# Chapter 12

# Cascade, Ratio, and Feedforward Control

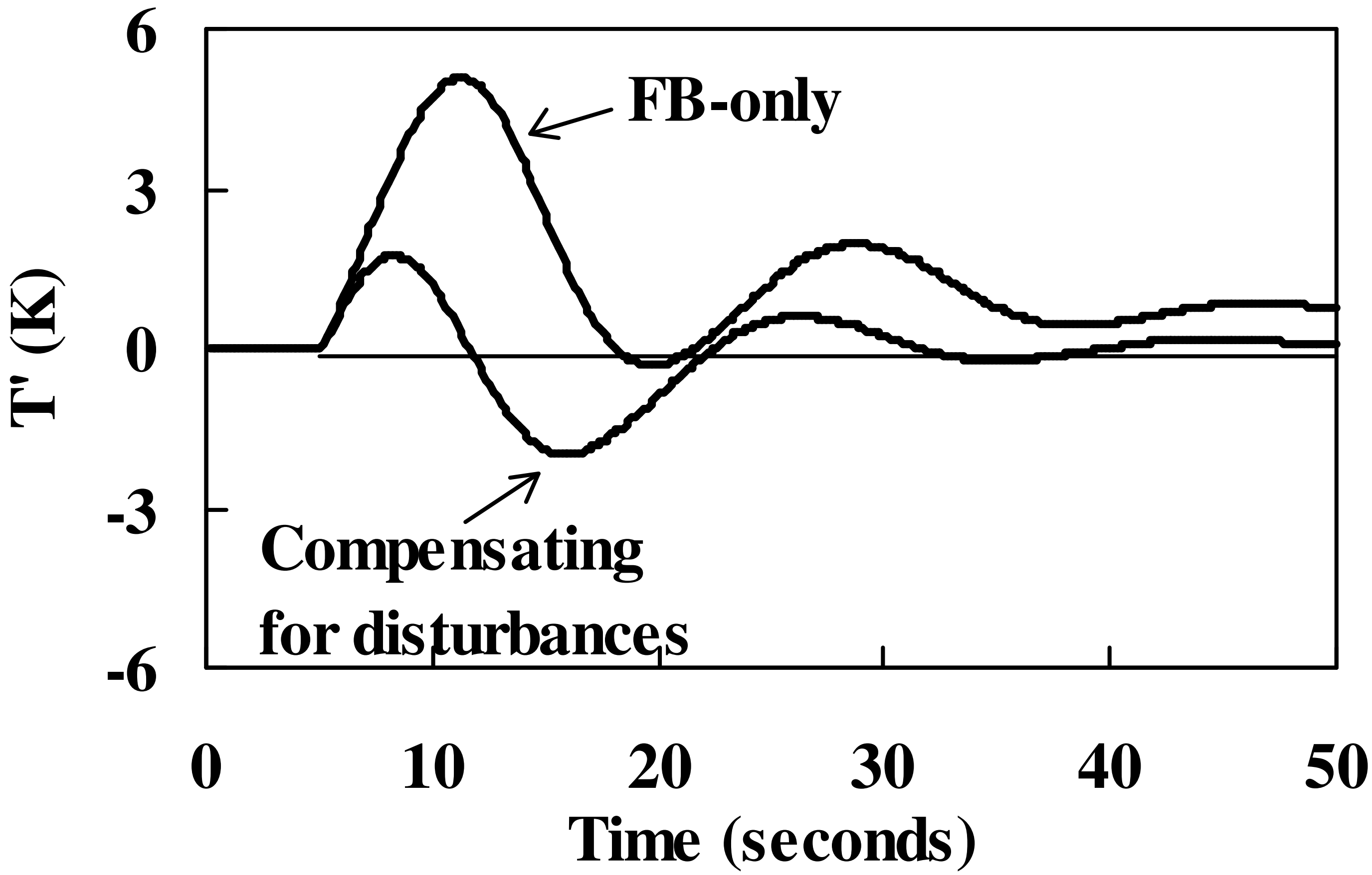
# Overall Course Objectives

- Develop the skills necessary to function as an industrial process control engineer.
  - Skills
    - Tuning loops
    - ***<u>Control loop design</u>***
    - Control loop troubleshooting
    - Command of the terminology
  - Fundamental understanding
    - Process dynamics
    - Feedback control

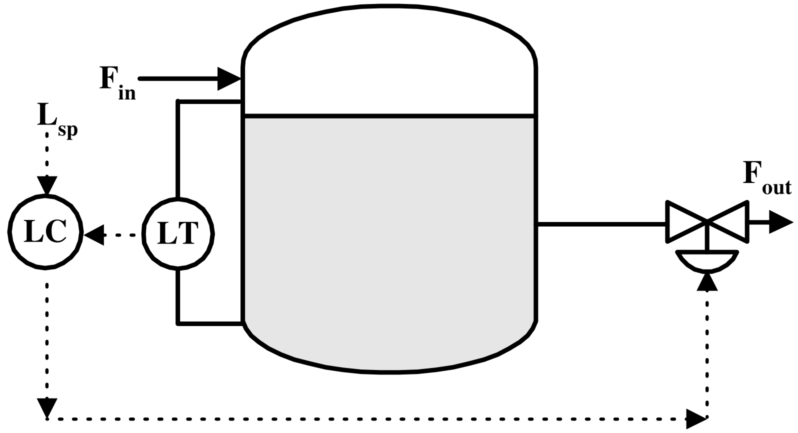
# Cascade, Ratio, and Feedforward Control

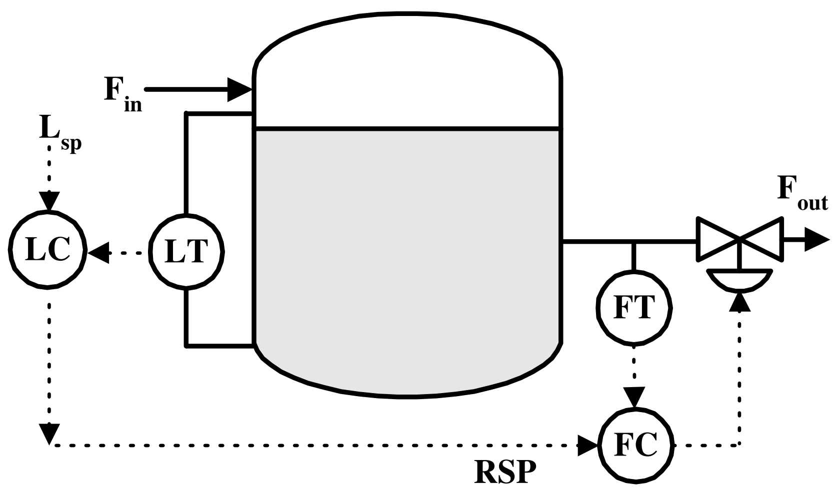
- Each of these techniques offers advantages with respect to **disturbance rejection:**
  - Cascade reduces the effect of specific types of disturbances.
  - Ratio reduces the effect of feed flow rates changes
  - Feedforward control is a general methodology for compensating for measured disturbances.

# Compensating for Disturbances Reduces Deviations from Setpoint and Settling Time



# Level Controller on a Tank With and Without Cascade Control



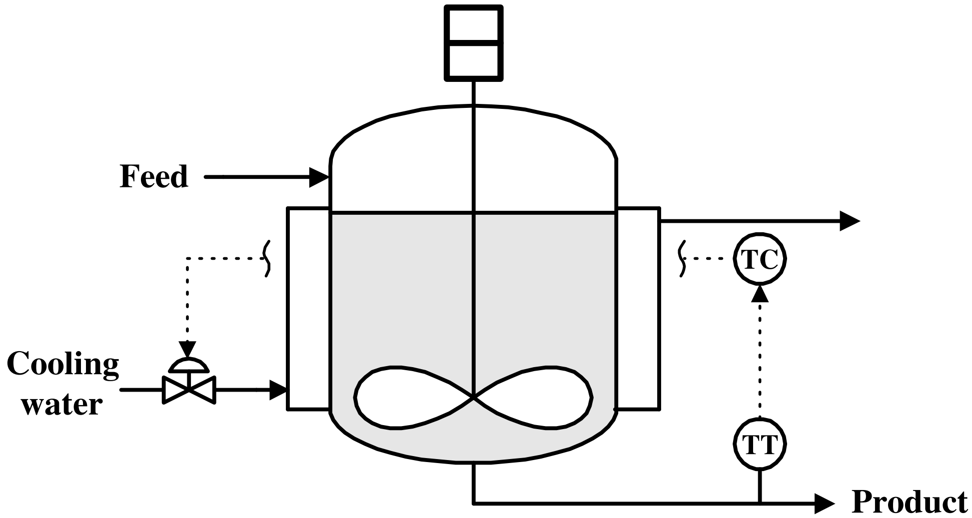
# Analysis of Cascade Example

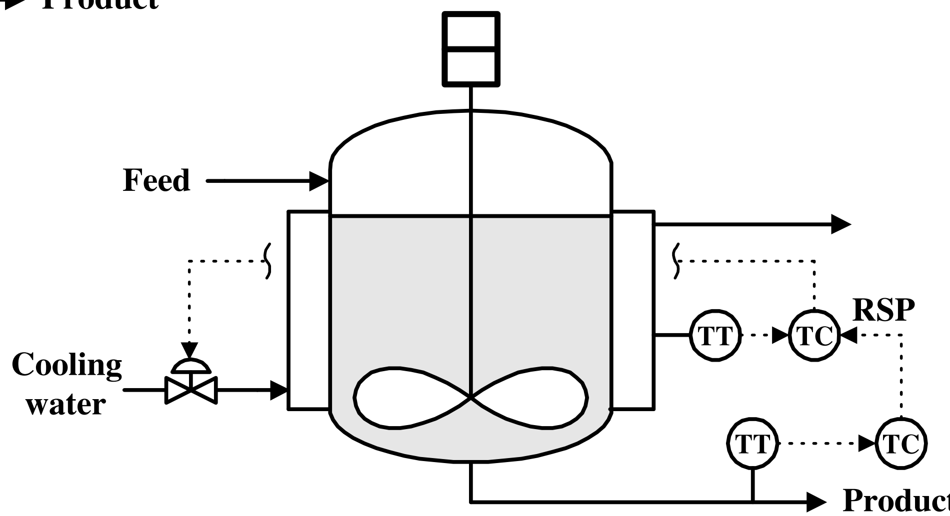
- Without a cascade level controller, changes in downstream pressure will disturb the tank level.
- With cascade level controller, changes in downstream pressure will be absorbed by the flow controller before they can significantly affect tank level because the flow controller responds faster to this disturbance than the tank level process.

# Key Features for Cascade Control to be Successful

- Secondary loop should reduce the effect of one or more disturbances.
- Secondary loop must be at least 3 times faster than master loop.
- The CV for the secondary loop should have a direct effect on the CV for the primary loop.
- The secondary loop should be tuned tightly.

# Cascade Reactor Temperature Control

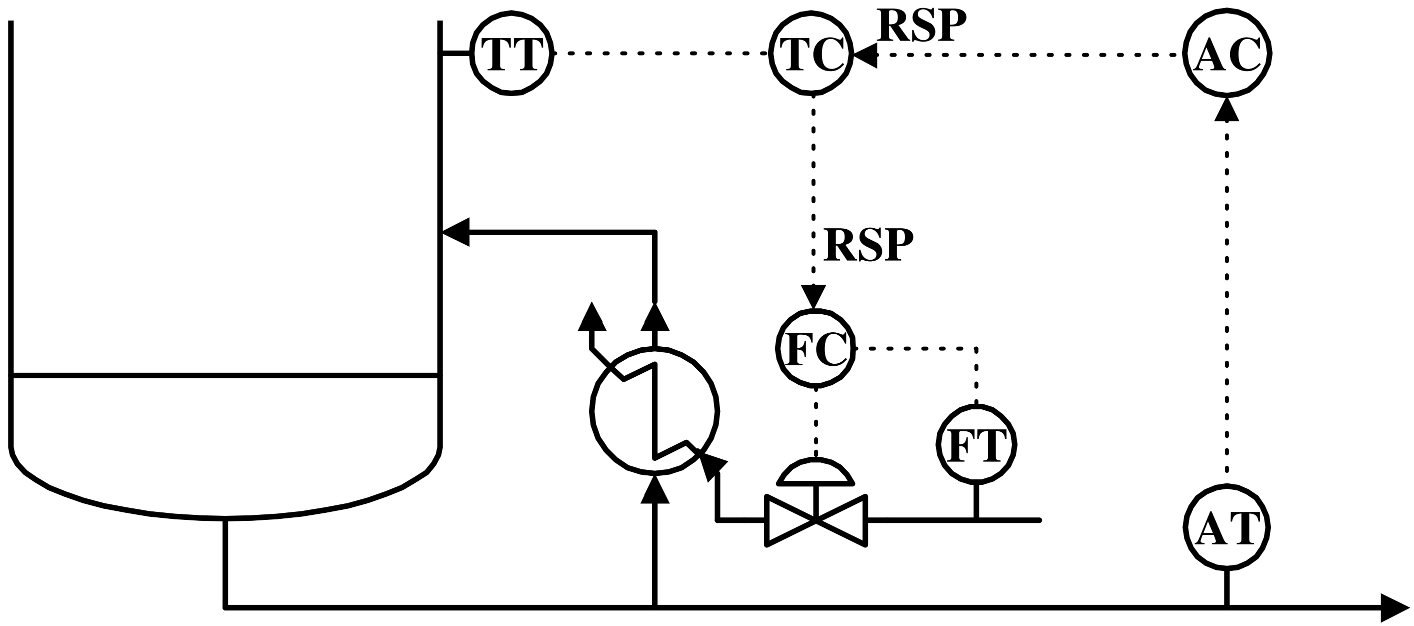


# Analysis of Example

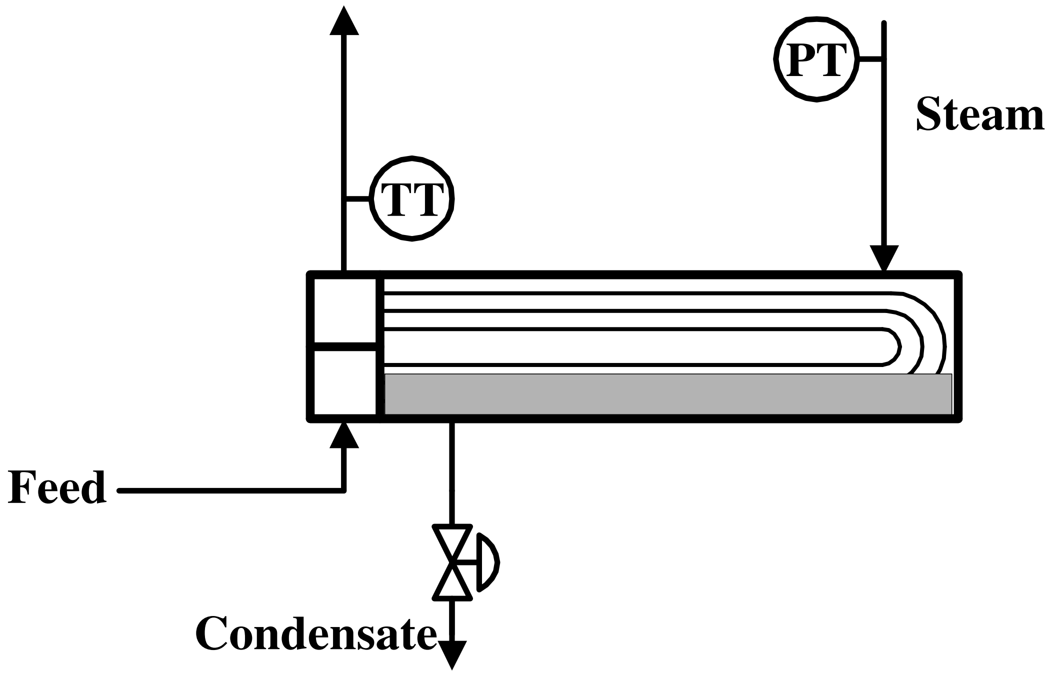
- Without cascade, changes in the cooling water temperature will create a significant upset for the reactor temperature.
- With cascade, changes in the cooling water temperature will be absorbed by the slave loop before they can significantly affect the reactor temperature.

# Multiple Cascade Example



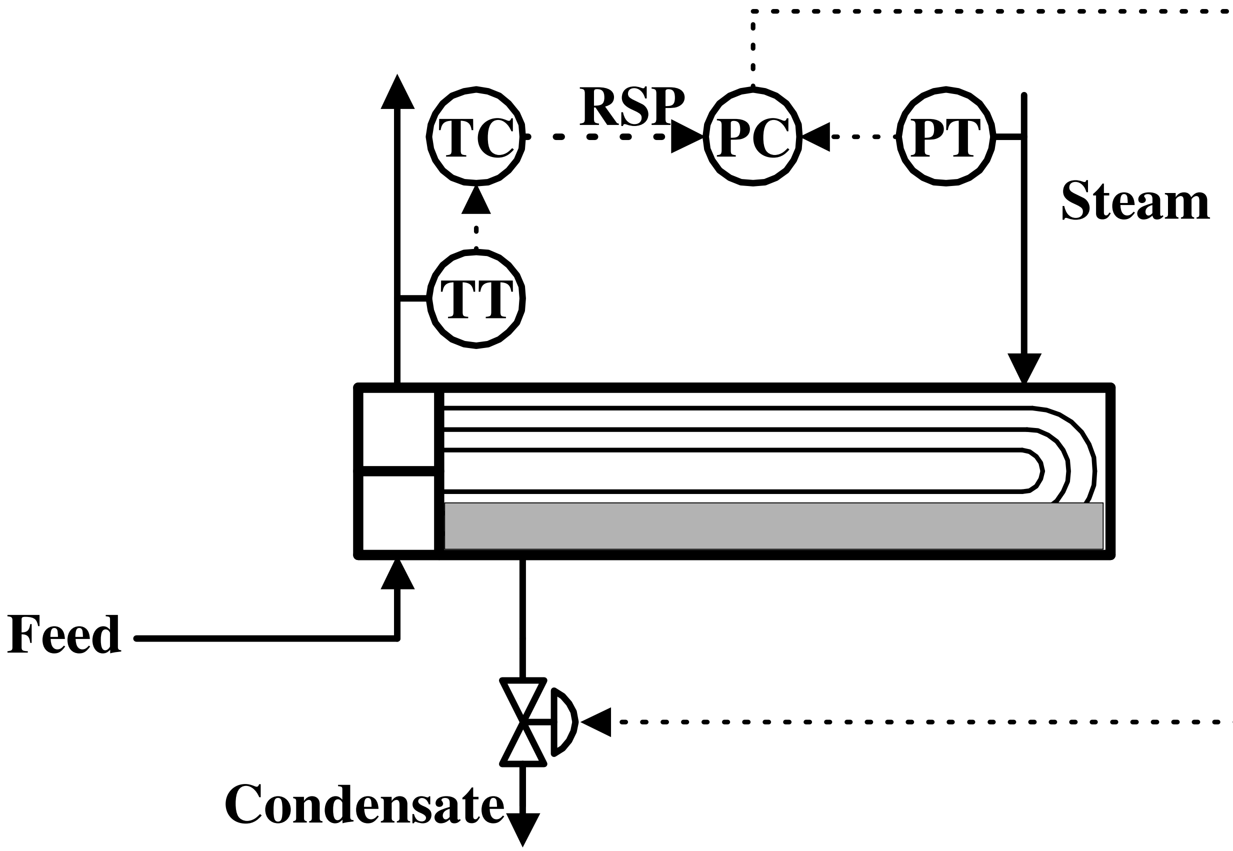

- This approach works because the flow control loop is much faster than the temperature control loop which is much faster than the composition control loop.

# Example




- Draw schematic:  A temperature controller on the outlet stream is cascaded to a pressure controller on the steam which is cascaded to a control valve on the condensate.

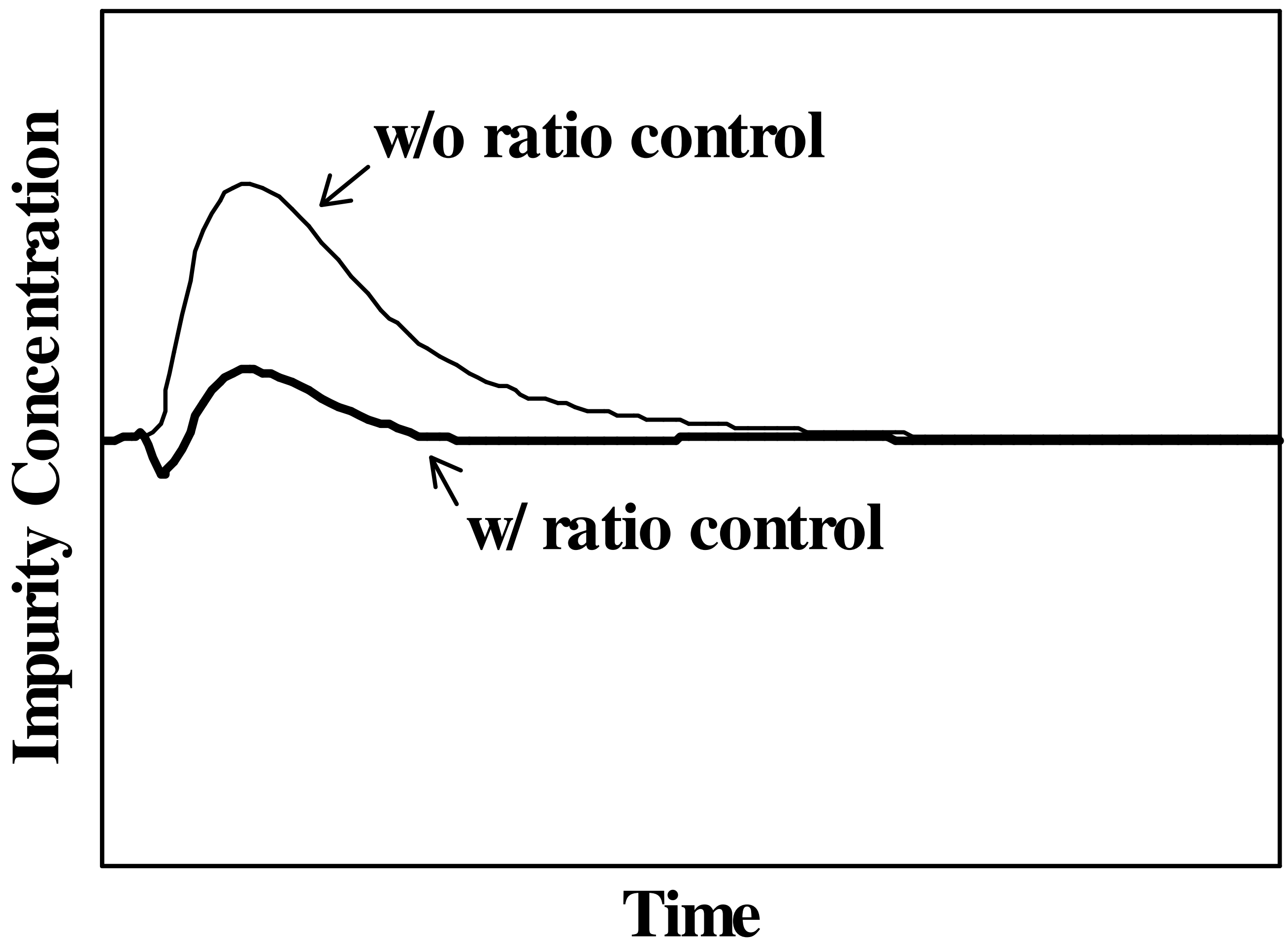
# Solution



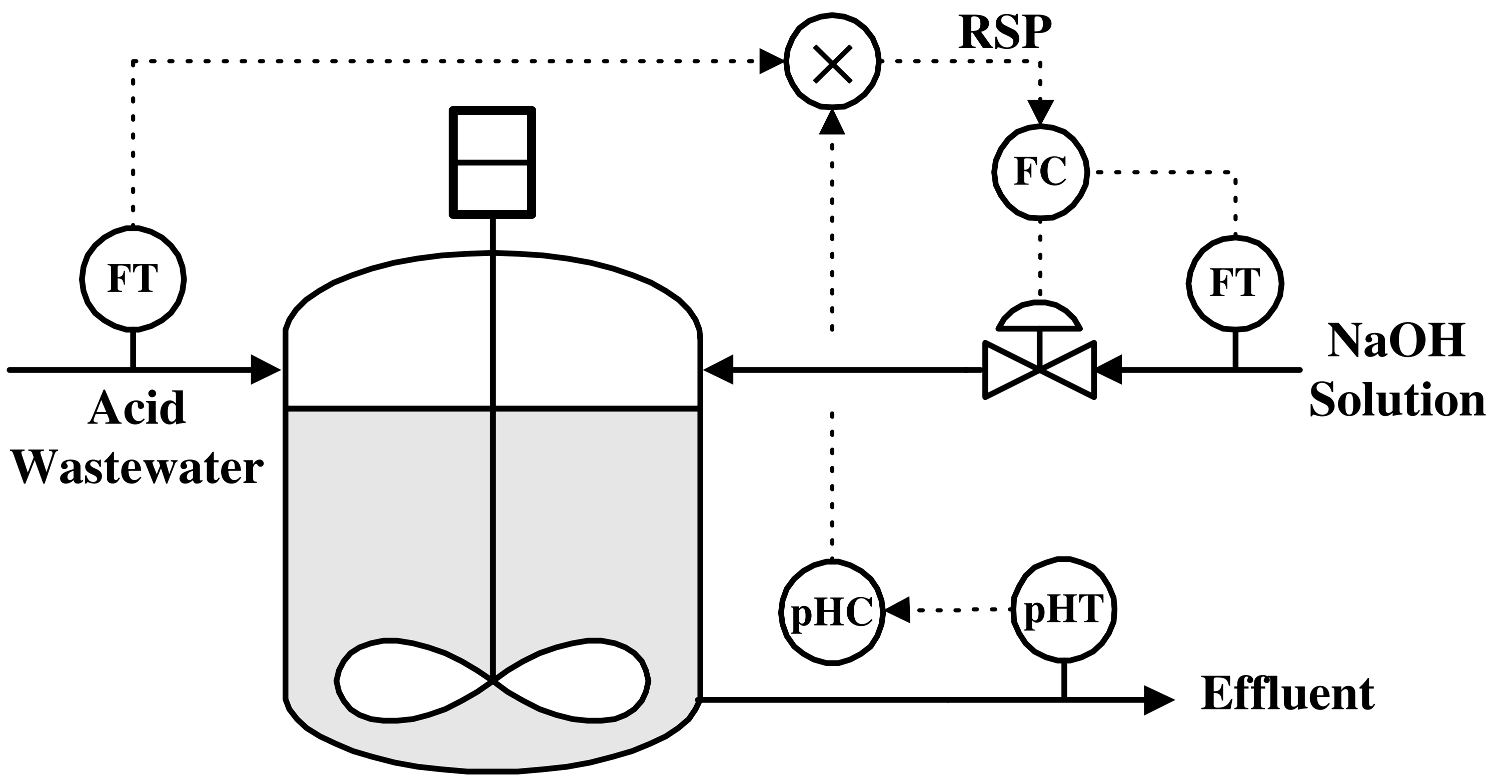
# Ratio Control

- Useful when the manipulated variable scales directly with the feed rate to the process.
- Dynamic compensation is required when the controlled variable responds dynamically different to feed rate changes than it does to a changes in the manipulated variable.

# Typical Performance Improvements using Ratio Control



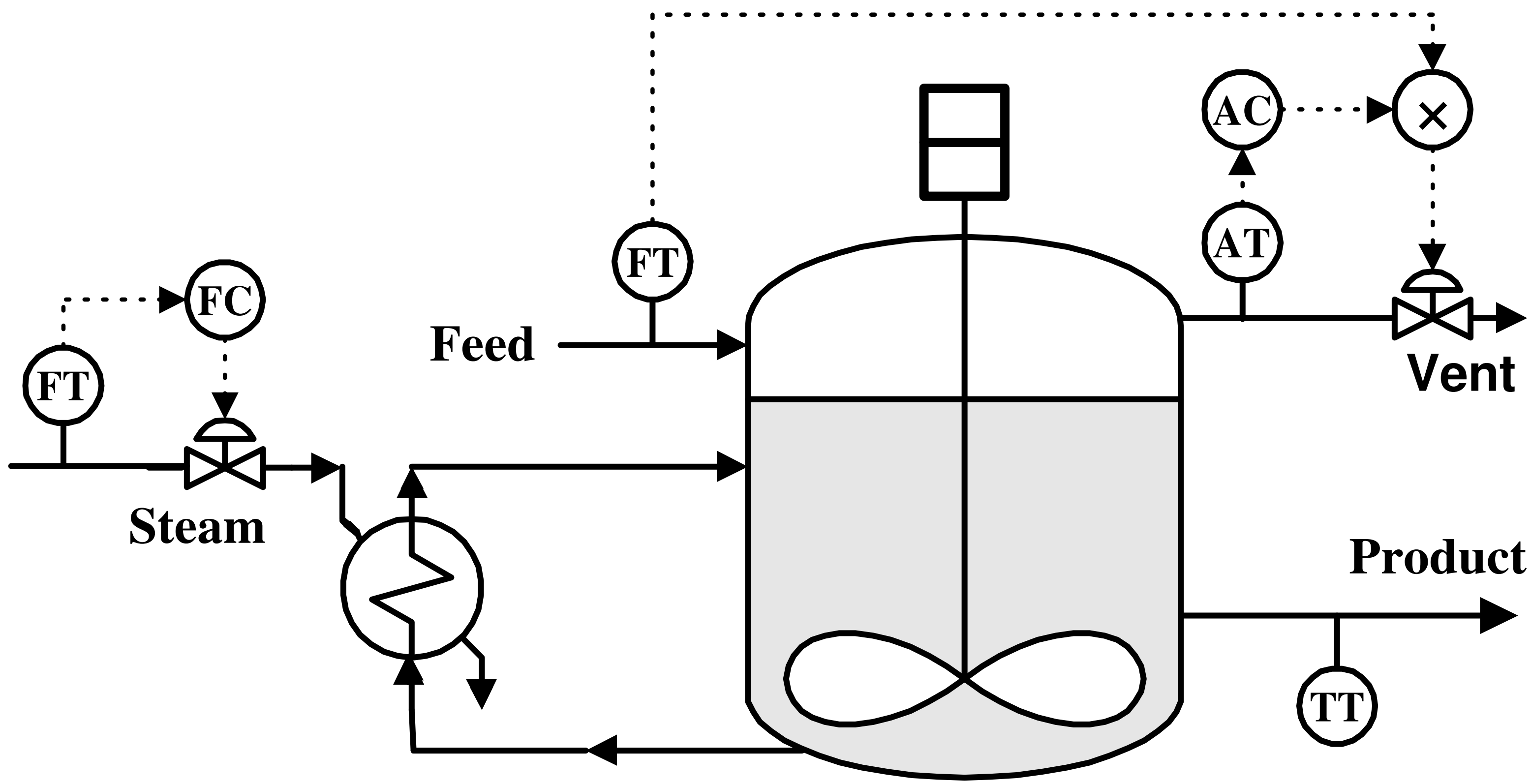
# Ratio Control for Wastewater Neutralization



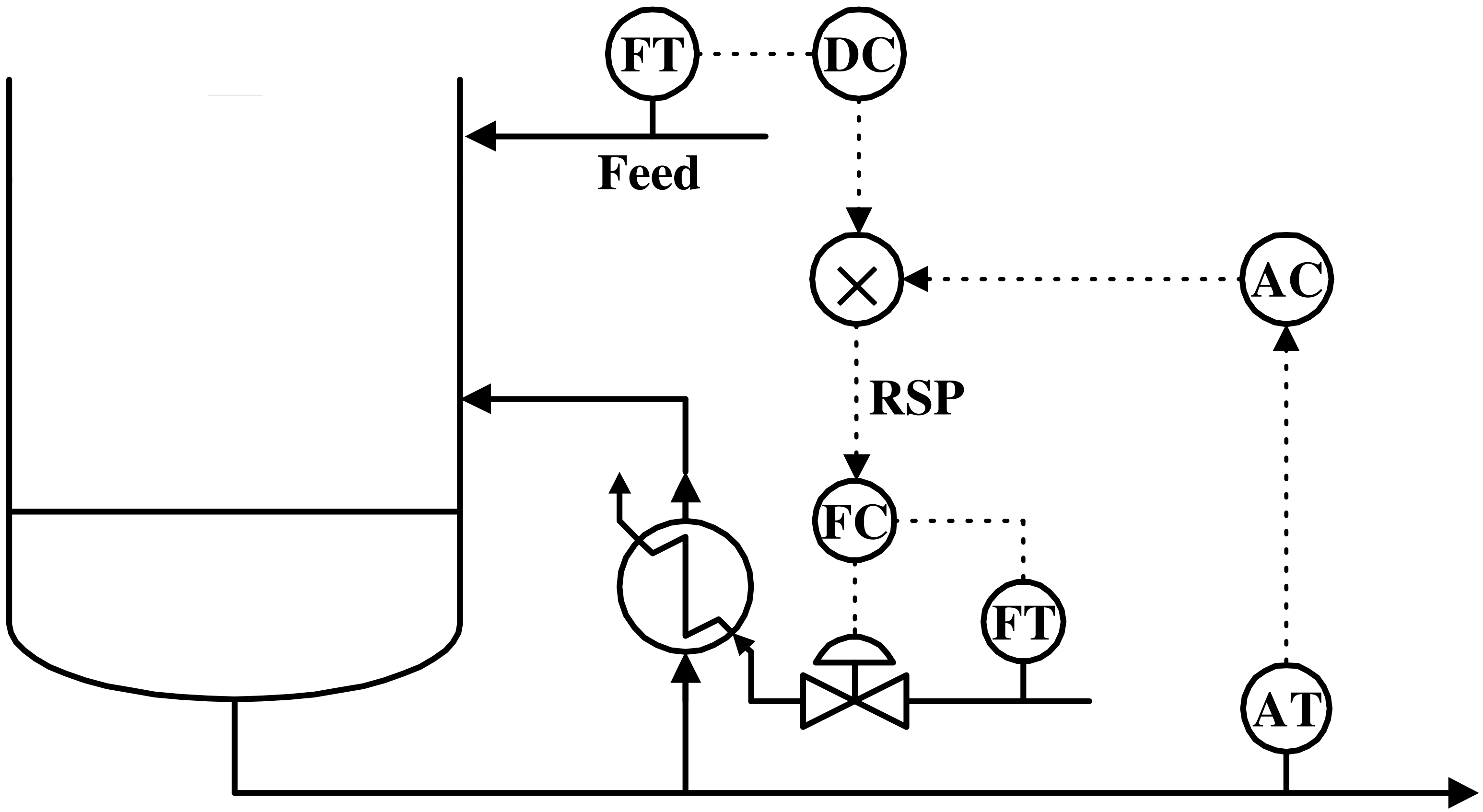
# Analysis of Ratio Control Example

- The flow rate of base scales directly with the flow rate of the acidic wastewater.
- The output of the pH controller is the ratio of NaOH flow rate to acid wastewater flow rate; therefore, the product of the controller output and the measured acid wastewater flow rate become the setpoint for the flow controller on the NaOH addition.

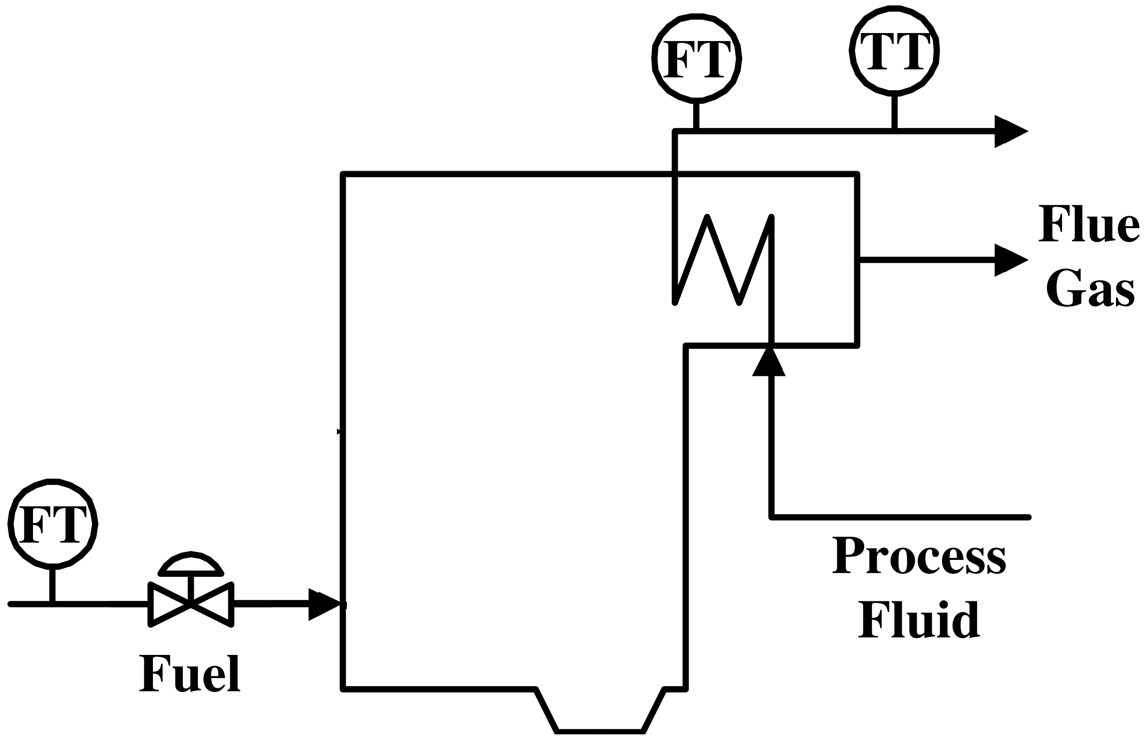
# Ratio Control Applied for Vent Composition Control



# Ratio Control Requiring Dynamic Compensation

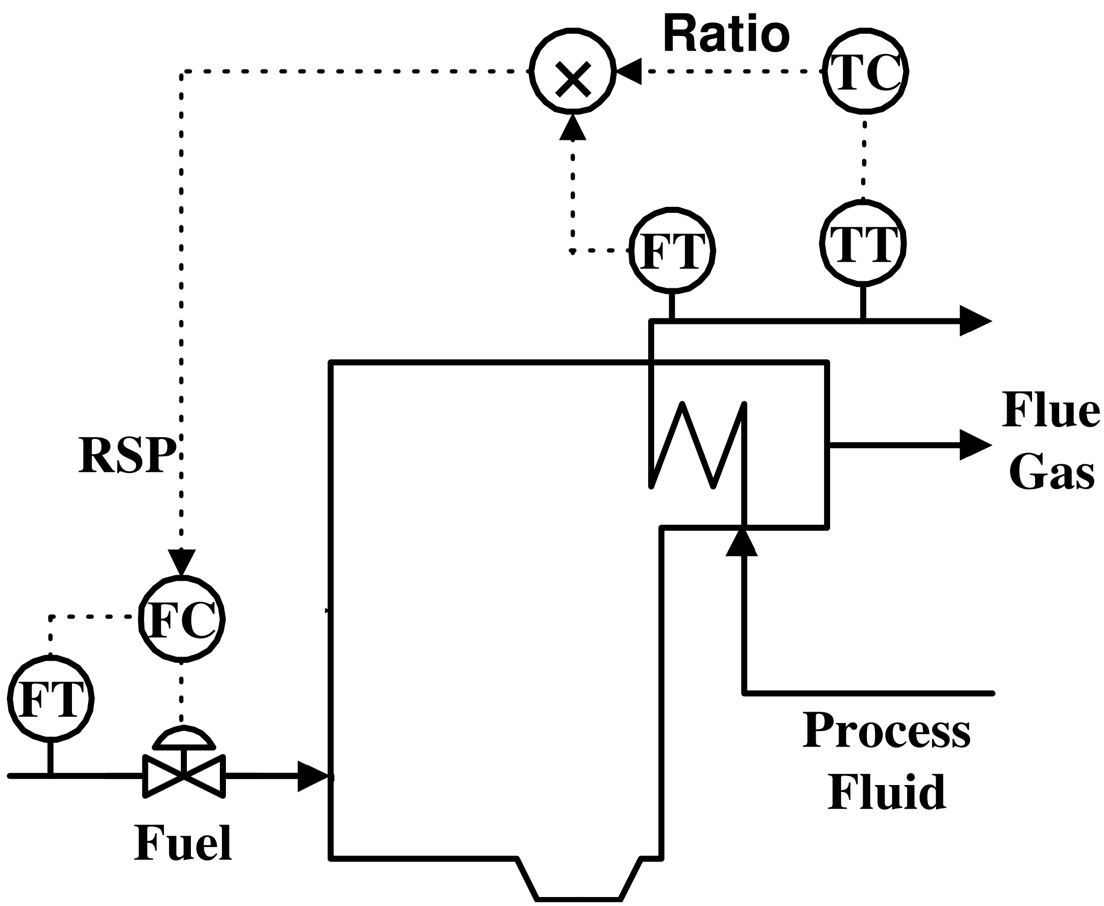


# Example

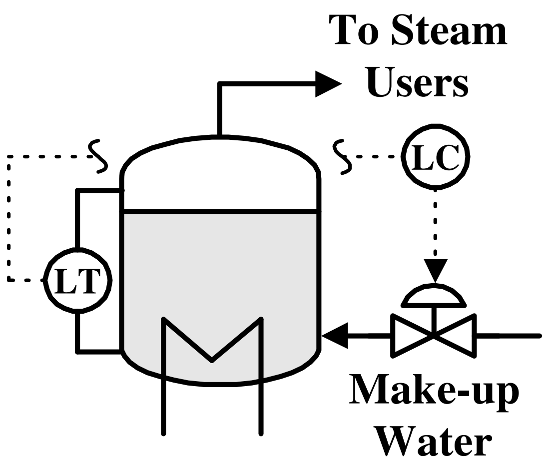


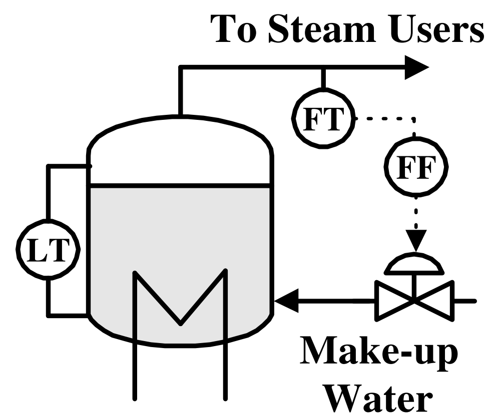

- Draw schematic: For a control system that adjusts the ratio of fuel flow to the flow rate of the process fluid to control the outlet temperature of the process fluid. Use a flow controller on the fuel.

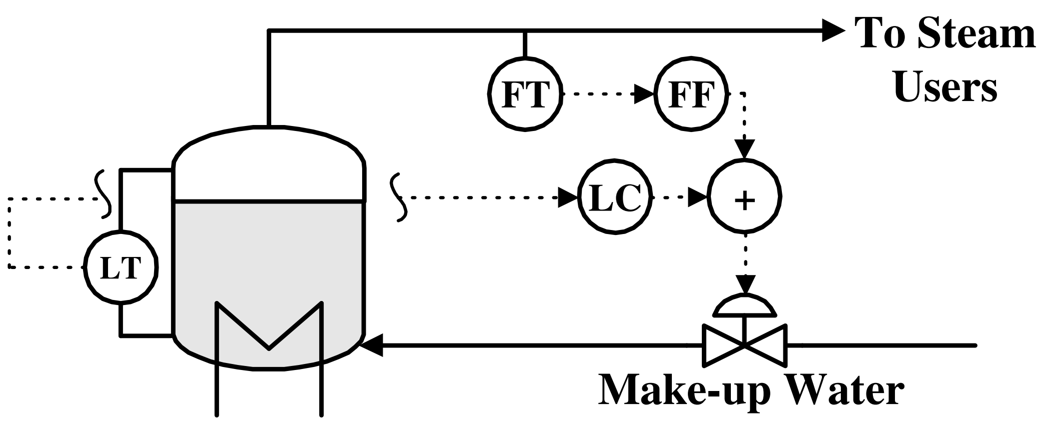
# Solution



# Feedforward and Feedback Level Control



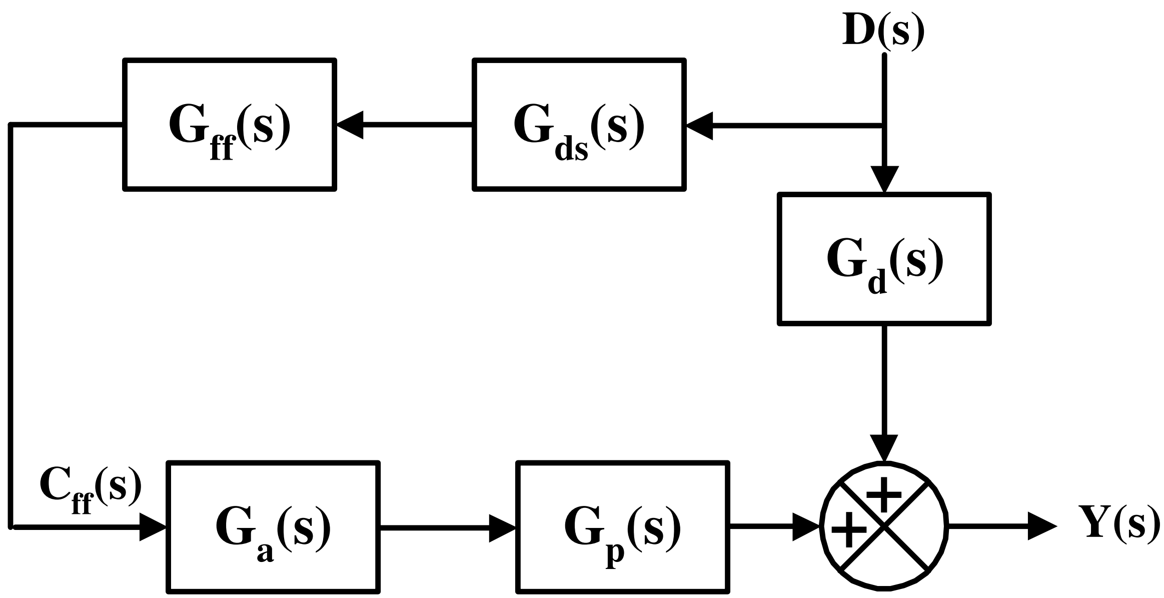



# Analysis of Feedforward and Feedback Level Control

- Feedback-only must absorb the variations in steam usage by feedback action only.
- Feedforward-only handle variation in steam usage but small errors in metering will eventually empty or fill the tank.
- Combined feedforward and feedback has best features of both controllers.

# Derivation of FF Controller




$$Y(s) = D(s)\,G_{ds}(s)\,G_{ff}(s)\,G_a(s)\,G_p(s) + D(s)\,G_d(s) = 0$$

Solving for $G_{ff}(s)$

$$G_{ff}(s) = \frac{-G_d(s)}{G_{ds}(s)\,G_a(s)\,G_p(s)}$$

# Lead/Lag Element for Implementing FF Control

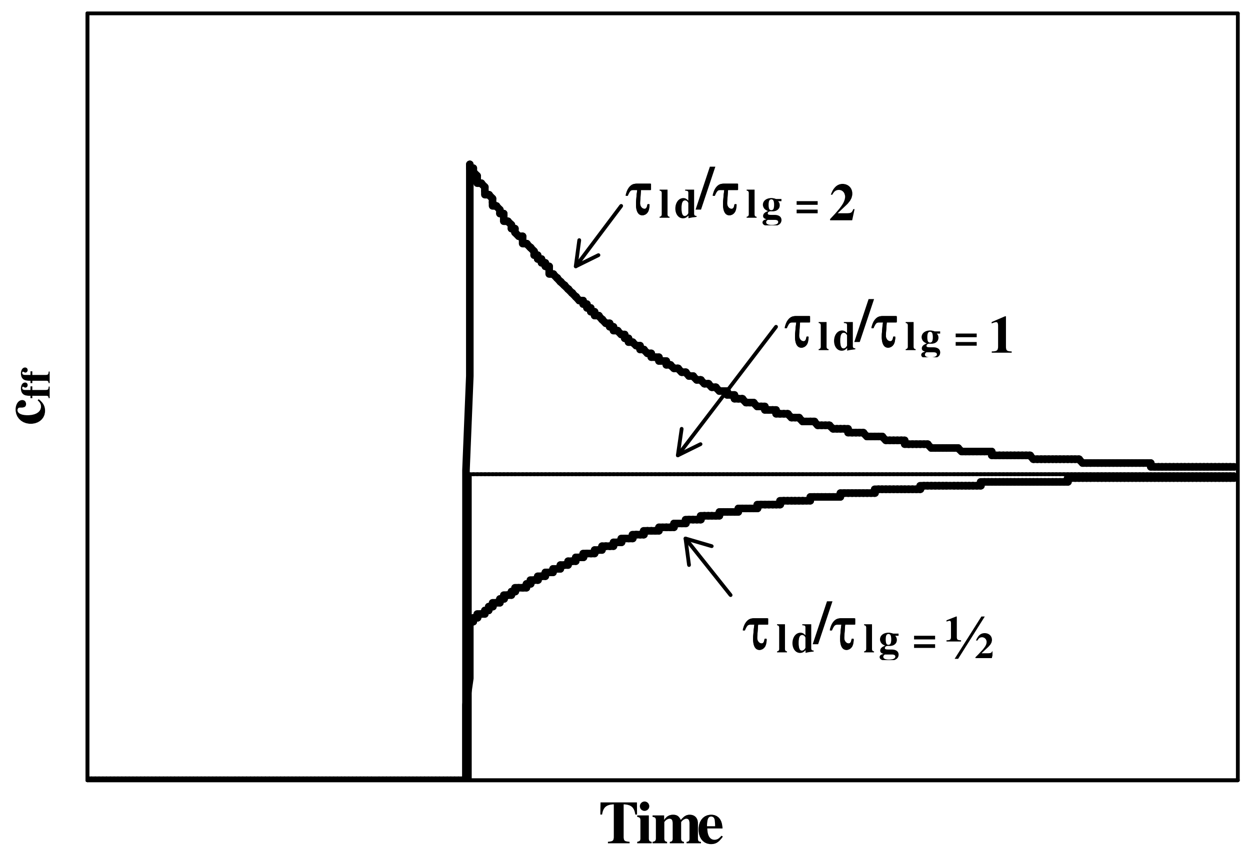
$$G_{ds}(s)\,G_a(s)\,G_p(s) = \frac{K_p\, e^{-\theta_p s}}{\tau_p s + 1}$$

$$G_d(s) = \frac{K_d\, e^{-\theta_d s}}{\tau_d s + 1}$$

$$G_{ff}(s) = -\frac{K_d\,(\tau_p s+1)\,e^{-\theta_d s}}{K_p\,(\tau_d s+1)\,e^{-\theta_p s}} = \frac{K_{ff}\,(\tau_{ld} s+1)\,e^{-\theta_{ff} s}}{(\tau_{\mathrm{lg}} s+1)}$$

Lead/Lag parameters: $K_{ff}\,, \tau_{ld}\,, \tau_{\mathrm{lg}}\,, \theta_{ff}$

# Effect of Lead/Lag Ratio

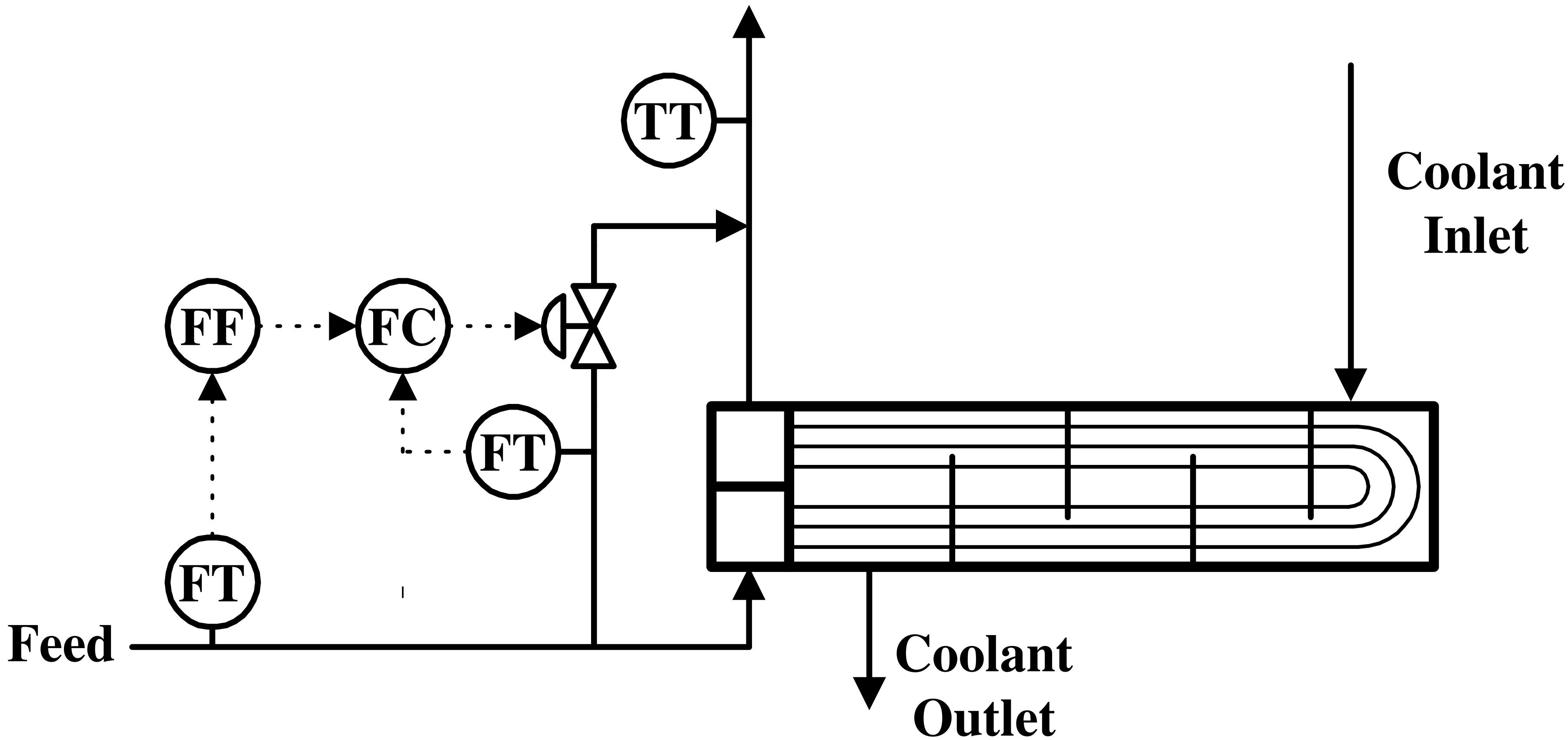


# Static Feedforward Controller

$$G_{ff}(s) = K_{ff}$$

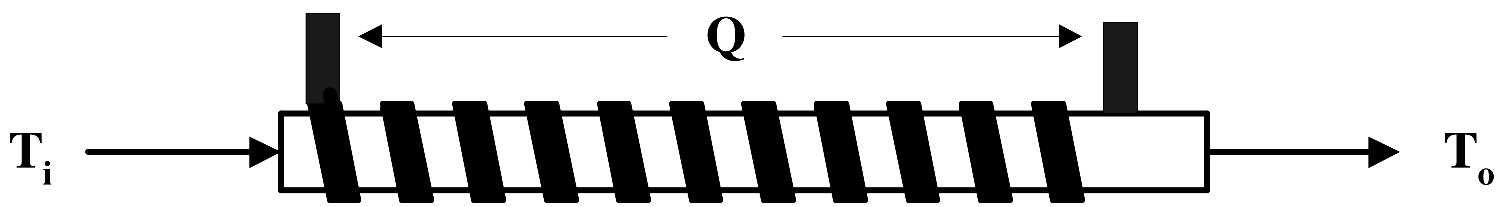
- A static feedforward controller make a correction that is directly proportional to the disturbance change.
- A static feedforward controller is used when the process responds in a similar fashion to a change in the disturbance and the manipulated variable.

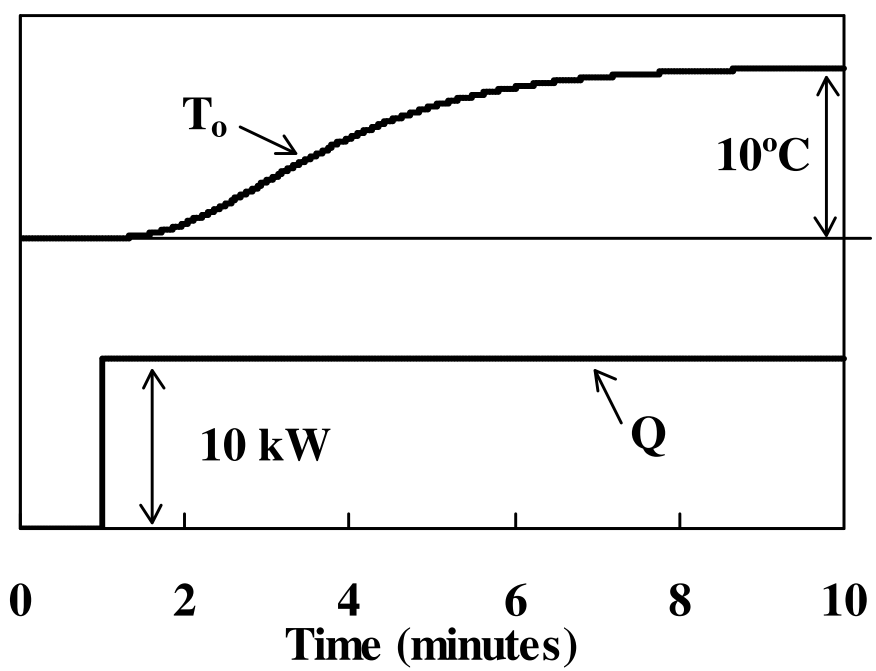
# Feedforward When $\tau_p \ll \tau_d$

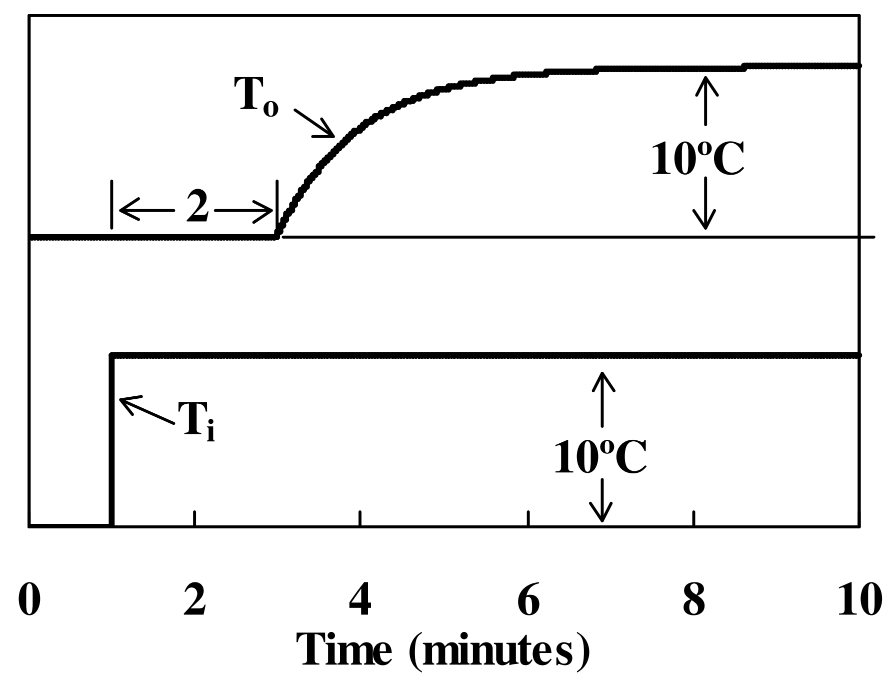



$$G_{ff}(s) = \frac{K_{ff}\, e^{-\theta_{ff} s}}{\tau_{ld} s + 1}$$

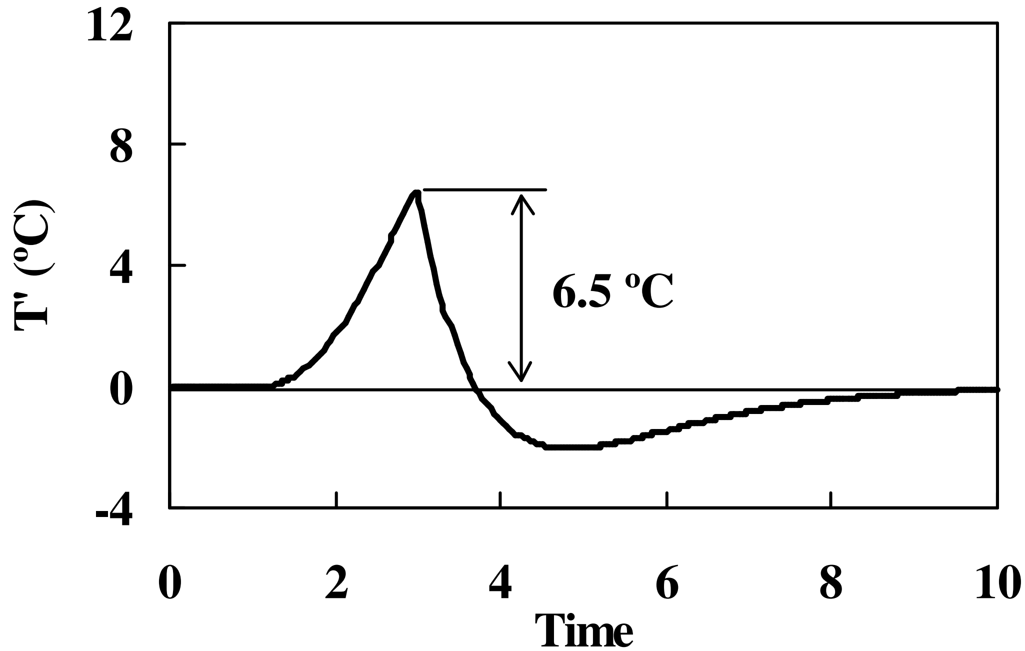
# Example of Feedforward Control for $\tau_d < \tau_p$



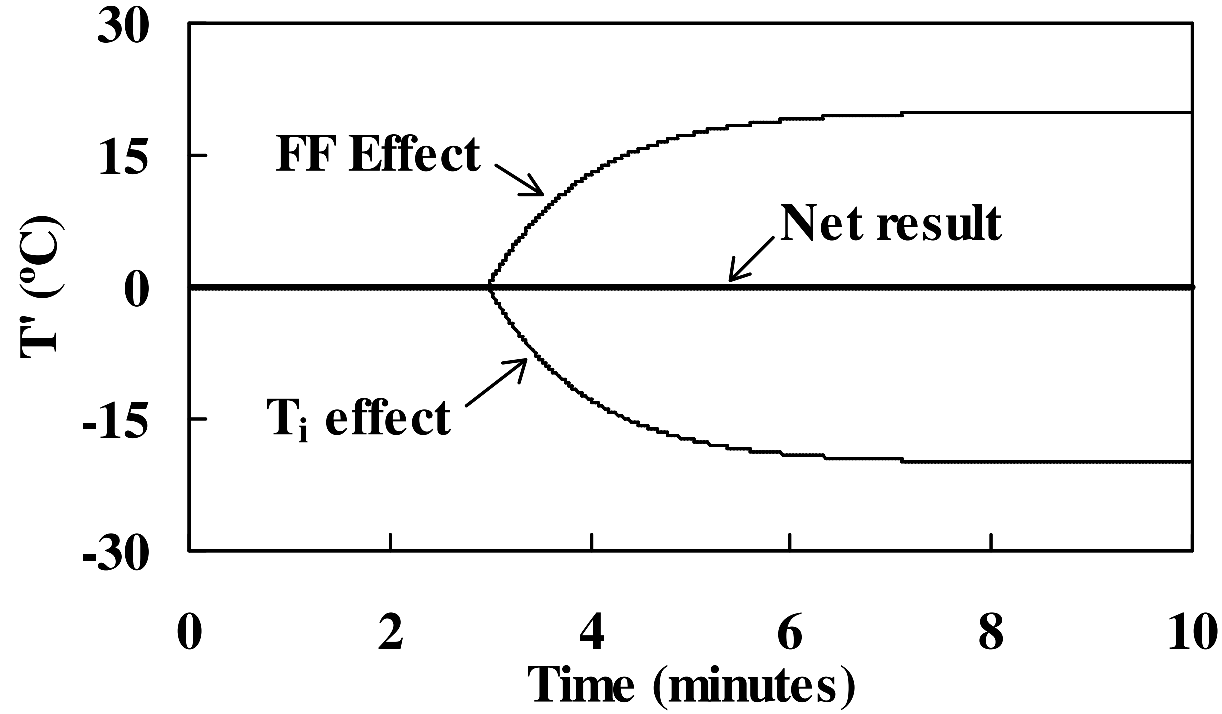



# Static Feedforward Results



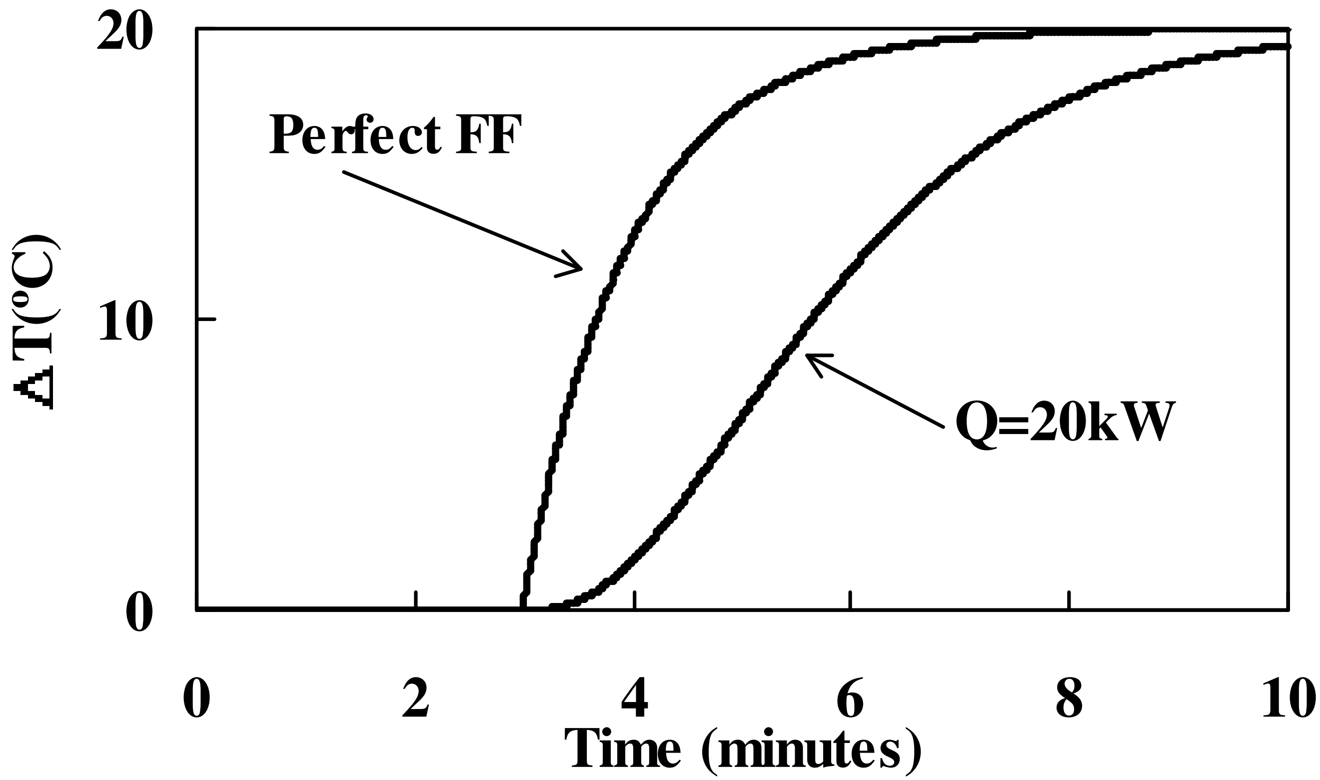

- When the inlet temperature drops by 20ºC, Q is immediately increased by 20 kW.
- Deviations from setpoint result from dynamic mismatch

# Perfect Feedforward Control



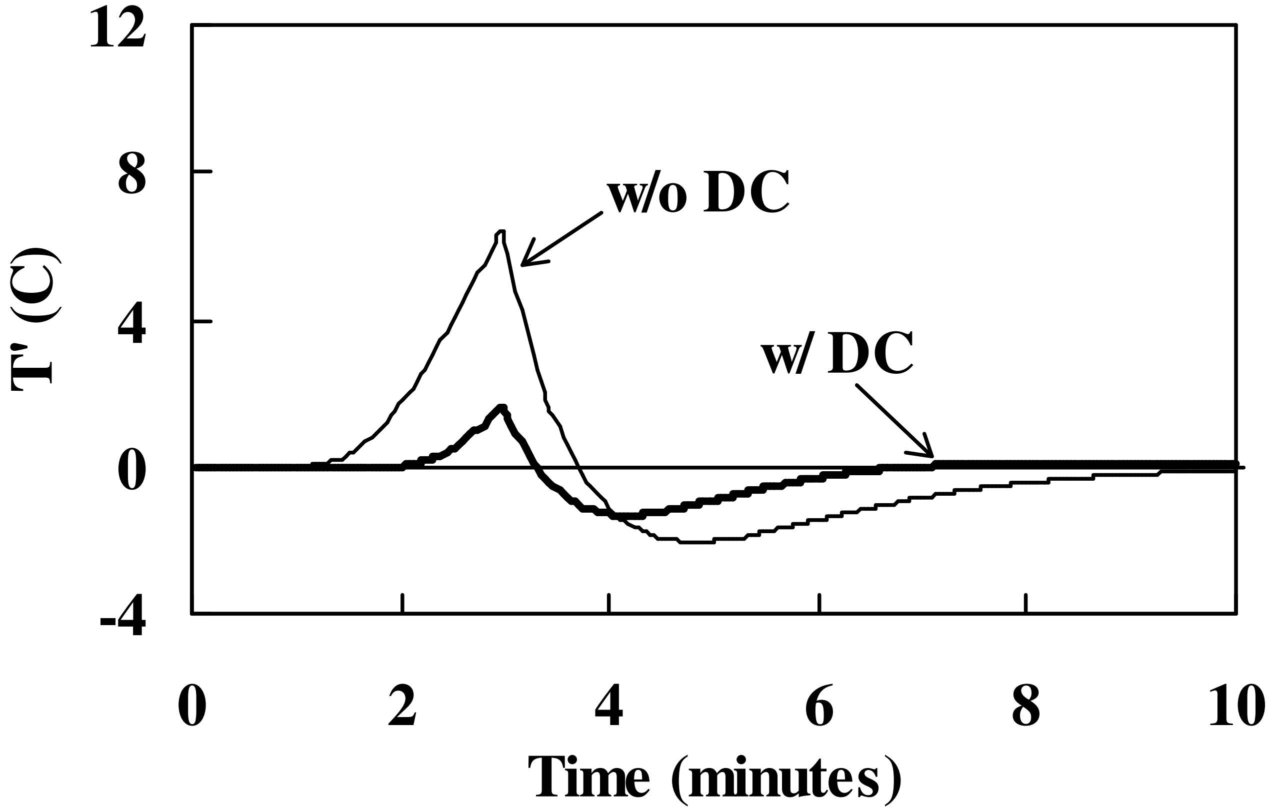

- FF correction is mirror image of disturbance effect.
- Net effect is no change in controlled variable.

# Required Dynamic Compensation

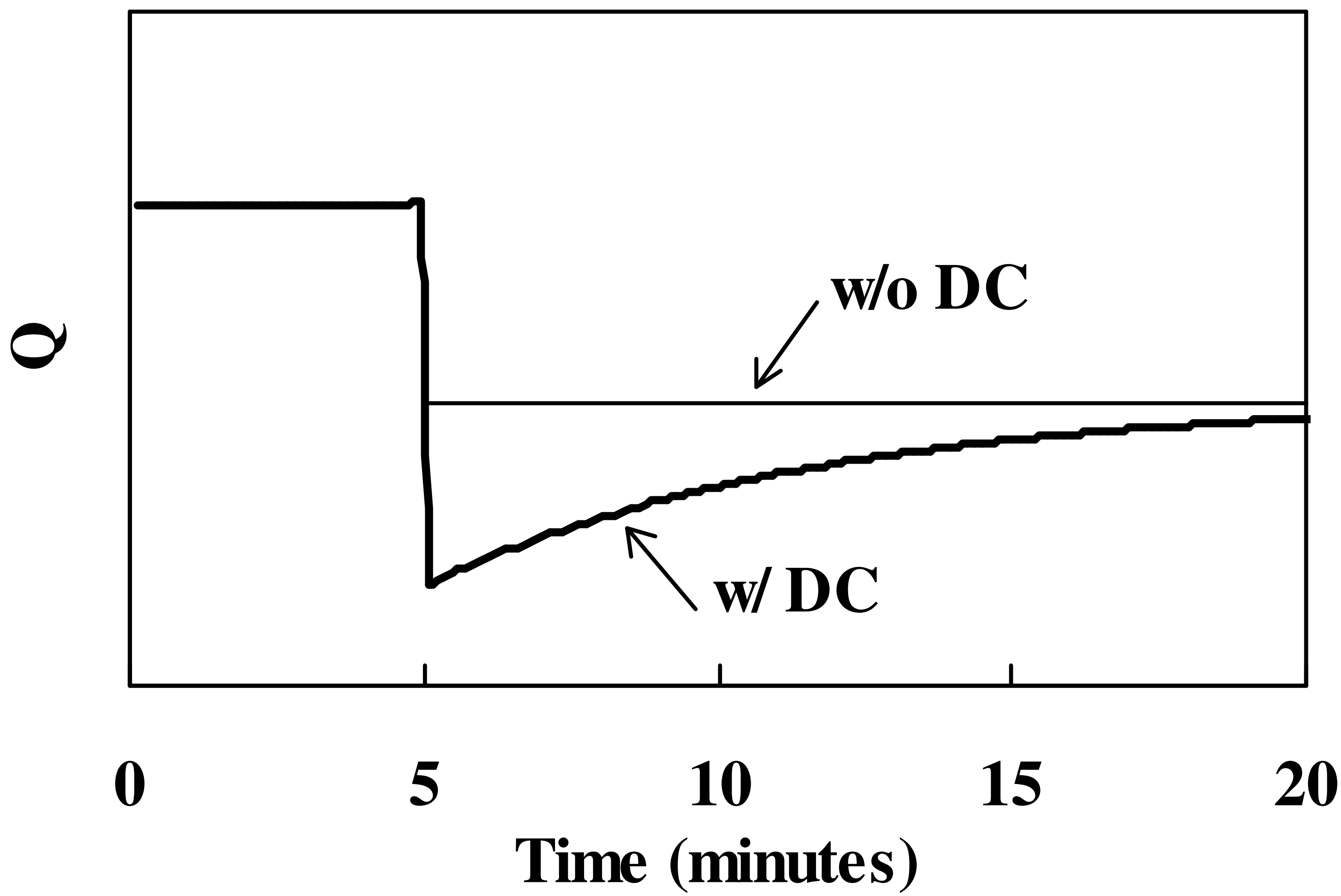



- Since the Q affects the process slower than $T_i$, initially overcompensation in Q is required followed by cutting back on Q to 20 kW.

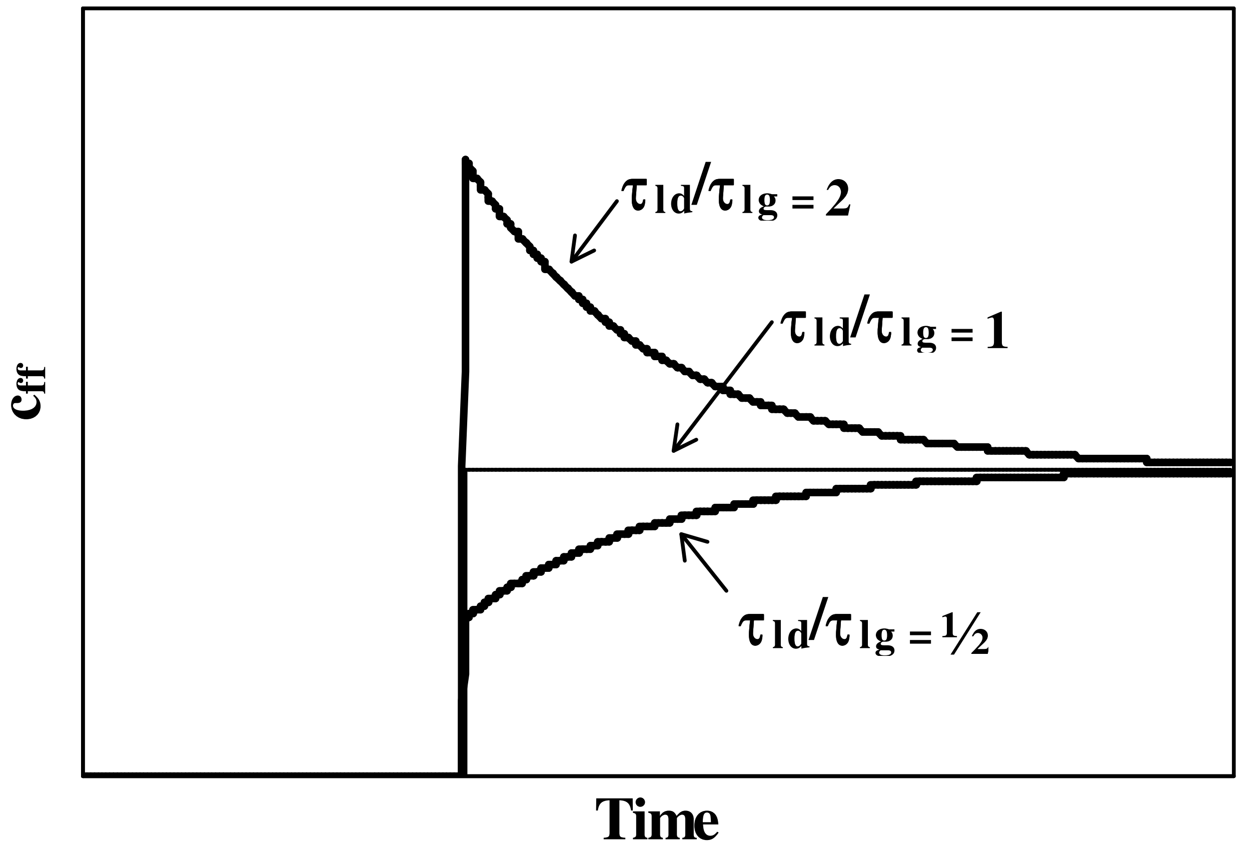
# Results with Dynamic Compensation



# Feedforward Control Action

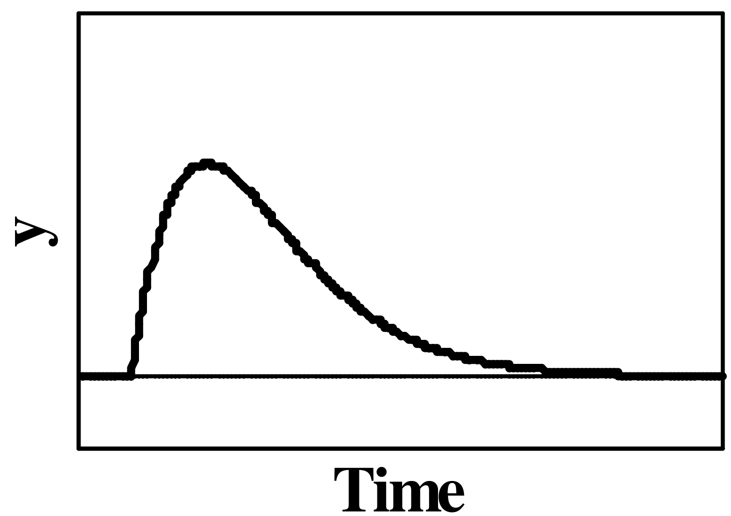


# Effect of Lead/Lag Ratio



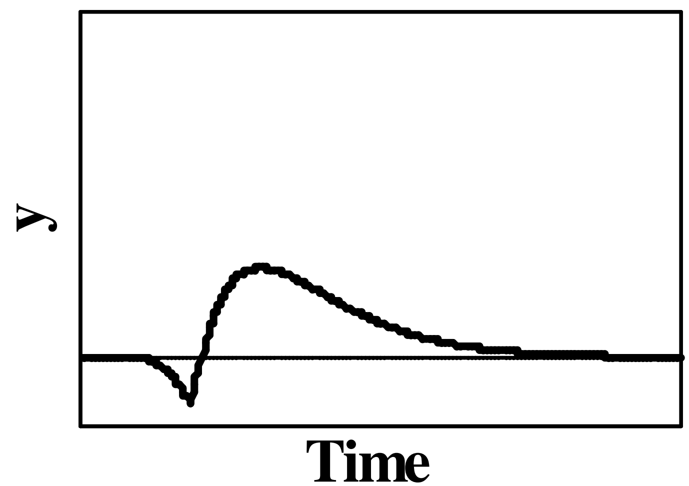
# Tuning a FF Controller

- Make initial estimates of lead/lag parameters based on process knowledge.
- Under open loop conditions, adjust $K_{ff}$ until steady-state deviation from setpoint is minimized.



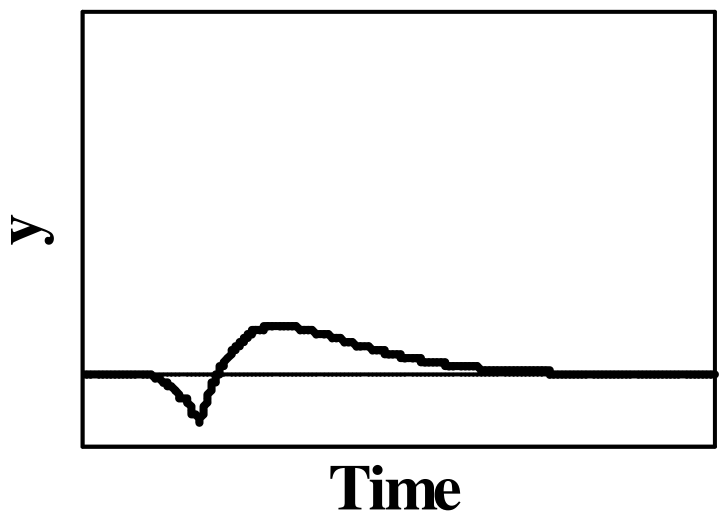
# Tuning a FF Controller

- Analyzing the dynamic mismatch, adjust $\theta_{ff}$.



# Tuning a FF Controller

- Finally, adjust ($\tau_{ld}$ - $\tau_{lg}$) until approximately equal areas above and below the setpoint result.



# Demonstration: Visual Basic Simulator

Tuning a FF Controller

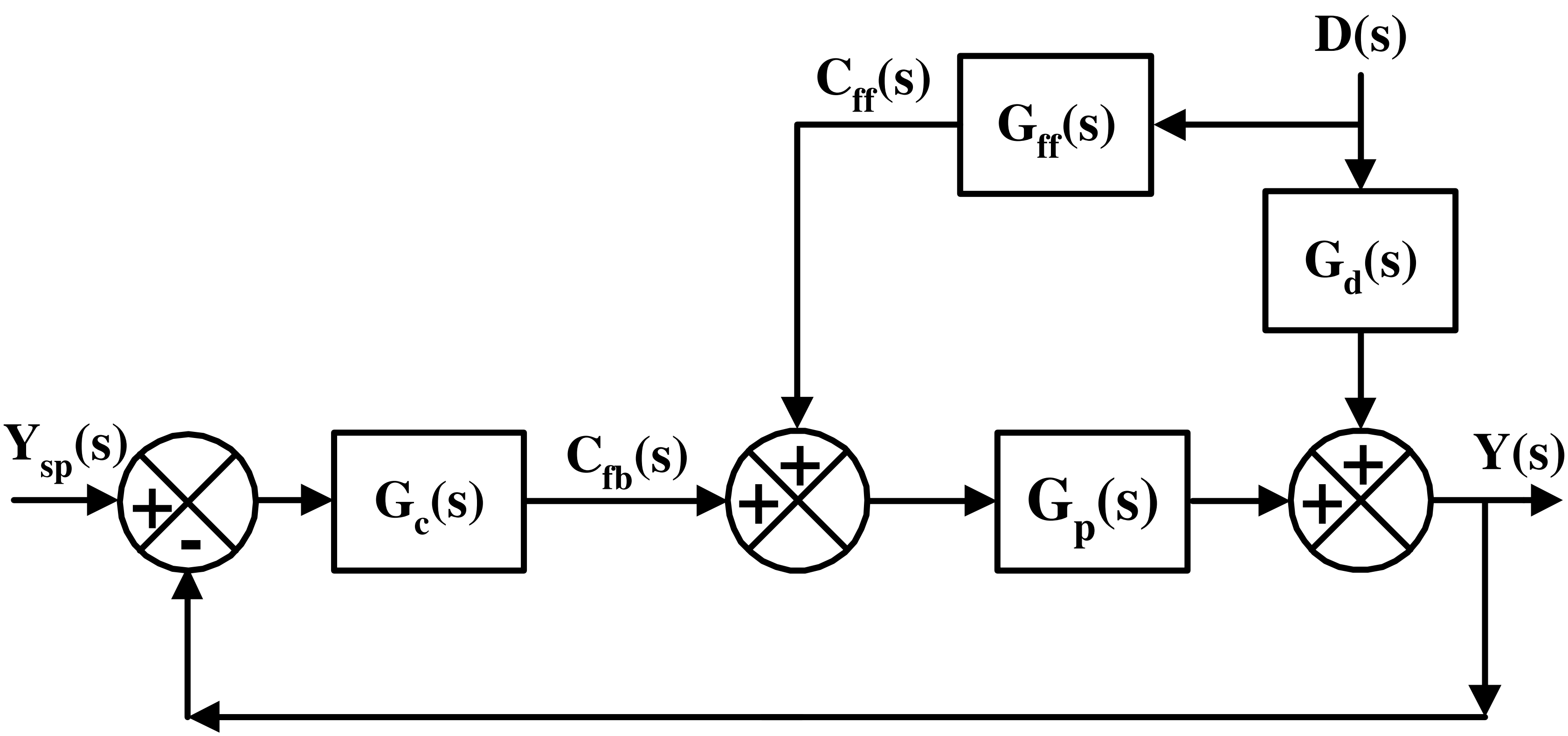
# Feedback Control

- Can effectively eliminate disturbances for fast responding processes.
- But it waits until the disturbance upsets the process before taking corrective action.
- Can become unstable due to nonlinearity and disturbance upsets.

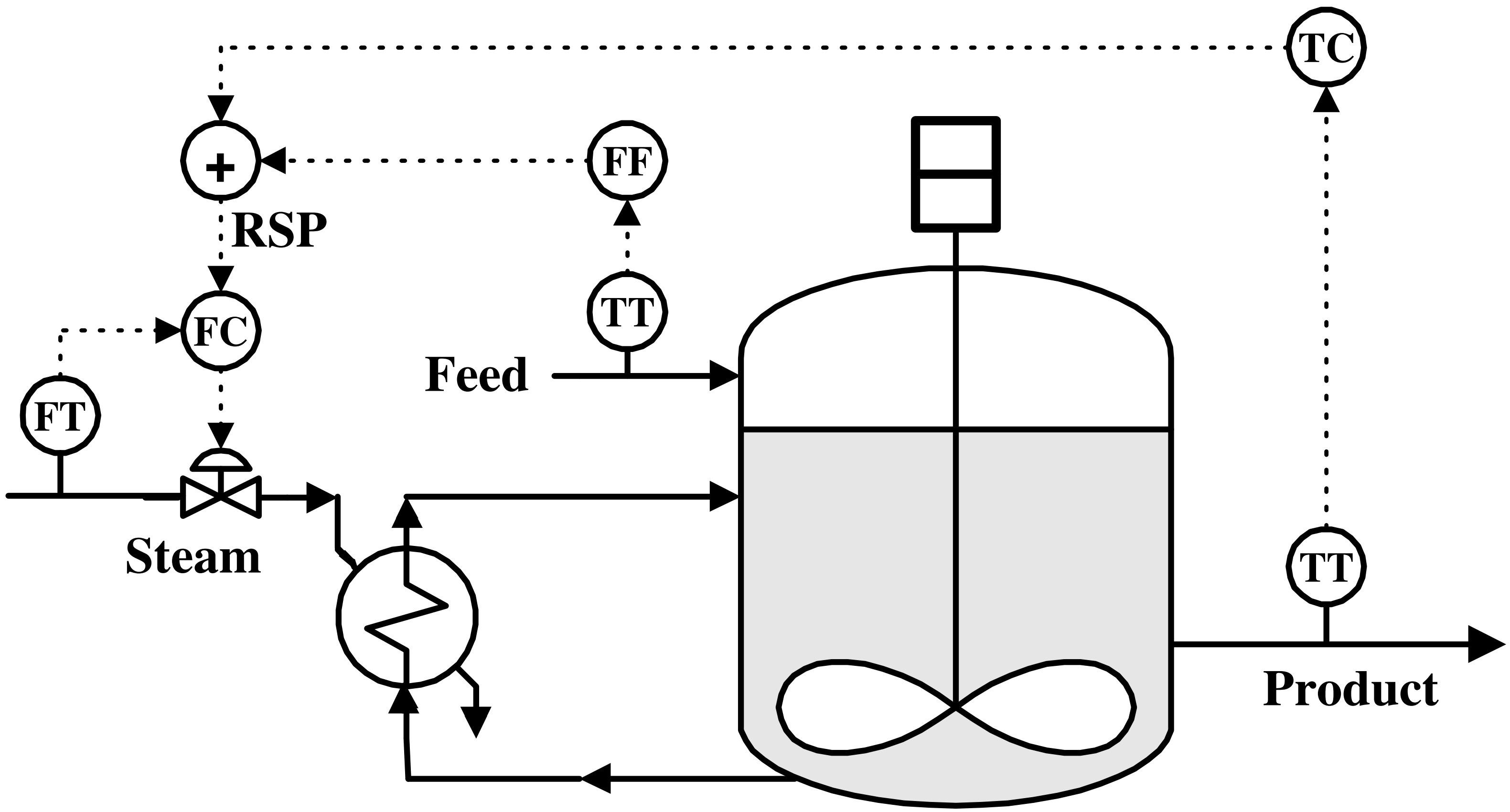
# Feedforward Control

- Compensates for d’s before process is affected
- Most effective for slow processes and for processes with significant deadtime.
- Can improve reliability of the feedback controller by reducing the deviation from setpoint.
- Since it is a linear controller, its performance will deteriorate with nonlinearity.

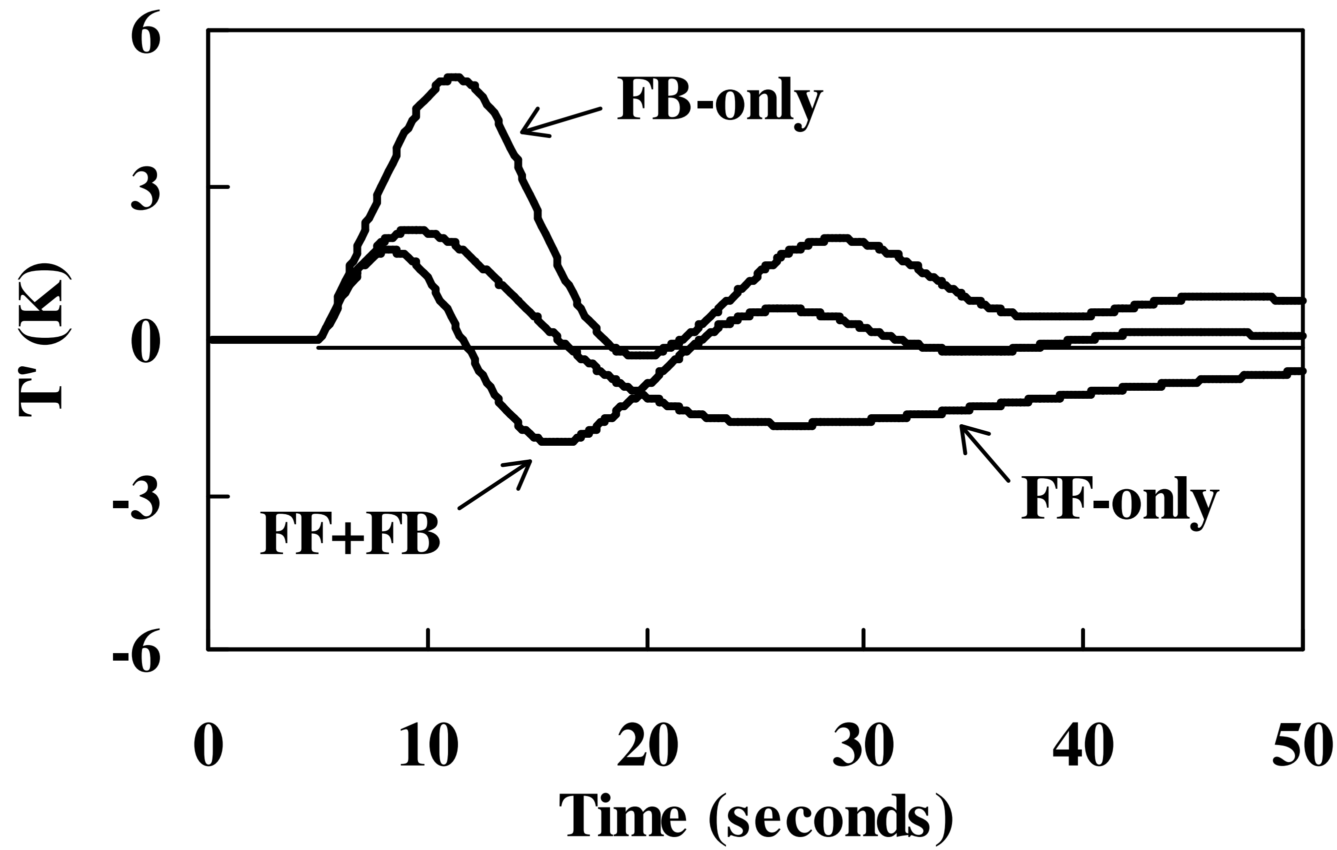
# Combined FF and FB Control



# Combined FF and FB for the CSTR



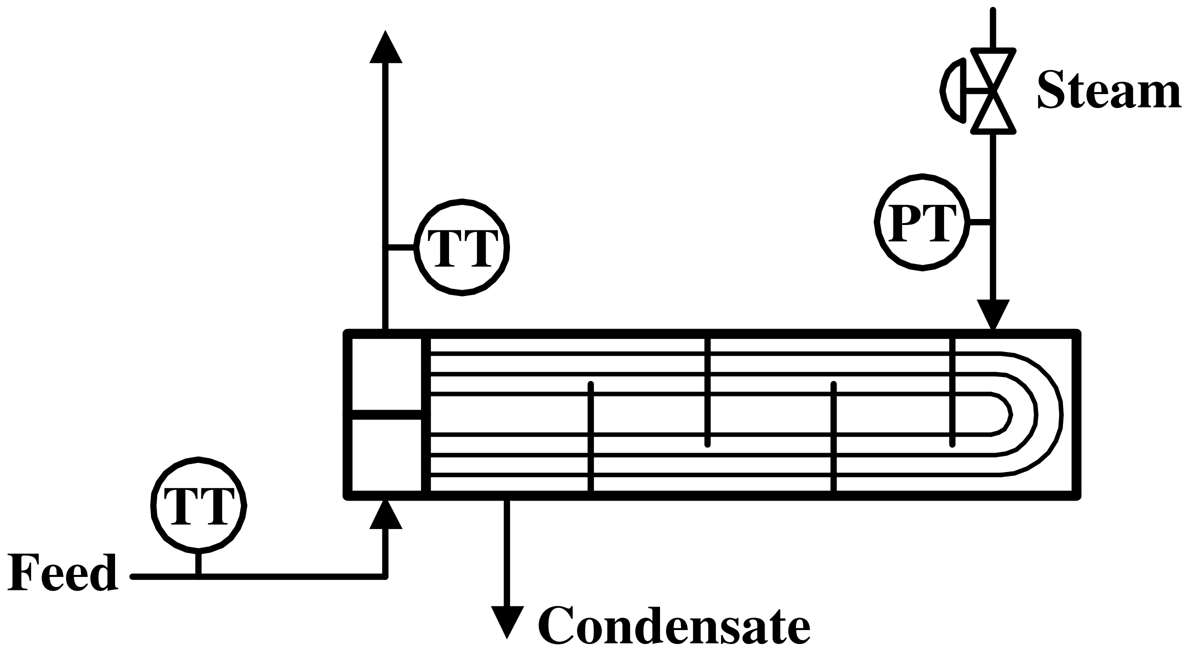
# Results for CSTR



# Analysis of Results for CSTR

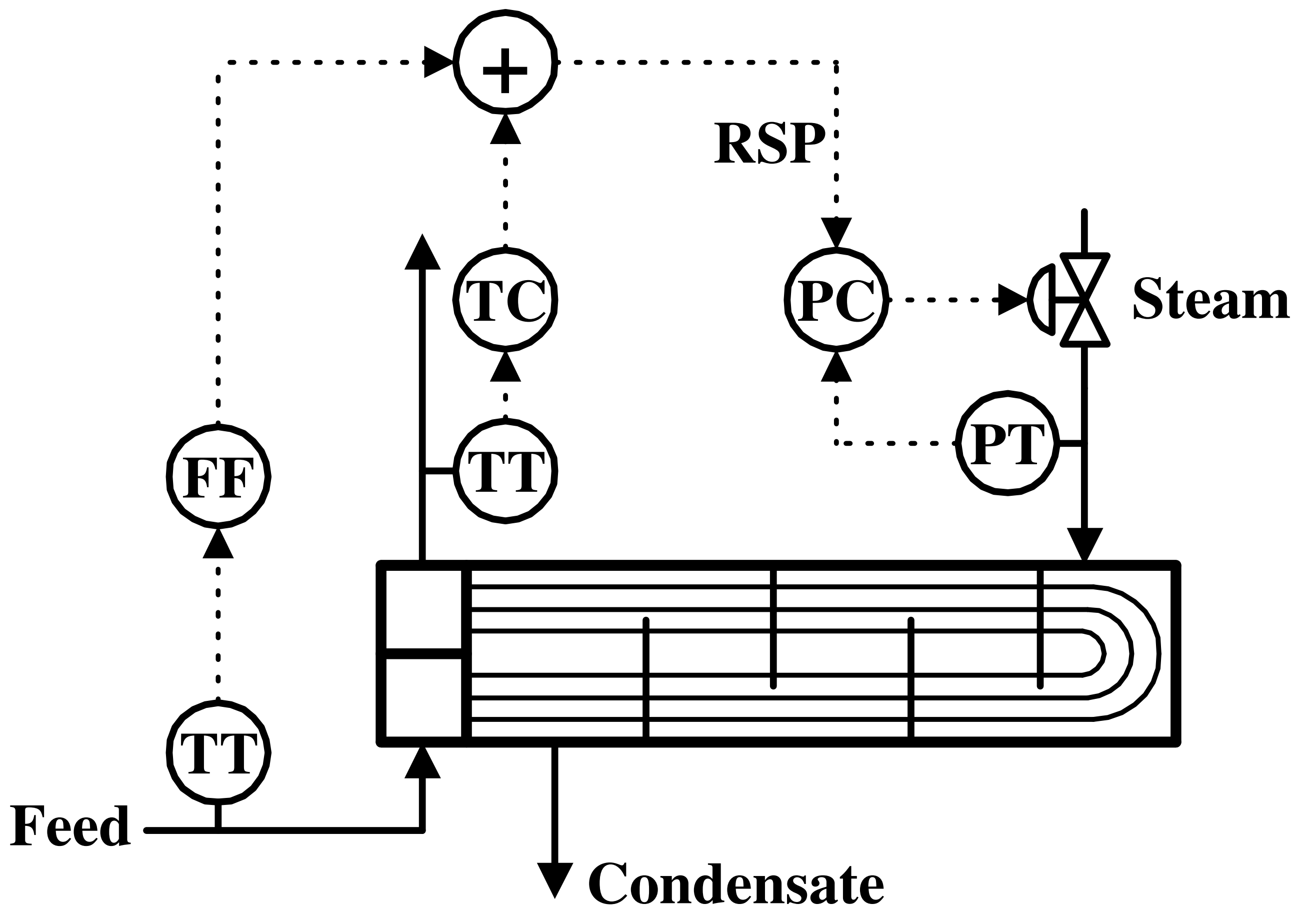
- FB-only returns to setpoint quickly but has large deviation from setpoint.
- FF-only reduces the deviation from setpoint but is slow to return to setpoint.
- FF+FB reduces deviation from setpoint and provides fast return to setpoint.

# Example




- Draw schematic: For a combined feedforward and feedback controller in which the inlet feed temperature is the feedforward variable and the outlet temperature is the feedback variable. The combined controller output is the setpoint for a steam pressure controller.

# Solution



# Overview

- Cascade can effectively remove certain disturbances if the slave loop is at least 3 times faster than the master loop.
- Ratio control is effective for processes that scale with the feed rate.
- Feedforward can be effective for measured disturbances for slow responding processes as long as the process nonlinearity is not too great.