Department of Chemical Engineering, NTNU

Examination paper for TKP4140 – Process Control

Examination date: 02 December 2020

Examination time (from-to): 09:00 – 13:00

Permitted examination support material: A / All support material is allowed

Academic contact during examination: Sigurd Skogestad
Phone: 91371669

Technical support during examination: Orakel support services
Phone: 73 59 16 00

OTHER INFORMATION

You may answer in Norwegian or English.

Make your own assumptions: If a question is unclear/vague, make your own assumptions and specify them in your answer. Only contact academic contact in case of errors or insufficiencies in the question set.

Saving: Answers written in Inspera Assessment are automatically saved every 15 seconds. If you are working in another program remember to save your answer regularly.

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ABOUT SUBMISSION

File upload: All files must be uploaded before the examination time expires. 30 minutes are added to the examination time to manage the sketches/calculations/files. (The additional time is included in the remaining examination time shown in the top left-hand corner.)

How to digitize your sketches/calculations
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NB! You are responsible to ensure that you upload the correct file(s) for all questions. Check the file(s) you have uploaded by clicking "Download" when viewing the question. All files can be removed or replaced as long as the test is open.

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Your answer will be submitted automatically when the examination time expires and the test closes, if you have answered at least one question. This will happen even if you do not click "Submit and return to dashboard" on the last page of the question set. You can reopen and edit your answer as long as the test is open. If no questions are answered by the time the examination time expires, your answer will not be submitted.

Withdrawing from the exam: If you become ill, or wish to submit a blank test/withdraw from the exam for another reason, go to the menu in the top right-hand corner and click "Submit blank". This cannot be undone, even if the test is still open.

Accessing your answer post-submission: You will find your answer in Archive when the examination time has expired.

Problem 1 (25%)

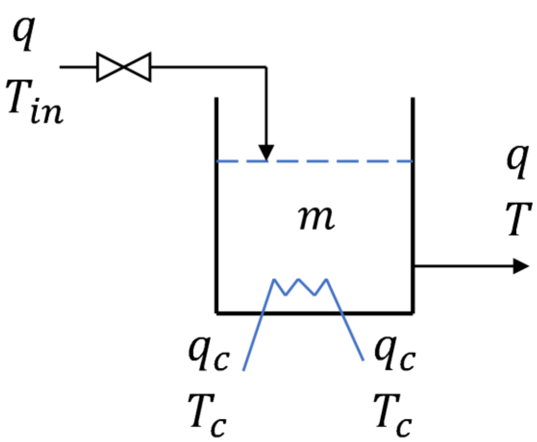
Consider a well-mixed tank where a hot fluid (q) is cooled as shown in the figure below. The cooling fluid (q_c) is a boiling liquid, so the temperature T_c on the cold side can be assumed constant through the heat exchanger. The heat transfer (a negative number) to the hot side is then

$Q = UA(T_c - T)$.

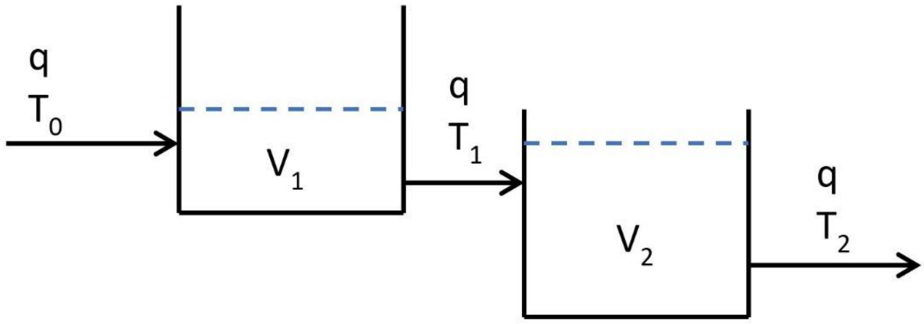
All the dynamics in the system are assumed to be related to the liquid mass m on the hot side.

Data: $c_p = 4.2$ *kJ/(K kg),* $m = 5000$ *kg (constant),* $q = 10$ *kg/s (nominal),* $q_c = 1$ *kg/s (nominal),* $T_{in} = 50°C$ *(nominal),* $T_c = 10°C$ *(nominal),* $UA = 42$ *kW/K (constant).*

(a) (7%) Derive the energy balance for the system.
(b) (3%) Find the steady-state nominal value for T.
(c) (15%) Linearize the model and derive the four transfer functions given below:
$T(s) = g_1(s)T_{in}(s) + g_2(s)T_c(s) + g_3(s)q(s) + g_4(s)q_c(s)$
(Note that one or more of these transfer functions may be zero)



Problem 2 (25%)



Consider a process with two well-mixed tanks in series, as shown in the figure above. All the dynamics in the system are assumed to be related to the liquid masses in the two tanks.

Data: $V_1 = 1$ *m³*, $V_2 = 4$ *m³*, $q = 0.2$ *m³/s (all assumed constant).*

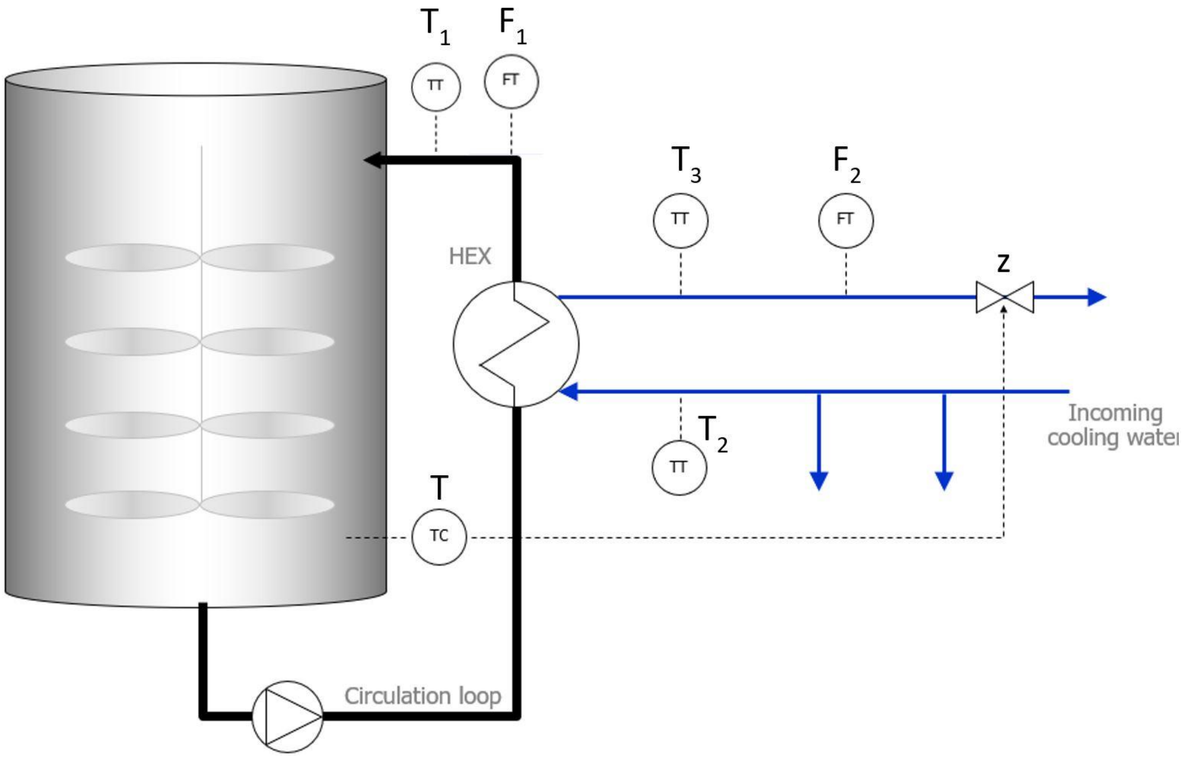
(a) (5%) The dynamics are given by $T_2 = g_2(s)T_1$, $T_1 = g_1(s)T_0$ (in deviation variables). What are the transfer functions g_1 and g_2? *(Comment: This is a simple system so you can write directly the transfer functions without showing the details of starting from the energy balances of the two tanks)*

To understand the temperature dynamics, we consider disturbances in the inlet temperature T_0. Give an analytical expression (in deviation variables) for $T_0(t)$, $T_1(t)$ and $T_2(t)$, and plot (sketch) them on the same figure for the following two cases:

(b) (10%) T_0 is a step change of magnitude 1 (Figure a)
(c) (10%) $T_0 = \sin(0.2t)$ (persistent sinusoid) (Figure b)

The time axis for the figures should be from 0 to 50s.

Problem 3 (15%)



We use a circulating liquid that exchanges heat with cooling water (manipulate valve position z) to control the temperature T in a well-mixed tank (CSTR) where an exothermic reaction is taking place. The figure shows the existing control structure. However, this structure is not working well. One reason for the problems is that the measurement of T has some delay, and there are also problems with dynamics in the heat exchanger and nonlinearity. Five additional measurements that may be used to improve control are shown on the figure.

(a) (5%) Classify the variables $(T, T_1, T_2, T_3, F_1, F_2, z)$ as inputs (u), primary outputs (y), measured secondary outputs (y_2) and measured disturbances (d).

(b) (10%) Suggest three possible improvements to the original control structure, with at least one cascade loop and one feedforward controller. Comment on why the improvements will be helpful.

Problem 4 (25%)

We consider the following process:

$$y_2(s) = \frac{3u(s)}{2s+1}$$

$$y_1(s) = \frac{y_2(s) + 2d(s)}{8s+1}$$

The measurement dynamics (for y_1, y_2 and d) are all first-order with time constant 0.5: $\frac{1}{0.5s+1}$.

The objective is to use u to control y_1 at the setpoint y_{1s}. We consider three alternative control structures (subscript m denotes measurement):

Control structure 1: Feedback only, $u = c(s)(y_{1s} - y_{1m})$, where $c(s)$ is a PI controller.

Control structure 2: Cascade control.

Slave loop: $u = c_2(s)\,(y_{2s} - y_{2m})$, where $c_2(s)$ is a PI-controller.
Master loop: $y_{2s} = c_1(s)\,(y_{1s} - y_{1m})$ where $c_1(s)$ is a PI controller.

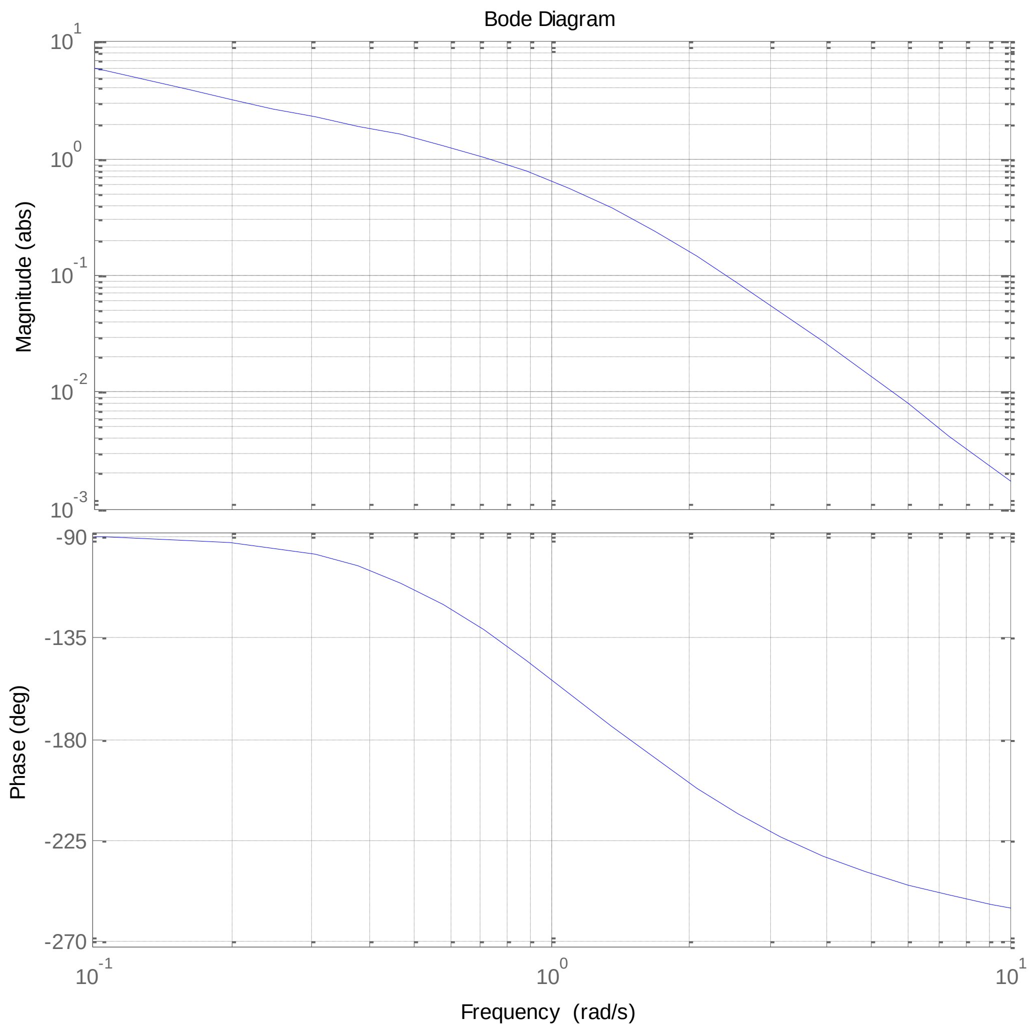
Control structure 3: Feedforward control, $u = c_{FF}(s)d_m$.

(a) (12%) Make block diagrams for the process and of the of the three structures.
(b) (10%) Suggest settings for the four controllers (don't forget to include the measurement dynamics when tuning the controllers).
(c) (3%) Which structure would you choose and why? Would you suggest using a PID controller instead of a PI for any of the three feedback controllers?

Problem 5 (10 %)

The frequency response of a loop transfer function $L(s) = g(s)c(s)g_m(s)$ is shown in the Bode diagram below.

(a) (2%) Formulate the Bode stability condition. Is the system stable?
(b) (8%) What is the gain margin, phase margin (show on the figure) and what is the allowed extra time delay in the loop to remain stable?



Comment: You may write on this paper and use it as your solution.