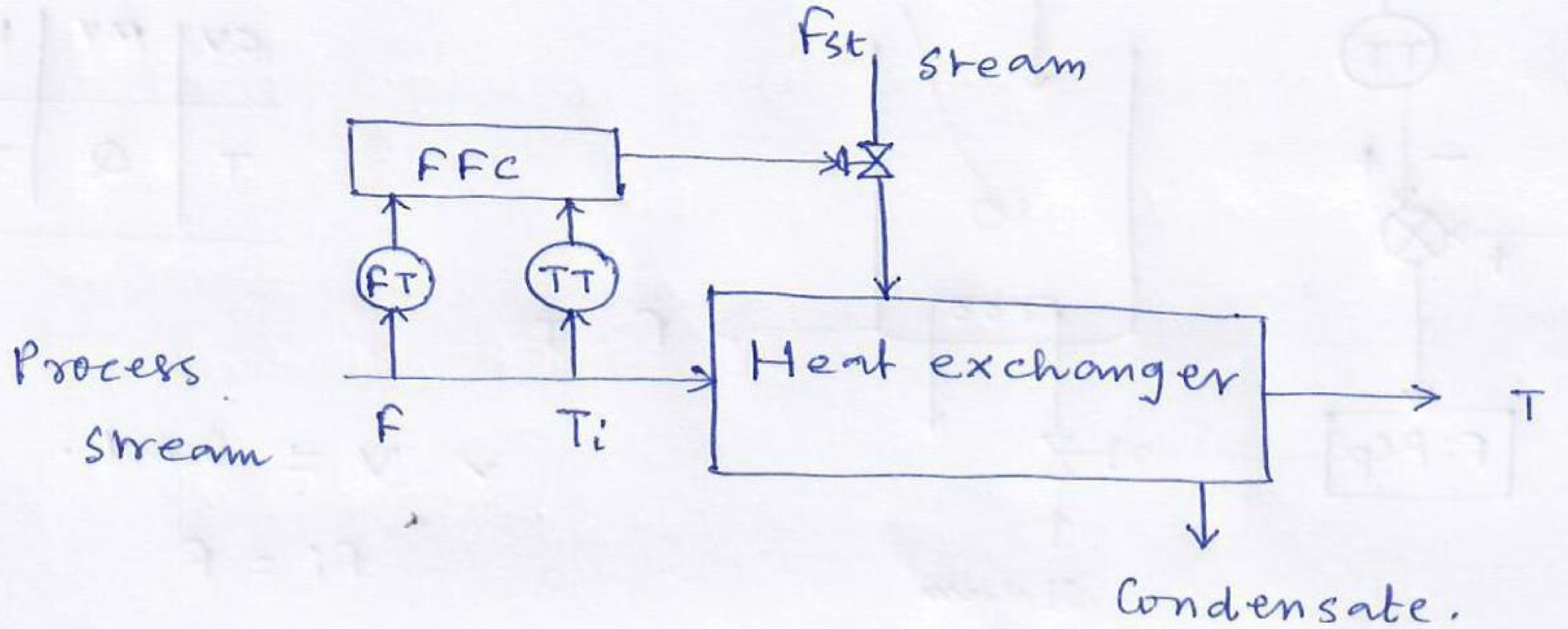
Feedforward controller acts beforehand in an anticipatory manner.

Feedforward control (contd..).

Ex 1. Heat exchanger

Control obj : $T = T_{sp}$.

CV	MV
T	F_{st}



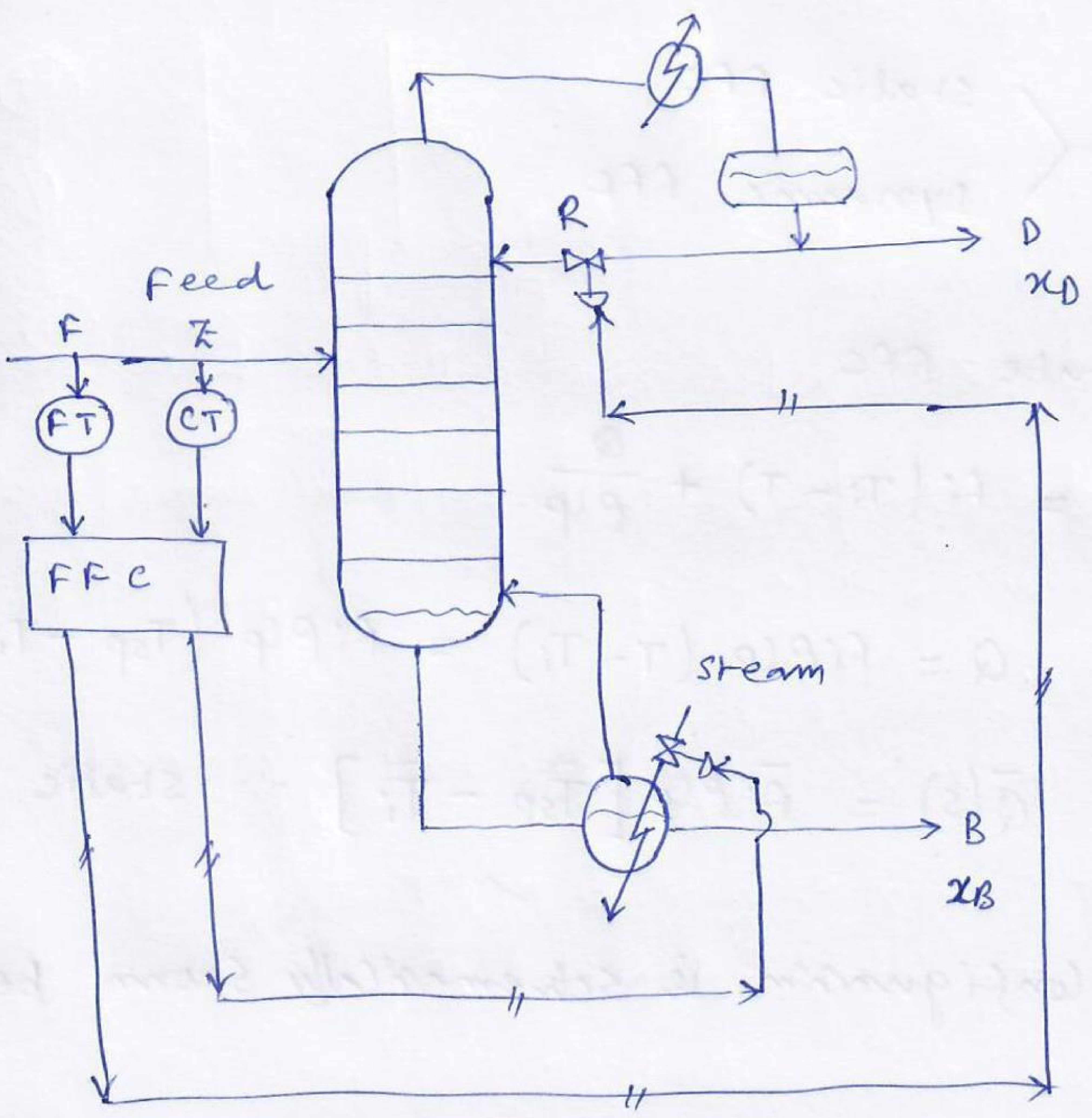
Disturbance : F, T_i

Ex 2. Distillation column.

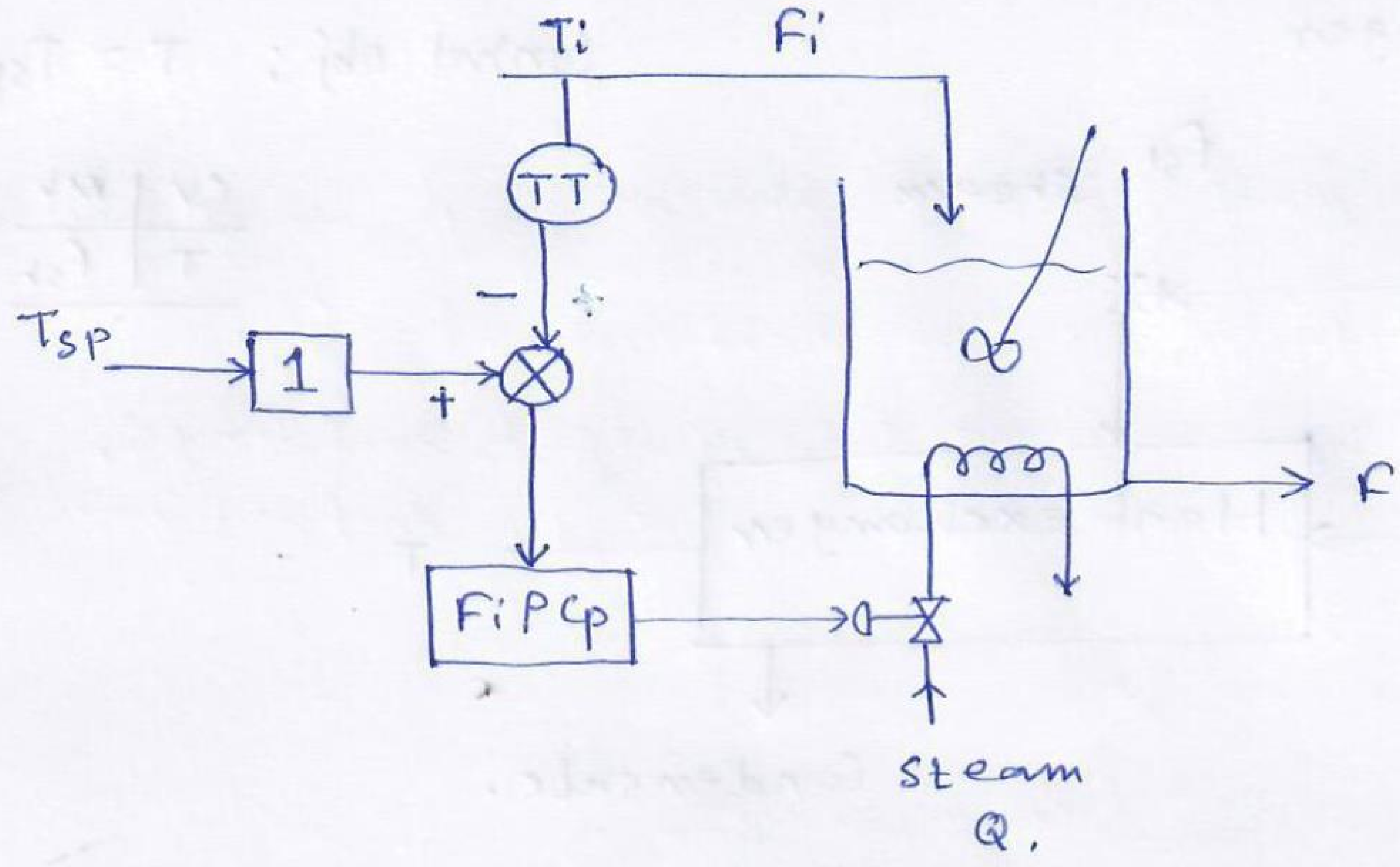
Control obj : $x_D = x_{Dsp}$

$x_B = x_{Bsp}$.

CV	MV	LV
x_D	R	F, Z
x_B	Q_R	



Deriving FFC : Stirred tank heater



✓ Control obj : $T = T_{sp}$

CV	MV	LV
T	Q	Ti

✓ V = Const.

$F_i = F$

✓ Energy bal. $\frac{d}{dt}(V\rho C_p T) = F_i \rho C_p T_i - F\rho C_p T + Q.$

$$V\frac{dT}{dt} = F_i(T_i - T) + \frac{Q}{\rho C_p}$$ -- final form.

✓ FF controller — Static FFC / Dynamic FFC

Static / steady state FFC

At SS : $0 = F_i(T_i - T) + \frac{Q}{\rho C_p}$.

Rearranging : $Q = F_i\rho C_p (T - T_i) = F_i \rho C_p (T_{sp} - T_i)$.

$\bar{Q}(s) = \bar{F_i}\rho C_p [\bar{T}_{sp} - \bar{T}_i]$ --- static FFC.

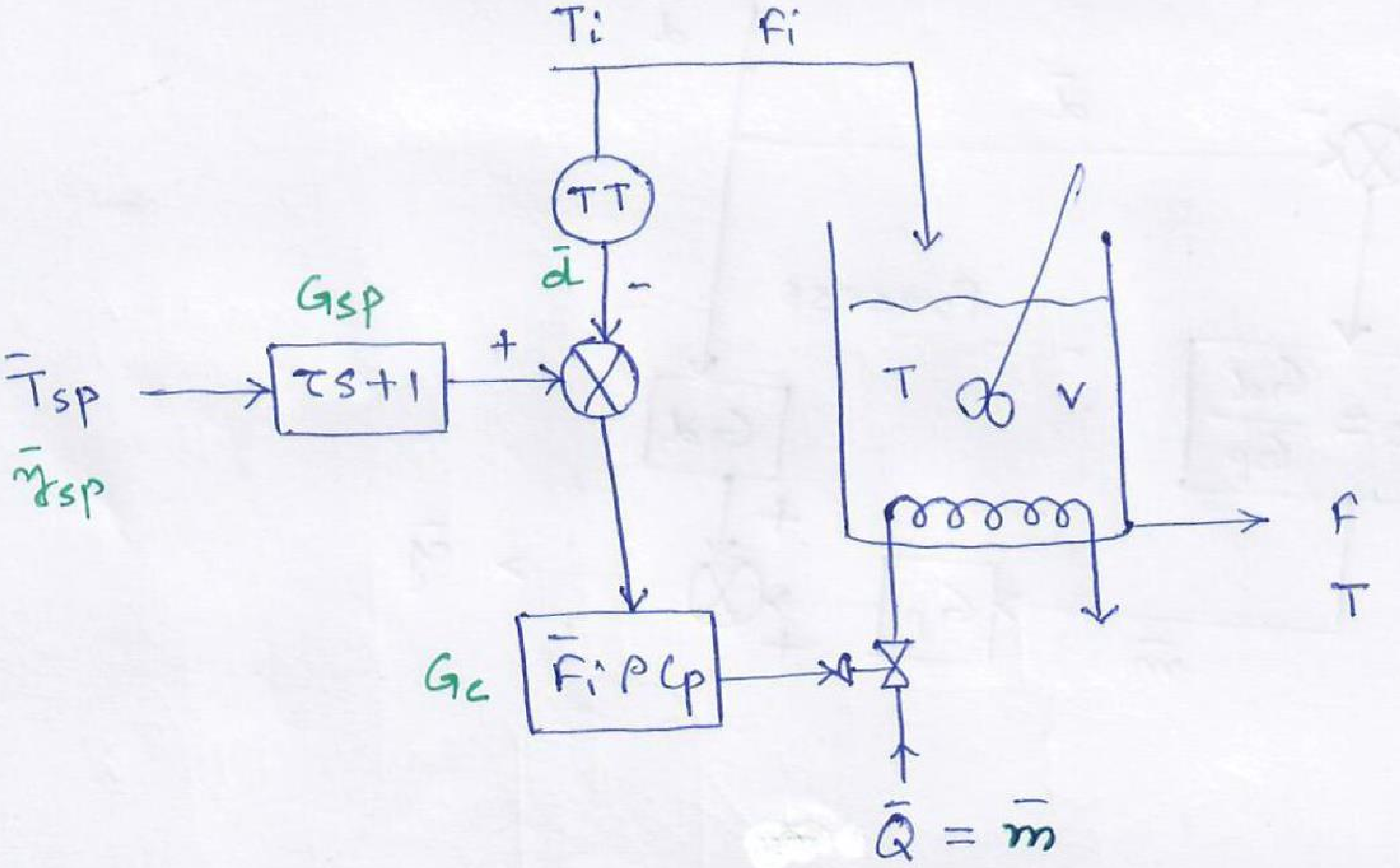
This static FFC configuration is schematically shown before.

Dynamic FFC

Dynamic model: $\dfrac{V}{F_i}\dfrac{dT}{dt} + T = T_i + \dfrac{Q}{F_i \rho C_p}$.

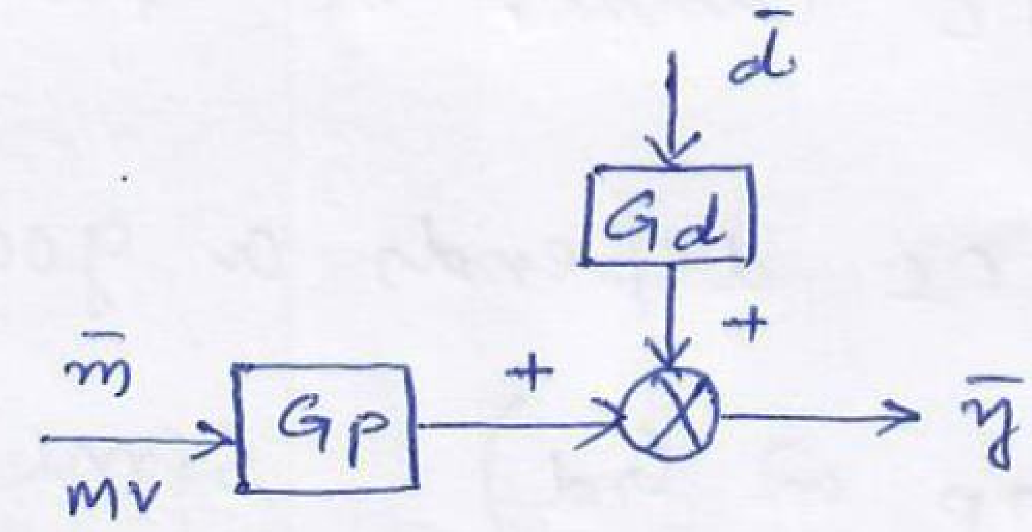
$$\bar{Q}(s) = \bar{F}_i \rho C_p \left[(\tau s+1)\bar{T}_{sp} - \bar{T}_i \right] \quad \text{-- dynamic FFC}$$

$$m = MV = G_c \left[G_{sp}\, \bar{y}_{sp} - \bar{d} \right] \qquad \tau = \frac{V}{F_i}$$



Generalized form of FFC

o open-loop block diagram



$$\bar{y} = G_p \bar{m} + G_d \bar{d}$$

$$\bar{y}_{sp} = G_p \bar{m} + G_d \bar{d}$$

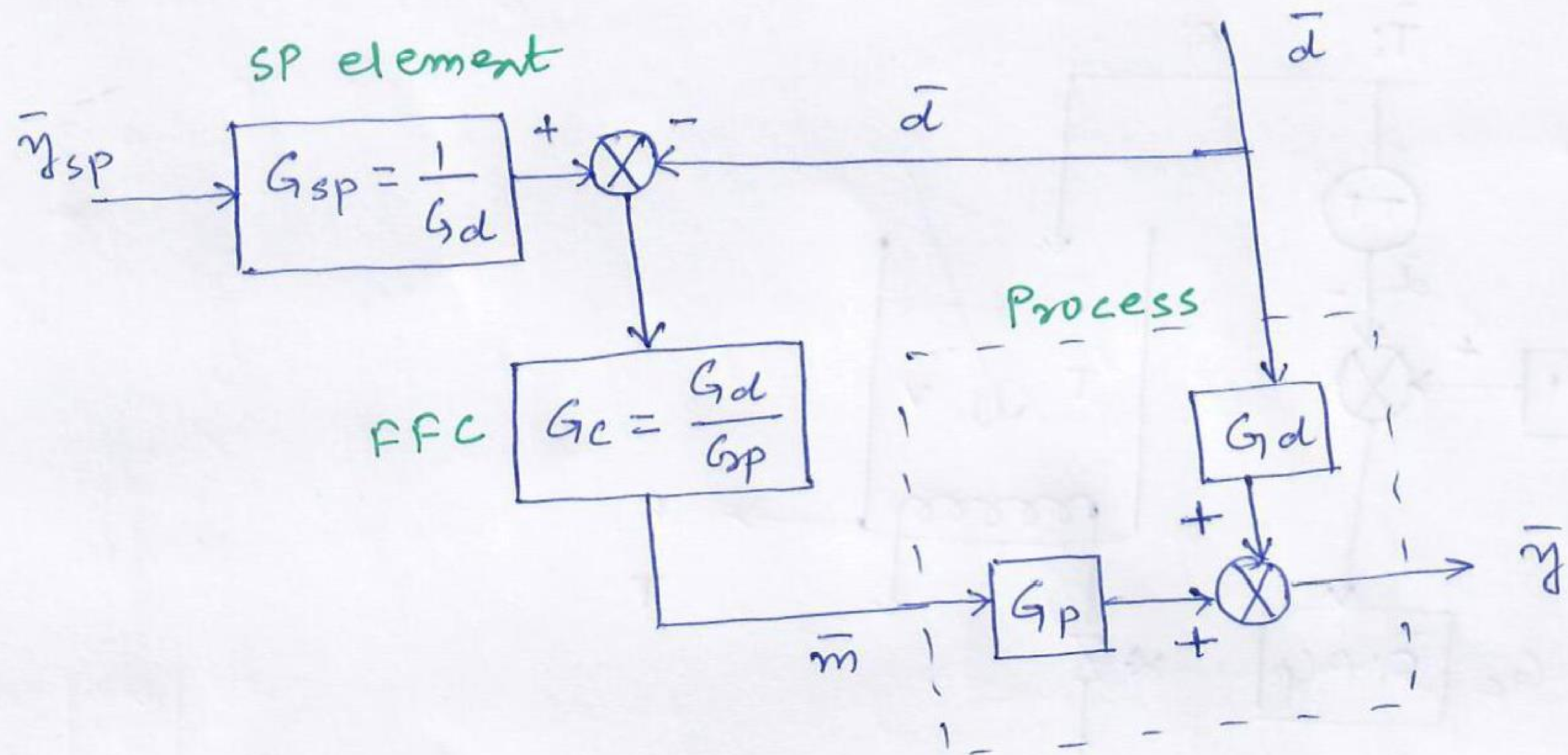
$$\bar{m} = \left[\frac{1}{G_d}\bar{y}_{sp} - \bar{d} \right] \frac{G_d}{G_p} \equiv \left[G_{sp}\,\bar{y}_{sp} - \bar{d} \right] G_c$$

Comparing,

$$G_c = \frac{G_d}{G_p} \equiv FFC$$

$$G_{sp} = \frac{1}{G_d} \equiv \text{SP element.}$$

o closed-loop block dig $\qquad \bar{m} = [G_{sp}\bar{y}_{sp} - \bar{d}]\,G_c$



Remarks.

1. FFC cannot be FBC, like P, PI or PID controller.

2. FFC depends a good knowledge of the process model (G_p and G_d) since $G_c = \frac{G_d}{G_p}$.

3. In the above block dig, $G_m = G_f = 1$. The inclusion of these two elements alter the design of the TFs G_c and G_{sp}.

Design of FFC

Ex 1. First-order system

✓ Given : $G_p(s) = \dfrac{K_p}{\tau_p s+1}$ $G_d(s) = \dfrac{K_d}{\tau_d s+1}$ $G_m = G_f = 1$

✓ FFC : $G_c(s) = \dfrac{G_d}{G_p} = \dfrac{K_d}{K_p}\dfrac{\tau_p s+1}{\tau_d s+1}$ --- lead-lag element

✓ This is called so because $(\tau_p s+1)$ introduces phase lead and $\dfrac{1}{\tau_d s+1}$ adds phase lag.

✓ If $\tau_p = \tau_d$, $G_c = \dfrac{K_d}{K_p} = K$ --- static FFC

Ex 2. First-order-plus-dead-time system.

✓ Given: $G_p = \dfrac{K_p e^{-\theta_p s}}{\tau_p s+1}$ $G_d = \dfrac{K_d e^{-\theta_d s}}{\tau_d s+1}$ $G_m = G_f = 1$

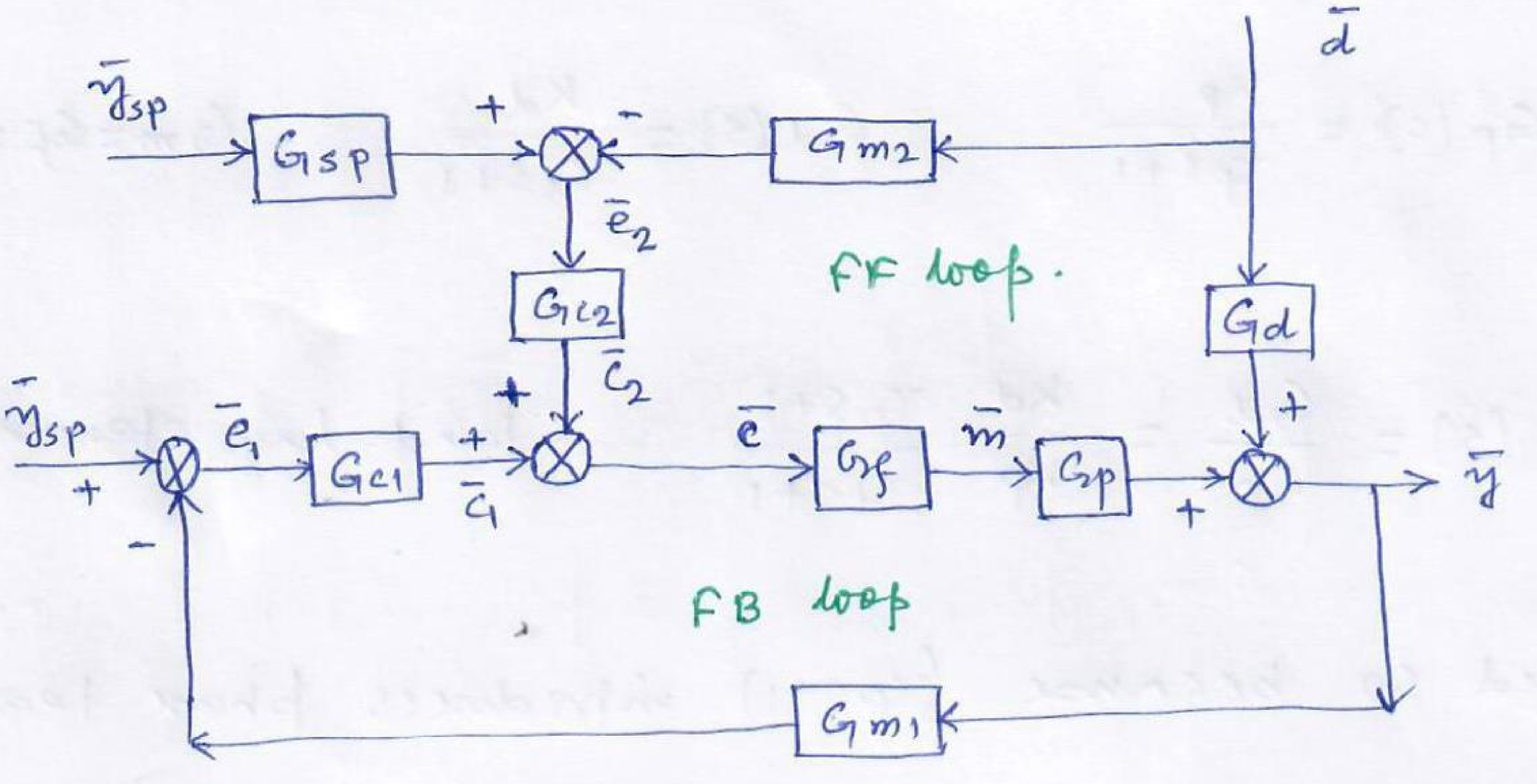
✓ FFC : $G_c = \dfrac{G_d}{G_p} = \dfrac{K_d}{K_p}\dfrac{\tau_p s+1}{\tau_d s+1} e^{-(\theta_d - \theta_p)s}$ --- lead-lag with time delay

✓ It should be physically realizable only if $\theta_d \geq \theta_p$.

$$L^{-1}\left[e^{-\theta s}\,\bar{y}(s)\right] = y(t-\theta)$$
$$L^{-1}\left[e^{\theta s}\,\bar{y}(s)\right] = y(t+\theta).$$

future y.

Feed forward - Feedback control.



$$\bar{y} = G_p \bar{m} + G_d \bar{d}$$

where $\bar{m} = G_f \bar{c} = G_f (c_1 + c_2) = G_f G_{c1} \bar{e}_1 + G_f G_{c2} \bar{e}_2$

$$= G_f G_{c1} (\bar{y}_{sp} - G_{m1} \bar{y}) + G_f G_{c2} (G_{sp} \bar{y}_{sp} - G_{m2} \bar{d}).$$

It gives:

$$\bar{y} = \frac{G_p G_f (G_{c1} + G_{c2} G_{sp})}{1 + G_p G_f G_{c1} G_{m1}} \bar{y}_{sp} + \frac{G_d - G_p G_f G_{c2} G_{m2}}{1 + G_p G_f G_{c1} G_{m1}} \bar{d}$$

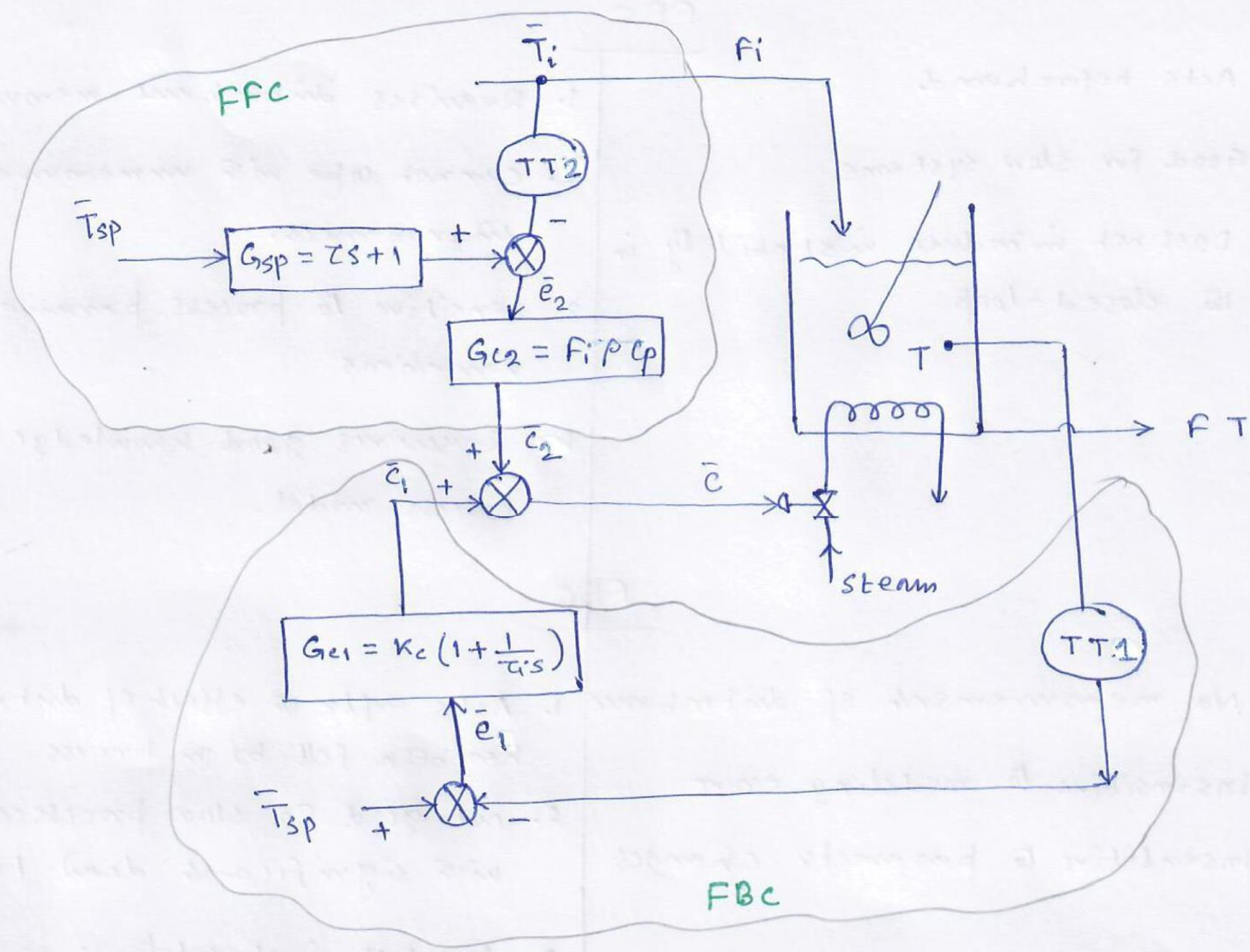
Remark.

CE: $1 + G_p G_f G_{c1} G_{m1} = 0$ ... FF + FB system

$1 + G_p G_f G_{c1} G_{m1} = 0$ ... FB system

The stability characteristics of a feedback system will not change with the addition of a feedforward loop.

Ex. (FF + FB) controller of heating tank system



FFC

Advantage	Disadvantage
1. Acts beforehand	1. Requires disturbance measurement
2. Good for slow systems	2. cannot cope with unmeasured disturbances.
3. Does not introduce instability in the closed-loop	3. sensitive to process parameter variations
	4. Requires good knowledge of the process model.

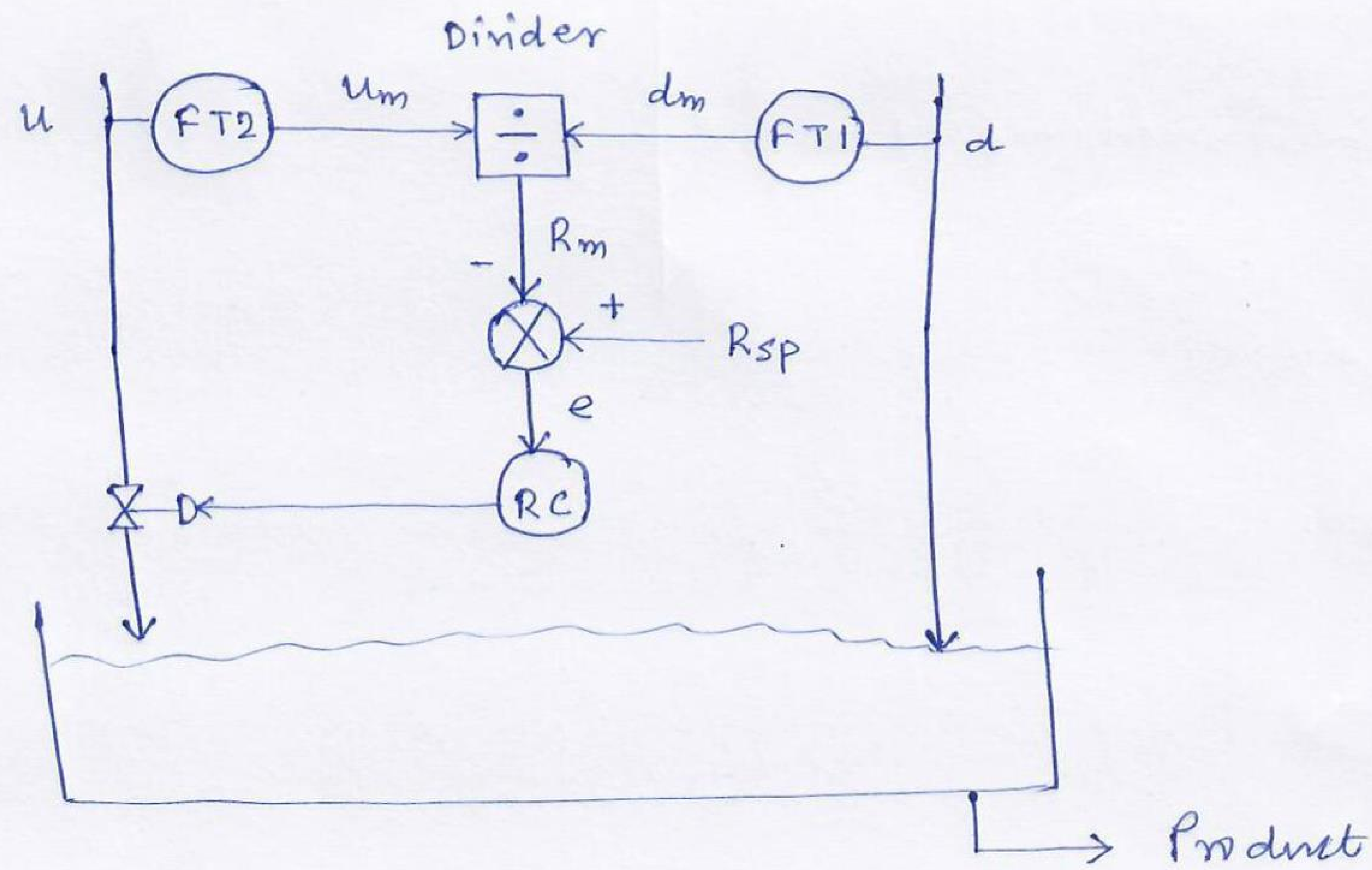
FBC

Advantage	Disadvantage
1. No measurement of disturbance	1. Acts after the effect of disturbance has been felt by the process
2. Insensitive to modeling error	2. not good for slow processes or with significant dead-time
3. Insensitive to parameter changes	3. Creates instability in the closed-loop response.

Ratio Control

- More than 1 measurement + 1 MV
- Objective is to maintain the ratio of two process variables (usually two flow rates) at a specified value
- Both flow rates are measured but only one can be controlled
- $\text{Ratio } (R) = \frac{u}{d} = \frac{\text{flow rate of a MV}}{\text{flow rate of a LV}}$
- disturbance variable (LV) is not under control and thus, it is called as "wild" stream
- It is a special type of FFC.

Ratio Control Configuration



$$R_m = \frac{u_m}{d_m} = \frac{\text{measured } u}{\text{measured } d}$$

$$e = R_{sp} - R_m$$

$$RC \equiv FBC \ (P, PI, PID).$$

Application of ratio control

- To control the reflux ratio in distillation
- To control the stoichiometric ratio of reactants in reactor / reactive distillation
- To control the ratio of two blended streams.