Emnemodul: Advanced Process Control

13. Nov. 2024. Time: 09:00 – 12:00.

Answer as carefully as possible, preferably using the available space. There are in total 6 questions. Answer all questions in either English or Norwegian.

No printed or hand-written support material is allowed. A specific basic calculator is allowed.

Problem 1: General questions (X %)

Figure 1 shows a gas-liquid separator with measurements, valves, and disturbances. This configuration resembles a setup for the separation of product gases from a liquid stream, as is encountered, e.g., in electrolysis processes for (green) hydrogen production.

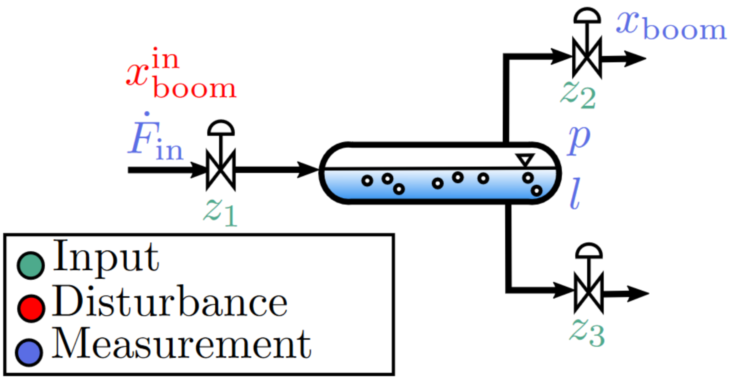

Figure 1: Gas-liquid separator with relevant measurements, inputs and disturbances.

(a) Explain the following terms:

- Throughput manipulator (TPM)
- Global consistency
- Local consistency

(b) Assuming that z_1 is the TPM of the process, propose an inventory control structure and argue based on your given explanations whether your control structure is locally and/or globally consistent.

(c) At the steady-state optimum, the flowrate F is at its upper constraint. How many steady-state degrees of freedom does the process have?

(d) How are degrees of freedom used in self-optimizing control?

(e) Consider the following equation:

$$Y = \left[F W_d \; W_n^y\right]$$
$$H^T = (YY^T)^{-1} G^y$$

What is the name and significance of H^T, W_d, W_n^y, respectively? How are F and G^y found?

(f) Two colleagues of yours are arguing whether it is best to control the value of the cost function J, or its gradient J_u. Explain to them which is the correct approach and why.

(g) Consider a manipulated variable that optimally saturates at steady-state. What should be considered when pairing it to a controlled variable? What should be considered in addition when the controller has integral action?

Problem 2: Feedback-optimizing control (X %)

We want to optimize a process (minimize the steady-state cost J) for a process with a set of constraints $g \leq 0$. There are disturbances d that change with time and influence the cost and the constraint values, but these cannot be measured. The gradient of the cost (J_u) can be estimated, the constraint values g can all me measured and the constraint gradient g_u can be estimated (typically, g_u is a constant). The objective is to find the manipulated variables u that minimize J for a varying set of active constraints (g_A).

From mathematics we have the necessary conditions of optimality (KKT-conditions):

(1) $L_u = J_u + \lambda^T g_u = 0$
(2) $\lambda \times g = 0$ (x=element-by-element multiplication)
(3) $\lambda \geq 0$

(a) Explain what λ is and what these conditions represent
(b) In self-optimizing control, we look for a variable for which we indirectly achieve optimal operation (minimize J) by controlling a variable at a constant setpoint. Explain this in a little more detail. Consider three cases:
    1. Use of a single measurement
    2. Use of measurement combinations using the nullspace method
    3. Use of measurement combinations using the exact local method
(c) Returning to equation (1): How can the cost gradient J_u be estimated?
(d) Returning to equations (1) to (3): Show a cascaded feedback-optimizing control structure which implements these equations in practice (it involves a max-selector).

Problem 3: Transformed Inputs (X %)

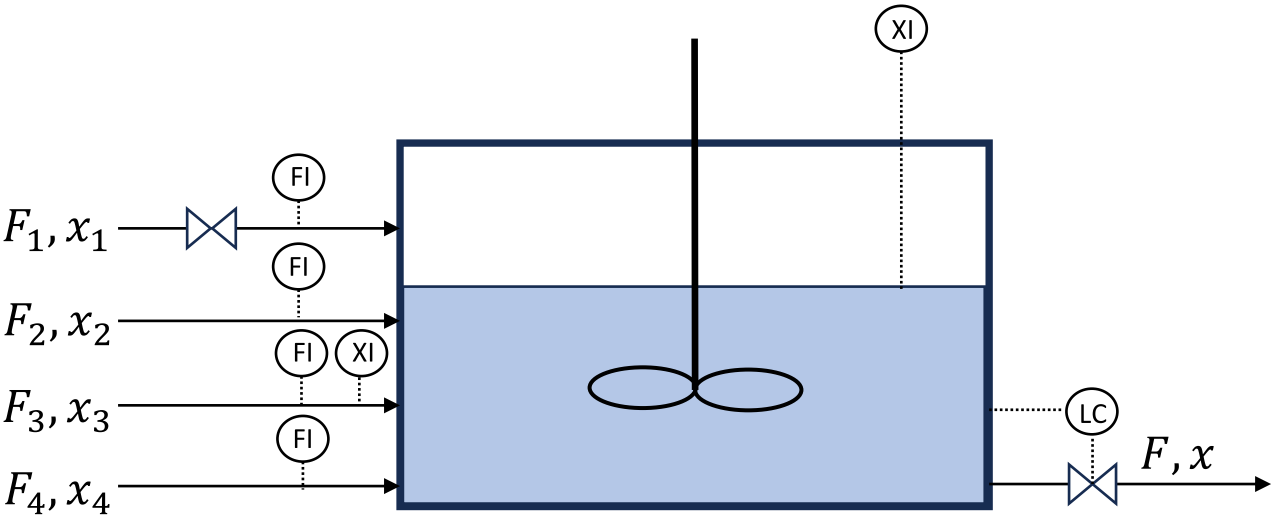

Figure 2: Process flow sheet of considered mixing process.

Consider the process shown in Figure 2. Four streams are mixed to make a product *F* with a desired fraction $x_s \approx 0.3$ kg/kg (setpoint) of methanol. The inflows are characterized as follows:

	Type	Concentration	Comment
F_1 [kg/s]	Manipulated variable	$x_1 = 0$	Pure water
F_2 [kg/s]	Disturbance	$x_2 = 1$ kg/kg	Pure methanol
F_3 [kg/s]	Disturbance	$x_3 \approx 0.5$ kg/kg	Varies
F_4 [kg/s]	Disturbance	$x_4 = 0.7$ kg/kg	Fixed composition

(a) Propose a feedforward control system with a feedback correction (write on the flowsheet), for example, a nonlinear model-based feedforward block based on the idea of transformed inputs.

(b) Explain why we need the feedback correction.

Hint: Start by writing steady-state material balances to find an equation for *x* as a function of the other variables.

Problem 4: Cascade control (X %)

Consider again the separation system shown in Problem 1, Figure 1. The most important disturbance of this process is the upstream concentration of an explosive compound, x_{boom}, which must never exceed 2% in the gas volume within the equipment. Concentration measurements for this compound are only available in the pure gas phase, i.e., at the gaseous outlet stream of the separator. The concentration of x_{boom} can be controlled using the pressure *p* of the separator (reducing the solubility of x_{boom} at the contamination source upstream).

You are tasked to tune a concentration controller CC for the component x_{boom} that adjusts the setpoint of an inner pressure controller PC. Below are shown relevant step response (Figure 3), and the proposed cascade control structure.

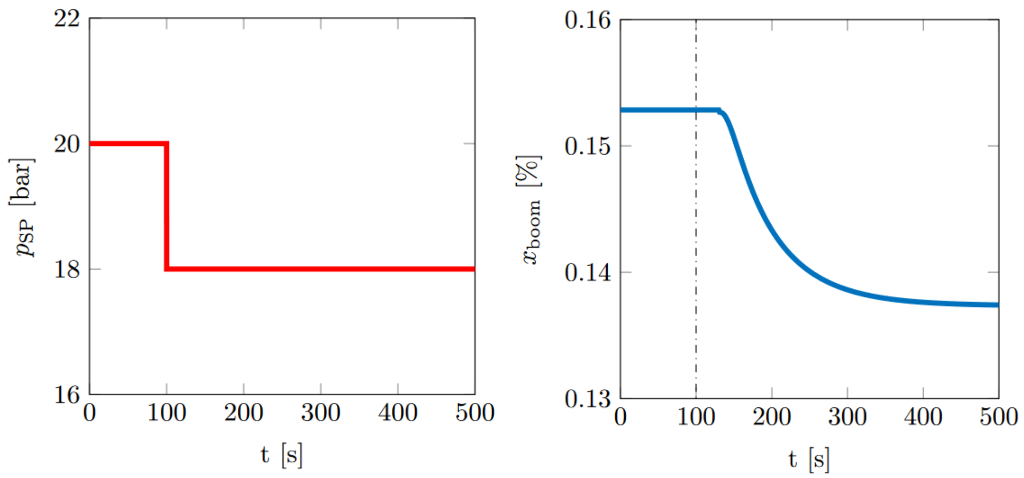

Figure 3: Pressure setpoint change (left), and its influence on the concentration (right).

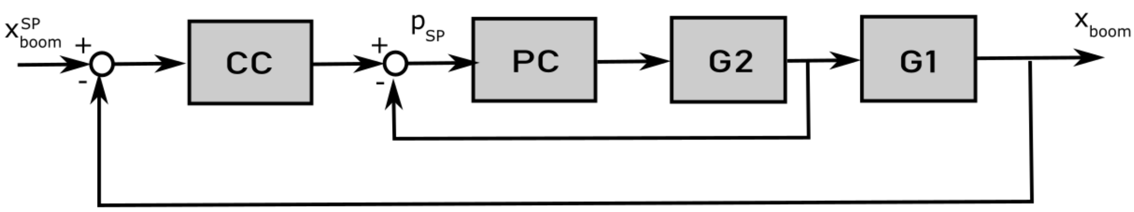

Figure 4: Proposed cascade control structure

(a) What are the benefits of a cascade control structure? Draw two disturbances into the block diagram of Figure 4, one that can be handled by the inner control loop (d_1), and one that cannot (d_2).

(b) Tune the concentration controller using the step response of the setpoint p_{SP} to x_{boom} shown in Figure 3 with tight tuning.

(c) PC is also tuned tightly, which gives a timescale separation of 10 between the outer and inner loop. What is the transfer function from p_{SP} to p?

(d) To reduce downstream compression requirements the pressure in the separator should be kept at 20 bar if possible, and it may not drop below 5 bar. Add one or more elements to the block diagram shown in Figure 4 to ensure this.

Problem 5: Evaporator control (X %)

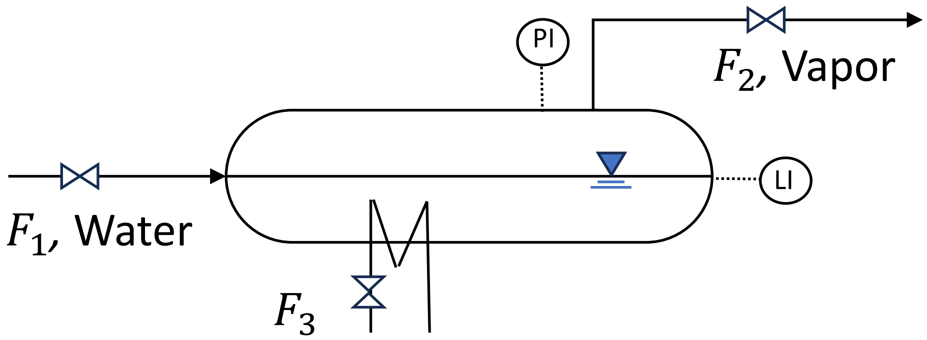

Figure 5: Process flow sheet of considered evaporator.

Consider the process diagram of an evaporator in Figure 5. Propose a control structure when:

(a) F1 is the TPM
(b) F2 is the TPM
(c) F3 is the TPM
(d) A bidirectional structure that handles all cases

You can add flow sensors (FI) as needed.

Note: Level can be a bit difficult to measure, so in the first three cases add also possible feedforward action from the TPM to the level control.