L-4/T-1/CHE  
BANGLADESH UNIVERSITY OF ENGINEERING AND TECHNOLOGY, DHAKA  
Sub: CHE 403 (Process Control)  
Full Marks: 210  
Time: 3 Hours  
The figures in the margin indicate full marks.  
USE SEPARATE SCRIPTS FOR EACH SECTION

SECTION – A

There are FOUR questions in this section. Answer any THREE.

1. (a) Figure 1(a) shows a typical feedback control loop.

If $G_c$ is a PI controller sketch qualitatively the response $Y$ for the following cases:

(i) If $D = 0$, $Y_{SP} =$ step input, the effect of change of proportional gain.
(ii) If $D = 0$, $Y_{SP} =$ unit step, the effect of change of integral time constant.
(iii) If $Y_{SP} = 0$, $D =$ step input, effect of change of integral time constant.

(b) Explain the concept of gain margin and phase margin using Bode diagram. How are they useful in designing controllers?

(c) Describe the three basic modes of feedback controllers including their merits and demerits.

2. (a) Describe Internal Model Control (IMC) method of designing feedback controllers.

(b) If a first order process is excited with a sinusoidal input, what will be its output response?
Given, $L \{ \sin \omega t \} = \frac{\omega}{s^2 + \omega^2}$. What conclusion can be drawn from this analysis?

3. (a) For a first order process, mathematically show that a P-controller cannot reject completely the effect of a disturbance change while a PI controller can do it.

(b) Write short notes with an appropriate example
(i) Cascade control
(ii) Selective control

(c) Write down five criteria of selecting a sensor.

Contd ........... P/2
4. (a) Compare briefly DCS with PLC (5)

(b) What is general stability criterion? Describe the effect of pole locations in s-plane on the stability of a system. (2+8)

(c) Describe the combined feedback-feedforward control of boiler drum level. (10)

(d) With the help of onion-layer diagram, describe the typical layers of protection in modern chemical plants. (10)

SECTION – B

There are FOUR questions in this section. Answer any THREE.

5. (a) Draw proper P&I diagram of the following processes (18)

(i) Reactants enter a jacketed CSTR where a reaction takes place and the products exit. The reactor is cooled via a coolant water stream. The temperature inside the reactor vessel is monitored with a temperature controller (also contained in the control system is a sensor, indicator and transmitter), which electrically controls a valve. The valve can alter the flowrate of the coolant water stream, thereby controlling the temperature inside the reactor. A pressure controller is also present which feeds back to an inlet valve. The reaction occurs most likely in gas phase and if the CSTR becomes too full (high pressure) the inlet valve will close.

(ii) A storage tank is filled with condensed products formed in the CSTR in above question. The tank contains a level controller at a set point on the top of the tank. If this tank were to fill, materials would get clogged up in the reactor. Therefore, if the tank reaches 90% of its total capacity, the level controller will send an electric signal, which opens an emergency drainage line located at the bottom of the tank. The level controller will also activate an alarm alerting plant engineers that there is a problem with the storage tank. Finally the level controller will also close the inlet valve to the storage tank. (b) The liquid storage tank shown in Fig. for Q. 5(b) has two inlet streams with mass flow rates \( W_1 \) and \( W_2 \) and an exit stream with flow rate \( W_3 \). The cylindrical tank is 2.5 m tall and 2 m in diameter. The liquid has a density of 800 kg/m\(^3\). Normal operating procedure is to fill the tank until the liquid level reaches a nominal value of 1.75 m using constant flow rates: \( W_1 = 120 \) kg/min, \( W_2 = 100 \) kg/min and \( W_3 = 200 \) kg/min. At that point, inlet flow rate \( W_1 \) is adjusted so that the level remains constant. However on this particular day, corrosion of the tank has opened up a hole in the wall at the height of 1 m, producing a leak whose volumetric flow rate \( q_4 \) (m\(^3\)/min) can be approximated by, \( q_4 = 0.025 \sqrt{h-1} \), where \( h \) is the height in meters. (17)

(i) If the tank was initially empty, how long did it take for the liquid level to reach the corrosion point?

(ii) If mass flow rates \( W_1 \), \( W_2 \) and \( W_3 \) are kept constant indefinitely, will the tank eventually over flow? Justify your answer.

Contd ............ P/3
6. (a) Describe the steps that are followed to develop dynamic models for process control purpose.

(b) Liquid flow out of a spherical tank discharging through a valve can be described approximately by the following non linear differential equation:

\[ \frac{dh}{dt} = \frac{1}{\pi(D-h)} \left(q_i - c_v \sqrt{h} \right) \]

where the variable used are consistent with other liquid level models developed for CHE 403 course.

(i) Derive a linearized model (in deviation variables) of the form,

\[ \frac{dh'}{dt} = ah' + bq' \]

(ii) Develop a transfer function relating the liquid level to the volumetric flow of liquid into the tank. Give the final expression in terms of the state space model co-efficients, a and b.

7. (a) Apply the initial and final value theorems to the following transfer function,

\[ \frac{(1-s)e^{-s}}{(12s + 1)(3s + 1)(0.2s + 1)(0.05s + 1)} \]

(b) An electrically heated process is known to exhibit second order dynamics with the following parameter values: \( K = 3°C/kW, \tau = 3 \text{ min}, \zeta = 0.7 \). If the process initially is at steady state at 70°C with heater input of 20 kW and the heater input is suddenly changed to 26 kW and held there,

(i) What will be the expression for the process temperature as a function of time?

(ii) What will be the maximum temperature that one observes? When will it occur?

8. (a) Consider the following transfer function:

\[ G(s) = \frac{5}{(10s + 1)(4s + 1)(s + 1)(0.2s + 1)} \]

Use Skogestad's method to derive two approximate models:

(i) A first order plus time delay model as \( G(s) = \frac{ke^{-\theta s}}{(\zeta s + 1)} \).

(ii) A second order plus time delay model as \( G(s) = \frac{ke^{-\theta s}}{(\zeta_1 s + 1)(\zeta_2 s + 1)} \).

(b) A process is described by the transfer function,

\[ \frac{Y(s)}{U(s)} = \frac{K}{s(\zeta s + 1)} \]

(i) What is the form of the process response to a step change in input of magnitude M?

(ii) Show how you could evaluate the parameters K and \( \zeta \) from the plot of the output response.
Fig. for Q. 5(b)
SECTION - A

There are FOUR questions in this section. Answer any THREE.

1. (a) Name different types of petroleum reservoirs. Write down the names of at least five parameters to recognize the types of reservoir without having Pressure-Volume or Pressure-Temperature diagram. (10)

(b) Explain retrograde condensation with the help of P-T diagram? Why is this undesirable and how can it be avoided? (5+5=15)

(c) Methane is a significant component in reservoir fluids. The Figure 01 is a sketch for a binary phase diagram of methane and n-decane (C_{10}). Illustrate the impact of methane on the critical point of C_{1} – C_{10} binary mixtures? (10)

2. (a) List the name of the sources from which gas comes out. Explain each of them. (8)

(b) A gas condensate produces gas and liquids with the compositions listed in table 01 with a producing GOR of 30000 scf/stb. Determine the composition of the reservoir gas. (20)

(c) The volumetric data at 150 °F for a natural gas is listed in table 02. Determine the coefficient of isothermal compressibility for this gas at 150 °F and 1000 psia. (7)

3. (a) Define "Deliverability test". State the purpose of the deliverability test. (2+3=5)

(b) An isothermal test is shown in the Figure 02. Assume the well has stabilized after three hours. Determine the followings– (6+6=12)

(i) n, C_{stab} and AOF

(ii) Construct inflow performance curve

(c) What is performance coefficient? Why does it change with time and flow rate? How can the values of exponent n of the deliverability equation indicate well bore damage and flow condition? (4+4=8)

(d) Draw the pressure and flow rate profiles for a modified isothermal deliverability gas well test. Use the typical symbols to indicate each of the point on the sketch. (5+5=10)

4. (a) Write the name of solid desiccants that are used for adsorption dehydration of natural gas. For petroleum fluid that come from dry gas reservoir, which type of solid desiccant you would recommend for adsorption dehydration and why? (2+3=5)

Contd ........ P/2
(b) What is meant by gas hydrate? Draw the Phase equilibrium diagram for gas water hydrate system. \(3+7=10\)

(c) To size a glycol dehydrator for a field installation from standard models following are the requirements.

- Gas flow rate = 10 MMscfd
- Gas specific gravity = 0.70
- Operating line pressure = 1000 psig
- Maximum working pressure of contactor = 1440 psig
- Gas inlet temperature = 100 °F
- Outlet gas water content = 7 lbH₂O/MMscf

Select additional design criteria:
- Glycol to water circulation rate = 3 gal TEG/H₂O
- Lean glycol concentration = 99.5 %
- Specific gravity of lean glycol at 100 °F = 1.111

Use trayed-type contactor with valve trays

Determine the followings—
- (i) Construct McCabe-Thiele diagram and find number of trays required.
- (ii) Required amount of heat load for the reboiler.

Assume values with basis if required.

Use the charts and other information attached in the question.

Cartesian graph paper is required.

**SECTION – B**

There are **FOUR** questions in this section. Answer any **THREE**.

5. (a) Draw a typical Production pressure profile showing pressure drop across all the system elements. Draw a Christmas Tree and label the major components. \(5+5=10\)

(b) Name the three major types of separators. \(5\)

(c) Determine the actual gas and oil capacity of a horizontal separator having a diameter of 36 in. and a seam to seam length of 14 ft given the following operating conditions: \(20\)

- Gas specific Gravity 0.6
- Oil gravity 35° API
- Operating Pressure 985 psi
- Operating Temperature 60° F
- Retention time 3 minutes
- Gas Compressibility factor at given condition 0.84
- Gas Viscosity 0.013 cp
- \(C_4\) 1.1709
- Liquid droplet to be separate 100 micron

Contd ........... P/3

(b) To design an Amine process for gas sweetening process using DEA as solvent below information is available:

- $Q_g = 100$ MMscfd
- S.G = 0.6
- $H_2S$ inlet = 10 ppm
- $H_2S$ outlet = 4 ppm
- $CO_2$ inlet = 4.33%
- $CO_2$ outlet = 2%
- $C_D$ (contactor) = 0.689
- Droplet diameter = 150 micron
- Gas Compressibility factor = 0.84
- $P = 1000$ psig
- $T = 100^\circ F$

(i) Determine DEA circulation rate using 35% DEA and an acid gas loading of 0.5 mole acid gas/mole DEA.

(ii) Determine preliminary height and diameter of DEA contact tower.

(iii) Calculate approximate reboiler duty with 250$^\circ$ F reboiler temperature.

7. (a) Write down the short notes on the following terminologies including their usage:

(i) NGL
(ii) LNG
(iii) LPG
(iv) CNG

(b) What is FSRU? Where does it fit in the LNG value chain?

(c) The annual natural gas demand of country X is 1.5 TCF. The shortage of gas supply is 30% which the government has decided to fulfill by importing LNG. If the capacity of an example LNG plant is 5 MTPA then how many of those would be required to meet the shortage of energy.

(d) What is the difference between MSA and ESA in NGL recovery?

8. (a) Name the potential sources of waste in a Petroleum Production System. Also name the most common migration path ways of those wastes.

(b) Elaborate the effect of petroleum wastes on environment?
(c) For the following data given for a horizontal pipeline. (10+10=20)

(i) Predict gas flow rate in ft³/hr through the pipeline by applying Weymouth equation.

(ii) If the last 50 miles of the pipeline was to be replaced with 16 in pipeline, what will be the percentage increase of gas flow rate?

<table>
<thead>
<tr>
<th>Diameter of pipeline</th>
<th>= 14 in</th>
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<tr>
<td>Length</td>
<td>= 150 miles</td>
</tr>
<tr>
<td>Average temperature</td>
<td>= 80 deg F</td>
</tr>
<tr>
<td>Specific gravity of gas</td>
<td>= 0.63</td>
</tr>
<tr>
<td>Upstream pressure</td>
<td>= 1050-psia</td>
</tr>
<tr>
<td>Downstream pressure</td>
<td>= 430-psia</td>
</tr>
<tr>
<td>Absolute roughness of pipe</td>
<td>= 0.0006-in</td>
</tr>
<tr>
<td>Standard temperature</td>
<td>= 60 deg F</td>
</tr>
<tr>
<td>Standard pressure</td>
<td>= 14.7 psia</td>
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<tr>
<td>Average z factor</td>
<td>= 0.8533</td>
</tr>
<tr>
<td>Viscosity of gas</td>
<td>= 0.0097 cp</td>
</tr>
</tbody>
</table>

(d) Name the only Exploration and Production Company in Bangladesh under Petrobangla. Also name the largest gas transmission company in Bangladesh. (2)

(e) Which is the highest producing field in Bangladesh per day as per Petrobangla 2014 report? Which company does it belong to? (3)
Figure-01: Phase diagram of binary HC mixtures

Table-01: Composition of petroleum fluid from gas condensate reservoir

<table>
<thead>
<tr>
<th>Components</th>
<th>Gas Composition</th>
<th>Liquid Composition</th>
<th>Molecular weight</th>
<th>Liquid Density (lb/cu.ft)</th>
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</thead>
<tbody>
<tr>
<td>Methane</td>
<td>0.84</td>
<td>16</td>
<td></td>
<td></td>
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<tr>
<td>Ethane</td>
<td>0.08</td>
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<td>Propane</td>
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<td>0.15</td>
<td>44</td>
<td>31.66</td>
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<td>Butane</td>
<td>0.01</td>
<td>0.36</td>
<td>58</td>
<td>35.78</td>
</tr>
<tr>
<td>Pentane</td>
<td></td>
<td>0.28</td>
<td>72</td>
<td>38.51</td>
</tr>
<tr>
<td>Hexane</td>
<td>0.12</td>
<td></td>
<td>86</td>
<td>41.3</td>
</tr>
<tr>
<td>Hexane plus</td>
<td>0.09</td>
<td>114</td>
<td>43.68</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1.00</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table-02: Volumetric data for natural gas at 150 °F

<table>
<thead>
<tr>
<th>Pressure (psia)</th>
<th>Molar Volume (cu.ft/lb mole)</th>
</tr>
</thead>
<tbody>
<tr>
<td>700</td>
<td>8.5</td>
</tr>
<tr>
<td>800</td>
<td>7.4</td>
</tr>
<tr>
<td>900</td>
<td>6.5</td>
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<tr>
<td>1000</td>
<td>5.7</td>
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<tr>
<td>1100</td>
<td>5.0</td>
</tr>
<tr>
<td>1200</td>
<td>4.6</td>
</tr>
<tr>
<td>1300</td>
<td>4.2</td>
</tr>
</tbody>
</table>
Figure-02: Isochronal Test
List of equations required for question (4):

\[ C_{\text{mW}} = \frac{C_{\text{tan}} \rho_{\text{W}}}{\rho_{\text{W}} + \frac{1}{L_w}} \]

\[ L = L_w \times W_w \times \frac{q}{24} \]

\[ Q_i = L \rho \times C(T_i - T_f) \]

\[ Q_o = 970.3 \times \frac{q}{24} (W_i - W_o) \]

For Pipeline Design

Weymouth Equation:

\[ q_h = \frac{18.062T_b}{P_b} \sqrt{\frac{(p_1^2 - p_2^2)}{\gamma_p^2 L}} \]

\[ \frac{q_2}{q_1} = \frac{\left( \frac{L}{D_1^{16/3}} \right)}{\sqrt{\frac{L_1}{D_1^{16/3}} + \frac{L_2}{D_2^{16/3}} + \frac{L_3}{D_3^{16/3}}}} \]
Equations and other relevant information:

For Horizontal Separator

\[ dL_{\text{eff}} = 420 \left( \frac{TQ_g}{p} \right) \left[ \left( \frac{\rho_g}{\rho_l - \rho_g} \right) \frac{C_P}{d_m} \right]^{1/2} \]

Gas capacity constraint

\[ d^2L_{\text{eff}} = \frac{t_r Q_t}{0.7} \]

Liquid capacity constraint

\[ L_{ss} = L_{\text{eff}} + \frac{d}{12} \]

Gas capacity constraint

\[ L_{ss} = \frac{4}{3} L_{\text{eff}} \]

Liquid capacity constraint

\[ \rho_l = \rho_{\text{water}} \left( \frac{141.5}{131.5 + \text{API Gravity}} \right) \]

\[ \rho_g = 2.7 \frac{SP}{TQ} \]

For Amine process Design

\[ L_{\text{DEA}} = \frac{192Q_g MF}{c \rho A_k} \]

20% MEA = 8.41 lb/gal = 0.028 mole MEA/gal
35% DEA = 8.71 lb/gal = 0.029 mole DEA/gal

\[ d^2 = 5,040 \left( \frac{TQ_g}{p} \right) \left[ \left( \frac{\rho_g}{\rho_l - \rho_g} \right) \frac{C_P}{d_m} \right]^{1/2} \]

Typically for a stripper with 20 trays, the reboiler duties will be as follows:

MEA system—1,000 to 1,200 Btu/gal lean solution
DEA system—900 to 1,000 Btu/gal lean solution
SECTION - A

There are **FOUR** questions in this section. Answer any **THREE**.

1. (a) What are the differences among the thermochemical processes of biomass conversion? Briefly discuss these processes.  
   
   (9)

(b) What are basic types of cell receptors? What are their functions?  
   
   (5)

(c) What is principle of similarity? Briefly explain the classifications of principle of similarity?  
   
   (9)

(d) An engineer is designing artificial tissue that mimics the stiffness of the physiological condition. During some receptor-ligand (spherical with diameter \(D\)) binding experiment a complex of radius \(d\) was formed at the binding site. Ligand solution was flown at velocity \(V\). It is known that dimensionless length \(d/D\) is a function of one or more dimensionless numbers consisting of velocity, density, elasticity and Poisson's ratio of the material. Do a dimensional analysis to predict the dimensionless number(s). Elasticity has a dimension of \(ML^{-1}T^{-2}\).  
   
   (12)

2. (a) What are the three major components of substrate consumption equation? Derive the equation for batch reaction time in terms of these three components?  
   
   (8)

(b) A biotech company produces a specialized cosmetic raw material by enzymatic reaction. Maximum rate, \(V_{\text{max}}\) is 5 mmol m\(^{-3}\)s\(^{-1}\) and the substrate concentration required to reach half of the maximum rate is 67 mM. Initial substrate concentration in 90 mM. How much time is required for 50% substrate conversion in a batch reactor? How much additional time will required for a 50% less \(V_{\text{max}}\)?  
   
   (5+3=8)

(c) What are the basic sequential steps in signal transduction in a cell? Discuss the benefits of microscopy over traditional approaches during quantification of signal transduction.  
   
   (3+6=9)

(d) What are the methods of cell communication? Briefly describe them with appropriate schematics.  
   
   (10)

3. (a) What are the basic steps followed in cloning process? Discuss the role of selected markers in recombinant DNA technology.  
   
   (5+4=9)

(b) With a schematic, briefly describe the working principle and salient features of packed-bed bioreactor.  
   
   (8)

(c) Write short notes on the followings:  
   
   (6x3=18)

   (i) Biofuel production  
   
   (ii) Bubble-column reactor  
   
   (iii) Taxis

Contd .......... P/2
4. (a) With the help of appropriate plots, describe the dynamic method of aeration capacity measurement process.  
(b) During dynamic method of aeration capacity measurement process in a 20 L fermenter, steady state dissolved oxygen tension was found to be 70% of saturation. Oxygen tensions calculated at 5 and 15 minute were 50 and 66, respectively. What was the aeration capacity?  
(c) Briefly describe the naming convention of the restriction endonucleases.  
(d) How does PCR amplification work? List major components required to perform a PCR reaction. Design a set of 12-nucleotide long forward and reverse primers to amplify the underlined sequence (gene of interest) in a PCR machine. Write down the primer sequence in proper convention and identify the amino acid sequence from the gene of interest.  

5' GGA TCT TGT GCA ATG ACG TCC GTA TAT CTA CGC GCG GTG GAT CGA TGT CCA AAC 3'  

5. (a) Describe in details any two mechanical methods for cell disruption, mention the relative stress and costs involved during these methods.  
(b) What is considered as a good partition coefficient for biological extraction processes? Show using appropriate mathematical terms, that, if partition coefficient is unfavourable, yield can be increased using a large volume of the phase preferred by the solute?  
(c) Discuss the advantages and disadvantages of using ‘filter aids’ in a filtration bioprocess.  
(d) List some types of chromatographic columns, along with the main property of the stationary phase which helps to carry out the chromatographic separations.  

There are FOUR questions in this section. Answer any THREE.

6. (a) List the sequence of steps of an ion exchange chromatographic operation along with appropriate diagrams. Write down the salient features of either anion exchange or cation exchange chromatography.  
(b) Figure below is the chromatogram for a two-component mixture.  
(i) Determine the capacity factor for each solute assuming the sample was injected at time \( t = 0 \). Comment on the values you got. (Are these capacity factors good for separation?)  
(ii) Determine the separation factor for the peaks. Comment on the separation of the peaks.  
(iii) What do you understand by resolution of the peaks? Estimate the baseline widths for both peaks from the graphs and calculate the resolution. Comment on the resolution value.  
(iv) Between 'separation factor' and "resolution" of peaks, which is a better measure of how well two peaks are separated? Why?
7. (a) Describe with the aid of a diagram the components of a biosensor. (For each component write its role in the biosensor along with examples). List any 4 techniques to immobilise the biosensing probe (biomolecule) onto a biosensor surface. (10)

(b) Define the various governing parameters/factors associated with biosensors; comment on each factor (should be high, should be low etc) for an ideal biosensor. (10)

(c) Using appropriate diagrams, define clean rooms and mention the various classes of clean rooms. Show how they are placed in a bioprocessing facility. (10)

(d) What do you understand by a clinical trial? Describe what happens in a clinical trial? (5)

8. (a) With simple drawings briefly discuss the 4 levels of protein structures. (10)

(b) An organism growing in a CSTR with an initial substrate concentrations of 50 g/l follows Monod kinetics. Maximum specific growth rate is 0.5/h and Monod constant is 2 g/L.

(i) For the maximum possible yield, what would be the optimum dilution rate? (3)

(ii) If the same dilution is used in a 2-stage CSTR series, what would be the substrate concentrations at the outlet of both reactors? (7)

(c) Write short notes on the following: (5x3=15)

(i) Oxygen transfer in bioreactor (ii) Aseptic operation (iii) Washout Condition
List of equations: (symbols have their usual meanings)

1. \( x = x_0 e^{\mu t} \)

2. \( \mu = \frac{\mu_{\text{max}} S}{K_s + S} \)

3. \( Y_{x/s} (S_0 - S) = x - x_0 \)

4. \( t_b = \frac{1}{\mu_{\text{max}}} \ln \left[ 1 + \frac{Y_{x/s} (s_0 - s_f)}{x_0} \right] \)

5. \( t_b = \frac{1}{\mu_{\text{max}}} \ln \left[ 1 + \frac{\mu_{\text{max}}}{x_0 q_p} (p_f - p_0) \right] \)

6. \( t_b = \frac{K_m}{v_{\text{max}}} \ln \frac{s_0}{s_f} + \frac{s_0 - s_f}{v_{\text{max}}} \)

7. \( \tau = \frac{1}{D} = \frac{V}{F} \)

8. \( D (s_i - s) = \frac{v_{\text{max}} s}{K_m + s} \)

9. \( D_{\text{opt}} = \mu_{\text{max}} \left( 1 - \sqrt{\frac{K_s}{K_s + s_i}} \right) \)

10. \( x = Y_{x/s} \left( S_0 - \frac{DK_s}{\mu_{\text{max}} - D} \right) \)
Table 1: Guideline for RNA to Nucleic acid conversion

<table>
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<tr>
<th>First letter</th>
<th>Second letter</th>
<th>Third letter</th>
</tr>
</thead>
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<td>Phenylalanine</td>
<td>Leucine</td>
</tr>
<tr>
<td><strong>UC</strong></td>
<td>UCU UCC UCA UCG</td>
<td>Serine</td>
</tr>
<tr>
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<td>UAU UAC</td>
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<td><strong>GG</strong></td>
<td>GGU GCC GGA GGG</td>
<td>Glycine</td>
</tr>
<tr>
<td><strong>UG</strong></td>
<td>UGU UGC</td>
<td>Cysteine</td>
</tr>
<tr>
<td><strong>UA</strong></td>
<td>UAU UAC</td>
<td>Tyrosine</td>
</tr>
<tr>
<td><strong>UG</strong></td>
<td>UGU UGC</td>
<td>Cysteine</td>
</tr>
</tbody>
</table>

Stop codon: UAA, UAG, UGA
SECTION - A

There are FOUR questions in this section. Answer any THREE.

1. (a) The following two (2) steps are taken from the 14 (fourteen) steps for - "Typical Design Steps for Chemical and Biochemical Processes" -
   • Prepare detailed engineering design
   • Compute the final engineering design.
   Write a discussion to fully explaining these two steps. (15)
   (b) Using any suitable example fully describe Pinch Technology Analysis. Your answer must use tables and figures to illustrate your point. (20)

2. A condenser for a distillation unit must be designed to condense 2500 kg of vapor per hour. The effective condensation temperature for the vapor is 77°C. The heat of condensation for the vapor is 475 kJ/kg. The cost of the cooling water at 21°C is $ 2.50 per 100 m$^3$. The overall heat-transfer coefficient at the optimum conditions may be taken as 0.290 kJ/(m$^2$.S.K.). The cost for the installed heat exchanger is $ 400 per square meter of heat transfer area, and the annual fixed charges including maintenance are 20 percent of the initial investment. The heat capacity of the water may be assumed to be constant at 4.2 kJ/(kg.K). If the condenser is to operate 5800 h/yr, determine the cooling water flow rate in kilograms per hour for optimum economic conditions. [Derive the formula used]. Use a simple iterative procedure or graphical solution. (35)

3. (a) The purchased cost of a 1 m$^3$, glass-lined jacketed kettle was $ 20,000 in 1988. Estimate the purchased cost of a similar 2 m$^3$, glass-lined jacketed kettle in 2001. Cost index data for a chemical engineering plant will apply to this case. If the inflation rate of the dollar ($) is 2.5% per annum, what will be the present price of the kettle? (12)
   (b) The total capital investment for a chemical plant is $ 1.5 million, and the working capital is $ 125,000. If the plant can produce an average of 9000 kg of final product per day during a 365 day year, what selling price in dollars per kilogram of product would be necessary to give a turnover ratio of 0.85? (8)

Contd ......... P/2
CHE 405

Contd … Q. No. 3

(c) The purchased equipment cost for a solid-fluid processing plant is $115 million. The following additional information is supplied –

• Building requirement in estimated to be on the lower side
• Highly instrumented plant
• Low engineering and supervision costs
• Legal problems are expected
• The plant to be built on own land.

Using the given table estimate the (i) Direct cost (ii) Indirect cost (iii) Fixed capital investment and (iv) Total investment.
[You must show the costs of all components].

4. (a) What is inherently safer design? Write down the process design features required or inherently safer design.

(b) A gas-fired furnace is shown in Figure for Q. No. 4(b). The hot combustion gases pass through a heat exchanger to heat fresh air for space heating. The gas flow is controlled by an electric solenoid valve connected to a thermostat. The gas is ignited by a pilot light flame. A high-temperature switch shuts off all gas by interlocking system in the event of high temperature in hot air space. Carry out a HAZOP study with an aim to prevent excessive heating of the hot air space and possible fire. Make your own HAZOP table and select study nodes as required.

SECTION – B

There are FOUR questions in this section. Answer any THREE.

5. (a) Discuss different properties of ferrous metals and alloys as construction materials of process equipment.

(b) Air at a flow rate of 0.115 kg/s is transferred through a straight horizontal steel pipe with an inside diameter of 0.05 m and a length of 1000 m. A compressor is located at the upstream end of the pipe with the air entering the compressor through a 0.05 m dia pipe. The pressure at the downstream end of the pipe is 135 kPa while the temperature is 21°C. If the air pressure in the pipe at the entrance in the compressor is 170 kPa and the temperature is 27°C. Determine:

(i) the pressure in the pipe as the air leaves the compressor and
(ii) the mechanical energy added to the air by the compressor in N-m/kg, assuming that the compression operation is isothermal.
6. (a) Describe briefly the following key heat exchanger types:

(i) Gasketed and welded plate exchangers
(ii) Spiral plate and tube exchangers
(iii) Compact exchangers

(b) A heat exchanger with two tube passes has been recommended for cooling distilled water from 34°C to 29°C. The proposed unit contains 160 tubes, each with a 0.0191-m outside diameter and 4.876-m in length. The tubes are laid out on a 0.0238-m triangular pitch within a 0.387 m inside diameter shell. Twenty five percent cut segmental baffles spaced 0.3 m apart are located within the shell. Cooling water at a temperature of 24°C and a flowrate of 2.0 m/s will be used in the tubes to provide the cooling. Under these conditions, the fouling coefficients for the distilled water and the cooling water can be assumed to be 11,360 and 5680 W/m².K respectively. The pressure drop on either the tube side or the shell side may not exceed 169 kPa. Would the recommended design be adequate for cooling 22 kg/s of distilled water? [Assume reasonable value for any missing data].

7. Use the Kern method to calculate the shell-side heat transfer coefficient and pressure drop for the cooling of a light hydrocarbon with a mass flow rate of 5.5 kg/s.

Physical properties for the light hydrocarbon are as follows:

\[ \rho_L = 730 \text{ kg/m}^3, \quad k_L = 0.13 \text{ W/m.K}, \quad C_p, L = 2470 \text{ J/kg.K}, \quad \mu_L = 4 \times 10^{-6} \text{ Pa.s} \]

The dimensions and internal configurations for the shell-and-tube heat exchanger are listed below:

- Inside tube diameter = 0.0206 m
- Outside tube diameter = 0.0254 m
- Inside shell diameter = 0.54 m
- Tube pitch (square) = 0.032 m
- Shell length = 4.26 m
- Number of tubes = 158
- Baffle spacing = 0.127 m
- Diametral clearances:
  - Tube-to-baffle = 0.0008 m
  - Shell-to-baffle = 0.005 m
- Number of tube passes = 4

[Note: Assume reasonable value for all missing data]
8. (a) In a depropenizer, a six component feed at 96°C and 2170 kPa has the following composition:

<table>
<thead>
<tr>
<th>Component</th>
<th>Feed, mol%</th>
<th>K value at 96°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Methane</td>
<td>26.0</td>
<td>15.0</td>
</tr>
<tr>
<td>Ethane</td>
<td>9.0</td>
<td>3.8</td>
</tr>
<tr>
<td>Propane</td>
<td>26.0</td>
<td>1.56</td>
</tr>
<tr>
<td>n-Butane</td>
<td>17.0</td>
<td>0.8</td>
</tr>
<tr>
<td>n-Pentane</td>
<td>11.0</td>
<td>0.38</td>
</tr>
<tr>
<td>n-Hexane</td>
<td>12.0</td>
<td>0.19</td>
</tr>
</tbody>
</table>

The feed is to be separated in a sieve tray distillation column with a recovery of 98.4 percent of the propane in the distillate product and 98.2 percent of the n-butane in the bottom product.

The feed quality is 66 percent vapor. The column is equipped with a partial condenser. What are the minimum number of stages and minimum reflux required for the separation? If a reflux ratio of 1.5 is selected how many theoretical stages are required and where is the feed location?

(b) Write general design concepts for separation by adsorption.

(c) Write general guidelines affecting extraction equipment selection.
Figure for Q 4(b): Furnace Control System

<table>
<thead>
<tr>
<th>Year</th>
<th>Marshall and Swift installed equipment indexes, 4026 = 100</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>814</td>
</tr>
<tr>
<td>1987</td>
<td>4406</td>
</tr>
<tr>
<td>1988</td>
<td>410</td>
</tr>
<tr>
<td>1989</td>
<td>1164.5</td>
</tr>
<tr>
<td>1990</td>
<td>1195.9</td>
</tr>
<tr>
<td>1991</td>
<td>1225.7</td>
</tr>
<tr>
<td>1992</td>
<td>1252.9</td>
</tr>
<tr>
<td>1993</td>
<td>1277.3</td>
</tr>
<tr>
<td>1994</td>
<td>1310.8</td>
</tr>
<tr>
<td>1995</td>
<td>1349.7</td>
</tr>
<tr>
<td>1996</td>
<td>1392.1</td>
</tr>
<tr>
<td>1997</td>
<td>1418.9</td>
</tr>
<tr>
<td>1998</td>
<td>1418.9</td>
</tr>
<tr>
<td>1999</td>
<td>1418.9</td>
</tr>
<tr>
<td>2000</td>
<td>1418.9</td>
</tr>
<tr>
<td>2001</td>
<td>1418.9</td>
</tr>
<tr>
<td>2002</td>
<td>1418.9</td>
</tr>
</tbody>
</table>

All costs presented in this text and in the McGraw-Hill website are based on this value for January 2002, obtained from the Chemical Engineering index unless otherwise indicated. The website provides the corresponding mathematical cost relationships for all the graphical cost data presented in the text.

Table 6-2 presents a list of values for various types of indexes over the past 15 years.
Typical exponents for equipment cost as a function of capacity

<table>
<thead>
<tr>
<th>Equipment</th>
<th>Size range</th>
<th>Exponent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blender, double cone rotary, carbon steel (c.s.)</td>
<td>1.4–7.1 m³ (50–250 ft³)</td>
<td>0.49</td>
</tr>
<tr>
<td>Blower, centrifugal</td>
<td>0.5–4.7 m³/s (10³–10⁴ ft³/min)</td>
<td>0.59</td>
</tr>
<tr>
<td>Centrifuge, solid bowl, c.s.</td>
<td>7.5–75 kW (10–10² hp) drive</td>
<td>0.67</td>
</tr>
<tr>
<td>Crystallizer, vacuum batch, c.s.</td>
<td>15–200 m³ (500–7000 ft³)</td>
<td>0.37</td>
</tr>
<tr>
<td>Compressor, reciprocating, air-cooled, two-stage, 1035-kPa discharge</td>
<td>0.005–0.19 m³ (10–400 ft³/min)</td>
<td>0.69</td>
</tr>
<tr>
<td>Compressor, rotary, single-stage, sliding vane, 1035-kPa discharge</td>
<td>0.05–0.5 m³/s (10⁴–10⁵ ft³/min)</td>
<td>0.79</td>
</tr>
<tr>
<td>Dryer, drum, single vacuum</td>
<td>1–10 m² (10²–10³ ft²)</td>
<td>0.76</td>
</tr>
<tr>
<td>Dryer, drum, single atmospheric</td>
<td>1–10 m² (10²–10³ ft²)</td>
<td>0.40</td>
</tr>
<tr>
<td>Evaporator (installed), horizontal tank</td>
<td>10–1000 m³ (10³–10⁴ ft³)</td>
<td>0.54</td>
</tr>
<tr>
<td>Fan, centrifugal</td>
<td>0.5–5 m³/s (10³–10⁴ ft³/min)</td>
<td>0.44</td>
</tr>
<tr>
<td>Fan, centrifugal</td>
<td>10–35 m³/s (2×10⁴–7×10⁴ ft³/min)</td>
<td>1.17</td>
</tr>
<tr>
<td>Heat exchanger, shell-and-tube, floating head, c.s.</td>
<td>1–3 m² (250–800 gal)</td>
<td>0.60</td>
</tr>
<tr>
<td>Heat exchanger, shell-and-tube, fixed sheet, c.s.</td>
<td>10–40 m² (10⁴–10⁵ ft²)</td>
<td>0.44</td>
</tr>
<tr>
<td>Kettle, cast-iron, jacketed</td>
<td>0.8–3 m³ (200–800 gal)</td>
<td>0.27</td>
</tr>
<tr>
<td>Kettle, glass-lined, jacketed</td>
<td>4–15 kW (5–20 hp)</td>
<td>0.69</td>
</tr>
<tr>
<td>Motor, squirrel cage, induction, 440-V, explosion-proof</td>
<td>15–150 kW (20–200 hp)</td>
<td>0.99</td>
</tr>
<tr>
<td>Motor, squirrel cage, induction, 440-V, explosion-proof</td>
<td>1×10⁴–6×10⁻³ m³/s (2–100 gpm)</td>
<td>0.34</td>
</tr>
<tr>
<td>Pump, reciprocating, horizontal cast-iron (includes motor)</td>
<td>4–40 m³/s/kPa (10³–10⁴ gpm psi)</td>
<td>0.33</td>
</tr>
<tr>
<td>Pump, centrifugal, horizontal, cast steel (includes motor)</td>
<td>0.2–2.2 m³ (50–600 gal)</td>
<td>0.54</td>
</tr>
<tr>
<td>Reactor, glass-lined, jacketed (without drive)</td>
<td>0.4–4.0 m³ (10²–10³ gal)</td>
<td>0.56</td>
</tr>
<tr>
<td>Reactor, stainless steel, 2070-kPa</td>
<td>1.5–7 m³ (50–250 ft³)</td>
<td>0.49</td>
</tr>
<tr>
<td>Separator, centrifugal, c.s.</td>
<td>0.4–40 m³ (10³–10⁴ ft³)</td>
<td>0.57</td>
</tr>
<tr>
<td>Tank, flat head, c.s.</td>
<td>0.4–4.0 m³ (10³–10⁴ gal)</td>
<td>0.49</td>
</tr>
<tr>
<td>Tank, c.s., glass-lined</td>
<td>5×10⁻⁵–10⁶ kg (10³–2×10⁴ lb)</td>
<td>0.62</td>
</tr>
<tr>
<td>Tower, c.s.</td>
<td>1–3 m (3–10 ft) diameter</td>
<td>1.20</td>
</tr>
<tr>
<td>Tray, bubble cap, c.s.</td>
<td>1–3 m (3–10 ft) diameter</td>
<td>0.86</td>
</tr>
<tr>
<td>Tray, sieve, c.s.</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Estimation of capital investment cost (showing individual components)

The percentages indicated in the following summary of the various costs constituting the capital investment are approximations applicable to ordinary chemical processing plants. It should be realized that the values given vary depending on many factors, such as plant location, type of process, and complexity of instrumentation.

I. Direct costs = material and labor involved in actual installation of complete facility (65–85% of fixed-capital investment)
   A. Equipment + installation + instrumentation + piping + electrical + insulation + painting (50–60% of fixed-capital investment)
      1. Purchased equipment (15–40% of fixed-capital investment)
      2. Installation, including insulation and painting (25–55% of purchased-equipment cost)
      3. Instrumentation and controls, installed (8–50% of purchased-equipment cost)
      4. Piping, installed (10–80% of purchased-equipment cost)
      5. Electrical, installed (10–40% of purchased-equipment cost)
   B. Buildings, process, and auxiliary (10–70% of purchased-equipment cost)
   C. Service facilities and yard improvements (40–100% of purchased-equipment cost)
   D. Land (1–2% of fixed-capital investment or 4–8% of purchased-equipment cost)

II. Indirect costs = expenses which are not directly involved with material and labor of actual installation of complete facility (15–35% of fixed-capital investment)
   A. Engineering and supervision (5–30% of direct costs)
   B. Legal expenses (1–3% of fixed-capital investment)
   C. Construction expense and contractor’s fee (10–20% of fixed-capital investment)
   D. Contingency (5–15% of fixed-capital investment)

III. Fixed-capital investment = direct costs + indirect costs

IV. Working capital (10–20% of total capital investment)

V. Total capital investment = fixed-capital investment + working capital
### Table D-4  Density, viscosity, and thermal conductivity of water

<table>
<thead>
<tr>
<th>Temperature K</th>
<th>Density of water at 1 atm</th>
<th>Viscosity of water in mPa.s</th>
<th>Specific heat of water at 1 atm</th>
<th>Thermal conductivity of water in Wm⁻¹K⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>273.15</td>
<td>999.9</td>
<td>1.750</td>
<td>4.217</td>
<td>0.669</td>
</tr>
<tr>
<td>275</td>
<td>1000.0</td>
<td>1.652</td>
<td>4.211</td>
<td>0.574</td>
</tr>
<tr>
<td>280</td>
<td>999.5</td>
<td>1.422</td>
<td>4.198</td>
<td>0.582</td>
</tr>
<tr>
<td>285</td>
<td>999</td>
<td>1.225</td>
<td>4.189</td>
<td>0.590</td>
</tr>
<tr>
<td>290</td>
<td>998</td>
<td>1.080</td>
<td>4.183</td>
<td>0.598</td>
</tr>
<tr>
<td>295</td>
<td>997</td>
<td>0.959</td>
<td>4.181</td>
<td>0.606</td>
</tr>
<tr>
<td>300</td>
<td>996</td>
<td>0.855</td>
<td>4.179</td>
<td>0.613</td>
</tr>
<tr>
<td>305</td>
<td>995</td>
<td>0.769</td>
<td>4.178</td>
<td>0.620</td>
</tr>
<tr>
<td>310</td>
<td>993</td>
<td>0.695</td>
<td>4.178</td>
<td>0.628</td>
</tr>
<tr>
<td>315</td>
<td>991</td>
<td>0.631</td>
<td>4.179</td>
<td>0.634</td>
</tr>
<tr>
<td>320</td>
<td>989</td>
<td>0.577</td>
<td>4.180</td>
<td>0.640</td>
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<tr>
<td>325</td>
<td>987</td>
<td>0.528</td>
<td>4.182</td>
<td>0.645</td>
</tr>
<tr>
<td>330</td>
<td>984</td>
<td>0.489</td>
<td>4.184</td>
<td>0.650</td>
</tr>
<tr>
<td>335</td>
<td>982</td>
<td>0.453</td>
<td>4.186</td>
<td>0.655</td>
</tr>
<tr>
<td>340</td>
<td>979</td>
<td>0.420</td>
<td>4.188</td>
<td>0.660</td>
</tr>
<tr>
<td>345</td>
<td>976</td>
<td>0.389</td>
<td>4.191</td>
<td>0.665</td>
</tr>
<tr>
<td>350</td>
<td>974</td>
<td>0.365</td>
<td>4.195</td>
<td>0.668</td>
</tr>
<tr>
<td>355</td>
<td>971</td>
<td>0.343</td>
<td>4.199</td>
<td>0.671</td>
</tr>
<tr>
<td>360</td>
<td>967</td>
<td>0.324</td>
<td>4.203</td>
<td>0.674</td>
</tr>
<tr>
<td>365</td>
<td>963</td>
<td>0.306</td>
<td>4.209</td>
<td>0.677</td>
</tr>
<tr>
<td>370</td>
<td>961</td>
<td>0.289</td>
<td>4.214</td>
<td>0.679</td>
</tr>
<tr>
<td>373.15</td>
<td>958</td>
<td>0.279</td>
<td>4.217</td>
<td>0.680</td>
</tr>
</tbody>
</table>


### Table D-5  Thermal conductivity of metals

<table>
<thead>
<tr>
<th>Metal</th>
<th>273.15 K</th>
<th>273.15 °C</th>
<th>298 K</th>
<th>298 °C</th>
<th>373.15 K</th>
<th>373.15 °C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum</td>
<td>202.5</td>
<td>205.9</td>
<td>230.1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Brass (70-30)</td>
<td>96.9</td>
<td>103.8</td>
<td>114.2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cast iron</td>
<td>55.4</td>
<td>51.9</td>
<td>45.0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Copper</td>
<td>387.7</td>
<td>377.3</td>
<td>366.9</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lead</td>
<td>34.6</td>
<td>32.9</td>
<td>31.1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nickel</td>
<td>62.3</td>
<td>58.8</td>
<td>55.4</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Silver</td>
<td>418.8</td>
<td>411.9</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Steel (mild)</td>
<td>—</td>
<td>45.0</td>
<td>43.3</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tin</td>
<td>62.3</td>
<td>58.8</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wrought iron</td>
<td>—</td>
<td>55.4</td>
<td>48.5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Zinc</td>
<td>112.5</td>
<td>110.8</td>
<td>102.1</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
1. (a) "When both operate at the same temperature, a CSTR will have to be significantly larger than a PFR to effect the same composition change in a given amount of fluid. However, by using a battery of stirred tanks in series, differences in total volume requirements can be significantly reduced" – Would you agree with the statement? Explain your answer with the help of a rate vs. reactant concentration plot.

(b) What are recycle reactors? Find the expression that relates "overall conversion" to "conversion per pass" for recycle reactors. Also find the expression for the volume of recycle reactors in terms of known quantities (e.g. feed molar flow, conversion etc.).

2. (a) What are the steps that occur during heterogeneous catalytic reactions? In order to find the intrinsic kinetics, how would you design your experiments to make sure that you do not have bulk or pore diffusion limitations?

(b) Explain the effect of temperature on amount adsorbed for simultaneous physical adsorption and activated chemisorption.

(c) The dehydrogenation of methylcyclohexane (M) to produce toluene (T) was carried out over a 0.3% Pt/Al₂O₃ catalyst in a differential catalytic reactor. The reaction is carried out in presence of hydrogen (H₂) to avoid coking. Interpret the data in the table below and suggest which of the following rate laws are most likely to fit the experimental data.

\[ \text{(i) } -r_M' = kP_M^\alpha P_{H_2}^\beta \]
\[ \text{(ii) } -r_M' = \frac{kP_M}{1 + K_M P_M} \]
\[ \text{(iii) } -r_M' = \frac{kP_M P_{H_2}}{(1 + K_M P_M)^2} \]
\[ \text{(iv) } -r_M' = \frac{kP_M P_{H_2}}{1 + K_M P_M + K_{H_2} P_{H_2}} \]
Data for dehydrogenation of methylcyclohexane

<table>
<thead>
<tr>
<th>P_H2 (atm)</th>
<th>P_M (atm)</th>
<th>r_T (mol toluene s.kg cat)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>1.2</td>
</tr>
<tr>
<td>1.5</td>
<td>1</td>
<td>1.25</td>
</tr>
<tr>
<td>0.5</td>
<td>1</td>
<td>1.30</td>
</tr>
<tr>
<td>0.5</td>
<td>0.5</td>
<td>1.1</td>
</tr>
<tr>
<td>1</td>
<td>0.25</td>
<td>0.92</td>
</tr>
<tr>
<td>0.5</td>
<td>0.1</td>
<td>0.64</td>
</tr>
<tr>
<td>3</td>
<td>3</td>
<td>1.27</td>
</tr>
<tr>
<td>1</td>
<td>4</td>
<td>1.28</td>
</tr>
<tr>
<td>3</td>
<td>2</td>
<td>1.25</td>
</tr>
<tr>
<td>4</td>
<td>1</td>
<td>1.30</td>
</tr>
<tr>
<td>0.5</td>
<td>0.25</td>
<td>0.94</td>
</tr>
<tr>
<td>2</td>
<td>0.05</td>
<td>0.41</td>
</tr>
</tbody>
</table>

3. (a) List the disadvantages of a fixed bed reactor. Out of these disadvantages which one do you think is of the highest concern? Explain.

(b) How can we differentiate between ordinary and Knudsen diffusion? What are combined and effective diffusivities?

(c) The square of Thiele modulus for first-order reaction in a straight cylindrical catalyst pore can be written as:

$$h_T^2 = \frac{(2\pi T_{\bar{L}})k}{\pi \bar{r}^2 [D_c (C_o - 0)/L]}$$

How would you interpret this expression? Using this equation would you be able to deduce the relationship between effectiveness factor and Thiele modulus? If yes, how?

4. The rate expression for the reaction of carbonyl sulphide (A) with 2-amino-2-methyl-1-propanol (B) in isopropanol solution is $r = k(C_A)^1 (C_B)^2$. At 25 °C $k = 0.66 \text{ m}^6/(\text{kmol}^2\text{.s})$.

The stoichiometry is $A + 2B \rightarrow C + D$.

(a) If the reaction is carried out at 25 °C in a CSTR under conditions such that stoichiometric quantities of reactants are employed, the feed concentration of the carbonyl sulphide is 1.2 mol/L, and the feed flow rate is 8.0 m$^3$/h, how large must be this reactor be to achieve 80% conversion?

(b) Find the reactor volume requirements for plug flow reactors operating at 25 °C, all other factors remaining the same.
There are **FOUR** questions in this section. Answer any **THREE**.

Symbols/notations indicate their usual meanings.

Assume reasonable value if any additional data is required.

5. (a) Explain the mechanisms how the temperature and pressure of a multiphase reactive system can affect the global reaction rate.

(b) In the context of reaction-progress-monitoring and kinetic-study, discuss the application and importance of: (i) In situ FT-IR, (ii) Reaction Calorimetry.

(c) The half-life of a limiting reactant with respect to its initial concentration is given as follows:

<table>
<thead>
<tr>
<th>Half-life (sec)</th>
<th>Initial concentration (mol/m$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>860</td>
<td>82.5</td>
</tr>
<tr>
<td>470</td>
<td>139</td>
</tr>
<tr>
<td>255</td>
<td>296</td>
</tr>
<tr>
<td>212</td>
<td>360</td>
</tr>
</tbody>
</table>

Deriving appropriate equation, determine reaction-order from the supplied data.

6. (a) What are the crucial criteria with which a proposed reaction mechanism must be consistent? Explain with example.

(b) State the fundamental differences between elementary and overall reactions.

(c) Describe the principle of two methods which can be employed for the determination of reaction mechanism experimentally.

(d) Derive the overall rate expression form the followings:

\[
\text{Overall reaction:} \quad 2 \text{N}_2\text{O}_5 \rightarrow \text{O}_2 + 4 \text{NO}_2
\]

\[
\text{Mechanism:} \quad \text{N}_2\text{O}_5 \xrightleftharpoons[k_2]{k_1} \text{NO}_2 + \text{NO}_3
\]

\[
\text{NO}_3 + \text{NO}_2 \xrightarrow[k_3]{k_2} \text{NO} + \text{O}_2 + \text{NO}_2 \text{ (slow)}
\]

\[
\text{NO} + \text{NO}_3 \xrightarrow[k_4]{k_2} 2 \text{NO}_2
\]

7. (a) Demonstrate the determination of forward and reverse reaction rate constants for the first order rapid reversible reaction given below. [Hint: Use relaxation technique and more if required].

\[
A \xrightleftharpoons[k_r]{k_f} B
\]
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Contd... Q. No. 7

(b) \[ \text{A} \xrightarrow{k_1} \text{B} \xrightarrow{k_2} \text{C} \xrightarrow{k_3} \text{D} \]

Show graphically the concentration profiles of A and B for the series reaction presented above when -

(i) \( k_2 = 0.5 \, k_1 \) and \( B_0 = 0.5 \, A_0 \)
(ii) \( k_2 = 2 \, k_1 \) and \( B_0 = 0.5 \, A_0 \)

(c) A coupled enzyme assay system may be represented as

\[ \text{A} \xrightarrow{k_1} \text{B} \xrightarrow{k_2} \text{C} \]

The reactions are irreversible and no B is present initially. How long does it take to reach 98% of the steady-state value if \( k_1 = 0.833 \, \text{mol/m}^3 \cdot \text{sec} \) and \( k_2 = 0.767 \, \text{sec}^{-1} \)? What is the steady-state value?

8. (a) Write down the differential equations for the following cases: (3+3=6)

(i) Reversible first order parallel reaction
(ii) Competitive parallel reaction
(b) State precisely five fundamental guidelines which can certainly used in postulating a mechanism from reaction stoichiometry. (1.5x5=7.5)
(c) Present and explain the general classification of the techniques which are used for the interpretation of reaction rate data.

(d) \[ \text{A} + \text{B} \xrightarrow{k_1 \text{94\%}} \text{C} \]
\[ \text{A} + \text{B} \xrightarrow{k_2 \text{6\%}} \text{D} \]

A and B are initially present in an equal amount. The change in concentration with time for A can be represented by the data given below.

<table>
<thead>
<tr>
<th>Time, ( t ) (k sec)</th>
<th>A (k mol/m(^3))</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0</td>
<td>0.181</td>
</tr>
<tr>
<td>21.6</td>
<td>0.131</td>
</tr>
<tr>
<td>37.8</td>
<td>0.111</td>
</tr>
<tr>
<td>86.4</td>
<td>0.0683</td>
</tr>
<tr>
<td>99.0</td>
<td>0.0644</td>
</tr>
<tr>
<td>108.0</td>
<td>0.0603</td>
</tr>
</tbody>
</table>

Determine the values of rate constants, \( k_1 \) and \( k_2 \).
N_A \frac{dX}{dt} = -r_A V

V = \frac{F_{AO} X}{-r_A}

F_{AO} \frac{dX}{dV} = -r_A

F_{AO} \frac{dX}{dW} = -r_A'

C_A = \frac{F_A}{u} = \frac{F_{AO} (1-X)}{u_0 (1+\varepsilon X)} T_0 \frac{P}{P_0} = C_{A0} \frac{(1-X)}{(1+\varepsilon X)} T_0 \frac{P}{P_0}

C_B = \frac{F_B}{u} = \frac{F_{AO} \left( \Theta_B - \frac{b}{a} X \right)}{u_0 (1+\varepsilon X)} T_0 \frac{P}{P_0} = C_{A0} \frac{\left( \Theta_B - \frac{b}{a} X \right)}{(1+\varepsilon X)} T_0 \frac{P}{P_0}

C_0 = \frac{F_{10}}{C_{A0} u_0} = \frac{C_{10}}{C_{A0}} = \frac{Y_{10}}{Y_{A0}}

\delta = \frac{d}{a} + \frac{c}{a} - \frac{b}{a} - 1

\frac{dP}{dz} = -\frac{G}{\rho_0 g_c D_p} \left( \frac{1-\phi}{\phi^3} \right) \left[ \frac{150 (1-\phi) \mu}{D_p} + 1.75 G \right] T_0 \frac{P}{P_0} \frac{T}{T_0} \frac{F_T}{F_{T0}}

\beta_0 = \frac{G}{\rho_0 g_c D_p} \left( \frac{1-\phi}{\phi^3} \right) \left[ \frac{150 (1-\phi) \mu}{D_p} + 1.75 G \right]

W = Z_A c_p b = Z_A c_b (1-\phi) c_p

\frac{d(P/P_0)}{dW} = -\frac{\alpha}{2} \left( \frac{P}{P_0} \right)^T \frac{T}{T_0} (1+\varepsilon X)

\frac{dY}{dW} = -\frac{\alpha}{2 Y} (1+\varepsilon X)

k = k_1 \exp \left[ \frac{E}{R \left( \frac{1}{T_1} - \frac{1}{T} \right)} \right]
1. (a) Derive the general solution of nonlinear Ricatti Equation.

(b) Acetone can be removed from acetone air mixture by simple counter current cascades, by adsorption onto charcoal. We wish to find the required number of equilibrium stages to reduce a gas stream carrying 0.222 kg acetone per kg air to 0.0202 kg acetone per kg air. Clean charcoal ($X_0 = 0$) enters the system at 2.5 kg/sec. and air rate is constant at 3.5 kg/sec. Equilibrium between the solid and gas can be taken to obey the Langmuir-type relationship

\[ Y_n = \frac{KX_n}{1 + KX_n}; \quad K = 0.5 \]

where $Y_n = \text{kg acetone} / \text{kg air}$

$X_n = \text{kg acetone} / \text{kg charcoal}$.

Arrange the material balance between the first stage and $n^{th}$ stage so that, Ricatti equation arises. Find the values of $A$, $B$ and $C$. When $A$, $B$, $C$ has the usual meaning.

2. (a) Schematic view of a counter current liquid-liquid heat exchanger is shown below

The heat exchanger can be modeled by the following equations:

- **Hot stream heat balance:** $q = m_h \cdot C_{ph} (T_{2h} - T_{1h})$
- **Cold stream heat balance:** $q = m_c \cdot C_{pc} (T_{2c} - T_{1c})$

Heat capacity are given by:

\[ C_{ph} = a_1 + b_1 \cdot T_h + c_1 \cdot (T_h^2) \]

\[ C_{pc} = a_2 + b_2 \cdot T_c + c_2 \cdot (T_c^2) \]

Where, $T_h = (T_{1h} + T_{2h})/2$ and $T_c = (T_{1c} + T_{2c})/2$

$a_1 = 5.05$, $b_1 = 1.7 \times 10^{-2}$, $c_1 = 6.0 \times 10^{-6}$

$a_2 = 7.70$, $b_2 = 4.6 \times 10^{-4}$, $c_2 = 2.5 \times 10^{-6}$
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Contd ... Q. No. 2

Develop the model. Rearrange the model equation into single variable form. Write the Jacobian matrix of single variable form model.

(b) Compare the merits and demerits of different types of chemical engineering models. (5)

(c) Describe the advantages of hierarchical structure of model development. (10)

3. (a) Using the Newton interpolation formula, derive the Euler method. (20)

(b) Show that Backward Euler Method is always stable. (15)

4. (a) Discuss the different step size control method for numerical integration method. (15)

(b) Benzene (1), Toluene (2), Styrene (3) and Xylene (4) are to be separated in a sequence of distillation column shown in Figure

Write the material balance equation. Solve using Gauss-Seidel method.
5. (a) Write down the necessary and sufficient conditions for a local minimum. (6)
(b) Using the Lagrangian function, write the QP problem. (5)
(c) Assume that you are in 1980 and you are assigned to optimise a nonlinear chemical process. Which nonlinear optimization method would you use? State the reasons for your choice. (12)
(d) Solve the following problem using Lagrange multipliers,

\[
\begin{align*}
\text{Minimize: } & \quad x_1^2 - x_2^2 \\
\text{Subject to: } & \quad x_1^2 + x_2^2 = 4
\end{align*}
\]

6. (a) What do you understand by sensitivity analysis in optimization? Discuss sensitivity analysis in optimization using an example. (7)
(b) Solve the following problem:

Maximize: \[ f = 7x_1 + 12x_2 + 3x_3 \]
\[
\begin{align*}
2x_1 + 2x_2 + x_3 & \leq 16 \\
4x_1 + 8x_2 + x_3 & \leq 40 \\
x_1, x_2, x_3 & \geq 0
\end{align*}
\]

7. (a) Discuss the advantages of duality formation in Linear Programming. (7)
(b) You are given the following LP equation sets:

\[
\begin{align*}
3x_1 - x_2 + x_3 & = -6 \\
4x_1 - 3x_2 + x_4 & = -4 \\
x_1 + 3x_2 + f & = 0
\end{align*}
\]

Discuss why is this formulation problematic.
\[
\begin{align*}
x_1 - 2x_2 + x_3 & = 7 \\
x_1 - 3x_2 + x_4 & = 4 \\
x_1 + 3x_2 + f & = 0
\end{align*}
\]

Is the problem that leads to the preceding formation solvable? How do you interpret this problem geometrically?

\[
\begin{align*}
4x_1 + 2x_2 + x_3 & = 6 \\
6x_1 + 3x_2 + x_4 & = 9 \\
x_1 + 3x_2 + f & = 0
\end{align*}
\]

Apply the simplex rules to minimize \( f \) for the formation. Is the solution unique?
8. (a) What is concavity and convexity of a function? Discuss the differences between concavity and convexity. (10)

(b) Discuss the essential features of optimization problems. (10)

(c) Determine the convexity or concavity of the following objective functions: (15)

(i) \( f(x_1, x_2) = (x_1 - x_2)^2 + x_2^2 \)

(ii) \( f(x_1, x_2, x_3) = x_1^2 + x_2^2 + x_3^2 \)

(iii) \( f(x_1, x_2) = e^x + e^{x^2} \)
L-4/T-1/CHE

Date: 06/08/2016

BANGLADESH UNIVERSITY OF ENGINEERING AND TECHNOLOGY, DHAKA
Sub: CHE 453 (Transport Phenomena)

Full Marks: 210  Time: 3 Hours

The figures in the margin indicate full marks.

USE SEPARATE SCRIPTS FOR EACH SECTION

SECTION – A
There are FOUR questions in this Section. Answer any THREE questions.

1. (a) Liquefied gases are sometimes stored in well insulated spherical containers vented to the atmosphere. Derive an expression for steady state heat transfer rate through the walls of such a container; call the radii of the inner and outer walls \( r_0 \) and \( r_1 \), respectively. Let it be assumed that the temperatures \( T_0 \) and \( T_1 \) (at \( r = r_0 \) and \( r = r_1 \)) are known. Assume that the thermal conductivity of the insulation varies linearly with the temperature according to the relation.

\[
k = k_0 + (k_1 - k_0) \frac{T - T_0}{T_1 - T_0}
\]

(b) Given that in the above problem \( \dot{Q}_0 = 4\pi r_0 r_1 \left( \frac{k_0 + k_1}{2} \right) \left( \frac{T_1 - T_0}{r_1 - r_0} \right) \), estimate the rate of evaporation of liquid oxygen from a spherical container of 6 ft inside diameter covered with a 1 ft thick annular evacuated jacket filled with particular insulation. The following information is available:

- Temperature at inner surface of insulation: \(-183^\circ C\)
- Temperature at outer surface of insulation: \(0^\circ C\)
- Boiling point of \(O_2\): \(-183^\circ C\)
- Heat of vaporization of \(O_2\): \(1636 \text{ Cal/g-mol}\)
- Thermal conductivity of insulation at \(0^\circ C\): \(9.0 \times 10^{-4} \text{ Btu/hr.ft}^\circ F\)
- Thermal conductivity of insulation at \(-183^\circ C\): \(7.2 \times 10^{-4} \text{ Btu/hr.ft}^\circ F\)

Note: \(1 \text{ Btu/hr.ft}^\circ F = 4.136 \times 10^{-3} \text{ Cal/s.cm.K}\)

2. (a) Consider a catalytic reactor shown in Fig. for Q. 2, in which the dimerization reaction \(2A \rightarrow A_2\) is being carried out. Assume the reaction at the catalyst surface occurs instantaneously.

- (i) Find out the expression for concentration profile by shell mass balance.
- (ii) Obtain the expression for molar mass flux through the film.

Contd ............ P/2
(iii) Consider the above system when the reaction \(2A \rightarrow A_2\) is not instantaneous at the catalytic surface at \(z = \delta\) and assume that the rate at which \(A\) disappears at the surface is proportional to the concentration of \(A\) at that surface:

\[ N_{Az} = KC_A = CKx_A; \]

in which \(k\) is the rate constant.

3. (a) Derive \(\nabla \cdot v = \frac{1}{c} (R_A + R_B)\) for a binary mixture of \(A\) and \(B\) in rectangular coordinates by means of a mass balance over a stationary volume element \(\Delta x \Delta y \Delta z\). The symbols have their usual meanings.

(b) A viscous fluid with constant physical properties is in laminar flow in a circular tube of radius \(R\). For \(z < 0\), the fluid temperature is uniform at \(T_0\); and for \(z > 0\) there is a constant wall heat flux \(q_1\), which flows from outer surface of the pipe to the fluid inside the pipe. Obtain the partial differential equation of temperature by simplifying the equation of change. Write all the boundary conditions to solve the partial differential equation. State all necessary assumptions. Give a neat sketch of the system.

4. (a) Derive an expression for the temperature distribution \(T(x)\) in a viscous fluid in steady laminar flow between large flat parallel plates, as shown in Fig. for Q. 4(a). Both plates are maintained at constant temperature \(T_0\). Take into account explicitly the heat generated by viscous dissipation. Negative the temperature dependence of \(\mu\) and \(k\).

(b) A furnace wall comprises of three layers as shown in Fig. for Q. 4(b). The first layer is refractory brick while the second layer is insulating brick. The third layer is a steel plate of \(\frac{1}{4}\) in thick. Calculate the thickness of each layer of brick to give minimum total wall thickness if the heat loss through the wall is to be 5000 \(\frac{Btu}{hr. ft^2}\), assuming that the layers are in good thermal contact. The following information is available:

<table>
<thead>
<tr>
<th>Material</th>
<th>Maximum Service Temperature</th>
<th>Thermal Conductivity (Btu/hr.ft.°F)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>at 100°F</td>
</tr>
<tr>
<td>Refractory brick</td>
<td>2600°F</td>
<td>1.8</td>
</tr>
<tr>
<td>Insulating Brick</td>
<td>2000°F</td>
<td>0.9</td>
</tr>
<tr>
<td>Steel</td>
<td>-</td>
<td>26.1</td>
</tr>
</tbody>
</table>

SECTION – B

There are FOUR questions in this Section. Answer any THREE questions.

Symbols have their usual meanings.

5. (a) What are transport phenomena? How are they related? Why should transport phenomena be studied together?
CHE 453

Contd...Q.No.5

(b) How can you differentiate between Newtonian and non-Newtonian fluids? Show the relationship between shear stress and shear rate for Newtonian and non-Newtonian fluids, in a single plot.

(c) What differences are there between the flow in a circular tube of radius R and the flow in the same tube with a thin wire placed along the axis?

(d) Two immiscible liquids, A and B, are flowing in laminar flow between two parallel plates. Is it possible that the velocity profiles would be of the form shown in the Figure 5(d).

6. (a) By making a mass balance over a volume element $(\Delta r)(\Delta \theta)(\Delta z)$ derive the equation of continuity in cylindrical coordinates. Also show that the vector field of fluid velocities for incompressible fluids must be a divergenceless field.

(b) When riding on a boat in the river Sangu (46 metres above sea level), your portable barometer indicates a pressure of 756 mm Hg. Use the equation of motion to estimate the barometric pressure at the top of Keokradong peak (986 m above sea level). Assume that the temperature at the boat is 30°C and that the temperature decreases at a steady rate of 0.6°C per 100 m. The gravitational acceleration is about 9.81 m/s², and its variation with altitude may be neglected.

7. A semi-infinite body of liquid with constant density and viscosity is bounded below by a horizontal surface. Initially the fluid and the solid are at rest. Then at time $t = 0$, the solid surface is set in motion in the positive x direction with velocity $v_0$ as shown in Figure 7. Find the velocity $v_x$ as a function of $y$ and $t$. Clearly mention all your assumptions.

8. (a) Explain Taylor-Prandtl analogy for heat and momentum transport and show that

$$st_n = \frac{1}{2} \frac{C_f}{1 + \frac{U}{U_m} (P_r - 1)}$$

Extend the analogy for mass transfer in turbulent flow and find the Taylor-Prandtl analogy for mass transfer.

(b) What do you understand by Reynolds decomposition? Why do you need to treat turbulent flow using Reynolds decomposition?

(c) Time-smoothed equation a motion can be written as:

$$\frac{\delta}{\delta t} \rho \vec{v} = -\nabla P - [\nabla, \rho \vec{v}] - \nabla \left[ \left( \tau^{(v)} + \tau^{(b)} \right) \right] + \rho g$$

Write down the physical significances of all the terms in that equation.
Spheres with coating of catalytic material

Edge of hypothetical stagnant gas film

Catalytic surface where $2A \rightarrow B$ irreversibly and instantaneously

Fig. for q. 2

Fig. for q. 4(a)  Fig. for q. 4(b)
$t < 0$
Fluid at rest

$t = 0$
Wall set in motion

$t > 0$
Fluid in unsteady flow

Figure for Question No. 7
Newton's Law of Viscosity

\[
\tau = -\mu(\nabla \mathbf{v} + (\nabla \mathbf{v})^\top) + (\frac{4}{3} \mu - \kappa)(\nabla \cdot \mathbf{v}) \mathbf{6}
\]

Cartesian coordinates \((x, y, z)\):

\[
\begin{align*}
\tau_{xx} &= -\mu \left( 2 \frac{\partial v_x}{\partial x} + \left( \frac{4}{3} \mu - \kappa \right) \nabla \cdot \mathbf{v} \right) \tag{B.1-1} \\
\tau_{yy} &= -\mu \left( 2 \frac{\partial v_y}{\partial y} + \left( \frac{4}{3} \mu - \kappa \right) \nabla \cdot \mathbf{v} \right) \tag{B.1-2} \\
\tau_{zz} &= -\mu \left( 2 \frac{\partial v_z}{\partial z} + \left( \frac{4}{3} \mu - \kappa \right) \nabla \cdot \mathbf{v} \right) \tag{B.1-3} \\
\tau_{xy} &= \tau_{yx} = -\mu \left( \frac{\partial v_y}{\partial x} + \frac{\partial v_x}{\partial y} \right) \tag{B.1-4} \\
\tau_{xz} &= \tau_{zx} = -\mu \left( \frac{\partial v_z}{\partial x} + \frac{\partial v_x}{\partial z} \right) \tag{B.1-5} \\
\tau_{yz} &= \tau_{zy} = -\mu \left( \frac{\partial v_z}{\partial y} + \frac{\partial v_y}{\partial z} \right) \tag{B.1-6}
\end{align*}
\]

in which

\[
(\nabla \cdot \mathbf{v}) = \frac{\partial v_x}{\partial x} + \frac{\partial v_y}{\partial y} + \frac{\partial v_z}{\partial z}
\]

Equation of Continuity

\[
[\frac{\partial \rho}{\partial t} + (\nabla \cdot \mathbf{v}) \rho = 0]
\]

Cartesian coordinates \((x, y, z)\):

\[
\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x} (\rho v_x) + \frac{\partial}{\partial y} (\rho v_y) + \frac{\partial}{\partial z} (\rho v_z) = 0
\]

Cylindrical coordinates \((r, \theta, z)\):

\[
\frac{\partial \rho}{\partial t} + \frac{1}{r} \frac{\partial}{\partial r} (r \rho v_r) + \frac{1}{r} \frac{\partial}{\partial \theta} (\rho v_\theta) + \frac{\partial}{\partial z} (\rho v_z) = 0
\]

Spherical coordinates \((r, \theta, \phi)\):

\[
\frac{\partial \rho}{\partial t} + \frac{1}{r^2} \frac{\partial}{\partial r} (r^2 \rho v_r) + \frac{1}{r \sin \theta} \frac{\partial}{\partial \theta} (\rho v_\theta \sin \theta) + \frac{1}{r \sin \theta} \frac{\partial}{\partial \phi} (\rho v_\phi) = 0
\]

* When the fluid is assumed to have constant mass density \(\rho\), the equation simplifies to \((\nabla \cdot \mathbf{v}) = 0\).
Equation of motion in terms of $\tau$

$$[pDv/ Dt = -\nabla P - [V \cdot \tau] + pg]$$

**Cartesian coordinates (x, y, z):**

$$\rho \left( \frac{\partial v_x}{\partial t} + v_x \frac{\partial v_x}{\partial x} + v_y \frac{\partial v_x}{\partial y} + v_z \frac{\partial v_x}{\partial z} - \frac{v_x^2}{r} \right) = \frac{\partial p}{\partial x} - \frac{1}{r} \frac{\partial}{\partial r} \left( r \frac{\partial (\tau_{xx})}{\partial r} + \frac{\partial (\tau_{xy})}{\partial \theta} + \frac{\partial (\tau_{xz})}{\partial \phi} \right) + \rho g_x \quad (B.5-1)$$

$$\rho \left( \frac{\partial v_y}{\partial t} + v_x \frac{\partial v_y}{\partial x} + v_y \frac{\partial v_y}{\partial y} + v_z \frac{\partial v_y}{\partial z} - \frac{v_y^2}{r} \right) = \frac{\partial p}{\partial y} - \frac{1}{r} \frac{\partial}{\partial r} \left( r \frac{\partial (\tau_{yx})}{\partial r} + \frac{\partial (\tau_{yy})}{\partial \theta} + \frac{\partial (\tau_{yz})}{\partial \phi} \right) + \rho g_y \quad (B.5-2)$$

$$\rho \left( \frac{\partial v_z}{\partial t} + v_x \frac{\partial v_z}{\partial x} + v_y \frac{\partial v_z}{\partial y} + v_z \frac{\partial v_z}{\partial z} - \frac{v_z^2}{r} \right) = \frac{\partial p}{\partial z} - \frac{1}{r} \frac{\partial}{\partial r} \left( r \frac{\partial (\tau_{zx})}{\partial r} + \frac{\partial (\tau_{zy})}{\partial \theta} + \frac{\partial (\tau_{zz})}{\partial \phi} \right) + \rho g_z \quad (B.5-3)$$

* These equations have been written without making the assumption that $\tau$ is symmetric. This means, for example, that when the usual assumption is made that the stress tensor is symmetric, $\tau_{xy} = \tau_{yx}$, may be interchanged.

**Cylindrical coordinates (r, $\theta$, z):**

$$\rho \left( \frac{\partial v_r}{\partial t} + v_r \frac{\partial v_r}{\partial r} + \frac{v_\theta v_r}{r} + \frac{v_z v_r}{r} - \frac{v_r^2}{r} \right) = \frac{\partial p}{\partial r} - \frac{1}{r} \frac{\partial}{\partial \theta} \left( \frac{\partial (\tau_{rr})}{\partial \theta} + \frac{\partial (\tau_{r\theta})}{\partial \phi} \right) + \rho g_r \quad (B.5-4)$$

$$\rho \left( \frac{\partial v_\theta}{\partial t} + v_r \frac{\partial v_\theta}{\partial r} + \frac{v_\theta v_r}{r} + \frac{v_z v_\theta}{r} - \frac{v_\theta^2}{r} \right) = \frac{\partial p}{\partial \theta} - \frac{1}{r} \frac{\partial}{\partial \theta} \left( \frac{\partial (\tau_{r\theta})}{\partial r} + \frac{\partial (\tau_{\theta\theta})}{\partial \phi} \right) + \rho g_\theta \quad (B.5-5)$$

$$\rho \left( \frac{\partial v_z}{\partial t} + v_r \frac{\partial v_z}{\partial r} + \frac{v_\theta v_z}{r} + \frac{v_z v_z}{r} - \frac{v_z^2}{r} \right) = \frac{\partial p}{\partial z} - \frac{1}{r} \frac{\partial}{\partial \theta} \left( \frac{\partial (\tau_{\phi\theta})}{\partial r} + \frac{\partial (\tau_{\phi\phi})}{\partial \phi} \right) + \rho g_z \quad (B.5-6)$$

* These equations have been written without making the assumption that $\tau$ is symmetric. This means, for example, that when the usual assumption is made that the stress tensor is symmetric, $\tau_{r\theta} = \tau_{\theta r}$, $\tau_{\theta\phi} = \tau_{\phi\theta}$, $\tau_{\phi z} = \tau_{z\phi}$, and $\tau_{z\theta} = \tau_{\theta z}$ may be interchanged.

**Spherical coordinates (r, $\theta$, $\phi$):**

$$\rho \left( \frac{\partial v_r}{\partial t} + v_r \frac{\partial v_r}{\partial r} + \frac{v_\theta v_r}{r} + \frac{v_\phi v_r}{r \sin \theta} - \frac{v_r^2}{r} \right) = \frac{\partial p}{\partial r} - \frac{1}{r} \frac{\partial}{\partial \theta} \left( \frac{\partial (\tau_{rr})}{\partial \theta} + \frac{\partial (\tau_{r\theta})}{\partial \phi} \right) + \rho g_r \quad (B.5-7)$$

$$\rho \left( \frac{\partial v_\theta}{\partial t} + v_r \frac{\partial v_\theta}{\partial r} + \frac{v_\theta v_\theta}{r} + \frac{v_\phi v_\theta}{r \sin \theta} - \frac{v_\theta^2}{r} \right) = \frac{\partial p}{\partial \theta} - \frac{1}{r} \frac{\partial}{\partial \theta} \left( \frac{\partial (\tau_{\theta\theta})}{\partial r} + \frac{\partial (\tau_{\theta\phi})}{\partial \phi} \right) + \rho g_\theta \quad (B.5-8)$$

$$\rho \left( \frac{\partial v_\phi}{\partial t} + v_r \frac{\partial v_\phi}{\partial r} + \frac{v_\theta v_\phi}{r} + \frac{v_\phi v_\phi}{r \sin \theta} - \frac{v_\phi^2}{r} \right) = \frac{\partial p}{\partial \phi} - \frac{1}{r} \frac{\partial}{\partial \theta} \left( \frac{\partial (\tau_{\phi\phi})}{\partial r} + \frac{\partial (\tau_{\phi\theta})}{\partial \theta} \right) + \rho g_\phi \quad (B.5-9)$$

* These equations have been written without making the assumption that $\tau$ is symmetric. This means, for example, that when the usual assumption is made that the stress tensor is symmetric, $\tau_{r\theta} = \tau_{\theta r}$, $\tau_{\theta\phi} = \tau_{\phi\theta}$, $\tau_{\phi z} = \tau_{z\phi}$, and $\tau_{z\theta} = \tau_{\theta z}$ may be interchanged.
Equation of motion for a Newtonian Fluid with constant $\rho$ and $\mu$

$$\rho \frac{D\mathbf{v}}{Dt} = -\nabla \rho + \mu \nabla^2 \mathbf{v} + \rho g \mathbf{g}$$

Cartesian coordinates $(x, y, z)$:

$$\rho \left( \frac{\partial v_x}{\partial t} + v_x \frac{\partial v_x}{\partial x} + v_y \frac{\partial v_x}{\partial y} + v_z \frac{\partial v_x}{\partial z} \right) = -\frac{\partial \rho}{\partial x} + \mu \left[ \frac{\partial^2 v_x}{\partial x^2} + \frac{\partial^2 v_x}{\partial y^2} + \frac{\partial^2 v_x}{\partial z^2} \right] + \rho g_x \quad (B.6-1)$$

$$\rho \left( \frac{\partial v_y}{\partial t} + v_x \frac{\partial v_y}{\partial x} + v_y \frac{\partial v_y}{\partial y} + v_z \frac{\partial v_y}{\partial z} \right) = -\frac{\partial \rho}{\partial y} + \mu \left[ \frac{\partial^2 v_y}{\partial x^2} + \frac{\partial^2 v_y}{\partial y^2} + \frac{\partial^2 v_y}{\partial z^2} \right] + \rho g_y \quad (B.6-2)$$

$$\rho \left( \frac{\partial v_z}{\partial t} + v_x \frac{\partial v_z}{\partial x} + v_y \frac{\partial v_z}{\partial y} + v_z \frac{\partial v_z}{\partial z} \right) = -\frac{\partial \rho}{\partial z} + \mu \left[ \frac{\partial^2 v_z}{\partial x^2} + \frac{\partial^2 v_z}{\partial y^2} + \frac{\partial^2 v_z}{\partial z^2} \right] + \rho g_z \quad (B.6-3)$$

Cylindrical coordinates $(r, \theta, z)$:

$$\rho \left( \frac{\partial v_r}{\partial t} + v_r \frac{\partial v_r}{\partial r} + \frac{v_\theta}{r} \frac{\partial v_r}{\partial \theta} + v_z \frac{\partial v_r}{\partial z} \right) = -\frac{\partial \rho}{\partial r} + \mu \left[ \frac{1}{r^2} \frac{\partial^2 v_r}{\partial \theta^2} + \frac{\partial^2 v_r}{\partial r^2} + \frac{1}{r^2} \frac{\partial^2 v_r}{\partial r \partial \theta} \right] + \rho g_r \quad (B.6-4)$$

$$\rho \left( \frac{\partial v_\theta}{\partial t} + v_r \frac{\partial v_\theta}{\partial r} + \frac{v_\theta}{r} \frac{\partial v_\theta}{\partial \theta} + v_z \frac{\partial v_\theta}{\partial z} \right) = -\frac{\partial \rho}{r \partial \theta} + \mu \left[ \frac{1}{r} \frac{\partial}{\partial r} \left( \frac{1}{r} \frac{\partial v_\theta}{\partial r} \right) + \frac{1}{r^2} \frac{\partial^2 v_\theta}{\partial \theta^2} + \frac{1}{r^2} \frac{\partial^2 v_\theta}{\partial r \partial \theta} + \frac{2}{r} \frac{\partial v_\theta}{\partial \theta} \right] + \rho g_\theta \quad (B.6-5)$$

$$\rho \left( \frac{\partial v_z}{\partial t} + v_r \frac{\partial v_z}{\partial r} + \frac{v_\theta}{r} \frac{\partial v_z}{\partial \theta} + v_z \frac{\partial v_z}{\partial z} \right) = -\frac{\partial \rho}{\partial z} + \mu \left[ \frac{1}{r^2} \frac{\partial^2 v_z}{\partial \theta^2} + \frac{\partial^2 v_z}{\partial z^2} + \frac{2}{r} \frac{\partial v_z}{\partial \theta} \right] + \rho g_z \quad (B.6-6)$$

Spherical coordinates $(r, \theta, \phi)$:

$$\rho \left( \frac{\partial v_r}{\partial t} + v_r \frac{\partial v_r}{\partial r} + \frac{v_\theta}{r} \frac{\partial v_r}{\partial \theta} + \frac{v_\phi}{r \sin \theta} \frac{\partial v_r}{\partial \phi} - \frac{\partial \rho}{\partial r} - \mu \left[ \frac{\partial^2 v_r}{\partial r^2} + \frac{1}{r^2} \frac{\partial^2 v_r}{\partial \theta^2} + \frac{\partial^2 v_r}{\partial \phi^2} \right] \right) + \rho g_r \quad (B.6-7')$$

$$\rho \left( \frac{\partial v_\theta}{\partial t} + v_r \frac{\partial v_\theta}{\partial r} + \frac{v_\theta}{r} \frac{\partial v_\theta}{\partial \theta} + \frac{v_\phi}{r \sin \theta} \frac{\partial v_\theta}{\partial \phi} - \frac{\partial \rho}{r \partial \theta} - \mu \left[ \frac{1}{r^2} \frac{\partial^2 v_\theta}{\partial \theta^2} + \frac{1}{r^2} \frac{\partial^2 v_\theta}{\partial \phi^2} + \frac{2}{r} \frac{\partial v_\theta}{\partial \phi} \right] \right) + \rho g_\theta \quad (B.6-8)$$

$$\rho \left( \frac{\partial v_\phi}{\partial t} + v_r \frac{\partial v_\phi}{\partial r} + \frac{v_\theta}{r} \frac{\partial v_\phi}{\partial \theta} + \frac{v_\phi}{r \sin \theta} \frac{\partial v_\phi}{\partial \phi} - \frac{\partial \rho}{r \sin \theta \partial \phi} - \mu \left[ \frac{1}{r^2} \frac{\partial^2 v_\phi}{\partial \phi^2} + \frac{2}{r^2} \frac{\partial^2 v_\phi}{\partial \phi \partial \theta} + \frac{2}{r^2} \frac{\partial v_\phi}{\partial \phi} \right] \right) + \rho g_\phi \quad (B.6-9)$$

* The quantity in the brackets in Eq. B.6.7 is not quite what one would expect from Eq. (M) for $(V \cdot V) \mathbf{v}$ in Table A.7-3, because we have added to Eq. (M) the expression for $(\mathbf{V} / r)(\mathbf{V} \cdot \mathbf{V})$, which is zero for fluids with constant $\rho$. This gives a much simpler equation.
The Equations of Motion for Nonisothermal Flow

The Equation of Energy in Terms of the Transport Properties

(Eq. 10.1-25 with viscous dissipation terms included)

Rectangular coordinates:

\[ \rho C_v \left( \frac{\partial T}{\partial t} + \mathbf{u} \cdot \nabla T + v \frac{\partial T}{\partial x} + w \frac{\partial T}{\partial y} + \frac{\partial T}{\partial z} \right) = k \left[ \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \right] + \rho \left( \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} \right) \nabla T \]

Cylindrical coordinates:

\[ \rho C_v \left( \frac{1}{r} \frac{\partial}{\partial r} \left( r \frac{\partial T}{\partial r} \right) + \frac{\partial T}{\partial \theta} + \frac{1}{r} \frac{\partial T}{\partial z} \right) = k \left[ \frac{1}{r^2} \frac{\partial}{\partial r} \left( r^2 \frac{\partial T}{\partial r} \right) + \frac{\partial^2 T}{\partial z^2} \right] + \rho \left( \frac{\partial u}{\partial r} + \frac{1}{r} \frac{\partial v}{\partial \theta} + \frac{\partial w}{\partial z} \right) \nabla T \]

Spherical coordinates:

\[ \rho C_v \left( \frac{1}{r^2} \frac{\partial}{\partial r} \left( r^2 \frac{\partial T}{\partial r} \right) + \frac{1}{r} \sin \theta \frac{\partial}{\partial \theta} \left( \sin \theta \frac{\partial T}{\partial \theta} \right) + \frac{1}{r \sin \theta} \frac{\partial T}{\partial \phi} \right) = k \left[ \frac{1}{r^2} \frac{\partial}{\partial r} \left( r^2 \frac{\partial T}{\partial r} \right) + \frac{\partial^2 T}{\partial \theta^2} + \frac{1}{\sin \theta} \frac{\partial}{\partial \phi} \left( \sin \theta \frac{\partial T}{\partial \phi} \right) \right] + \rho \left( \frac{\partial u}{\partial r} + \frac{1}{r} \frac{\partial v}{\partial \theta} + \frac{1}{r \sin \theta} \frac{\partial w}{\partial \phi} \right) \nabla T \]

Note: The terms contained in braces \( \{ \} \) are associated with viscous dissipation and may usually be neglected, except for systems with large velocity gradients.

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The Equations of Change for Nonisothermal Systems

**TABLE 10.2-3**

The Equation of Energy in Terms of Energy and Momentum Fluxes

(Eq. 10.1-19)

Rectangular coordinates:

\[ \rho C_v \left( \frac{\partial^2 T}{\partial t^2} + v \frac{\partial T}{\partial x} + w \frac{\partial T}{\partial y} + \frac{\partial T}{\partial z} \right) = \left[ \frac{\partial q_x}{\partial x} + \frac{\partial q_y}{\partial y} + \frac{\partial q_z}{\partial z} \right] \]

Cylindrical coordinates:

\[ \rho C_v \left( \frac{1}{r} \frac{\partial}{\partial r} \left( r \frac{\partial T}{\partial r} \right) + \frac{\partial T}{\partial \theta} + \frac{1}{r} \frac{\partial T}{\partial z} \right) = \left[ \frac{1}{r^2} \frac{\partial}{\partial r} \left( r^2 \frac{\partial T}{\partial r} \right) + \frac{\partial^2 T}{\partial \theta^2} + \frac{1}{\sin \theta} \frac{\partial}{\partial \phi} \left( \sin \theta \frac{\partial T}{\partial \phi} \right) \right] \]

Spherical coordinates:

\[ \rho C_v \left( \frac{1}{r^2} \frac{\partial}{\partial r} \left( r^2 \frac{\partial T}{\partial r} \right) + \frac{1}{r} \sin \theta \frac{\partial}{\partial \theta} \left( \sin \theta \frac{\partial T}{\partial \theta} \right) + \frac{1}{r \sin \theta} \frac{\partial T}{\partial \phi} \right) = \left[ \frac{1}{r^2} \frac{\partial}{\partial r} \left( r^2 \frac{\partial T}{\partial r} \right) + \frac{\partial^2 T}{\partial \theta^2} + \frac{1}{\sin \theta} \frac{\partial}{\partial \phi} \left( \sin \theta \frac{\partial T}{\partial \phi} \right) \right] \]

Note: The terms contained in braces \( \{ \} \) are associated with viscous dissipation and may usually be neglected, except for systems with large velocity gradients.