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UNIVERSITI SAINS MALAYSIA

Second Semester Examination  
2010/2011 Academic Session

April/May 2011

**EKC 561 – Model Based Process Control**

Duration : 3 hours

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Please ensure that this examination paper contains SIX printed pages and TWO printed page of Appendix before you begin the examination.

**Instruction:** Answer **ALL** questions.

1. [a] Use the Skogestad's half rule to obtain a first-order-plus-time-delay approximation for the following transfer function:

$$g_0(s) = \frac{7(1.5 - s)e^{-2s}}{(3s + 1)(10s + 1)(0.2s + 1)(0.05s + 1)^2}$$

Design PID controller using IMC-Based PID procedure using the reduced model.

Given:

$$\begin{aligned} & T_0 / \tau_0 && \text{for } T_0 \geq \tau_0 \geq \theta && (\text{Rule T1}) \\ & T_0 / \theta && \text{for } T_0 \geq \theta \geq \tau_0 && (\text{Rule T1a}) \\ \frac{T_0 s + 1}{(\tau_0 s + 1)} \approx 1 && \text{for } \theta \geq T_0 \geq \tau_0 && (\text{Rule T1b}) \\ & T_0 / \tau_0 && \text{for } \tau_0 \geq T_0 \geq 5\theta && (\text{Rule T2}) \\ & \frac{\tilde{\tau}_0 / \tau_0}{(\tilde{\tau}_0 - T_0)s + 1} && \text{for } \tilde{\tau}_0 \stackrel{\text{def}}{=} \min(\tau_0, 5\theta) \geq T_0 && (\text{Rule T3}) \end{aligned}$$

[17 marks]

- [b] Explain the following:

- [i] Inferential Control
- [ii] Adaptive Control

[8 marks]

2. [a] Figure Q.2.[a] shows a step response behavior for a packed-bed reactor. A step decrease in steam valve position was made at  $t = 5$  minutes.

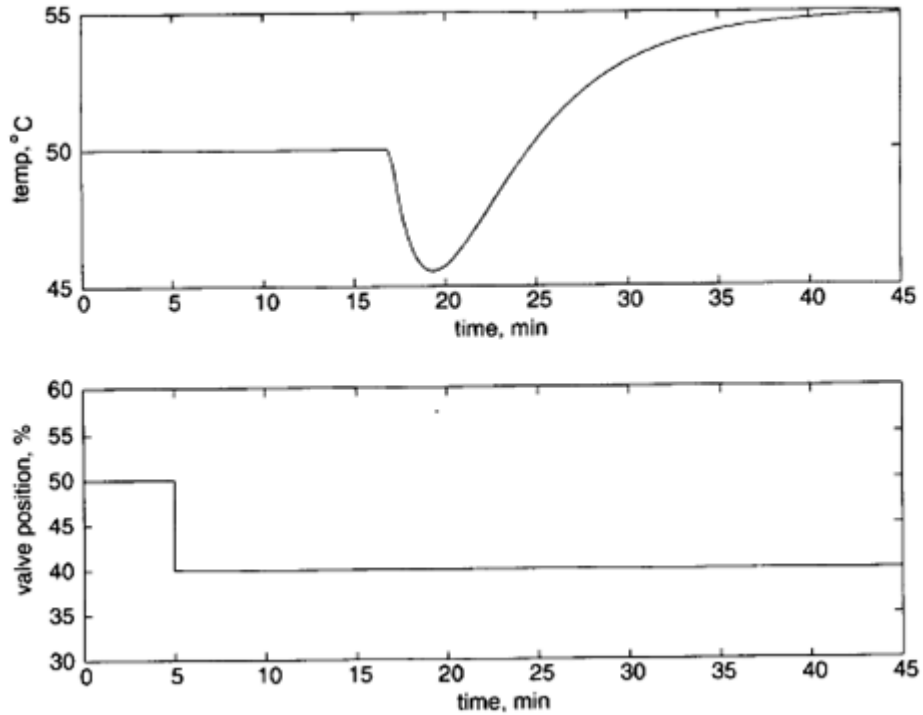


Figure Q.2.[a]: Step Response Behavior for a Packed-Bed Reactor

The process model (the time unit is minutes) that representing the process is given as:

$$\tilde{g}_p(s) = \frac{K(-10s + 1)e^{-\theta s}}{(5s + 1)(3s + 1)}$$

- [i] From Figure Q.2.[a], calculate the value of  $K$  and  $\theta$ . What are the units for both values?
- [ii] Design an Internal Model Control (IMC) for this process. Use the all-pass factorization and assume that  $q(s)$  is semiproper.
- [iii] Assuming a perfect model, plot qualitatively how the temperature will respond to a step change of  $1^\circ\text{C}$ .

[18 marks]

- [b] A waste stream (dilute nitric acid) is neutralized by adding a base stream (sodium hydroxide) of known concentration to a stirred neutralization tank, as shown in Figure Q.2 [b]. The concentration and the flow rate of the waste acid stream vary unpredictably. The flow rates of the waste stream and base stream can be measured. The effluent stream pH can be measured, but a significant time delay occurs due to the downstream location of the pH probe. Past experience has indicated that it is not possible to tune a standard PID controller so that satisfactory control occurs over the full range of operating conditions. As a process control specialist, you have been requested to recommend an advanced control strategy that has the potential of greatly improved control. Justify your proposed method, being as specific as possible. Also, cite any additional information that you will need.

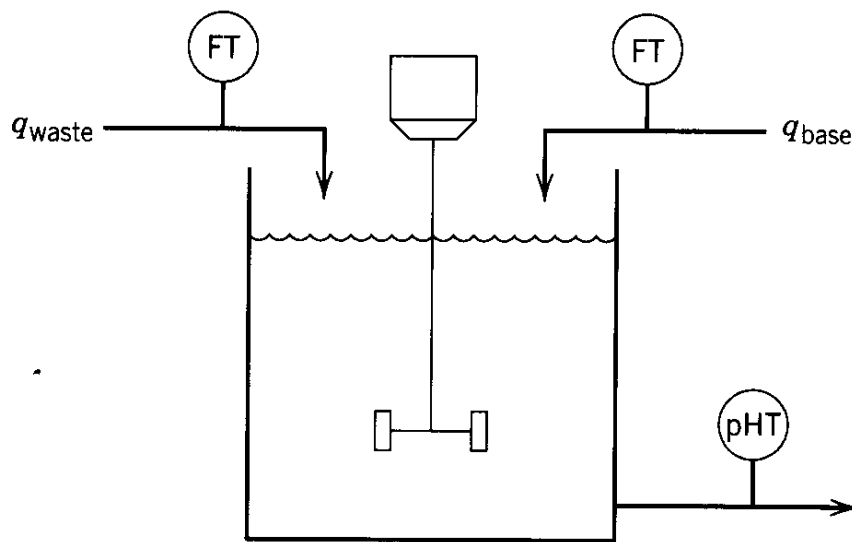


Figure Q.2 [b]: Stirred Neutralization Tank

[7 marks]

3. [a] Discuss the principle of model predictive control (MPC) scheme based on the receding horizon approach. In addition, assist your explanation with diagram. Discuss the advantages and disadvantages of the MPC.

[10 marks]

- [b] The cooling water enters the reactor jacket, makes a single pass, and then exits the jacket. A flow controller is provided for the cooling water flow, and the model predictive controller will output to the setpoint of this controller. The objective is to control the reactor temperature. A finite step response model will be developed for this process. Table Q.3. shows the finite step response model for the reactor with the jacket. Complete the table in the Appendix.

[5 marks]

Table Q.3.

Time, $t$ (min)	Actual cooling water flow (lb/min)	Change in cooling water flow (lb/min)	Actual reactor temperature ( $^{\circ}$ F)	Change in reactor temperature ( $^{\circ}$ F)	Step response [ $^{\circ}$ F/(lb/min)]	Impulse response [ $^{\circ}$ F/(lb/min)]
-15	108.8	0	150.0			
0	88.8	-20	150.0			
15	88.8	-20	151.0			
30	88.8	-20	151.9			
45	88.8	-20	152.5			
60	88.8	-20	153.0			
75	88.8	-20	153.4			
90	88.8	-20	153.7			
105	88.8	-20	153.9			
120	88.8	-20	154.1			
135	88.8	-20	154.2			
150	88.8	-20	154.3			
165	88.8	-20	154.4			
180	88.8	-20	154.4			
195	88.8	-20	154.5			
210	88.8	-20	154.5			
225	88.8	-20	154.5			
240	88.8	-20	154.5			

- [c] With the low dimension configuration of horizon  $R = 4$  and number of control moves  $L = 2$ , it is to formulate the controller for the reactor temperature. Show the final computation of the control moves using the data of Table Q.3.

[10 marks]

4. Figure Q.4. shows control configuration for a purified water supply process with a variable speed drive for the pump. The designated manipulated and controlled variables are

- $M_1$ : recirculation valve opening (%)
- $M_2$ : recirculation pump speed (rpm)
- $C_1$ : recirculation pressure (psig)
- $C_2$ : recirculation flow (gpm)

The process gain matrix  $K$  are as follows:

$$K = \begin{bmatrix} -0.636 \text{ psig} / \% & 0.0495 \text{ psig} / \text{rpm} \\ 1.132 \text{ gpm} / \% & 0.0121 \text{ gpm} / \text{rpm} \end{bmatrix}$$

- [a] Obtain the decoupler matrix  $G$  using the V-Canonical Decoupler. [5 marks]
- [b] Use the calibrated range below for the manipulated variable and convert the resulting matrix into a new one. [3 marks]

Manipulated variable	Range
Recirculation valve opening	0 to 100%
Recirculation pump speed	0 to 4000 rpm

- [c] Later provide two options in table form which must include the manipulated variable involved, process gain matrix  $K$ , inverse  $K^{-1}$  decoupler inputs and the decoupler matrix  $G$ . [12 marks]

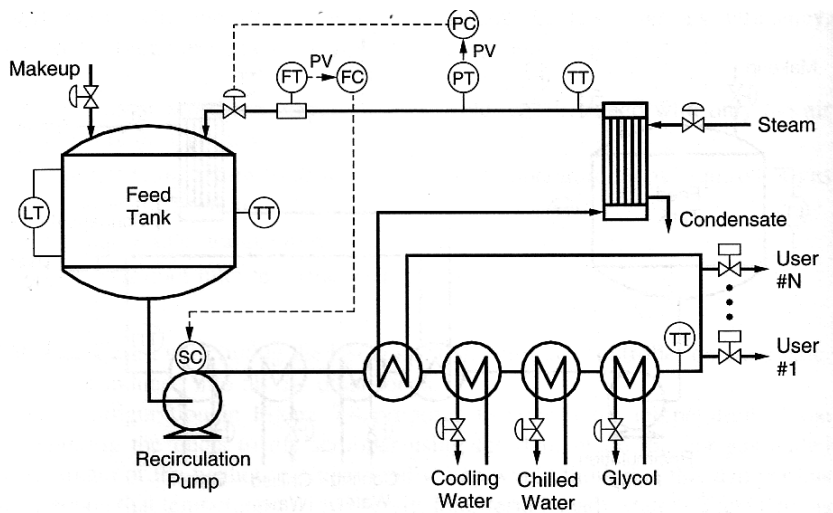


Figure Q.4.: The configuration of purified water supply

- [d] Discuss coupling effect in a binary distillation column. [5 marks]

Appendix

Table Laplace Transforms for Various Time-Domain Functions<sup>a</sup>

$f(t)$	$F(s)$
1. $\delta(t)$ (unit impulse)	1
2. $S(t)$ (unit step)	$\frac{1}{s}$
3. $t$ (ramp)	$\frac{1}{s^2}$
4. $t^{n-1}$	$\frac{(n-1)!}{s^n}$
5. $e^{-bt}$	$\frac{1}{s+b}$
6. $\frac{1}{\tau} e^{-t/\tau}$	$\frac{1}{\tau s + 1}$
7. $\frac{t^{n-1} e^{-bt}}{(n-1)!}$ ( $n > 0$ )	$\frac{1}{(s+b)^n}$
8. $\frac{1}{\tau^n (n-1)!} t^{n-1} e^{-t/\tau}$	$\frac{1}{(\tau s + 1)^n}$
9. $\frac{1}{b_1 - b_2} (e^{-b_1 t} - e^{-b_2 t})$	$\frac{1}{(s+b_1)(s+b_2)}$
10. $\frac{1}{\tau_1 - \tau_2} (e^{-t/\tau_1} - e^{-t/\tau_2})$	$\frac{1}{(\tau_1 s + 1)(\tau_2 s + 1)}$
11. $\frac{b_3 - b_1}{b_2 - b_1} e^{-b_1 t} + \frac{b_3 - b_2}{b_1 - b_2} e^{-b_2 t}$	$\frac{s + b_3}{(s+b_1)(s+b_2)}$
12. $\frac{1}{\tau_1} \frac{\tau_1 - \tau_3}{\tau_1 - \tau_2} e^{-t/\tau_1} + \frac{1}{\tau_2} \frac{\tau_2 - \tau_3}{\tau_2 - \tau_1} e^{-t/\tau_2}$	$\frac{\tau_3 s + 1}{(\tau_1 s + 1)(\tau_2 s + 1)}$
13. $1 - e^{-t/\tau}$	$\frac{1}{s(\tau s + 1)}$
14. $\sin \omega t$	$\frac{\omega}{s^2 + \omega^2}$
15. $\cos \omega t$	$\frac{s}{s^2 + \omega^2}$
16. $\sin(\omega t + \phi)$	$\frac{\omega \cos \phi + s \sin \phi}{s^2 + \omega^2}$
17. $e^{-bt} \sin \omega t$	$\left\{ \begin{array}{l} \frac{\omega}{(s+b)^2 + \omega^2} \\ \frac{s+b}{(s+b)^2 + \omega^2} \end{array} \right.$
18. $e^{-bt} \cos \omega t$	
$b, \omega$ real	
19. $\frac{1}{\tau \sqrt{1-\zeta^2}} e^{-\zeta t/\tau} \sin(\sqrt{1-\zeta^2} t/\tau)$ ( $0 \leq  \zeta  < 1$ )	$\frac{1}{\tau^2 s^2 + 2\zeta \tau s + 1}$
20. $1 + \frac{1}{\tau_2 - \tau_1} (\tau_1 e^{-t/\tau_1} - \tau_2 e^{-t/\tau_2})$ ( $\tau_1 \neq \tau_2$ )	$\frac{1}{s(\tau_1 s + 1)(\tau_2 s + 1)}$
21. $1 - \frac{1}{\sqrt{1-\zeta^2}} e^{-\zeta t/\tau} \sin[\sqrt{1-\zeta^2} t/\tau + \psi]$ $\psi = \tan^{-1} \frac{\sqrt{1-\zeta^2}}{\zeta}$ , ( $0 \leq  \zeta  < 1$ )	$\frac{1}{s(\tau^2 s^2 + 2\zeta \tau s + 1)}$
22. $1 - e^{-\zeta t/\tau} [\cos(\sqrt{1-\zeta^2} t/\tau) + \frac{\zeta}{\sqrt{1-\zeta^2}} \sin(\sqrt{1-\zeta^2} t/\tau)]$ ( $0 \leq  \zeta  < 1$ )	$\frac{1}{s(\tau^2 s^2 + 2\zeta \tau s + 1)}$
23. $1 + \frac{\tau_3 - \tau_1}{\tau_1 - \tau_2} e^{-t/\tau_1} + \frac{\tau_3 - \tau_2}{\tau_2 - \tau_1} e^{-t/\tau_2}$ ( $\tau_1 \neq \tau_2$ )	$\frac{\tau_3 s + 1}{s(\tau_1 s + 1)(\tau_2 s + 1)}$
24. $\frac{df}{dt}$	$sF(s) - f(0)$
25. $\frac{d^n f}{dt^n}$	$s^n F(s) - s^{n-1} f(0) - s^{n-2} f^{(1)}(0) - \dots - s f^{(n-2)}(0) - f^{(n-1)}(0)$ ...2/-
26. $f(t-t_0)S(t-t_0)$	$e^{-t_0 s} F(s)$

<sup>a</sup>Note that  $f(t)$  and  $F(s)$  are defined for  $t \geq 0$  only.

Table Q.3.

Time, <i>t</i> <i>Masa, t</i> (min)	Actual cooling water flow <i>Aliran air penyejuk sebenar</i> (lb/min)	Change in cooling water flow <i>Perubahan aliran air penyejuk</i> (lb/min)	Actual reactor temperature <i>Suhu reaktor sebenar</i> (°F)	Change in reactor temperature <i>Perubahan suhu reaktor</i> (°F)	Step response <i>Sambutan langkah</i> [°F/(lb/min)]	Impulse response <i>Sambutan dedenyut</i> [°F/(lb/min)]
-15	108.8	0	150.0			
0	88.8	-20	150.0			
15	88.8	-20	151.0			
30	88.8	-20	151.9			
45	88.8	-20	152.5			
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