

Designing Controls for the Process Industries

by Wayne Seames, Ph.D.

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

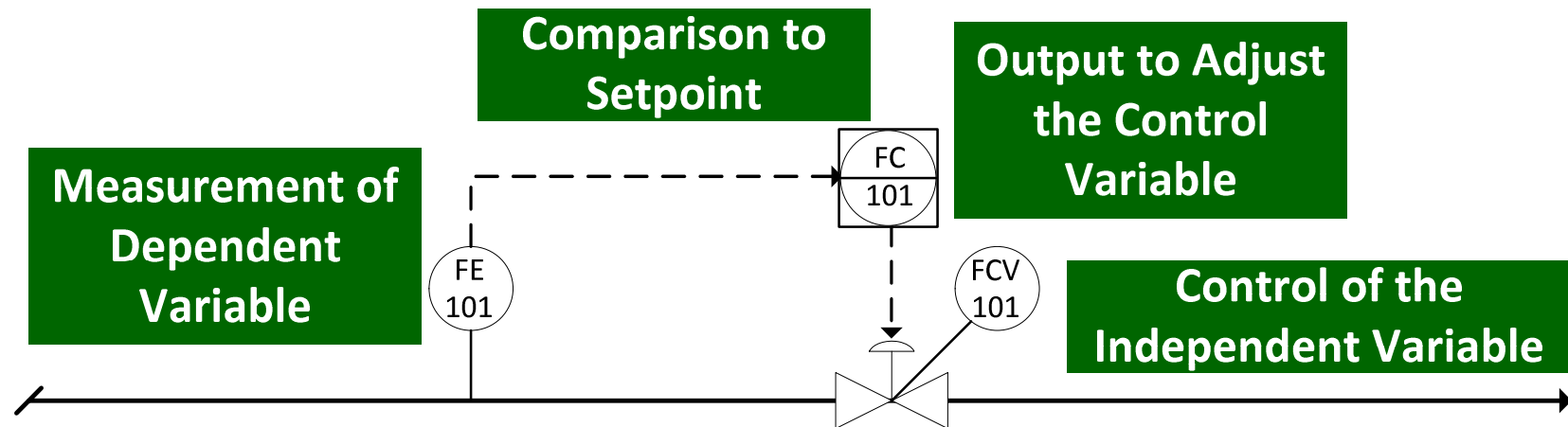
Measurement variables - dependent:

- **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

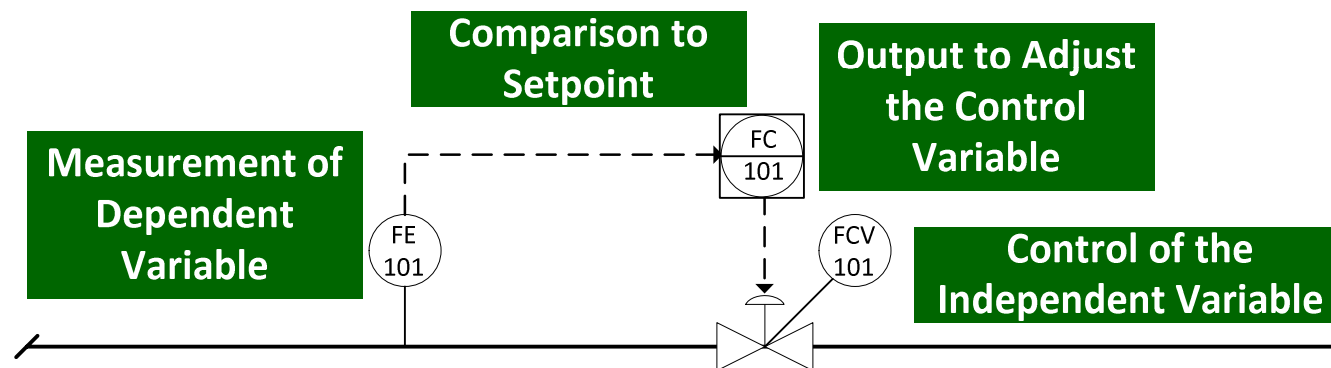


- **Manipulate the control valve**
- **Measure the effect**
- **Compare the measured parameter to a setpoint**
- **Determine the degree of manipulation of the control valve based on this comparison**

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

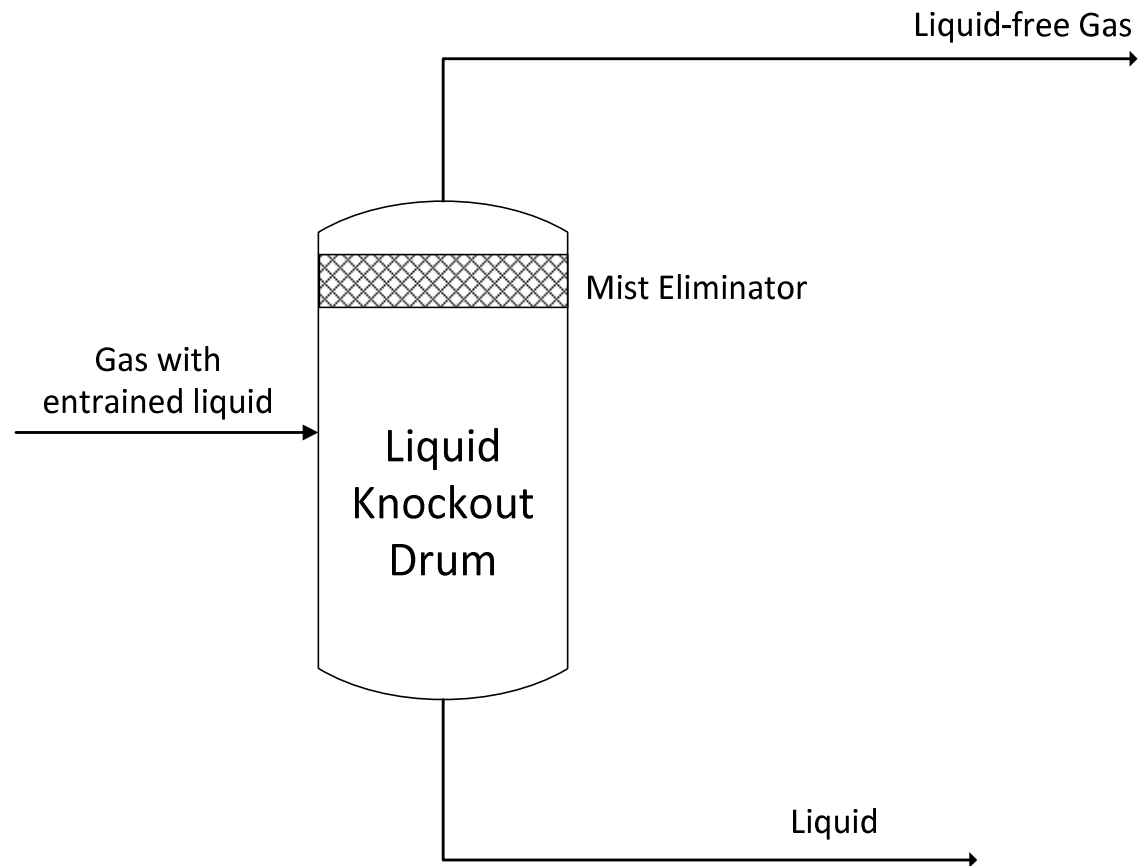
➤ **These should be based on the objectives of the unit operation**

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

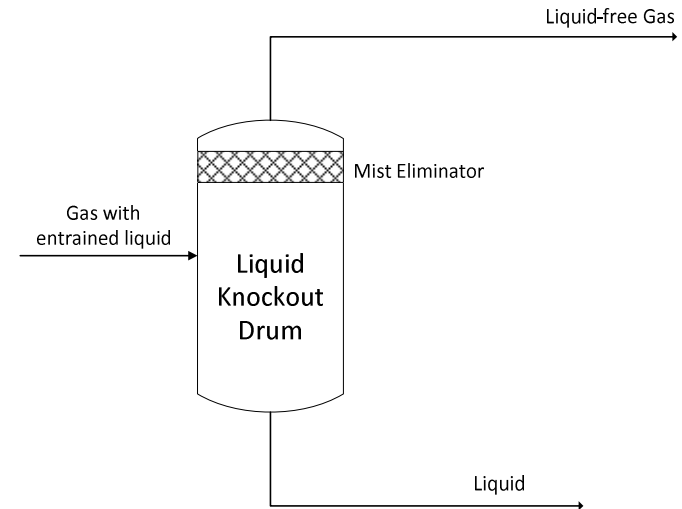
Example problem 1: the liquid knockout drum



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

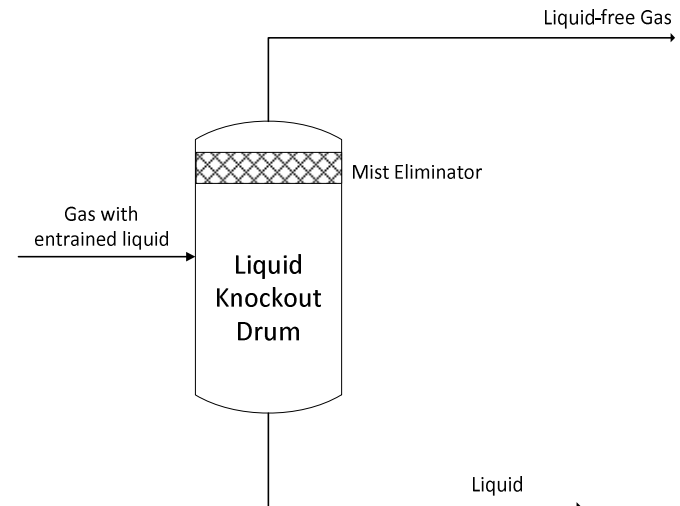
M_{O2} is the mass of material leaving through the bottom outlet nozzle

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**

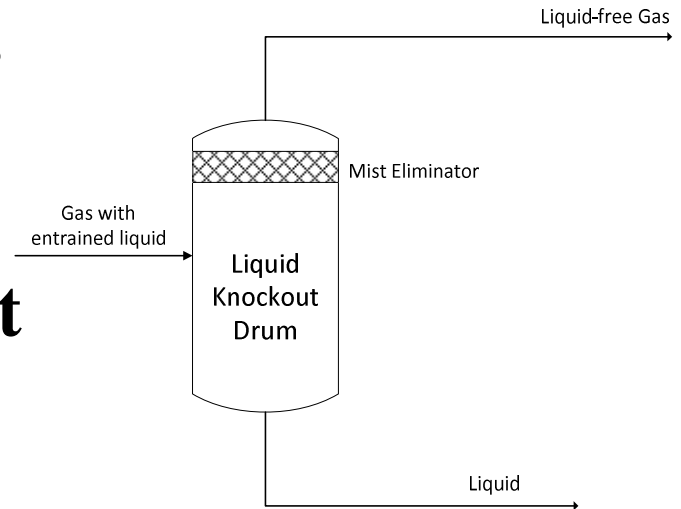
Example problem 1: the liquid knockout drum

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**

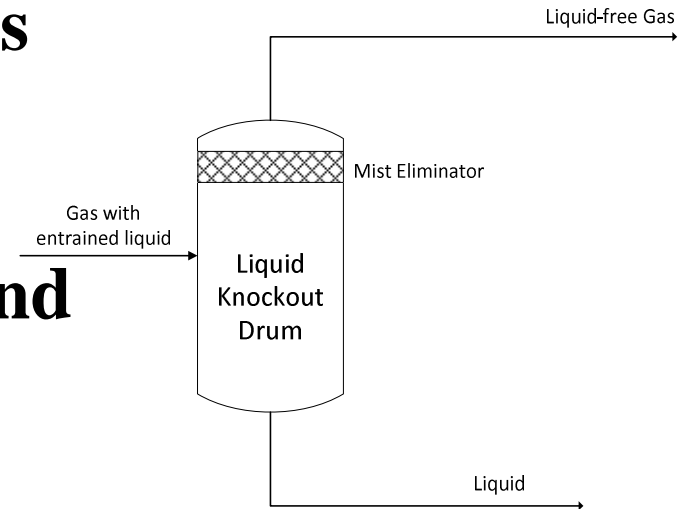


Example problem 1: the liquid knockout drum

Step 2

2 CVs needed for the two degrees of freedom:

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



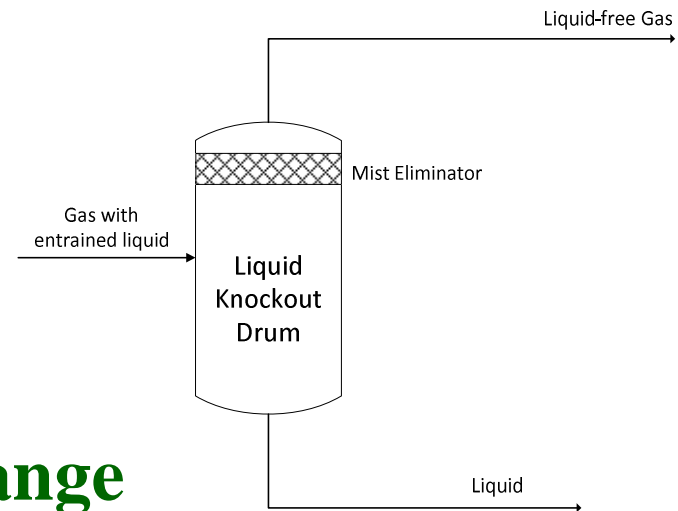
Example problem 1: the liquid knockout drum

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

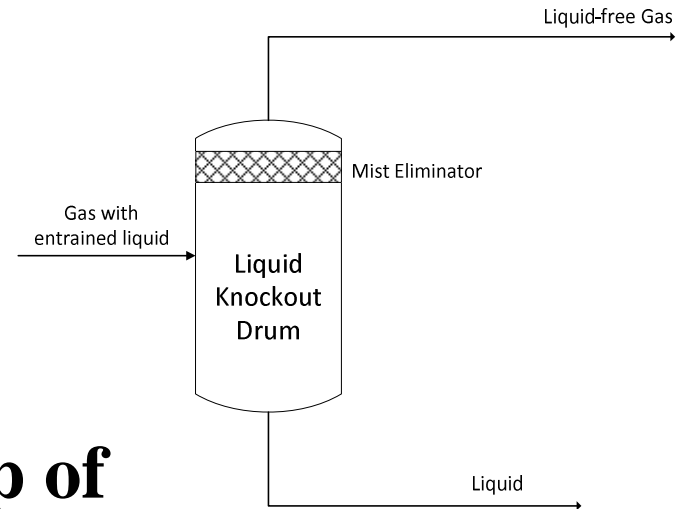


Example problem 1: the liquid knockout drum

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

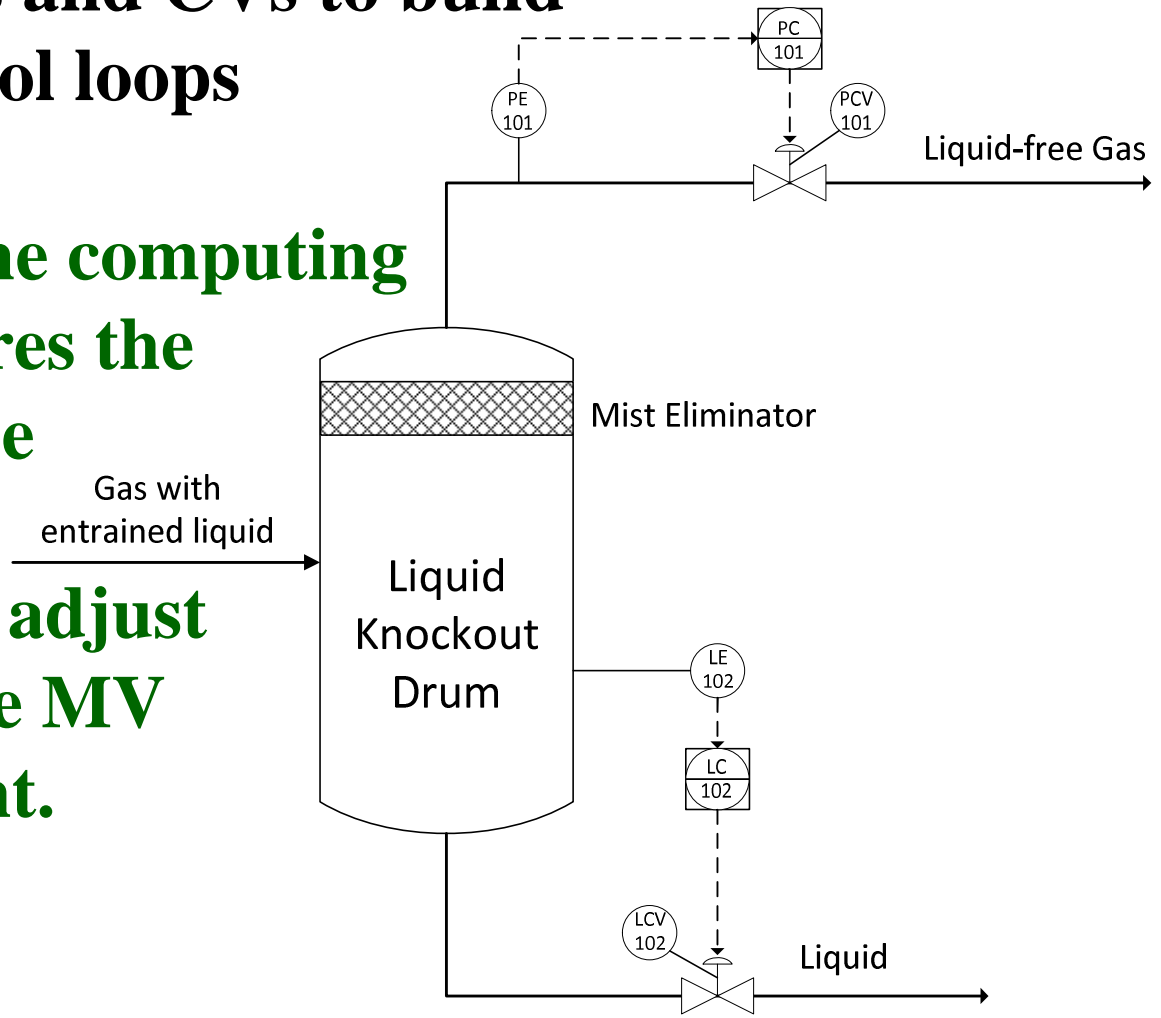


Example problem 1: the liquid knockout drum

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.



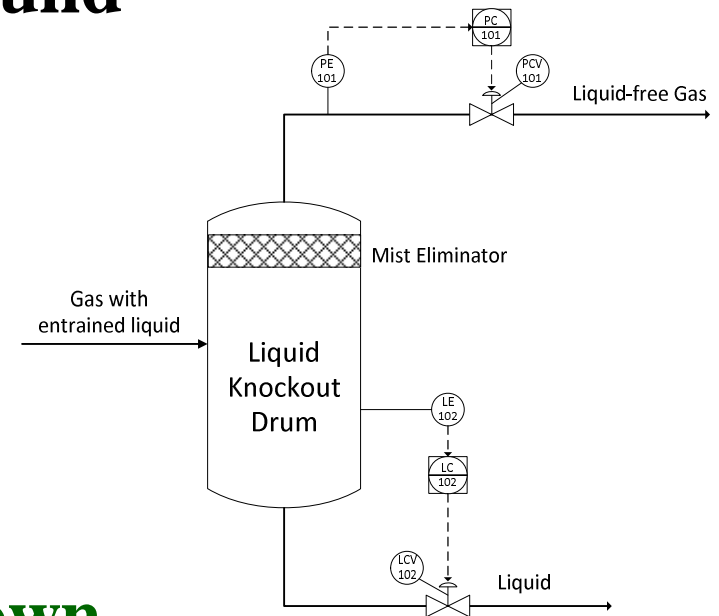
Example problem 1: the liquid knockout drum

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.

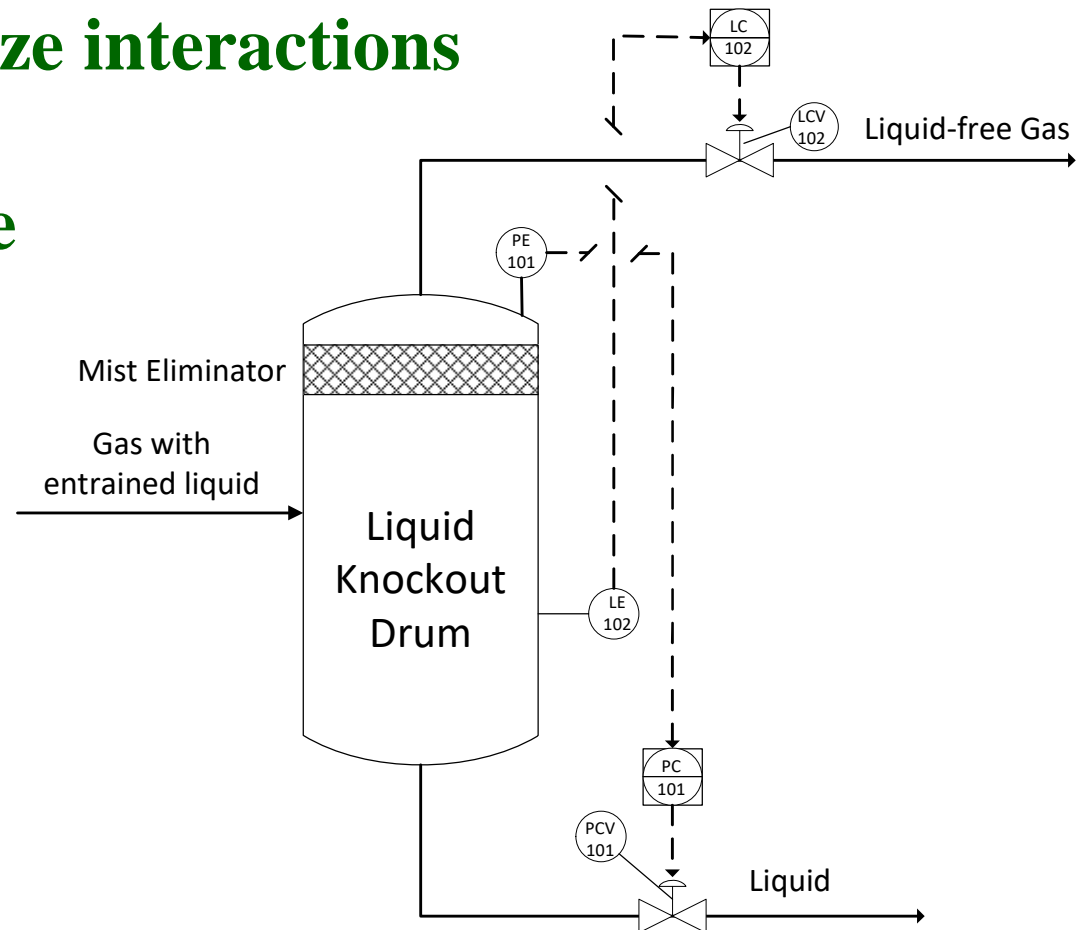


Example problem 1: the liquid knockout drum

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

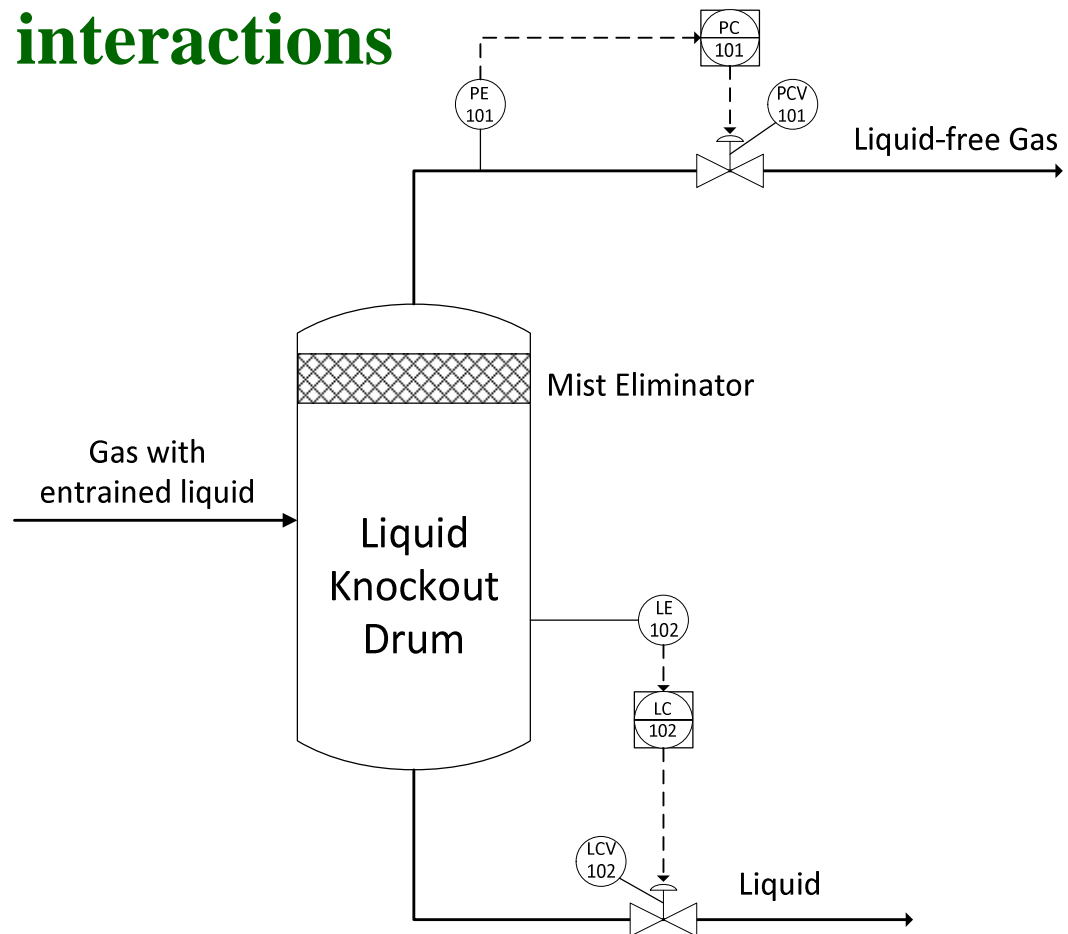


Example problem 1: the liquid knockout drum

Step 4

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

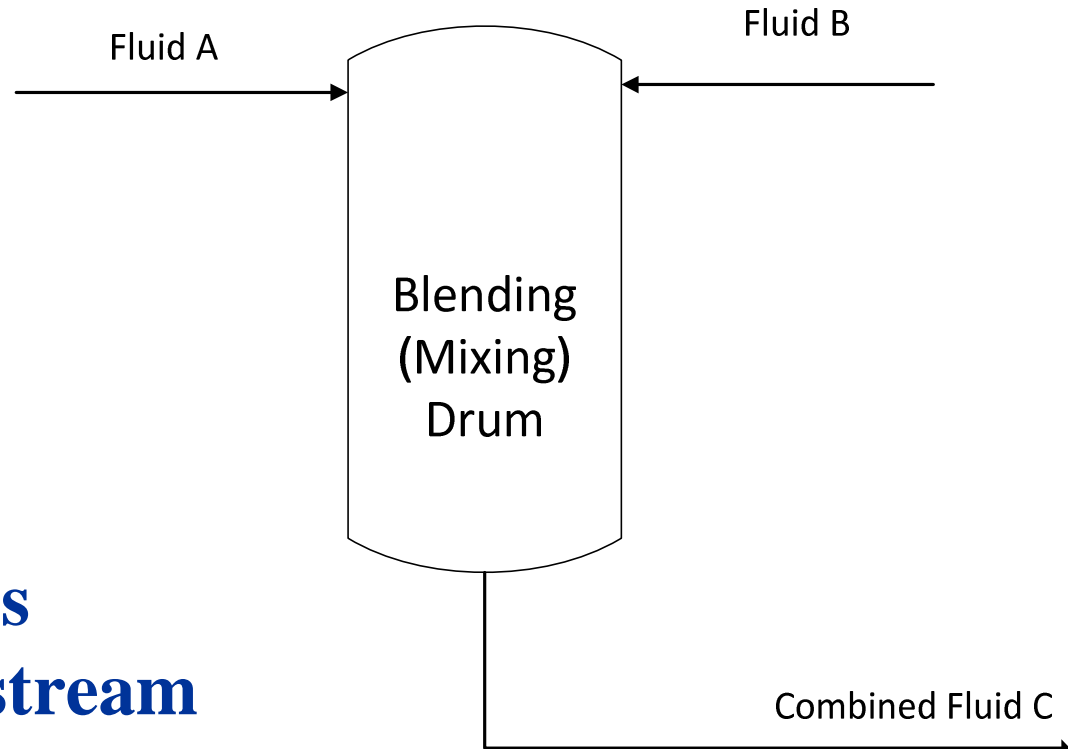
This is an example of a decoupled control system



Example problem 2: A Mixing Drum

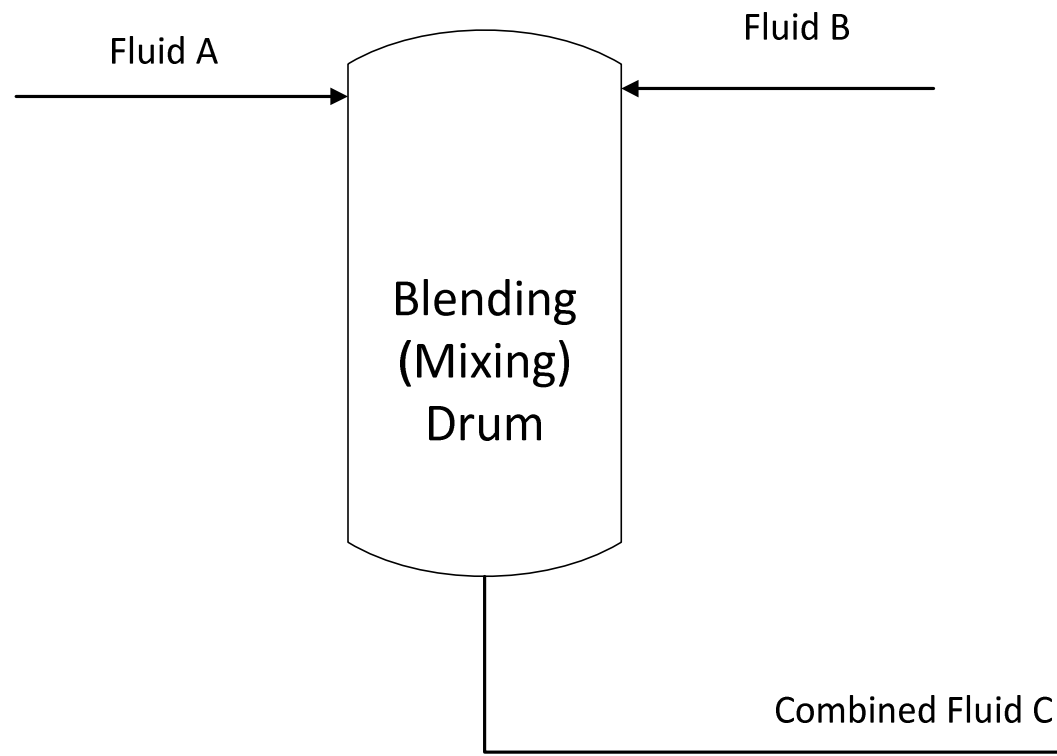
Try this one . . .

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

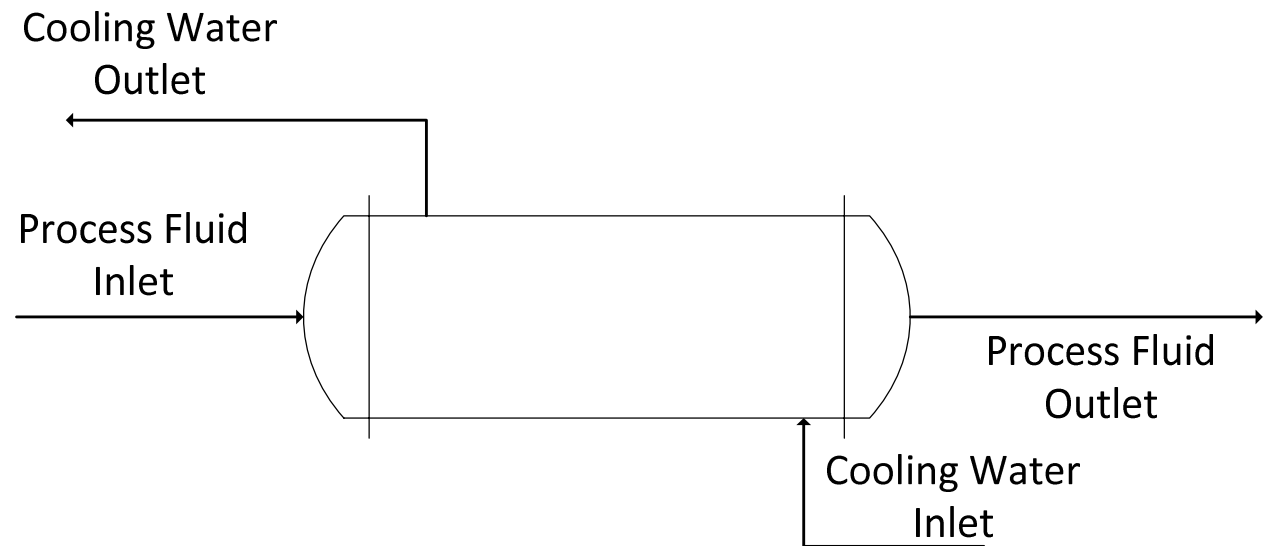
Answer. . .



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

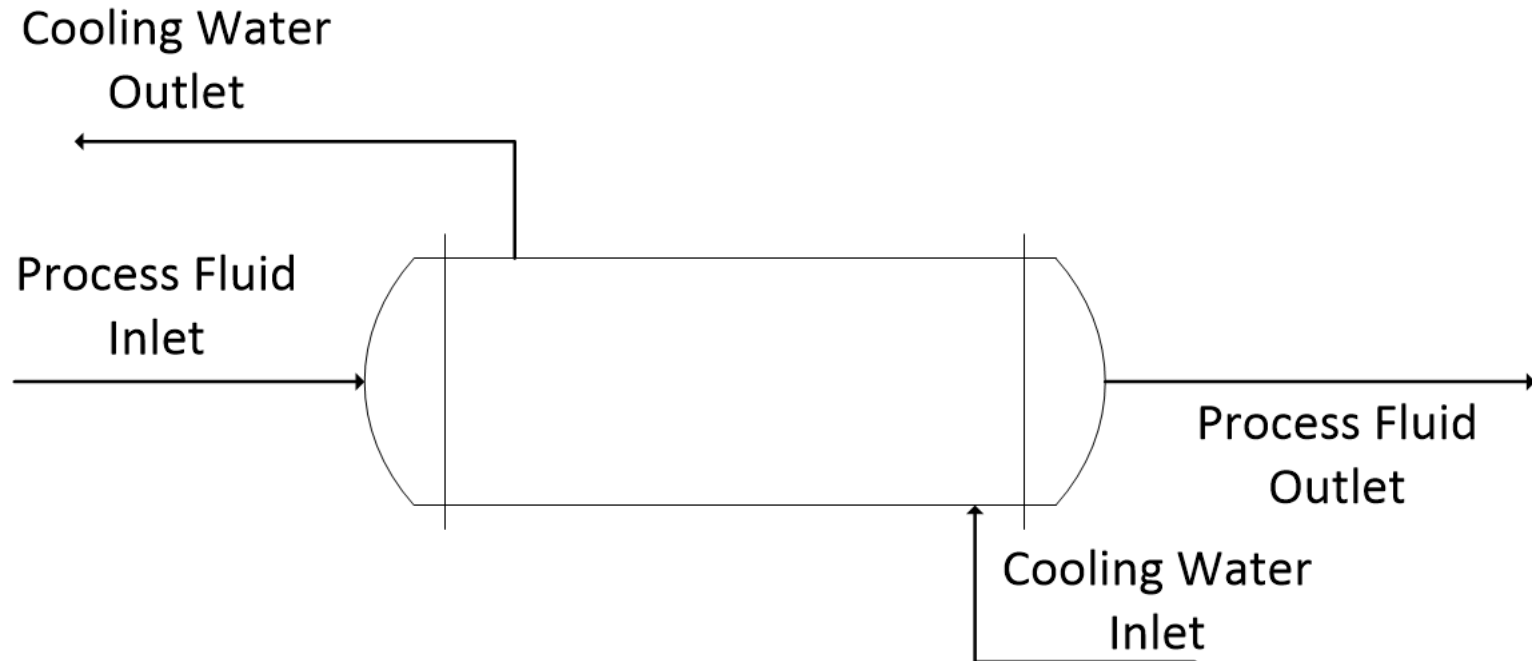
Now try this one . . .

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 . . .

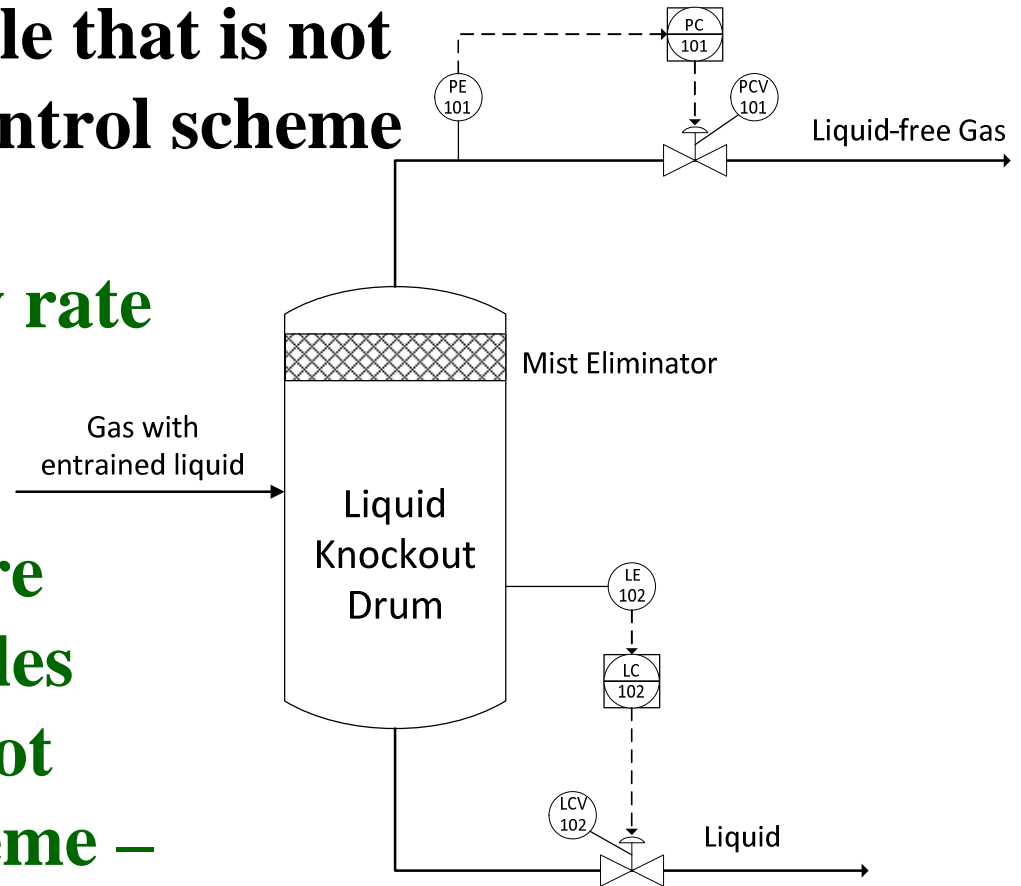


Disturbance Variables

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

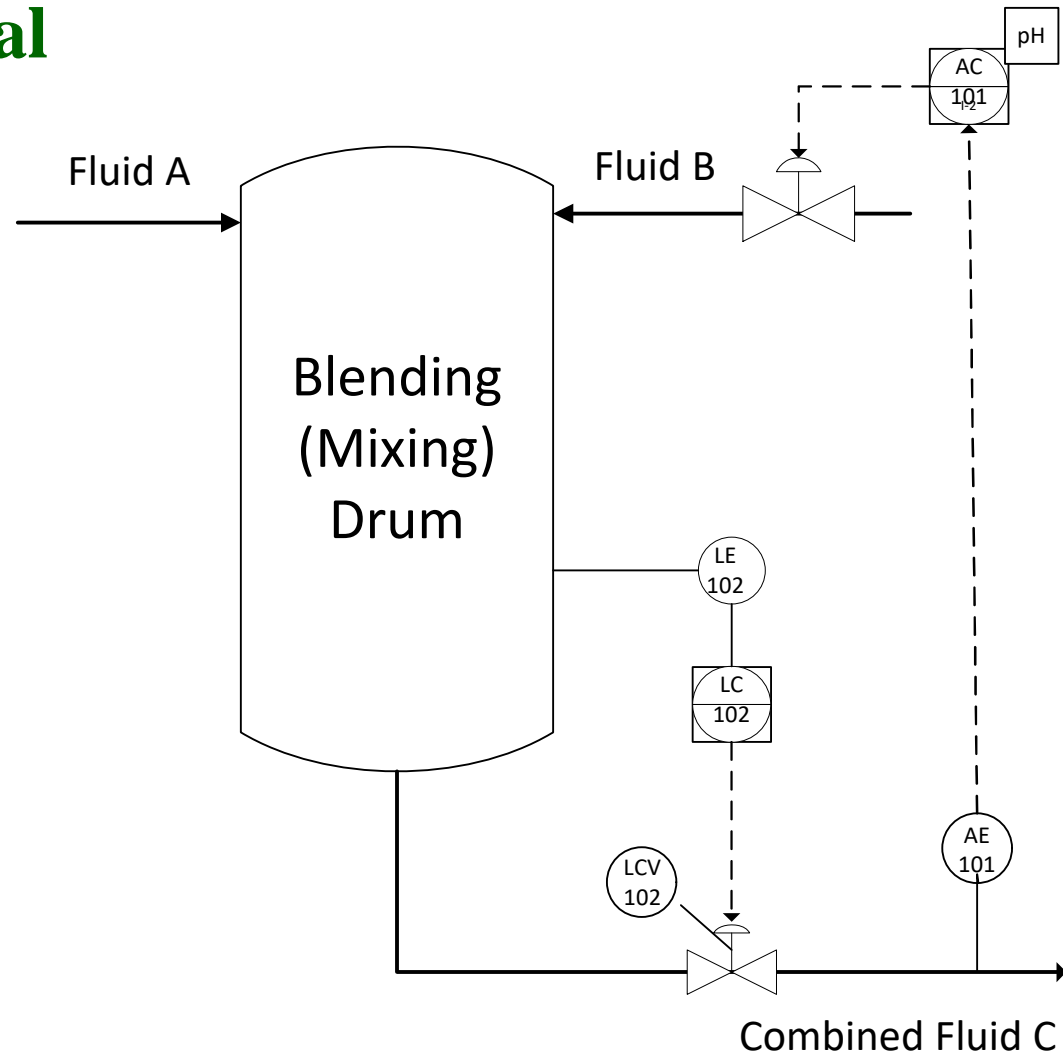
Example: the inlet flow rate

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



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

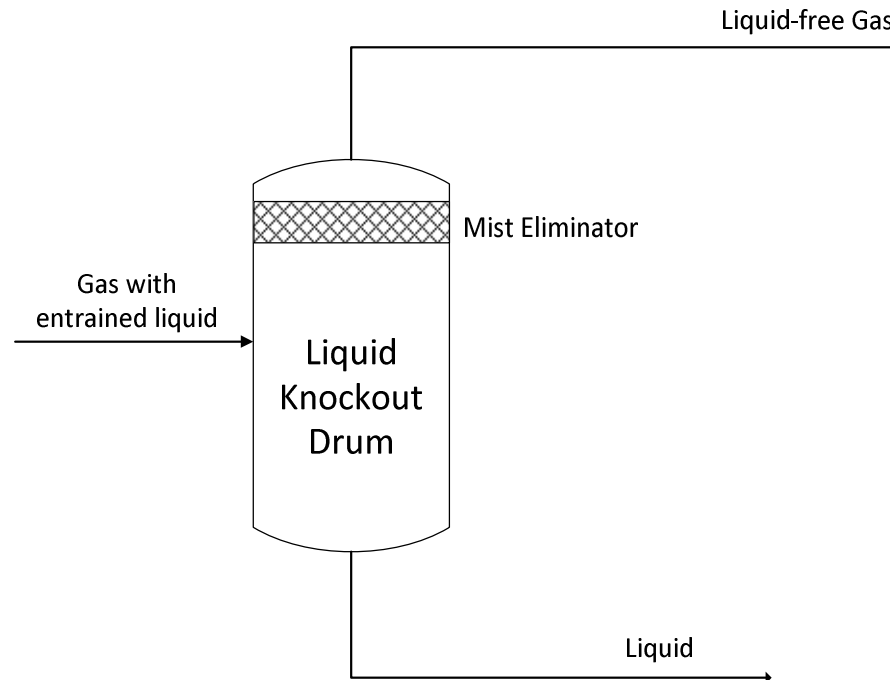
Step 3. Construct a feedforward control loop

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

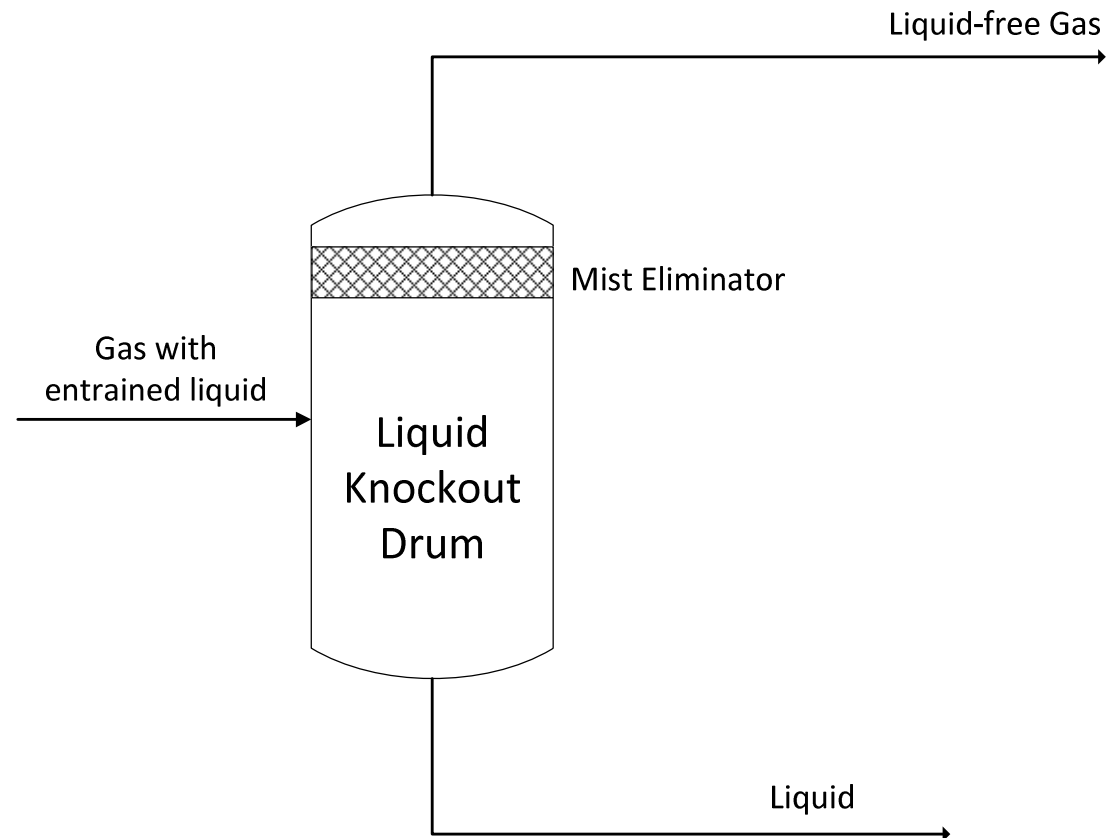
Example 1

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



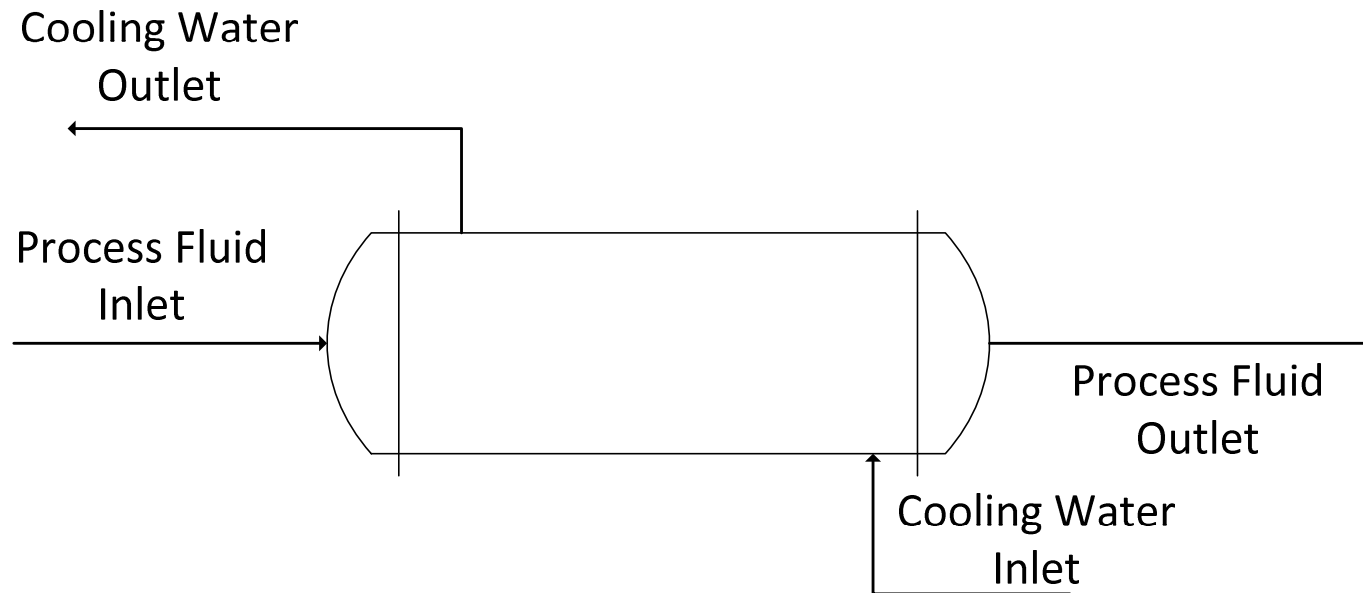
Example 1

Answer . . .



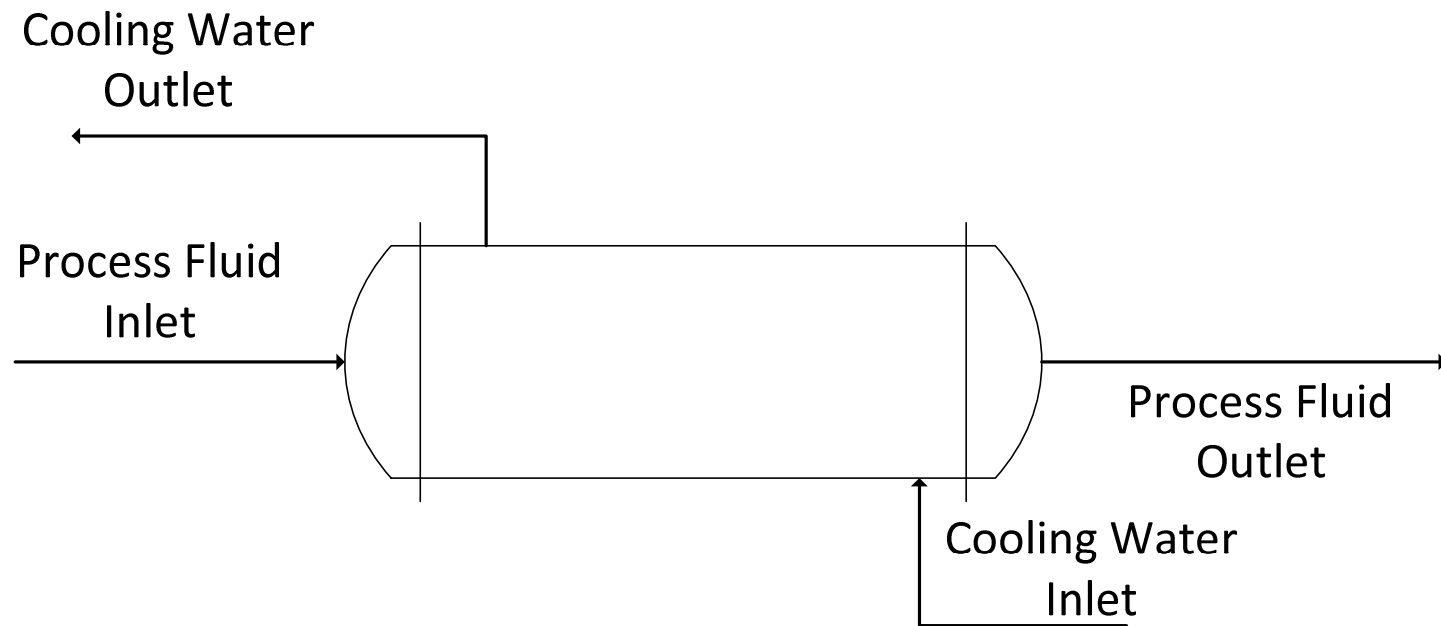
Example 2

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



Example 2

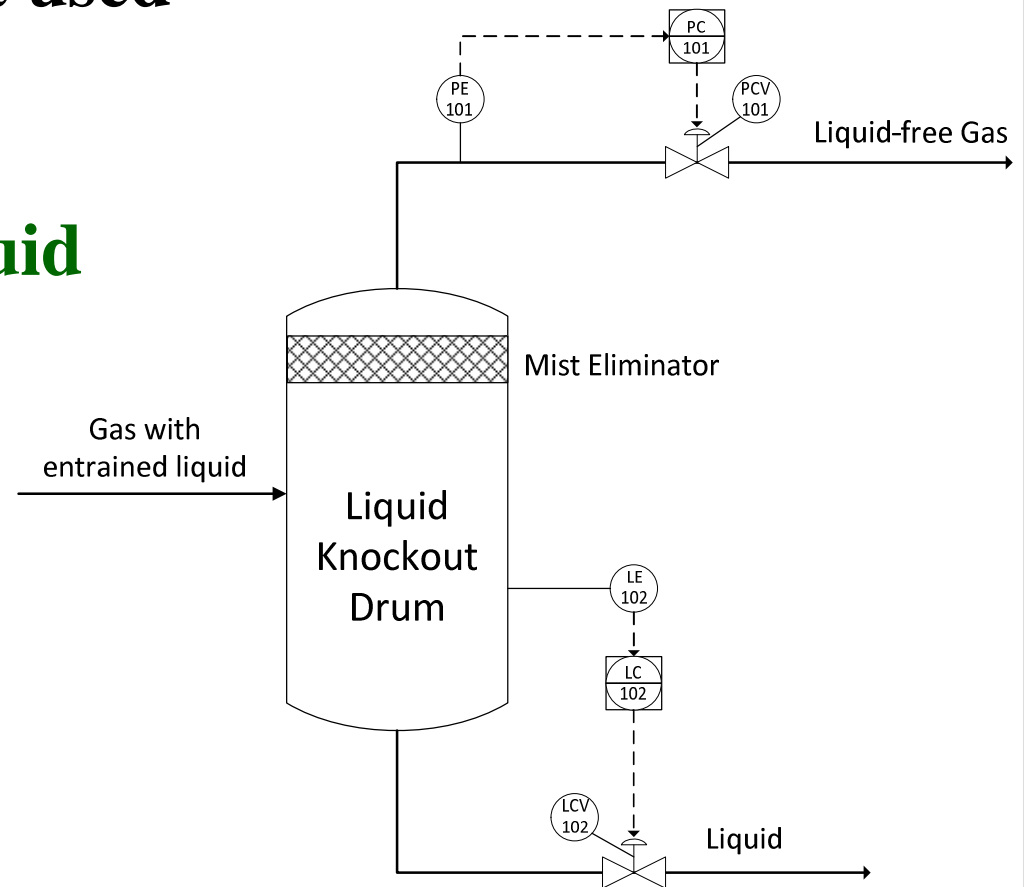
Answer . . .



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 - - -



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.

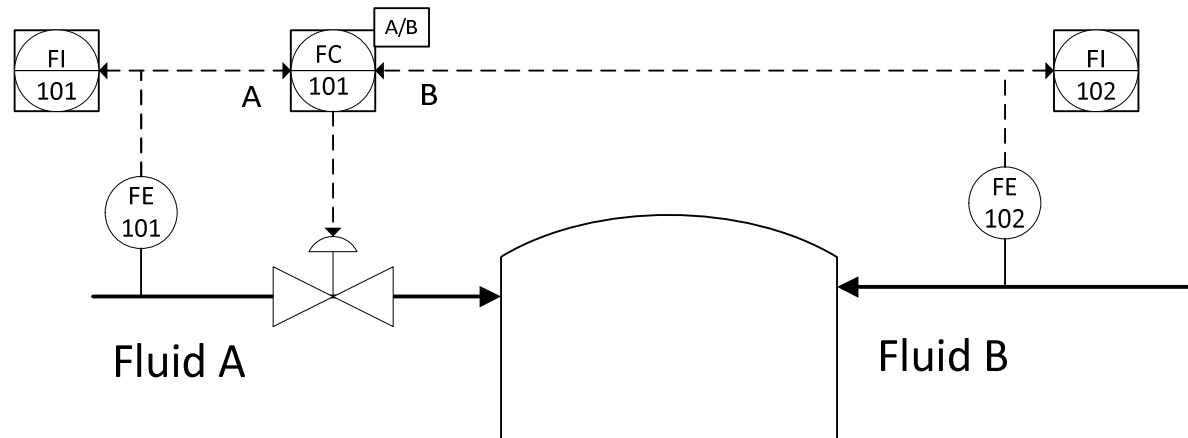
This ratio is known as the measurement ratio.

Ratio Controls

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

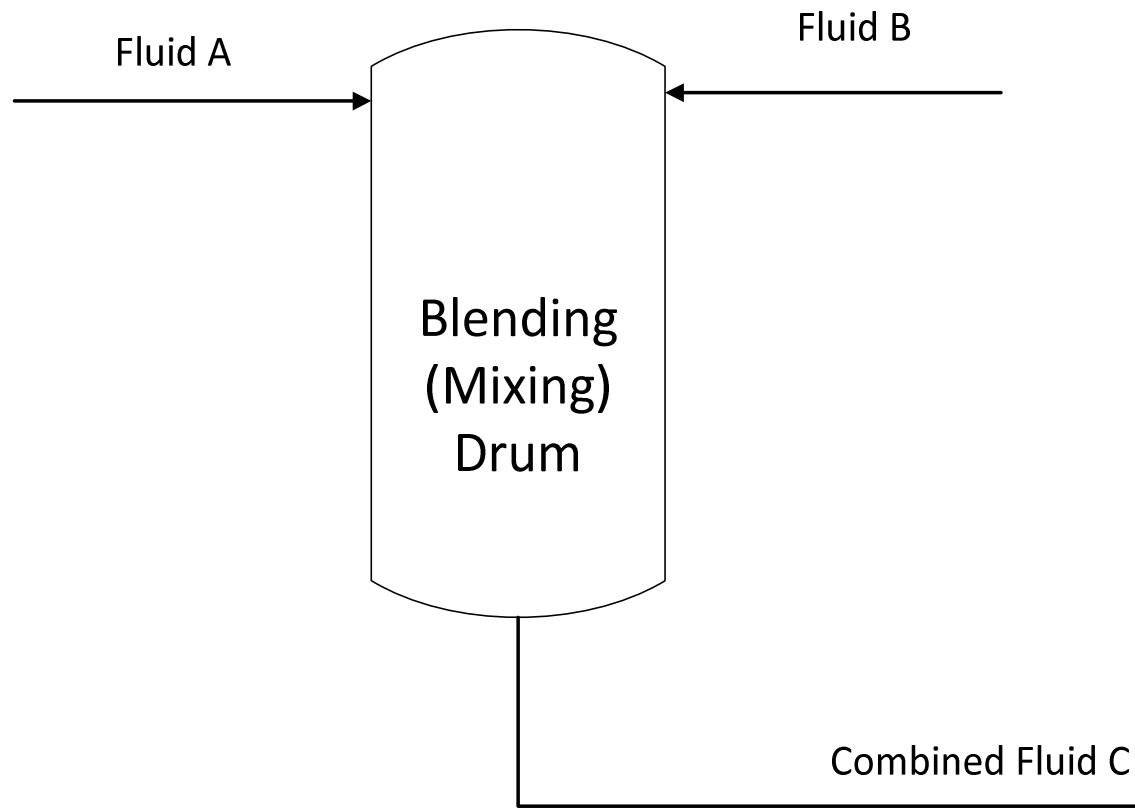


Instead of just setting the flow rate of B into a reactor, I can take the ratio of A to B and compare this ratio to the setpoint – the desired value (ideally 0.5) and used by the controller.



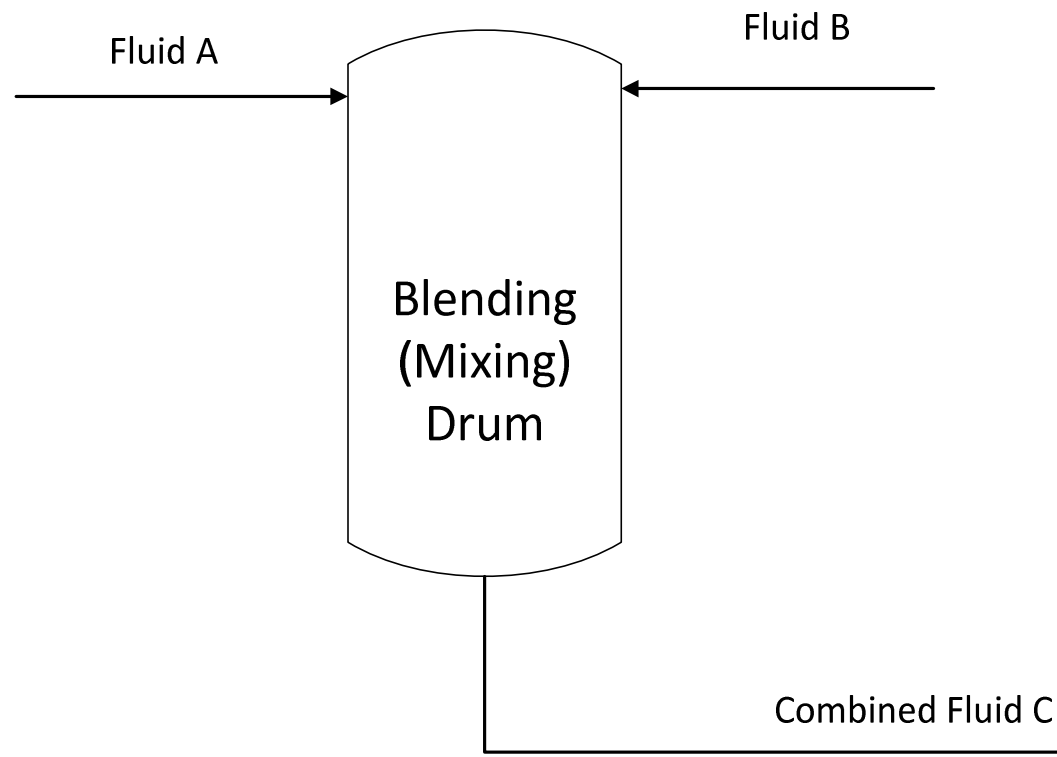
Ratio Controls

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



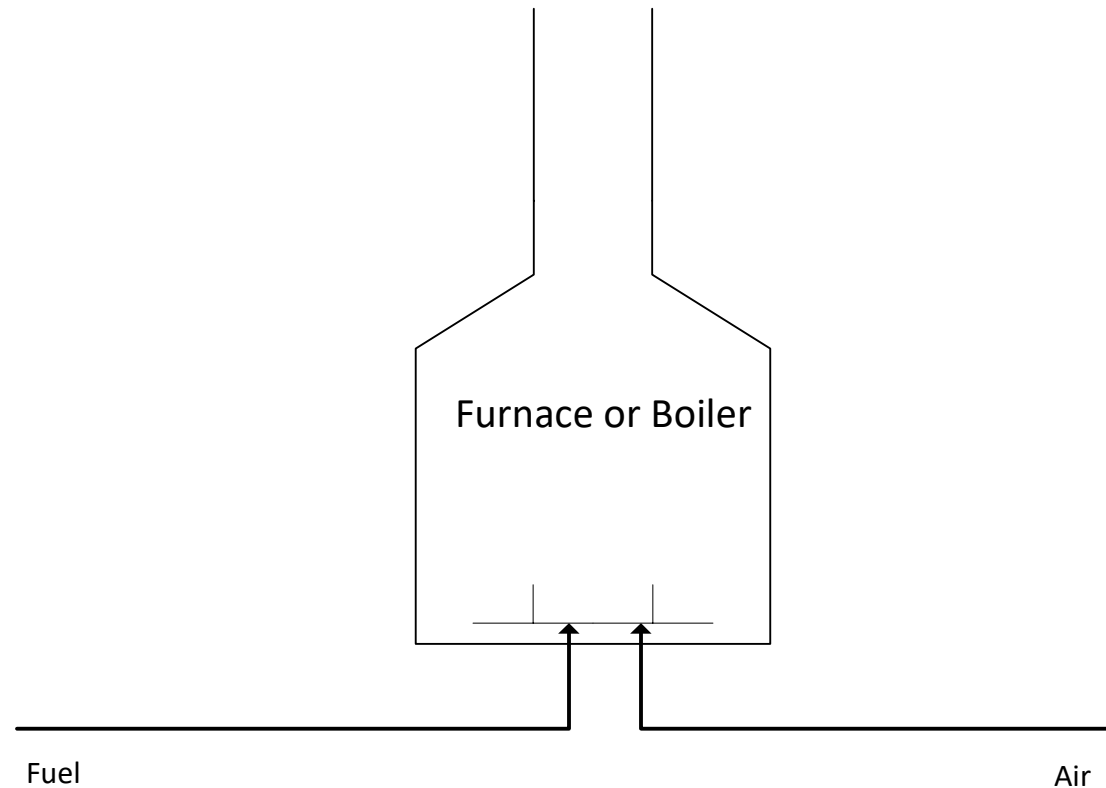
Ratio Controls

Answer . . .



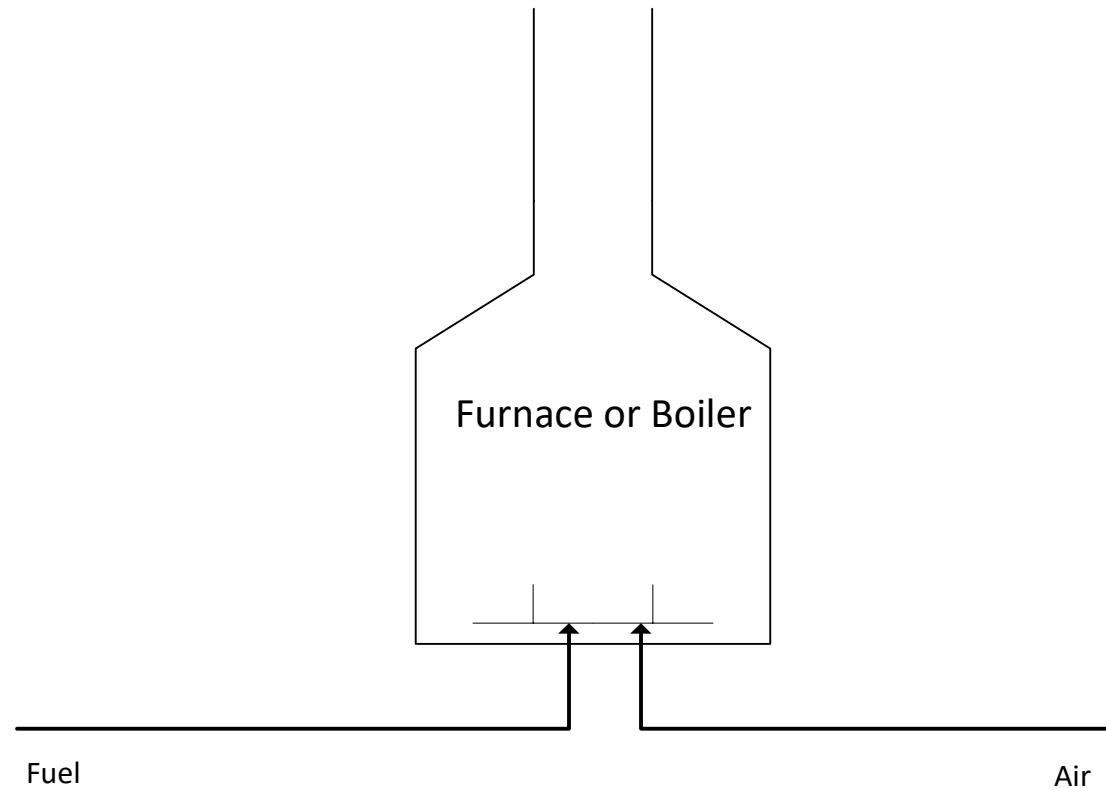
Ratio Controls

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.**

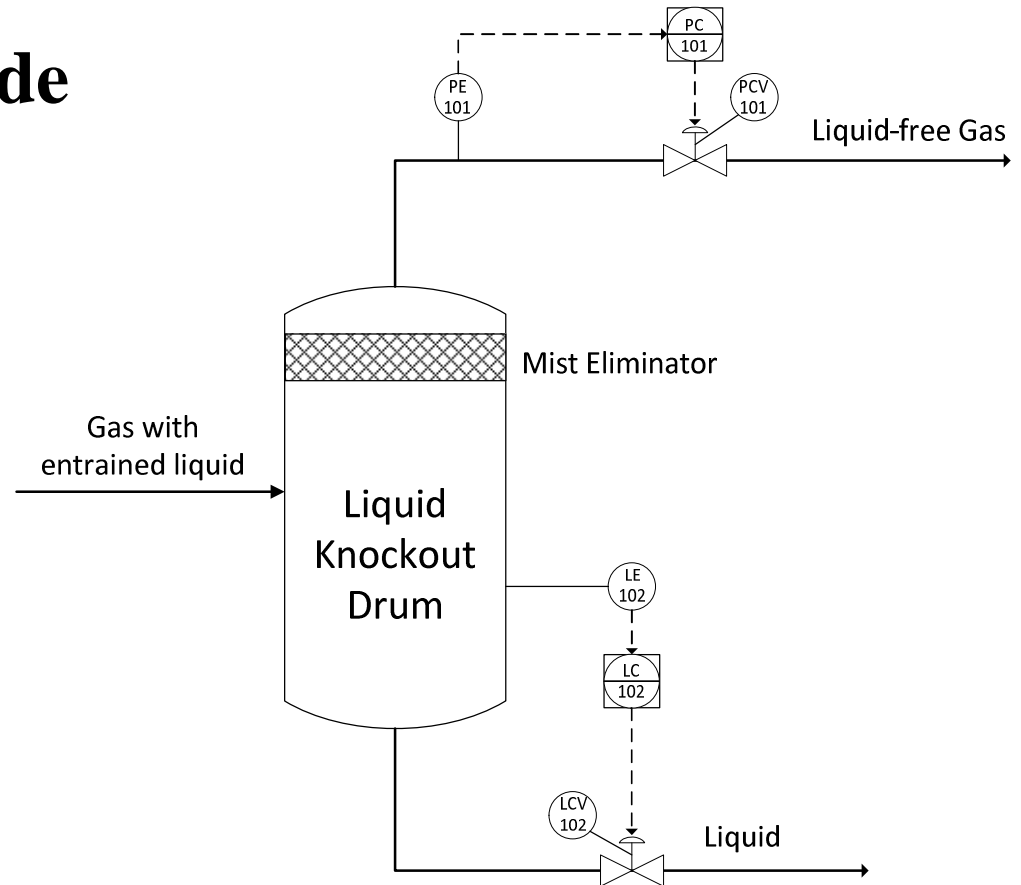
Cascade Control Loops

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.**

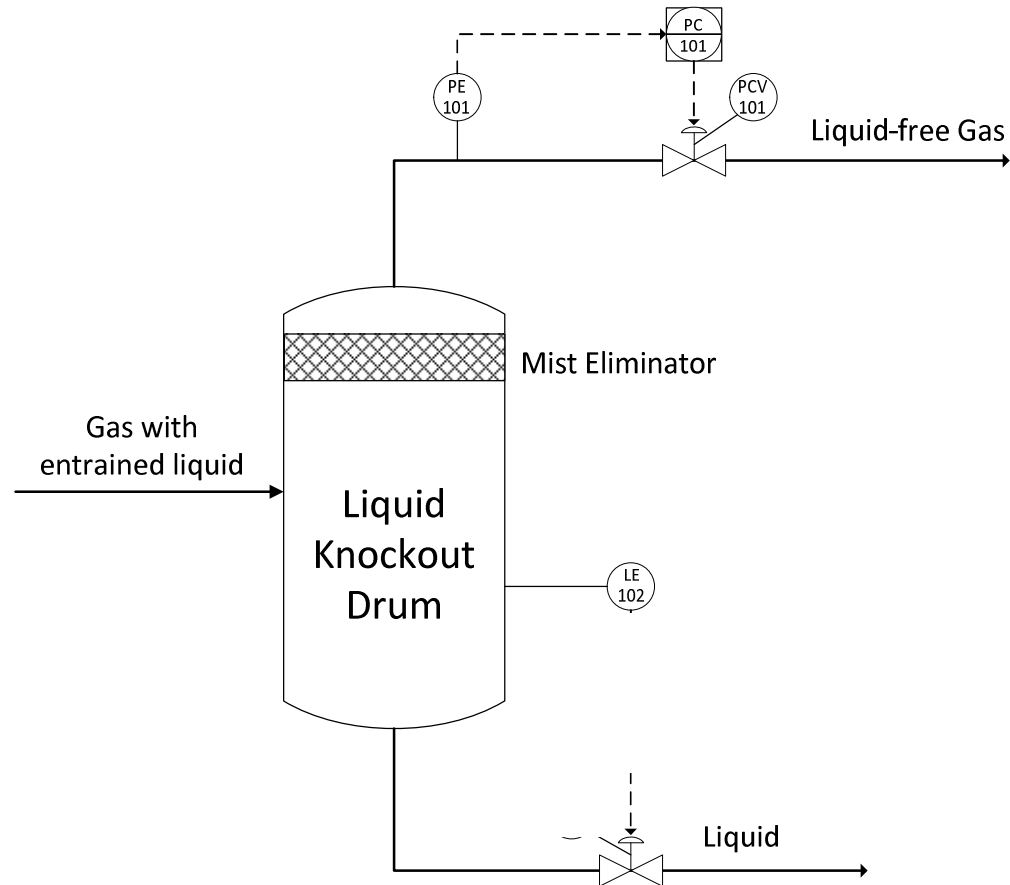
Cascade Control Loops

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



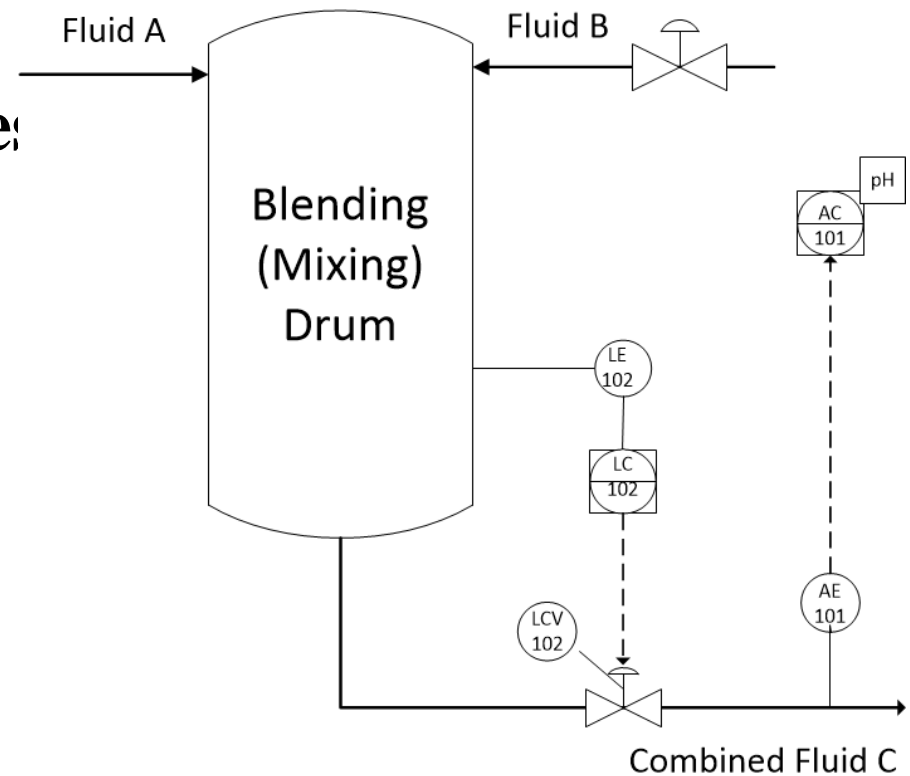
Cascade Control Loops

Answer . . .



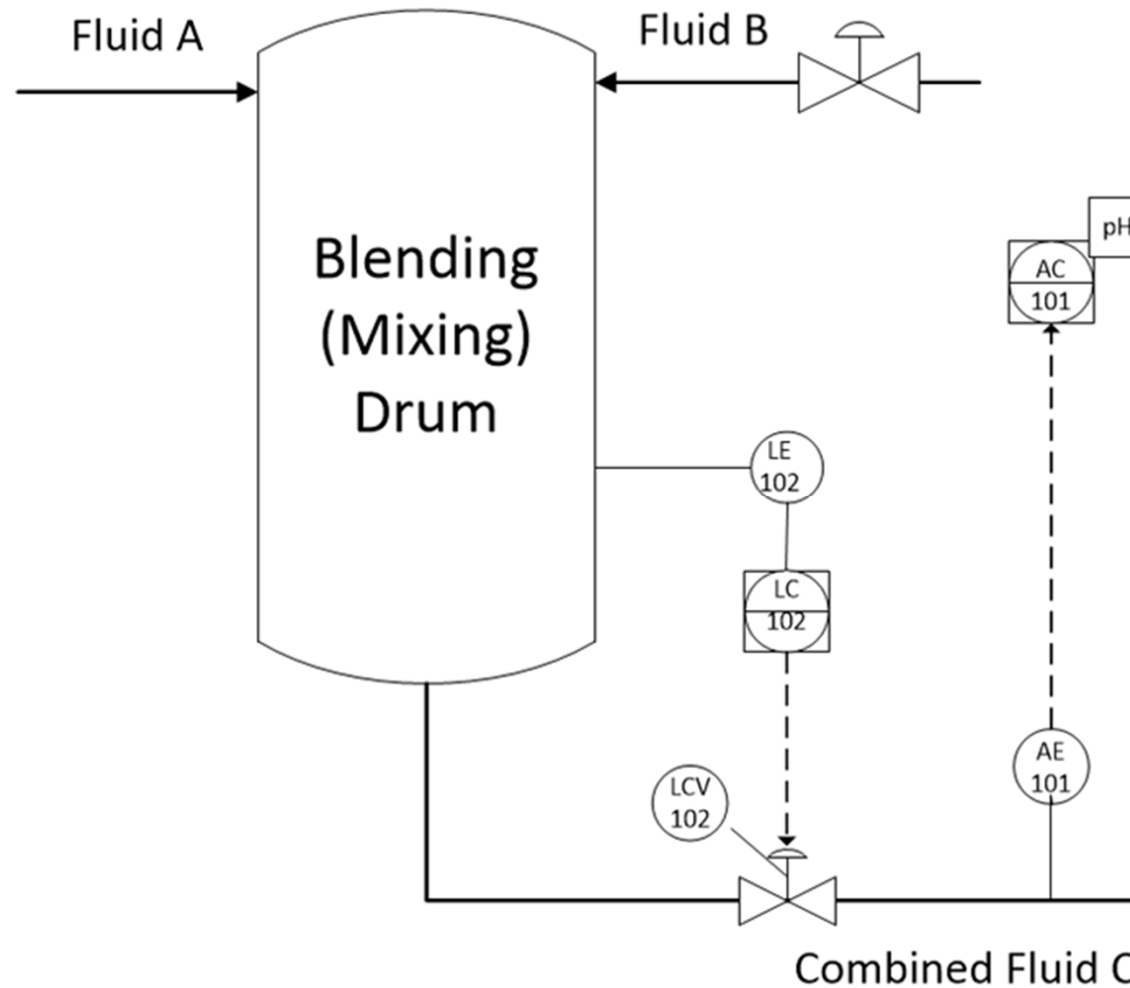
Cascade Controls

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 responsiveness of this control loop.



Cascade Controls

Answer . . .



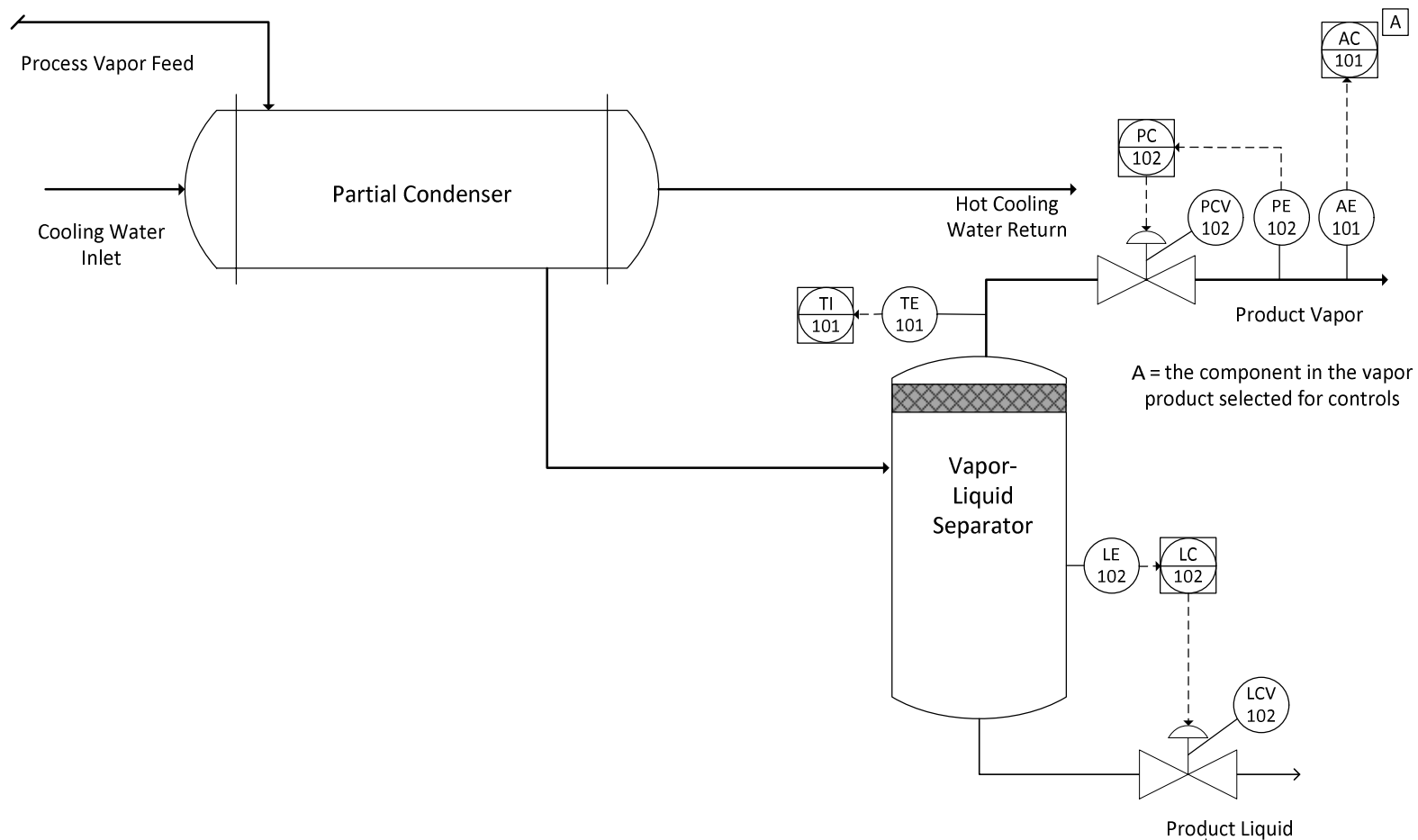
Cascade Control Loops

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

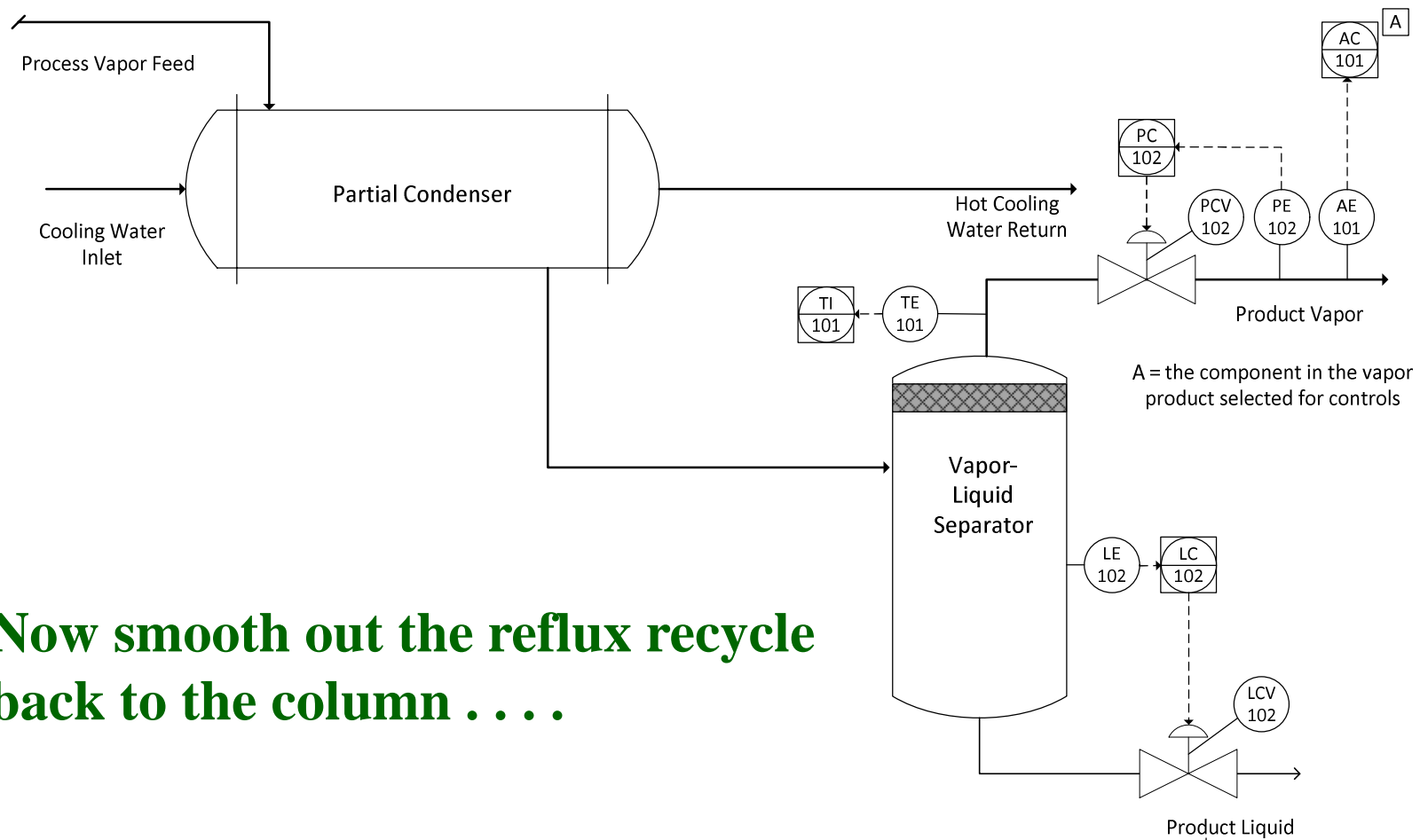
Example: Use FF/FB type cascade control scheme to minimize the possibility that a change in the overhead vapor flow rate will cause the distillate product to go off-specification for component

A.



Cascade Controls

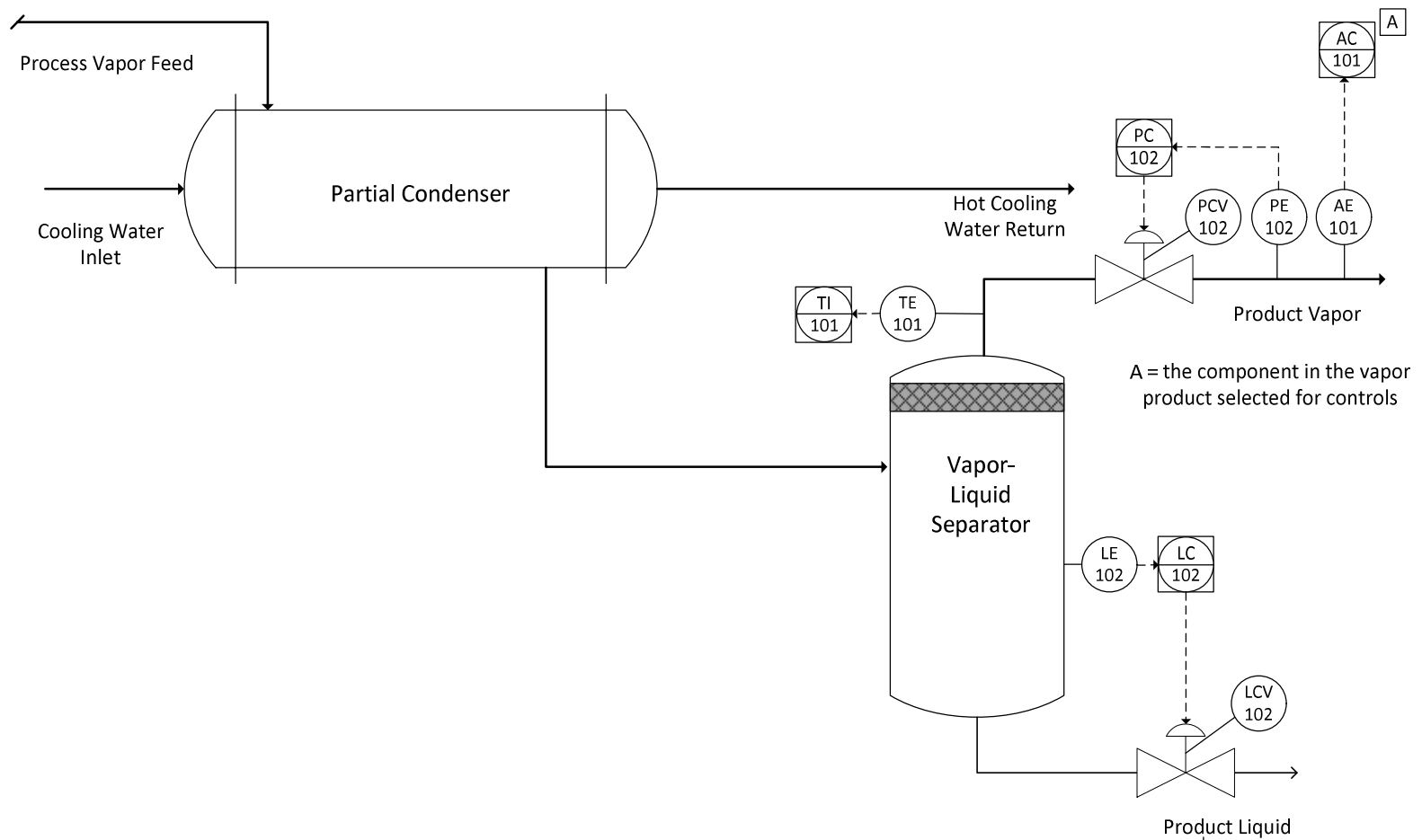
Answer:



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

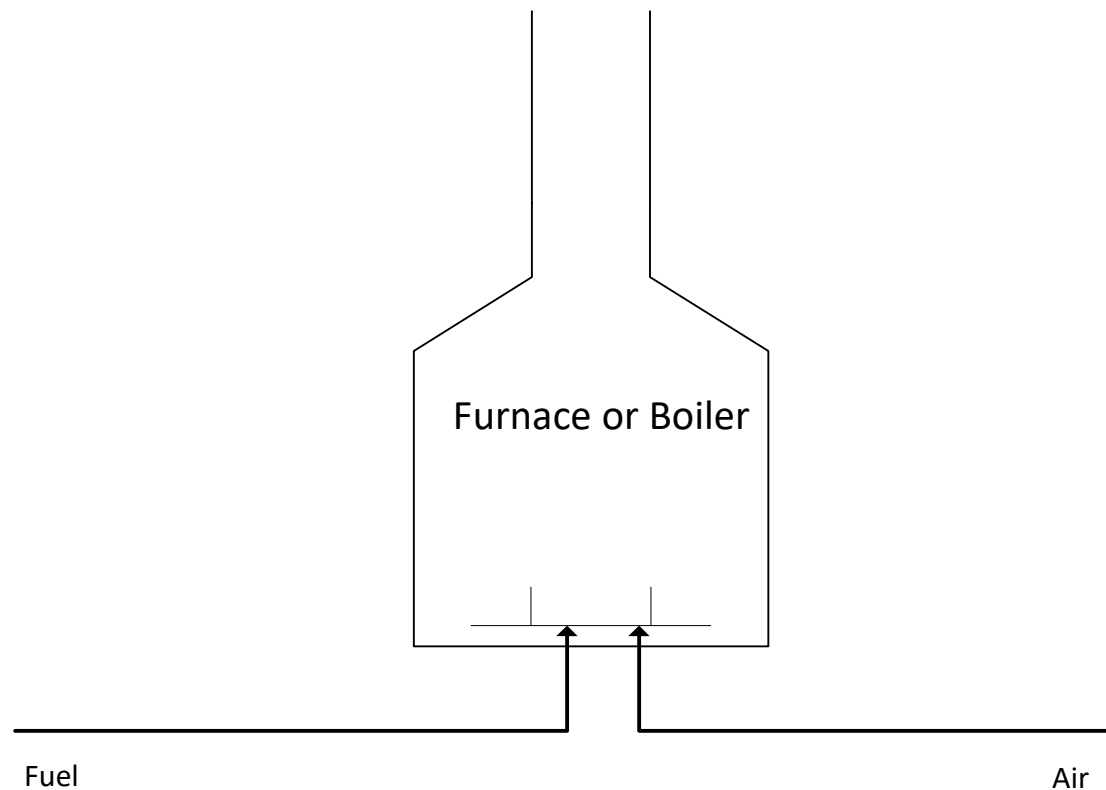
Cascade Controls

Answer:



Cascade Controls

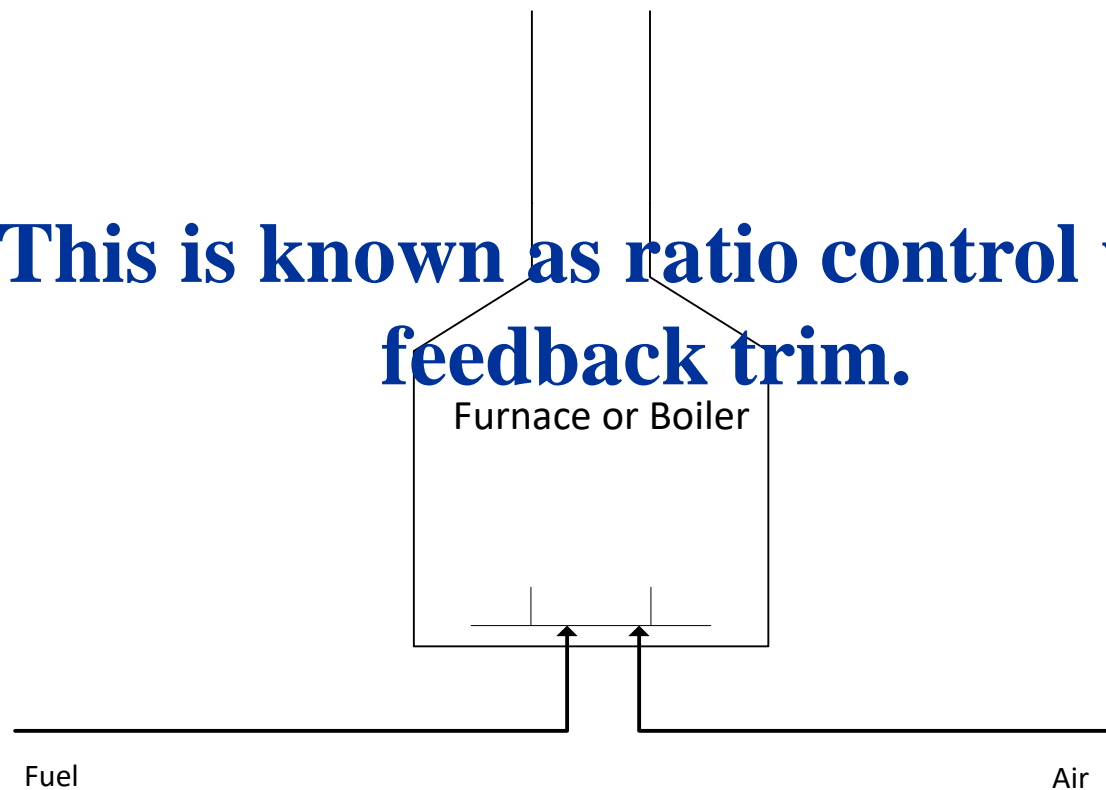
Example: How can you insure that the ratio you specify for the air/fuel ratio is correct? Use a cascade control scheme to accomplish this.



Cascade Controls

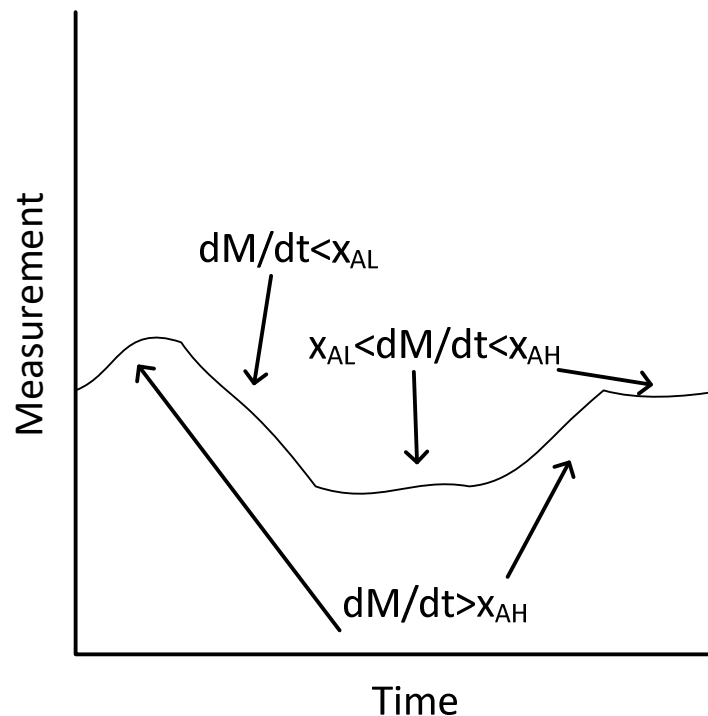
Answer . . .

**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

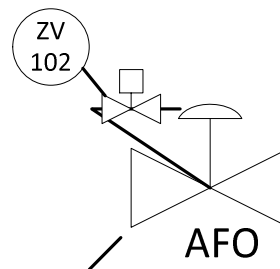
- **Independent of the process measurement and control functions**
- **Are invoked only in an emergency**
 - **Will cause upsets in the process**
 - **Used only when these upsets are less of a problem than not invoking the action of the safety system**

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.

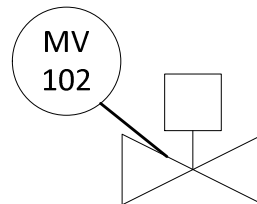
AFO = air fail to open (AFO)

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

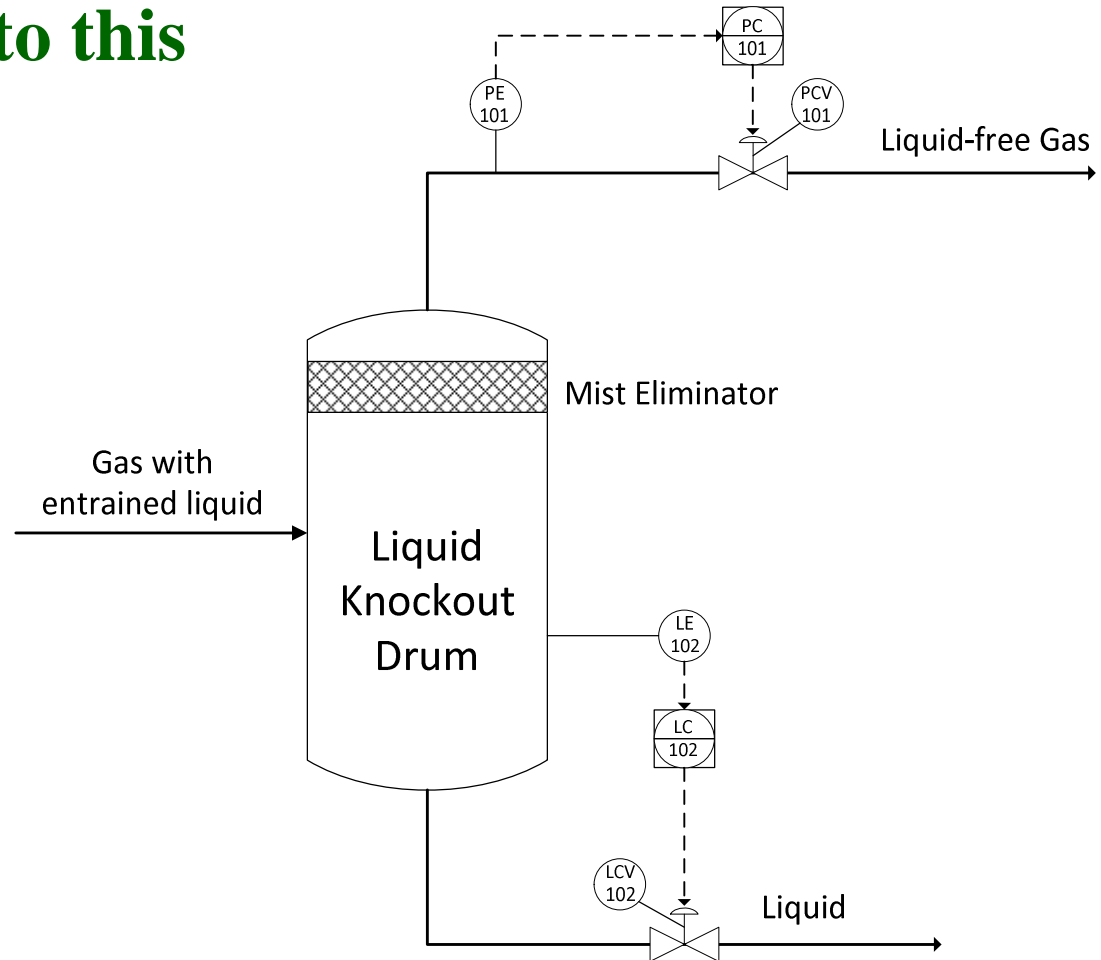
- The most common include a high-high and/or low-low alarm of a critical measurement variable
- When the setpoint is reached, the safety controller interferes with the normal operation of a control variable.
- **An electrical contact may be opened (or closed)**
 - Note: just shutting off a pump or compressor 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

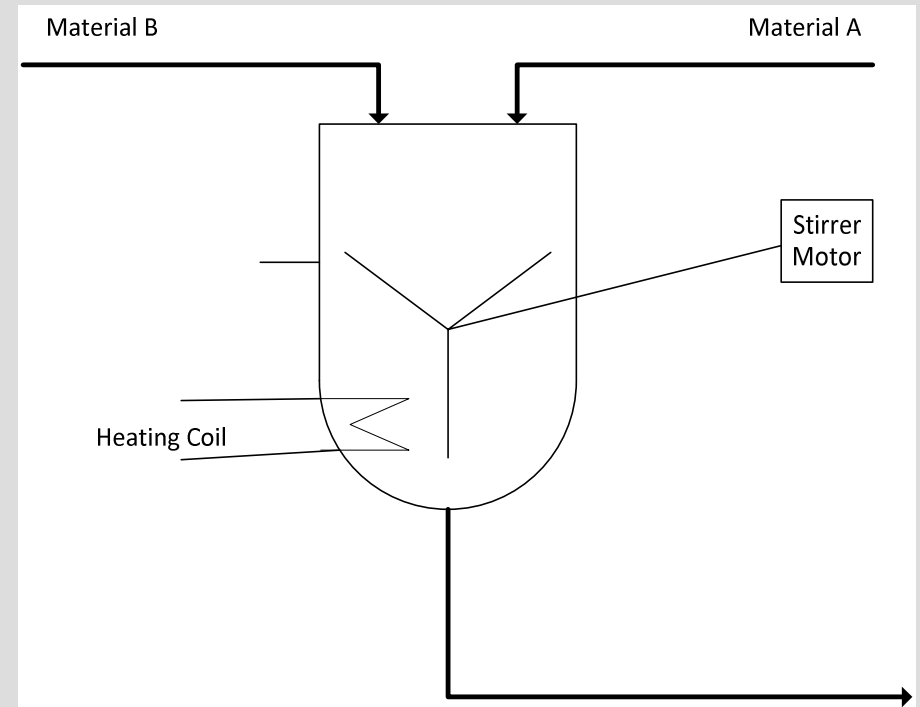
- **SQL is specified using logic flow diagrams and sequential events tables**
- **The basic instruments and control blocks are shown on the P&IDs, just like continuous controls**

Sequential Logic Control

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

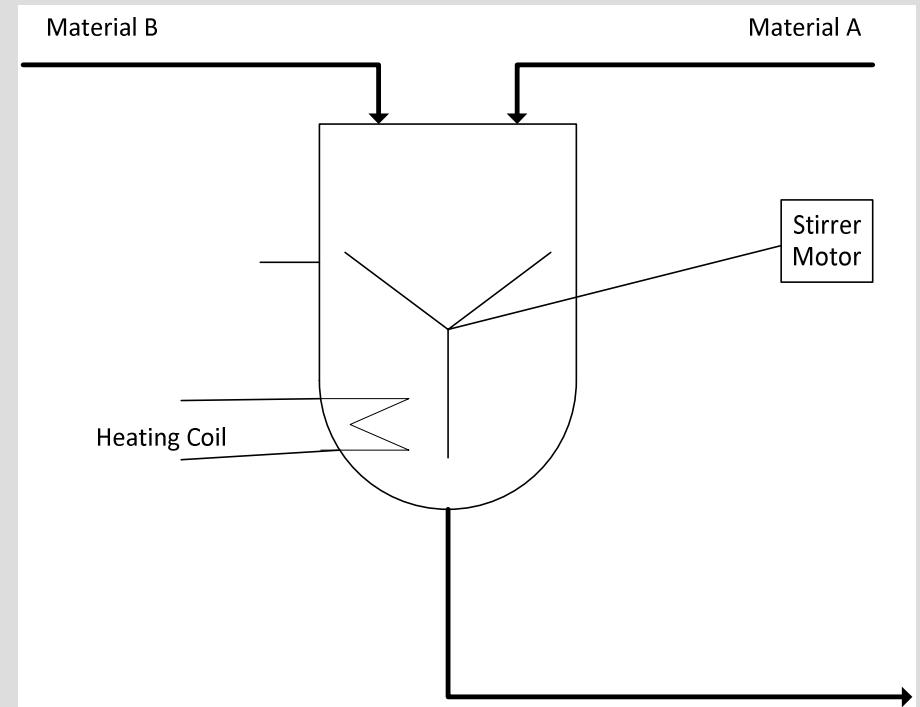
The goal of this process is to add small increments of component B to a drum or tank containing a stoichiometric excess of component A, then heat and mix the two components together until all of component B has been consumed in the reaction of $A+B \rightarrow C$.

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.



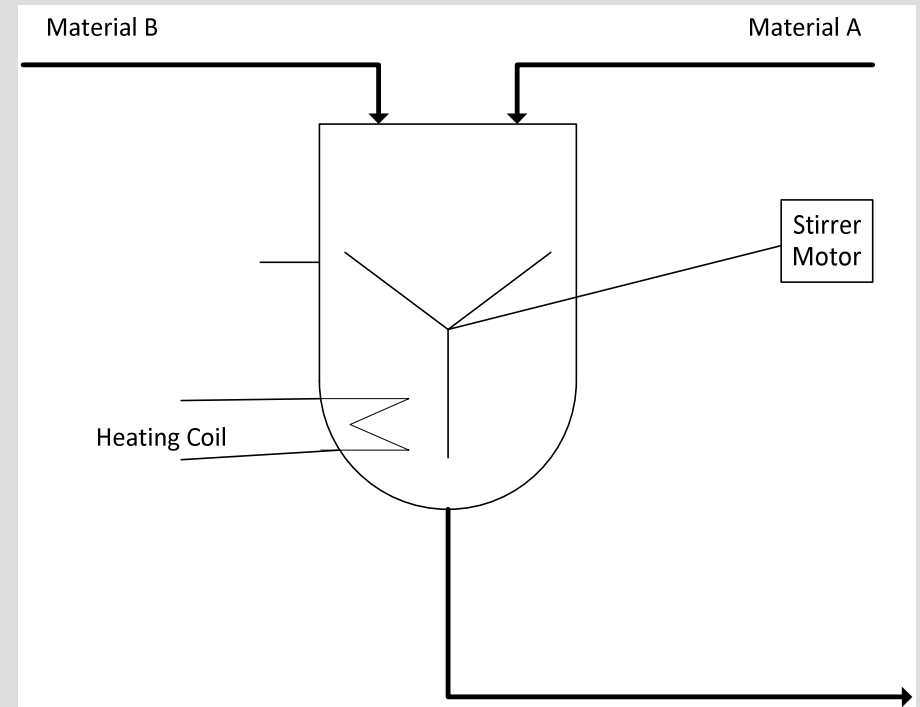
Sequential Logic Control

Answer . . .



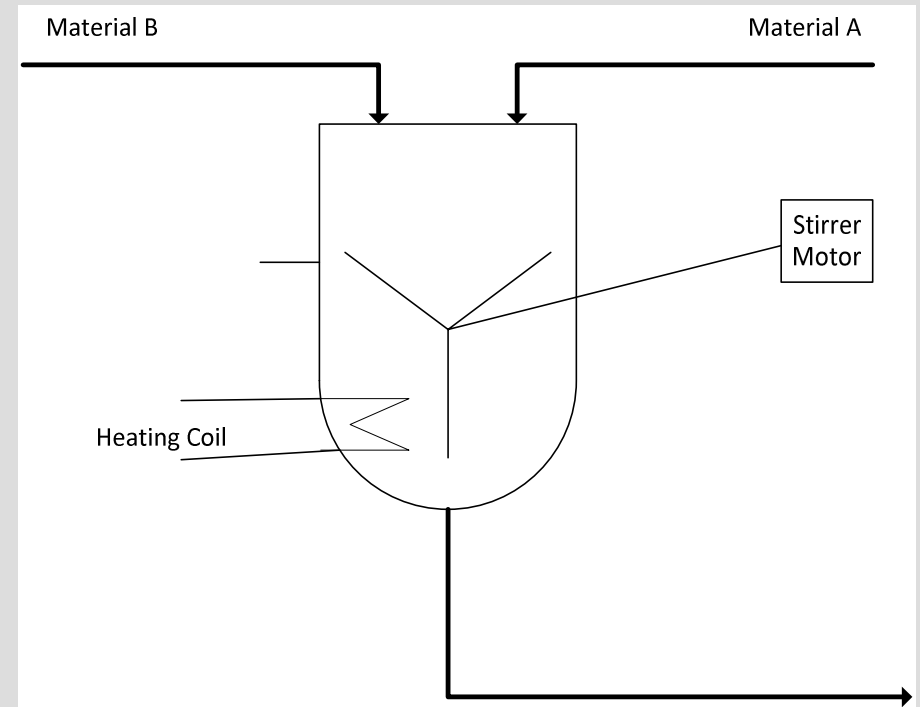
Sequential Logic Control

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



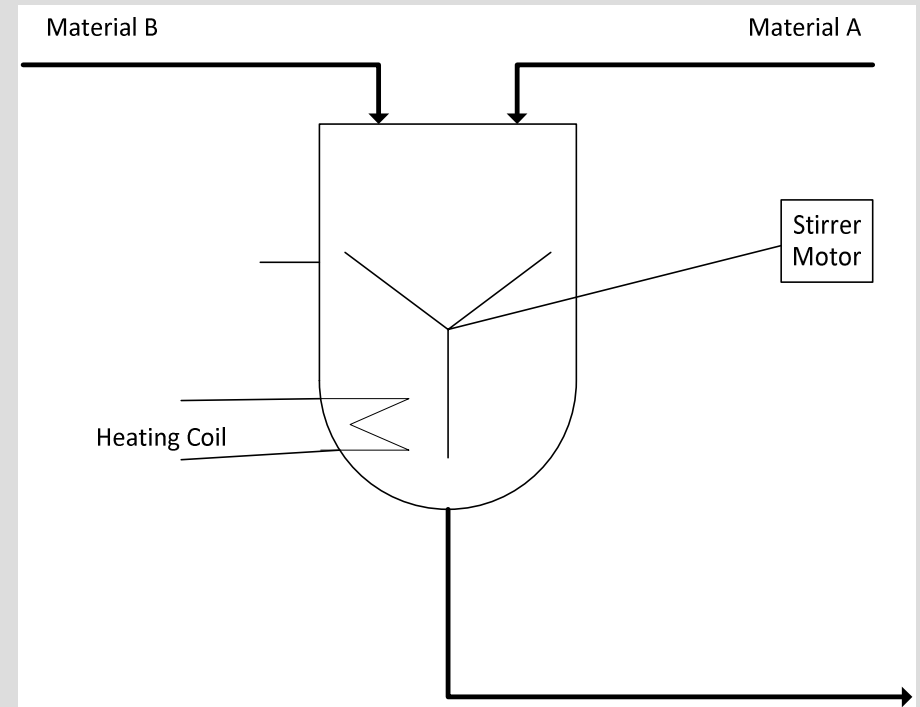
Sequential Logic Control

Answer . . .



Sequential Logic Control

Answer . . .



CHAPTER 2

Control System Fundamentals