Solutions for Tutorial 7
Selecting Controlled and Manipulating Variables

Before designing process control, we must know the control objectives!

7.1 Designing a feedback control system involves the selection of controlled and manipulated variables, and sensors for measuring the controlled variables. In addition, we have to know the possible disturbances occurring in the process in order to design a control system with good dynamic performance.

In this exercise, you are going to select the variables to be controlled for the CSTR in Figure 7.1 to satisfy the seven control objectives. The seven control objectives were introduced in Chapter 2 and are listed in Table 7.1. Complete Table 7.1 by filling in the selected controlled and manipulated variables, sensor principle (e.g., orifice meter) for the measurements and the possible disturbances occurring in the CSTR. You may add valves and sensors to the figure, if necessary.

Hint: Review the discussion on control objectives for the flash separator presented in Chapter 2.

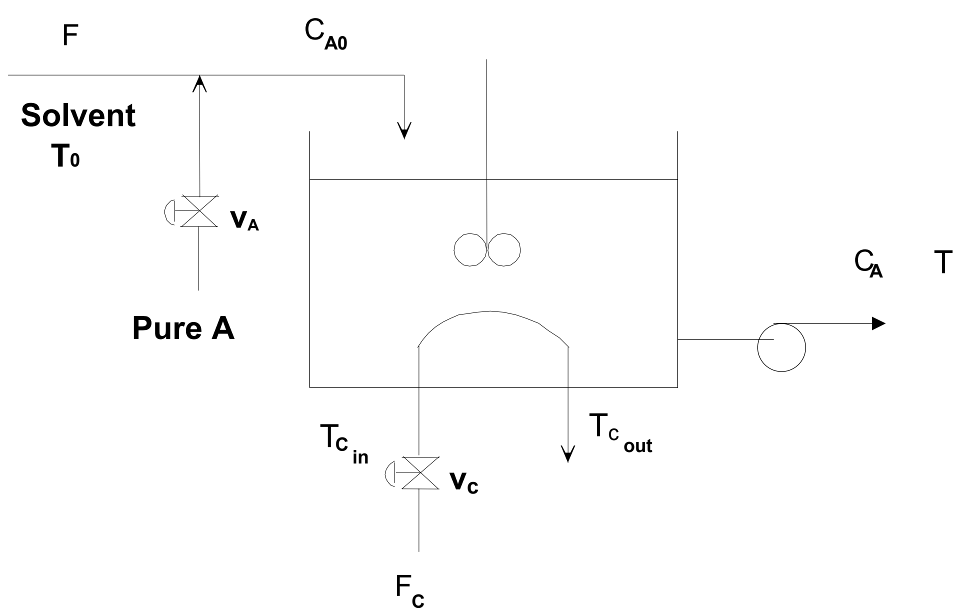


Figure 7.1 CSTR with heat exchange for the reaction system A → B → C.

Table 7.1 Control objectives for the non-isothermal CSTR.

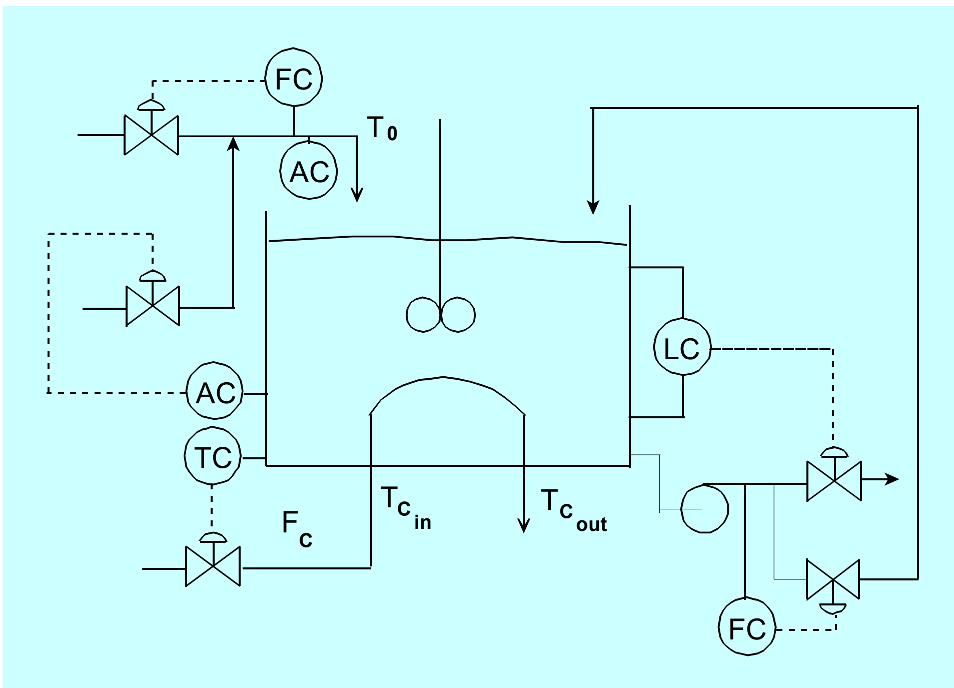
Control Objective	Controlled Variable	Sensor Principle	Manipulated Variable	Disturbances that would affect the controlled variable
Safety Maintain liquid in the reactor	1.Liquid level 2 Liquid level	1. Pressure difference 2. position of float	1. Valve after pump 2. valve in feed pipe	1. Flow in and pump pressure 2. feed pressure
Environmental Protection None				
Equipment Protection Maintain flow through the pump	Exit flow rate through the pump	Head (ΔP) across orifice meter	Valve in recycle back to tank	• Pump pressure • Liquid availability
Smooth Plant Operation and Production Rate 1. Reactor space time 2. Reactor inlet concentration 3. Feed flow rate 4. Reactor exit flow 5. Reactor temperature	1. Liquid level 2. Inlet concentration 3. total feed flow 4. flow rate 5. Temperature	1. Pressure difference 2. Composition analyzer 3. Pressure drop across orifice 4. Orifice head 5. thermocouple	1. valve after pump 2. valve in reactant pipe 3. valve in solvent flow 4. valve in exit pipe 5. coolant flow rate	1. Pressure of pump 2. Pressure of reactant 3. Pressure of solvent 4. flow in and level sensor noise 5. coolant temperature and pressure

Product Quality Reaction product concentration	Product concentration	Composition analyzer		1. Impurities affecting rate 2. Flow rate 3. Liquid volume 4. Temperature
Profit Optimization Yield of valuable (B) vs. undesired (C) product **A → B → C**	Reaction environment, temperature	Thermocouple or RTD	Valve in coolant pipe	1. Coolant pressure 2. Coolant temperature
Monitoring and Diagnosis **A.** Yield of valuable vs. undesired product **B.** Variability of 1. reactant concentration from set point 2. reactor volume 3. outlet flow rate **C.** Behavior of input (disturbance) variables **D.** Calculated heat transfer coefficient	Maximum yield (?) 1. low variance 2. low variance 3. acceptable variance limited disturbances near clean value		N/A	

The control strategy is shown in the following figure. Recall that the "circles" with a "C" within represents a controller. The first letter indicates the process variable being measured; for example, "F" represents flow. The dashed line is connected to the valve being manipulated. The controller applies the feedback principle. The calculations used by the controller will be explained in the next topic.

Notes:

1. We have decided not to control the feed composition. We have decided to adjust the reactant valve to control the product concentration of B.
2. We have controlled the reactor temperature. We can adjust the temperature value, i.e., the controller set point, to affect the yield.

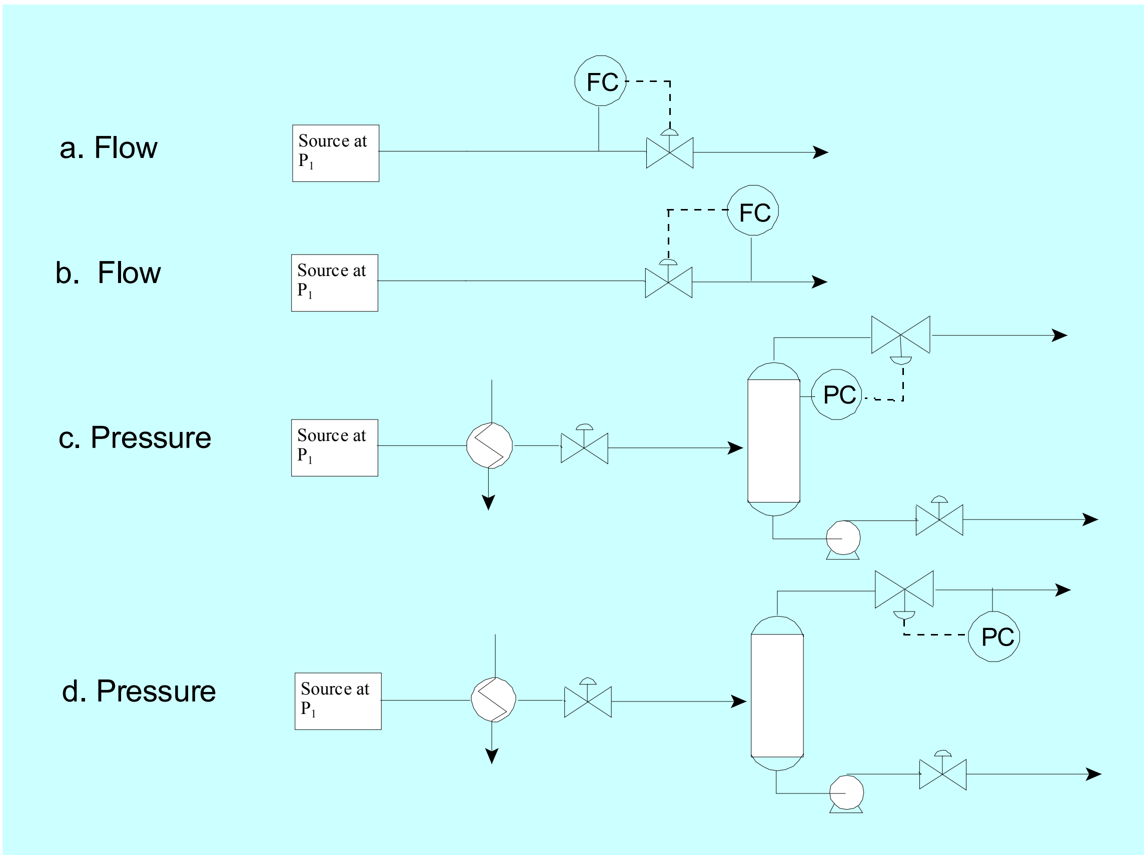


Discussion questions:

1. **Why didn't we control the reactant concentration of B by adjusting the coolant flow rate?**
2. **Why don't we maximize the yield by adjusting the coolant flow rate?**

7.2 Discuss whether each of the following control designs satisfies the specified control objective.

a. Control the flow in a pipe.
b. Control the flow in a pipe.
c. Control the pressure in an enclosed vessel.
d. Control the pressure in an enclosed vessel.



a. Yes, the sensor measures the flow rate and the valve changes the restriction for flow. Thus, the flow through the pipe is controlled.

b. Yes, this is essentially the same as (a) above. Note that the location of the measurement (before or after the valve) does not affect the application of feedback. Feedback depends on a casual relationship.

c. Yes, the pressure is measured correctly in the vessel, and the pressure is influenced by changing the restriction to flow in the (vapor) exit pipe.

d. No, the pressure is not measured in the vessel. Therefore, feedback control is not possible.

7.3 Possibility of feedback control.

Engineers must be able to quickly determine whether feedback control is possible. For many "straightforward" process systems, we can make this determination using qualitative analysis of the process behavior. If we do not have sufficient insight, we can develop mathematical models and perform identification experiments.

In this exercise, we will build our ability to use the modelling principles developed in prior lessons to predict the behavior of process systems. Here, we will apply qualitative reasoning to determine whether feedback control is possible for some proposed designs. Feedback is possible if a causal relationship exist between the manipulated and controlled variables. Later, we will consider other factors to find the best variables, but now we will concentrate on the possibility of control.

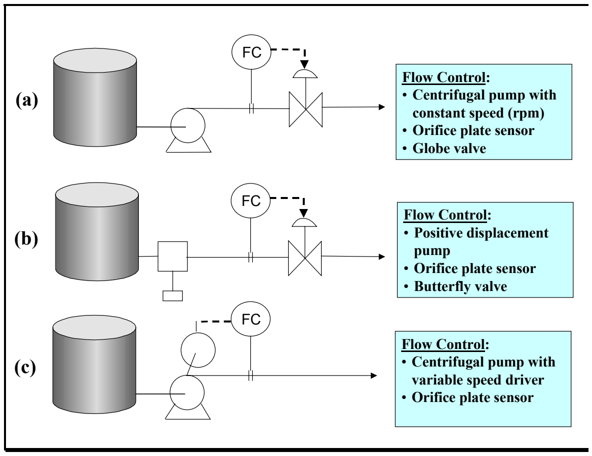
In addition, engineers must actually do it in the real world. Thus we require sensors and final elements (valves). The designs provide proposals for the equipment associated with each design; we will evaluate these as well.

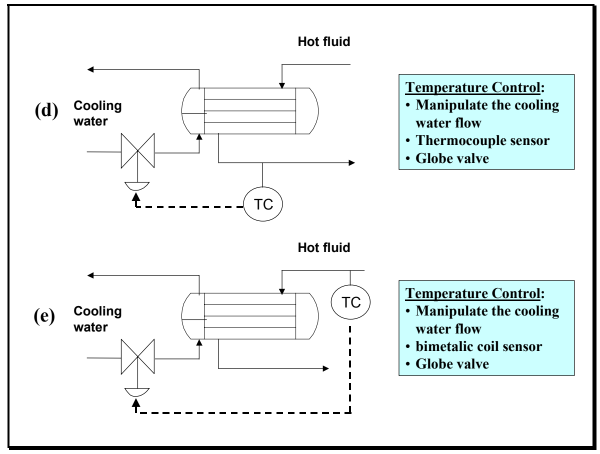
Prior to Chapter 8, we do not know what calculation is required to implement feedback control. Therefore, we will look for the causal relationship. We recall that the symbol for a controller is a circle or "bubble" with letters inside, such as "TC" for temperature controller.

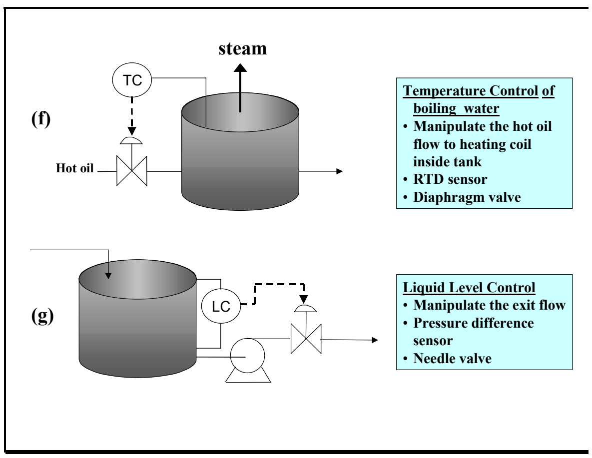
Scenario: You are working as an engineer and a colleague has asked you to evaluate some designs that she has prepared. She says that she does not have as much experience as you have in control and would appreciate your assistance.

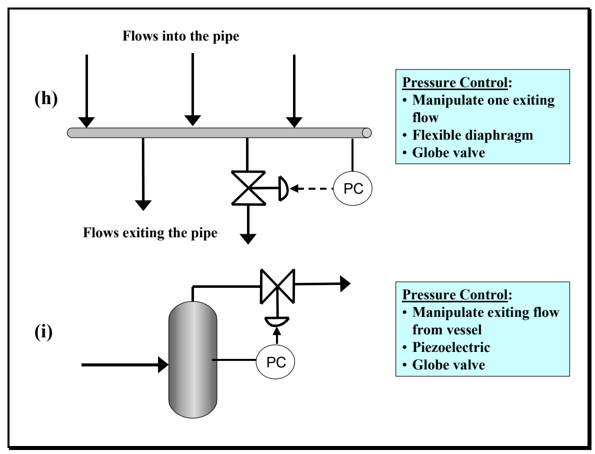
For each of the designs, determine whether feedback control is possible and evaluate the instrumentation recommendations.

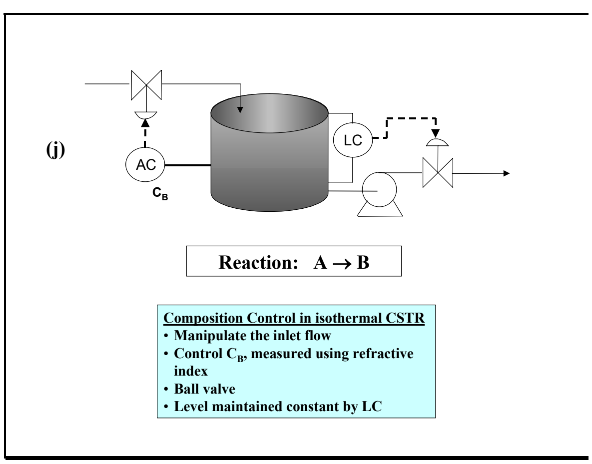
The proposed designs are presented in Figure 7.3.











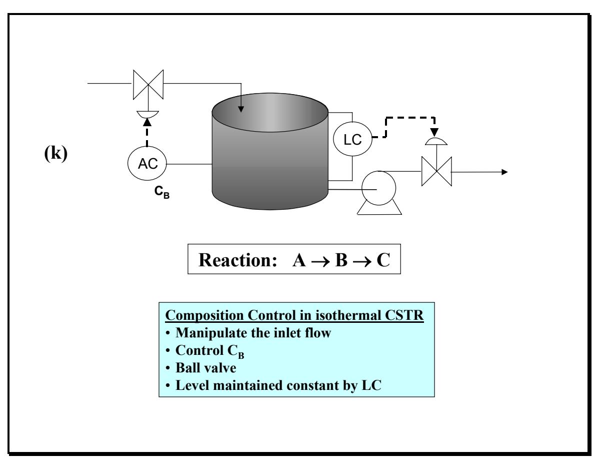


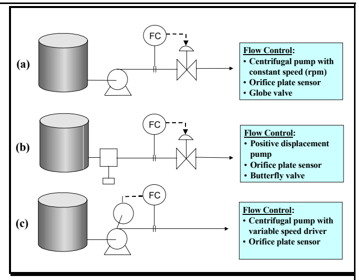
Table 7.3 Proposed Control Designs with instrumentation recommendations.

Solutions for proposed designs

a) The centrifugal pump increases the pressure of the fluid, i.e., it provides "head". The pump can operate at low or no flow, at least for a short time; the speed of the rotor does not determine the flow through the pump. Thus, the fluid flow rate is determined by the "driving force" (pressure) and the resistances to flow. The pump provides the driving force and the valve provides an adjustable resistance. Opening the valve increases the flow rate.

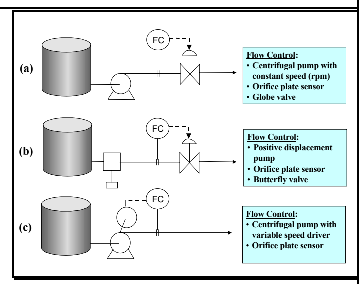
<u>Yes</u>, feedback control is possible. There is a causal relationship between the valve (resistance) and the flow rate

The orifice plate is a good sensor for clean fluids, and the globe valve is the "workhorse" control valve body in the process industries.



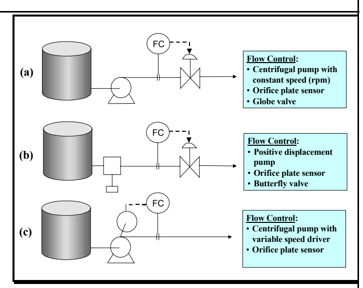
b) The positive displacement pump has moving components that define the liquid flow rate by the speed of rotation or by the linear movement distance and speed. Therefore the valve resistance does not affect the flow rate, and if the valve is closed too far could result in damage to the pump.

<u>No</u>, feedback control is not possible in this situation. The operation of the pump could be adjusted to influence the flow rate; in this case the control valve should be removed.

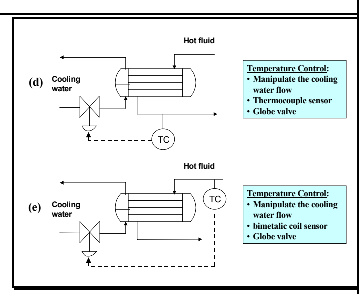


c) The pressure increase from a centrifugal pump depends on the rotor speed – the fast the rotation, the higher the pressure. A variable speed motor can be adjusted to achieve the desired flow rate, which is more energy efficient than adjusting a variable pressure drop (valve) in the pipe. Increasing the speed increases the flow rate.

<u>Yes</u>, feedback control is possible.



d) The temperature of the hot fluid needs to be controlled because of changes in its flow rate and inlet temperature. The heat transferred depends upon many factors, including the tube film heat transfer coefficient and the cooling water temperature. Increasing the cooling water flow rate will (1) increase the tube film coefficient and (2) decrease the average cooing water temperature in the tubes (its flowing faster). Both changes will increase the heat transfer and decrease the hot fluid exit temperature.

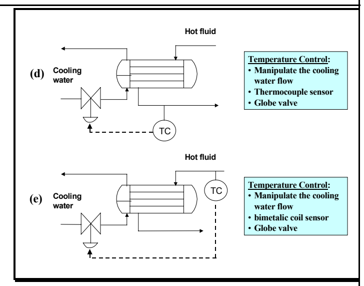


Yes, feedback control is possible.
A thermocouple provides a good balance of cost and accuracy. Again, the globe valve is a typical choice for a clean fluid.

e) The temperature sensor is located at the inlet to the heat exchanger. The heat transfer in the exchanger does not influence the fluid before it enters the exchanger. If we want to control the temperature at the inlet, we must adjust heat transfer upstream.

No, feedback control is not possible with the equipment shown.

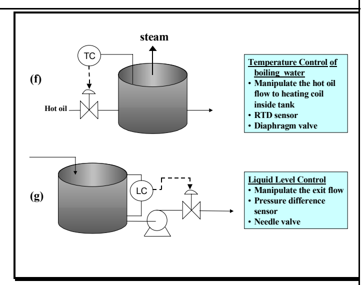
The bimetallic coil is often used for local temperature display; it is not used for sensors that transmit their readings.



f) The temperature of boiling water at atmospheric pressure is constant. Changing the heat transferred affects the rate of boiling, but not the temperature of the boiling water.

No, feedback control is not possible with the equipment shown.

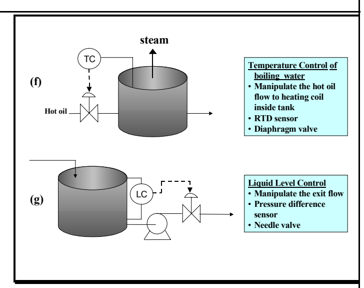
The diaphragm valve would not be used for clean, hot oil; it is used for slurries at lower temperatures.



g) In this example, the inlet flow is not manipulated, and the valve in the exit pipe is manipulated. Certainly, the outlet flow is influenced by the valve position (see (a) above), so a causal relationship exists. Since the level is unstable without control, feedback control is especially important.

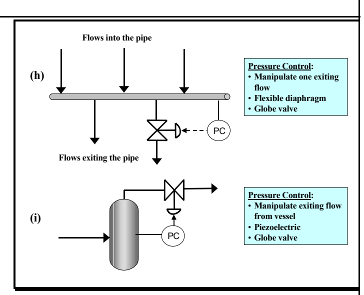
Yes, feedback control is possible.

Measuring the liquid level using differential pressure is one of the common methods in the process industries. A needle valve would not be used for control; a globe or ball valve would be typical choices.



h) The pressure in a pipe can be controlled by adjusting one of the flows. We can prove this by formulating a dynamic material balance. Naturally, successful control can only be achieved over a range of flows; when the valve is either fully opened or closed, control is no longer possible.

Yes, feedback control is possible.

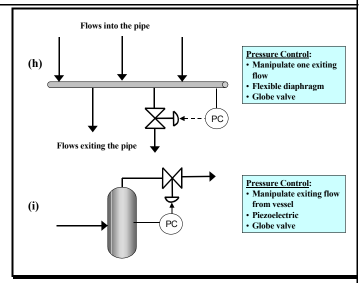


A pressure sensor that deflected because of pressure and converted the deflection to an electronic signal is used in such circumstances. A globe valve is acceptable here.

i) The pressure in a vessel can be controlled using the exit (or inlet) flow. The principles are identical to the previous design.

Yes, feedback control is possible.

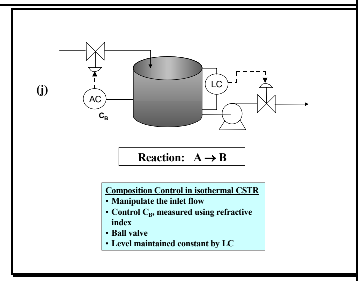
A piezoelectric sensor generates a small electronic signal when a pressure is applied; it can be used in this application.



j) The conversion (or extent of reaction) depends on the space time in the reactor. Clearly, the flow rate affects the space time. The model for this system was derived in Tutorial 3, which could be extended to the concentration of C_B.

Yes, feedback control is possible.

A sensor like refractive index can be used when the property of the product is significantly different from reactant and solvent. The level must be controlled, because it is unstable without control.

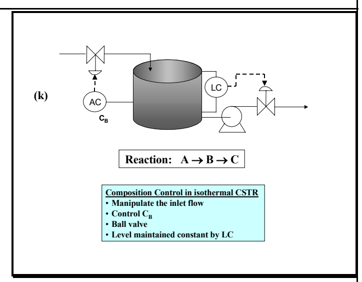


k) The conversion (or extent of reaction) depends on the space time in the reactor. Clearly, the flow rate affects the space time.

However, this process is more complex, some might say. "Tricky." For control to be successful, we need to have a controller gain that has a non-zero gain. The gain can be either positive or negative, but it should not change sign! What happens in this example? The figure below shows that the gain changes sign, because of the two reactions. In two regions, control is possible, but would only function within the region. At the maximum C_B point, control is not possible by adjusting the feed flow rate.

While control is possible, great care would have to be employed when implementing. A different manipulated variable, such as feed concentration should be investigated.

A ball valve would be an acceptable choice.



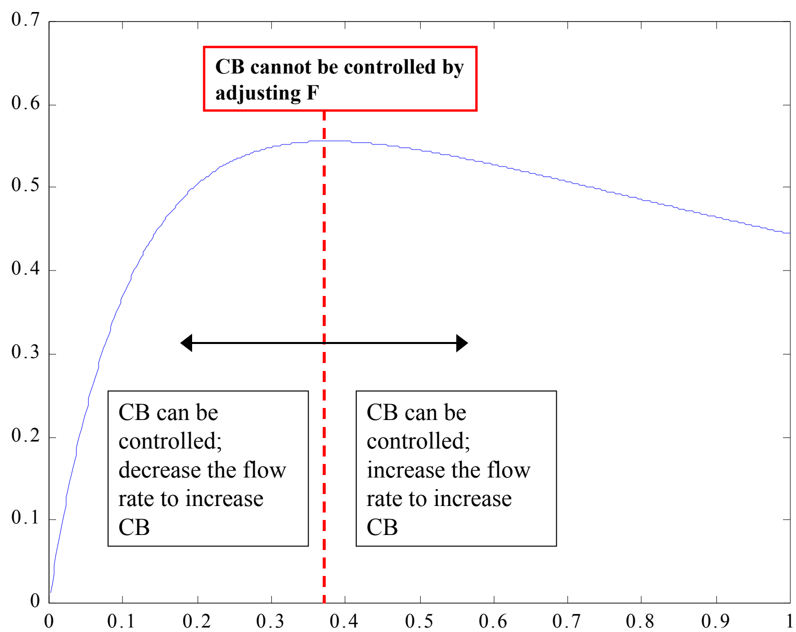


Figure showing the effect of flow (and volume) on the effluent concentration of the intermediate product B. When the flow is large (residence time is small) reducing the flow gives more time to form B (since CB is small, the loss to C is small). When the flow is small (the residence time is high) reducing the flow gives more time for the loss of B to C (since CA is low and CB is high).