2015-2016
M.TECH. AUTUMN (I SEMESTER) EXAMINATION
(PETROCHEMICAL ENGINEERING)
ADVANCED MATHEMATICS
MATHEMATICS
[AM 641]

Max Marks: 60
Duration: Three Hours

Note: Answer five questions, selecting at least two from each section.
Programmable calculators are not allowed.

SECTION — ‘A’

1. (a) Let L be the set of all vectors of the form \((x, 2x, -3x, x)\) in the vector space \(V_4\).
   Show that L is a subspace of \(V_4\).
   \[6+6\]

(b) Let \(T : V_2 \to V_3\) be a linear transformation defined by \(T(x_1, x_2) = (x_1 + x_2, 2x_1 - x_2, 7x_2)\).
   Determine the matrix \(T\) relative to the standard bases \(B_1 = \{e_1, e_2\}\) and \(B_2 = \{f_1, f_2, f_3\}\).

2. (a) Use power method to find the largest eigenvalue in modulus and corresponding eigenvector of the matrix
   \[
   A = \begin{bmatrix}
   -15 & 4 & 3 \\
   10 & -12 & 6 \\
   20 & -4 & 2
   \end{bmatrix}
   \]
   \[6+6\]

(b) Show that the eigenvalues of a real symmetric matrix are real.

3. (a) Prove that the eigen vector \(u^j\) of a real matrix \(A\) corresponding to the eigen values \(\lambda_i\) is orthogonal to the complex conjugate of every eigen vector \(v^j\) of \(A^T\) corresponding to an eigen value \(\lambda_j\) distinct from \(\lambda_i\).
   \[6+6\]

(b) State Fredholm alternative solvability conditions. Let
   \[
   A = \begin{bmatrix}
   2 & 1 & -3 \\
   1 & -3 & 2 \\
   -3 & 2 & 1
   \end{bmatrix}
   \]
   determine –
   (i) whether \(Au = (2, 4, 7)^T\) has a solution
   (ii) for what value of \(a\), does \(Au = (2, a, 8)^T\) possess a solution.

SECTION — ‘B’

4. (a) Convert the following second order initial value problem into the system of first order initial value problem –
   \[ty'' - y' + 4t^2y = 0, \quad y(1) = 1, \quad y'(1) = 2.\]
   \[5+7\]

(b) Solve the initial value problem
   \[
   \frac{du}{dt} = Au, \quad u(0) = [1, 0]^T, \text{ where}
   \]
   \[
   A = \begin{bmatrix}
   -2 & 1 \\
   1 & -20
   \end{bmatrix}
   \quad \text{and} \quad u = \begin{bmatrix} u_1 \\ u_2 \end{bmatrix}
   \]
   Is the system asymptotically stable?

Contd……2
5. (a) Solve the system of equations
\[ u' = -3u + 2v, \quad u(1.1) = 0 \]
\[ v' = 3u - 4v, \quad v(1.1) = 0.5 \]
with \( h = 0.2, \ 1.1 \leq t \leq 1.3 \) by using Runge–Kutta fourth order method.

(b) Solve \( \frac{\partial u}{\partial t} = \frac{\partial^2 u}{\partial x^2} \), subject to the initial condition \( u = \sin \pi x \) at \( t = 0 \) for \( 0 \leq x \leq 1 \) and the boundary conditions \( u = 0 \) at \( x = 0 \) and \( x = 1 \) for \( t > 0 \). Taking \( h = 0.2, \lambda = 1 \) and compute the values of \( u \) at the internal mesh points upto two time steps.

6. (a) Solve the boundary value problem \( \frac{\partial^2 u}{\partial t^2} = \frac{\partial^2 u}{\partial x^2} \), subject to the condition
\[ u(0, t) = u(4, t) = 0. \]
\[ \frac{\partial u}{\partial t}(x, 0) = 0, \quad u(x, 0) = 4x - x^2 \] upto two time levels. Taking \( h = \alpha = 1 \).

(b) Solve the Laplace’s equation over the boundary of a square of unit length with \( u(x, y) = 16x^2y^2 \) on the boundary. Taking \( h = k = \frac{1}{4} \).

7. Do any two parts:

(a) State and prove the change of scale property of Fourier transform.

(b) Find the Fourier transform of \( f(x) \) defined as
\[ f(x) = \begin{cases} 1, & |x| < a \\ 0, & |x| > a \end{cases} \]
and hence evaluate
\[ (i) \int_{-\infty}^{\infty} \frac{\sin s \cos x}{s} ds \quad (ii) \int_{0}^{\infty} \frac{\sin s}{s} ds \]

(c) Find the Fourier cosine transform of \( f(x) = e^{ax^2} \).
2015-16
M.TECH.(AUTUMN SEMESTER) EXAMINATION
CHEMICAL/PETROCHEMICAL ENGINEERING
PROCESS MODELLING & SIMULATION-1
CH-615/PK-616

Maximum Marks: 60  
Credits: 04  
Duration: Three Hours

Answer all the questions.
Assume suitable data if missing.
Notations used have their usual meaning.
Use of transport phenomena equations is allowed.

Q.No.  Question  M.M.

1(a) Explain the application of process modelling in chemical processing.  [6]

OR

1'(a) Write about the use of algebraic equations, ordinary differential equations and partial
differential equations in process modelling.  [6]

1(b) Explain and differentiate between the models:
(I) Linear model and nonlinear model
(II) Static model and dynamic model
(III) Lumped parameter model and distributed parameter model  [9]

2 Consider that benzoic acid (BA) is continuously extracted from toluene using water as a
solvent. The two streams are fed into tank A (mixer) where they are stirred vigorously and mixture then pumped into tank B (settler) where it is allowed to settle into two layers (extract and raffinate). The upper toluene layer (raffinate) and lower the water layer (extract) are removed separately.
(I) Develop a model and obtain an expression for the extraction of BA in a
steady state operation with two stages. Each stage still consists of two
tanks, a mixer and a settler with counter-current flow through the stages.
Find out what fraction of BA has passed into the solvent phase.

(II) Compute the fraction of solute (BA) that can be extracted in a two stage
counter-current solvent extraction using numerical values of S=14R,
m=1/9 and c=0.15 kg/m³. Also find out fraction (E) of BA extracted.

Contd.....2.
Where \( R \) (m\(^3\)/s) toluene; \( c \) (kg/m\(^3\)) BA; \( S \) (m\(^3\)/s) water, \( m \) is distribution coefficient, \( \alpha \) is the ratio of rates of feed to the solvent, \( E \) is the fraction extracted.

A closed kettle as shown in the figure below having total surface area \( A \) m\(^2\) is heated through this surface by condensing steam at temperature \( T \) (K). The kettle is charged with \( M \) kg of liquid of heat capacity \( C_p \) (J/Kg at a temperature of \( T_0 \) (K). If the process is controlled by heat transfer coefficient \( h \) (W/m\(^2\)K), how does the temperature of the liquid vary with time?

A wetted wall column is to be used for absorption of gas A. The gas is consumed in the liquid phase by first order reaction in terms of the gas concentration of A in the liquid phase. Develop a mathematical model in the form of a differential equation. Let \( L \) be the uniform thickness of the film, \( v(x) \) is the velocity distribution, \( v=V[1-(x/L)^2] \) where \( V \) is the maximum velocity (at \( x=0 \)).

Contd.....3.
3'(b) Derive the equation to obtain following form of the VLE (vapour liquid equilibrium) relationship for multi component mixture used in the design of distillation column.

\[ y_i = \frac{\alpha_{ij} x_i}{1 + \sum_{i=1}^{N_c} (\alpha_{ij} - 1) x_i} \]

\( \alpha_{ij} \) = relative volatility
\( x_i \) = mole fraction of component i in liquid phase
\( y_i \) = mole fraction of component i in vapour phase
\( N_c \) = number of components present in the mixture
\( j \) = reference component

Consider a continuous stirred tank bioreactor (CSTB) the substrate (S) promotes the growth of biomass (x). A biochemical first order reaction takes place \( A \rightarrow P \) (where A is reactant and P is the product and k is reaction rate constant)

Develop dynamic model of (CSTB) in the following form.

\[ \begin{align*}
\frac{dx}{dt} &= (\mu - D)x \\
\frac{dS}{dt} &= D(S_p - S) - \frac{\mu x}{y} \\
\mu &= \frac{\mu_m S}{K_m + S}
\end{align*} \]
where \( x \) is the biomass concentration (mass of cell/volume)
\( S \) is the substrate concentration (mass of substrate/volume)
\( F \) = volumetric flow rate of feed stream
\( V \) = volume of bioreactor
\( x_f \) and \( S_f \) is the biomass and substrate concentration respectively in the feed stream
\( \mu_m \) = maximum achievable growth
\( K_m \) is limiting substrate concentration
\( D \) is the dilution rate
\( Y \) is the yield

Continuous Stirred Tank Bioreactor
Note: All questions carry equal marks. Answer any four questions.

1. (a) Explain when a heat exchanger is called as compact heat exchanger. List the various types of compact heat exchangers and describe the working principle of a compact heat exchange with a schematic diagram.
   \[ \text{[05]} \]

(b) Draw the temperature profile for a co-current heat exchanger and explain its significance from industrial point of view.
   \[ \text{[02]} \]

(c) Show/derive an equation, for a fluid flowing in laminar flow in a pipe/tube, to calculate the friction factor.
   \[ \text{[04]} \]

(d) Define NPSH and its importance and Gross flow.
   \[ \text{[04]} \]

2. (a) Explain the pinch technology and its application in the petroleum refining industries with an example.
   \[ \text{[04]} \]

(b) In a refining, exhaust steam at low pressure is available in abundance. The exhaust steam is of limited use or of process value as its saturation is low. However it has been found from various estimates that the cost of the exhaust steam is \( \frac{1}{4} \) to \( \frac{1}{8} \) of the live process stream. In view of this, it has been decided to use this stream by employing two heat exchangers in perview to preheat the feed water to an intermediate temperature in the first heat exchanger and then to desired temperature in the second heat exchanger. Derive an equation to calculate the intermediate temperature so that exhaust steam is utilized effectively.
   \[ \text{[09]} \]

(c) Explain the sub cooled and saturated boiling.
   \[ \text{[02]} \]

3. (a) Draw the heat transfer coefficient profile along the length of a long heat vertical plate if air enter from the bottom of the plate.
   \[ \text{[02]} \]

(b) Draw the temperature profile for the wall temperature and liquid temperature along the long heated vertical pipe/tube if a sub cooled liquid enters through the tube and explain the same.
   \[ \text{[03]} \]

(c) Describe the basis on which the film boiling equation for the prediction of heat transfer coefficient has been developed.
   \[ \text{[03]} \]

(d) A heated surface of Radius \( R \) is suspended in a large motionless body of fluid. It is desired to study the heat conduction in the fluid surrounding the sphere. Show that temperature distribution, \( T_r \), corresponding to any radius \( r \) in the sphere is;
   \[ \frac{Tr - T_\infty}{Tr - T_\infty} = \frac{R}{r}, \text{where,} \quad T_R = \text{Surface temperature,} \]

and \( T_\infty = \text{Fluid temperature at infinite radius from the Centre} \)

and the heat transfer coefficient expressed as Nusselt number, \( N_u \), in dimensionless form is \( Nu = 2 \). Steady state heat conduction equation through the sphere is

\[ \frac{1}{r^2} \frac{d}{dr} \left( r^2 \frac{dT}{dr} \right) = 0 \]
4. (a) Derive the one dimensional in equation for variable cross section. State the assumption clearly.

(b) A thin fin of length L has its two ends attached to two large parallel plates which are maintained at temperature $T_1$ and $T_2$. The ambient air which is at a temperature $T_a$ surrounds the fin. Show that the temperature distribution along the length of the fin is given by:

$$T = (T_1 - T_\infty) \frac{\sin h mL (L - x)}{\sin h mL} + (T_2 - T_\infty) \frac{\sin h mx}{\sin h mL}$$

The equation derived in question 4 (a) is to be employed. Where $m = \left(\frac{2k}{\lambda_t}\right)^{\frac{1}{2}}$ and $k$ = thermal conductivity and $t$ = thickness of the fin.

5. (a) Explain the various flow patterns observed for a gas and liquid mixture flowing concurrently in a horizontal pipe with the help of suitable diagrams, if the gas flow rate is increased slowly.

(b) A mixture of gas and liquid flows through a pipe of internal diameter 0.015m at a steady flow rate of 1.0 kg/s. The dynamic viscosities of gas and liquid are 80 Kg/m$^3$ and 1200 Kg/m$^3$ respectively. The wt fraction of the gas is 0.149. Calculate the pressure gradient in the pipe using Lockhart - Martinelli method.

Given: 1000 cp = 1.0 Ns/m$^2$

The two phase correction factor, $\phi$, can be calculated by Chisholm equation

$$\phi^2 = 1 + \frac{C}{X}$$

Where $X$ is the Lockhart Mortenilli parameter and 'C' can be calculated from the table given as below:

<table>
<thead>
<tr>
<th>Liquid</th>
<th>Gas</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Turbulent</td>
<td>Turbulent</td>
<td>20</td>
</tr>
<tr>
<td>Laminar</td>
<td>Turbulent</td>
<td>12</td>
</tr>
<tr>
<td>Turbulent</td>
<td>Laminar</td>
<td>10</td>
</tr>
<tr>
<td>Laminar</td>
<td>Laminar</td>
<td>05</td>
</tr>
</tbody>
</table>

Where $X = \left[\left(\frac{1-x}{x}\right)^{0.9}, \left(\frac{\mu_G}{\mu_L}\right)^{0.5}\right]$ when both phases are in turbulent flow

$$X = \left[\left(\frac{1-x}{x}\right), \left(\frac{\mu_G}{\mu_L}\right)^{0.5}\right]$$ when both phases are in laminar flow

$$f = 16 / Re$$ for laminar flow and

$$f = 0.306 / Re^{0.25}$$ for turbulent flow

Why pressure drop is more for a gas=liquid mixture over the single phase flowing with the same flow rate.

6. Derive the Von-Karmann integral equation for the boundary layer flow of a Newtonian liquid over a horizontal flat plate with zero pressure gradient and calculate the thickness of boundary layer for a fluid flowing, in turbulent region over a flat plate employing the Von-Karmann integral equation.
<table>
<thead>
<tr>
<th>Q.No.</th>
<th>Question</th>
<th>M.M.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1(a)</td>
<td>Name at least 5 Indigenous and 5 Imported Crude resources in India. Discuss the quality of Bombay High and Ankleshwar Crudes.</td>
<td>04</td>
</tr>
<tr>
<td>1(b)</td>
<td>Differentiate between different types of rocks. Discuss about migration of Oil and Gas and different types of “Traps” with figure.</td>
<td>06</td>
</tr>
<tr>
<td>1(c)</td>
<td>Differentiate between Gravity and Seismic methods of oil exploration and, also name some non-explosive &amp; environmental friendly techniques of Seismic surveys.</td>
<td>05</td>
</tr>
<tr>
<td>2(a)</td>
<td>Differentiate between Cable tool method and Rotary Drilling method. What are the limitations of the Cable Tool method?</td>
<td>04</td>
</tr>
<tr>
<td>2(b)</td>
<td>Name different types of drill fluids and describe their functions. Why crew members put additives in drill fluids?</td>
<td>06</td>
</tr>
<tr>
<td>2(c)</td>
<td>Discuss briefly different techniques of Enhanced oil recovery. Explain three approaches of Microbial injection.</td>
<td>05</td>
</tr>
</tbody>
</table>

OR

<table>
<thead>
<tr>
<th>2'(a)</th>
<th>Differentiate any two of the following:</th>
<th>04</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>a) Jack up Rig and Semisubmersible rig.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>b) Kick and BOP.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>c) Kelly and Top drive system</td>
<td></td>
</tr>
</tbody>
</table>

| 2'(b) | Name and explain different types of Bits. When the lower bottom hole assembly becomes stuck which tool can be used to free it and how? | 06   |

Contd...2.
2(c) What are the different steps of oil well completion? Describe Casing and Gravel Pack in detail.

3(a) Give the different products of Crude oil Distillation, mentioning their boiling range and carbon range. What are the critical parameters you will select to evaluate a crude oil and why?

3(b) Differentiate between ASTM and TBP distillation. How TBP distillation data help in the evaluation of crude oil?

3(c) Explain the method of operation of a multidraw atmospheric distillation column. How does it differ from conventional distillation? Describe the significance of Flash zone, Refluxing and Steam Stripping and explain why reboilers are not used in a crude distillation column.

OR

3(c') What is the need of Desalting of Crude Oil? Discuss Electrical Desalting of crude oil with the effect of Desalter Temperature, Pressure and water injection rate.

4(a) What are the different streams that can be used for producing motor Gasoline and Diesel Fuel? Discuss the principles behind Spark Ignition Engine and Compression Ignition Engine.

4(b) Discuss Vapour Locking and Crankcase dilution. Differentiate between Diesel Index and Performance Number.

OR

4(b') Differentiate between Cloud Point, pour Point and Cold Flow Plugging Point. What will be the right position of thermometer bulb for the measurement of cloud point and why?

4(c) What are the objectives of Reforming in the present day scenario? Draw a neat process flow sheet of semi regenerative catalytic reforming process for the enhancement of octane number of gasoline and describe it with the help of its reaction mechanism and reasons of using more than one reactor.
Maximum Marks: 60  Credits: 04  Duration: Three Hours

**Answer all the questions. Assume suitable data if missing. Notations used have their usual meaning.**

**Q1(a).** Describe with the help of examples various mechanism/means of separations used in Petrochemical/Chemical Industries. [5]

**Q1(b)** Following is the composition of feed to the distillation tower: (n-butane \( x_A = 0.40 \)), n-pentane \( x_B = 0.25 \)), n-hexane \( x_C = 0.20 \)), n-heptane \( x_D = 0.15 \)). At a pressure of 405.3 kPa, boiling point of the feed is 70°C. Calculate the

1. Dew point of the feed and composition of liquid in equilibrium
2. Temperature and composition of both the phases when 40 % of the feed is vaporized in a flash distillation.

**OR**

**Q1(b').** The Liquid feed of 100 mol/h having composition in mole fraction as (n-butane \( x_A = 0.35 \)), n-pentane \( x_B = 0.20 \)), n-hexane \( x_C = 0.25 \)), n-heptane \( x_D = 0.20 \)) is fed to a distillation tower at pressure 405.3 kPa. Boiling and dew point is 130 °C and 65 °C respectively. Calculate the following:

1. Minimum Number of stages, \( N_m \)
2. If \( R = 1.5 \) \( R_m \) and \( R_m = 0.532 \), determine the number of theoretical stages and feed tray location.

Contd.....2.
Q2. For the distillation column shown in Figure 1, use Tridiagonal Matrix procedure to compute $x_{ij}$ for component nC₄ (2). Use composition independent K-values from the Table 1.

![Distillation Column Diagram](image)

Figure 1

<table>
<thead>
<tr>
<th>Component</th>
<th>$K_{ij}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C_3(1)$</td>
<td>1.23</td>
</tr>
<tr>
<td>nC₄(2)</td>
<td>0.33</td>
</tr>
<tr>
<td>nC₅(3)</td>
<td>0.103</td>
</tr>
<tr>
<td></td>
<td>1.63</td>
</tr>
<tr>
<td></td>
<td>2.17</td>
</tr>
<tr>
<td></td>
<td>2.70</td>
</tr>
<tr>
<td></td>
<td>3.33</td>
</tr>
<tr>
<td></td>
<td>0.50</td>
</tr>
<tr>
<td></td>
<td>0.71</td>
</tr>
<tr>
<td></td>
<td>0.95</td>
</tr>
<tr>
<td></td>
<td>1.25</td>
</tr>
<tr>
<td></td>
<td>0.166</td>
</tr>
<tr>
<td></td>
<td>0.255</td>
</tr>
<tr>
<td></td>
<td>0.36</td>
</tr>
<tr>
<td></td>
<td>0.49</td>
</tr>
</tbody>
</table>

Table 1

Q3. Explain with the help of neat sketch any three of the following [15]

1. Spray Extraction Towers
2. Residue Curve Maps
3. Homogeneous Azeotropic Distillation
4. Distillation Curve Maps

Q4(a) Toluene as dispersed phase is being used to extract diethylamine [6]

Contd....3.
from a dilute water solution in a packed tower of 1-in Pall rings at 26.7°C. The flow rate of toluene \( V = 84 \text{ ft}^3/\text{h} \) and of water solution \( L = 56 \text{ ft}^3/\text{h} \). The physical properties of dilute solutions are: for the aqueous continuous phase (C), \( \rho_c = 62.2 \text{ lb/ft}^3 \), \( \mu_c = 0.860 \text{ cp} \); for the dispersed phase, \( \rho_D =\text{54.0lb/ft}^3 \). The interfacial tension (\( \sigma = 25 \text{ dyn/cm} \)). Calculate

1. Flooding Velocity
2. Using 50% flooding, determine the tower diameter
3. Using 50% flooding with aqueous phase dispersed phase instead of the toluene find the diameter of the tower.

Q4(b)

(i) A mixture weighing 1000 kg contains 23.5 wt% acetone and 76.5 wt% water and is to be extracted by 500 kg methyl isobutyl ketone in a single stage extraction. Determine the amounts and compositions of the extract and raffinate phases. Equilibrium data is given in Table 2.

(ii) Acetic acid is being extracted from water by the solvent methyl isobutyl ketone in a perforated plate tower at 25°C. The flow rate of the continuous phase is 120 \( \text{ft}^3/\text{h} \) and that of the disperses solvent phase is 240 \( \text{ft}^3/\text{h} \). the interfacial tension is 9.1 dyn/cm. The tray spacing is 1.0 ft and the hole size on the tray is 0.25 in. Estimate the fraction tray efficiency.

OR

Q4(b'). An aqueous feed solution of 1000 kg/h containing 23.5 wt% acetone and 76.5 wt% water is being extracted in a countercurrent multistage extraction system using pure methyl isobutyl ketone solvent at 298-299 K. The outlet water raffinate will contain 2.5wt% acetone. Equilibrium data is given in Table 2.

1. Calculate the minimum solvent that can be used.
2. Using a solvent flow rate of 1.5 times the minimum, calculate the number of theoretical stages.

Contd.....4.
Table 2

<table>
<thead>
<tr>
<th>MIK</th>
<th>Acetone (wt%)</th>
<th>Water (wt%)</th>
<th>Water Phase (wt%)</th>
<th>MIK Phase (wt%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>98.0</td>
<td>0</td>
<td>2.00</td>
<td>2.5</td>
<td>4.5</td>
</tr>
<tr>
<td>93.2</td>
<td>4.6</td>
<td>2.33</td>
<td>5.5</td>
<td>10.0</td>
</tr>
<tr>
<td>77.3</td>
<td>18.95</td>
<td>3.86</td>
<td>7.5</td>
<td>13.5</td>
</tr>
<tr>
<td>71.0</td>
<td>24.4</td>
<td>4.66</td>
<td>10.0</td>
<td>17.5</td>
</tr>
<tr>
<td>65.5</td>
<td>28.9</td>
<td>5.53</td>
<td>12.5</td>
<td>21.3</td>
</tr>
<tr>
<td>54.7</td>
<td>37.6</td>
<td>7.82</td>
<td>15.5</td>
<td>25.5</td>
</tr>
<tr>
<td>46.2</td>
<td>43.2</td>
<td>10.7</td>
<td>17.5</td>
<td>28.2</td>
</tr>
<tr>
<td>12.4</td>
<td>42.7</td>
<td>54.0</td>
<td>20.0</td>
<td>31.2</td>
</tr>
<tr>
<td>5.01</td>
<td>30.9</td>
<td>64.2</td>
<td>22.5</td>
<td>34.0</td>
</tr>
<tr>
<td>3.23</td>
<td>20.9</td>
<td>75.8</td>
<td>25.0</td>
<td>36.5</td>
</tr>
<tr>
<td>2.12</td>
<td>3.73</td>
<td>94.2</td>
<td>26.0</td>
<td>37.5</td>
</tr>
<tr>
<td>2.20</td>
<td>0</td>
<td>97.8</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
### Table 3: Packing Factors for Random and Structured Packing

<table>
<thead>
<tr>
<th>Type</th>
<th>Material</th>
<th>Nominal size, in</th>
<th>Void fraction, ε</th>
<th>Surface area, m²/ft³</th>
<th>Packing factor, f</th>
<th>Relative mass- transfer coefficient, k</th>
</tr>
</thead>
<tbody>
<tr>
<td>Random Packing</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Raschig Rings</td>
<td>Ceramic</td>
<td>1/2</td>
<td>0.64</td>
<td>119 (344)</td>
<td>590 (1900)</td>
<td>1.52</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1</td>
<td>0.74</td>
<td>28 (1990)</td>
<td>179 (587)</td>
<td>1.20</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1/2</td>
<td>0.73</td>
<td>37 (121)</td>
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<td>CY</td>
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<td>213 (700)</td>
<td>70 (230)</td>
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<td>Wire</td>
<td>0.90</td>
<td>150 (492)</td>
<td>21 (69)</td>
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### Table 4: Typical Performance for Several Types of Commercial Extraction Towers

<table>
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<tr>
<th>Type</th>
<th>Capacity of Combined Stages, (V_p + V_c) m³/h</th>
<th>Approximate Flooding, (V_p + V_c) m³/h</th>
<th>Spacing between Stages, T, cm</th>
<th>Overall Height of Transfer Unit, H_o, m</th>
<th>Plate Efficiency, η, %</th>
<th>Height of Equilibrium Stage, HETS, m</th>
<th>Ref.</th>
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<tbody>
<tr>
<td>Spray Tower</td>
<td>15-75</td>
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<td>3-6</td>
<td>3-6</td>
<td>M4</td>
<td>S5</td>
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<tr>
<td>Packed Tower</td>
<td>12-30</td>
<td></td>
<td>0.9-1.7</td>
<td>0.4-1.5</td>
<td>S4</td>
<td>S5</td>
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<tr>
<td>Structured Packing Tower</td>
<td>65-90</td>
<td></td>
<td>0.5-1.6</td>
<td>H4</td>
<td></td>
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<td>Sieve-Tray Tower</td>
<td>27-60</td>
<td>10-25</td>
<td>8-30</td>
<td>0.8-1.2</td>
<td>M4</td>
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<td>Pulsed Packed Tower</td>
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<td>5.1</td>
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<td>S4</td>
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<td>Schreiber Tower</td>
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<td>0.1-0.3</td>
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<td>Karr Tower</td>
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<td>80-100</td>
<td>5-15</td>
<td>0.2-0.6</td>
<td>S2</td>
<td>S4</td>
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Figure 3. Equilibrium K values for light hydrocarbon systems at 405.3 kPa absolute

Figure 4