Enhanced PID Control: Cascade Control

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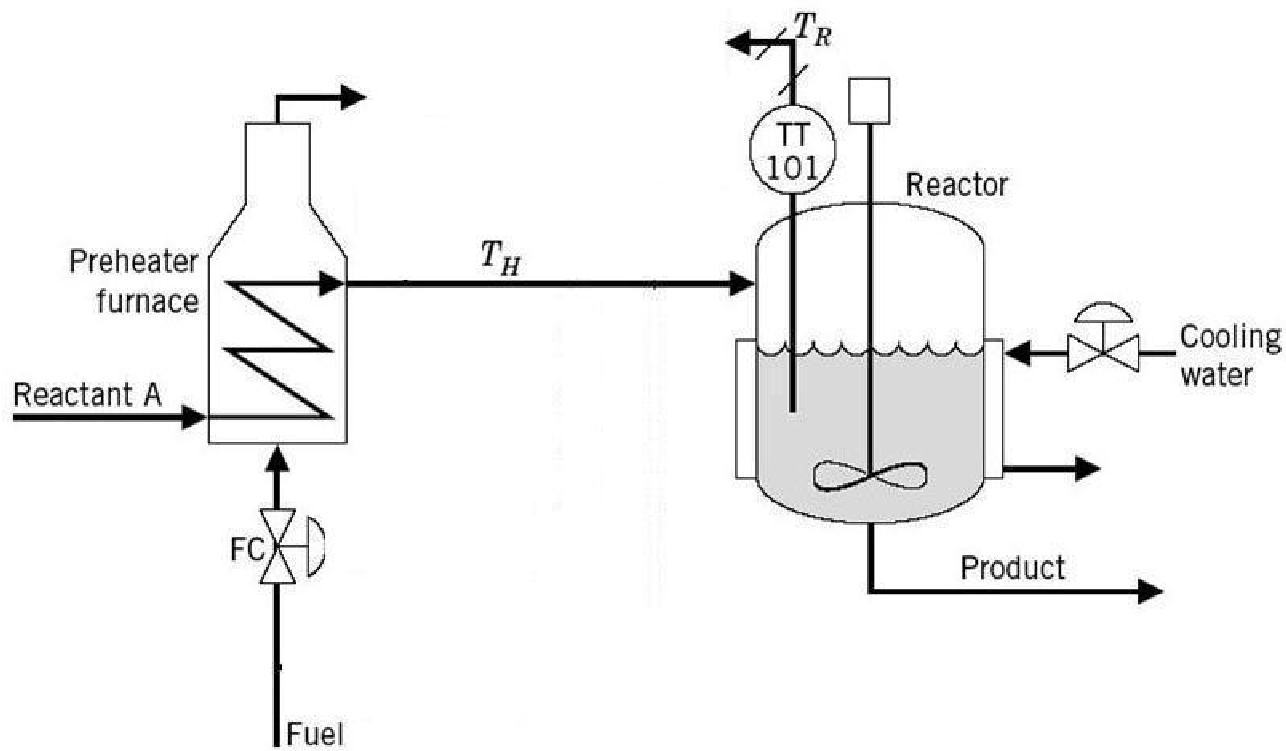
Enhanced PID Control: Cascade Control

- What is **Cascade Control** ?
- Motivation of using **CC** Control
  Simple feedback $\leftrightarrow$ **CC** Control
- Major advantages of using **CC** Control
- When to Use **CC** Control
- Selection of **CC** Controller modes
- Tuning of **CC** Controllers
- Applications

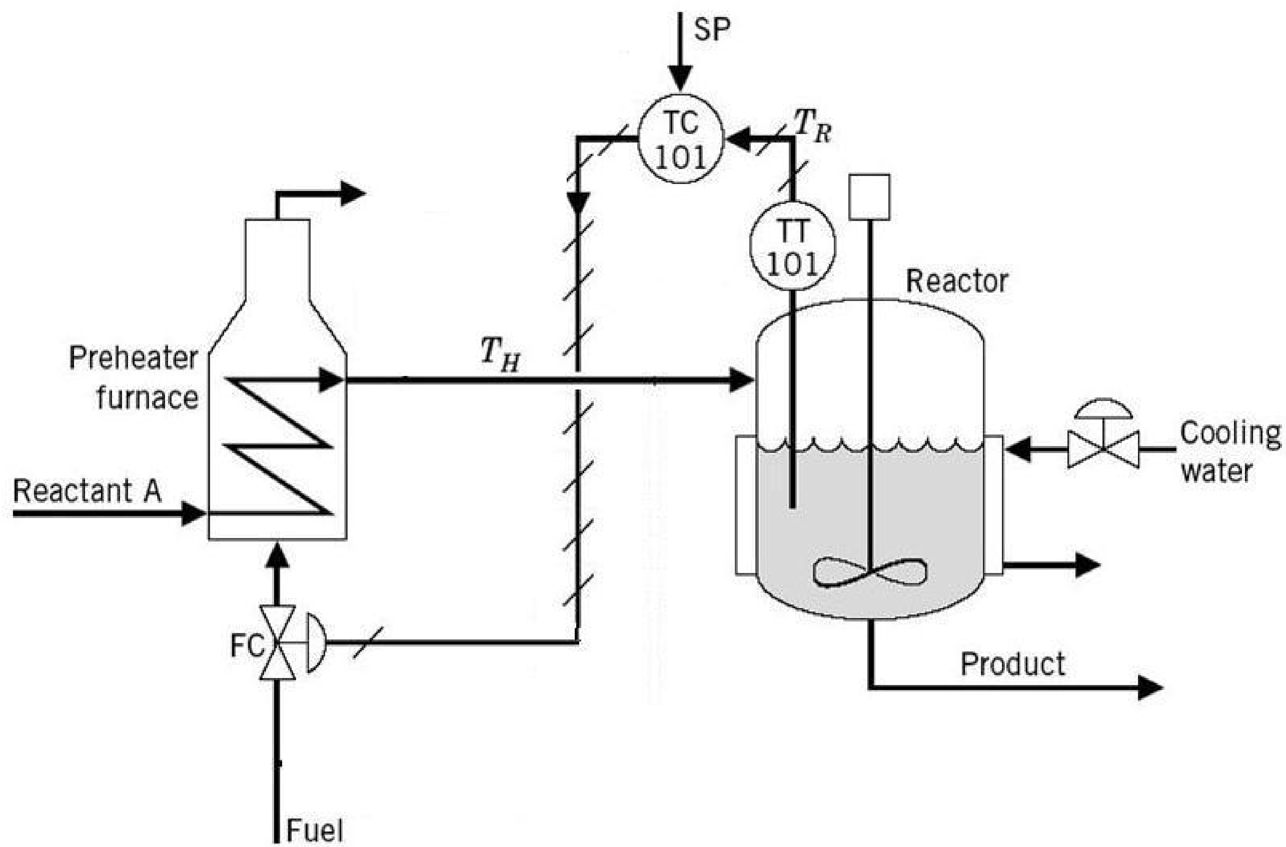
A Preheater/Reactor Process

The Control Target



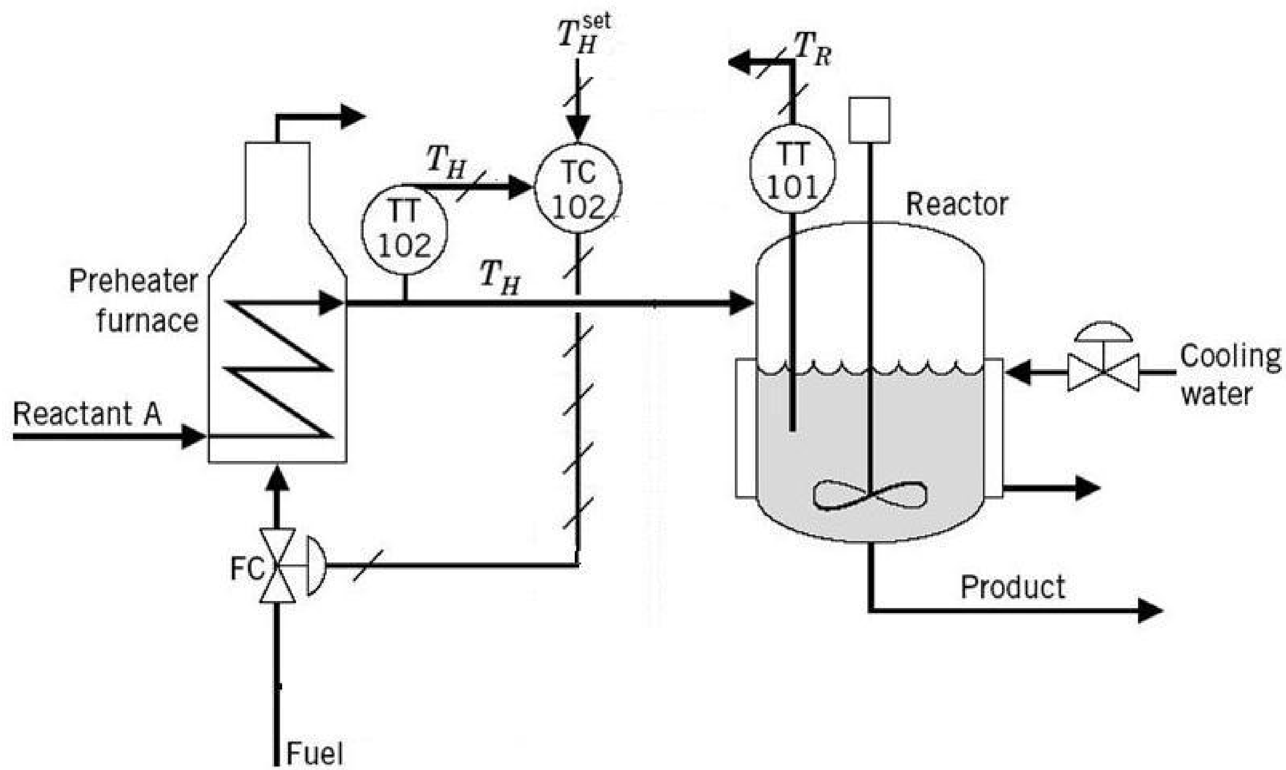
A Preheater/Reactor Process

Simple Feedback Control



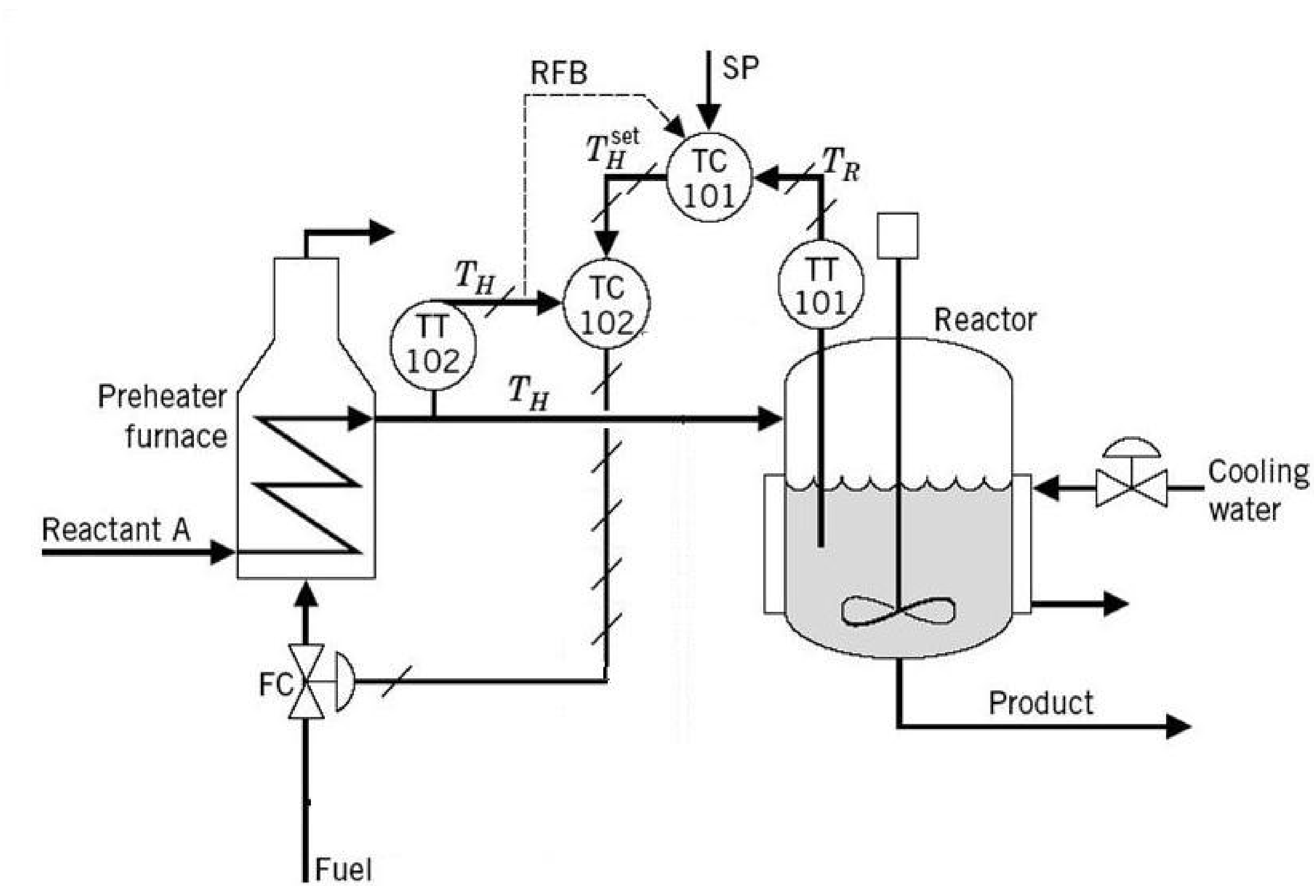
A Preheater/Reactor Process

Another Feedback Control



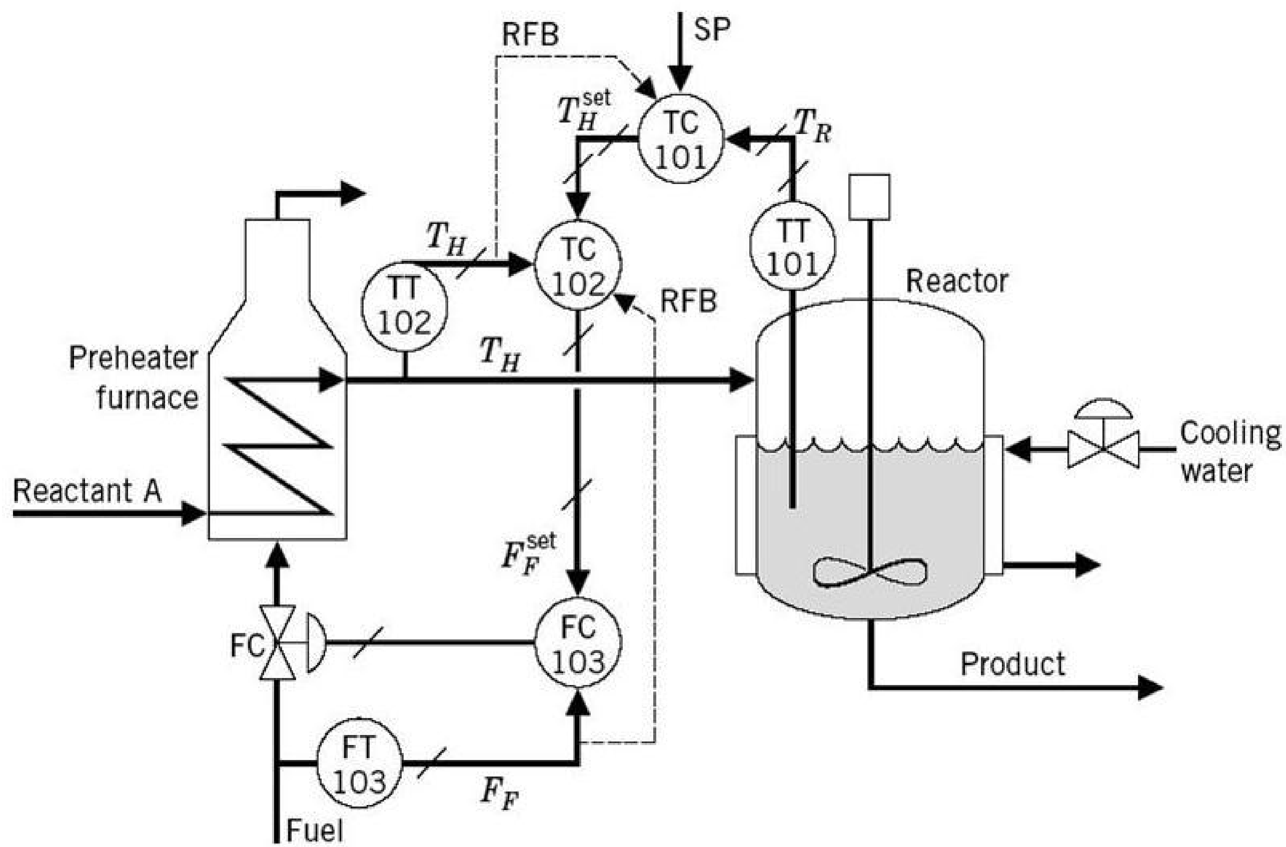
A Preheater/Reactor Process

Two-Level Cascade Control



A Preheater/Reactor Process

Three-Level Cascade Control



A Preheater/Reactor Process

Response of Feedback and 2-L Cascade

-25^oC change in feed temperature to heater

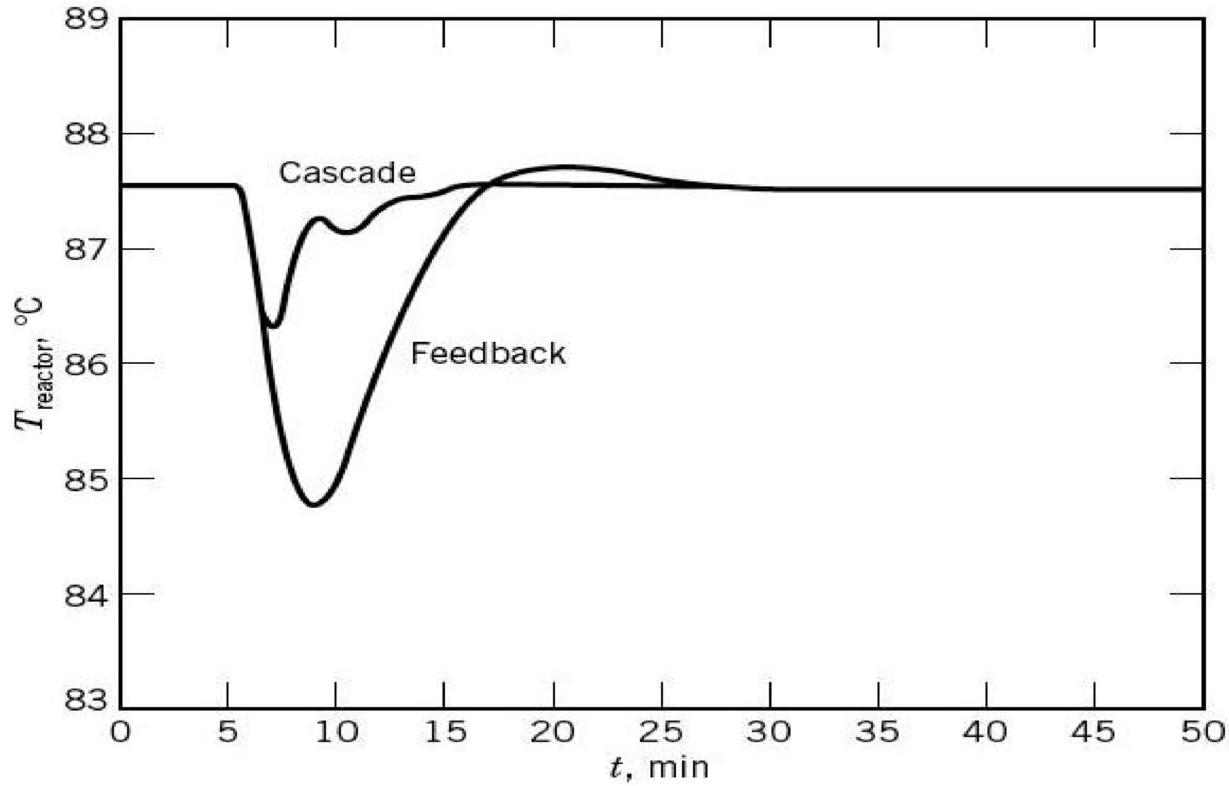


Figure 9-1.3 Response of feedback and cascade control to a $-25°$C change in feed temperature to heater.

A Preheater/Reactor Process

Stability Considerations

➢ Process transfer functions:

$$
\begin{aligned}
K_V &= 3 \text{ gpm/\%CO} & \tau_V &= 0.2 \text{ min} \\
K_1 &= 1 \text{ C/gpm} & \tau_1 &= 3 \text{ min} \\
K_3 &= 0.8 \text{ C/C} & \tau_2 &= 1 \text{ min} \\
\tau_4 &= 4 \text{ min} & \tau_5 &= 1 \text{ min} \\
K_{T_1} &= 0.5 \text{ \%TO/C} & K_{T_2} &= 0.5 \text{ \%TO/C}
\end{aligned}
$$

➢ Simple Feedback:

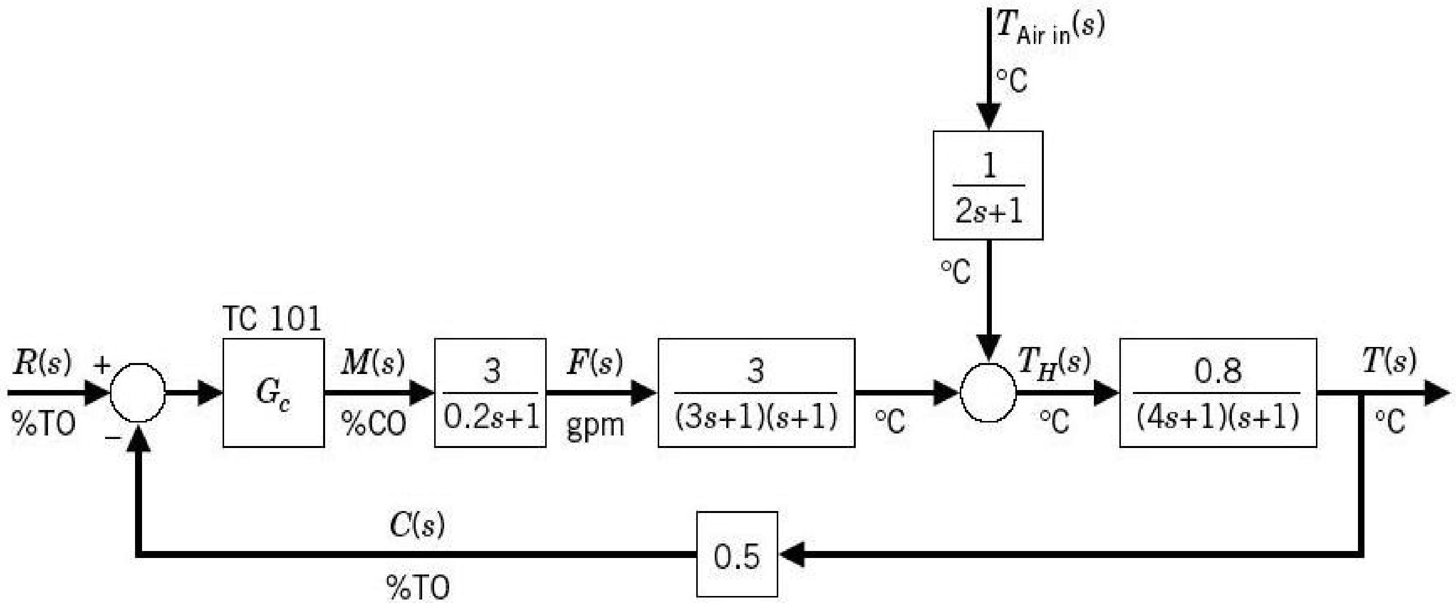


Figure 9-2.1 Block diagram of the process shown in 9-1.1.

Char. Eq.: $$1+\frac{1.2G_{c1}}{(0.2s+1)(3s+1)(s+1)(4s+1)(s+1)}=0$$

$$\Rightarrow\ K_{cu}=4.33\ \frac{\%\text{CO}}{\%\text{TO}},\qquad \omega_u=0.507\ \frac{\text{rad}}{\text{min}}$$

➢ 2-L Cascade:

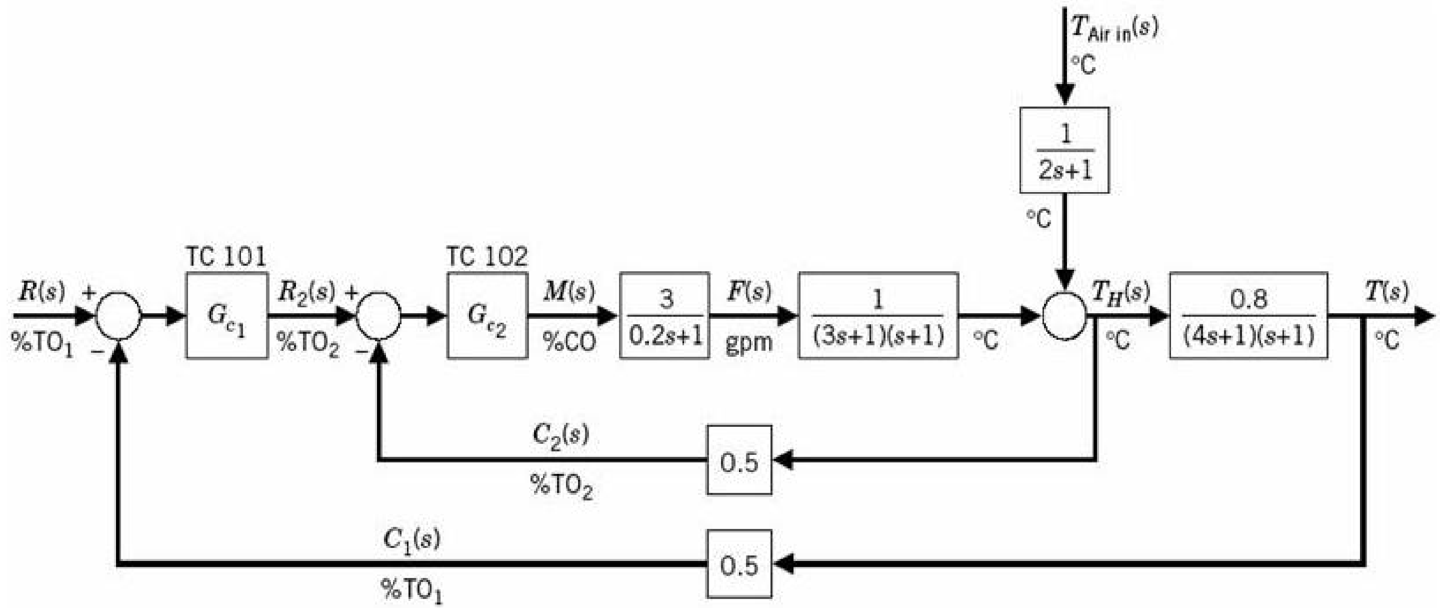


Figure 9-2.2 Block diagram of the process shown in 9-1.2.

$$\textbf{Inner: } 1+\frac{1.5G_{c2}}{(0.2s+1)(3s+1)(s+1)} = 0$$

$$\Rightarrow K_{cu_2} = 17.06\ \frac{\%\mathrm{CO}_2}{\%\mathrm{TO}_2} \quad \Rightarrow \quad K_{c_2} = 0.5K_{cu_2} = 8.53\ \frac{\%\mathrm{CO}_2}{\%\mathrm{TO}_2}$$

$$\textbf{Overall: } 1+\frac{\frac{1.2G_{c1}G_{c2}}{(0.2s+1)(3s+1)(s+1)(4s+1)(s+1)}}{1+\frac{1.5G_{c2}}{(0.2s+1)(3s+1)(s+1)}} = 0$$

$$\Rightarrow K_{cu_1} = 7.2\ \frac{\%\mathrm{CO}_1}{\%\mathrm{TO}_1} \qquad \omega_u = 1.54\ \frac{\mathrm{rad}}{\mathrm{min}}$$

➢ **Summary:** ultimate data for FB and cascade controls

$$\begin{aligned}
\textbf{Simple FB:}\quad K_{cu_1} &= 4.33 && \%\text{CO}/\%\text{TO} \\
\omega_u &= 0.507 && 1/\text{min} \\
\textbf{Cascade:}\quad K_{cu_2} &= 17.06 && \%\text{CO}/\%\text{TO} \\
\Rightarrow\quad K_{C_2} &= 8.53 && \%\text{CO}/\%\text{TO} \qquad (= 0.5K_{cu_2}) \\
\Rightarrow\quad K_{cu_1} &= 7.2 && \%\text{CO}/\%\text{TO} \\
\omega_u &= 1.54 && 1/\text{min}
\end{aligned}$$

➢ **Conclusion:**

Cascade makes overall loop more stable and faster responding

(TO: Transmitter Output   CO: Controller Output)

Major Advantages of Using CC Control

- Any disturbances that affect slave variable are detected and compensated by slave controller **BEFORE** they affect primary variable
- **Controllability** of outside loop is improved because inside loop speeds up response between valve and slave variable
- **Nonlinearities** of process in inner loop are handled by that loop and removed from the more important outer loop

When to Use CC Control

- When the **three advantages** result in significant improvement in control performance
- Use **CC** control only when inner loop responding **faster** than outer loop
- **NOTE:**
  CC control requires additional sensor and controller

Remarks of Using CC Control

- **If inner loop is NOT faster than outer loop:**
  - Disturbances into inner loop will not be eliminated fast enough to avoid affecting primary variable
  - Speeding up of inner loop would decrease controllability of overall loop because:
    - Ratio of dead time to time constant would increase
    - Nonlinearities would become a part of slower loop
- **Sensor of the inner loop should be fast and reliable**

- **Integral mode of master controller** will compensate for errors in measurement of slave variable

  ⇒ **repeatability** is more important than **accuracy** for inner loop sensor

- **CC** control would **NOT** be able to improve performance of loops **when**:

  ☞ These loops are already very controllable

  ☞ These loops do not need tight control (averaging level control)

Selection of Cascade Controller Modes

Master Controller

- **Master controller** has the same function as **single feedback controller**
- Selection of modes for master controller should follow the same guidelines for single controller

Proportional Mode in Slave Controller

- **Slave** controller must have *proportional* mode, act on error signal
- Slave controller should follow *setpoint* changes as quickly as possible with a small overshoot and decay ratio
- Slave controller should transmit changes in master controller output (slave setpoint) to final control element at least as fast as if it is not there
- Slave controller should transmit changes in its setpoint to its output as quickly as possible and amplify them
- P control mode: $K_c \geq 1$ if stability permits it
  $\Rightarrow$ Changes in master controller output result in higher immediate changes in final control element than when a single feedback loop is used
  $\Rightarrow$ Faster response of master loop

Integral Mode in Slave Controller

- Adding **I** mode results in a reduction of proportional gain
- **I** mode is not needed in slave controller to eliminate offset
  (**I** mode of master controller can adjust setpoint
  of slave controller to compensate for offset)
- IF slave loop is fast and subject to large disturbances
  $\Rightarrow$ Offset in slave controller would require
  corrective action by master controller
  $\Rightarrow$ A deviation of primary CV from its setpoint
- A fast-acting **I** mode on slave controller would eliminate the need for corrective action from master controller
- **I**ntegral mode should not be used in these slave loops:
  - ☞ Gain is limited by stability
  - ☞ Disturbances into inner loop do not cause large offsets in secondary CV

Derivative Mode in Slave Controller

- ➢ Slave controller does not require derivative mode when inner loop is fast and very controllable
- ➢ D mode in slave controller is usually not suggested:
  - ☞ PID + PID $\Rightarrow$ too many tuning variables
  - ☞ Undesirable to put two derivative units in series
- ➢ Derivative of slave controller should act on process variable instead of error
- ➢ Derivative unit could be used to compensate for sensor lag or loop dead time
- ➢ Use derivative unit to allow for a higher slave controller gain with less overshoot and low decay ratio

Tuning of Cascade Controllers

General Guidelines

➢ Tuning cascade control system: from **inside out**

☞ Tune innermost loop first, then the loop around it

☞ Inner loop is part of the process for the outer loop

➢ A loop must be tuned tighter and faster than the loop around it
Otherwise, setpoint of slave loop would vary more than its measured variable $\Rightarrow$ poorer control of master variable

➢ Slave variable should follow its setpoint as quickly as possible with little overshoot (5%) and oscillations
$\Rightarrow$ $1/4$ decay ratio response is not recommended (overshoot: 50%)
$\Rightarrow$ Use **IAE** tunings for set point changes

➢ Master loop can be tuned to follow any desired performance criterion

Tuning of Cascade Controllers

Slave Flow Loop

- Flow is the innermost loop in most cascade control system
- Flow controller in a cascade system must be tuned tight
- A **PI** controller can be used:
  - With a gain greater than 1.0
  - With integral time set equal to time constant of valve actuator

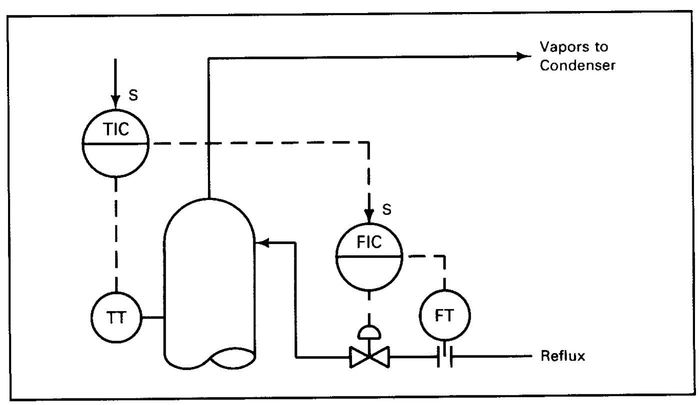


Fig. 7-3. Flow as the Slave Variable in a Cascade Control Scheme (Distillation Column Reflux).

Tuning of Cascade Controllers

Slave Temperature Loop

➢ Difficulties with using temperature as slave variable:

☞ Sensor lag

☞ Possibility of reset windup

➢ Use derivative mode to compensate for sensor lag:

☞ Derivative time equal to sensor time constant

☞ Derivative unit act on measured variable to prevent connection of two D units in series

Tuning of Cascade Controllers
Slave Temperature Loop: Example
CC Control on Jacketed Chemical Reactor

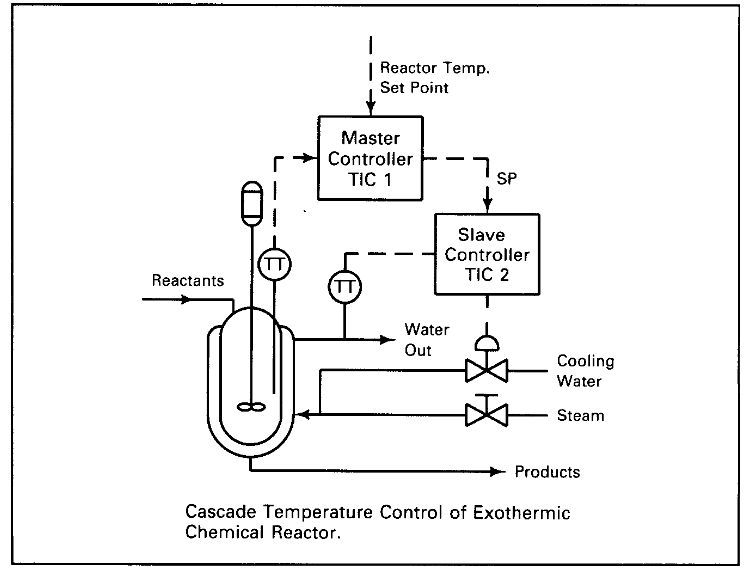


Fig. 7-1. Cascade Temperature Control on a Jacketed Exothermic Chemical Reactor.

➢ If TIC1 cascades FIC:
cooling flow could compensate only for variations in coolant header pressure

➢ If TIC1 cascades TIC2:

- ☞ Temperature could compensate for changes in both coolant header pressure and temperature
- ☞ It closes a loop around the jacket
  $\Rightarrow$ reducing effective time constant
  $\Rightarrow$ making reactor temperature control loop more controllable

Tuning of Cascade Controllers
Slave Pressure Loop

➢ Pressure can be measured easily, fast, and reliably
⇒ a good slave variable

➢ TIC cascades PIC:
pressure controls steam condensing temperature

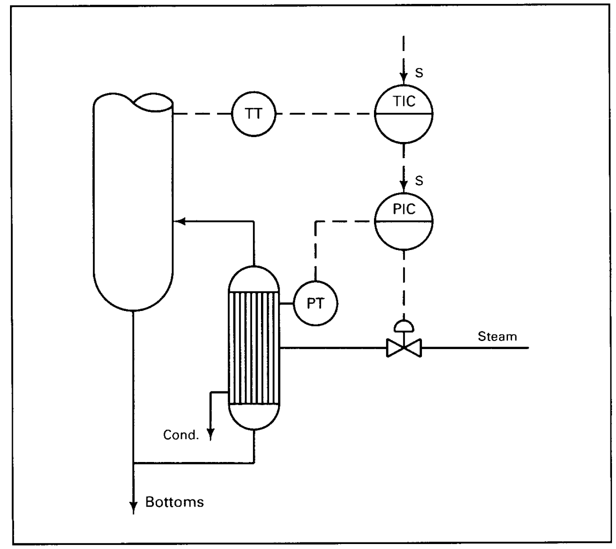


Fig. 7-4. Pressure as the Slave Variable in a Cascade Control Scheme (Distillation Column Reboiler).

➢ Pressure might move out of transmitter range and get out of control

Computer Cascade Control

➢ Inner loop is usually processed at a higher frequency
slave controller has time to respond to a setpoint change from master controller before next change takes place

➢ Bumpless (smooth) transfer from manual to automatic:

☞ Initializing master controller output to measured slave variable when switch from M to A

Control of H_2/N_2 Ratio in Ammonia Synthesis

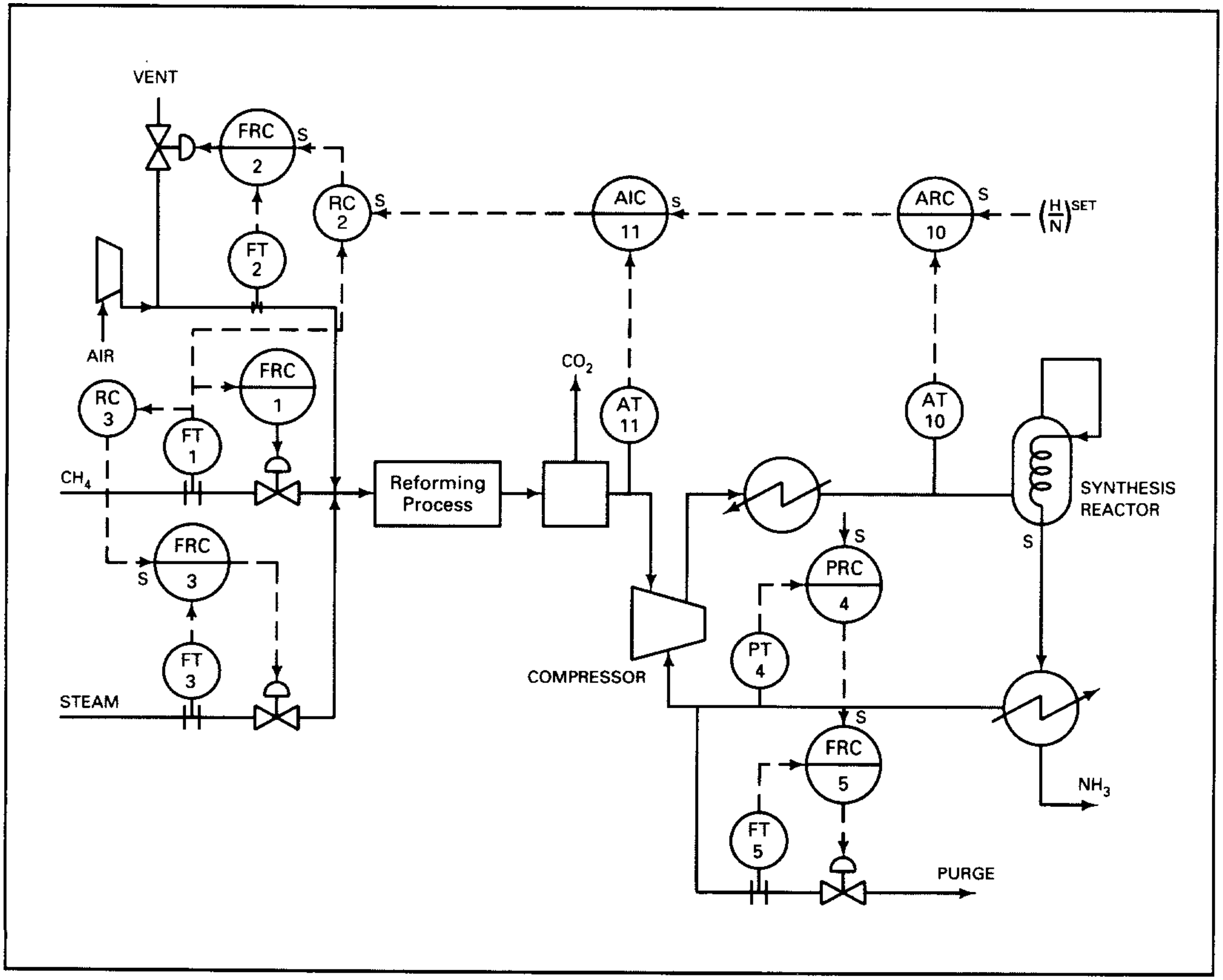


Fig. 7-5. Cascade Control of Reactor Inlet Composition and Pressure in the Ammonia Synthesis Loop.

Control of H_2/N_2 Ratio in Ammonia Synthesis

Process Description

- Air, natural gas (CH_4), steam are mixed in reforming furnace ($CH_4 + 2H_2O \longrightarrow CO_2 + 4H_2$)
- Removing CO_2, feeding mixture of H_2 and N_2 to synthesis loop compressor
- $\sim 15\%$ of H_2 and N_2 mixture is converted to NH_3
  $\Rightarrow$ flow of synthesis loop is about six to seven times the flow of fresh feed
- High recycle-to-fresh ratio
  $\Rightarrow$ long time constant for synthesis loop (short for reforming)

Control of H_2/N_2 Ratio in Ammonia Synthesis

Control Algorithm

- **Control objective:**
  to keep H/N ratio at its optimal value ($\sim$ 2.85)
- Master controller (ARC10) receives composition at reactor inlet from an accurate analyzer AT10
- ARC10 *adjusts set point* on slave controller AIC11
- AIC11 receives composition of fresh feed from a fast and inexpensive analyzer AT11
  (say, thermal conductivity detector)
- AIC11 adjusts ratio of air to natural gas
- Ratio controller (RC2) adjusts setpoint of air flow controller (FRC2)
- Pressure controller (PRC4) *cascade* purge flow controller (FRC5) to eliminate accumulation of inert gases and excess nitrogen

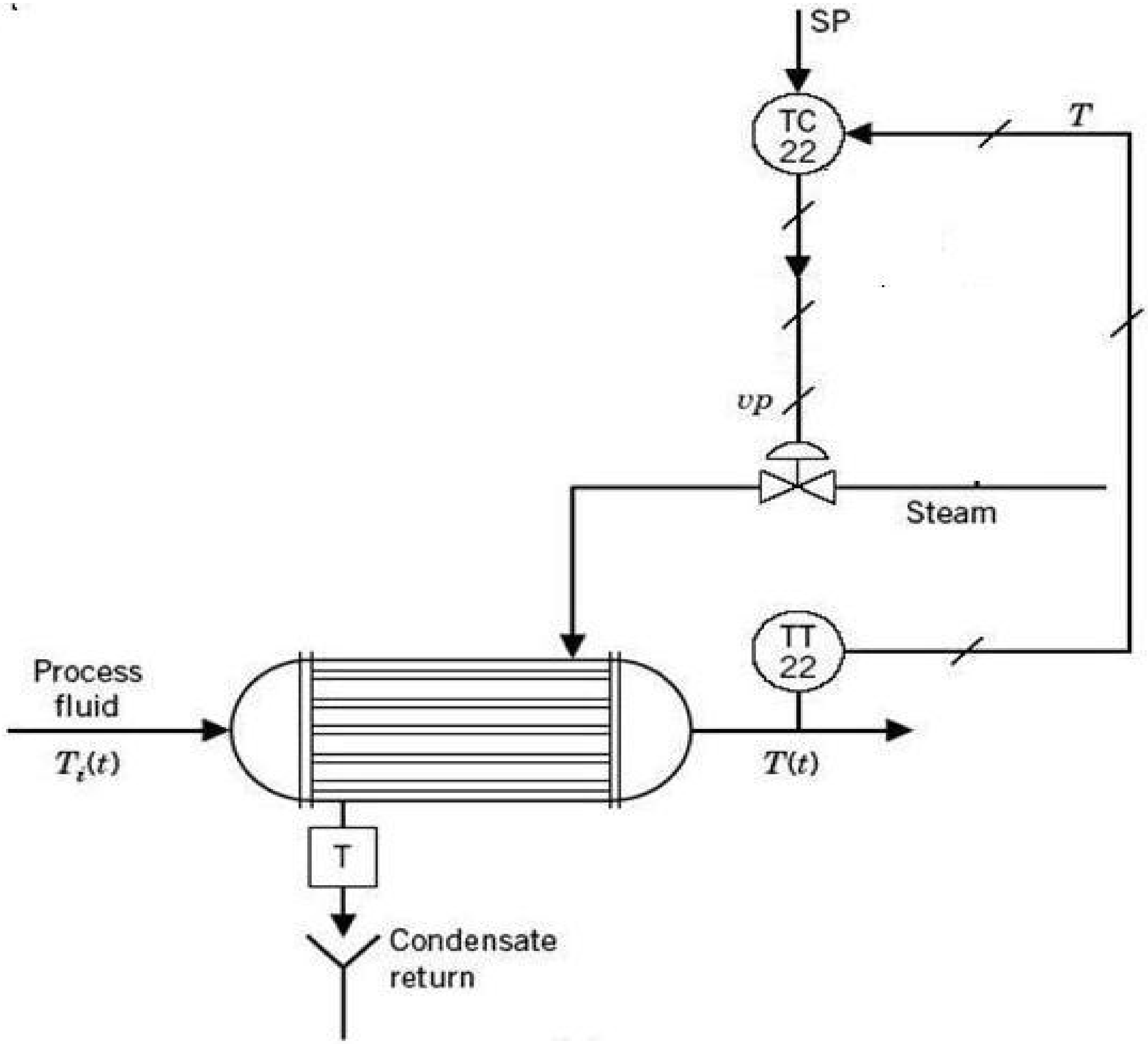
Control of H_2/N_2 Ratio in Ammonia Synthesis

Remarks

- Slave measurement need not be accurate but must be fast
- Errors in slave measurement are corrected by integral mode of master controller
- Measurement of master controller can be slow but must be accurate
- Disturbances in reforming process are handled quickly by slave controller before they have a chance to affect the primary controlled variable
- Analog pressure controller:
  - Large process time constant (one hour)
    $\Rightarrow$ Swinging purge flow all over its range
    $\Rightarrow$ Operate on manual !
- Digital pressure controller:
  5 min sampling time, 45 min integral time is able to maintain pressure at its optimum setpoint

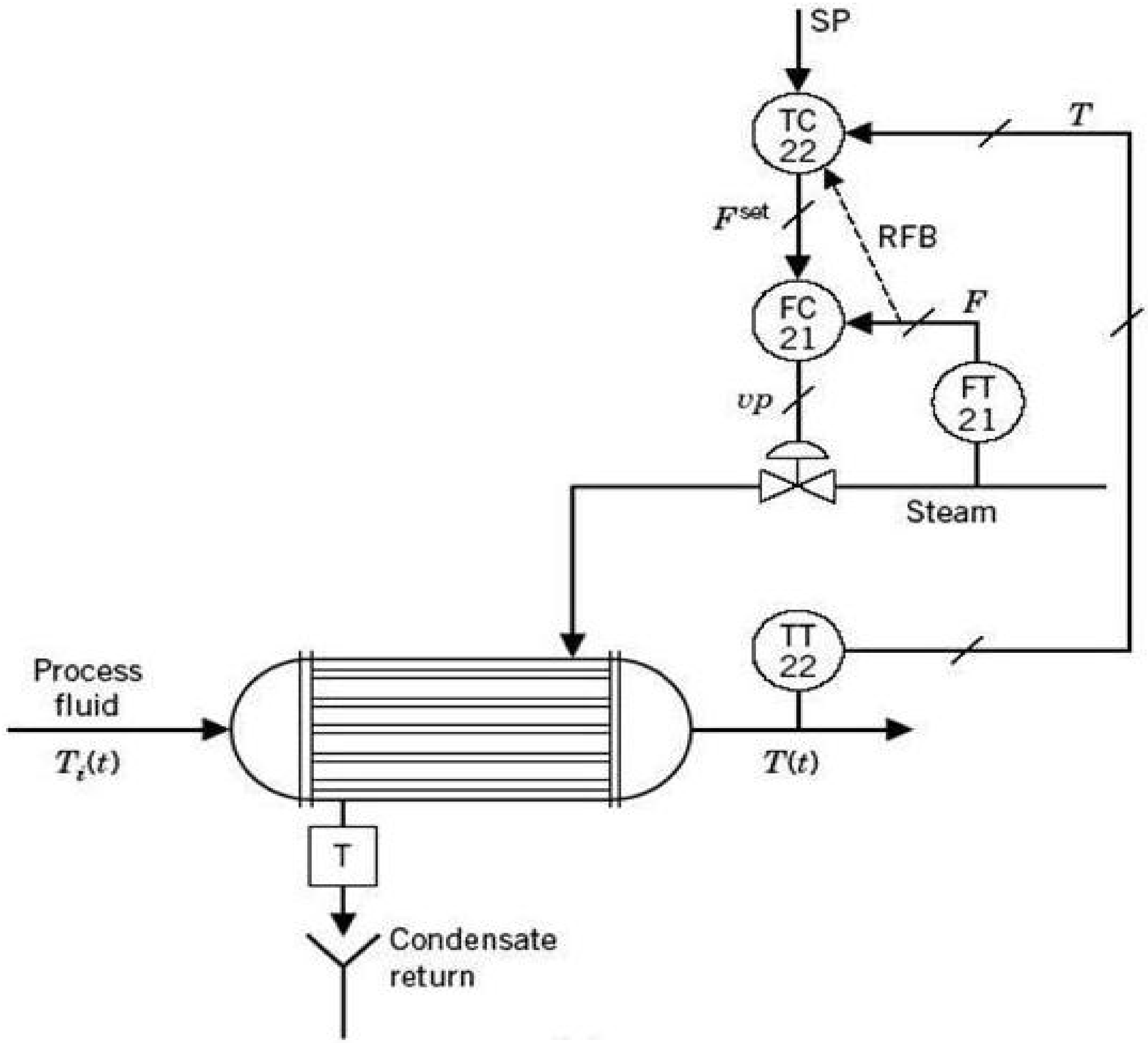
Example: A Heat Exchanger

Simple Feedback Control



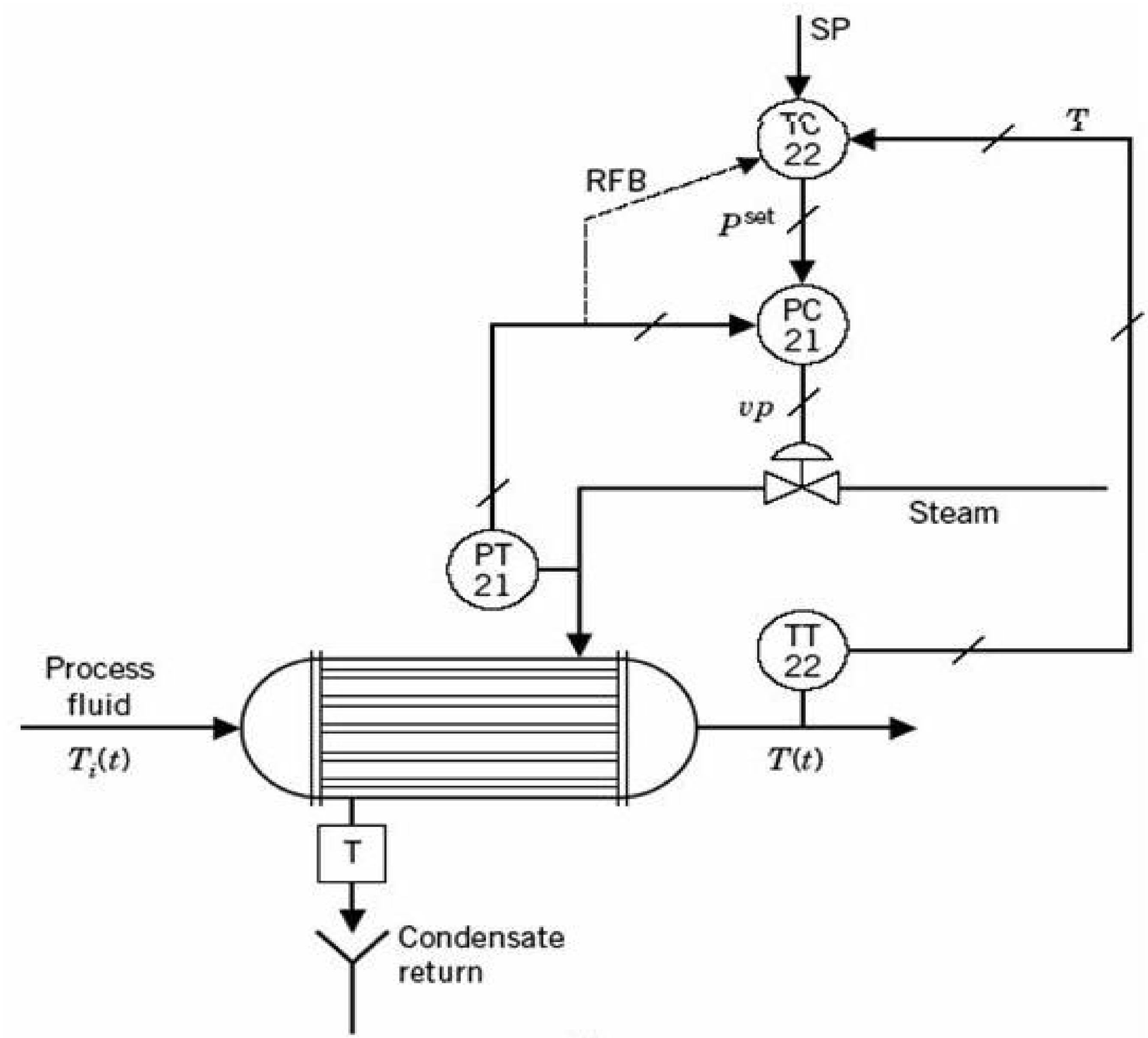
Example: A Heat Exchanger

Cascade Control (I)



Example: A Heat Exchanger

Cascade Control (II)



Example: A Jacketed Reactor
Cascade Temperature Control

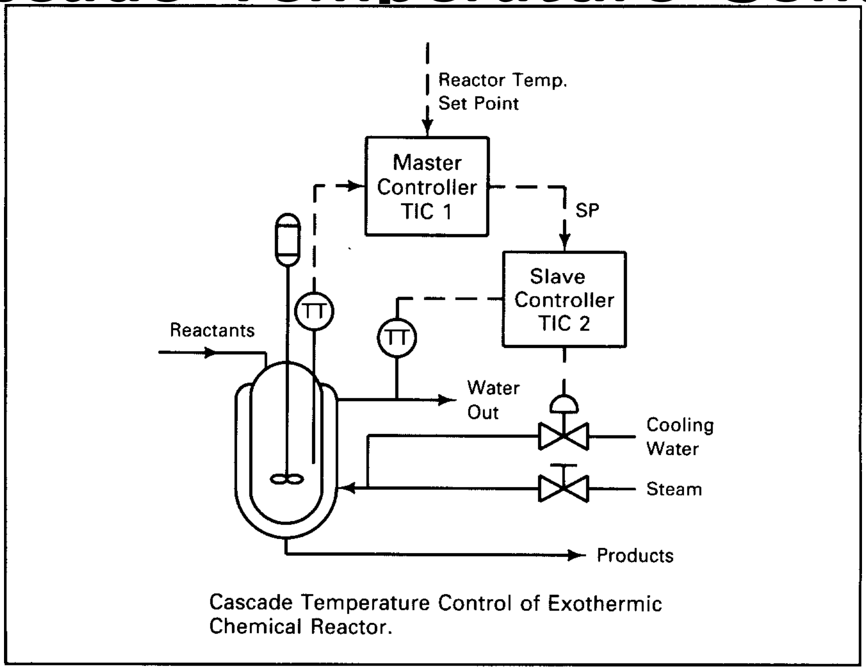


Fig. 7-1. Cascade Temperature Control on a Jacketed Exothermic Chemical Reactor.

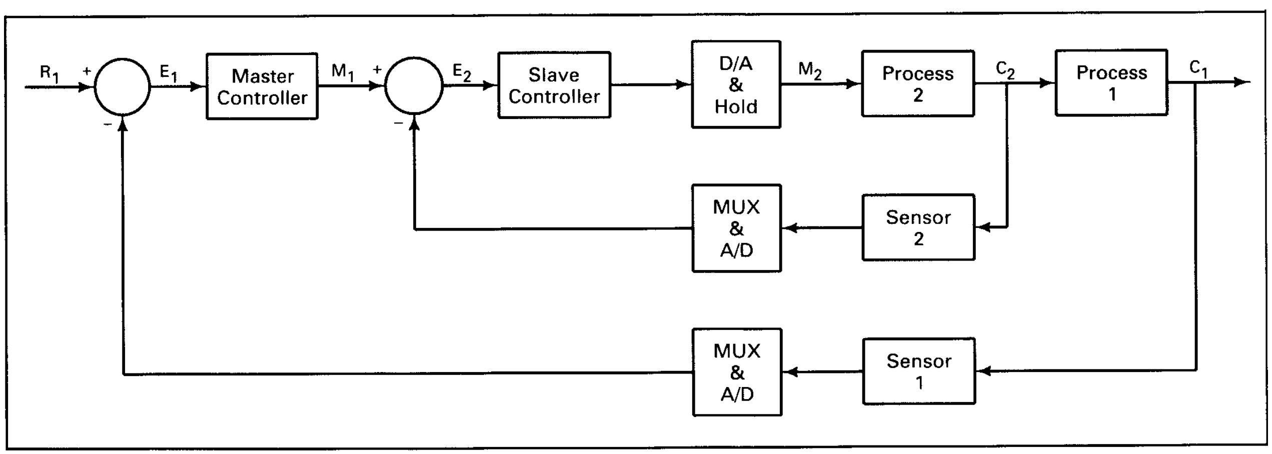


Fig. 7-2. Block Diagram of Cascade Control System.

Example: Multilevel Cascade Control

Four Level Cascade Control for A Distillation Tower

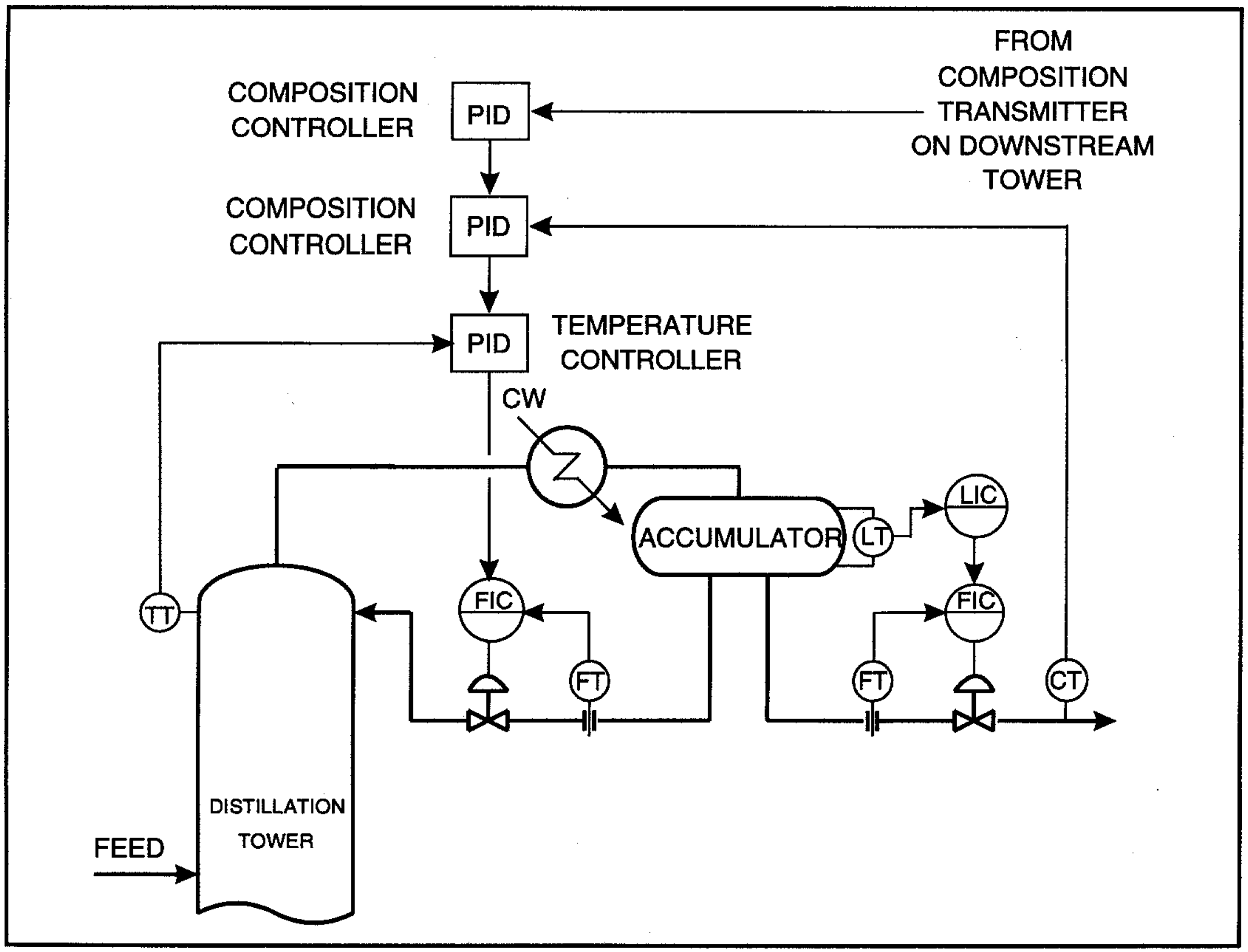


Figure 12-6: Example of Multilevel Cascade Control.

Example: A Heater

- Simple **Feedback**:

  changes in fuel-gas header pressure (load disturbance)

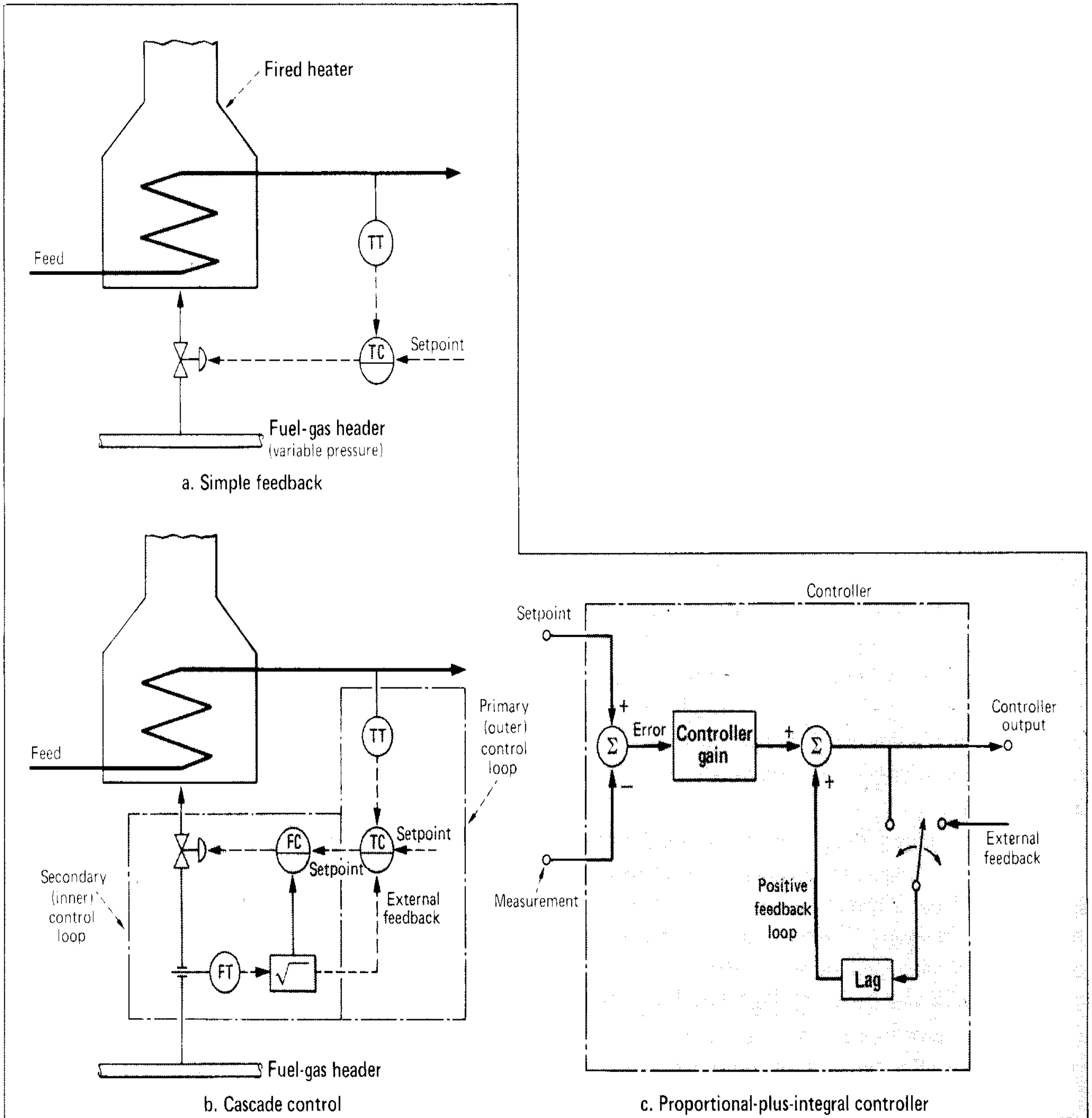
  $\Rightarrow$ change in fuel-gas flow $\Rightarrow$ temperature upset

- **Cascade** Control:

  - ☞ Load disturbances is eliminated by an additional measurement for fuel-gas flow and a fuel-gas FC
  - ☞ TC manipulates setpoint of the fuel-gas FC

- Why external reset feedback ?

  - ☞ If inner FC is placed in manual
    $\Rightarrow$ TC could no longer manipulate fuel-gas flow
    $\Rightarrow$ sustained error in TC
    $\Rightarrow$ TC saturated if integral action exists
  - ☞ Integral saturation is prevented by feeding back fuel-gas flow measurement to TC

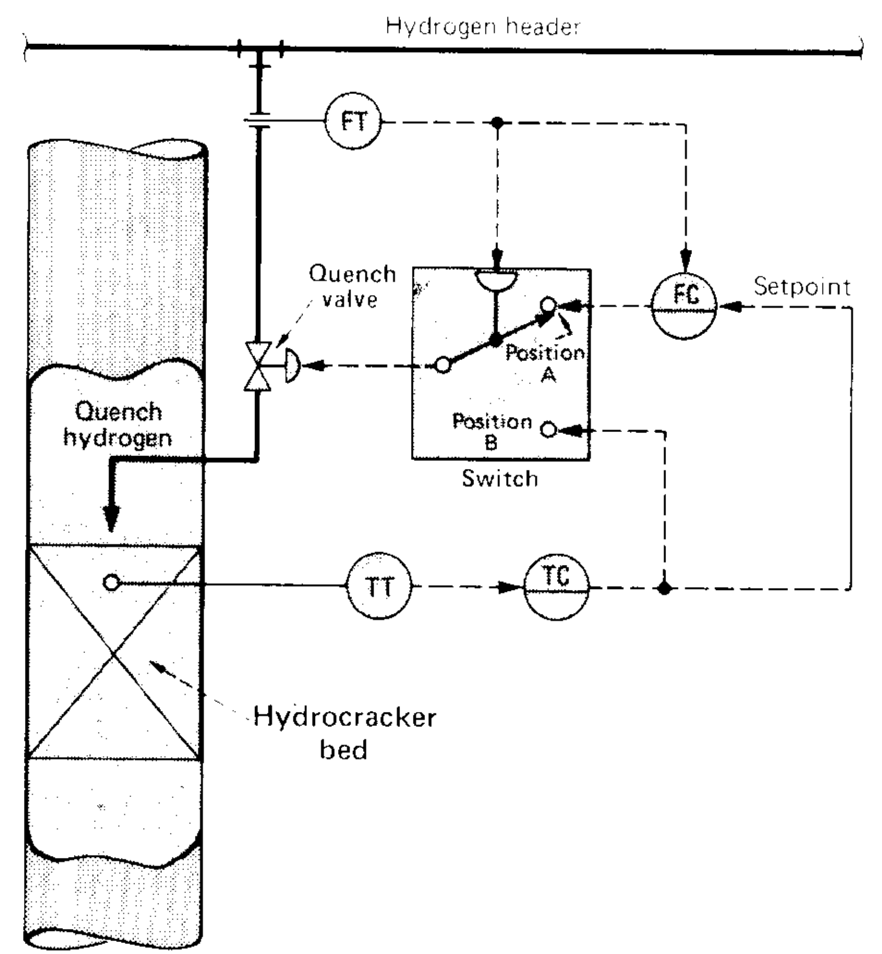


Cascade control for temperature improves performance of heater **Fig. 3**

Example: Switching Scheme on A CC Loop

Switching Between Cascade and Single Loops

- Maintaining hydrogen-bed inlet temperature by manipulating hydrogen quench-valve position
- Valves are connected to a hydrogen header
  $\Rightarrow$ manipulation of one hydrogen valve will influence all other hydrogen flows
  $\Rightarrow$ Cascade Control
- Useful turndown of flow transmitter is limited
  $\Rightarrow$ bypass FC at low hydrogen flows
- When FC is bypassed, it must track valve position to prevent a bump when being switched back into service
- Use two TC tunings for two conditions



Switch changes loop from cascade to temperature control to accommodate turndown **Fig. 12**