Solutions for Designing Controls for the Process Industries 1st Edition by Seames

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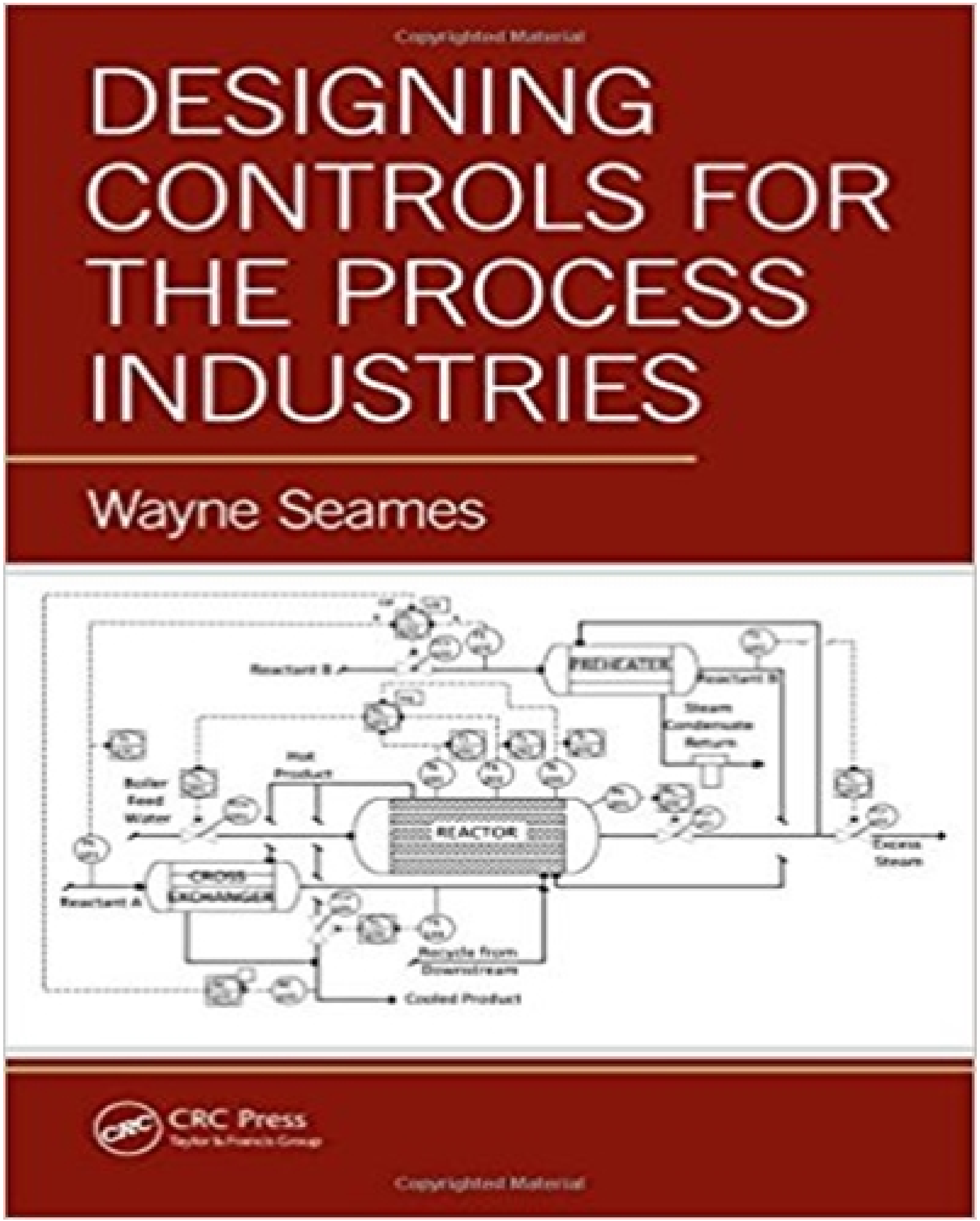

Solutions

Chapter 2 Problem Solutions

2.1 Define the following terms: measurement variable, control variable, dependent variable, valve position, operational objective, control objective, controller, setpoint, measurement error, controller output, manual mode, high-high level alarm, low-low level alarm, air fail open, and air fail closed.

- **Measurement Variable**: The subset of the dependent variables affected by changes to the process that are used to determine the effect of a change to the process by a related independent (control) variable. For feedback control loops measurement variables are also used to evaluate the effectiveness of changes in the control variable. Examples: flow rate, pressure, temperature, level, motor speed, and material properties such as chemical composition.
- **Control Variable**: An independent variable which is used in a process control loop to keep a portion of the process at its desired condition. The main control variables are: control valves, motor speed, electrical supply interruption time, and electrical current resistance.
- **Dependent Variable**: These are variables affected by changes to the process made by a related independent variable. They are used to determine the condition of the process. When used in a feedback control loop, they are measurement variables. When used in a feedforward control loop, they are measurement variables related to disturbance variables. When used in the slave feedback control loop of a cascade control scheme, they are related variables. Examples: flow rate, pressure, temperature, level, and material properties such as chemical composition.
- **Valve Position**: The valve opening area. This is used to adjust the rate of flow through and the pressure drop incurred by a process fluid in a control valve in order to achieve the process or operational objectives of a unit operation. Valve position is typically measured on a scale from 0 to 100%.
- **Operational Objective**: A functional goal of a unit operation. It defines the unit operation's purpose. Tasks are designed to accomplish the operational objectives.
- **Control Objective**: A goal of the plant automation system. It defines the purpose for the controls applied to a given unit operation.
- **Controller**: The portion of the control system that determines how the related control variable shall be adjusted to meet the control objectives of the control loop. A typical controller compares the measurement variable to a setpoint to generate an error. The error is used by the controller in a control algorithm to determine an output for the control variable.
- **Setpoint**: The desired value of the measurement variable. It is specified by an operator or by another part of the plant automation system.

- **Measurement Error**: The difference between the measured value of the measurement variable and the setpoint, as calculated by the controller.
- **Controller Output**: The change to the control variable requested by the controller in response to the measurement error.
- **Manual Mode**: When an operator overrides the controller output, in order to impose their own output for the control variable.
- **High-High Level Alarm**: An additional piece of safety equipment, which activates once the level of a unit operation has exceeded the high value set for the control system. These alarms are activated if an operator does not respond to the high level alarm or if there is an issue with the primary level measurement device.
- **Low-Low Level Alarm**: An additional piece of safety equipment, which activates once the level of a unit operation has fallen below the low value set for the control system. These alarms are activated if an operator does not respond to the low level alarm or if there is an issue with the primary level measurement device.
- **Air Fail Open**: When removing or blocking the pneumatic air from a control valve, the valve will open to its maximum. This is a forward acting valve.
- **Air Fail Closed**: When removing or blocking the pneumatic air from a control valve, the valve will close completely. This is a reverse acting valve.

2.2 Describe each of the types of independent variables that are typically available for use in process control.

- **Control valve:** Operates by changing the size of the opening of a choke point in a pipe which changes the quantity of fluid that can flow through the pipe for a given pressure drop. Conversely, the pressure drop incurred to force a given quantity of fluid through an opening can be adjusted.
- **Electrical supply interruption time:** This independent variable works to open and close a contact on the electrical supply so that the equipment receives electric current for only a fraction of the time. For example, by varying the fraction of time a heater is energized, the energy input to the heater can be adjusted, which adjusts the surface temperature of the heating element
- **Electrical current resistance:** A rheostat is used to vary the resistance to current flow in an electrical circuit. This in turn varies the electrical power available to power a motor or provide frictional heating to a heater element. For example, the flow of fluids can be controlled by varying the momentum introduced into the fluid by a pump or compressor. The momentum is varied by varying the electrical current supplied to the motor that drives the device which, in turn, varies the speed (rotation, piston travel speed, etc.) of the pump or compressor. The same concept applies to solids by changing the speed of conveyors or extruders.
- **Block valve open/close status:** A block valve can be opened or closed on a fluid contained in a pipe. In this case, the quantity of fluid moving from one unit

operation to another has only two states: full flow or no flow. This strategy is often employed for batch unit operations.

2.3 Describe a coupled control system and why such systems should be avoided whenever possible.

- A coupled control system is one in which an independent variable has a direct and immediate effect on a dependent variable which is not part of its own control loop. When this happens, the control system is less stable, less responsive, and less capable of handling disturbances to the system, all which lead to a system which is more difficult to control. An example of this is trying to control liquid level in a drum by changing the pressure of the overhead gas stream, instead of changing the flow of the liquid bottoms.

2.4 For the following unit operations, a) identify the governing mass balance equations, b) determine the number of independent variables, c) determine the number of control variables, and d) design simple feedback control loops for each control variable.

2.4.1 A single effect evaporator

a. Mass Balance:

Process: $M_{feed}=M_{vapor}+M_{liquid}+M_{acc}$

Utility: $M_{steam}=M_{condensate}+M_{acc}$

b. Number of independent variables:

M_{feed} is satisfied by the upstream unit

M_{acc} is satisfied by the mass balance

This gives 2 DoF for the process mass balance and 1DoF for the utility balance, and 1 DoF for compressibility (phase change).

5 independent variables: 4 control and 1 disturbance (M_{feed})

c. Number of control Variables:

4 Control Variables

d. **See Drawing 2.4.1-A-001/1**

2.4.2 A crystallizer

a. Mass Balance:

Process: $M_{feed}= M_{slurry}+M_{acc}$

Utility: $M_{ref.}=M_{warm}+M_{acc}$

b. Number of independent variables:

M_{feed} is satisfied by the upstream unit

M_{acc} is satisfied by the mass balance

This gives 1 DoF for the process mass balance and 1DoF for the utility balance, assuming an incompressible coolant is used.

3 independent variables: 2 control and 1 disturbance (M_{feed})

c. Number of control Variables:

2 Control Variables

d. **See Drawing 2.4.2-A-001/1**

2.4.3 A polymer extruder

a. Mass Balance:

Process: $M_{feed}=M_{product} + M_{acc}$

b. Number of independent variables:

M_{feed} is satisfied by the upstream unit

M_{acc} is satisfied by the mass balance

This gives 1 DoF for the process mass balance.

2 independent variable: 1 control and 1 disturbance (M_{feed})

c. Number of control Variables:

1 Control Variable

d. **See drawing 2.4.3-A-001/1**

2.4.4 A gas phase endothermic reactor with a steam heating jacket

a. Mass Balance:

Process: $M_{feed}=M_{vapor} + M_{acc}$

Utility: $M_{steam}=M_{condensate}+M_{acc}$

b. Number of independent variables:

M_{feed} is satisfied by the upstream unit

M_{acc} is satisfied by the mass balance

This gives 1 DoF for the process mass balance and 1DoF for the utility balance, and 1 DoF for compressibility (phase change).

4 independent variables: 3 control and 1 disturbance (M_{feed})

c. Number of control Variables:

3 Control Variables

d. **See drawing 2.4.4-A-001/1**

2.5 For the following unit operations, a) identify the governing mass balance equations, b) determine the number of independent variables, c) determine the number of control variables, and d) design at least one combined feedforward-feedback control loop for each unit operation.

2.5.1 Three liquid streams are combined and fed to a pump that includes a low flow recycle line. The flow of the largest of these streams varies greatly and results in pump cavitation if the low flow recycle system does not react in time.

a. $M_{I1} + M_{I2} + M_{I3} = M_O + M_a$

b. $M_{I1},\ M_{I2}, and\ M_{I3}$ are all set by the upstream unit

M_a is satisfied by the mass balance

There are 4 independent variable: 1 control and 3 disturbance (M_{I1-3})

c. **There is 1 control variable**

d. **See drawing 2.5.1-A-001/1**

2.5.2 A three-effect evaporator with countercurrent flow is used to concentrate an aqueous liquid stream.

a. Mass Balance:

Evaporator #1: $M_{feed}=M_{waste3}+M_{liquid1}+M_{acc}$

Utility Evap #1: $M_{vapor2}=M_{waste2}+M_{acc}$

Evaporator #2: $M_{liquid1}=M_{vapor2}+M_{liquid2}+M_{acc}$

Utility Evap #2: $M_{vapor3}=M_{waste1}+M_{acc}$

Evaporator #3: $M_{liquid2}=M_{vapor3}+M_{liquid3}+M_{acc}$

Utility Evap #3: $M_{steam}=M_{condensate}+M_{acc}$

b. Number of independent variables:

Evaporator #1:

$M_{feed,}$ M_{vapor2} are satisfied by the upstream unit

M_{acc} is satisfied by the mass balance

Evaporator #2:

$M_{liquid1,}$ M_{vapor3} are satisfied by the upstream unit

M_{acc} is satisfied by the mass balance

Evaporator #3:

$M_{liquid2}$ is satisfied by the upstream unit

M_{acc} is satisfied by the mass balance

This gives 3 DoF for evap #1, 3 DoF for evap #2, 4 DoF for evap #3

11 independent variables: 10 control and 1 disturbance (M_{feed})

c. Number of control Variables:

10 Control Variables

d. **See drawing 2.5.2-A-001 sheets 1 and 2**

2.5.3 A two stage crystallizer system is used to remove a contaminant to a low level via precipitation from an aqueous liquid stream.

a. Mass Balance:

Unit #1: $M_{feed} = M_{slurry1} + M_{acc}$

Utility #1: $M_{ref.} = M_{warm} + M_{acc}$

Unit #2: $M_{slurry1} = M_{slurry2} + M_{acc}$

Utility #2: $M_{ref.} = M_{warm} + M_{acc}$

b. Number of independent variables:

Unit #1:

M_{feed} is satisfied by the upstream unit

M_{acc} is satisfied by the mass balance

Unit #2:

$M_{slurry1}$ is satisfied by the upstream unit

M_{acc} is satisfied by the mass balance

This gives 2 DoF for unit #1, 2 DoF for unit #2

5 independent variables: 4 control and 1 disturbance (M_{feed})

c. Number of control Variables:

4 Control Variables

d. **See drawing 2.5.3-A-001/1**

2.5.4 A three step distillation system to separate a mixed feed stream into propane, butane, pentane, and hexanes.

a. Mass Balances

$$M_I = M_{O1} + M_{I2} + M_a$$
$$M_{I2} = M_{O2} + M_{I3} + M_a$$
$$M_{I3} = M_{O3} + M_{O4} + M_a$$

For each step of the separation there are 2 control variables.

b. Number of independent variables:

M_a is satisfied by the mass balance

There are 7 Independent variables: 6 control and 1 disturbance (M_I)

c. Number of control variables:

There are 6 control variables

d. **See drawing 2.5.4-A-001 sheets 1 through 3**

2.6 For the following unit operations, a) identify the governing mass balance equations, b) determine the number of independent variables, c) determine the number of control variables, and d) design at least one ratio control loop for each unit operation.

2.6.1 An endothermic tubular reactor, with multiple reaction tubes, that uses a fired heater section to provide energy at a high temperature in the vessel space surrounding the tubes

a. Tubes:

$M_I = M_O + M_a$ (All satisfied)

Fired Heater:

$$M_{I1} + M_{I2} = M_a$$

b. $M_I \text{ and } M_{I1}$ are set by the upstream unit.

M_a is satisfied by the mass balance

There are 4 independent variables: 2 control and 2 disturbance

c. There are 2 control variables

d. **See drawing 2.6.1-A-001/1**

2.6.2 A neutralization tank that adds acid to a high pH waste stream

a. $M_{I1} + M_{I2} = M_O + M_a$

b. M_{I1} is set by the process

M_a is satisfied by the mass balance

There are 3 independent variables: 2 control and 1 disturbance

c. **There are 2 Control Variables**

d. **See drawing 2.6.2-A-001/1**

2.6.3 A process stream and a nutrient stream are added to a photobioreactor. In the photoreactor, light banks are cycled on and off to add the correct amount of energy (which can be correlated to the temperature of the outlet stream) to a water-based bioreactor.

a. $M_{I2} + M_{I1} = M_O + M_a$

b. M_{I1} is set by the process

M_a is satisfied by the mass balance

There are 2 independent variables: 1 control and 1 disturbance

c. **There is 1 Control Variable**

d. **See drawing 2.6.3-A-001/1**

2.7 For the following unit operations, a) identify the governing mass balance equations, b) determine the number of independent variables, c) determine the number of control variables, and d) design at least one cascade control loop for each unit operation.

2.7.1 A neutralization tank that adds acid to a high pH waste stream

a. $M_{I1} + M_{I2} = M_O + M_a$

b. M_{I1} is set by the process

M_a is satisfied by the mass balance

There are 3 independent variables: 2 control and 1 disturbance

c. **There are 2 Control Variables**

d. **See drawing 2.7.1-A-001/1**

2.7.2 Three process streams of varying flow rates are mixed together in a pressure vessel that is used to smooth out the combined flow rate into the next unit operation.

a. Mass Balance:

Vessel: $M_{feed1} + M_{feed2} + M_{feed3} = M_{outlet} + M_{acc}$

b. Number of independent variables:

Evaporator #1:

M_{feed1}, M_{feed2}, M_{feed3} are satisfied by the upstream unit

M_{acc} is satisfied by the mass balance

4 independent variable: 1 control and 3 disturbance

c. Number of control Variables:

1 Control Variables

d. **See drawing 2.7.2-A-001/1**

2.7.3 A filtration system that adjusts the recycle rate of a waste stream back through the filter, along with new waste liquid based on the particle concentration in the outlet waste stream.

a. $M_{I1} = M_O + M_a$

b. M_{I1} is set by the process

M_a is satisfied by the mass balance

There are 2 Independent variables: 1control and 1 disturbance

c. **There is 1 Control variable**

d. **See drawing 2.7.3-A-001/1**

2.8 Another example of the use of a feedback trim cascade control loop is in the operation of a Claus sulfur process. In this process, a feed gas containing H_2S is partially combusted with air to yield a mixture of H_2S, SO_2, and S via the reactions:

$$2H_2S + O_2 \rightarrow 2H_2O + 2S \quad (2.2)$$

$$2H_2S + 3O_2 \rightarrow 2SO_2 + 2H_2O \quad (2.3)$$

The flue gas is cooled to condense out the sulfur. It is then sent through a series of reheaters, catalytic reactors, and condensers to produce additional sulfur via the reaction:

$$2H_2S + SO_2 \rightarrow 2H_2O + 3S \quad (2.4)$$

The key to maximizing sulfur recovery is to have the correct H_2S to oxygen ratio in the initial thermal oxidizer. Theoretically, this is a simple 2:1 ratio. However, due to variations in the concentration and flow rate of H_2S in the process gas stream plus variations in the reaction efficiency of the thermal oxidizer and the three catalyst beds, the true optimum can only be found experimentally. As a result, the composition of either H_2S or SO_2 is measured in the final stream and this measurement is used in a feedback trim cascade controller to the inlet air ratio controller.

Duplicate the drawing shown in Figure 2.28 and add a ratio with feedback trim control scheme to meet the operational objectives described above.

- **See Drawing 2.8-A-001/1**

2.9 Consider the control scheme described on Figure 2.18 and the accompanying text. A more stable and responsive scheme uses the inlet cooling water flow and temperature of the outlet gas in a feedforward/feedback control as the slave in a cascade control scheme with an analyzer on the outlet stream as the master control loop. Modify Figure 2.18 to show this improved control scheme.

- **See Drawing 2.9-A-001/1**

2.10 Consider the system shown in Figure 2.21. Many local regulatory agencies require that the opacity of the flue gas exiting the furnace or boiler stack be measured. Opacity is a measure of the quality of the combustion. If combustion is inefficient, then the flue gas will include soot and/or unburned fuel which will decrease the opacity of the exiting gas. If the opacity exceeds a certain point, action must be taken to increase the air to fuel ratio in order to insure that the discharge is within acceptable limits. Duplicate the scheme shown in Figure 2.21 and add a safety automation system control scheme that will take "last resort" action to add air into the burner if the opacity meter reaches its low-low alarm, analysis point.

- **See Drawing 2.10-A-001/1**

2.11 Consider the neutralization system shown in Figure 2.14. This scheme can be improved by adding a cascade control loop that uses the outlet pH reading as the master dependent variable. Duplicate the scheme shown in Figure 2.14 and show how this improved scheme would be depicted.

- **See Drawing 2.11-A-001/1**

Designing Controls for the Process Industries

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CHAPTER 2

Control System Fundamentals

Basic Unit Operations

Motive Force – momentum transfer:

- **Fluids – gases and liquids**
  - Movement due to a pressure difference between upstream and downstream unit operations
  - Movement due to an external force such as gravity
  - Usually an external force is used to increase the pressure of the fluid at strategic points in the process
  - The external force is usually provided by a pump (liquids) or compressor/blower/fan (gases)

Basic Unit Operations

Motive Force – momentum transfer:

- **Fluids – gases and liquids**
- **Solids**
  - Conveyors/extruders
  - Gravity
  - Fluidization – entrainment in a gas
  - Slurry – entrainment in a liquid

Basic Unit Operations

Heat transfer:

- **Fluids – usually by indirect heating**
  - Most commonly in heat exchangers
  - Steam is the most common heating fluid
  - Very high temperatures usually involves the flue gas from a combustion process
  - Water is the most common cooling fluid
  - Very low temperatures usually involves some type of refrigerant or cryogenic process

Basic Unit Operations

Heat transfer:

- Fluids – usually by indirect heating
- Solids – by either indirect or direct heating
  - A hot gas passed through or over the material
- Electrical resistance is common in small-scale facilities for both fluids and solids

Basic Unit Operations

Mass transfer:

- Separating a stream into multiple streams
- Changing the composition of a stream

Basic Unit Operations

Mass transfer - separations:

- **By phase – gas, polar liquid, non-polar liquid, solid**
- **By differences phase equilibria**
- **By differences in chemical solubility – absorption/extraction/leaching**
- **By differences in physical attraction - adsorption**

Basic Unit Operations

Mass transfer - reactions:

- **By chemical reactions**
  - **Transforming the molecular makeup of a substance**
- **Key parameters – stoichiometry, temperature, residence time, pressure, contaminants, competing reactions**
- **Most reactions are facilitated by a catalyst**

Independent and Dependent Process Variables

Control variables - independent:

- **For fluids:**
  - Adjustable throttle in a pipe – control valve (CV)
  - Changing the opening changes the pressure drop and flow rate of the fluid
  - This is the most common independent variable in the process industries

Independent and Dependent Process Variables

Control variables - independent:

- **Fluids - Variations in a motive force device**
  - Change the amount of momentum transfer into the fluid
  - Vary the electrical current provided to the motor
  - Use a recycle of discharge fluid with a fixed speed motor
  - Change the fraction of time the pump or compressor is in operation (start/stop, on/off, etc.)

Independent and Dependent Process Variables

Control variables - independent:

- **Solids - Variations in a motive force device**
  - Change the amount of momentum transfer used to transport the solid
  - Vary the electrical current provided to the motor
  - Change the fraction of time the conveyor or extruder motor is in operation

Independent and Dependent Process Variables

Control variables - independent:

- **Electrical Resistance Heating**
  - **Vary the electrical current using an adjustable resistance source – rheostat**
  - **Change the fraction of time electricity is flowing through the heating circuit – open/close contact**

Independent and Dependent Process Variables

Measurement variables - dependent:

- **We use these to:**
  1. Measure the effect of independent variable manipulation on the process
  2. Determine how to manipulate independent variables

Independent and Dependent Process Variables

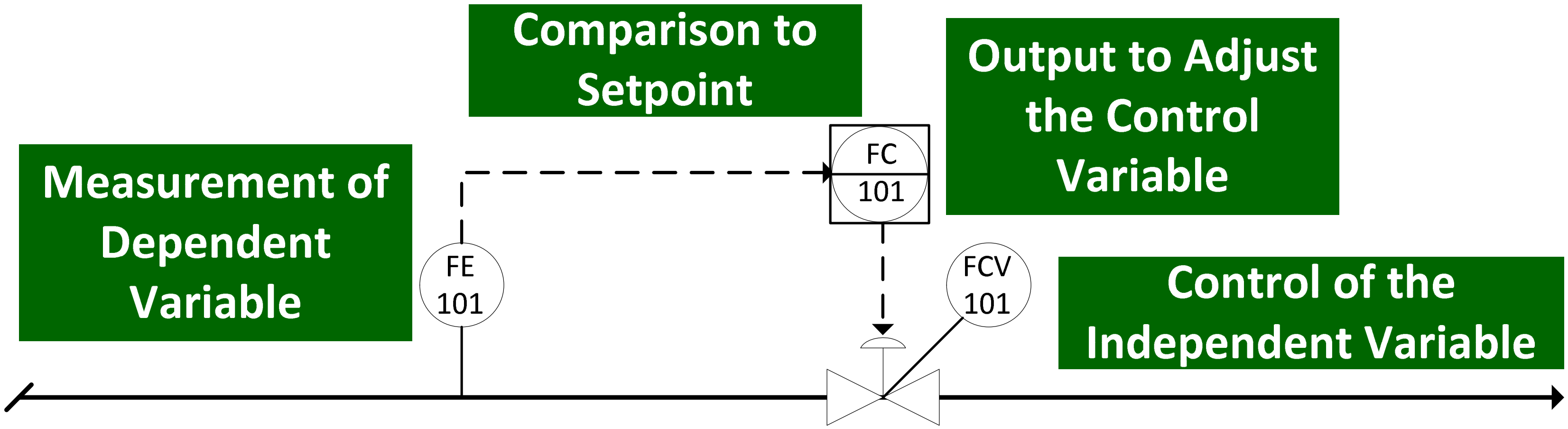
Measurement variables - dependent:

- **The most common are:**
  - Flow rate (volumetric for fluids, mass for solids)
  - Pressure
  - Temperature
  - Fluid level (or weight of a solid)
  - Material properties (composition, density, etc.)
  - Rotational speed

Independent and Dependent Process Variables

- In a single parameter control loop, one dependent variable is paired with one independent variable.
- We try to select a measurement (dependent) variable that is very sensitive to changes in the control (independent) variable
- This is known as regulatory control

The Feedback Control Loop

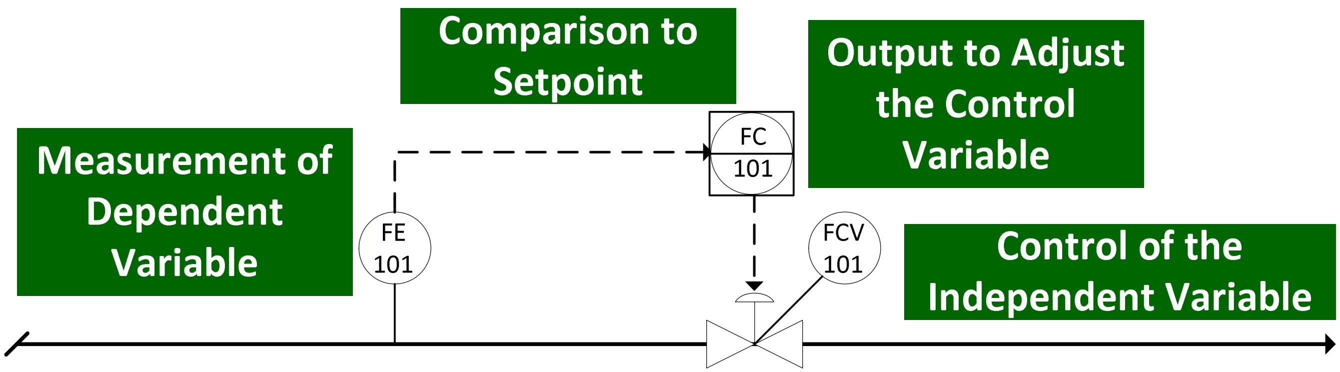


- Manipulate the control valve
- Measure the effect
- Compare the measured parameter to a setpoint
- Determine the degree of manipulation of the control valve based on this comparison

The Feedback Control Loop

Feedback control loops are how we control the process!

- **Almost everything else we will learn about process control will use the feedback control loop within its strategy**



How to Use Feedback Control Loops to Control a Unit Operation

Step 1: Determine the degrees of control freedom using one or more material and/or energy balance(s)

Step 2: Identify what independent variables to use – one control variable for each degree of freedom

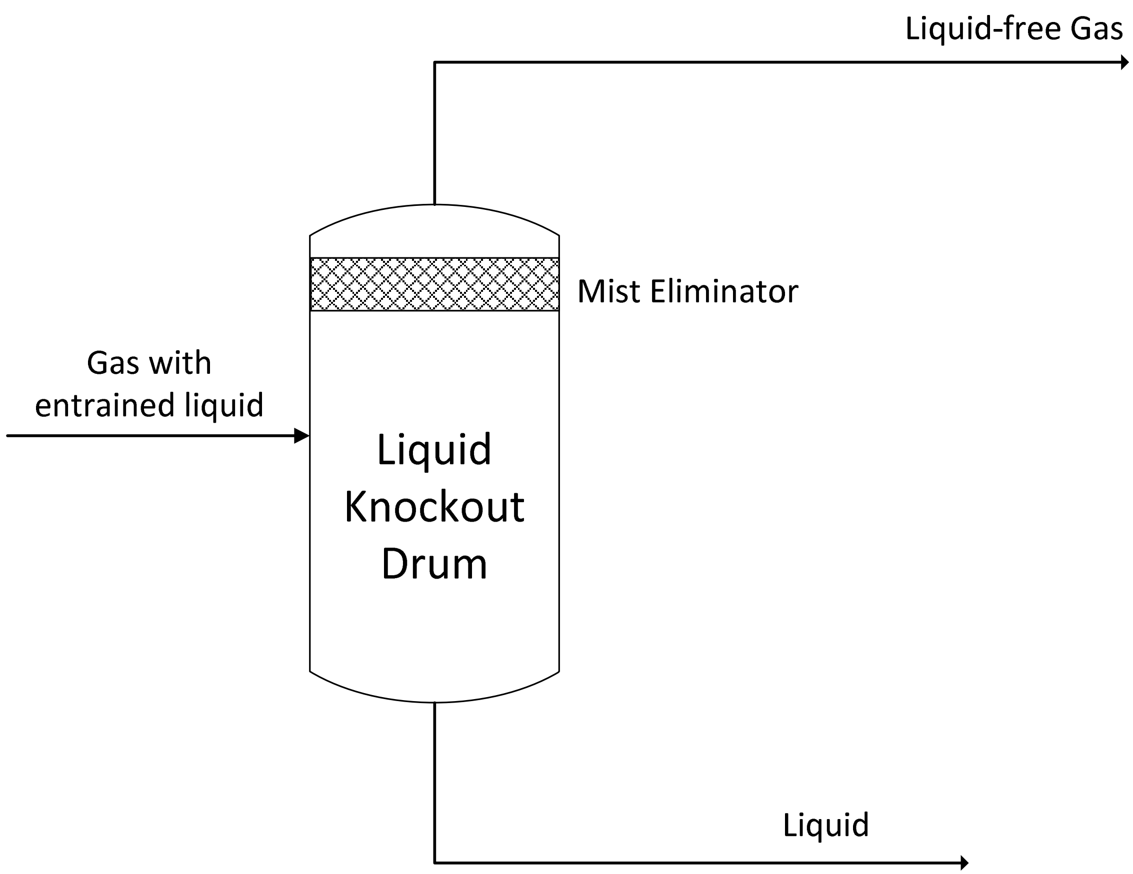
- **These should be based on the objectives of the unit operation**

Step 3: Identify one measurement variable for each control variable – choose a variable that is sensitive to changes in the control variable

Step 4: Construct a feedback control loop using the CV and MV you identified

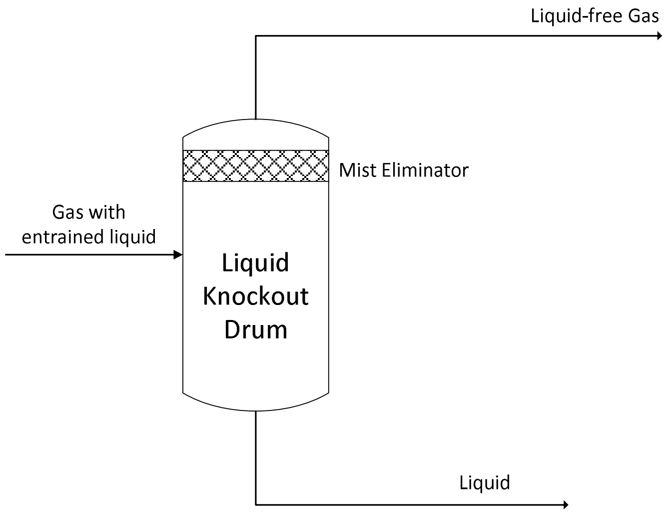
How to Use Feedback Control Loops to Control a Unit Operation

Example problem 1: the liquid knockout drum



Example problem 1: the liquid knockout drum Step 1

$$M_I = M_{O1} + M_{O2} + M_a$$



Where:

M_I is the mass of material entering through the feed nozzle

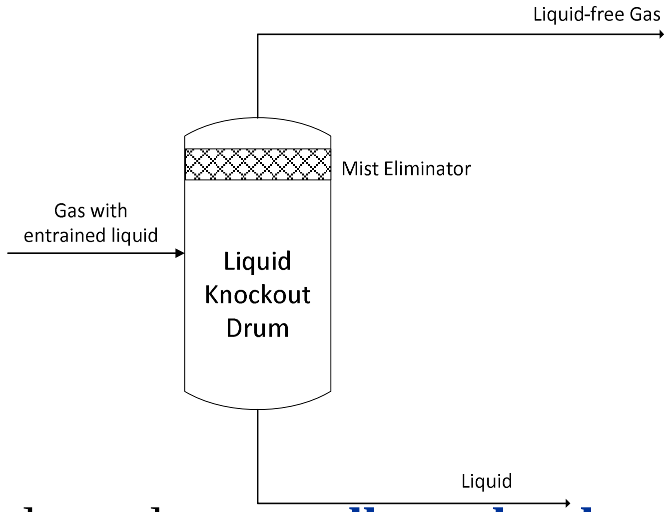
M_{O1} is the mass of material leaving through the top outlet nozzle

M_{O2} is the mass of material leaving through the bottom outlet nozzle

M_a is the accumulation (or reduction) in material in the vessel

Example problem 1: the liquid knockout drum Step 1

$$M_I = M_{O1} + M_{O2} + M_a$$



Where:

M_I is the mass of material entering through the feed nozzle **– usually set by the upstream operation (we'll cover exceptions later)**

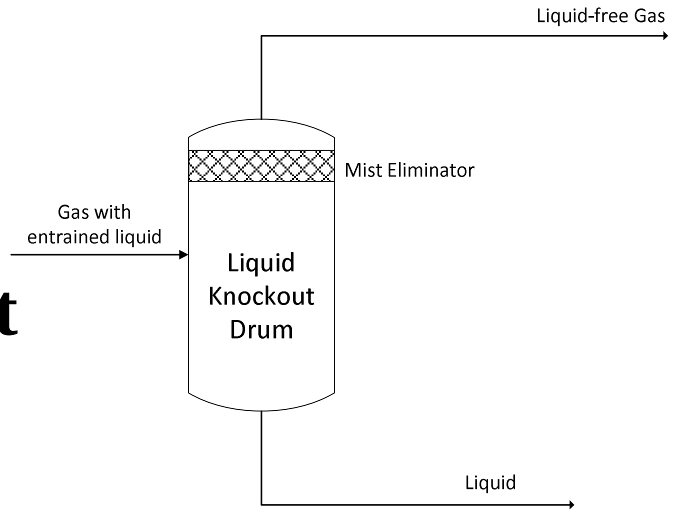
M_{O1} is the mass of material leaving through the top outlet nozzle **– one degree of freedom**

M_{O2} is the mass of material leaving through the bottom outlet nozzle **– one degree of freedom**

M_a is the accumulation (or reduction) in material in the vessel **– satisfied by the mass balance**

Example problem 1: the liquid knockout drum
Step 2

2 CVs needed for the two degrees of freedom.



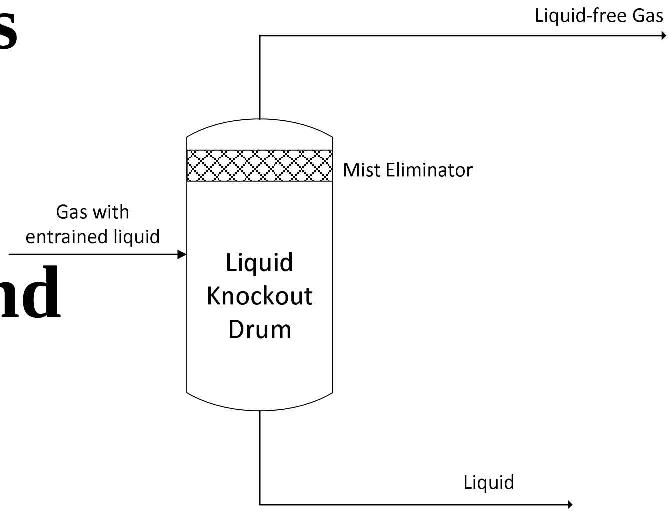
What are the objectives of the unit Operation?

1. **Remove liquid from the gas**
2. **Avoid losing gas out the bottom**
3. **Keep the pressure within the correct range**

Example problem 1: the liquid knockout drum
Step 2

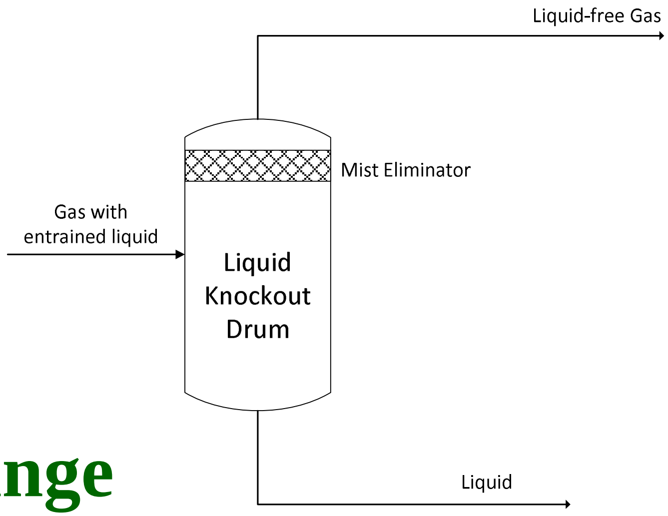
2 CVs needed for the two degrees of freedom:

-- put CVs on the overhead gas and bottoms liquid streams



Example problem 1: the liquid knockout drum
Step 3

2 MVs needed to pair to the two CVs

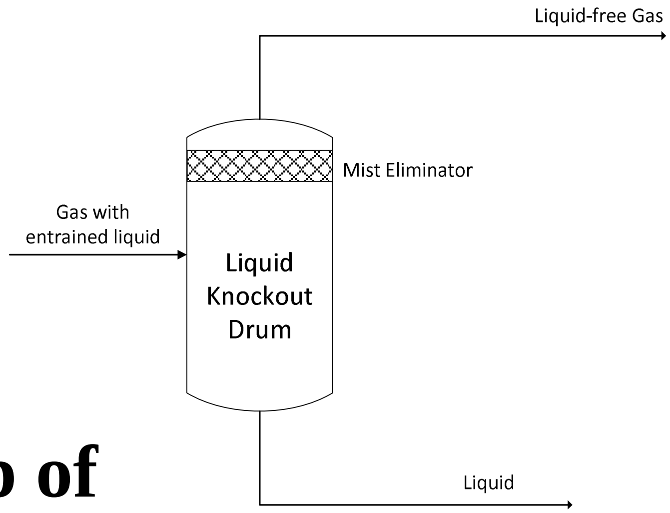


-- Measure the liquid level in the KO drum

- **keep it within the correct range and no gas will leave with the liquid and the drum's function to remove liquid from the gas will also be accomplished**

Example problem 1: the liquid knockout drum
Step 3

2 MVs needed to pair to the two CVs



-- Measure the liquid level in the KO drum

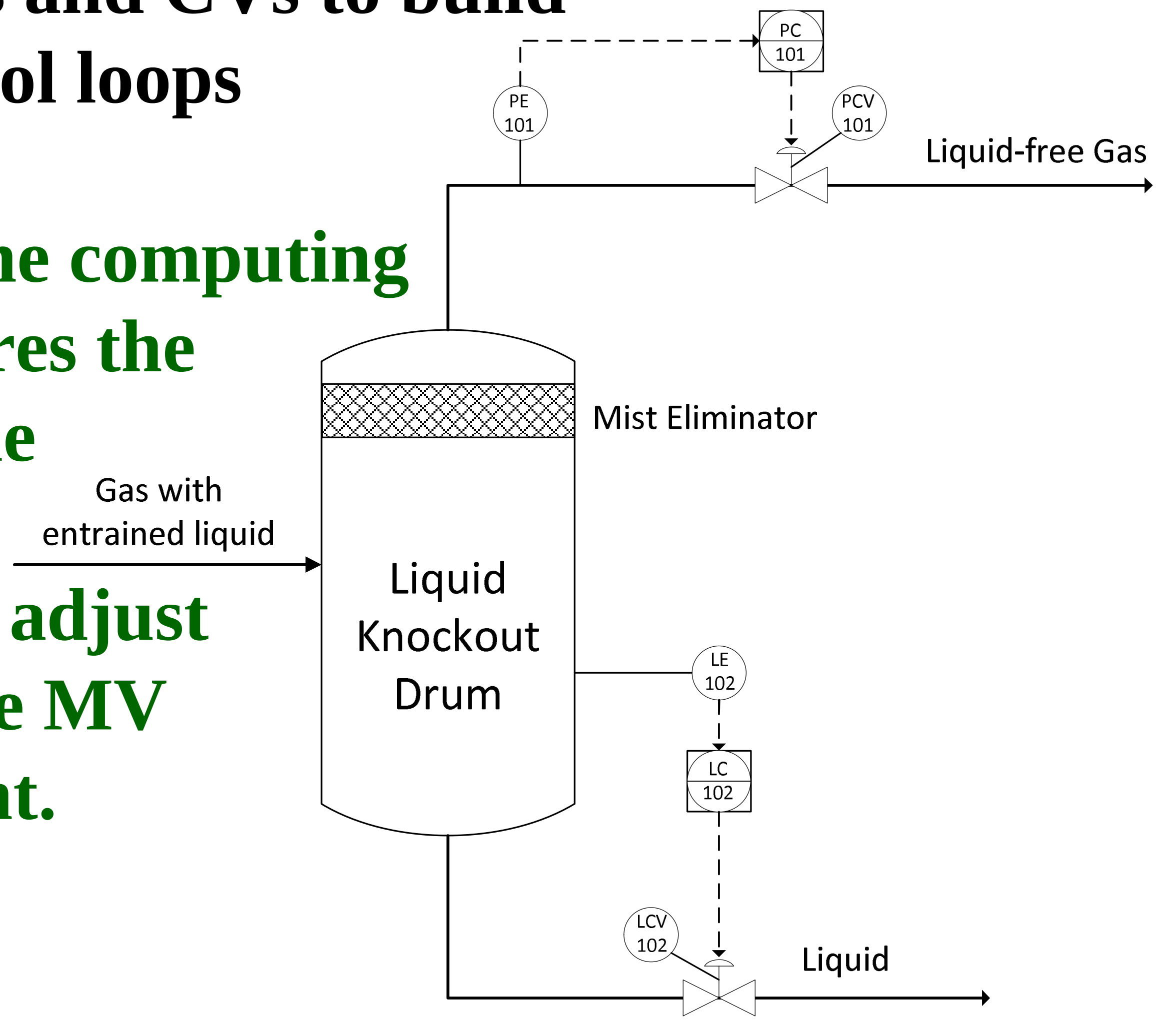
-- Measure the pressure in the top of the drum

- **Will insure that the overhead gas pressure is sufficient for downstream operations**

Example problem 1: the liquid knockout drum
Step 4

Match up the MVs and CVs to build the feedback control loops

The controller is the computing device that compares the measurement to the setpoint and determines how to adjust the CV to bring the MV closer to its setpoint.

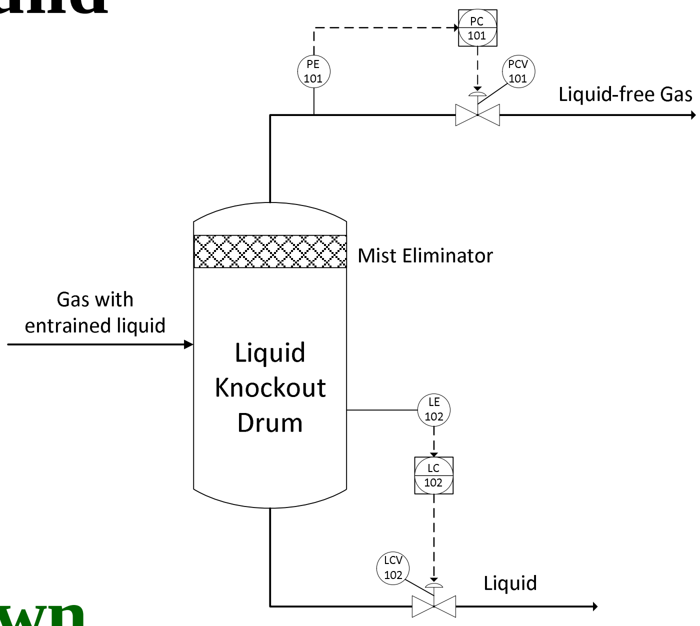


Example problem 1: the liquid knockout drum
Step 4

Match up the MVs and CVs to build the feedback control loops

The difference between the measurement and the setpoint is known as the error, E.

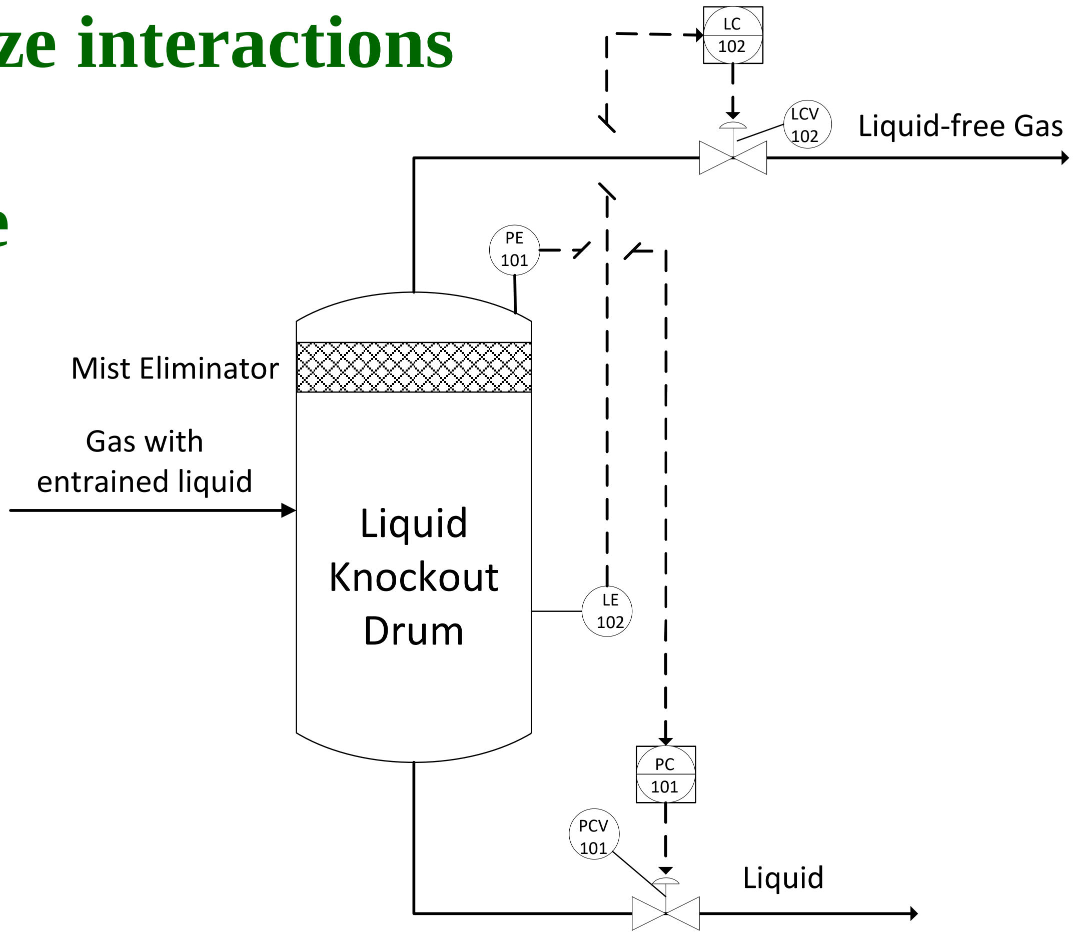
The controller adjustment is known as the output.



Example problem 1: the liquid knockout drum
Step 4

Match up the MVs and CVs to build the feedback control loops – match them up for best stability -- minimize interactions

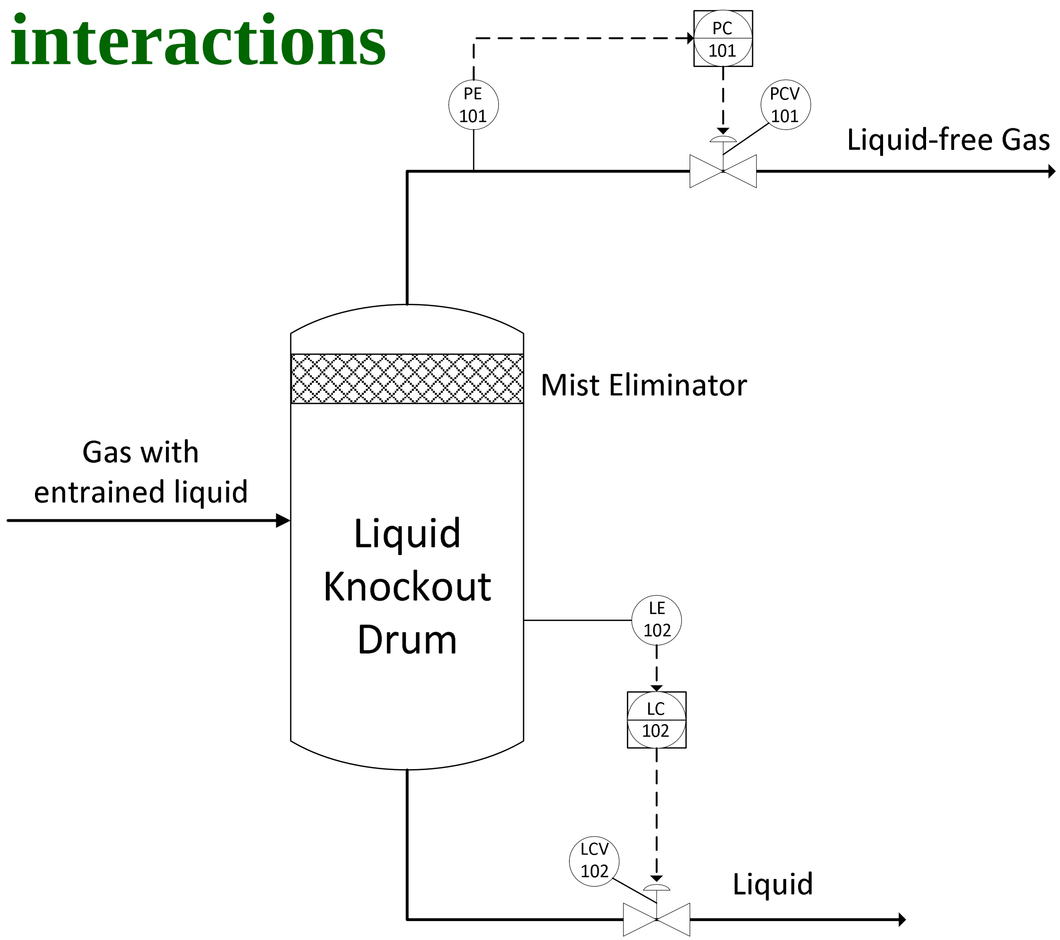
This is an example of a coupled control system



Example problem 1: the liquid knockout drum
Step 4

Match up the MVs and CVs to build the feedback control loops – match them up for best stability -- minimize interactions

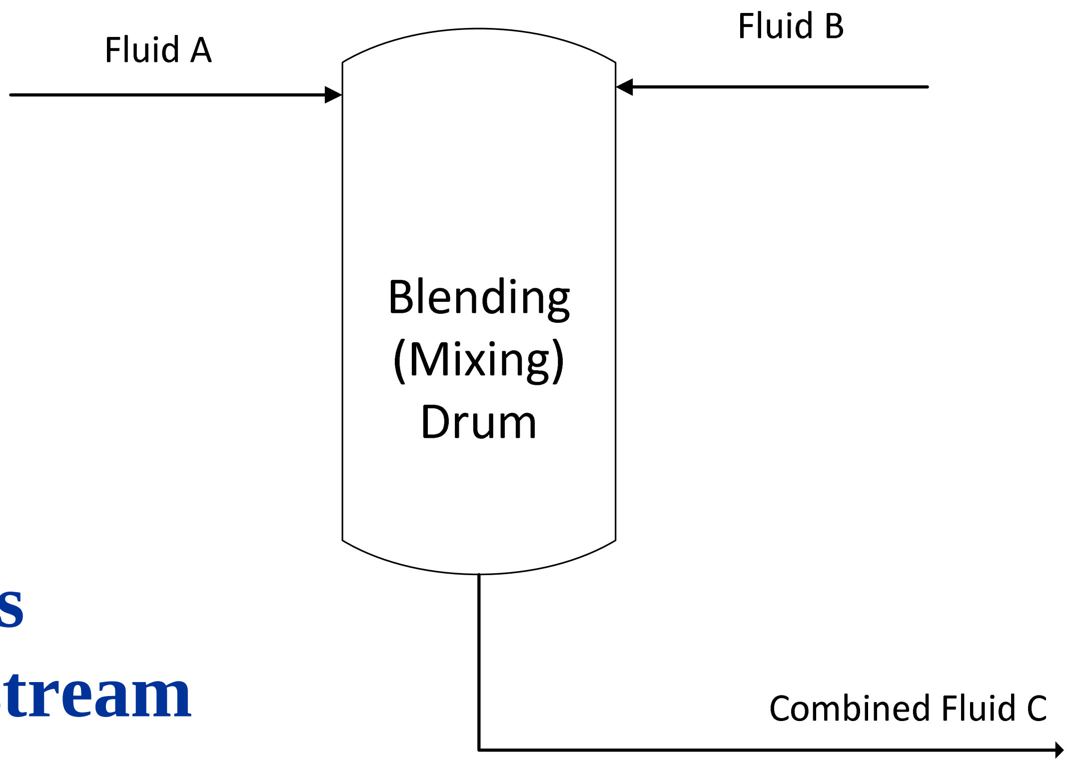
This is an example of a decoupled control system



Example problem 2: A Mixing Drum

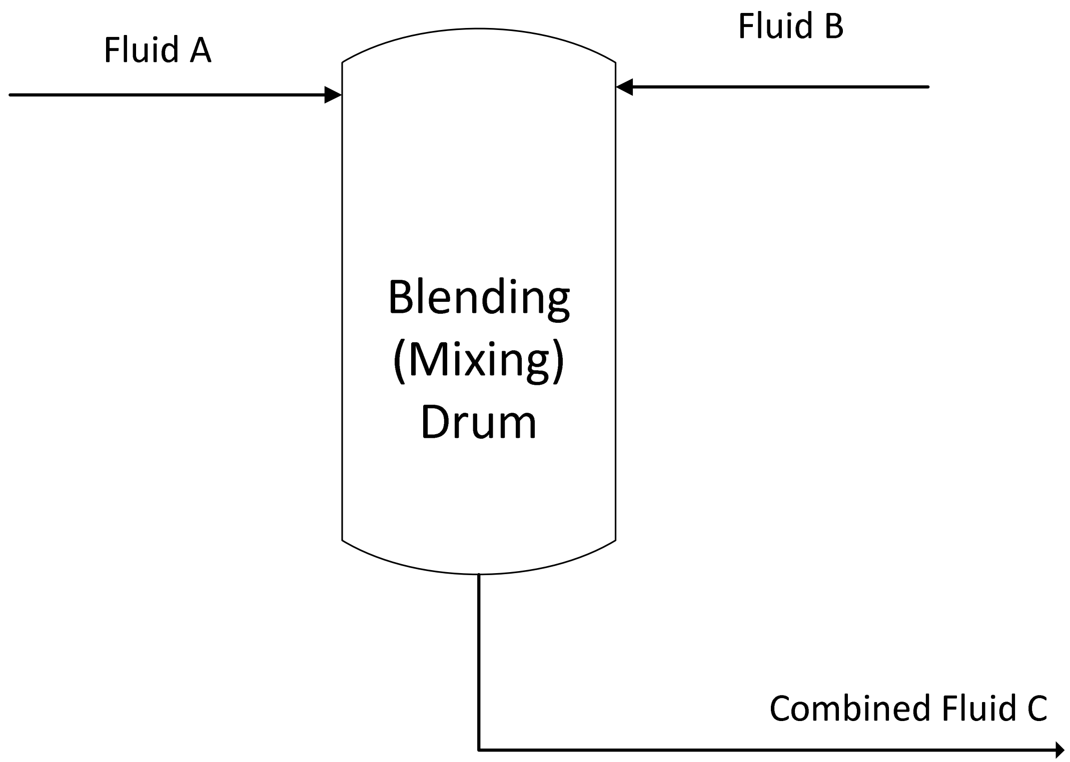
Try this one . . .

Blend in the amount of fluid B necessary so that the combined fluid has a pH that matches the desired value. Fluid A flow is controlled by the upstream process.



Example problem 2: A Mixing Drum

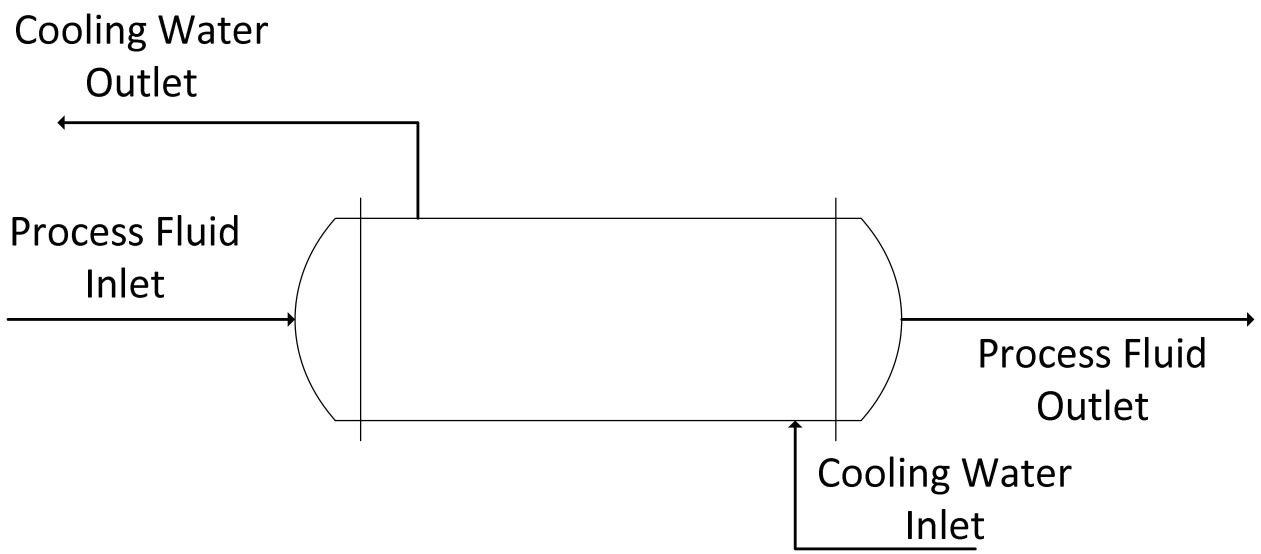
Answer. . .



Example problem 3: A Process-Utility Heat Exchanger to Cool the Process Stream

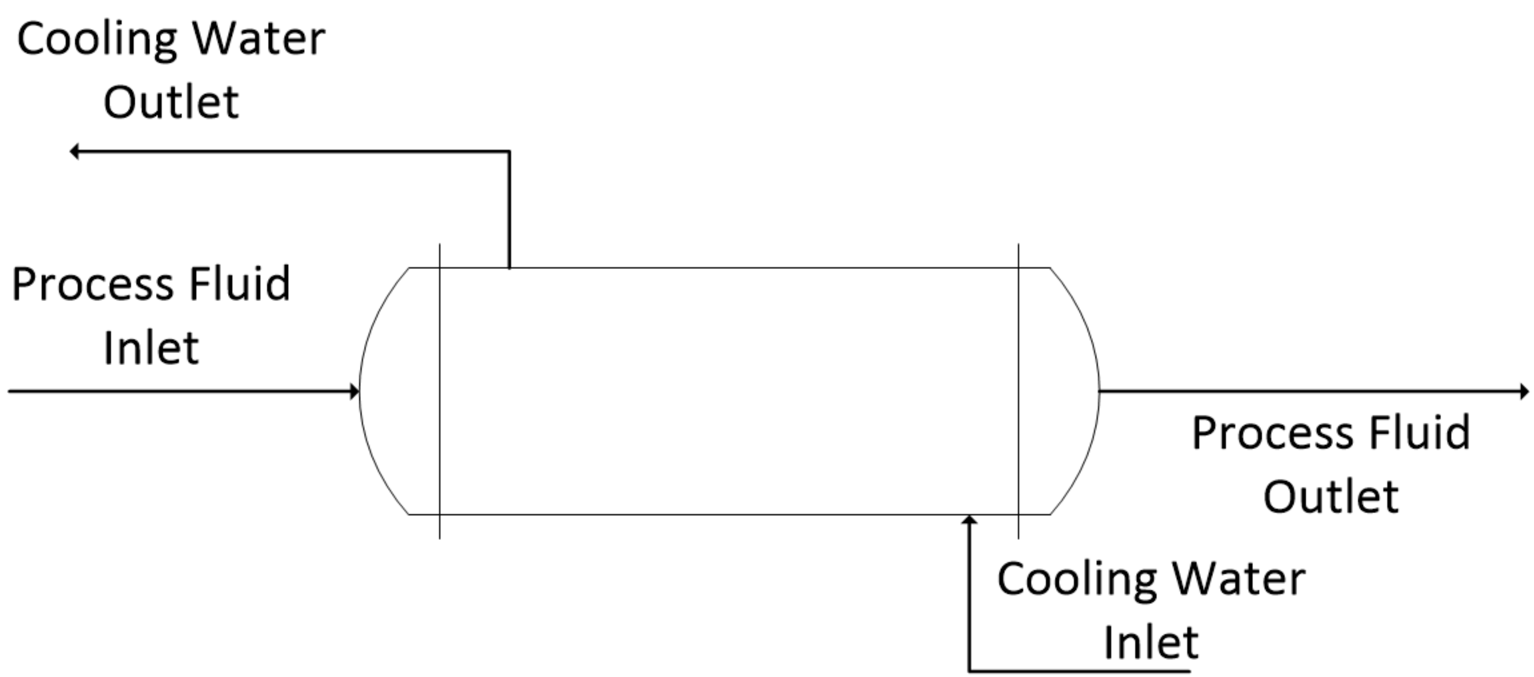
Now try this one . . .

Use cooling water to reduce the temp of the process fluid to a desired value



Example problem 3: A Process-Utility Heat Exchanger to Cool the Process Stream

Answer . . .

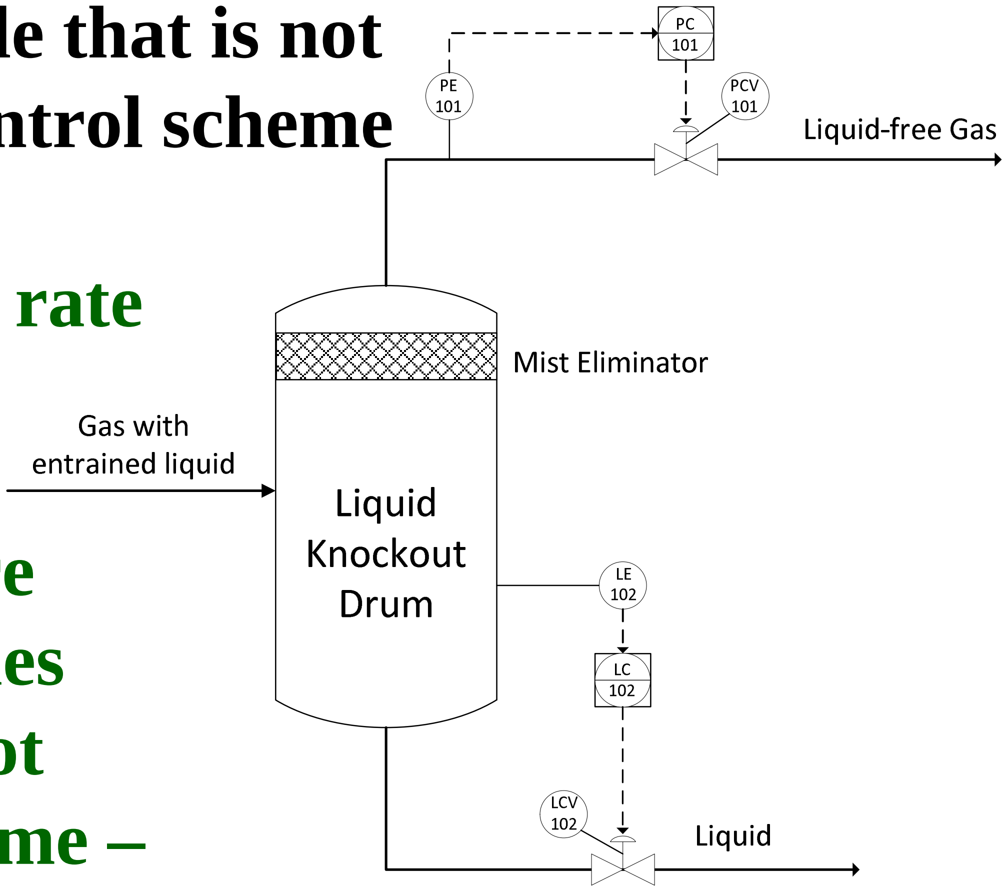


Disturbance Variables

An independent variable that is not part of the feedback control scheme

Example: the inlet flow rate

The outlet flow rates are not disturbance variables even though they are not part of the control scheme – they are dependent variables



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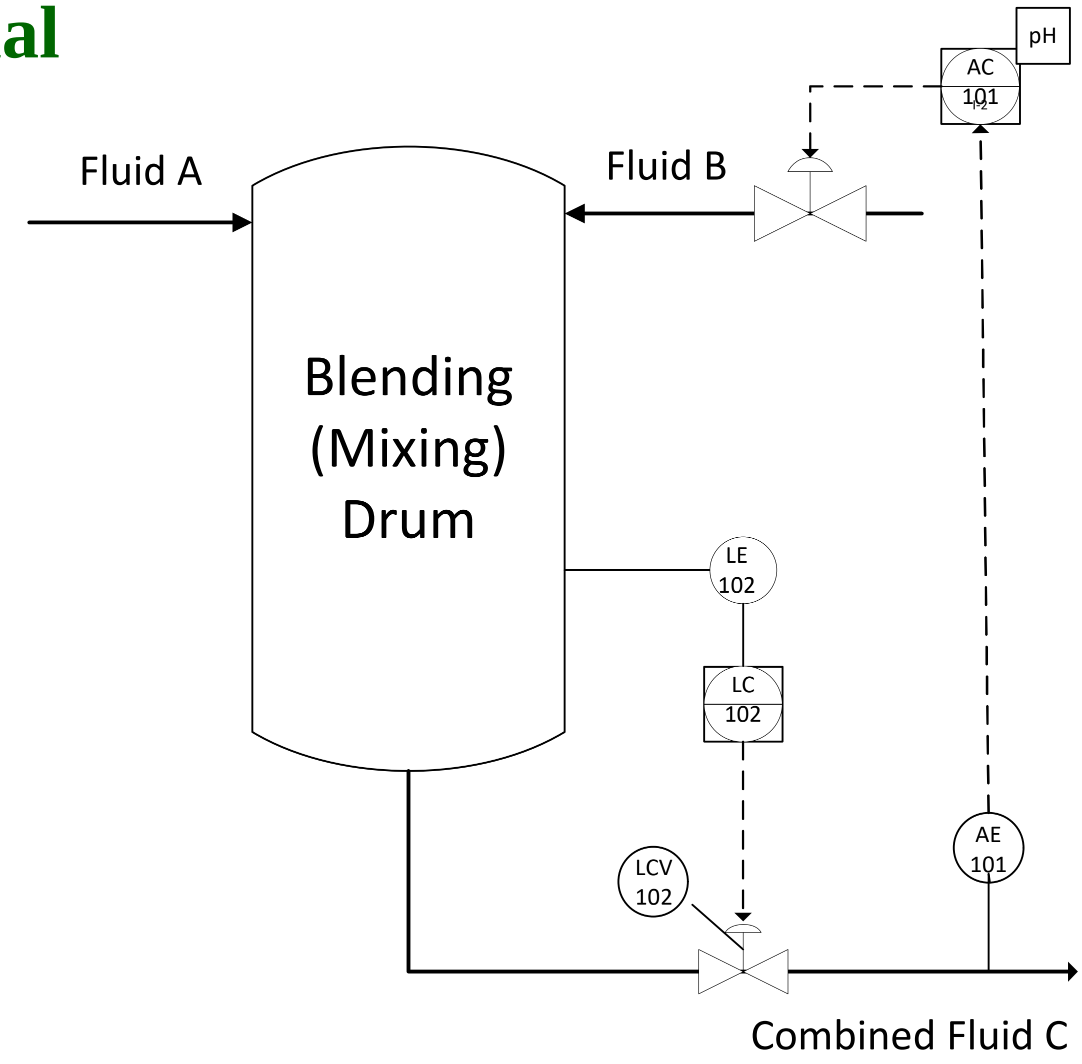
Disturbance Variables

What are the potential DVs for this system?



Feedforward Control

- **Is a way to use the measurement associated with a disturbance variable to adjust the control scheme.**
- **Also known as open loop control. Why?**
  - **There is no direct feedback from the MV to measure how well the adjustment works**
- **A FF control loop is almost always combined with a FB control loop rather than used by itself**

Feedforward Control

A FF control loop is almost always combined with a FB control loop rather than used by itself:

1. **The error from the FF and FB controllers are added together when the responsiveness of the two control loops are similar.**
2. **The two controllers are nested in a cascade control scheme (will cover later in this chapter) when the FF control loop is much more responsive than the FB control loop.**

Feedforward Control – Configuration #1

Step 1. Identify a key disturbance variable

Step 2. Identify a good measurement variable for the disturbance variable

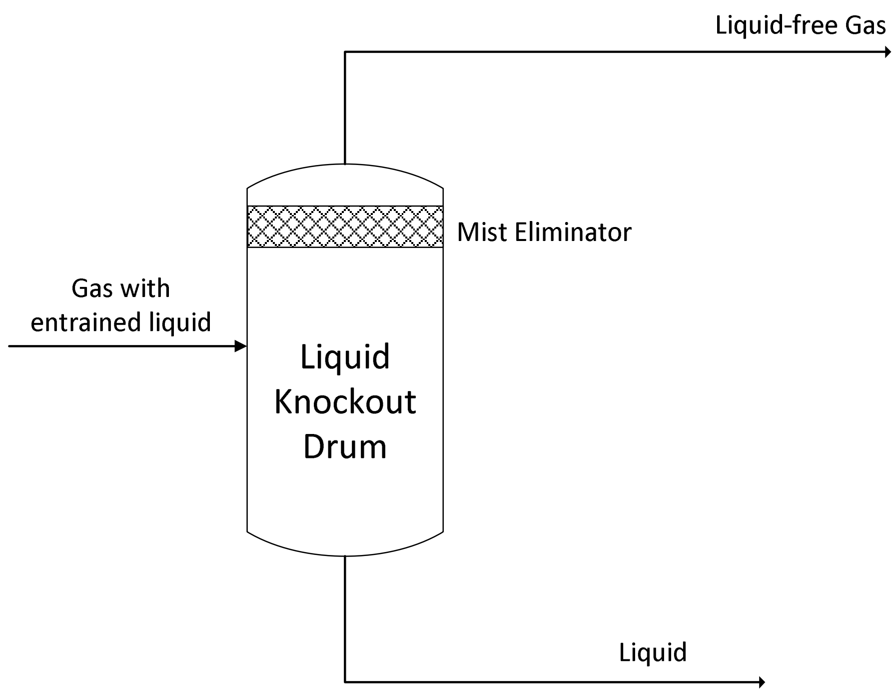
Step 3. Construct a feedforward control loop

Step 4. Identify which feedback control loop is most sensitive to changes in the disturbance variable.

Step 5. Add the FF and FB outputs together and use the combined output to adjust the CV

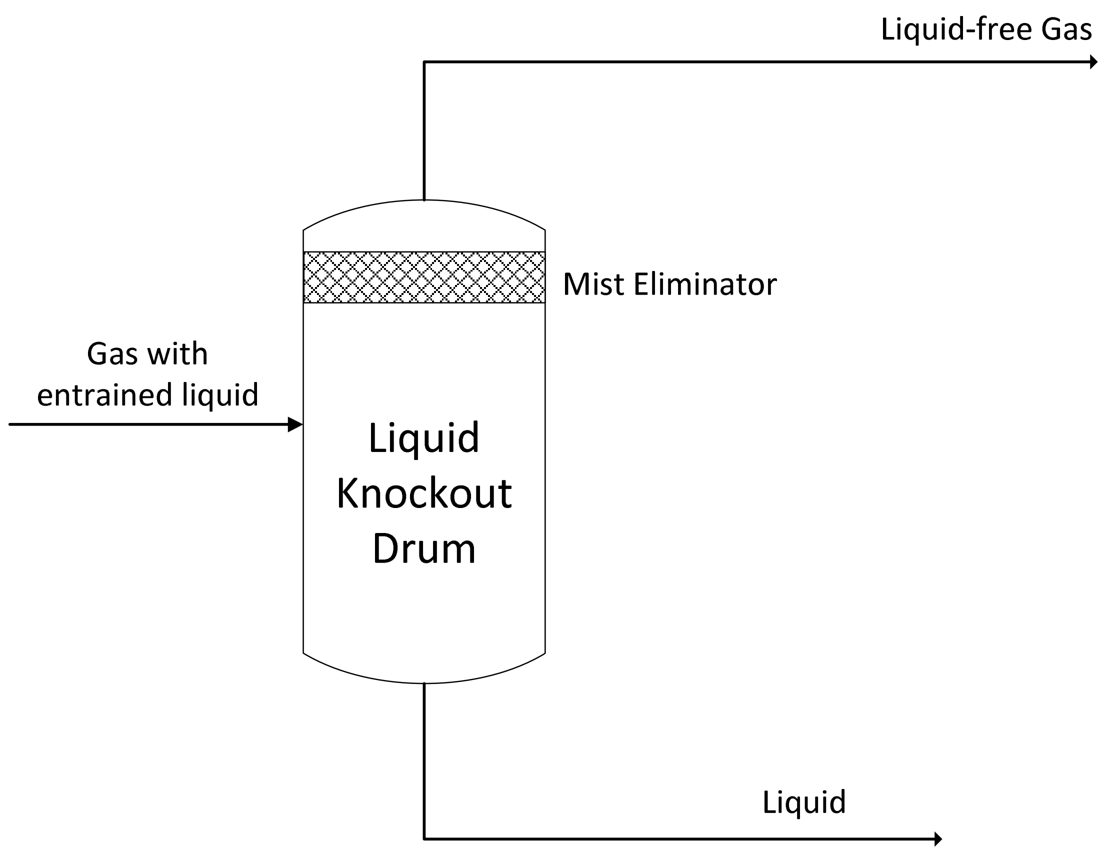
Example 1

How would you construct a FF/FB control scheme to adjust for changes in the inlet flow rate into a liquid knockout drum?



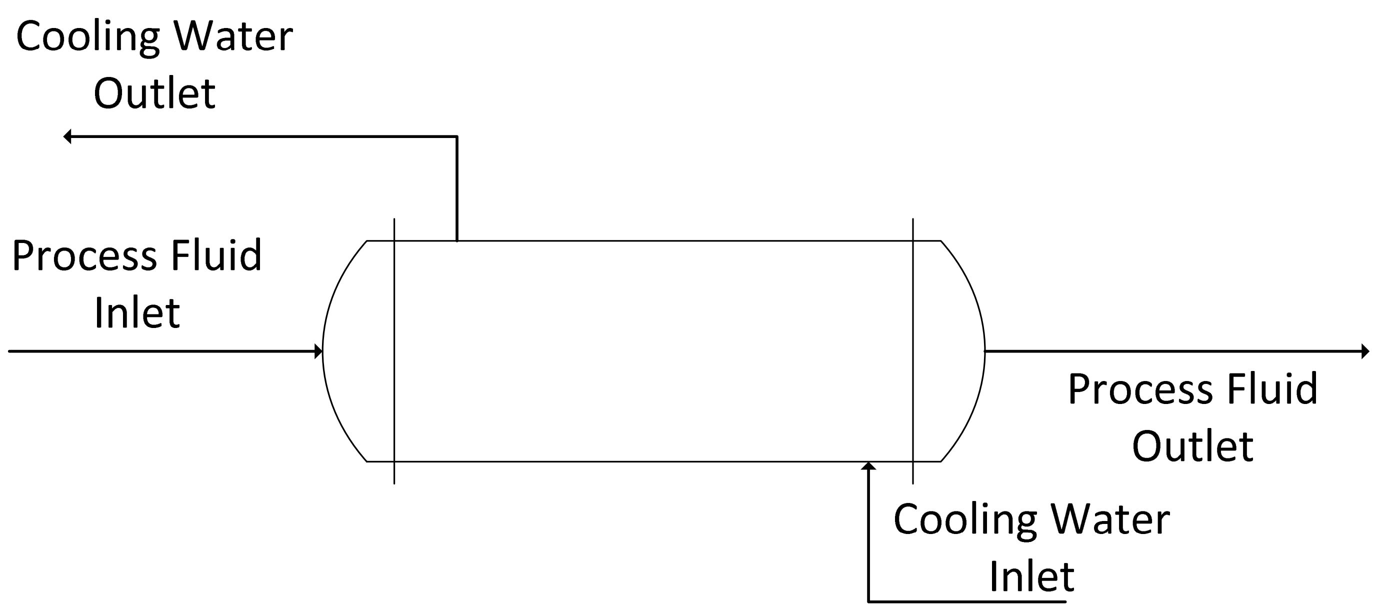
Example 1

Answer . . .



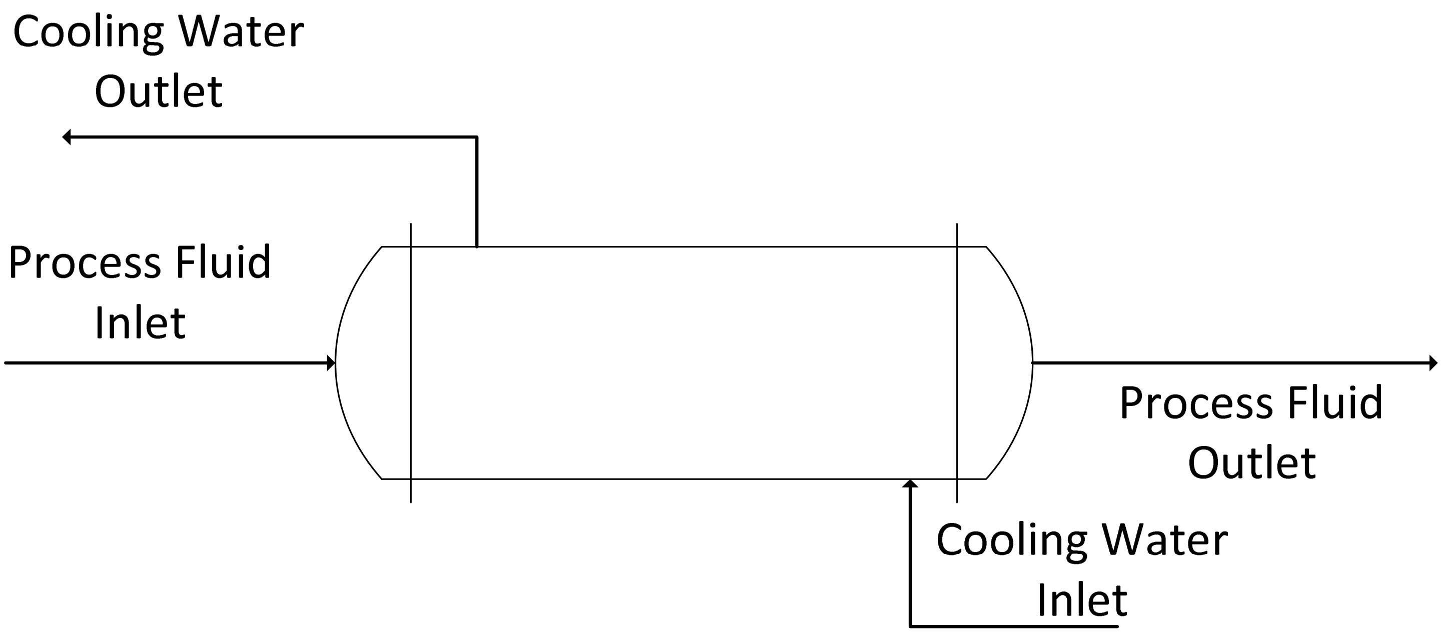
Example 2

How would you construct a FF/FB control scheme to adjust for changes in the temperature of the inlet cooling water?



Example 2

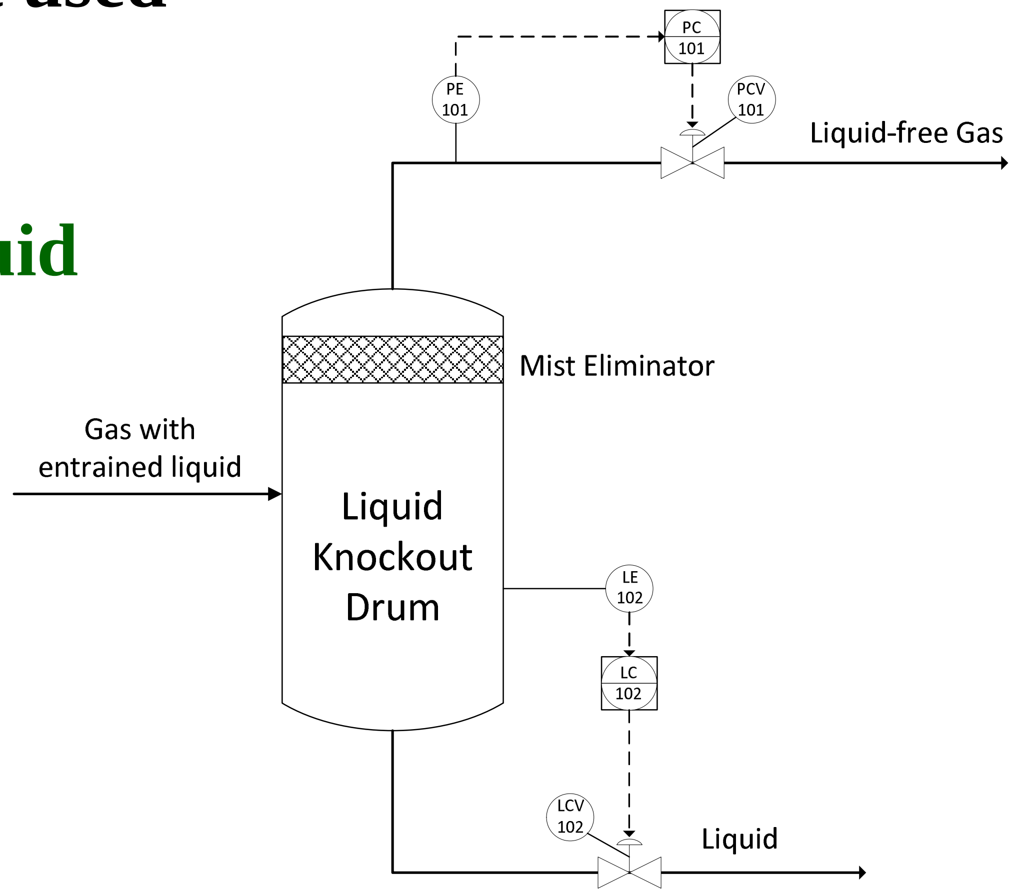
Answer . . .



Related Variables

A dependent variable that is affected by a control variable but not used as an MV

Example: the outlet liquid flow rate



Related Variables

There are many reasons why a variable may be related:

- **Due to chemical or physical properties – VLE, *f*(T), *f*(P), etc.**
- **Due to the design of the unit operation – Pump curves, etc.**

Related Variables

Two ways to use the information contained in related variables to improve a control scheme are:

1. **Ratio controls**

2. **Cascade controls – which can also be used to configure FF/FB schemes**

Ratio Controls

Are used when there is a correlation between the desired values of two separate MVs.

Example: I want to make the correct stoichiometric ratio for a reaction - - -

$$A + 2B \rightarrow C$$

Instead of just setting the flow rate of B into a reactor, I can take the ratio of B to A and compare this ratio to the setpoint – the desired value (ideally 0.5) and used by the controller.

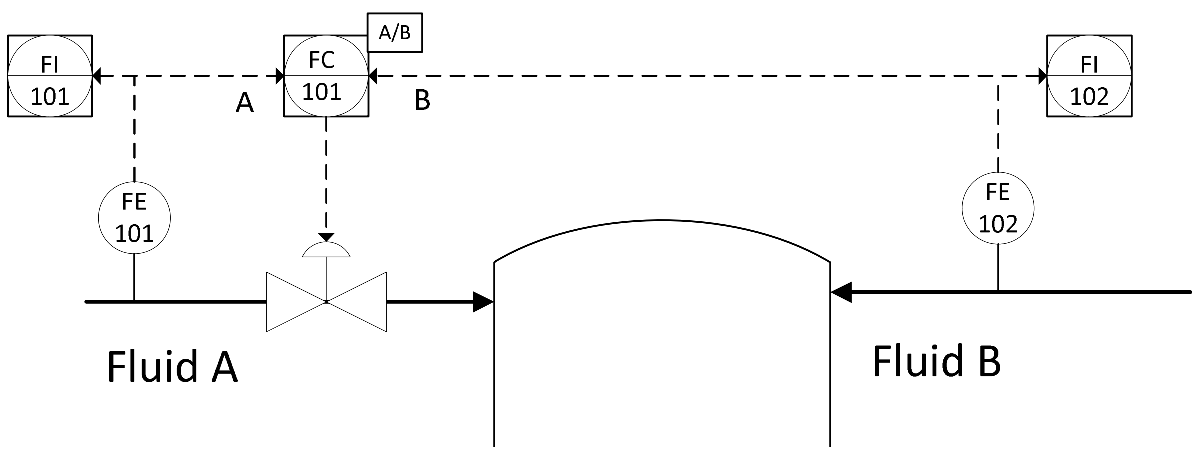
This ratio is known as the measurement ratio.

Ratio Controls

Example: I want to make the correct stoichiometric ratio for a reaction - - -

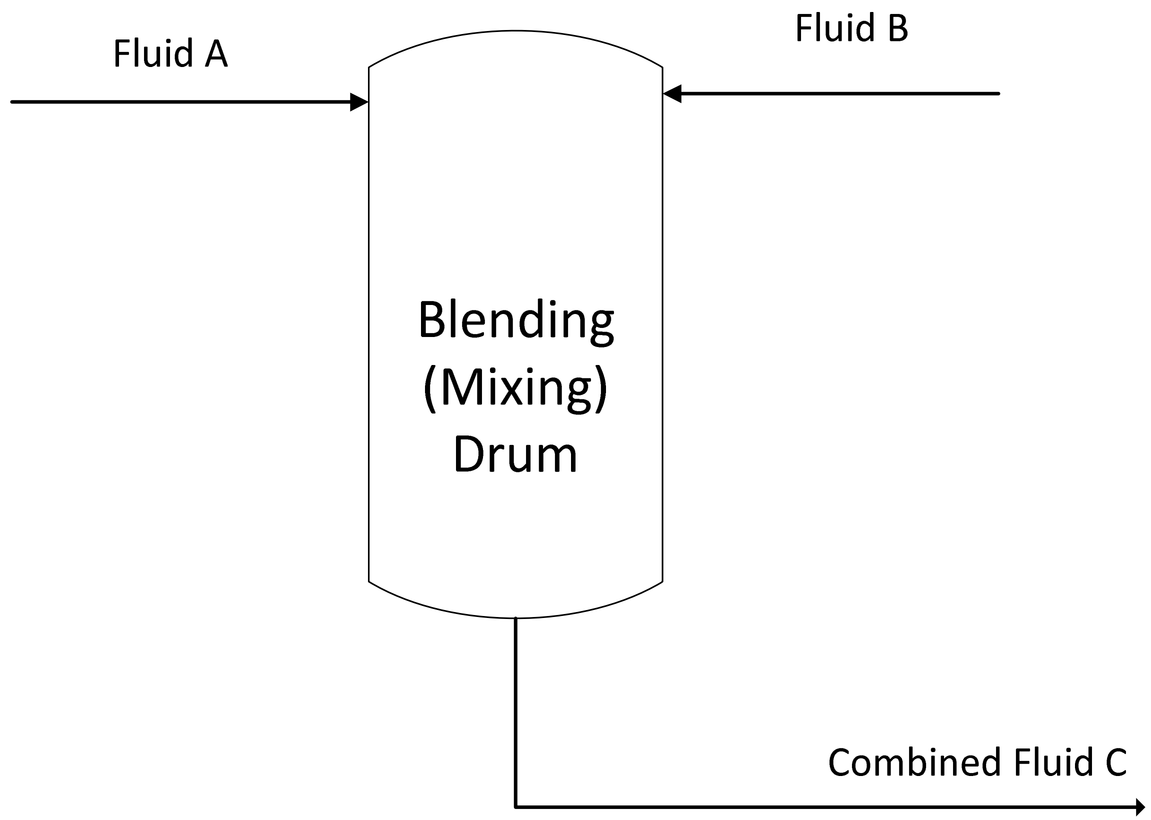
$$A + 2B \rightarrow C$$

Instead of just setting the flow rate of B into a reactor, I can take the ratio of A to B and compare this ratio to the setpoint – the desired value (ideally 0.5) and used by the controller.



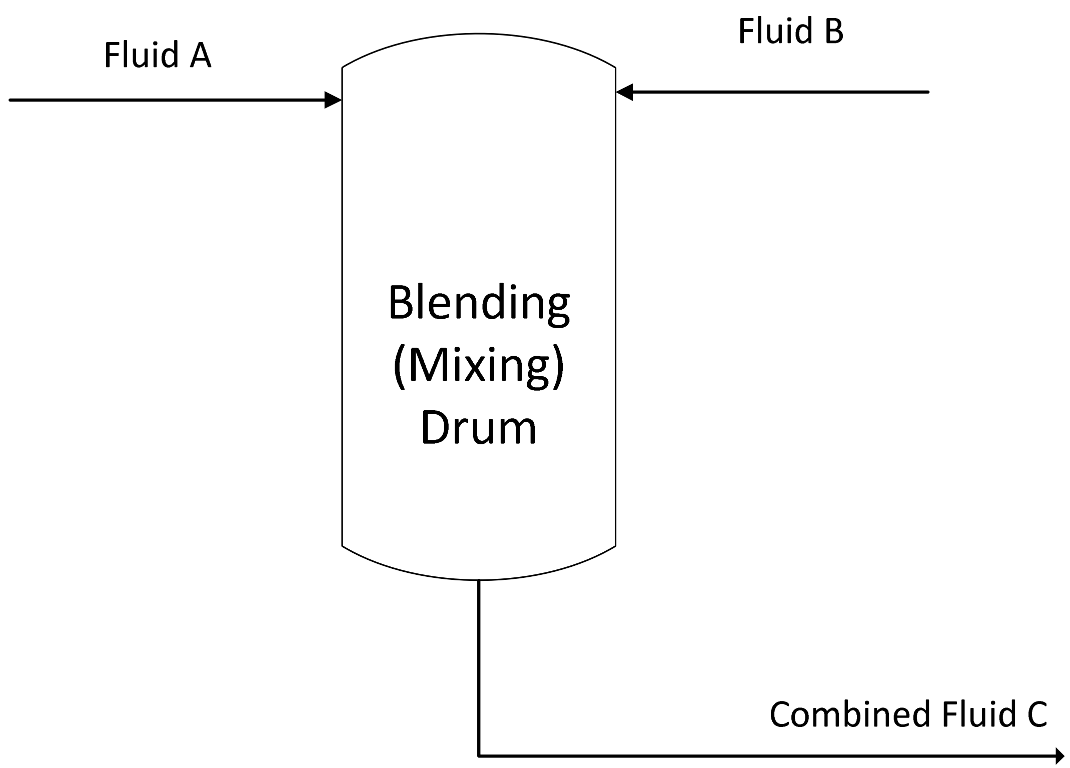
Ratio Controls

Example: How do you get the correct ratio of B to A?



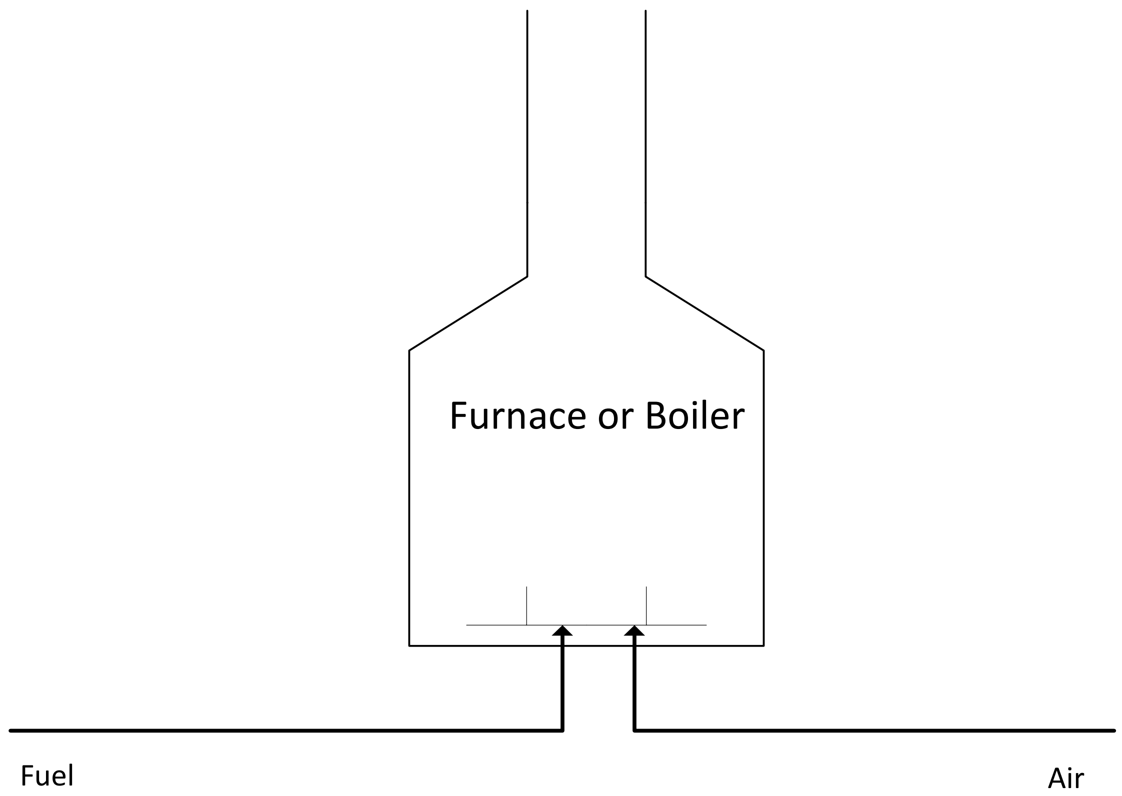
Ratio Controls

Answer . . .



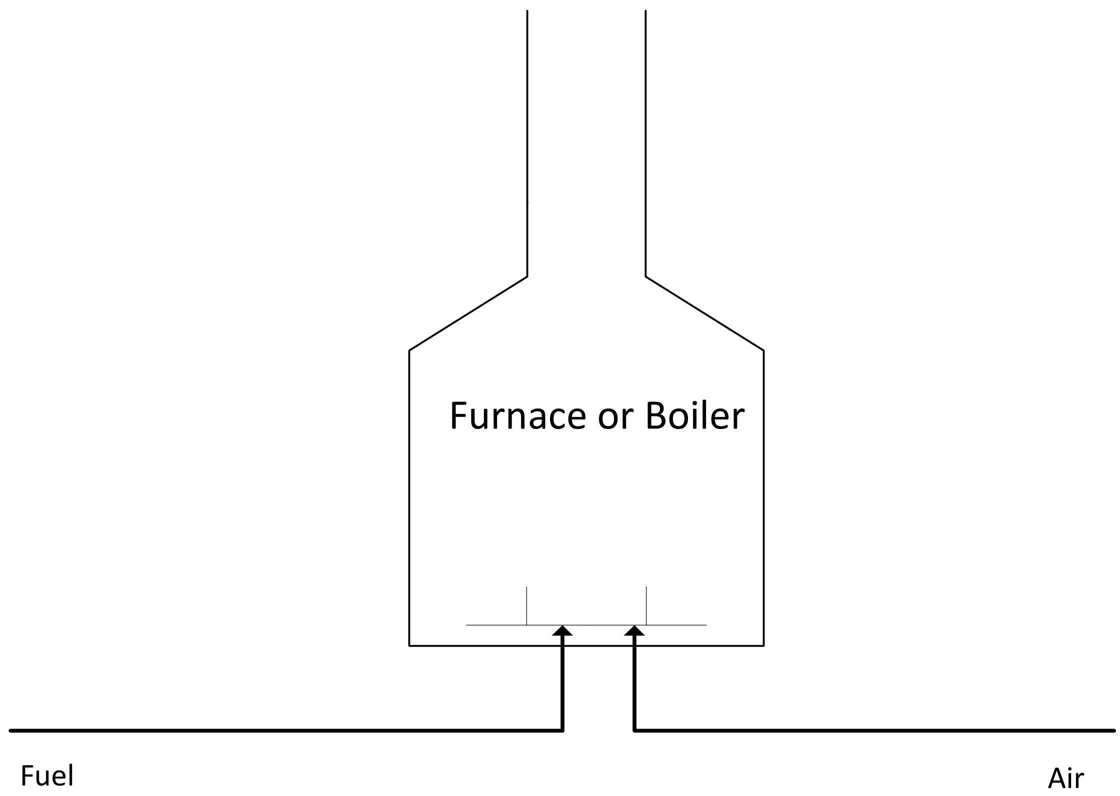
Ratio Controls

Example: How do you get the correct air to fuel ratio?



Ratio Controls

Answer . . . .



Cascade Control Loops

- **Pairs two control loops together.**
  - **The overall governing loop is known as the Master or outer loop**
  - **One or more additional control loops are included. These are known as Slave or inner loops. When there are more than one slave loops, they are known as Nested Slave loops.**
  - **The Master loop output is used to adjust the setpoint of the slave loop.**

Cascade Control Loops

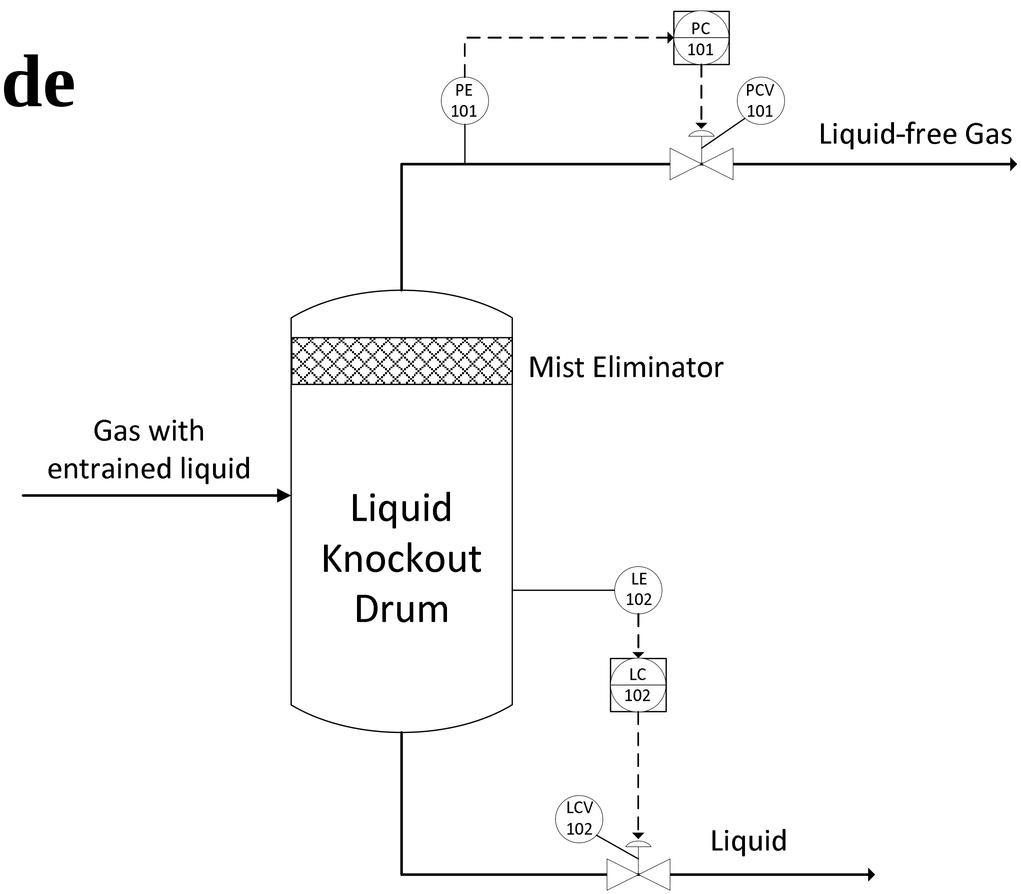
- **Pairs two control loops together.**
  - **The Master loop output is used to adjust the setpoint of the slave loop.**
  - **This adjustment is known as an external setpoint (ESP) or remote setpoint.**
    - **When an ESP is not used, the setpoint is specified by the control (board) operator**
  - **The Slave loop must be around an order of magnitude more responsive to changes in its MV than the Master loop.**

Cascade Control Loops

1. **Are used to make a non-responsive FB control loop more responsive.**
   - Recall that level and analysis are the most non-responsive of the MV parameters
   - The most common is using flow slave loop to improve the responsiveness of a level control master.
   - The next most common is to using a slave loop to improve the responsiveness of an analyzer control master.

Cascade Control Loops

Example: Make the bottoms level control more responsive using a cascade control loop.



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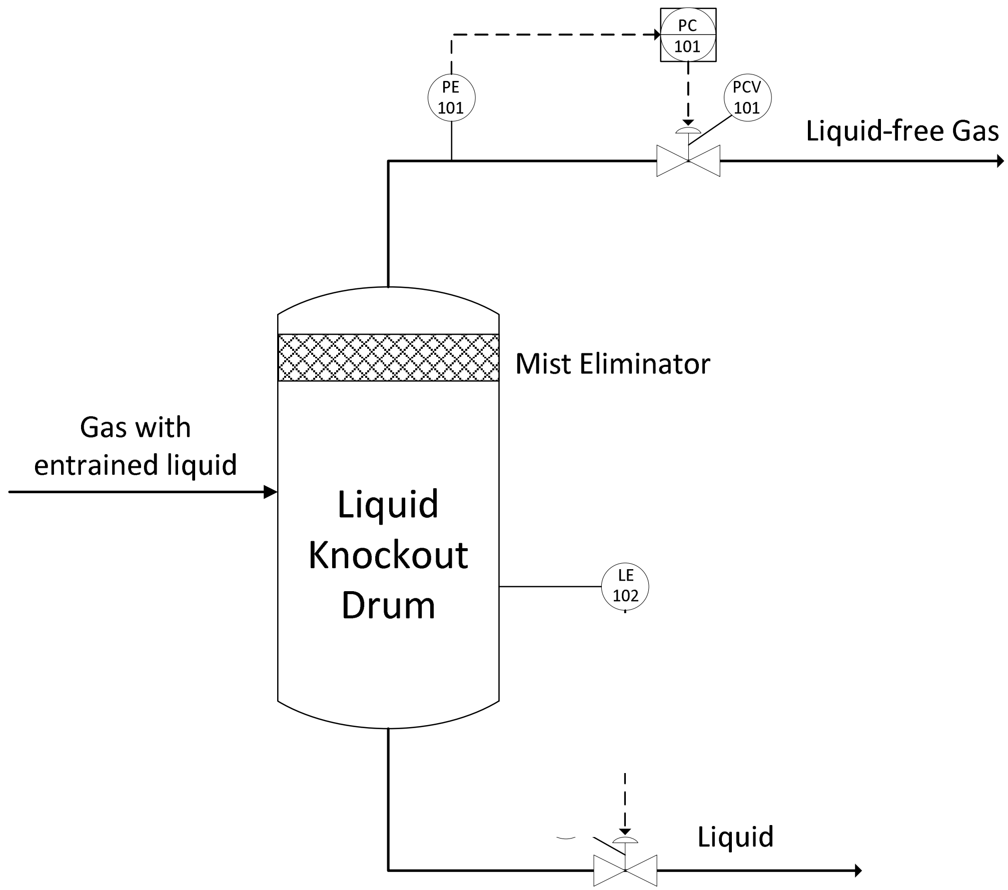
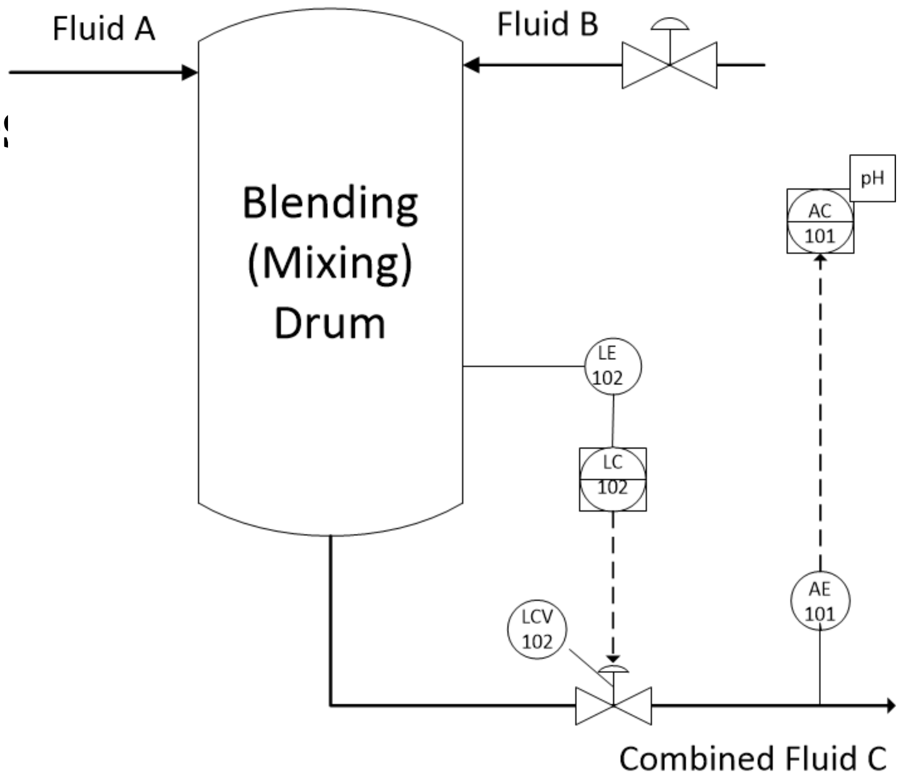
Cascade Control Loops

Answer . . .



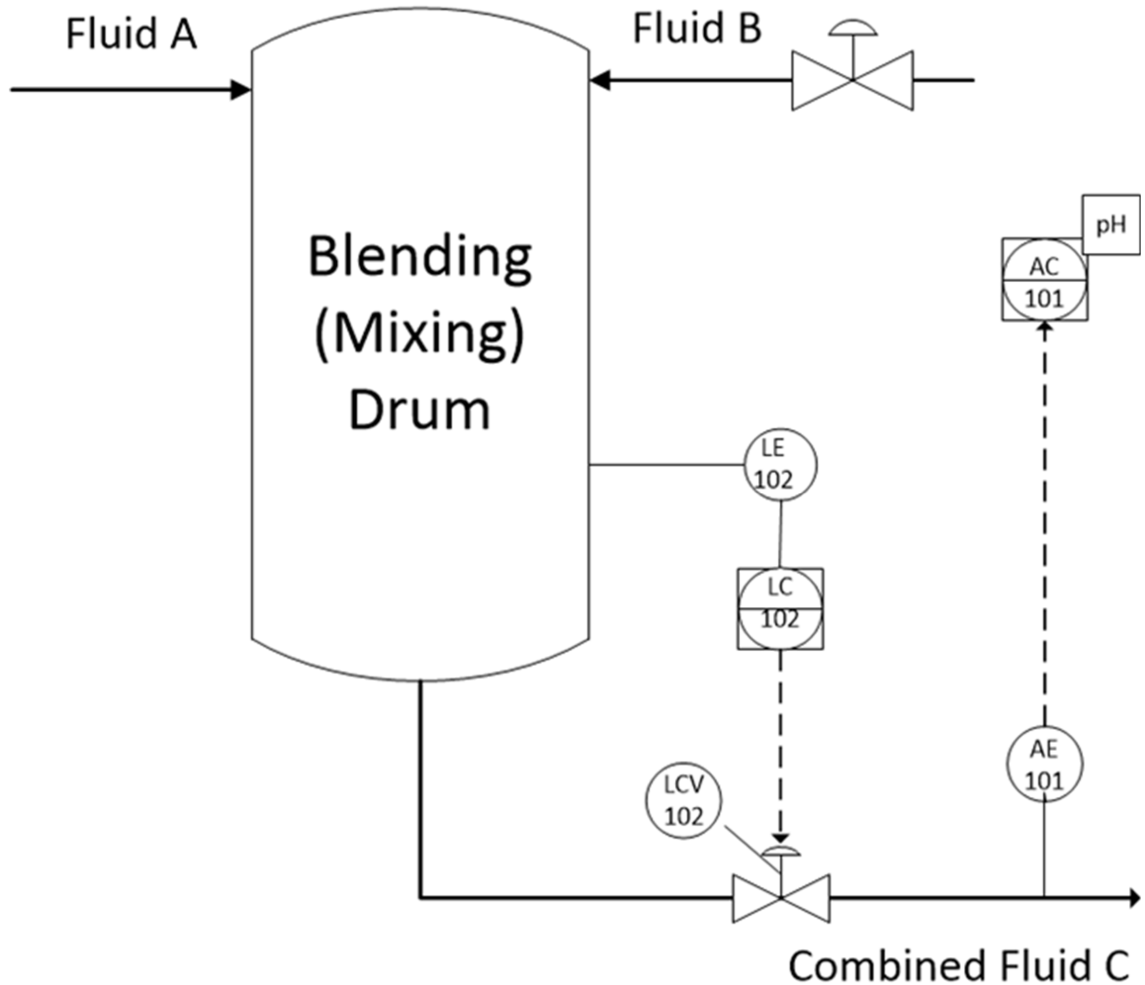
Cascade Controls

Example: Instead of measuring pH, which is an indirect but responsive MV, modify the control scheme to measure composition of "A" in the combined fluid outlet stream. Use a cascade control to improve the responsivene[ss] of this control loop.



Cascade Controls

Answer . . .

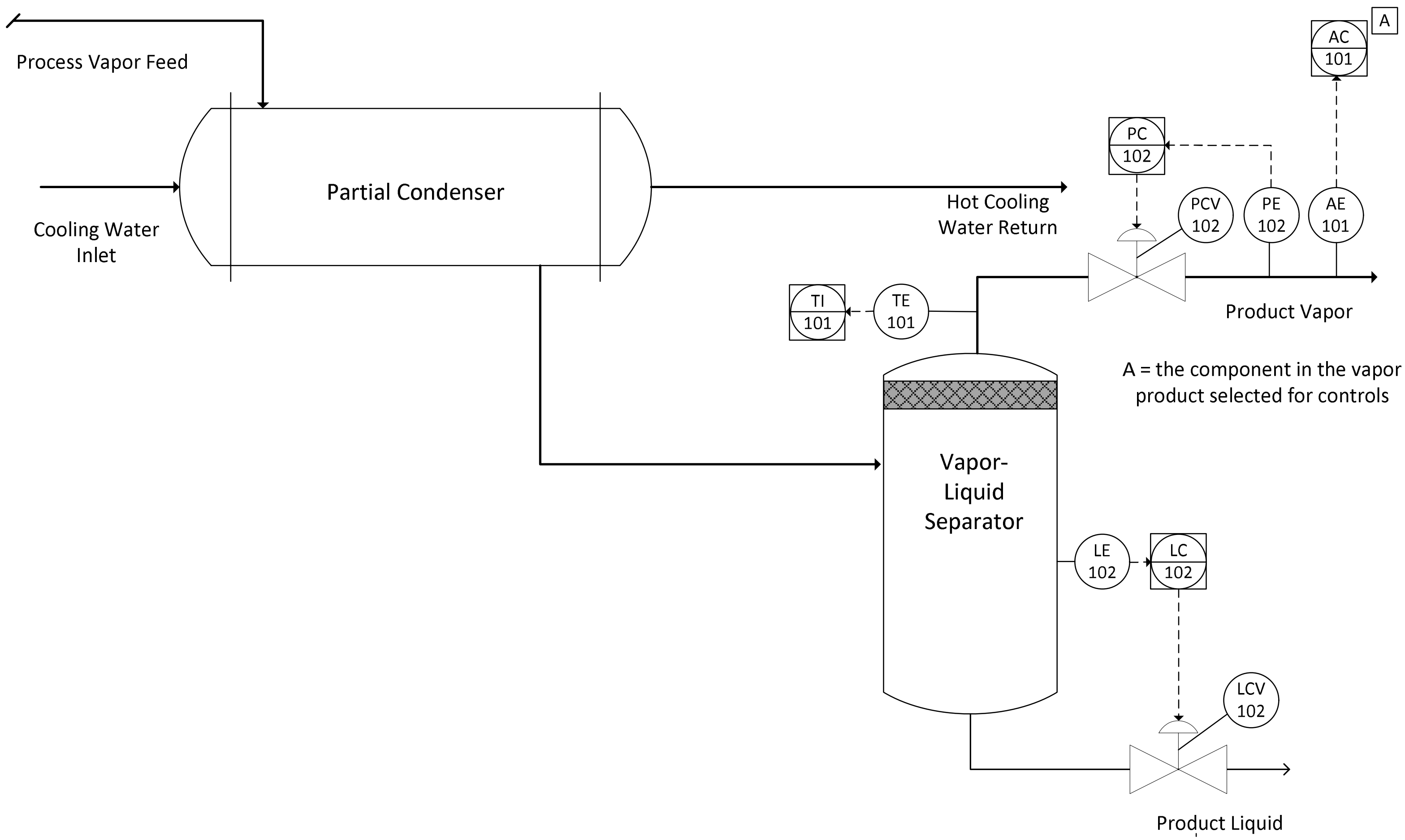


Cascade Control Loops

1. Are used to make a non-responsive FB control loop more responsive.
2. Used to couple a responsive FF control loop with a less responsive FB control loop.

Cascade Controls

Example: Use FF/FB type cascade control scheme to minimize the possibility that a change in the overhead vapor flow rate will cause the distillate product to go off-specification for component A.



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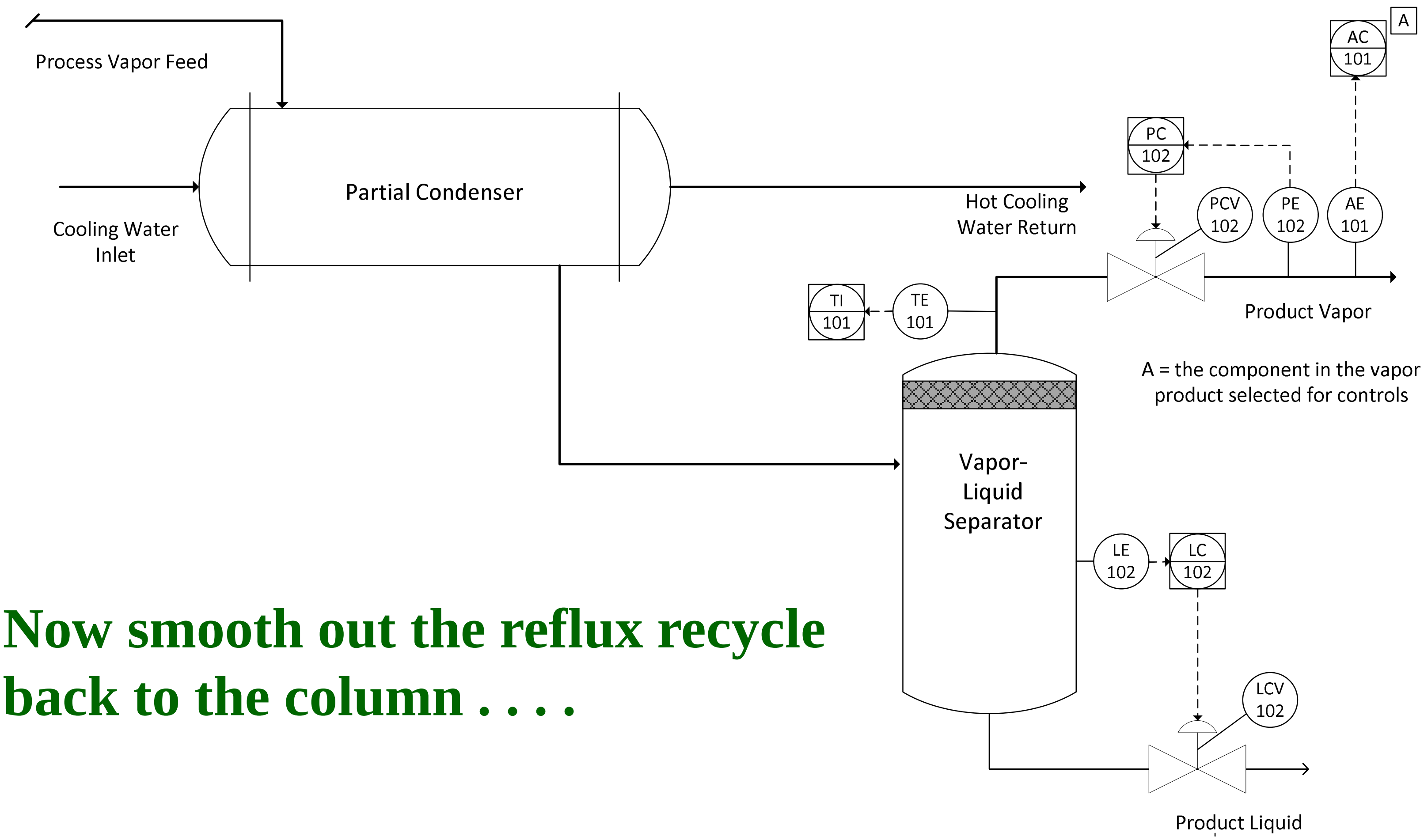
Cascade Controls

Answer:



Now smooth out the reflux recycle back to the column . . . .

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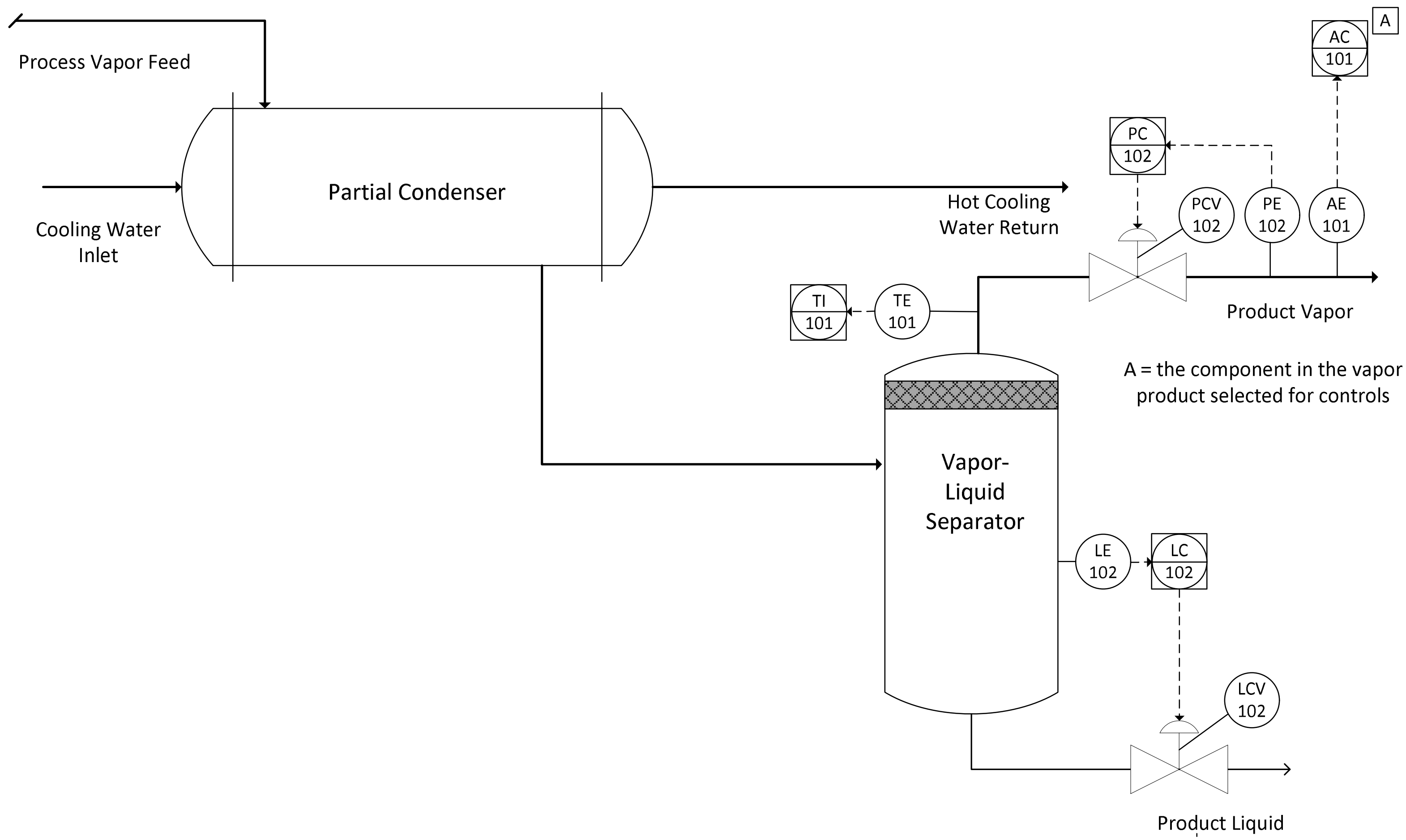
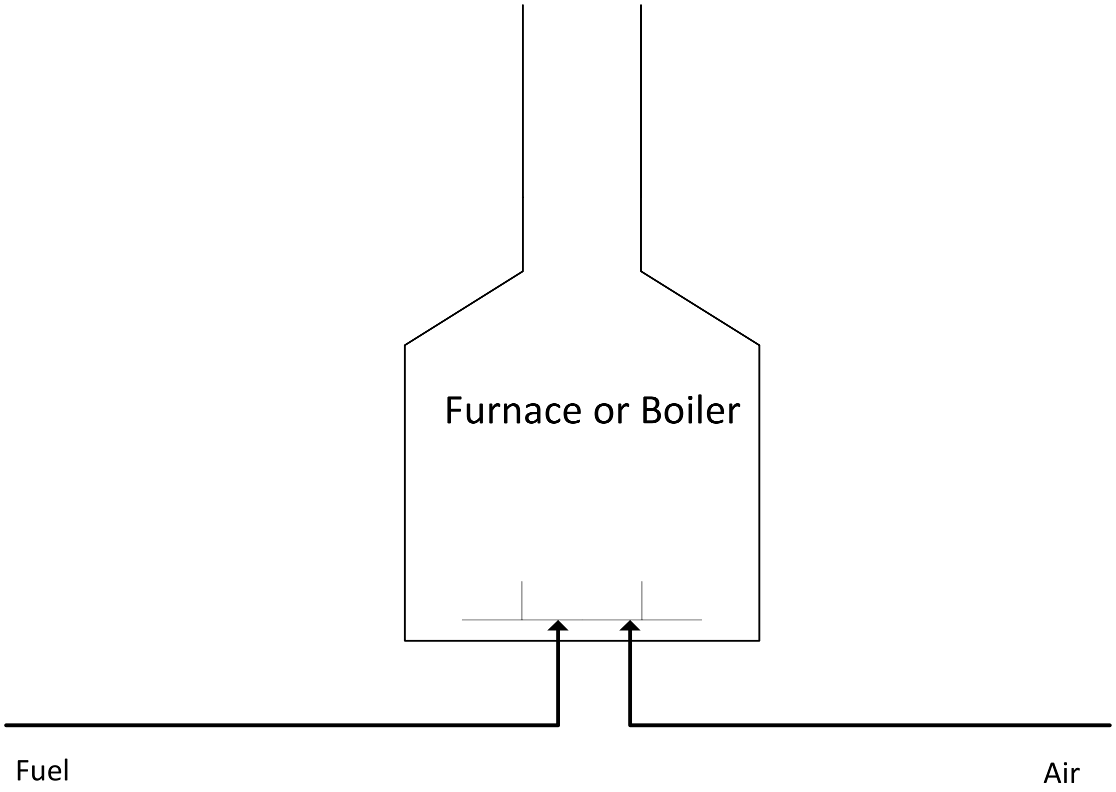
Cascade Controls

Answer:



Cascade Controls

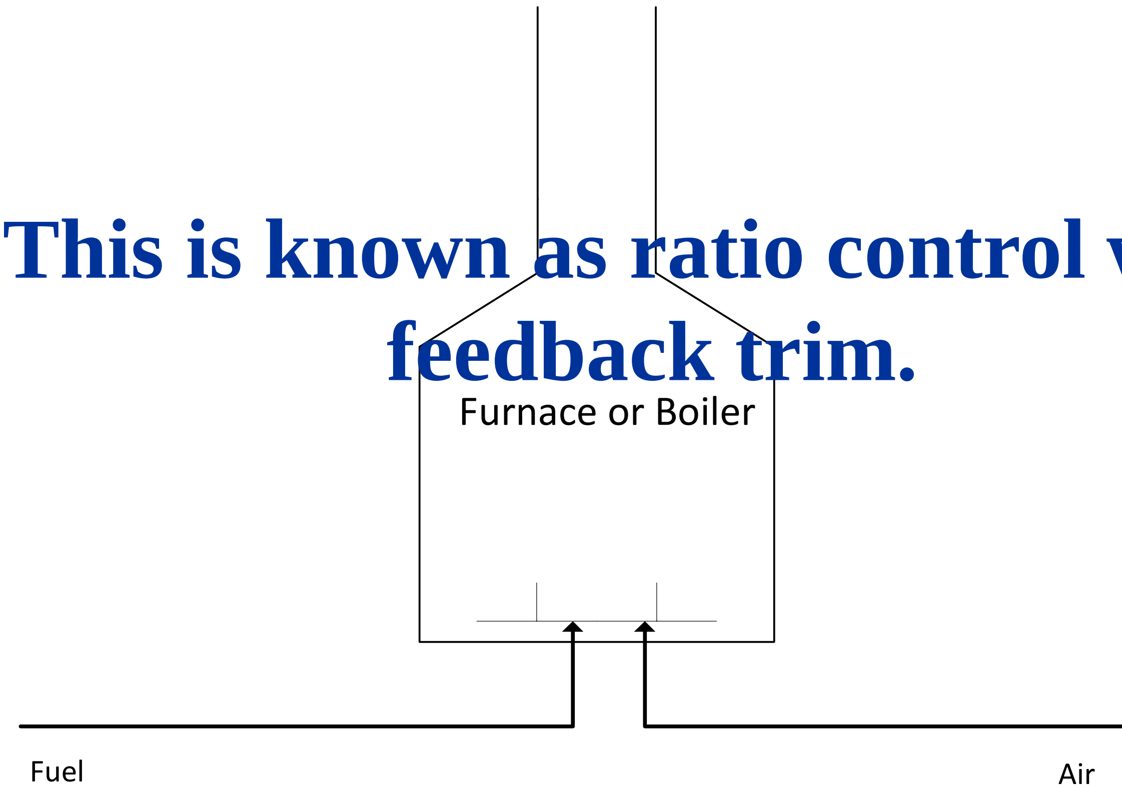
Example: How can you insure that the ratio you specify for the air/fuel ratio is correct? Use a cascade control scheme to accomplish this.



Cascade Controls

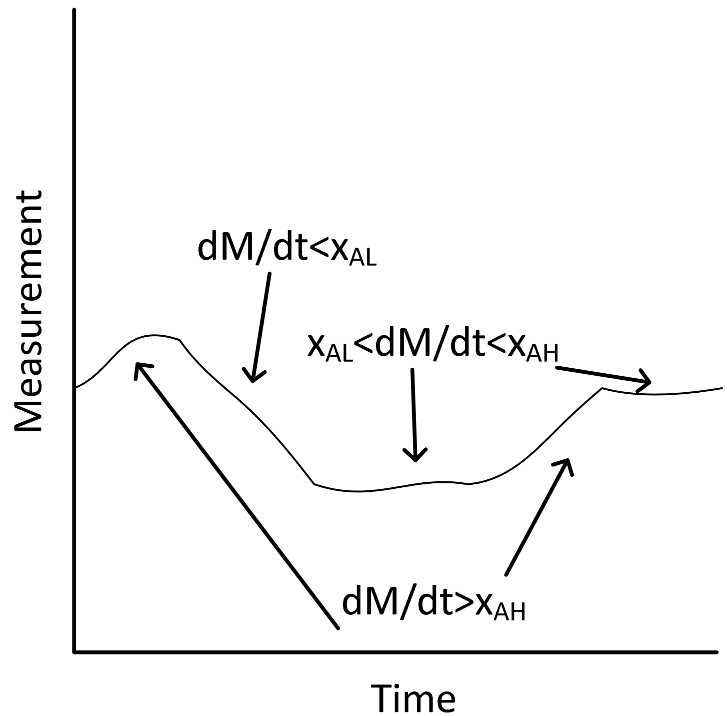
Answer . . .

This is known as ratio control with feedback trim.



Process Alarms

- **All DCS controller blocks contain high and low level alarm functions**
  - **Usually based on the measurement value**
  - **Can also be based on the rate of change of the MV. This is known as a deviation alarm.**



Safety Systems

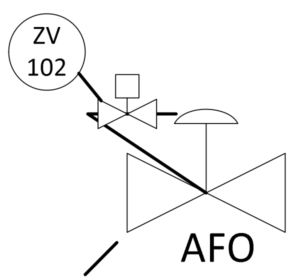
- **Independent of the process measurement and control functions**
- **Are invoked only in an emergency**
  - **Will cause upsets in the process**
  - **Used only when these upsets are less of a problem than not invoking the action of the safety system**

Safety Systems

- The most common include a high-high and/or low-low alarm of a critical measurement variable
- When the setpoint is reached, the safety controller interferes with the normal operation of a control variable.
  - The air supply on a pneumatically operated control valve can cutoff with a block valve. The valve will go to its designed “fail” position.

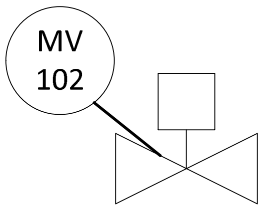
AFO = air fail to open (AFO)

AFC = air fail to close (AFC)



Safety Systems

- The most common include a high-high and/or low-low alarm of a critical measurement variable
- When the setpoint is reached, the safety controller interferes with the normal operation of a control variable.
  - A remotely operated block valve on the process line may be closed.
  - A remotely operated block valve on a secondary fluid line may be opened.



Safety Systems

- The most common include a high-high and/or low-low alarm of a critical measurement variable
- When the setpoint is reached, the safety controller interferes with the normal operation of a control variable.
  - An electrical contact may be opened (or closed)
    - Note: just shutting off a pump or compressor motor is not sufficient, the piping must be physically blocked closed.

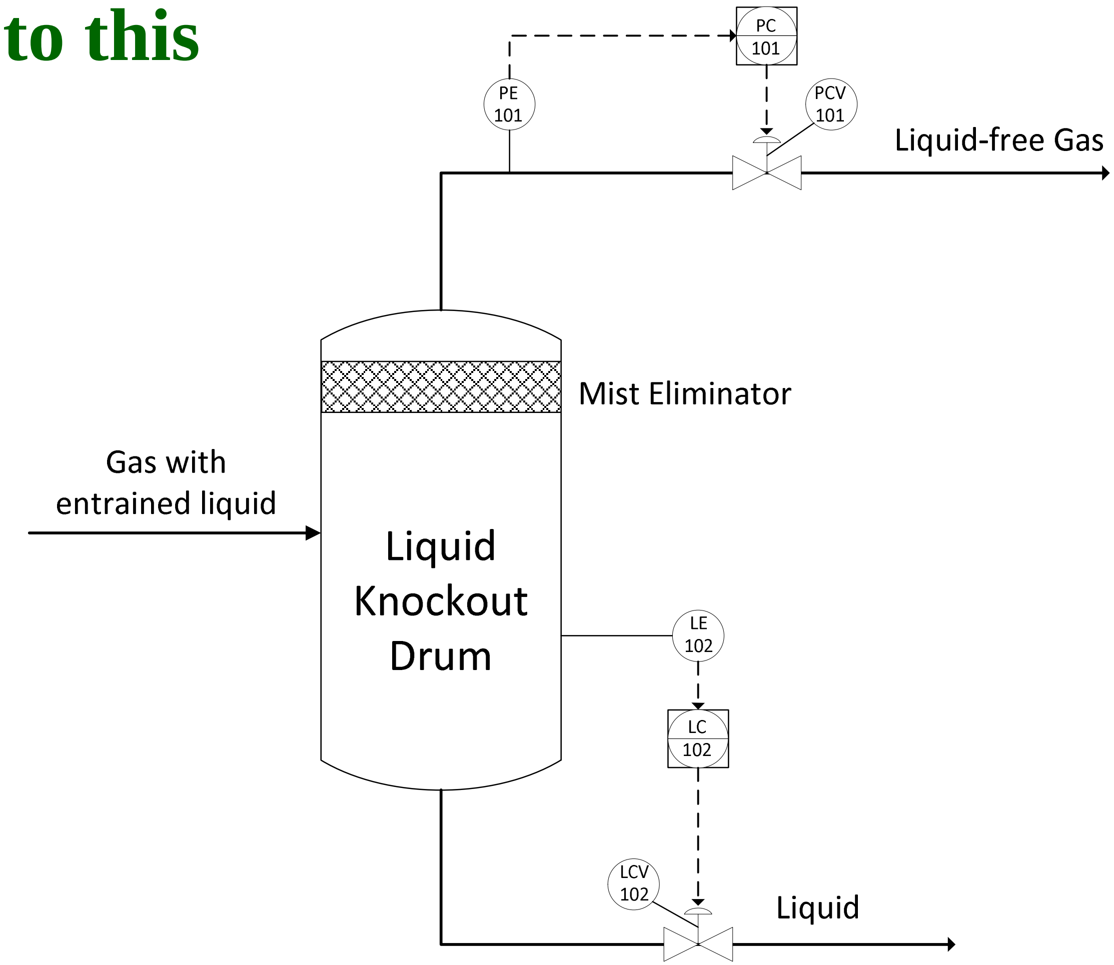
Safety Systems

- **Pressure relief valves, also known as just "relief valves, RVs" are mechanically controlled block valves.**
  - **The valve goes 100% open when the set pressure is reached**
  - **The valve goes 100% closed when the pressure drops below the set pressure**
    - **There is often an offset factor that keeps the valve open below the set pressure until the pressure drops by the offset amount).**

Cascade Control Loops

Add LLAL and HHAL

Safety system loops to this KO drum.



Sequential Logic Control

- **Used for batch and semi-batch processes**
- **A completely different paradigm compared to continuous controls**
- **SQL is often executed in programmable logic controllers, PLCs.**
  - **PLC is the hardware; SQL is the functions performed – we specify the SQL and then program the SQL in the PLC (anyone need to buy a vowel?).**

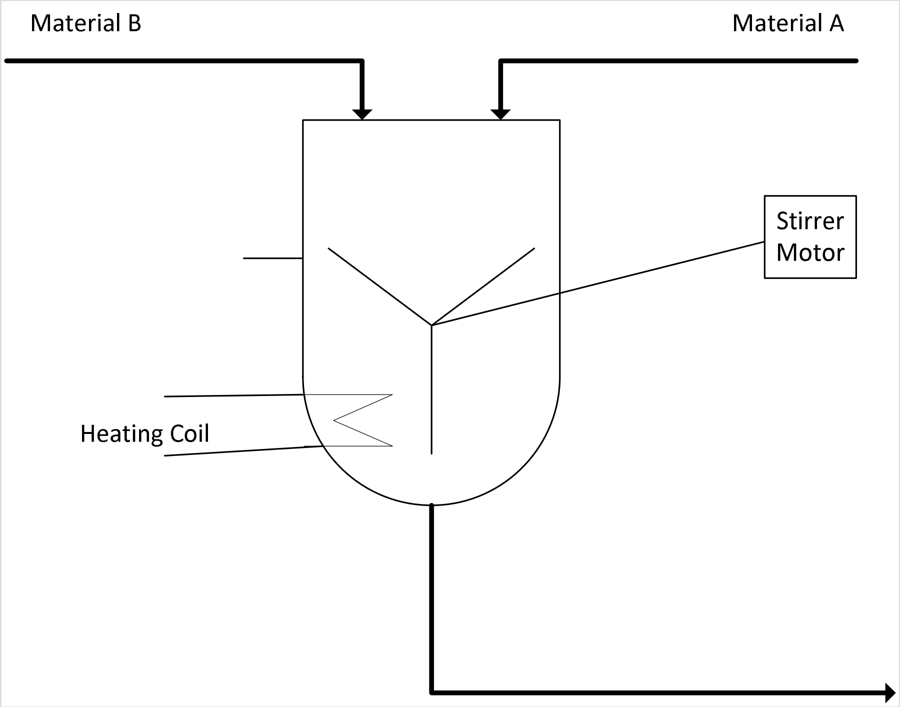
Sequential Logic Control

- **SQL is specified using logic flow diagrams and sequential events tables**
- **The basic instruments and control blocks are shown on the P&IDs, just like continuous controls**

Sequential Logic Control

Example: Batch mixing process. Generate a sequence of steps to perform the following batch process:

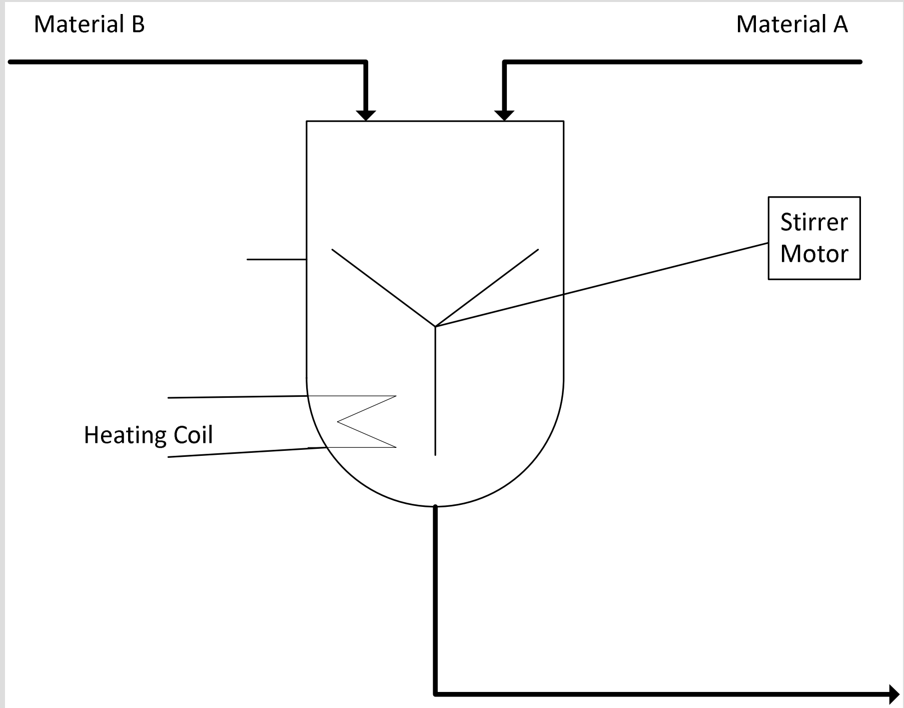
The goal of this process is to add small increments of component B to a drum or tank containing a stoichiometric excess of component A, then heat and mix the two components together until all of component B has been consumed in the reaction of A+B ➔ C.



Once all of B has been consumed, additional component B is added to the reactor and the process is repeated until all of component A has been consumed. Now that the drum/tank contains virtually all component C, the fluid is drained out of the drum/tank.

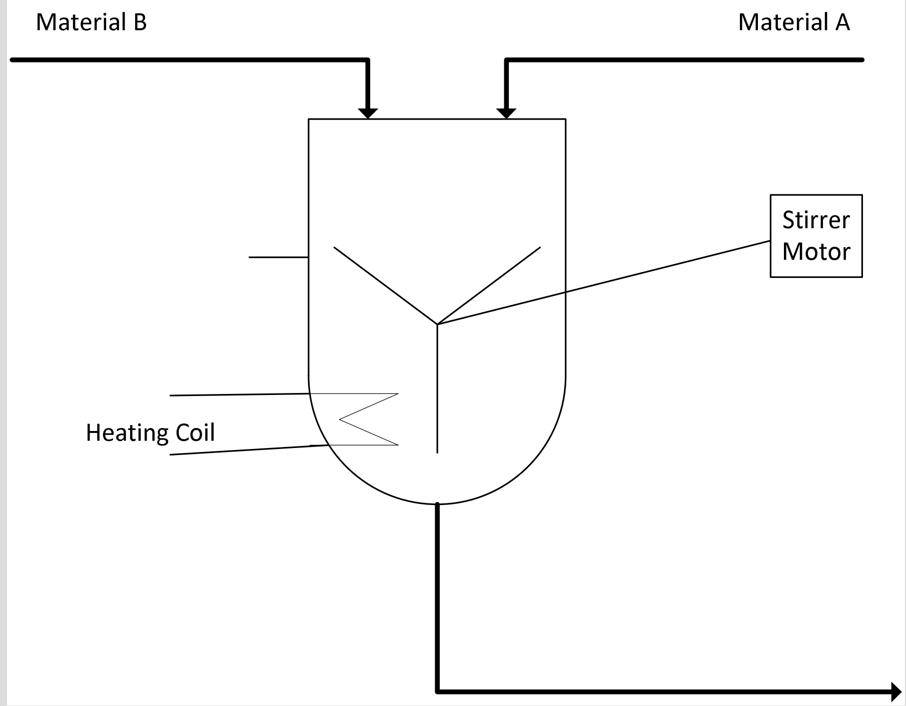
Sequential Logic Control

Answer . . .



Sequential Logic Control

Now develop the logic flow diagram and the sequential logic table for this problem.



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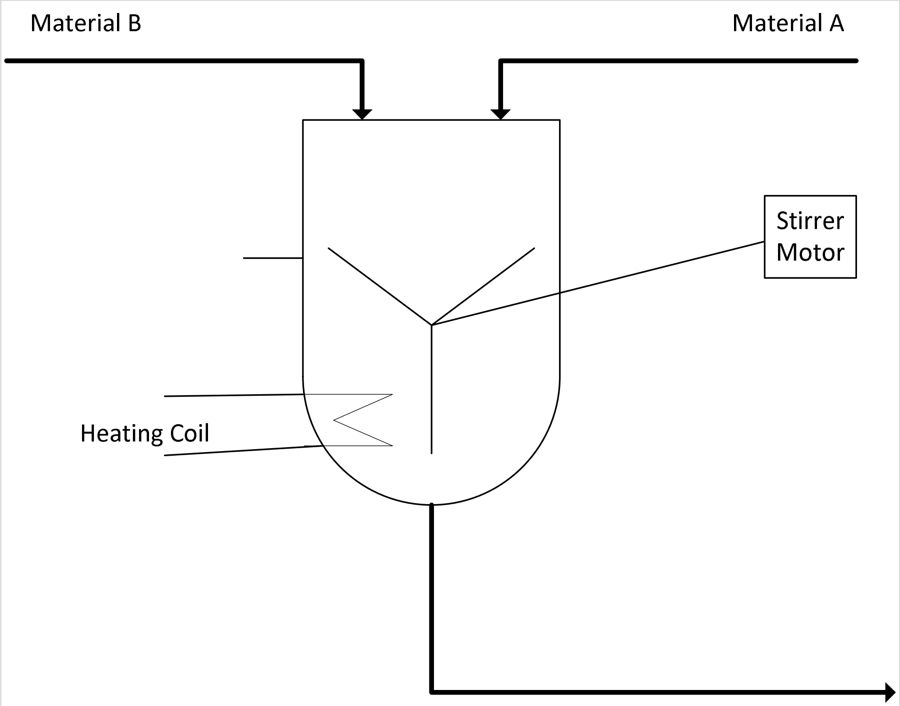
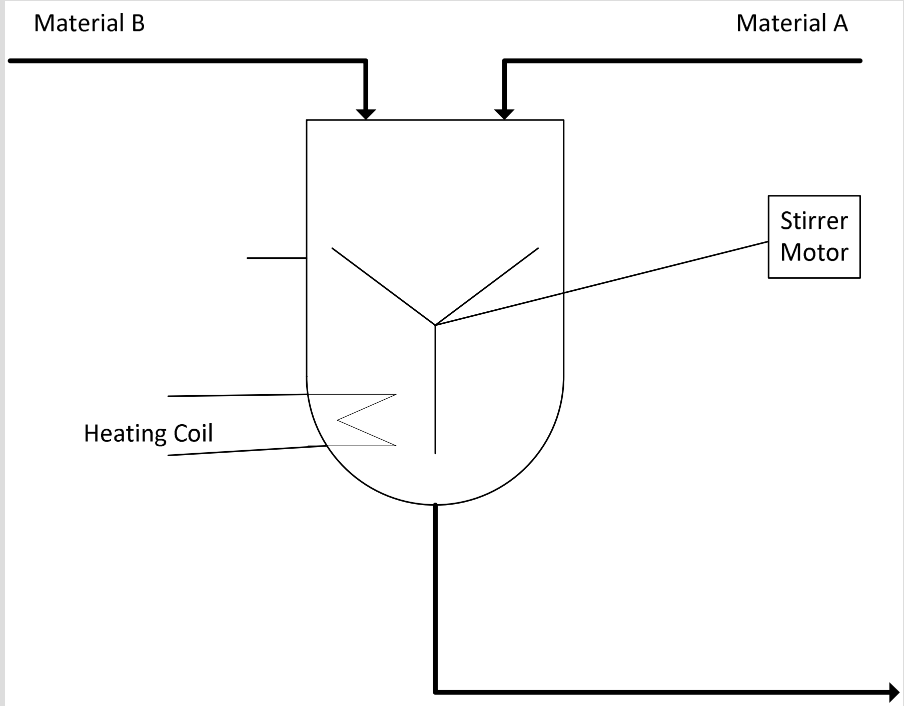
Sequential Logic Control

Answer . . .



Sequential Logic Control

Answer . . .



CHAPTER 2

Control System Fundamentals