## *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 ($M_{I1\text{-}3}$)

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. $M_I\ and\ M_{I1}$ 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:

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

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

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:

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

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**