UNIVERSITI MALAYSIA PERLIS

Peperiksaan Akhir Semester 1
Sidang Akademik 2025/2026

Februari 2026

KMJ32104 – Process Dynamics and Control
[Kawalan Proses dan Dinamik]

Masa : 3 jam

Please make sure that this question paper has **TWEENTY ONE (21)** printed pages including this front page before you start the examination.
*[Sila pastikan kertas soalan ini mengandungi **DUA PULUH SATU (21)** muka surat yang bercetak termasuk muka hadapan sebelum anda memulakan peperiksaan ini.]*

This question paper has **TWO** parts that consist of **SIX (6)** questions. Answer **ALL FOUR (4)** questions in **PART A** and **ANY ONE (1)** question in **PART B**. Each question contributes 20 marks.
*[Kertas soalan ini mengandungi **DUA** bahagian yang terdiri daripada **ENAM (6)** soalan. Jawab **SEMUA EMPAT (4)** soalan di **BAHAGIAN A** dan **MANA-MANA SATU (1)** soalan di **BAHAGIAN B**. Markah bagi tiap-tiap soalan adalah 20 markah.]*

Dicetak oleh Unit Peperiksaan & Pengijazahan, Bahagian Pengurusan Akademik, Pusat Pengurusan Akademik UniMAP

PART A
[Bahagian A]

Answer ALL FOUR (4) questions in PART A.
[Jawab SEMUA EMPAT (4) soalan di BAHAGIAN A.]

Question 1
[Soalan 1]

(a) The Laplace transformation is a valuable technique for converting ordinary differential equations to algebraic equations and convolution into multiplication. Using partial fraction expansion where required, find $x(t)$ for:
[Transformasi Laplace merupakan teknik yang berharga untuk menukar persamaan pembezaan biasa kepada persamaan algebra dan konvolusi kepada pendaraban. Menggunakan pengembangan pecahan separa jika diperlukan, cari x(t) untuk:]

(i) $X(s) = \frac{s(s+1)}{(s+2)(s+3)(s+4)}$

(ii) $X(s) = -\frac{2}{s^2} + \frac{1}{s+1}$

(iii) $X(s) = \frac{s+4}{(s+2)^2}$

(6 Marks/ *Markah*)

(b) Consider the stirred-tank heating system illustrated in Figure Q1.1. The liquid input stream is made up of one component with a mass flow rate (w) and an inlet temperature (T_i). The tank contents are agitated and heated using an electrical heater, which gives a heating rate, Q.
[Pertimbangkan sistem pemanasan tangki teraduk yang digambarkan dalam Rajah S1.1. Aliran masuk cecair terdiri daripada satu komponen dengan kadar aliran jisim (w) dan suhu masuk (T_i). Kandungan tangki dikacau dan dipanaskan menggunakan pemanas elektrik, yang memberikan kadar pemanasan, Q.]

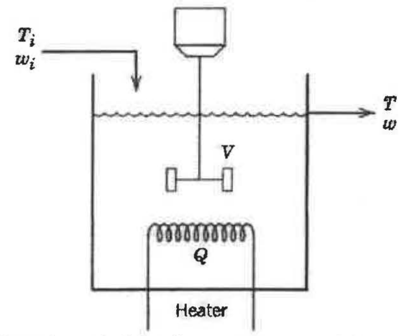

Figure Q1.1: Stirred-tank heating process with constant holdup, V.
[Rajah S1.1: Proses tangki teraduk pemanas dengan penahanan malar, V.]

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(i) Identify **FOUR (4)** distinct assumptions based on Figure Q1.1 before beginning to create a dynamic model of the system.
*[Kenalpastikan **EMPAT (4)** andaian berbeza berdasarkan Rajah S1.1 sebelum mula mencipta model dinamik sistem.]*

(4 Marks/ *Markah*)

(ii) Develop a dynamic model of the above-mentioned system using the overall mass balance and energy balance equations.
[Bangunkan model dinamik bagi sistem yang dinyatakan di atas menggunakan persamaan imbangan jisim keseluruhan dan imbangan tenaga.]

(8 Marks/ *Markah*)

(iii) Demonstrate a degree of freedom analysis. Identify each input and output variable.
[Tunjukkan analisis darjah kebebasan. Kenal pasti setiap pembolehubah input dan output satu analisis darjah kebebasan.]

(2 Marks/ *Markah*)

Question 2
[Soalan 2]

(a) Consider a transfer function:
[Pertimbangkan fungsi rangkap pindah:]

$$G(s) = \frac{6e^{-2s}}{(8s+1)(3s+1)(2s+1)(s+1)^2}$$

Derive an approximate first-order-plus-time-delay (FOPDT) model by Skogestad's half rule.
[Terbitkan anggaran model kelewatan-tambah-masa-pertama (FOPDT) mengikut peraturan separuh Skogestad.]

(4 Marks/ *Markah*)

(b) A step change from 10 to 26 psi in actual pressure results in the measured response from a pressure-indicating element shown in Figure Q2.1.
[Perubahan langkah daripada 10 kepada 26 psi dalam tekanan sebenar menghasilkan tindak balas yang diukur daripada unsur penunjuk tekanan yang ditunjukkan dalam Rajah S2.1.]

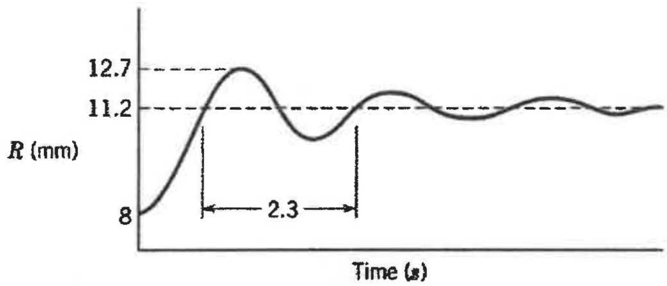


Figure Q2.1: Performance characteristics for the step response.
*[**Rajah Q2.1:** Ciri-ciri prestasi untuk tindak balas langkah.]*

(i) By assuming the above-mentioned response is a second-order dynamics system, calculate all important parameters and write an approximate transfer function in the form of Equation Q2.1.
[Andaikan dinamik tertib kedua, kirakan semua parameter penting dan tulis satu anggaran fungsi rangkap pindah dalam bentuk Persamaan S2.1.]

$$\frac{R'(s)}{P'(s)} = \frac{K}{\tau^2 s^2 + 2\zeta\tau s + 1} \qquad \text{(Equation Q2.1)}$$

(Persamaan S2.1)

where R' is the instrument output deviation (mm), P' is the actual pressure deviation (psi).

....5/-

[yang mana R' ialah sisihan keluaran alatan (mm), P' ialah sisihan tekanan sebenar (psi).]

(8 Marks/ *Markah*)

(ii) Show an equivalent differential equation model in terms of actual (not deviation) variables.
[Tunjukkan model persamaan pembezaan setara dari segi pembolehubah sebenar (bukan sisihan).]

(4 Marks/ *Markah*)

(c) Figure Q2.2 depicts response of the temperature, *T* in a continuous stirred-tank reactor to a step change in feed flow rate w from 120 to 125 kg/min. Write an approximate first-order model for the process with these operating conditions.
[Rajah Q2.2 menggambarkan tindak balas suhu, T dalam reaktor tangki teraduk berterusan terhadap perubahan langkah dalam kadar aliran suapan w dari 120 hingga 125 kg/min. Tuliskan model tertib pertama anggaran untuk proses bagi keadaan operasi ini.]

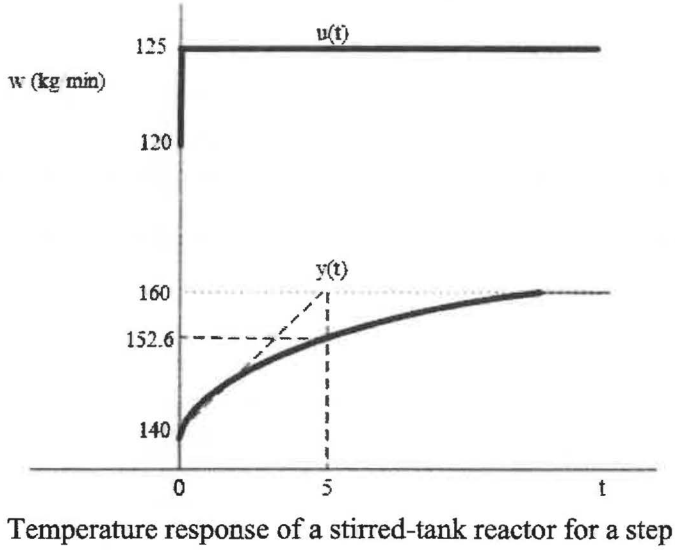


Figure Q2.2: Temperature response of a stirred-tank reactor for a step change in feed flow rate.
[Rajah S2.2: Tindak balas suhu reaktor tangki teraduk untuk perubahan langkah dalam kadar aliran suapan.]

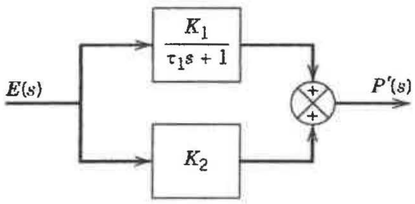
(4 Marks/ *Markah*)

Question 3
[Soalan 3]

(a) A physically realizable form of the ideal PD controller transfer function is given by:
[Satu bentuk fungsi rangkap pindah pengawal PD ideal yang boleh direalisasikan secara fizikal dinyatakan sebagai:]

$$\frac{P'(s)}{E(s)} = \frac{K_c(\tau_D s + 1)}{\alpha\tau_D s + 1}$$

(i) Show how to obtain the above transfer function with a parallel arrangement of two much simpler functions as shown below.
[Tunjukkan bagaimana untuk memperolehi fungsi pindahan di atas dengan satu susunan selari dua fungsi yang lebih mudah seperti ditunjukkan di bawah.]



(2 Marks/ *Markah)*

(ii) Develop expressions for K_1, K_2 and τ_1 that can be used to obtain desired values of K_c, τ_D and α.
[Bina ungkapan bagi K_1, K_2 dan τ_1 yang boleh digunakan untuk mendapatkan nilai K_c, τ_D dan α yang diingini.]

(4 Marks/ *Markah)*

(b) An electronic PID temperature controller is at steady state with an output of 12 mA. The set point equals the nominal process temperature initially. At t = 0, the error signal is increased at the rate of 0.5 mA/min (which is equivalent to a rate of 2 °C/min).
[Sebuah pengawal suhu PID elektronik berada pada keadaan mantap dengan satu keluaran sebanyak 12 mA. Pada awalnya, titik set bersamaan dengan suhu proses namaan. Pada t = 0, ralat isyarat meningkat pada kadar 0.5 mA/min (yang setara dengan satu kadar sebanyak 2 °C/min).]

(i) Develop an expression for the controller output, $p(t)$ if the current settings are $K_c = 2$, $\tau_I = 1.5$ min, and $\tau_D = 0.5$ min.
[Bangunkan satu ungkapan bagi keluaran pengawal, p(t) jika pengesetan semasa adalah $K_c = 2$, $\tau_I = 1.5$ min, dan $\tau_D = 0.5$ min.]

(3 Marks/ *Markah)*

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(ii) Develop an expression for the controller output, $p(t)$, in the scenario where a PI controller is used in place of the PID controller.
[Bangunkan satu ungkapan bagi keluaran pengawal, p(t), dalam senario dimana satu pengawal PI digunakan bagi menggantikan pengawal PID.]

(2 Marks/ *Markah)*

(iii) Construct a plot of the two controller outputs on graph paper and qualitatively explain their differences.
[Binakan satu plot keluaran bagi kedua-dua pengawal di atas kertas graf dan jelaskan secara kualitatif perbezaan mereka.]

(4 Marks/ *Markah)*

(c) The two-phase feed stream for the gas-liquid separator shown in Figure Q3.1 consists of a hydrocarbon mixture. Part of the liquid feed evaporates to form a gas phase because the pressure in the vessel is significantly lower than the feed pressure. The hydrocarbons are flammable and hazardous.
[Aliran suapan dua-fasa untuk pemisah gas-cecair yang ditunjukkan dalam Rajah S3.1 terdiri daripada satu campuran hidrokarbon. Sebahagian daripada suapan cecair menyejat untuk membentuk satu fasa gas kerana tekanan dalam turus adalah jauh lebih rendah daripada tekanan suapan. Hidrokarbon tersebut mudah terbakar dan berbahaya.]

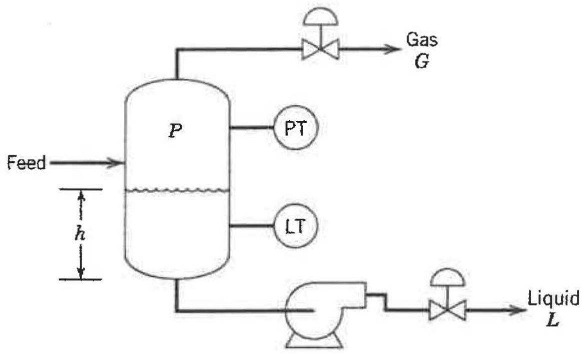

Figure Q3.1: Schematic diagram of a gas-liquid separator.
[Rajah S3.1: Rajah skematik bagi sebuah pemisah gas-cecair.]

With the aid of a diagram, propose an alarm/Safety Instrumented System (SIS) strategy for the gas-liquid separator by considering the pressure and level in the separator.
[Dengan bantuan satu rajah, cadangkan satu strategi penggera/Sistem Teralat Keselamatan (SIS) bagi pemisah gas-cecair dengan mengambil kira tekanan dan aras dalam pemisah tersebut.]

(5 Marks/ *Markah)*

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Question 4
[Soalan 4]

(a) Based on the pole locations shown in Figure Q4.1, explain the stability and typical time response when the poles are located:
[Berdasarkan lokasi kutub yang ditunjukkan dalam Rajah S4.1, jelaskan kestabilan dan tindak balas masa yang biasa apabila kutub berada:]

(i) in the left half of the complex plane
[di separuh kiri satah kompleks]

(ii) in the right half of the complex plane
[di separuh kanan satah kompleks]

(iii) on the left half of the imaginary axis
[pada separuh kiri paksi khayalan]

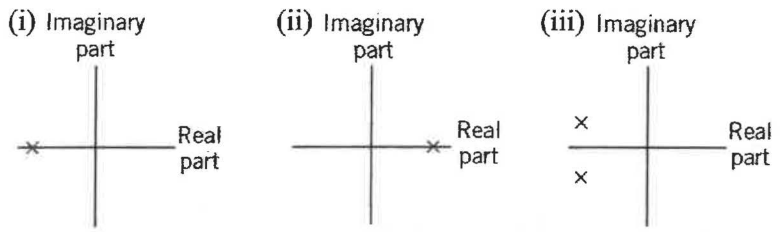

Figure Q4.1: Poles locations.
[Rajah S4.1: Lokasi kutub.]

(6 Marks/ *Markah)*

(b) Consider the liquid level PI control system as shown in Figure Q4.2 with the following parameter values:
[Pertimbangkan sistem kawalan PI aras cecair seperti ditunjukkan dalam Rajah S4.2 dengan nilai-nilai parameter seperti berikut:]

- $K_p = 1.0$ min/ft^2
- $\tau = 3.0$ min
- $K_v = 0.2$ ft^3/min psi
- $K_m = 4$ mA/ft
- $K_c = 5.33$
- $K_{IP} = 0.75$ psi/mA
- $\tau_I = 3.0$ min

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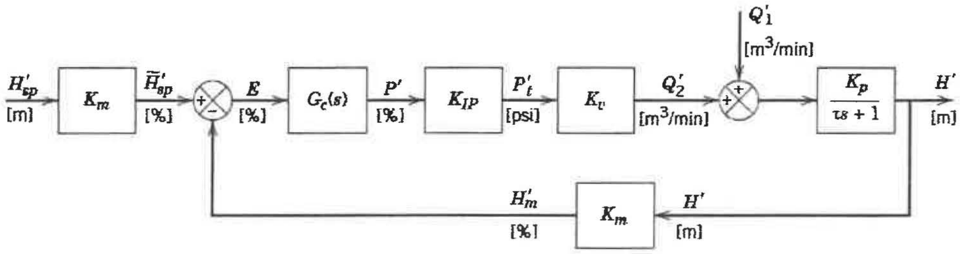

Figure Q4.2: Liquid level PI control system.
[Rajah S4.2: Sistem kawalan PI aras cecair.]

Suppose that the system is initially at the nominal steady state with a liquid level of 2 ft. If the set point is suddenly changed from 2 ft to 3 ft, determine how long it will take for the system to reach liquid level of 2.5 ft.
[Katakan bahawa sistem tersebut pada mulanya berada pada keadaan mantap nominal dengan aras cecair 2 kaki. Jika titik tetapan secara tiba-tiba bertukar daripada 2 kaki kepada 3 kaki, tentukan berapa lama masa yang diperlukan untuk sistem mencapai aras cecair 2.5 kaki.]

Closed-loop transfer function for set point changes is given by:
[Fungsi pindahan gelung-tertutup bagi perubahan titik set diberi oleh:]

$$\frac{Y}{Y_{sp}} = \frac{K_m G_c G_v G_p}{1 + G_c G_v G_p G_m}$$

(8 Marks/ *Markah)*

(c) The block diagram of a feedback control system is shown in Figure Q4.3. Solve for the values of K_c that will result in a stable closed-loop system.
[Rajah blok bagi satu sistem pengawal suap balik ditunjukkan dalam Rajah S4.3. Selesaikan bagi nilai K_c yang akan membawa kepada satu sistem gelung-tertutup yang stabil.]

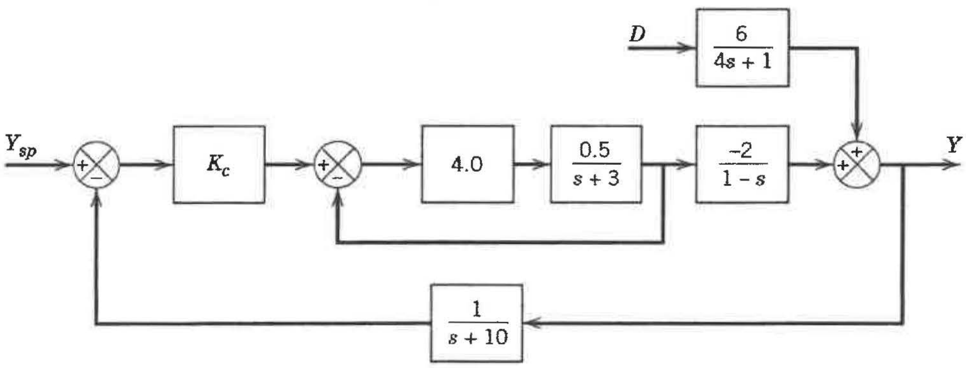

Figure Q4.3: Block diagram of a feedback control system.
[Rajah S4.3: Rajah blok bagi satu sistem pengawal suap balik.]

(6 Marks/ *Markah)*

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PART B
[Bahagian B]

Answer ANY ONE (1) question in PART B.
[Jawab MANA-MANA SATU (1) soalan di BAHAGIAN B.]

Question 5
[Soalan 5]

(a) A sudden change in feed temperature is a common disturbance in a heat exchanger. Explain how feedforward control helps improve temperature control.
[Satu perubahan mendadak dalam suhu suapan adalah satu gangguan biasa dalam penukar haba. Jelaskan bagaimana kawalan suapan hadapan membantu meningkatkan kawalan suhu.]

(2 Marks/ *Markah)*

(b) It is desired to reduce the concentration of CO_2 in the flue gas from a coal-fired power plant, to reduce the greenhouse gas emissions. The effluent flue gas is sent to an ammonia scrubber, where most of the CO_2 is absorbed in a liquid ammonia solution, as shown in Figure Q5.1. A feedforward control system will be used to control the CO_2 concentration in the flue gas stream leaving the scrubber C_{CO_2} which is unable to be measured on-line. The flow rate of the ammonia solution entering the scrubber Q_A can be manipulated via a control valve. The inlet flue gas flow rate Q_F is a measured disturbance variable.
[Ianya dikehendaki untuk mengurangkan kepekatan CO_2 dalam gas serombong daripada sebuah loji kuasa arang batu, bagi mengurangkan pelepasan gas rumah hijau. Aliran keluar gas serombong dihantar ke sebuah penggahar ammonia, dimana hampir kesemua CO_2 diserap dalam satu larutan cecair ammonia, seperti ditunjukkan dalam Rajah S5.1. Satu sistem pengawal suap depan akan digunakan untuk mengawal kepekatan CO_2 dalam aliran gas serombong yang meninggalkan penggahar C_{CO_2} yang tidak dapat diukur secara dalam talian. Kadar aliran larutan ammonia yang memasuki pembersih Q_A boleh dimanipulasi melalui satu injap pengawal. Kadar aliran gas penggahar alur masuk Q_F adalah satu pembolehubah gangguan terukur.]

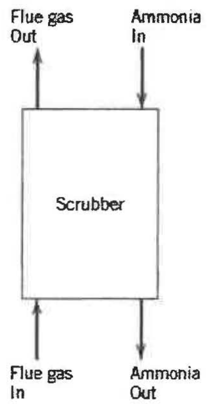

Figure Q5.1: Schematic diagram of a flue gas scrubber.
[Rajah S5.1: Rajah skematik bagi sebuah pembersih gas penggahar.]

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Construct a block diagram of the feedforward control system without deriving the transfer functions.
[Binakan satu rajah blok bagi sistem pengawal suap depan tanpa menerbitkan fungsi pindahan.]

(6 Marks/ *Markah)*

(c) A process stream is heated using a shell and tube heat exchanger. The exit temperature is controlled by adjusting the steam control valve shown in Figure Q5.2. During an open-loop experimental test, the steam pressure P_s was suddenly changed from 18 psig to 20 psig where the temperature data was obtained as shown in Table Q5.1.
[Satu aliran proses dipanaskan menggunakan sebuah penukar haba tiub dan kelompang. Suhu keluar dikawal dengan melaraskan injap pengawal stim seperti ditunjukkan dalam Rajah S5.2. Semasa satu ujian ujikaji gelung-terbuka, tekanan stim P_s secara tiba-tiba berubah daripada 18 psig kepada 20 psig dimana data suhu diperolehi seperti yang ditunjukkan dalam Jadual S5.1.]

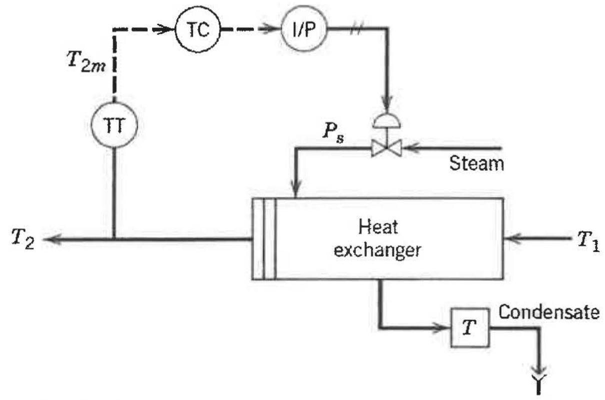

Figure Q5.2: Schematic diagram of a shell and tube heat exchanger.
[Rajah S5.2: Rajah skematik bagi sebuah penukar haba tiub dan kelompang.]

Table Q5.1: Temperature data observed after the changes in steam pressure, P_s.
[Jadual S5.1: Data suhu yang diperhatikan selepas perubahan tekanan stim, P_s.]

t (min)	T_{2m} (mA)
0	12.0
1	12.0
2	12.5
3	13.1
4	14.0
5	14.8
6	15.4
7	16.1
8	16.4
9	16.8
10	16.9
11	17.0
12	16.9

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At the nominal conditions, the control valve and current-to-pressure transducer have gains of $K_v = 0.9$ psi/psi and $K_{IP} = 0.75$ psi/mA. By selecting a reasonable value of τ_c, determine appropriate PID controller settings for an Internal Model Control (IMC).

[Pada keadaan-keadaan nonimal, injap pengawal dan pemindaharuh arus-kepada-tekanan mempunyai gandaan $K_v = 0.9$ psi/psi dan $K_{IP} = 0.75$ psi/mA. Dengan memilih satu nilai τ_c yang munasabah, tentukan pengesetan pengawal PID yang sesuai bagi satu Pengawal Model Dalaman (IMC).]

(12 Marks/ *Markah)*

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Question 6
[Soalan 6]

(a) Explain why Internal Model Control (IMC) is often preferred over Direct Synthesis (DS) for real chemical processes.
[Jelaskan mengapa Kawalan Model Dalaman (IMC) sering diutamakan berbanding Sintesis Langsung (DS) untuk proses-proses kimia sebenar.]

(2 Marks/ *Markah*)

(b) The level in a tank responds to step change in its inlet flow. The data shown in Table Q6.1 below were gathered after the inlet flow was increased from 1 m^3/s to 5 m^3/s at time t = 0.
[Aras di dalam sebuah tangki bertindak balas kepada perubahan langkah dalam aliran kemasukannya. Data yang ditunjukkan dalam Jadual S6.1 di bawah di kumpul selepas aliran masuk ditingkatkan daripada 1 m^3/s kepada 5 m^3/s pada masa t = 0.]

Table Q6.1: Level in the tank after inlet flow changes.
[Jadual S6.1: Aras di dalam tangki selepas perubahan aliran kemasukan.]

t (min)	Level (m)
0	0
1	0
2	0
3	0.3
4	0.6
5	0.9
6	1.3
7	1.8
8	2.4
9	2.7
10	2.8
11	2.9
12	3.0
13	3.0

Construct a second-order plus time delay model transfer function for the changes in the form of:
[Binakan satu model fungsi pindahan tertib-kedua dengan lengah masa bagi perubahan tersebut dalam bentuk:]

$$\frac{Y(s)}{U(s)} = \frac{Ke^{-\theta s}}{\tau^2 s^2 + 2\tau\zeta s + 1}$$

(10 Marks/ *Markah*)

....14/-

(c) A process has the following transfer function:
[Satu proses mempunyai fungsi pindahan berikut:]

$$G(s)=\frac{K}{(10s+1)(5s+1)}$$

where K has a nominal value of $K = 1$. PID controller settings are to be calculated using the Direct Synthesis approach with $\tau_c = 5$ min. Suppose that these controller constants are employed and that K changes unexpectedly from 1 to $1 + \alpha$. Determine the range values of α which will resulted in a stable closed-loop system.
[where K mempunyai satu nilai namaan $K = 1$. Tetapan pengawal PID akan dikira menggunakan pendekatan Sintesis Langsung dengan $\tau_c = 5$ min. Katakan pemalar-pemalar pengawal ini digunakan dan K berubah secara tidak dijangka daripada 1 kepada $1 + \alpha$. Tentukan julat nilai α yang akan menghasilkan sistem gelung-tertutup yang stabil.]

(8 Marks/ *Markah*)

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APPENDIX

A. Formulas:

1. Overall mass balance:
$$\{rate\ of\ mass\ accumulation\} = \{rate\ of\ mass\ in\} - \{rate\ of\ mass\ out\}$$

2. Component i mass balance:
$$\{rate\ of\ component\ i\ accumulation\} = \{rate\ of\ component\ i\ in\} - \{rate\ of\ component\ i\ out\} + \{rate\ of\ component\ i\ produced\}$$

3. Energy balance:
$$\{rate\ of\ energy\ accumulation\} = \{rate\ of\ energy\ in\ by\ convection\} - \{rate\ of\ energy\ out\ by\ convection\ out\} + \{net\ rate\ of\ heat\ addition\ to\ the\ system\ from\ the\ surroundings\} + \{net\ rate\ of\ work\ performed\ on\ the\ system\ by\ the\ surroundings\}$$

4. Total energy of a thermodynamic system, U_{tot}:
$$U_{tot} = U_{int} + U_{KE} + U_{PE}$$
where; U_{int} is the internal energy, U_{KE} is the kinetic energy and U_{PE} is the potential energy.

5. The rate of internal accumulation:
$$\frac{dU_{int}}{dt} = \frac{\rho V \hat{U}_{int}}{dt} = \rho V C \frac{dT}{dt}$$

6. Internal energy balance:
$$\frac{dU_{int}}{dt} = -\Delta\left(w\hat{H}\right) + Q$$
where; $\hat{H}$ is the enthalpy per unit mass.

7. Mass, $m = \rho V$; where ρ is the density and V is the volume.

8. The number of degrees of freedom:
$N_F = N_V - N_E$; where N_V is the total number of process variables, and N_E is the number of independent equations.

9. The change of internal energy per unit mass, $\hat{U}_{int}$:
$d\hat{U}_{int} = d\hat{H} = CdT$, where C is the heat capacity.

10. The enthalpy per unit mass:
$$\hat{H} = C(T - T_{ref})$$

11. First order transfer function:
$$G(s) = \frac{Y(s)}{U(s)} = \frac{K}{\tau s + 1}$$

12. Second order transfer function:

$$G(s) = \frac{Y(s)}{U(s)} = \frac{K_1K_2}{(\tau_1 s + 1)(\tau_2 s + 1)} = \frac{K}{(\tau_1 s + 1)(\tau_2 s + 1)} = \frac{K}{(\tau^2 s^2 + 2\zeta\tau s + 1)}$$

where ζ is the damping coefficient (zeta).

13. Steady-state gain:

$$K = \frac{\Delta\, ouput}{\Delta\, input} = \frac{\Delta\, y}{\Delta\, u}$$

14. Parallel form of PID controller:

$$\frac{P'(s)}{E(s)} = K_c\left[1 + \frac{1}{\tau_1 s} + \tau_D s\right]$$

15. Closed-loop transfer function for set point changes:

$$\frac{Y}{Y_{sp}} = \frac{K_m G_c G_v G_p}{1 + G_c G_v G_p G_m}$$

16. Closed-loop transfer function for disturbance changes:

$$\frac{Y}{D} = \frac{G_d}{1 + G_c G_v G_p G_m}$$

17. Transfer function of feedforward controller:

$$G_F(s) = -\frac{K_d}{K_t K_v K_p}$$

18. First-order-plus-time-delay (FOPDT) model:

$$\check{G}(s) = \frac{Ke^{-\theta s}}{\tau s + 1}$$

19. Deviation variable, Y:

$Y = y - y_s$, where s = steady state

20. Offset = $Y'_{set\ point}(\infty) - Y_s(\infty)$

21. Final value theorem:

$$\lim_{t\to\infty} x(t) = x(\infty) = \lim_{s\to 0} sX(s)$$

22. $K_v = \frac{\Delta\, Flow}{\Delta\, Pressure}$

23. $K_T = \frac{\Delta\, Electrical\ signal}{\Delta\, Concentration}$

24. Transfer function for parallel form of PID controller:

$$G_c = \frac{P'(s)}{E(s)} = K_c\left[1 + \frac{1}{\tau_1 s} + \tau_D s\right]$$

where:

$$K_c = \frac{1}{K}\frac{\tau_1+\tau_2}{\tau_c+\theta},\ \ \tau_I = \tau_1 + \tau_2,\ \ \tau_D = \frac{\tau_1\tau_2}{\tau_1+\tau_2}$$

25. Transfer function for PI controller:

$$G_c = \frac{P'(s)}{E(s)} = K_c\left[1 + \frac{1}{\tau_1 s}\right]$$

26. Closed-loop transfer function for set point changes:

$$\frac{Y}{Y_{sp}} = \frac{K_m G_c G_v G_p}{1 + G_c G_v G_p G_m}$$

27. Closed-loop transfer function for disturbance changes:

$$\frac{Y}{D} = \frac{G_d}{1 + G_c G_v G_p G_m}$$

28. Characteristic equation:

$$1 + G_{OL} = 0$$

29. Transfer function of feedforward controller:

$$G_F(s) = -\frac{K_d}{K_t K_v K_p}$$

30. Skotgestad's time constant:

$$\tau_{skog} = \tau_{largest} + 1.5\tau_{next\ largest}$$

31. Skotgestad's time delay:

$$\theta_{skog} = 1.5\tau_{next\ largest} + \sum \tau_{other} + \theta_{HO}$$

B. IMC Controller Settings for Parallel-Form PID Controller.

Case	Model	K_cK	τ_I	τ_D
A	$\dfrac{K}{\tau s+1}$	$\dfrac{\tau}{\tau_c}$	τ	-
B	$\dfrac{K}{(\tau_1 s+1)(\tau_2 s+1)}$	$\dfrac{\tau_1+\tau_2}{\tau_c}$	$\tau_1+\tau_2$	$\dfrac{\tau_1\tau_2}{\tau_1+\tau_2}$
C	$\dfrac{K}{\tau^2 s^2+2\zeta\tau s+1}$	$\dfrac{2\zeta\tau}{\tau_c}$	$2\zeta\tau$	$\dfrac{\tau}{2\zeta}$
D	$\dfrac{K(-\beta s+1)}{\tau^2 s^2+2\zeta\tau s+1},\ \beta>0$	$\dfrac{2\zeta\tau}{\tau_c+\beta}$	$2\zeta\tau$	$\dfrac{\tau}{2\zeta}$
E	$\dfrac{K}{s}$	$\dfrac{2}{\tau_c}$	$2\tau_c$	-
F	$\dfrac{K}{s(\tau s+1)}$	$\dfrac{2\tau_c+\tau}{\tau_c^2}$	$2\tau_c+\tau$	$\dfrac{2\tau_c\tau}{2\tau_c+\tau}$
G	$\dfrac{Ke^{-\theta s}}{\tau s+1}$	$\dfrac{\tau}{\tau_c+\theta}$	τ	-
H	$\dfrac{Ke^{-\theta s}}{\tau s+1}$	$\dfrac{\tau+\frac{\theta}{2}}{\tau_c+\frac{\theta}{2}}$	$\tau+\dfrac{\theta}{2}$	$\dfrac{\tau\theta}{2\tau+\theta}$
I	$\dfrac{K(\tau_3 s+1)e^{-\theta s}}{(\tau_1 s+1)(\tau_2 s+1)}$	$\dfrac{\tau_1+\tau_2-\tau_3}{\tau_c+\theta}$	$\tau_1+\tau_2-\tau_3$	$\dfrac{\tau_1\tau_2-(\tau_1+\tau_2-\tau_3)\tau_3}{\tau_1+\tau_2-\tau_3}$
J	$\dfrac{K(\tau_3 s+1)e^{-\theta s}}{\tau^2 s^2+2\zeta\tau s+1}$	$\dfrac{2\zeta\tau-\tau_3}{\tau_c+\theta}$	$2\zeta\tau-\tau_3$	$\dfrac{\tau^2-(2\zeta\tau-\tau_3)\tau_3}{2\zeta\tau-\tau_3}$
K	$\dfrac{K(-\tau_3 s+1)e^{-\theta s}}{(\tau_1 s+1)(\tau_2 s+1)}$	$\dfrac{\tau_1+\tau_2+\frac{\tau_3\theta}{\tau_c+\tau_3+\theta}}{\tau_c+\tau_3+\theta}$	$\tau_1+\tau_2+\dfrac{\tau_3\theta}{\tau_c+\tau_3+\theta}$	$\dfrac{\tau_3\theta}{\tau_c+\tau_3+\theta}+\dfrac{\tau_1\tau_2}{\tau_1+\tau_2+\frac{\tau_3\theta}{\tau_c+\tau_3+\theta}}$
L	$\dfrac{K(-\tau_3 s+1)e^{-\theta s}}{\tau^2 s^2+2\zeta\tau s+1}$	$\dfrac{2\zeta\tau+\frac{\tau_3\theta}{\tau_c+\tau_3+\theta}}{\tau_c+\tau_3+\theta}$	$2\zeta\tau+\dfrac{\tau_3\theta}{\tau_c+\tau_3+\theta}$	$\dfrac{\tau_3\theta}{\tau_c+\tau_3+\theta}+\dfrac{\tau^2}{2\zeta\tau+\frac{\tau_3\theta}{\tau_c+\tau_3+\theta}}$
M	$\dfrac{Ke^{-\theta s}}{s}$	$\dfrac{2\tau_c+\theta}{(\tau_c+\theta)^2}$	$2\tau_c+\theta$	-
N	$\dfrac{Ke^{-\theta s}}{s}$	$\dfrac{2\tau_c+\theta}{\left(\tau_c+\frac{\theta}{2}\right)^2}$	$2\tau_c+\theta$	$\dfrac{\tau_c\theta+\frac{\theta^2}{4}}{2\tau_c+\theta}$
O	$\dfrac{Ke^{-\theta s}}{s(\tau s+1)}$	$\dfrac{2\tau_c+\tau+\theta}{(\tau_c+\theta)^2}$	$2\tau_c+\tau+\theta$	$\dfrac{(2\tau_c+\theta)\tau}{2\tau_c+\tau+\theta}$

C. Laplace Table for Various Time-Domain Functions:

Function, $f(t)$	$F(s)$
$\delta(t)$ (unit impulse)	1
$S(t)$ (unit step)	$\frac{1}{s}$
t (ramp)	$\frac{1}{s^2}$
t^{n-1}	$\frac{(n-1)!}{s^n}$
e^{-bt}	$\frac{1}{s+b}$
$\frac{1}{\tau}e^{-\frac{t}{\tau}}$	$\frac{1}{\tau s+1}$
$\frac{t^{n-1}e^{-bt}}{(n-1)!}$ $(n>0)$	$\frac{1}{(s+b)^n}$
$\frac{1}{t^n(n-1)!}t^{n-1}e^{-\frac{t}{\tau}}$	$\frac{1}{(\tau s+1)^n}$
$\frac{1}{b_1-b_2}(e^{-b_2t}-e^{-b_1t})$	$\frac{1}{(s+b_1)}+\frac{1}{(s+b_2)}$
$\frac{1}{\tau_1-\tau_2}\left(e^{-\frac{t}{\tau_1}}-e^{-\frac{t}{\tau_2}}\right)$	$\frac{1}{(\tau_1 s+1)(\tau_2 s+1)}$
$\frac{b_3-b_1}{b_2-b_1}e^{-b_1t}+\frac{b_3-b_1}{b_1-b_2}e^{-b_2t}$	$\frac{1+b_3}{(s+b_1)(s+b_2)}$
$\frac{1}{\tau_1}\frac{\tau_1-\tau_3}{\tau_1-\tau_2}e^{-\frac{t}{\tau_1}}-\frac{1}{\tau_2}\frac{\tau_2-\tau_3}{\tau_2-\tau_1}e^{-\frac{t}{\tau_2}}$	$\frac{\tau_3 s+1}{(\tau_1 s+1)(\tau_2 s+1)}$
$1-e^{-\frac{t}{\tau}}$	$\frac{1}{s(\tau s+1)}$
$\sin\omega t$	$\frac{\omega}{s^2+\omega^2}$
$\cos\omega t$	$\frac{s}{s^2+\omega^2}$
$\sin(\omega t+\emptyset)$	$\frac{\omega\cos\emptyset+s\sin\emptyset}{s^2+\omega^2}$
$e^{-bt}\sin\omega t$	$\frac{\omega}{(s+b)^2+\omega^2}$
$e^{-bt}\cos\omega t$	$\frac{s+b}{(s+b)^2+\omega^2}$
$1+\frac{1}{\tau\sqrt{1-\xi^2}}e^{-\xi t/\tau}\sin\left(\sqrt{1-\xi^2}\,t/\tau\right)$ $(0\le\lvert\xi\rvert<1)$	$\frac{1}{\tau^2s^2+2\xi\tau s+1}$
$1+\frac{1}{\tau_2-\tau_1}(\tau_1e^{-t/\tau_1}-\tau_2e^{-t/\tau_2})$ $(\tau_1\neq\tau_2)$	$\frac{1}{s(\tau_1 s+1)(\tau_2 s+1)}$

$1-\frac{1}{\sqrt{1-\xi^2}}e^{-\xi t/\tau}\sin\left(\sqrt{1-\xi^2}\frac{t}{\tau}+\psi\right)$ where, $\psi=\tan^{-1}\frac{\sqrt{1-\xi^2}}{\xi}, (0\le\lvert\xi\rvert<1)$	$\frac{1}{s(\tau^2s^2+2\xi\tau s+1)}$
$1-e^{-\xi t/\tau}\sin\left[\left(\sqrt{1-\xi^2}\frac{t}{\tau}\right)+\right.$ $\left.\left(\frac{\xi}{\sqrt{1-\xi^2}}\sin\sqrt{1-\xi^2}\frac{t}{\tau}\right)\right]\ (0\le\lvert\xi\rvert<1)$	$\frac{1}{s(\tau^2s^2+2\xi\tau s+1)}$
$1+\frac{\tau_3-\tau_1}{\tau_1-\tau_2}e^{-t/\tau_1}+\frac{\tau_3-\tau_1}{\tau_2-\tau_1}e^{-t/\tau_2}$ $(\tau_1\neq\tau_2)$	$\frac{\tau_3s+1}{s(\tau_1s+1)(\tau_2s+1)}$
$\frac{df}{dt}$	$sF(s)-f(0)$
$\frac{d^2f}{dt^n}$	$s^nF(s)-s^{n-1}f(0)-s^{n-2}f^{(1)}(0)$ $-\cdots s^{(n-2)}(0)f^{(n-1)}(0)$
$f(t-t_0)S(t-t_0)$	$e^{-t_0s}F(s)$

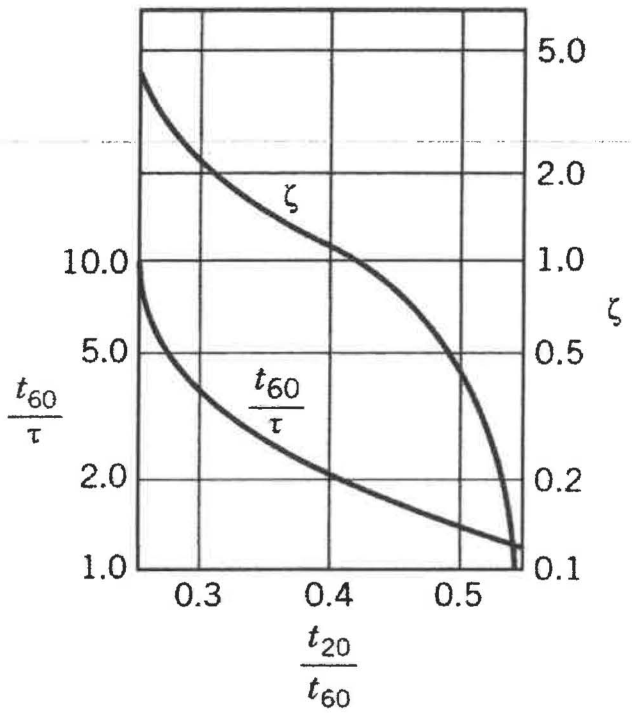

Figure A1: Smith's method – Relationship of ζ and τ to τ_{20} and τ_{60}