SECTION - A

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

1. (a) Discuss briefly how the concepts of other chemical engineering courses are related to chemical reaction engineering taking a gas-liquid-solid reactive system as an example.

(b) What are the different ways to define reaction rate? Define mathematically reaction rate in each different way. For each different way, write down the condition(s) at which it is normally used to define the reaction rate.

(c) How does an open sequence reaction differ from a chain reaction?

(d) Write down the kinetic parameters which are required to develop a reactor for a homogeneous reactive process.

(e) Write down the basic reaction rate equation in terms of concentration, order, and rate constant for the following cases:
   (i) Second-order reaction opposed by first-order reaction.
   (ii) Irreversible first-order simple parallel reactions.

2. (a) A reaction having very small conversion of limiting reagent (A) has the following overall rate expression:

   \[ r = \frac{k_1 c_A}{1 + k_1 + k_2 c_A} \]

Describe the determination of \( k_1 \) and \( k_2 \) briefly choosing a suitable method from the methods available for determining kinetic parameters.

(b) Dyashkovkii and Shilov studied the kinetics of the reaction between ethyl-lithium and ethyl-iodide in decalin solution.

\[ C_2H_5Li + C_2H_5I \rightarrow 2 C_2H_5 + LiI \]

The following data are typical of those observed by these authors at 20°C. They correspond to initial ethyl-lithium and ethyl-iodide concentrations of 2.0 and 1.0 kmoles/m³, respectively.

Contd ........... P/2
What rate expression is consistent with these data? What is the reaction rate constant at 20°C? You are allowed to make all the reasonable assumption(s) which are necessary to solve this problem.

3. (a) What do you understand by reaction mechanism? Write down five guidelines which are used in postulating a mechanism. What are the two crucial criteria with which a proposed mechanism must be consistent?

(b) The following mechanism has been proposed for the oxidation of nitric oxide to nitrogen di-oxide (NO + \( \frac{1}{2} \) O\(_2\) \( \rightarrow \) NO\(_2\)).

\[
\begin{align*}
NO + O_2 & \rightleftharpoons NO_3; \text{ equilibrium constant } K_c \\
NO_3 + NO & \rightleftharpoons NO_3 \cdot NO \\
NO_3 + NO & \rightleftharpoons 2NO_2 \\
NO + NO_3 \cdot NO & \rightleftharpoons 2NO_2 + NO \\
O_2 + NO_3 \cdot NO & \rightleftharpoons 2NO + 2O_2
\end{align*}
\]

Derive a rate expression that is consistent with this mechanism. Theacy and Daniels determined that the orders of the reaction with respect to oxygen and nitric oxide are one and two, respectively, at high pressures and less than one and greater than two at low pressures. Is the proposed mechanism consistent with this data?

4. (a) A consecutive first order reaction sequence is given below:

\[
A \underset{k_1}{\rightarrow} B \underset{k_2}{\rightarrow} F \underset{k_3}{\rightarrow} P
\]

(i) Derive expressions for the maximum concentration of B and the time at which the concentration of species B reaches at its maximum value.

(ii) Show graphically how the concentrations of A, B, and P change with time provided that \( k_2 = 2.25 \) \( k_1 \) and \( B_0 = 0.5 \) \( A_0 \). (There is no need to use separate graph paper)
(iii) Briefly discuss a method to determine the individual value of $k_1$ and $k_2$ for such a consecutive reaction.

(b) Write a short note on the relaxation technique which is used to study rapid reversible reaction.

SECTION – B

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

5. (a) Discuss the assumptions and limitations of Langmuir Adsorption Isotherm. The BET approach is essentially an extension of the Langmuir approach — Explain the statement.
(b) What do you understand by the term physical and chemical characterization of heterogeneous catalyst? Write a short note on components of industrial catalyst.
(c) Some investigators have studied the decomposition of ammonia over a headed platinum filament at $1000^\circ$C. The reaction stoichiometry is

$$2 \text{NH}_3 \rightarrow \text{N}_2 + 3 \text{H}_2$$

Initially, pure NH$_3$ was present in the reaction vessel. The data shown below are representative of the kinetics of the reaction. The reactor volume is constant.

<table>
<thead>
<tr>
<th>Time, t (sec)</th>
<th>Total pressure (kPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>26.7</td>
</tr>
<tr>
<td>60</td>
<td>34.1</td>
</tr>
<tr>
<td>240</td>
<td>38.5</td>
</tr>
<tr>
<td>720</td>
<td>42.7</td>
</tr>
</tbody>
</table>

It has been postulated that the rate expression for the reaction is of the form

$$r = k \frac{P_{\text{NH}_3}}{P_{\text{H}_2}}$$

Is the experimental data consistent with this rate expression? If so, what is the value of the rate constant? What type of Hougen-Watson model gives rise to this form for the rate expression?

6. (a) What is the set of information necessary to start reactor design?
(b) Discuss the advantages and disadvantages of Plug Flow and Stirred Tank reactors.
(c) Explain the graphical approach to the analysis of Batteries of Stirred Tank Reactors operating at steady state.
7. (a) Derive an expression for Recycle reactor.
(b) Two gaseous streams are available for use in carrying out a chemical reaction. The first contains pure A and is produced at a rate of 400 $ft^3/min$. The second contains 50% B (remainder is an inert material) and has a flow rate of 200 $ft^3/min$. These streams are mixed instantaneously and fed to a flow reactor. Both streams are at the same temperature (80°C) and pressure (1 atm) and these quantities remain unchanged during the instantaneous mixing process. The gases behave ideally. A and B react to form an addition product.

\[ A + B \rightarrow C \]

with \[ r_C = k C_A C_B \]

The reaction is carried out isothermally in two flow reactors (plug flow and stirred tank). Both reactors operate at a constant total pressure of 1 atm. If the reactor is a plug flow reactor with a volume of 600 $ft^3$ and 90% of the B is converted to C, determine
(i) The space velocity in the reactor
(ii) The effluent volumetric flow rate
(iii) The rate constant $k$
(iv) The average holding time in the reactor.

8. (a) Discuss the advantages and disadvantages of fixed bed reactor design models.
(b) Point out the problems encountered in deriving the equation applicable for calculation of effectiveness factors for non-isothermal catalyst pellets.
(c) Write short note on the followings:
   (i) Effectiveness factor and Effective diffusivity
   (ii) Knudsen diffusion and Combined diffusivity
   (iii) Global and Intrinsic reaction rates.
SECTION – A

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

1. (a) Describe the direct synthesis method of designing a PID controller for a second-order plus time delay (SOPTD) process.
   (b) An experiment has been performed to determine the steady-state power delivered by a gas turbine generator as a function of fuel flow rate. N data points for two variables fuel flow rate \( u \) and power output \( y \) have been recorded during the experiment. Describe the least square method to estimate a quadratic model of the form: \( y = \beta_0 + \beta_1 u + \beta_2 u^2 \).

2. (a) Describe the effect of pole locations in the s-plane on the stability of a system.
   (b) IMC controller tuning method does not work well for lag dominant processes. Suggest two methods for overcoming this limitation.
   (c) Describe combined feedback-feedforward control strategy for controlling the level of a boiler drum. Express such a control system using a general block diagram and find the expression of a dynamic feedforward controller using block diagram algebra.

3. (a) What is a DCS? Compare briefly DCS and PLC.
   (b) For Figure 3(b), find the closed loop response relation between \( Y \) and \( Y_{sp} \).

\[
\text{Fig. 3(b): Figure for Q 3(b)}
\]

For \( G_c^* = K_c \), \( G = \frac{2}{(2s + 1)(4s + 1)} \) and \( G = \frac{1}{(2s + 1)} \),

using Routh array, find the maximum values of \( K_c \) for which the system remains stable.

(c) Describe typical layers of safety protection used in modern plants.

Contd ............ P/2
4. (a) What is a Bode diagram? Describe the concept of gain margin and phase margin using Bode diagram. How gain margin and phase margin are useful in designing a controller. (15)

(b) Find the expressions for Amplitude ratio and phase lag of a PI controller. Sketch qualitatively these expressions as a function of frequency. (10)

(c) Write down five criteria for selecting a sensor. (5)

(d) What are the performance criteria for a closed loop control system? (5)

SECTION - B

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

5. Show that the step response of a second order underdamped process can be expressed as (20+15=35)

\[ y(t) = KM \left[ 1 - e^{-\frac{\zeta}{\tau} t} \left( \cos \left( \frac{\sqrt{1 - \zeta^2}}{\tau} t \right) + \frac{\zeta}{\sqrt{1 - \zeta^2}} \sin \left( \frac{\sqrt{1 - \zeta^2}}{\tau} t \right) \right) \right] \]

where the symbol carries their usual meaning. Also find the expression for Decay Ratio.

6. (a) Discuss the advantages and disadvantages of feedback and feedforward control loops. (10)

(b) A surge tank shown in the Figure 6(b) is designed so that the outflow rate, \( \omega_o \), is proportional to the liquid level to the 1.5 power, that is

\[ \omega_o = R h^{1.5} \]

where \( R \) is a constant. If a single stream enters the tank with flow rate \( \omega_i \), find the transfer function \( H'(s)/\omega_i(s) \). Identify the gain and time constant and show their units. The cross sectional area of the tank is \( A \), and density is constant.

7. (a) Explain the terms:

(i) Reset windup
(ii) Derivative kick
(iii) Bumpless transfer

Contd ............ P/3
(b) Show that, for a first order process, a time interval of $t$ (i.e., $t = \tau$) is required to complete 63.2% of the process response. Also determine the time needed to complete 99% of the response.

(c) Consider the following transfer function

$$G(s) = \frac{K(3 - s)e^{-2.5s}}{(12s + 1)(5.2s + 1)(0.2s + 1)(0.05s + 1)}$$

Use Skogestad's method to derive two approximate models:

(i) A first-order-plus-time-delay model

(ii) A second-order-plus-time-delay model in the form

$$\bar{G}(s) = \frac{Ke^{-\theta s}}{(\tau_1s + 1)(\tau_2s + 1)}$$

8. A MIMO mixing process is shown in the Figure.

The level, $h$ and the temperature, $T$ are to be controlled by manipulating mass flow rates $w_h$ and $w_c$. The temperatures of the inlet stream $T_h$ and $T_c$ are considered as disturbance variables. The outlet flow-rate $w$ can be assumed constant. Derive a state-space model of the system in terms of deviation variables.
SECTION – A
There are FOUR questions in this Section. Answer any THREE.

1. (a) Make a study estimate of the fixed capital investment for a process plant if the purchased-equipment cost is Taka one crore. Use the ranges of process-plant component cost outlined in given Table for a process plant handling both solids and fluids with a high degree of automatic controls and essentially outdoor operation. Do not include Land.

(b) If the above chemical process plant is erected in Mountain area for a fixed-capital investment as calculated in 1(a) in 1988, estimate the fixed-capital investment in 1999 for a similar process plant located in New England with three times the process capacity but with an equal number of process units. Use the power factor method (direct + indirect plant cost) to evaluate the new fixed-capital investment, and assume the factors given in supplied Table apply.

(c) The purchased cost of a 8 m$^2$ single atmospheric drum dryer was $12,000 in 1992. Estimate the purchased cost of a similar 10 m$^2$ dryer in 2000. Use the annual average "Chemical Engineering Plant Cost Index" to update the purchase cost of the dryer.

2. (a) A process for making a single product involves reacting two liquids in a continuously agitated reactor and distilling the resulting mixture. Unused reactants are recovered as overhead and are recycled. The product is obtained in sufficiently pure form as bottoms from the distillation tower.

(i) Prepare a qualitative flowsheet for the process showing all pieces of equipment.

(ii) Tabulate the information needed concerning chemicals and the process, in order to design the agitated reactor.

(b) Write briefly on (i) Control of exposure hazards (ii) Patent search, and, (iii) Safety factor in equipment sizing.
3. A process flowsheet diagram is supplied. In it, (H) denotes a heat exchanger where the stream temperature is increased and (C), where stream temperature is lowered. Since the reboiler temperature is too high for heat exchange with any of the process streams, it becomes an independent heat exchange problem. A hot oil utility stream available at 320°C and cooled to 310°C is to be used for heating the reboiler, as well as any process heating loads not met by process-process exchange. The cost of the hot oil is $2.25/GJ. The condenser temperature is in a range that could be used to heat some of the process stream; however, for brevity purpose it will not be included in the present analysis. The cooling utility is cooling water available at 10°C with an allowable temperature rise of 10°C and a cost of $0.25/GJ.

For your convenience the "Initial Temperature Interval Table" and "Composite diagram with 33°C approach temperature" are provided. Using the above mentioned Table and Figure as the starting point for your solution.

(a) Construct the revised temperature interval table.  
(b) Reconstruct the composite diagram to achieve a ΔT_{min} of 20°C.  
(c) Construct the balanced composite diagram for the process with a ΔT_{min} of 20°C, and find the minimum utility duties and the annual cost for the utilities after the heat integration.  
(d) Compare the cost with case where only hot and cold utilities are used.

4. Air must be cooled from 120°C to 80°C. Cooling water is available at 50°C. It is advised to use a floating heat Shell and Tube heat exchanger for this operation. Determine the tube length, number of tubes and installed cost for the optimum exchanger which will handle 9000 kg air/hr. Use data from the supplied Tables for properties of air and water. Other information are given as below:

(a) Exchanger Specifications:  
   (i) Steel Shell and Tube exchanger with cross flow baffling  
   (ii) Cooling water passes through shell side  
   (iii) One tube pass and counter-current flow  
   (iv) Tube OD = 1.0 in; Tube ID = 0.782 inch  
   (v) 1/16 inch triangular pitch. Tubes are staggered.

(b) Costs:  
   (i) Purchased cost: per square foot outside heat transfer area = $34.  
   (ii) Installation cost = 15% of purchased cost  
   (iii) Annual-fixed cost including maintenance = 20% of installed cost  
   (iv) Cost for cooling water (not including pumping cost) = $0.009/450 kg  
   (v) Cost for energy supplied to force the cooling water and the gas through the exchanger (including effect of pump and motor efficiency and cost is $0.04/kWh).  

Contd ........... P/3
(c) **General:**

(i) Average absolute pressure of gas in exchanger is 10 atm.

(ii) Unit operates 7000 hr/year.

(iii) In the friction relations, take

\[ B_i = 1.2 \]

\[ B_0 = \text{number of crosses} \]

(iv) Safety factor for outside film co-efficient, \( F_s = 1.3 \)

(v) Fouling co-efficient for cooling water = 3000 kcal/(hr. m\(^2\).°C)

\[ \text{Fouling co-efficient for air} = 4000 \text{ kcal/(hr.m}^2\text{.°C)} \]

(vi) Optimum flow conditions are turbulent both for shell and tube side.

(vii) \( \frac{N_r N_s}{N_f} = 1 \)

(viii) \( \psi_t \) (see attached file)

(ix) \( \psi_B \) (see attached file)

---

**SECTION - B**

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

5. A distillation column is separating a feed that is 50 mol% n-hexane and 50 mole% n-heptane. Feed is a saturated liquid. Average column pressure is 1 atm. Distillate composition is \( X_o = 0.99 \) (mole fraction of n-hexane) and \( X_B = 0.001 \). Feed rate is 1000 lb moles/hr. Internal reflux ratio \( L/V = 0.8 \). The column has a total reboiler and a total condenser. Determine the diameter and packing height of the column if random packing is used. Physical properties for pure n-hexane at 69°C are given below:

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Liquid specific gravity</td>
<td>0.659</td>
</tr>
<tr>
<td>Surface tension ( \sigma )</td>
<td>13.2 dynes/cm</td>
</tr>
<tr>
<td>Saturated vapor density</td>
<td>0.1917 lb/ft(^3)</td>
</tr>
</tbody>
</table>

Following design equations are also provided

\[ V_v = 0.38 \left( \frac{\sigma}{20} \right)^{0.2} \left( \frac{\rho_f - \rho_v}{\rho_v} \right)^{0.5} \]

For random packing:

\[ HETP = \begin{cases} 
D & \text{for } D \leq 0.5 \text{ m} \\
0.5 D^{0.3} & \text{for } D > 0.5 \text{ m} \\
D^{0.3} & \text{for absorption columns with } D > 0.5 \text{ m}
\end{cases} \]
6. (a) Write down the general aspects that need to be evaluated in selecting piping materials.

(b) Liquid benzene at 38°C with a vapor pressure of 26.4 kN/m² and a density of 860 kg/m³ is to be pumped at a rate of 0.0025 m³/s from a storage tank to a discharge location 3 m above the liquid level in the tank. The pump with a mechanical efficiency of 60 percent is 1 m above the liquid level. The storage tank is at atmospheric pressure. The pressure at the end of the discharge line is 445 kPa absolute. The inside diameter of the pipe used to transfer the benzene is 0.0409 m. The frictional pressure drops in the suction line and the discharge line are 3.45 and 37.9 kN/m², respectively. Determine the head developed by the pump and the total power requirement. If the pump manufacturer specifies a required net positive suction head of 0.3 m, will such a pump be applicable for this service.

7. (a) In order to design a batch distillation column the designer needs to estimate the quantity of liquid that need to be distilled. In a given batch. distillation of a binary mixture the concentration of the liquid need to be changed from $x_{1i}$ to $x_{1f}$ (in mole fraction of the more volatile component). A single batch will be operated to produce W kmol residual liquid. If the relative volatility of the components in the mixture is $\alpha$, estimate the amount of initial liquid to be charged in the batch.

(b) A centrifugal pump is tested with water and found at 1800 rpm to deliver 200 gal/min at a pressure rise of 50 psi. Determine optimum economic pipe diameter for installation of the pump system.

8. A gas fired furnace is shown in the figure for question 8. 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 value connected to a thermostat. The gas is ignited by a pilot light flame. A high temperature switch sheets off all gas in the of high temperature in the air space.

Perform a HAZOP study on the furnace control system. Note that failure of the system will lead to excessive heating of the air space and possible fire. Besides, failure of the pilot light will lead to combustible gas in the furnace, heat exchanger and chimney which may lead to explosion.
Typical percentages of fixed-capital investment values for direct and indirect cost segments for multipurpose plants or large additions to existing facilities

<table>
<thead>
<tr>
<th>Components</th>
<th>Range of FCI, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Direct costs</td>
<td></td>
</tr>
<tr>
<td>Purchased equipment</td>
<td>15-40</td>
</tr>
<tr>
<td>Purchased-equipment installation</td>
<td>6-14</td>
</tr>
<tr>
<td>Instrumentation and controls (installed)</td>
<td>2-12</td>
</tr>
<tr>
<td>Piping (installed)</td>
<td>4-17</td>
</tr>
<tr>
<td>Electrical systems (installed)</td>
<td>2-10</td>
</tr>
<tr>
<td>Buildings (including services)</td>
<td>2-18</td>
</tr>
<tr>
<td>Yard improvements</td>
<td>2-5</td>
</tr>
<tr>
<td>Service facilities (installed)</td>
<td>8-30</td>
</tr>
<tr>
<td>Land</td>
<td>1-2</td>
</tr>
<tr>
<td>Indirect costs</td>
<td></td>
</tr>
<tr>
<td>Engineering and supervision</td>
<td>4-20</td>
</tr>
<tr>
<td>Construction expenses</td>
<td>4-17</td>
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<tr>
<td>Legal expenses</td>
<td>1-3</td>
</tr>
<tr>
<td>Contractor’s fee</td>
<td>2-6</td>
</tr>
<tr>
<td>Contingency</td>
<td>5-15</td>
</tr>
</tbody>
</table>

Cost indexes as annual averages

<table>
<thead>
<tr>
<th>Year</th>
<th>Direct</th>
<th>Indirect</th>
</tr>
</thead>
<tbody>
<tr>
<td>1987</td>
<td>814</td>
<td>956</td>
</tr>
<tr>
<td>1988</td>
<td>852</td>
<td>980</td>
</tr>
<tr>
<td>1989</td>
<td>895</td>
<td>1001</td>
</tr>
<tr>
<td>1990</td>
<td>915.1</td>
<td>1026</td>
</tr>
<tr>
<td>1991</td>
<td>930.6</td>
<td>1049</td>
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<tr>
<td>1992</td>
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<td>1993</td>
<td>964.2</td>
<td>1130</td>
</tr>
<tr>
<td>1994</td>
<td>993.4</td>
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</tr>
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<td>1995</td>
<td>1027.5</td>
<td>1187</td>
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<tr>
<td>1996</td>
<td>1039.1</td>
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<td>1056.8</td>
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<td>1998</td>
<td>1061.9</td>
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<td>1999</td>
<td>1068.3</td>
<td>1315</td>
</tr>
<tr>
<td>2000</td>
<td>1089.0</td>
<td>1350</td>
</tr>
<tr>
<td>2001</td>
<td>1093.9</td>
<td>1376</td>
</tr>
<tr>
<td>2002</td>
<td>1102.5</td>
<td>1408</td>
</tr>
</tbody>
</table>

1 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.

2 Projected.


Relative labor rate and productivity indexes in chemical and allied products industries for the United States (1999)

<table>
<thead>
<tr>
<th>Region</th>
<th>New England</th>
<th>Middle Atlantic</th>
<th>South Atlantic</th>
<th>Midwest</th>
<th>Gulf</th>
<th>Southwest</th>
<th>Mountain</th>
<th>Pacific Coast</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1.14</td>
<td>1.06</td>
<td>0.84</td>
<td>1.03</td>
<td>0.95</td>
<td>0.88</td>
<td>0.88</td>
<td>1.22</td>
</tr>
</tbody>
</table>

1 Adapted from J. M. Winton, Chem. Week, 121(24): 49 (1977), and updated with data from M. Kiley, ed., National Construction Estimator, 37th ed., Craftsman Book Company of America, Carlsbad, CA, 1989. Productivity, as considered here, is an economic term that gives the value added (products minus raw materials) per dollar of total payroll cost. Relative values were determined by taking the average of Kiley’s weighted state values in each region divided by the weighted-average value of all the regions. See also Tables 6-14 and 6-15.
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 (10³–10⁶ ft³/min)</td>
<td>0.59</td>
</tr>
<tr>
<td>Centrifuge, solid bowl, c.s.</td>
<td>7.5–75 kW (10³–10⁴ hp) drive</td>
<td>0.67</td>
</tr>
<tr>
<td>Crystallizer, vacuum batch, c.s.</td>
<td>15–200 m² (500–7000 ft²)</td>
<td>0.57</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 m³ (10³–10⁴ ft³)</td>
<td>0.76</td>
</tr>
<tr>
<td>Dryer, drum, single atmospheric</td>
<td>1–10 m³ (10³–10⁴ ft³)</td>
<td>0.40</td>
</tr>
<tr>
<td>Evaporator (installed), horizontal tank</td>
<td>10–1000 m³ (10⁵–10⁶ 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>10–40 m² (100–400 ft²)</td>
<td>0.60</td>
</tr>
<tr>
<td>Heat exchanger, shell-and-tube, fixed sheet, c.s.</td>
<td>1–3 m² (250–800 gal)</td>
<td>0.27</td>
</tr>
<tr>
<td>Kettle, cast-iron, jacketed</td>
<td>0.8–3 m³ (200–800 gal)</td>
<td>0.31</td>
</tr>
<tr>
<td>Kettle, glass-lined, jacketed</td>
<td>4–15 kW (5–20 hp)</td>
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</tr>
<tr>
<td>Motor, squirrel cage, induction, 440-V, explosion-proof</td>
<td>15–150 kW (20–200 hp)</td>
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<tr>
<td>Motor, squirrel cage, induction, 440-V, explosion-proof</td>
<td>4–40 m³/s (10⁵–10⁶ gpm)</td>
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<tr>
<td>Motor, squirrel cage, induction, 440-V, explosion-proof</td>
<td>1×10⁻⁶–6×10⁻⁵ m³/s (2–100 gpm)</td>
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<td>Pump, reciprocating, horizontal cast-iron (includes motor)</td>
<td>0.2–2.2 m³ (50–600 gal)</td>
<td>0.54</td>
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<tr>
<td>Pump, centrifugal, horizontal cast steel (includes motor)</td>
<td>4–40 m³/s (10⁵–10⁶ gpm psi)</td>
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<tr>
<td>Reactor, glass-lined, jacketed (without drive)</td>
<td>0.4–4.0 m³ (10⁴–10⁵ gal)</td>
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<tr>
<td>Reactor, stainless steel, 2070-kPa</td>
<td>1.5–7 m³ (50–250 ft³)</td>
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<td>Separator, centrifugal, c.s.</td>
<td>0.4–40 m³ (10⁴–10⁵ gal)</td>
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<td>Tower, c.s.</td>
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<td>Tray, sieve, c.s.</td>
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Process Flowsheet for Q. 3
Initial temperature interval table

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*See Figure... to identify these streams

![Composite diagram with 33°C approach temperature](image)

\[ \psi_i = B_i \left[ \frac{12,200 D_i^{1.5} \mu_i^{1.83} \left( \frac{\mu_{o_i}}{\mu_i} \right)^{0.63}}{g_c D_o \rho_i k_i^{2.33} c_{p_i}^{1.17}} \right] \]

\[ \psi_o = \frac{B_o N_r N_c}{n_b N_t} \left( \frac{2b_o D_c D_o^{0.75} F_s^{4.75} \mu_{o_o}^{1.42}}{\pi a_o^{4.75} g_c \rho_o k_{f_o}^{3.17} c_{p_o}^{1.58}} \right) \]
Table A-5 I Properties of air at atmospheric pressure.

The values of $\mu$, $\nu$, $\gamma$, and $Pr$ are not strongly pressure-dependent and may be used over a fairly wide range of pressures.

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<th>$\sigma$, kJ/kg · °C</th>
<th>$\mu \times 10^3$ (kg m/s)</th>
<th>$\nu \times 10^8$ m$^2$/s</th>
<th>$k$ W/m · °C</th>
<th>$\alpha \times 10^4$ m$^2$/s</th>
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\[ V_{nt} = C_{sb} \left( \frac{6}{20} \right)^{0.2} \left( \frac{P_r - P_v}{P_r} \right)^{0.5} \]

**Figure**
Chart for estimating values of \( C_{sb} \) (±10 percent) [Adapted from J. R. Fair, Petrol/Chem. Eng., 33(10): 45 (1961) with permission.]

**Figure for Question No. 5**

**Figure** Furnace control system.

**Figure for Question No. 8**
Table A-9: Properties of water (saturated liquid).

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<th>°F</th>
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<th>σ</th>
<th>k</th>
<th>λ</th>
<th>Pr</th>
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<tr>
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<td>879.6</td>
<td>0.79</td>
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<td>4.398</td>
<td>873.4</td>
<td>0.68</td>
<td>0.569</td>
<td>0.59</td>
</tr>
<tr>
<td>370</td>
<td>188.1</td>
<td>4.414</td>
<td>867.2</td>
<td>0.60</td>
<td>0.555</td>
<td>0.56</td>
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<tr>
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<td>4.430</td>
<td>861.0</td>
<td>0.52</td>
<td>0.541</td>
<td>0.53</td>
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<tr>
<td>390</td>
<td>199.3</td>
<td>4.446</td>
<td>854.8</td>
<td>0.45</td>
<td>0.527</td>
<td>0.50</td>
</tr>
<tr>
<td>400</td>
<td>204.9</td>
<td>4.462</td>
<td>848.5</td>
<td>0.39</td>
<td>0.513</td>
<td>0.47</td>
</tr>
</tbody>
</table>

Notes:
- σ: Surface tension
- k: Thermal conductivity
- λ: Thermal diffusivity
- Pr: Prandtl number
- \(\frac{\sigma^2 Pr}{1000}\): Viscosity

SECTION - A

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

1. (a) Explain Reynolds analogy and Taylor-Prandtl analogy and show that \( J_H = \frac{1}{2} C_f \). \((20)\)

(b) The following equation gives the asymptotic temperature profile for heating a fluid of constant \( \rho, \mu, C_p \) and \( k \) in a long tube with constant heat flux at the wall. \((15)\)

\[
T = T_0 - \frac{4zq_1}{\rho C_p \nu_{z,max} R} + \frac{q_1 R}{k} \left[ -\frac{\xi^2}{5} + \frac{\xi^4}{35} - \frac{\xi^6}{24} \right]
\]

where \( \xi = \frac{t}{R} \)

Use this temperature profile to show that the limiting Nusselt number for these conditions is \( \frac{48}{11} \).

2. (a) A solid body occupying the space from \( y = 0 \) to \( y = \infty \) is initially at temperature \( T_0 \). At time \( t = 0 \), the surface at \( y = 0 \) is suddenly raised to temperature \( T_1 \) and maintain at that temperature for \( t > 0 \). Find:

(i) The time-dependant temperature profiles \( T(y, t) \). \((20)\)

(ii) The expression for thermal penetration thickness. \((3)\)

(iii) The expression for wall heat flux. \((5)\)

(b) Prove that

(i) \( \dot{v} - \dot{v}^* = \omega_A (v_A - v_A^*) + \omega_B (v_B - v^*) \) \((3)\)

(ii) \( N_A = J_A^* + C_A v^* \) \((4)\)

3. Consider a catalytic reactor shown in Fig. for Q. 3, in which the dimerization reaction \( 2A \rightarrow A_2 \) is being carried out. Find:

(i) The expression for concentration profile \((15)\)

(ii) The expression for molar mass flux through the film \((5)\)

(iii) Consider the above system when the reaction \( 2A \rightarrow A_2 \) is not instantaneous at the catalytic surface at \( (z = 8) \) and assume that the rate at which \( A \) disappears at the surface is proportional to the concentration: \( N_{AZ} = K_{CA} \) where \( K \) is a rate constant. \((15)\)

Contd .......... P/2
4. (a) Consider porous catalyst particles in the shape of thin disks, such that the surface area of the edge of the disk is small in comparison with that of the two circular faces. Obtain the expression for the effectiveness factor.

(b) Consider the leaching of a substance A from solid particles by a solvent B. Obtain a differential equation for \( C_A \) as a function of \( z \) by making a man balance on A over a thin slab of thickness \( \Delta z \). Show the rate of leaching is given by \( N_{AB} = \frac{D_{AB}}{\delta} (C_{A0} - C_{AB}) \).

SECTION – B

There are FOUR questions in this section. Answer Q. No. 5 and any TWO from the rest.

Q. No. 5 is compulsory.

The symbols have their usual meaning.

COMPULSORY

5. (a) Transform the x-component of equation of motion given below into Navier-Stokes equation and Euler equation by making necessary assumptions and simplifications:

\[
\frac{\partial}{\partial t} (\rho v_x) = -\left( \frac{\partial}{\partial x} \rho v_x v_x + \frac{\partial}{\partial y} \rho v_y v_x + \frac{\partial}{\partial z} \rho v_z v_x \right) - \left( \frac{\partial P}{\partial x} + \rho g_x \right)
\]

(b) Neglecting the viscous dissipation terms make equation (A) of table 10.2.3 dimensionless.

(c) What are the usual boundary conditions encountered in fluid flow problems?

(d) Give comparison between forced and free convection in non-isothermal systems.

(e) Explain the physical significance and mention application area for the dimensionless groups:

\[
\left( \frac{\rho g b^3 \Delta p}{\mu^2} \right); \left( \mu v^2 / k(T_b - T_0) \right); \left( \frac{h b}{2k} \right)
\]

6. (a) Derive the equation of continuity in cylindrical co-ordinates.

(b) Determine \( v_\theta(r) \) between two coaxial cylinders of radii \( R \) and \( kR \) rotating at angular velocities \( \Omega_0 \) and \( \Omega_i \), respectively. Assume the space between cylinders is filled with an incompressible isothermal fluid in laminar flow.
7. (a) Find the bulk temperature (mixing-cup temperature) for the fluid being heated inside a tube for the following velocity and temperature profiles:

\[ v_z = v_{z, \text{max}} \left[ 1 - \frac{r^2}{R^2} \right] \]

\[ T = T_{\text{centre}} + A \left( \frac{r^2}{R^2} - \frac{1}{4} \left( \frac{r^4}{R^4} \right) \right) \]

where, A is constant.

(b) A standard schedule 40 two-inch steel pipe (inside diameter 2.067 in. and wall thickness 0.154 in.) carrying steam is insulated with 2 in. of 85 percent magnesia covered in turn with 2 in. of cork. Estimate the heat loss per hour per foot of pipe if the inner surface of the pipe is at 250°F and the outer surface of the cork is at 90°F. The thermal conductivities of the substances concerned are:

- Steel: 26.1 Btu hr⁻¹ ft⁻¹ °F⁻¹
- 85 percent magnesia: 0.04 Btu hr⁻¹ ft⁻¹ °F⁻¹
- Cork: 0.03 Btu hr⁻¹ ft⁻¹ °F⁻¹

(c) A thermocouple is inserted into a gas stream (Figure 7c). Estimate the true temperature of the gas stream if:

\[ T_1 = 525°F \]
\[ T_w = \text{wall temperature} = 360°F \]
\[ h = 120 \text{ Btu hr}^{-1} \text{ ft}^{-2} \text{ (°F)}^{-1} \]
\[ k = 60 \text{ Btu hr}^{-1} \text{ ft}^{-1} \text{ (°F)}^{-1} \]
\[ B = \text{thickness of well wall} = 0.08 \text{ in.} \]
\[ L = \text{length of wall} = 0.2 \text{ ft} \]

[Hints: The temperature profile of a fin is expressed as: \( \theta = \frac{\cosh N (1 - C)}{\cosh N} \)]

8. (a) A viscous fluid is in laminar flow in a horizontal slit formed by two parallel walls a distance 2B apart, where y is the distance from the mid-plane and x is the distance in the direction of flow. The fluid is under pressure gradient. Carry out shell momentum balance to final an expression for velocity profile and make a sketch of the profile. Sketch the system and list the assumptions made.

(b) Derive an expression for the temperature distribution \( T(\infty) \) in a viscous fluid in steady laminar flow between large flat parallel plates, as described in question 8(a). Both plates are maintained at constant temperature \( T_0 \). Take into account explicitly the heat generated by viscous dissipation. Neglect the temperature dependence of \( \mu \) and \( k \).
Fig. for Q: 3. Spheres with coating of catalytic material.

Pipe wall at $T_w$. Gas stream at $T_a$.
Thermocouple junction at $T_1$.
Thermocouple wires to potentiometer.
Well wall of thickness $B$.

Fig. for $G$: 76: Thermocouple in cylindrical wall.
TABLE 3.4-1
THE EQUATION OF CONTINUITY IN SEVERAL
COORDINATE SYSTEMS

Rectangular coordinates (x, y, z):
\[
\frac{\partial p}{\partial t} + \frac{\partial}{\partial x} (\rho u_x) + \frac{\partial}{\partial y} (\rho u_y) + \frac{\partial}{\partial z} (\rho u_z) = 0
\]  
(A)

Cylindrical coordinates (r, θ, z):
\[
\frac{\partial p}{\partial t} + \frac{\partial}{\partial r} (\rho r u_r) + \frac{1}{r} \frac{\partial}{\partial \theta} (\rho r u_\theta) + \frac{\partial}{\partial z} (\rho u_z) = 0
\]  
(B)

Spherical coordinates (r, θ, φ):
\[
\frac{\partial p}{\partial t} + \frac{1}{r^2} \frac{\partial}{\partial r} (r^2 u_r) + \frac{1}{r \sin \theta} \frac{\partial}{\partial \theta} (\rho u_\theta) + \frac{1}{r \sin \theta} \frac{\partial}{\partial \phi} (\rho u_\phi) = 0
\]  
(C)

TABLE 3.4-2
THE EQUATION OF MOTION IN RECTANGULAR COORDINATES (x, y, z)

In terms of \( \tau \):

- z-component \( \rho \left( \frac{\partial u_z}{\partial t} + u_x \frac{\partial u_z}{\partial x} + u_y \frac{\partial u_z}{\partial y} + u_z \frac{\partial u_z}{\partial z} \right) = -\frac{\partial p}{\partial z} - \rho \left( \frac{\partial \tau_{xz}}{\partial x} + \frac{\partial \tau_{yz}}{\partial y} + \frac{\partial \tau_{zz}}{\partial z} \right) + \rho g_z \)  
  \( \text{(A)} \)

- y-component \( \rho \left( \frac{\partial u_y}{\partial t} + u_x \frac{\partial u_y}{\partial x} + u_y \frac{\partial u_y}{\partial y} + u_z \frac{\partial u_y}{\partial z} \right) = -\frac{\partial p}{\partial y} - \rho \left( \frac{\partial \tau_{yx}}{\partial x} + \frac{\partial \tau_{yz}}{\partial y} + \frac{\partial \tau_{yy}}{\partial z} \right) + \rho g_y \)  
  \( \text{(B)} \)

- z-component \( \rho \left( \frac{\partial u_z}{\partial t} + u_x \frac{\partial u_z}{\partial x} + u_y \frac{\partial u_z}{\partial y} + u_z \frac{\partial u_z}{\partial z} \right) = -\frac{\partial p}{\partial z} - \rho \left( \frac{\partial \tau_{xz}}{\partial x} + \frac{\partial \tau_{yz}}{\partial y} + \frac{\partial \tau_{zz}}{\partial z} \right) + \rho g_z \)  
  \( \text{(C)} \)

In terms of velocity gradients for a Newtonian fluid with constant \( \rho \) and \( \mu \):

- z-component \( \rho \left( \frac{\partial u_z}{\partial t} + u_x \frac{\partial u_z}{\partial x} + u_y \frac{\partial u_z}{\partial y} + u_z \frac{\partial u_z}{\partial z} \right) = -\frac{\partial p}{\partial z} + \mu \left( \frac{\partial^2 u_z}{\partial x^2} + \frac{\partial^2 u_z}{\partial y^2} + \frac{\partial^2 u_z}{\partial z^2} \right) + \rho g_z \)  
  \( \text{(D)} \)

- y-component \( \rho \left( \frac{\partial u_y}{\partial t} + u_x \frac{\partial u_y}{\partial x} + u_y \frac{\partial u_y}{\partial y} + u_z \frac{\partial u_y}{\partial z} \right) = -\frac{\partial p}{\partial y} + \mu \left( \frac{\partial^2 u_y}{\partial x^2} + \frac{\partial^2 u_y}{\partial y^2} + \frac{\partial^2 u_y}{\partial z^2} \right) + \rho g_y \)  
  \( \text{(E)} \)

- z-component \( \rho \left( \frac{\partial u_z}{\partial t} + u_x \frac{\partial u_z}{\partial x} + u_y \frac{\partial u_z}{\partial y} + u_z \frac{\partial u_z}{\partial z} \right) = -\frac{\partial p}{\partial z} + \mu \left( \frac{\partial^2 u_z}{\partial x^2} + \frac{\partial^2 u_z}{\partial y^2} + \frac{\partial^2 u_z}{\partial z^2} \right) + \rho g_z \)  
  \( \text{(F)} \)
THE EQUATION OF MOTION IN CYLINDRICAL COORDINATES \((r, \theta, z)\)

In terms of \(\tau\):

- **r-component**
  \[
  \rho \left( \frac{\partial v_r}{\partial t} + v_r \frac{\partial v_r}{\partial r} + \frac{v_z \partial v_r}{r \partial \theta} - \frac{v_r^2}{r} + v_r \frac{\partial v_r}{\partial z} \right) = - \frac{\partial p}{\partial r} - \left( \frac{1}{r} \frac{\partial}{\partial r} (r \frac{\partial v_r}{\partial r}) \right) + \rho g \theta^* \quad (A)
  \]

- **\(\theta\)-component**
  \[
  \rho \left( \frac{\partial v_\theta}{\partial t} + v_r \frac{\partial v_\theta}{\partial r} + v_\theta \frac{\partial v_\theta}{\partial \theta} + \frac{v_\theta v_r}{r} + v_z \frac{\partial v_\theta}{\partial z} \right) = - \frac{1}{r} \frac{\partial p}{\partial \theta} + \frac{1}{r} \frac{\partial}{\partial \theta} (r \frac{\partial v_\theta}{\partial r}) + \rho g \theta^* \quad (B)
  \]

- **z-component**
  \[
  \rho \left( \frac{\partial v_z}{\partial t} + v_r \frac{\partial v_z}{\partial r} + v_\theta \frac{\partial v_z}{\partial \theta} + v_z \frac{\partial v_z}{\partial z} \right) = - \frac{\partial p}{\partial z} - \left( \frac{1}{r} \frac{\partial}{\partial \theta} (r \frac{\partial v_z}{\partial r}) \right) + \rho g \theta^* \quad (C)
  \]

In terms of velocity gradients for a Newtonian fluid with constant \(\rho\) and \(\mu\):

- **r-component**
  \[
  \rho \left( \frac{\partial v_r}{\partial t} + v_r \frac{\partial v_r}{\partial r} + \frac{v_z \partial v_r}{r \partial \theta} - \frac{v_r^2}{r} + v_r \frac{\partial v_r}{\partial z} \right) = - \frac{\partial p}{\partial r} + \mu \left[ \frac{\partial}{\partial r} \left( \frac{1}{r} \frac{\partial v_r}{\partial r} \right) \right] + \frac{1}{r} \frac{\partial v_z}{\partial \theta} + \frac{1}{r^2} \frac{\partial v_z}{\partial z} + \rho g \theta^* \quad (D)
  \]

- **\(\theta\)-component**
  \[
  \rho \left( \frac{\partial v_\theta}{\partial t} + v_r \frac{\partial v_\theta}{\partial r} + v_\theta \frac{\partial v_\theta}{\partial \theta} + \frac{v_\theta v_r}{r} + v_z \frac{\partial v_\theta}{\partial z} \right) = - \frac{1}{r} \frac{\partial p}{\partial \theta} + \mu \left[ \frac{\partial}{\partial \theta} \left( \frac{1}{r} \frac{\partial v_\theta}{\partial r} \right) \right] + \frac{2}{r^2} \frac{\partial v_z}{\partial \theta} + \frac{1}{r^2} \frac{\partial v_z}{\partial z} + \rho g \theta^* \quad (E)
  \]

- **z-component**
  \[
  \rho \left( \frac{\partial v_z}{\partial t} + v_r \frac{\partial v_z}{\partial r} + v_\theta \frac{\partial v_z}{\partial \theta} + v_z \frac{\partial v_z}{\partial z} \right) = - \frac{\partial p}{\partial z} + \mu \left[ \frac{\partial}{\partial z} \left( \frac{1}{r \partial \theta} \frac{\partial v_z}{\partial r} \right) \right] + \frac{1}{r^2} \frac{\partial v_z}{\partial \theta} + \frac{1}{r^2} \frac{\partial v_z}{\partial \theta} + \rho g \theta^* \quad (F)
  \]

* The term \(\rho \alpha \theta^* r^2\) is the centrifugal force. It gives the effective force in the \(r\)-direction resulting from fluid motion in the \(\theta\)-direction. This term arises automatically on transformation from rectangular to cylindrical coordinates; it does not have to be added on physical grounds. Two problems in which this term arises are discussed in Examples 3.5-1 and 3.5-2.

* The term \(\rho \alpha \theta \theta^*/r\) is the Coriolis force. It is an effective force in the \(\theta\)-direction when there is flow in both the \(r\)- and \(\theta\)-directions. This term also arises automatically in the coordinate transformation. The Coriolis force arises in the problem of flow near a rotating disk (see, for example, H. Schlichting, Boundary-Layer Theory, McGraw-Hill, New York (1955), Chapter 5, §49.

---

**TABLE 3.4-3**

<table>
<thead>
<tr>
<th>Coordinate</th>
<th>Equation</th>
</tr>
</thead>
<tbody>
<tr>
<td>(r, \theta, z)</td>
<td>(\rho \left( \frac{\partial v_r}{\partial t} + v_r \frac{\partial v_r}{\partial r} + \frac{v_z \partial v_r}{r \partial \theta} - \frac{v_r^2}{r} + v_r \frac{\partial v_r}{\partial z} \right) = - \frac{\partial p}{\partial r} )</td>
</tr>
<tr>
<td>(r, \theta, z)</td>
<td>(\rho \left( \frac{\partial v_\theta}{\partial t} + v_r \frac{\partial v_\theta}{\partial r} + v_\theta \frac{\partial v_\theta}{\partial \theta} + \frac{v_\theta v_r}{r} + v_z \frac{\partial v_\theta}{\partial z} \right) = - \frac{1}{r} \frac{\partial p}{\partial \theta} )</td>
</tr>
<tr>
<td>(r, \theta, z)</td>
<td>(\rho \left( \frac{\partial v_z}{\partial t} + v_r \frac{\partial v_z}{\partial r} + v_\theta \frac{\partial v_z}{\partial \theta} + v_z \frac{\partial v_z}{\partial z} \right) = - \frac{\partial p}{\partial z} )</td>
</tr>
</tbody>
</table>
In terms of $\dot{r}$:

<table>
<thead>
<tr>
<th>Term</th>
<th>Equation</th>
</tr>
</thead>
<tbody>
<tr>
<td>$r$-component</td>
<td>[ \rho \left( \frac{\partial u_r}{\partial t} + u_r \frac{\partial u_r}{\partial r} + u_\theta \frac{\partial u_r}{\partial \theta} + u_\phi \frac{\partial u_r}{\partial \phi} - \frac{u_r^2 + u_\phi^2}{r} \right) = -\frac{\partial p}{\partial r} - \frac{1}{r^2} \left( \frac{\partial}{\partial \theta} \left( r^2 \tau_{r\theta} \right) + \frac{1}{r^2 \sin \theta} \frac{\partial}{\partial \phi} \left( r^2 \tau_{r\phi} \right) \right) - \frac{1}{r \sin \theta} \frac{\partial \tau_{r\phi}}{\partial \phi} + \frac{1}{r \sin \theta} \frac{\partial \tau_{\theta\phi}}{\partial \theta} + \frac{1}{r \sin \theta} \frac{\partial \tau_{\phi\theta}}{\partial \phi} + \frac{1}{r \sin \theta} \frac{\partial \tau_{\phi\phi}}{\partial \phi} ]</td>
</tr>
<tr>
<td>$\theta$-component</td>
<td>[ \rho \left( \frac{\partial u_\theta}{\partial t} + u_r \frac{\partial u_\theta}{\partial r} + u_\theta \frac{\partial u_\theta}{\partial \theta} + u_\phi \frac{\partial u_\theta}{\partial \phi} - \frac{u_r u_\theta}{r} + \frac{u_\phi^2}{r \sin \theta} + \frac{u_\phi^2 \cot \phi}{r} \right) = -1 \frac{\partial p}{r^2 \sin \theta} \frac{\partial}{\partial \theta} \left( r^2 \tau_{r\theta} \right) + \frac{1}{r^2 \sin \theta} \frac{\partial}{\partial \phi} \left( r^2 \tau_{r\phi} \right) + \frac{1}{r \sin \theta} \frac{\partial \tau_{r\phi}}{\partial \phi} + \frac{1}{r \sin \theta} \frac{\partial \tau_{\theta\phi}}{\partial \theta} + \frac{1}{r \sin \theta} \frac{\partial \tau_{\phi\theta}}{\partial \phi} + \frac{1}{r \sin \theta} \frac{\partial \tau_{\phi\phi}}{\partial \phi} ]</td>
</tr>
<tr>
<td>$\phi$-component</td>
<td>[ \rho \left( \frac{\partial u_\phi}{\partial t} + u_r \frac{\partial u_\phi}{\partial r} + u_\theta \frac{\partial u_\phi}{\partial \theta} + u_\phi \frac{\partial u_\phi}{\partial \phi} - \frac{u_r u_\phi}{r} - \frac{u_\phi^2}{r \sin \theta} \right) = -\frac{\partial p}{r \sin \theta} \frac{\partial}{\partial \theta} \left( r \tau_{r\phi} \right) + \frac{1}{r \sin \theta} \frac{\partial}{\partial \phi} \left( r \tau_{r\phi} \right) + \frac{1}{r \sin \theta} \frac{\partial \tau_{r\phi}}{\partial \phi} + \frac{1}{r \sin \theta} \frac{\partial \tau_{\theta\phi}}{\partial \theta} + \frac{1}{r \sin \theta} \frac{\partial \tau_{\phi\theta}}{\partial \phi} + \frac{1}{r \sin \theta} \frac{\partial \tau_{\phi\phi}}{\partial \phi} ]</td>
</tr>
</tbody>
</table>

In terms of velocity gradients for a Newtonian fluid with constant $\rho$ and $\mu$:

<table>
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<tr>
<th>Term</th>
<th>Equation</th>
</tr>
</thead>
<tbody>
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<td>$r$-component</td>
<td>[ \rho \left( \frac{\partial u_r}{\partial t} + u_r \frac{\partial u_r}{\partial r} + u_\theta \frac{\partial u_r}{\partial \theta} + u_\phi \frac{\partial u_r}{\partial \phi} - \frac{u_r^2 + u_\phi^2}{r} \right) = -\frac{\partial p}{\partial r} + \mu \left( \frac{\partial^2 u_r}{\partial r^2} + \frac{1}{r^2} \frac{\partial}{\partial \theta} \left( r^2 \frac{\partial u_r}{\partial \theta} \right) - \frac{1}{r^2 \sin \theta} \frac{\partial}{\partial \phi} \left( r^2 \frac{\partial u_r}{\partial \phi} \right) \right) + \frac{1}{r^2 \sin \theta} \frac{\partial \tau_{r\phi}}{\partial \phi} + \frac{1}{r^2 \sin \theta} \frac{\partial \tau_{\theta\phi}}{\partial \theta} + \frac{1}{r^2 \sin \theta} \frac{\partial \tau_{\phi\theta}}{\partial \phi} + \frac{1}{r^2 \sin \theta} \frac{\partial \tau_{\phi\phi}}{\partial \phi} ]</td>
</tr>
<tr>
<td>$\theta$-component</td>
<td>[ \rho \left( \frac{\partial u_\theta}{\partial t} + u_r \frac{\partial u_\theta}{\partial r} + u_\theta \frac{\partial u_\theta}{\partial \theta} + u_\phi \frac{\partial u_\theta}{\partial \phi} - \frac{u_r u_\theta}{r} + \frac{u_\phi^2}{r \sin \theta} + \frac{u_\phi^2 \cot \phi}{r} \right) = -\frac{\partial p}{r^2 \sin \theta} \frac{\partial}{\partial \theta} \left( r^2 \tau_{r\theta} \right) + \mu \left( \frac{\partial^2 u_\theta}{\partial \theta^2} + \frac{1}{r^2} \frac{\partial}{\partial \phi} \left( r^2 \frac{\partial u_\theta}{\partial \phi} \right) \right) + \frac{1}{r^2 \sin \theta} \frac{\partial \tau_{r\phi}}{\partial \phi} + \frac{1}{r^2 \sin \theta} \frac{\partial \tau_{\theta\phi}}{\partial \theta} + \frac{1}{r^2 \sin \theta} \frac{\partial \tau_{\phi\theta}}{\partial \phi} + \frac{1}{r^2 \sin \theta} \frac{\partial \tau_{\phi\phi}}{\partial \phi} ]</td>
</tr>
<tr>
<td>$\phi$-component</td>
<td>[ \rho \left( \frac{\partial u_\phi}{\partial t} + u_r \frac{\partial u_\phi}{\partial r} + u_\theta \frac{\partial u_\phi}{\partial \theta} + u_\phi \frac{\partial u_\phi}{\partial \phi} - \frac{u_r u_\phi}{r} - \frac{u_\phi^2}{r \sin \theta} \right) = -\frac{\partial p}{r \sin \theta} \frac{\partial}{\partial \theta} \left( r \tau_{r\phi} \right) + \mu \left( \frac{\partial^2 u_\phi}{\partial r^2} + \frac{1}{r^2} \frac{\partial}{\partial \phi} \left( r^2 \frac{\partial u_\phi}{\partial \phi} \right) \right) + \frac{1}{r \sin \theta} \frac{\partial \tau_{r\phi}}{\partial \phi} + \frac{1}{r \sin \theta} \frac{\partial \tau_{\theta\phi}}{\partial \theta} + \frac{1}{r \sin \theta} \frac{\partial \tau_{\phi\theta}}{\partial \phi} + \frac{1}{r \sin \theta} \frac{\partial \tau_{\phi\phi}}{\partial \phi} ]</td>
</tr>
</tbody>
</table>
COMPONENTS OF THE STRESS TENSOR FOR NEWTONIAN FLUIDS

IN RECTANGULAR COORDINATES (x, y, z)

\[
\begin{align*}
\tau_{xx} &= -\mu \left[ \frac{\partial u_x}{\partial x} - \frac{1}{2} \delta(x-x) \right] \\
\tau_{xy} &= -\mu \left[ \frac{\partial u_y}{\partial x} - \frac{1}{2} \delta(y-y) \right] \\
\tau_{xz} &= -\mu \left[ \frac{\partial u_z}{\partial x} - \frac{1}{2} \delta(z-z) \right] \\
\tau_{yx} &= \tau_{xy} \\
\tau_{yy} &= -\mu \left[ \frac{\partial u_x}{\partial y} - \frac{1}{2} \delta(x-x) \right] \\
\tau_{yz} &= \tau_{zy} \\
\tau_{zx} &= \tau_{xz} \\
\tau_{yz} &= -\mu \left[ \frac{\partial u_y}{\partial z} - \frac{1}{2} \delta(y-y) \right] \\
\tau_{zy} &= \tau_{yz} \\
\tau_{zx} &= \tau_{xz} \\
\tau_{zy} &= \tau_{yz} \\
(\mathbf{\tau} \cdot \mathbf{v}) &= \frac{\partial u_x}{\partial x} + \frac{\partial u_y}{\partial y} + \frac{\partial u_z}{\partial z}
\end{align*}
\]

TABLE 3.4-4
COMPONENTS OF THE STRESS TENSOR FOR NEWTONIAN FLUIDS
IN CYLINDRICAL COORDINATES (r, \theta, z)

\[
\begin{align*}
\tau_{rr} &= -\mu \left[ \frac{\partial u_r}{\partial r} - \frac{1}{r} \delta(r-r) \right] \\
\tau_{\theta r} &= -\mu \left[ \frac{\partial u_\theta}{\partial r} - \frac{\partial u_r}{\partial \theta} \right] + \frac{1}{r} \delta(r-r) \\
\tau_{z r} &= -\mu \left[ \frac{\partial u_z}{\partial r} - \frac{\partial u_r}{\partial z} \right] \\
\tau_{\theta \theta} &= -\mu \left[ \frac{\partial u_\theta}{\partial \theta} - \frac{1}{r} \delta(\theta-\theta) \right] + \frac{1}{r^2} \delta(\theta-\theta) \\
\tau_{z \theta} &= \tau_{\theta z} \\
\tau_{zz} &= -\mu \left[ \frac{\partial u_z}{\partial z} - \frac{\partial u_z}{\partial z} \right] \\
(\mathbf{\tau} \cdot \mathbf{v}) &= \frac{\partial u_x}{\partial x} + \frac{\partial u_y}{\partial y} + \frac{\partial u_z}{\partial z}
\end{align*}
\]

TABLE 3.4-7
COMPONENTS OF THE STRESS TENSOR FOR NEWTONIAN FLUIDS
IN SPHERICAL COORDINATES (r, \theta, \phi)

\[
\begin{align*}
\tau_{rr} &= -\mu \left[ \frac{\partial u_r}{\partial r} - \frac{1}{r} \delta(r-r) \right] \\
\tau_{\theta r} &= -\mu \left[ \frac{\partial u_\theta}{\partial r} - \frac{\partial u_r}{\partial \theta} + \frac{u_r}{r} \cot \theta \right] + \frac{1}{r^2} \delta(\theta-\theta) \\
\tau_{z r} &= -\mu \left[ \frac{\partial u_z}{\partial r} - \frac{\partial u_r}{\partial z} + \frac{u_r}{r} \right] \\
\tau_{\theta \theta} &= -\mu \left[ \frac{\partial u_\theta}{\partial \theta} - \frac{1}{r} \delta(\theta-\theta) \right] + \frac{1}{r^2} \delta(\theta-\theta) \\
\tau_{z \theta} &= \tau_{\theta z} \\
\tau_{zz} &= -\mu \left[ \frac{\partial u_z}{\partial z} - \frac{\partial u_z}{\partial z} \right] \\
(\mathbf{\tau} \cdot \mathbf{v}) &= \frac{\partial u_x}{\partial x} + \frac{\partial u_y}{\partial y} + \frac{\partial u_z}{\partial z}
\end{align*}
\]
### TABLE 10.2-1

**COMPONENTS OF THE ENERGY FLUX \( q \)**

<table>
<thead>
<tr>
<th>Rectangular</th>
<th>Cylindrical</th>
<th>Spherical</th>
</tr>
</thead>
<tbody>
<tr>
<td>( q_x = -k \frac{\partial T}{\partial x} ) (A)</td>
<td>( q_r = -k \frac{\partial T}{\partial r} ) (D)</td>
<td>( q_r = -k \frac{\partial T}{\partial r} ) (G)</td>
</tr>
<tr>
<td>( q_y = -k \frac{\partial T}{\partial y} ) (B)</td>
<td>( q_\theta = -k \frac{\partial T}{\partial \theta} ) (E)</td>
<td>( q_\phi = -k \frac{\partial T}{\partial \phi} ) (H)</td>
</tr>
<tr>
<td>( q_z = -k \frac{\partial T}{\partial z} ) (C)</td>
<td>( q_z = -k \frac{\partial T}{\partial z} ) (F)</td>
<td>( q_z = -k \frac{\partial T}{\partial z} ) (I)</td>
</tr>
</tbody>
</table>

### TABLE 10.2-2

**THE EQUATION OF ENERGY IN TERMS OF ENERGY AND MOMENTUM FLUXES**

(Eq. 10.1-19)

#### Rectangular coordinates:

\[
\rho C_v \left( \frac{\partial T}{\partial t} + U_x \frac{\partial T}{\partial x} + U_y \frac{\partial T}{\partial y} + U_z \frac{\partial T}{\partial z} \right) = - \left( \frac{\partial q_x}{\partial x} + \frac{\partial q_y}{\partial y} + \frac{\partial q_z}{\partial z} \right) 
- T \left( \frac{\partial p}{\partial x} \right) \left( \frac{\partial U_x}{\partial x} + \frac{\partial U_y}{\partial y} + \frac{\partial U_z}{\partial z} \right) - \tau_{xx} \frac{\partial U_x}{\partial x} - \tau_{xy} \frac{\partial U_y}{\partial y} - \tau_{xz} \frac{\partial U_z}{\partial z} 
+ \tau_{xy} \left( \frac{\partial U_x}{\partial y} + \frac{\partial U_y}{\partial x} \right) + \tau_{xz} \left( \frac{\partial U_x}{\partial z} + \frac{\partial U_z}{\partial x} \right) + \tau_{yz} \left( \frac{\partial U_y}{\partial z} + \frac{\partial U_z}{\partial y} \right) 
+ \tau_{zz} \left( \frac{\partial U_z}{\partial z} \right) \right) \]  

#### Cylindrical coordinates:

\[
\rho C_v \left( \frac{\partial T}{\partial t} + U_r \frac{\partial T}{\partial r} + \frac{1}{r} \frac{\partial T}{\partial \theta} + U_\theta \frac{\partial T}{\partial \theta} + U_\phi \frac{\partial T}{\partial \phi} \right) = - \left( \frac{\partial q_r}{\partial r} + \frac{1}{r} \frac{\partial q_\theta}{\partial \theta} + \frac{\partial q_\phi}{\partial \phi} \right) 
- T \left( \frac{\partial p}{\partial r} \right) \left( \frac{\partial U_r}{\partial r} + \frac{1}{r} \frac{\partial U_\theta}{\partial \theta} + \frac{\partial U_\phi}{\partial \phi} \right) - \tau_{rr} \frac{\partial U_r}{\partial r} - \tau_{r\theta} \frac{\partial U_\theta}{\partial \theta} - \tau_{r\phi} \frac{\partial U_\phi}{\partial \phi} 
+ \tau_{\theta r} \left( \frac{\partial U_r}{\partial \theta} + \frac{1}{r} \frac{\partial U_\theta}{\partial r} \right) + \tau_{\theta\theta} \left( \frac{\partial U_\theta}{\partial \theta} + \frac{\partial U_\theta}{\partial \theta} \right) + \tau_{\theta\phi} \left( \frac{\partial U_\phi}{\partial \theta} + \frac{\partial U_\theta}{\partial \phi} \right) + \tau_{\phi r} \left( \frac{\partial U_r}{\partial \phi} + \frac{\partial U_\phi}{\partial r} \right) + \tau_{\phi\phi} \left( \frac{\partial U_\phi}{\partial \phi} \right) 
+ \tau_{\phi\phi} \left( \frac{\partial U_\phi}{\partial \phi} \right) \right) \]  

#### Spherical coordinates:

\[
\rho C_v \left( \frac{\partial T}{\partial t} + U_r \frac{\partial T}{\partial r} + \frac{1}{r} \frac{\partial T}{\partial \theta} + \frac{1}{r \sin \theta} \frac{\partial T}{\partial \phi} + U_\theta \frac{\partial T}{\partial \theta} + U_\phi \frac{\partial T}{\partial \phi} \right) = - \left( \frac{\partial q_r}{\partial r} + \frac{1}{r} \frac{\partial q_\theta}{\partial \theta} + \frac{1}{r \sin \theta} \frac{\partial q_\phi}{\partial \phi} \right) 
- T \left( \frac{\partial p}{\partial r} \right) \left( \frac{\partial U_r}{\partial r} + \frac{1}{r} \frac{\partial U_\theta}{\partial \theta} + \frac{1}{r \sin \theta} \frac{\partial U_\phi}{\partial \phi} \right) - \tau_{rr} \frac{\partial U_r}{\partial r} - \tau_{r\theta} \frac{\partial U_\theta}{\partial \theta} - \tau_{r\phi} \frac{\partial U_\phi}{\partial \phi} 
+ \tau_{\theta r} \left( \frac{\partial U_r}{\partial \theta} + \frac{1}{r} \frac{\partial U_\theta}{\partial r} \right) + \tau_{\theta\theta} \left( \frac{\partial U_\theta}{\partial \theta} + \frac{\partial U_\theta}{\partial \theta} \right) + \tau_{\theta\phi} \left( \frac{\partial U_\phi}{\partial \theta} + \frac{\partial U_\theta}{\partial \phi} \right) + \tau_{\phi r} \left( \frac{\partial U_r}{\partial \phi} + \frac{\partial U_\phi}{\partial r} \right) + \tau_{\phi\phi} \left( \frac{\partial U_\phi}{\partial \phi} \right) 
+ \tau_{\phi\phi} \left( \frac{\partial U_\phi}{\partial \phi} \right) \right) \]

**Note:** The terms contained in braces \( \{ \} \) are associated with viscous dissipation and may usually be neglected, except for systems with large velocity gradients.
**TABLE 3.4-8**

THE FUNCTION \(-r \cdot \nabla \psi = \mu \Phi_v\) FOR NEWTONIAN FLUIDS*

<table>
<thead>
<tr>
<th>Type</th>
<th>Expression</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rectangular</td>
<td>[\Phi_v = 2 \left[ \frac{\partial^2 \psi}{\partial x^2} + \frac{\partial^2 \psi}{\partial y^2} + \frac{\partial^2 \psi}{\partial z^2} \right] + \left[ \frac{\partial^2 \psi}{\partial x \partial y} + \frac{\partial^2 \psi}{\partial y \partial z} + \frac{\partial^2 \psi}{\partial z \partial x} \right]^2 - \frac{2}{3} \left[ \frac{\partial^2 \psi}{\partial x^2} + \frac{\partial^2 \psi}{\partial y^2} + \frac{\partial^2 \psi}{\partial z^2} \right]^2 ] (A)</td>
</tr>
<tr>
<td>Cylindrical</td>
<td>[\Phi_v = 2 \left[ \frac{\partial^2 \psi}{\partial r^2} + \frac{\partial^2 \psi}{\partial \theta^2} + \frac{\partial^2 \psi}{\partial \phi^2} \right] + \left[ \frac{\partial^2 \psi}{\partial r \partial \theta} + \frac{\partial^2 \psi}{\partial \theta \partial \phi} + \frac{\partial^2 \psi}{\partial \phi \partial r} \right]^2 - \frac{2}{3} \left[ \frac{\partial^2 \psi}{\partial r^2} + \frac{\partial^2 \psi}{\partial \theta^2} + \frac{\partial^2 \psi}{\partial \phi^2} \right]^2 ] (B)</td>
</tr>
<tr>
<td>Spherical</td>
<td>[\Phi_v = 2 \left[ \frac{\partial^2 \psi}{\partial r^2} + \frac{\partial^2 \psi}{\partial \theta^2} + \frac{\partial^2 \psi}{\partial \phi^2} \right] + \frac{1}{\sin \theta} \left[ \frac{\partial \psi}{\partial \theta} + \frac{\partial \psi}{\partial \phi} \right]^2 + \left[ \frac{\partial \psi}{\partial r} + \frac{1}{r} \frac{\partial \psi}{\partial \theta} \right]^2 + \left[ \frac{1}{r \sin \theta} \frac{\partial \psi}{\partial \phi} + \frac{1}{r \sin \theta} \frac{\partial \psi}{\partial \phi} \right]^2 - \frac{2}{3} \left[ \frac{\partial^2 \psi}{\partial r^2} + \frac{\partial^2 \psi}{\partial \theta^2} + \frac{\partial^2 \psi}{\partial \phi^2} \right]^2 ] (C)</td>
</tr>
</tbody>
</table>

* These expressions are obtained by inserting the components of \(r\) from Tables 3.4–5,6,7 into the expression for \((-r \cdot \nabla \psi)\) given in Appendix A. (See Tables A.7–1, 2, and 3.)
TABLE 10.2-3
THE EQUATION OF ENERGY IN TERMS OF THE TRANSPORT PROPERTIES
(for Newtonian fluids of constant $p$ and $k$)
(Eq.-10.1-25 with viscous dissipation terms included)

Rectangular coordinates:

$$
\rho C_v \left( \frac{\partial T}{\partial t} + v_x \frac{\partial T}{\partial x} + v_y \frac{\partial T}{\partial y} + v_z \frac{\partial T}{\partial z} \right) = k \left[ \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \right] + 2\mu \left[ \left( \frac{\partial v_x}{\partial x} \right)^2 + \left( \frac{\partial v_y}{\partial y} \right)^2 + \left( \frac{\partial v_z}{\partial z} \right)^2 \right] + \mu \left( \frac{\partial v_x}{\partial x} + \frac{\partial v_y}{\partial y} + \frac{\partial v_z}{\partial z} \right)^2
$$

$$(A)$$

Cylindrical coordinates:

$$
\rho C_v \left( \frac{\partial T}{\partial t} + v_r \frac{\partial T}{\partial r} + v_\theta \frac{\partial T}{\partial \theta} + v_z \frac{\partial T}{\partial z} \right) = k \left[ \frac{1}{r} \frac{\partial}{\partial r} \left( r \frac{\partial T}{\partial r} \right) + \frac{1}{\sin \theta} \frac{\partial}{\partial \theta} \left( \sin \theta \frac{\partial T}{\partial \theta} \right) \right] + 2\mu \left[ \left( \frac{\partial v_r}{\partial r} \right)^2 + \left( \frac{1}{r} \frac{\partial v_\theta}{\partial \theta} \right)^2 + \left( \frac{\partial v_z}{\partial z} \right)^2 \right] + \mu \left( \frac{\partial v_r}{\partial r} + \frac{1}{r} \frac{\partial v_\theta}{\partial \theta} + \frac{\partial v_z}{\partial z} \right)^2
$$

$$(B)$$

Spherical coordinates:

$$
\rho C_v \left( \frac{\partial T}{\partial t} + v_r \frac{\partial T}{\partial r} + v_\theta \frac{\partial T}{\partial \theta} + \frac{v_\phi}{\sin \theta} \frac{\partial T}{\partial \phi} \right) = k \left[ \frac{1}{r^2} \frac{\partial}{\partial r} \left( r^2 \frac{\partial T}{\partial r} \right) + \frac{1}{r^2 \sin^2 \theta} \frac{\partial}{\partial \theta} \left( \sin \theta \frac{\partial T}{\partial \theta} \right) + \frac{1}{r^2 \sin^2 \theta} \frac{\partial}{\partial \phi} \left( \sin \theta \frac{\partial T}{\partial \phi} \right) \right] + 2\mu \left[ \left( \frac{\partial v_r}{\partial r} \right)^2 + \left( \frac{1}{r} \frac{\partial v_\theta}{\partial \theta} \right)^2 + \left( \frac{1}{r \sin \theta} \frac{\partial v_\phi}{\partial \phi} + \frac{\partial v_\phi}{r \sin \theta} \right)^2 \right] + \mu \left[ \frac{2}{r^2} \left( \frac{\partial v_\theta}{\partial \theta} \right)^2 + \frac{1}{r^2 \sin \theta} \left( \frac{\partial v_\phi}{\partial \phi} + \frac{\partial v_\phi}{r \sin \theta} \right)^2 \right]
$$

$$(C)$$

Note: The terms contained in braces $\{\}$ are associated with viscous dissipation and may usually be neglected, except for systems with large velocity gradients.
1. (a) Derive the general solution of Riccati Equation

Riccati Equation: \( y_{n+1} y_n + A y_{n+1} + B y_n + C = 0 \)

(b) It is desired to find the required number of ideal stages in the extraction cascade in Figure below

Here, feed-to-solvent ratio \( L/V = 1 \)

Equilibrium distribution constant \( K = 1 \)

Pure solvent is assumed.

Feed composition \( X_0 = 1 \) kg solute/kg carrier. It is desired to produce a rich extract product such that

\( Y_1 = 0.9 \) kg solute/kg solvent

Use the following formula:

\[
N + 1 = \log \left( \frac{1 - \frac{Y_{N+1}}{Y_N} (1 - \beta) - \frac{KX_0}{Y_1} \beta}{1 - \frac{KX_0}{Y_1}} \right) \log \beta
\]

where \( N = \) number of stages

\( \beta = \frac{L}{KVN} \)

(c) Find the particular solution using Inverse Operator Method

\( y_{n+2} - 2y_{n+1} - 8y_n = e^n \)

2. (a) Show that Backward Euler Method is always stable.

(b) What do we mean explicit and implicit method?

(c) What is the role of step size control for integration method?
3. (a) What are the types of mathematical model in chemical engineering? Develop a model for simple flash and analyse in terms of variables, degrees of freedom, no of equations.
(b) Consider a reaction

\[ A \rightarrow B \]

The differential equation for species A is

\[
\frac{dC_A}{dt} = -kC_A
\]

The initial condition is: at \( t = 0 \), \( C_A = 1 \) mol/m³.

The rate constant of the reaction is 1 s⁻¹. Using the Runge-Kutta fourth order method, determine the concentration of A at 5 s. Assume step size = 0.1 s.

4. (a) What are the uses of Mathematical Model. Consider the following flowsheet

Calculate the degrees of Freedom according to Westerberg et al (CAPD).

(b) Benzene(1), toluene(2), styrene(3) are to be separated in the sequence of distillation column in Figure below. Determine molar flow rates of \( D_1 \), \( B_1 \), \( D_2 \), and \( B_2 \) using Gauss-Seidel method.
There are FOUR questions in this Section. Answer any THREE.

5. Figure for Question No. 5 shows a single vapor-liquid equilibrium stage. The liquid and the vapor streams pot of the stage are in equilibrium.

The model to calculate the stage temperature can be written as:

\[ y_{out,i} = k_i x_{out,i} \quad \text{and} \quad \sum y_{out,i} = 1.0 \]

\[ k_i = \frac{p_i^*}{P} \quad \text{where,} \quad p_i^* \text{ is the pure component vapor pressure in mm Hg and} \ P \ \text{is the total pressure in mm Hg.} \]

Where, \( \log_{10}(p_i^*) = A_i - \left( \frac{B_i}{C_i + T} \right) \), \( T \) is the stage temperature in °C.

Given: \( P = 760 \) mm Hg; and there are two components and \( x_{out,1} = 0.5 \) and \( x_{out,2} = 0.5 \).

(a) Write the model equations in function form.

(b) Convert the set of non-linear equations to a set of linear equations.

(c) Write the Jacobian Matrix of the model.

(d) Write a Matlab code to solve the model.

6. (a) Write down the steps that should be followed to solve an optimization problem.

(b) What are the major difficulties experienced in formulating optimization problems?

(c) Find the point on the curve \( f = 3x^2 + 5x + 2 \) nearest the origin.

(d) The dependent variable \( y \) is related with the independent variable \( x \) by \( y = a x \exp(-bx) \). You are supplied with ten experimental data points for \( y \) vs \( x \). Show how would you use least-squares method to find \( a \) and \( b \).
7. (a) Does the following constraint set form a convex region?

\[ x_1^2 + x_2^2 - 9 = 0 \]
\[ x_1 + x_2 \leq 1 \]
\[ x_1 + x_2 \leq 1 \]

(b) Find the maximum of the function \( f(x) = 1 - 8x + 2x^3 - \frac{10}{3}x^3 + \frac{1}{4}x^4 + \frac{4}{5}x^5 + \frac{1}{6}x^6 \)

(i) Analytically [ Hint: \( f'(x) = (1 + x)^2(2 - x) \) ]

(ii) By Newton's method (two iterations will suffice). Start at \( x = -2 \)

(iii) By quadratic interpolation (three iterations will suffice). Start from \( x = -2, 0 \) and 1.

8. A farmer is raising pigs for market, and he wishes to determine the quantities of the available types of feed that should be given to each pig to meet certain nutritional requirements at a minimum cost. The numbers of each type of basic nutritional ingredient contained within a kg of each feed type is given in the following table, along with the daily nutritional requirements and the feed costs:

<table>
<thead>
<tr>
<th>Nutritional ingredient</th>
<th>Corn</th>
<th>Slaughterhouse Waste</th>
<th>Slaughterhouse Oil cake</th>
<th>Minimum daily requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbohydrate</td>
<td>9</td>
<td>2</td>
<td>4</td>
<td>20</td>
</tr>
<tr>
<td>Protein</td>
<td>3</td>
<td>8</td>
<td>6</td>
<td>18</td>
</tr>
<tr>
<td>Vitamin</td>
<td>1</td>
<td>2</td>
<td>6</td>
<td>15</td>
</tr>
<tr>
<td>Cost, Tk/kg</td>
<td>21</td>
<td>18</td>
<td>15</td>
<td></td>
</tr>
</tbody>
</table>

(a) Formulate the linear programming model for the problem.

(b) Construct the initial simplex tableau, introducing artificial variables and so forth as needed for applying the simplex method.

(c) Solve the problem by simplex method.

(d) Write a Matlab code to solve the problem by linear programming.
SECTION – A

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

1. (a) What are the basic components in any Environmental Management system? Write a short note on: ISO series related to Environmental Management System. (10+10)
   (b) How environmental auditing help to any control environmental hazard of industry? (10)
   (c) Compose different types of auditing. (5)

2. (a) Describe the factors affecting dispersion of air pollutants. What is Gaussian dispersion model? Write down the types of air monitoring instrumentation. (8+3)
   (b) Why Air/Fuel ratio is important in combustion process? (8)
   (c) Write down the mechanism of FGD for SO₂ gas removal. (8)
   (d) On a clear summer afternoon with a wind speed of 3.20 m/s, the TSP concentration was found to be 2,000 glm⁻³ at a point 3 km downwind and 0.5 km perpendicular to the plume centerline from a coal-fired power plant. Given the following parameters and conditions, determine the TSP emission rate for power plant: (8)

<table>
<thead>
<tr>
<th>Stack parameters:</th>
<th>Atmospheric Conditions:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Height = 75.0 m</td>
<td>Pressure = 100 kPa</td>
</tr>
<tr>
<td>Diameter = 1.5 m</td>
<td>Temperature = 28°C</td>
</tr>
<tr>
<td>Exit velocity = 12.0 m/s</td>
<td>Temperature = 322°C</td>
</tr>
</tbody>
</table>

   See attached figures 2(d) (i) and 2d (ii) and Table 2(d) for additional data.

3. (a) Write a short note on different water quality parameters: (4+4)
   (i) Turbidity (ii) BOD
   (b) How water is purified in natural "water cycle"? What is "acid rain"? (4+3)
   (c) Draw and describe the water filtration plant? (6)
   (d) What are the parameters that affect the colloid stability? Show the reaction mechanism of any coagulant. (9)
   (e) What are the pH values of lime soda and Mg(OH)₂ for softening process? Name three disinfectant used in water treatment process. (2+3)

Contd ............... P/2
ChE 485

4. (a) Write a short notes on:
   (i) Primary clarifier (ii) Dechlorination (iii) the role of ultraviolet light in wastewater treatment plant.
   (b) Create a wastewater treatment model to cleanwater from textile process. (Here (i) draw the block diagram (ii) Describe primary and secondary wastewater treatment)
   (c) What are the common microbes in wastewater system and their operation ranges? Briefly describe the role of "Digester" for removing microbes from wastewater?

   \((5 \times 3)\)
   \((10)\)
   \((5+5)\)

SECTION – B

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

5. (a) Compare the main features of the Environment Conservation Acts adopted in Bangladesh.
   (b) Write down the requirements of Environmental clearance for four categories of industries.
   (c) What do you understand by the term-"EIA"?

   \((10)\)
   \((20)\)
   \((5)\)

6. (a) Draw a simplified flow chart of a Nitrogenous Fertilizer Production Unit and point out the origins of pollutants.
   (b) Suggest some \(\text{NO}_x\) and \(\text{SO}_2\) reduction methods suitable for Ammonia - Urea plants.
   (c) Write a short note on Environmental Management System of a fertilizer plant.

   \((15)\)
   \((15)\)
   \((5)\)

7. (a) Discuss the environmental impact of Petroleum Industries.
   (b) Suggest some remedies for reduction of air pollution level of a Refinery.

   \((25)\)
   \((10)\)

8. (a) Draw a block diagram of a Leather industry pointing the sources of air and water pollution components.
   (b) Explain the steps that are involved in Effluent Treatment Process of Leather and Textile industries of Bangladesh.

   \((10)\)
   \((25)\)
**TABLE 20**  
Table for $2(d)$  

<table>
<thead>
<tr>
<th>Surface Wind speed (at 10 m) (m/s)</th>
<th>Incoming solar radiation</th>
<th>Night*</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Strong</td>
<td>Moderate</td>
</tr>
<tr>
<td>&lt;2</td>
<td>A</td>
<td>A-B</td>
</tr>
<tr>
<td>2-3</td>
<td>A-B</td>
<td>B</td>
</tr>
<tr>
<td>3-5</td>
<td>B</td>
<td>B-C</td>
</tr>
<tr>
<td>5-6</td>
<td>C</td>
<td>C-D</td>
</tr>
<tr>
<td>&gt;-6</td>
<td>C</td>
<td>D-D</td>
</tr>
</tbody>
</table>

*The neutral class, D, should be assumed for overcast conditions during day or night. Note that "thinly overcast" is not equivalent to "overcast."

Notes: Class A is the most unstable and class F is the most stable class considered here. Night refers to the period from one hour before sunset to one hour after sunrise. Note that the neutral class, D, can be assumed for overcast conditions during day or night, regardless of wind speed.

"Strong" incoming solar radiation corresponds to a solar altitude greater than 60° with clear skies; "slight" insolation corresponds to a solar altitude from 15° to 35° with clear skies. Table 170, Solar Altitude and Azimuth, in the Smithsonian Meteorological Tables, can be used in determining solar radiation. Incoming radiation that would be strong with clear skies can be expected to be reduced to moderate with broken (5/8 to 7/8 cloud cover) middle clouds and to slight with broken low clouds.


---

**FIGURE 20**  
1. (a) A sample natural gas has the following composition.

<table>
<thead>
<tr>
<th>Component</th>
<th>Mol wt</th>
<th>Mole frac</th>
</tr>
</thead>
<tbody>
<tr>
<td>N₂</td>
<td>28.02</td>
<td>0.0062</td>
</tr>
<tr>
<td>CO₂</td>
<td>44.01</td>
<td>0.0084</td>
</tr>
<tr>
<td>H₂S</td>
<td>32.06</td>
<td>0.0068</td>
</tr>
<tr>
<td>C₁</td>
<td>16.04</td>
<td>0.8668</td>
</tr>
<tr>
<td>C₂</td>
<td>30.07</td>
<td>0.0391</td>
</tr>
<tr>
<td>C₃</td>
<td>44.09</td>
<td>0.0280</td>
</tr>
<tr>
<td>nC₄</td>
<td>58.12</td>
<td>0.0224</td>
</tr>
<tr>
<td>nC₅</td>
<td>72.15</td>
<td>0.0224</td>
</tr>
</tbody>
</table>

Assuming real gas behavior, calculate molecular weight specific gravity, pseudocritical pressure and temperature, and density at 1000 Psia and 100°F.

(b) Show that the isothermal compressibility of an ideal gas at any pressure is inverse of that pressure.

(c) Draw and explain Z vs P graph.

2. (a) What are the phase diagrams? What are the uses of phase diagrams?

(b) Draw the followings:
- Density – Temperature diagram of a single component system
- PV diagram of a two components system
- Composite P-T diagram of a two components system
- Pressure – composition diagram for a two components system at temperature between the critical temperature of the two pure components.
- PV diagram of a multicomponents system

(c) State the law of rectilinear diameter. What are the uses of a density – temperature diagram of a single component system?
3. (a) Write short notes on the followings- (3x5=15)
   (i) Dew point depression
   (ii) Partial pressure approach for water content calculation.
   (iii) Conditions promoting hydrate formation.

(b) List three methods for preventing hydrate formation at wellsites
   (5)

(c) Justify the following statement:
   - Natural gas hydrates can be a future source of energy.
   (5)

(d) A gas at 1000 psia has the following analysis: N₂ = 1.7%, CO₂ = 0.3%, C₄ = 65.5%,
    C₂ = 16.61%, C₃ = 8.8%, n-C₄ = 3%, i-C₄ = 1.6%, n-C₅ = 0.9%, C₆ = 0.5%,
    C₇ = 0.2%.

   What is the water content of this gas at 120°F? Use all the methods applicable and
   compare the results. (10)

4. (a) What are the criteria for the selection of a dehydration plant? (5+10+5=20)

   List the properties of a good solid and liquid dessicant.
   Name some widely used solid and liquid dessicants.

(b) What are the available processes for NGL extraction? (5)

(c) Draw natural gas cycle. (5)

(d) Write a short note on natural gas transportation (5)

SECTION – B

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

5. (a) With the help of illustrations explain the reasons why regular flow after flow back pressure test evolved to modified isochronal test? (18)

(b) Explain the variation in the index (n) and co-efficient (c) of the back pressure
equations
   \[ q = c (p_2^2 - p_w^2)^n \]
   with time and flow. (5)

(c) Starting from Darcy's equation for a spherical flow system, derive an expression for
   pressure p at any radius r for gas. (12)

6. (a) Estimate AOF from the modified isochronal test data provided in Table 1. (20)

Contd ……….. P/3
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Contd ... Q. No. 6(a)

Table 1: Modified isochronal Test Data.

<table>
<thead>
<tr>
<th>Test</th>
<th>Duration</th>
<th>( P_{\text{w}1} ) or ( P_{\text{w}2} ) (hrs)</th>
<th>( q_g ) (MMscf/D)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pretest shut-in</td>
<td>20</td>
<td>1,948</td>
<td>—</td>
</tr>
<tr>
<td>First flow</td>
<td>12</td>
<td>1,784</td>
<td>4.50</td>
</tr>
<tr>
<td>First shut-in</td>
<td>12</td>
<td>1927</td>
<td>—</td>
</tr>
<tr>
<td>Second flow</td>
<td>12</td>
<td>1,680</td>
<td>5.60</td>
</tr>
<tr>
<td>Second shut-in</td>
<td>12</td>
<td>1911</td>
<td>—</td>
</tr>
<tr>
<td>Third flow</td>
<td>12</td>
<td>1,546</td>
<td>6.85</td>
</tr>
<tr>
<td>Third shut</td>
<td>12</td>
<td>1,887</td>
<td>—</td>
</tr>
<tr>
<td>Fourth flow</td>
<td>12</td>
<td>1,355</td>
<td>8.25</td>
</tr>
<tr>
<td>Extended flow (stabilized)</td>
<td>81</td>
<td>1,233</td>
<td>8.00</td>
</tr>
<tr>
<td>Final shut-in</td>
<td>120</td>
<td>1948</td>
<td>—</td>
</tr>
</tbody>
</table>

(b) Suggest 5 measures to improve energy management in Bangladesh

(c) What are acid gases? Why are they needed to be removed from the produced gas?

7. (a) What is vertical separator? Write down its advantage and disadvantage. Draw neat sketch of vertical separator and level it. When vertical separator is preferable over horizontal separator?\( (3+4+5+3=15) \)

(b) Explain the Low Temperature Separation (LTS) process plant in Titas gas field with flow diagram starting from wellhead to sales point.

(c) In the tree format, name all the gas sweetening processes. Which would you prefer for Bangladeshi gas field.

8. (a) Derive an expression for the size of the smallest droplet that can be removed by a centrifuge? \( (10) \)

(b) What happens to separation quality and the separator when
   (i) the gas flow rate exceeds the allowable rate through the separator.
   (ii) the liquid flow rate exceeds the allowable rate through the separator.

(c) What is gas cleaning? Why it is necessary? Write down the different gas cleaning methods.

(d) In designing a separator, describe the gas capacity and liquid capacity of a separator.

(e) List at least three basic factors that must be considered in designing separator.
Fig. 4. Campbell's correlation for water content of sweet gases. (After Campbell, 1984a; courtesy of Campbell Petroleum Series.)

Fig. 5. Water content of CO₂ in saturated natural gas mixtures. (After Campbell, 1984a; courtesy of Campbell Petroleum Series.)

Fig. 6. Water content of H₂S in saturated natural gas mixtures. Note: Solid curved lines are for pure H₂S only. (After Campbell, 1984a; courtesy of Campbell Petroleum Series.)
Robinson et al. correlation for water content of sour gases in the 3,000-6,000 psia pressure range, and at 10,000 psia. (After Robinson et al., 1978; courtesy of Oil & Gas Journal.)
Fig. 2. Robinson et al. correlation for water content of sour gases in the 300–2,000 psia pressure range. (After Robinson et al., 1978; courtesy of Oil & Gas Journal.)

For a no. 1(a)
Compressibility factors for natural gases. (After Standing and Katz, Trans.)