28451 - Optimizing Plantwide Control

Project Assignment: Plantwide Control of a Evaporator System.

February 12, 2024

Objective

The objective of this project is to design and test a plantwide control system for a realistic process example with multiple and interacting control loops. The control needs to ensure stable and safe operation as well as respecting quality constraints and optimize process economics. The processing plant used in this assignment is the forced circulation evaporation process, illustrated in Fig. 1. The procedure for the design of the control system should be based on sound engineering judgement and the top-down/bottom-up approach for plantwide control presented in Chap. 24 in Seborg et al.

Project Assignment Tasks and Time Plan

The assignment is completed in groups and runs throughout the semester. There will be three milestones in the project that need to be respected in order to successfully complete the assignment. The assessment of the whole project is based on what is delivered at all three milestones. The first Milestone covers the assignment tasks a)-c) and constitutes the work involved in part 1 of you report which is the open loop system analysis. The evaluation at the first milestone is based on the following:

- you have a working implementation
- can produce process response plots
- that you have found the operating point you will use in part 2

Milestone 2 is the full written report of all assignment tasks in both part 1 and part 2. Milestone 3 is an oral presentation of your solution to be given at the exam date.

Assignment tasks - Part 1

Part 1 consist of the following 3 tasks which needs to be completed by the group and approved as milestone 1.

a) Model implementation and analysis
Perform an open loop implementation of the evaporator system model in Matlab/Simulink using the process values given in table 1. A correct implementation can be verified by showing that the system is in steady state given these operational conditions. Make a degrees of freedom analysis and classify the inputs as actuator or disturbance variables according to you own judgment. Choose some realistic values for the measurement noise.

b) Optimize steady state operation conditions
The operation cost of the evaporator is the price of utilities. In case product quality and other constraints are met the process is economical feasible and the economical optimal process operation is achieved by minimizing operational cost. Find the optimal steady state conditions for the plant given the nominal values for the disturbances.

c) Open loop analysis
Use your model implementation to test the open loop response of the system to step changes in actuator and disturbance variables. If you have unstable or integrating modes these need to be stabilized using a simple P or PI controller.

Assignment tasks - Part 2

Part 2 consists of three tasks which combined gives the design and evaluation of one control design option. These three tasks need to be completed as many times as there are members in a group. I.e. a group with two members needs to come up with 2 control system design and evaluations and a group with three members need to come up with 3. These different designs alternatives also needs to be compared as part of the final report. A written report covering all the tasks in part 1 and part 2 is handed in as milestone 2. The report should be well structured, informative and follow the standards for academic reporting in general.

d) Control design
Propose a control structure for this process using the systematic plantwide control approach. Define realistic process constrains on actuators and performance constraints on process outputs. Make sure that you can stabilize the system and achieve some level of performance in relation to your performance constraints by proper tuning of the controllers.

e) Closed loop evaluation
Test your control system based on a range of realistic process disturbances. Show that the controller can move the operation of the process to a new desired operating point. Quantify the performance of the controller in these tests by some metric and discuss the dynamic performance. Can you identify limitation in the process conditions where your control system fails?

f) Process model uncertainty
Often the real world and the process model we use are not in perfect agreement. Play with minor (realistic) changes in some process parameters in the evaporator model implementation which could be uncertain. Check how these changes may affect the performance of your control system. Is it robust to these changes?

Time plan

The deadlines for the three milestones are (see course plan for explicit dates):

1. **Week 7**. Approval by one of the instructors. In case it has not been possible to complete this part a working implementation will be provided. This will reduce the final grade by 15% but allow you to continue.

2. **Week 13**. On DTU Learn as a single pdf file. 2 copies of the signed printed report must be delivered to the instructors.

3. **Exam date**. Short presentation by each group for the instructors and questions. A time plan will be distributed during the semester.

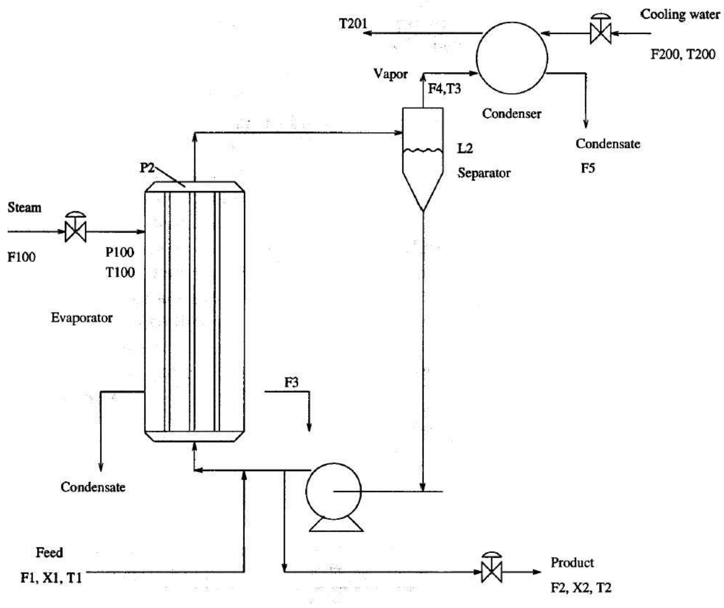

Figure 1: The evaporator system

It should be noted that the minimum requirement for passing is a report and an oral presentation showing part 1 plus at least one plantwide control implementation and close loop analysis!

Process Description

The plant used in this assignment is a forced circulation evaporator process model. This nonlinear, multi loop process is a very convenient example for illustration and benchmarking of process control technologies. The process and the process variables are depicted in Fig. 1 and the model equations will briefly be presented in the following. The evaporator model is representative for a number of industrial evaporation processes. Evaporation is found in sugar and paper mills as well as in a range of food and pharmaceutical industries. In these processes, some solvent (typically water) is removed to concentrate a stream before drying or crystallization.
The principle in the evaporation process is separation by evaporation from a liquid mixture where at least one component is not volatile. The evaporation chamber is designed as a heat exchanger where latent heat from condensation of steam is used to heat up and evaporate a fraction of the circulating process stream. The gas and liquid phases from the evaporator are separated and the gas is condensed before leaving the system. A fraction of the liquid is taken out as product before the remaining fraction is mixed with fresh feed and fed to the evaporator again. Due to the material loop created by the forced circulation of the liquid stream, the dynamic coupling of the system is known to be strong and disturbances anywhere in the system can propagate throughout the process.

The model equations

In the following a simplified system model will be presented which is sufficiently detailed to simulate the dynamic system behavior. As illustrated in Fig. 1, the model for the forced circulation evaporator can be divided into four parts: The separator, the evaporator, the steam jacket and the condenser. The equations are given in the following and the nomenclature used is: Fi, Xi, Ti refers to flow rates, composition and temperature of stream i. Li, Pi and Qi are levels, pressures and duties in unit i.

The separator

A total mass balance around the separator gives

$$\rho A \frac{dL2}{dt} = F1 - F4 - F2 \tag{1}$$

where ρ is the liquid density and A is the cross sectional area of the separator and ρA is assumed to be 20 $^{kg}/_{m}$.

The evaporator

The evaporator itself is modeled by the following 5 equations:

$$M \frac{dX2}{dt} = F1X1 - F2X2 \tag{2}$$

$$C \frac{dP2}{dt} = F4 - F5 \tag{3}$$

$$T2 = 0.5616P2 + 0.3126X2 + 48.43 \tag{4}$$

$$T3 = 0.507P2 + 55.0 \tag{5}$$

$$F4 = \frac{Q100 - F1Cp(T2 - T1)}{\lambda} \tag{6}$$

where M is a constant liquid hold up in the evaporator of 20 kg. Cp and λ are the heat capacity and the latent heat of evaporation of the process liquid which is assumed constant at 0.07 $^{kW}/_{K(kg/min)}$ and 38.5 $^{kW}/_{(kg/min)}$ respectively. The constant $C = 4$ $^{kg}/_{kPa}$ is used to convert a mass of vapor into a pressure in the vessel.

The steam jacket

The steam side of the evaporator is modeled with three algebraic equations as the dynamics are assumed to be very fast, i.e. pseudo steady state.

$$T100 = 0.1538P100 + 90.0 \tag{7}$$

$$Q100 = 0.16(F1 + F3)(T100 - T2) \tag{8}$$

$$F100 = \frac{Q100}{\lambda_s} \tag{9}$$

where $\lambda_s = 36.6$ $^{kW}/_{(kg/min)}$ is the latent heat for steam. The term $0.16(F1 + F3)$ correlates the flow to the evaporator to the overall heat transfer coefficient times the area, $UA1$, at the given process conditions.

The condenser

The condenser is also modeled as a set of algebraic equations assuming pseudo steady state.

$$Q200 = \frac{UA2(T3 - T200)}{1 + UA2/(2CpF200)} \tag{10}$$

$$T201 = T200 + \frac{Q200}{F200Cp} \tag{11}$$

$$F5 = \frac{Q200}{\lambda} \tag{12}$$

where $UA2 = 6.84\ ^{kW}/_{K}$ is the overall heat transfer coefficient times the area.

Operational conditions

The evaporator model has a number of degrees of freedom which can be classified as manipulated variables, u, and disturbance variables, d. The states of the system, x, is seen from the differential equations in the model and these are all measured. These three process variables are the desired control variable of the system. This gives the following general system description of the model.

$$\frac{dx}{dt} = f(x, u, d), \quad x(t = 0) = x_{ss} \tag{13a}$$

where

$$x = \begin{bmatrix} L2 & X2 & P2 \end{bmatrix}^T \tag{13b}$$
$$u = \begin{bmatrix} u_1 & u_2 & \cdots & u_n \end{bmatrix}^T \tag{13c}$$
$$d = \begin{bmatrix} d_1 & d_2 & \cdots & d_m \end{bmatrix}^T \tag{13d}$$

and x_{ss} is the steady state solution for the nominal operation. Table 1 lists the system variables for the nominal system.

Table 1: Nominal steady state process conditions for the evaporator system.

Variable	Description	Value	Unit
$F1$	Feed flowrate	10.0	$^{kg}/_{min}$
$F2$	Product flowrate	2.0	$^{kg}/_{min}$
$F3$	Criculating flowrate	50.0	$^{kg}/_{min}$
$F4$	Vapor flowrate	8.0	$^{kg}/_{min}$
$F5$	Condensate flowrate	8.0	$^{kg}/_{min}$
$X1$	Feed composition	5.0	%
$X2$	Product composition	25.0	%
$T1$	Feed temperature	40.0	°C
$T2$	Product temperature	84.6	°C
$T3$	Circulating temperature	80.6	°C
$L2$	Separator level	1.0	m
$P2$	Operating pressure	50.5	kPa
$F100$	Steam flowrate	9.3	$^{kg}/_{min}$
$T100$	Steam temperature	119.9	°C
$P100$	Steam pressure	194.7	kPa
$Q100$	Heater duty	339.0	kW
$F200$	Cooling water flowrate	208.0	$^{kg}/_{min}$
$T200$	Cooling water inlet temp.	25.0	°C
$T201$	Cooling water outlet temp.	46.1	°C
$Q200$	Condenser duty	307.9	kW

You have to assume that the true system, i.e. the nonlinear simulation model, is monitored by a control system which logs data for all three states every minute. This implies that the data logging system and controllers work in discrete time (sampled every minute) but the true system, i.e. the simulation model, is of course running in continuous time. Each discrete time measurement, y_k, of the states is the current state value for the process variable, x_k, corrupted by Gaussian distributed noise, i.e.

$$y_k = x_k + v_k, \tag{14a}$$

where

$$v_k \in N_{iid}\left(\begin{bmatrix}0\\0\\0\end{bmatrix}, \begin{bmatrix}\sigma_L^2 & 0 & 0\\ 0 & \sigma_X^2 & 0\\ 0 & 0 & \sigma_P^2\end{bmatrix}\right) \tag{14b}$$

where $\{\sigma_L^2, \sigma_X^2, \sigma_P^2\}$ are the stochastic variances on a typical level, composition and pressure measurement respectively.

Production cost and operational window

The optimal profitability of the process is achieved by respecting the quality constraint at a given production rate while minimizing operational cost. Hence a performance cost function will consist of a sum of terms representing the balance between the cost of different utilities times there amounts which may be related to one or a sum of process streams.

The process constraints for safety and product specification are:

$$X2 \geq X2_{min} \tag{15}$$
$$P2 \in [40; 80]\, kPa \tag{16}$$
$$P100 \leq 400\, kPa \tag{17}$$
$$F200 \leq 400\, {}^{kg}/_{min} \tag{18}$$
$$F3 \leq 100\, {}^{kg}/_{min} \tag{19}$$
$$L2 \in [0.3 - 2.0]\, m \tag{20}$$

As the constraints on $\{P2, P100, F200, F3, L2\}$ are safety constraints these must be respected at all times, i.e. these are hard constraints. The constraint on the product purify $X2$ must be respected on average. Hence small violations in dynamic simulations of the constraint can be accepted for a short time. Violations of the purity constraint in steady state is not acceptable. Choose your products constraint in the interval $X2_{min} \in [20; 35]$ and a reasonable economic cost function for your optimization of the operational point for the process.