Answer all the questions. Notations used have their usual meaning. Use of transport equation is permitted. Write the simplifying assumptions.

Q.No. 

1(a) An incompressible flow at steady state is given by its vector components:

\[ v_r = r^2 \theta, \ v_\theta = 2r^2 \theta z \] and \( v_z \) is unknown. Find \( v_z \).

1(b) Explain the steps involved in transport analysis of any viscous flow problem.

1(c) Consider the flow in a liquid film of constant thickness \( \delta \) along a vertical wall as shown in the accompanying figure.

Equation of motion reduces to:

\[ \mu \frac{d^2 v_y}{dx^2} + \rho g = 0, \quad \text{(Eq. A)} \]

where \( v_y \) is the velocity in the \( y \)-direction.

i. List down the assumptions which leads to equation (A)

ii. State the boundary conditions to be used for the solution of velocity profile.

iii. Solve for the velocity profile.

iv. Oil has a kinematic viscosity of 0.2 cp and density of 0.8 \( \times \) \( 10^3 \) \( \text{kg/m}^3 \). What should be the mass flow rate \( (w) \) of the liquid for a falling film thickness \( (\delta) \) of 2.5 mm on a vertical wall per metre of vertical plate? 

\[ \text{Contd. \ldots .2} \]
2(a) Velocity profile of a liquid is shown below:

\[ V = 0.25 \text{ m/s} \]

If the shear stress per unit surface area on the rigid plate over which the liquid flows is measured to be \( 0.083 \text{ N/m}^2 \).

i. Calculate the viscosity of the liquid.

ii. What is the maximum velocity at the free surface if the plate is tilted by an angle of 60° to the horizontal plane and the liquid is allowed to flow freely keeping the same film thickness? There is no pressure gradient in the direction of flow.

Density of the liquid is 887 kg/m³.

2(b) A cylindrical rod of radius \( kR \) moves with velocity \( V_0 \) along the axis of cylindrical cavity of radius \( R \) as shown below. The pressure at both ends of the cavity is same so that the fluid moves through the annular region solely because of the rod motion.

Derive the expression for velocity distribution and mass flow rate through the narrow annular region. Write down the simplifying assumptions.

OR

2' A liquid is falling in steady laminar flow over an inclined plane surface as shown in figure on the next page. Conditions are such that free liquid surface is maintained at \( T_0 \) and the solid surface at \( x = \delta \) is maintained at \( T = T_0 \). The corresponding fluid viscosities...
are $\mu_0$ and $\mu_0'\text{respective}$ respectively. The density and the thermal conductivity may be assumed constant. Develop an expression for the velocity distribution as a function of fluid properties. Assume that the temperature dependence of viscosity may be expressed by the equation of this form, $\mu=\mu_0 e^{B/T}$, where $A$ and $B$ are empirical constants. End effects and viscous heating may be neglected.

Temperature distribution in the film is given as:

$$\frac{T - T_0}{T' - T_0} = \frac{x}{\delta}$$

Consider two concentric porous spherical shells of radii 'KR' and 'R' (shown in figure on next page). The inner surface of the outer one is at $T = T_1$, and the outer surface of the inner one is to be maintained at lower temperature $T = T_k$. Dry air at temperature $T = T_k$ is blown outward radially from the inner shell into the intervening space and out through the outer shell. (i) Develop an expression for the required heat removal from the inner sphere as a function of mass rate of flow of gas, $w_r$. Assume steady laminar flow, and low gas velocity. Temperature distribution between the two shells is given as:

$$\frac{T - T_1}{T_k - T_1} = \frac{e^{-Ro}}{e^{-Ro}} - \frac{e^{-Ro}}{e^{-Ro}}$$

Where, $Ro = \frac{w_rC_p}{4\pi k}$

(ii) List down the assumptions which leads to equation (B). Obtain the expression for the temperature distribution when 'Ro' is very small.
(iii) Calculate the temperature distribution between the two shells for radial mass flow rates \(w_r\) of zero and \(10^{-5}\) g/sec for the following conditions:

\[
R = 500 \text{ microns}; \quad T_R = 300^\circ C \\
KR = 100 \text{ microns}; \quad T_K = 100^\circ C \\
k = 6.13 \times 10^{-5} \text{ cal/(gm}^\circ \text{C)} \\
C_p = 0.25 \text{ cal/(gm}^\circ \text{C)}
\]

Compare the rates of heat conduction to the surface at 'KR' in the presence and absence of convection.

OR

3' Determine the temperature distribution in an incompressible Newtonian fluid held between two infinitely long vertical coaxial cylinders of radii 'KR' and 'R'. In which the outer cylinder is rotating at a steady angular velocity \(\Omega\) . Due to rotation, there is a viscous heat generation in the fluid. Therefore, the wetted surface of the outer and inner cylinders is at temperatures \(T_1\) and \(T_k\) respectively. Neglect the temperature dependence of \(\mu\) and \(k\).

Velocity distribution is given by:

\[
v_\theta = \Omega R \left[ \frac{KR}{r} - \frac{r}{KR} \right] \\
\left( K - \frac{1}{K} \right) \\
\left( K - \frac{1}{K} \right)
\]

(i) Show that the energy equation reduces to:

\[\text{contd... 5.}\]
\[ k \left( \frac{1}{r} \frac{d}{dr} \left( r \frac{dT}{dr} \right) \right) + \frac{4\mu \Omega^2 K^4}{(1-K^2)^2 r^4} = 0 \]

Solve the differential equation in terms of the following dimensionless quantities:

\[ \xi = \frac{r}{R} = \text{dimensionless radial coordinate} \]

\[ \theta = \frac{T - T_K}{T_1 - T_K} = \text{dimensionless temperature} \]

\[ N = \frac{\mu \Omega^2 R^2}{k(T_1 - T_K)} * \frac{K^4}{(1-K)^2} = Br \frac{K^4}{(1-K^2)^2} \]

Where 'Br' is the Brinkman for the system.

4 Liquid B is flowing in laminar motion down a vertical wall (figure on next page). For \( z < 0 \) the wall does not dissolve in fluid, but for \( 0 < z < L \) the wall contains a species 'A' that is slightly soluble in 'B'. The film begins far above the wall so that \( v_z \) depends only on \( y \) for \( z \geq 0 \).

In the vicinity of the wall, velocity profile can be approximated by:

\[ v_z = \frac{\rho g \delta}{\mu} y \]

Show that equation of continuity for species 'A' reduces to:

\[ a y \frac{\partial C_A}{\partial z} = D_{AB} \frac{\partial^2 C_A}{\partial y^2} \text{, where } a = \frac{\rho g \delta}{\mu} \]

Boundary conditions for short contact times are:

B.C1 at \( z = 0 \) \( C_A = 0 \)

B.C2 at \( y = \infty \) \( C_A = 0 \)

B.C3 at \( y = 0 \) \( C_A = C_{A_0} \)

Where \( C_{A_0} \) is the solubility of 'A' in 'B'.

Solve the above partial differential equation for the concentration profile in terms of reduced variables:

\[ \phi = \frac{C_A}{C_{A_0}} \; ; \; \eta = y \left( \frac{a}{gD_{AB}Z} \right)^{\frac{1}{3}} \]

Contd... - 6.
### Question 1

**Q. No.**

<table>
<thead>
<tr>
<th>Q.No.</th>
<th>Question</th>
<th>M.M.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1(a)</td>
<td>Explain the advantage of approach of Mathematics over Physics in defining and expressing vectors with examples.</td>
<td>05</td>
</tr>
<tr>
<td></td>
<td><strong>1(b)</strong> The liquid phase autocatalytic reaction?</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>[ A + B \rightarrow 3B ]</td>
<td></td>
</tr>
<tr>
<td></td>
<td>[ B \rightarrow C ]</td>
<td></td>
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<tr>
<td></td>
<td>occurs in a batch reactor, and in a CSTR.</td>
<td></td>
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<tr>
<td></td>
<td>Derive the governing equations for the two systems. Assume that the outlet concentrations of A, B are given by ( C_{Af}, C_{Bf} ) and initial concentrations by ( C_{A0}, C_{B0} ). Assume ( q ) to be the volumetric flow rate into the reactor, V to be the Reactor volume. Is this system linear or non-linear? Is it an initial value problem? Would the equation change if the reaction was to be in gas phase?</td>
<td>CO 1</td>
</tr>
<tr>
<td></td>
<td><strong>OR</strong></td>
<td></td>
</tr>
<tr>
<td>1(b')</td>
<td>It is desired to develop the steady-state tray compositions for a six-plate absorption column. It can be assumed that a linear equilibrium relation holds between liquid ( X_m ) and vapor ( Y_m ) on each plate: [ Y_m = aX_m + b ]</td>
<td>10</td>
</tr>
</tbody>
</table>

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Contd... 2.
The inlet composition to the column $x_0$ and $y_0$ are specified along with the liquid (L) and gas (G) phase flow rates (moles/time). The system is shown schematically in Figure 1. Write material balances on each tray and represent the set of equations so obtained in the vectorial form.

![Absorption Column Diagram]

Figure 1: Absorption Column.

2. Consider the following nonlinear homogeneous equation,

$$x \frac{d^2 y}{dx^2} + \left( \frac{dy}{dx} \right)^2 - \left( \frac{y}{x} \right)^2 = 0$$

Under the condition when the boundary conditions are

$$\frac{dy}{dx} = 1, y = 0 \text{ at } x = 1$$

Find the suitable solution.
2'. A family of curves is represented by

\[ x^2 + y^2 - \lambda x = 0 \]

Where \( \lambda \) is an arbitrary parameter
Determine the defining differential equation.

3. A constant-volume batch reactor undergoes the series reaction sequence

\[ A \overset{k_1}{\rightarrow} B \overset{k_2}{\rightarrow} C \]

The initial concentration of A is denoted by \( C_{A0} \), whereas that of B and C is zero. The reaction rates per unit reactor volume are describe by

\[ R_A = k_1 C_A^n, \quad R_B = k_1 C_A^n - k_2 C_B^m \]

For \( n=1, m=2 \), apply material balances and show that the resulting material balance on \( C_B \) finally leads to Riccati’s Equation

4. What are Exact and Inexact Differential Equations along with examples state general procedure of solution
2018-19
M.TECH. (AUTUMN SEMESTER) EXAMINATION
CHEMICAL ENGINEERING
CHEMICAL REACTOR ANALYSIS & DESIGN
CH-613

Maximum Marks: 60

Answer all the questions.
Assume suitable data if missing.
Notations used have their usual meanings.
Use of Graph paper is allowed.

<table>
<thead>
<tr>
<th>Q.No.</th>
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<th>M.M.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1(a)</td>
<td>Derive the general performance equation for the steady state and non-isothermal operation of a CSTR in which following elementary liquid phase reaction: ( A + B \rightarrow C + D ) is taking place. Assume that there is a negligible change in the kinetic and potential energies of the flowing mixture and that the work done by stirrer can be neglected. Besides, there is no heat of mixing and no phase change takes place.</td>
<td>[10]</td>
</tr>
</tbody>
</table>

| 1(b)  | For the steady state and non-isothermal operation of a CSTR in which the following exothermic, elementary, liquid phase reaction: \( A \rightarrow B \) is taking place. Using the equations for heat removal and heat generation curves, develop the criterion depicting the run-away situation in terms of temperature difference. | [05]  |

OR

1(b'). With the help of a neat diagram explain the relevance of ignition-extinction curve in the design of a CSTR sustaining an exothermic chemical reaction and operating under steady state. | [05]  |

2. Adsorption is a necessary step in most of the heterogeneous catalytic reactions and experiments suggest that it is not only specific to the species being adsorbed but also | [15]  |
to the surface on which adsorption is taking place. For example adsorption of carbon monoxide (CO) on nickel (Ni) takes place in molecular form (non-dissociative adsorption), whereas on iron (Fe) CO adsorbs in atomic form (dissociative adsorption). Develop the adsorption isotherm equations for both types of CO adsorption and highlight the important assumptions made in their derivation.

OR

2'. To remove oxides of nitrogen (assumed to be NO) from automobile exhaust, a scheme has been proposed that uses unburned carbon monoxide (CO) in the exhaust to reduce the NO over a solid catalyst, according to the reaction

\[
\text{CO + NO} \rightarrow \text{Products (N}_2, \text{ CO}_2)
\]

Experimental data for a particular solid catalyst indicate that the reaction rate can be well represented over a large range of temperatures by

\[
-r_N = \frac{k P_N P_C}{(1 + K_1 P_N + K_2 P_C)^2}
\]

where \( P_N \) = gas phase partial pressure of NO

\( P_C \) = gas phase partial pressure of CO

\( k, K_1, K_2 \) = Coefficients depending on temperature

Propose an adsorption-surface reaction-desorption mechanism that will explain the experimentally observed kinetics.

3. A first-order, heterogeneous, isothermal and irreversible reaction: \( A \rightarrow B \), is taking place within a spherical catalyst pellet. Bulk concentration of the reactant \( A \) \( (C_{ab}) \) is different from its surface concentration \( (C_{as}) \) as the external mass transfer resistance is also present along with internal diffusion. Derive the expression of overall effectiveness factor (\( \Omega \)) in terms of internal effectiveness factor (\( \eta \)) and show that for very large value of Thiele modulus (\( \Phi \rightarrow \infty \)) \( \Omega \approx \eta \). Also explain the physical significance of this approximate equality.

4. Calculate the mass flux of reactant A to a single catalyst pellet 1 cm in diameter suspended in a large body of liquid. The reactant is present in dilute concentrations, and the reaction is considered to take place instantaneously at the external pellet surface (i.e., \( C_{as} = 0 \)). The bulk concentration of the reactant is 1.0 \( M \), and the free-system liquid velocity is 0.1 m/s. The kinematic viscosity is 0.5 centistoke (1 centistoke = \( 10^{-6} \) m\(^2\)/s), and the liquid diffusivity of A is \( 10^{-10} \) m\(^2\)/s.

***THE END***
### Question 1

**Q.No.** | **Question** | **M.M.**
--- | --- | ---
1(a) | Discuss various sources of waste heat in process industries? Explain with a line diagram any two methods to recover this waste energy. Also mention the challenges to implement them if any. | [06] CO1
1(b) | Define and discuss the following dimensionless numbers in the study of transfer operations: (i) Biot number (ii) Schmidt number (iii) and Stanton number | [06] CO1
1(c) | Discuss three important properties of a thermal fluid and an insulating material with examples of each category. | [03] CO1 & CO2

### OR

**1'(a)** | Discuss briefly with the help of a suitable diagram, at least the three important regions of flow if vapour and liquid phases are flowing in a horizontal tube. | [09] CO1 & CO2

**1'(b)** | A steel tube is fitted with transverse circular steel fins of constant cross section, It has the following dimensions:  

i) Tube O.D.= 60 mm (ii) Fin dia.=65 mm  

iii) Fin thickness = 2.75 mm and  

iv) No. of fins = 260/m.  

Determine the heat loss per unit length of the tube when surface temperature is 380K and the surrounding temperature is 280K. The heat transfer coefficient...
between the fin and and gas is 36 W/m²K and thermal conductivity is 45 W/m K.

<table>
<thead>
<tr>
<th>Question</th>
<th>Description</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>2(a)</td>
<td>Enumerate the steps to design a shell and tube heat exchanger (heat transfer coefficient and Pressure drop) by Kern/Bell’s method. Also explain the differences between them.</td>
<td>[08] CO2</td>
</tr>
<tr>
<td>2(b)</td>
<td>Discuss the merits and demerits of a Plate heat exchanger over a Shell and tube heat exchanger.</td>
<td>[07] CO2</td>
</tr>
<tr>
<td><strong>OR</strong></td>
<td><strong>OR</strong></td>
<td></td>
</tr>
<tr>
<td>2′(a)</td>
<td>Explain the design procedure of a plate heat exchanger.</td>
<td>[05] CO3</td>
</tr>
<tr>
<td>2′(b)</td>
<td>What are the types of corrosion and Discuss the mechanism of corrosion due to heating of a surface.</td>
<td>[05] CO3</td>
</tr>
<tr>
<td>2′(c)</td>
<td>A jacketed agitated reactor consists of a vertical cylinder 1.5 m diameter, with a hemispherical base and a flat flanged, top. The jacket is fitted to the cylindrical section only and extends to a height of 1 m. The spacing between the jacket and vessel walls is 75 mm. The jacket is fitted with a spiral baffle. The pitch between the spirals is 200 mm. The jacket is used to cool the reactor contents. The coolant used is the chilled water at 8 °C; flow rate 32000 kg/h, the exit temperature 24 °C. Estimate the heat transfer coefficient at the outside wall of the reactor and the pressure drop through the jacket. Physical properties at 16 °C: Density = 1000 kg/m³, Thermal conductivity = 600x 10⁻³ W/m °C, Viscosity = 1.135 N.s/m, and Pr = 7.95</td>
<td>[05] CO2</td>
</tr>
</tbody>
</table>
3(a) Discuss with the help of a neat diagram of boiling curve, the procedure of calculating boiling heat transfer coefficient of two regimes for pure liquids.

3(b) A 0.013 m OD, 1.5 m long long tube is to be used to condense steam at 40,000 N/m², T<sub>av</sub> = 349K. Estimate the heat transfer coefficients for this tube in (a) the horizontal position and (b) the vertical position. Assume the average tube wall temperature is 325K.

Data: Saturated water, liquid (100 °C): ρ<sub>l</sub>= 980.9 kg/m³, c<sub>p,l</sub>= 4.184 kJ/kg-K, μ<sub>l</sub> = 4.48 x10<sup>-6</sup> N-s/m², Pr<sub>l</sub> = 1.76, h<sub>fg</sub> = 2349 kJ/kg, and σ = 58.9 x 10<sup>-3</sup> N/m

Saturated water vapour (100 °C): ρ<sub>v</sub>= 0.25 kg/m³, c<sub>p,v</sub> = c<sub>p,l</sub>, and μ<sub>v</sub> = μ<sub>l</sub>.

3(c) Discuss briefly a passive method of augmentation of boiling heat transfer coefficient of liquids to calculate the heat transfer coefficient.

4(a) Ammonia gas is diffusing at a constant rate through a layer of stagnant air of 1 mm thickness. The conditions are fixed so that the gas contains 50% by volume of ammonia at one boundary of the stagnant layer. The ammonia diffusing to the other boundary is quickly absorbed and the concentration is negligible at that plane. The temperature is 298 K and the pressure is atmospheric. Under these conditions, the diffusivity of ammonia in air is 0.18 x 10<sup>-4</sup> m²/s. Calculate the rate of diffusion of ammonia through the layer. The gas constant, R= 8.314 kJ/kmol-K

4(b) Define and discuss the significance of Wilke-Chang equation in the study of diffusion operations. How will you calculate the diff. coefficient, D<sub>AB</sub> for a dilute and non-electrolytic solution?
Derive the process model and write the assumptions to obtain the following equations:

(i) \( \frac{dx_1}{dt} = \frac{F_A}{V} (x_{1,i} - x_1) - \frac{F_B}{V} x_1 \)

(ii) \( \frac{dx_2}{dt} = \frac{F_B}{V} (x_{2,i} - x_2) - \frac{F_A}{V} x_2 \)

(iii) \( \frac{dx_3}{dt} = \frac{F_B}{V} (x_{3,i} - x_3) - \frac{F_A}{V} x_3 \)

(iv) \([H^+] x_2 + x_3 - x_1 - \frac{K_d}{[H^+]} x_2 - \frac{K_d}{K_b} [H^+] = 0\)

and

\[ pH = -\log_{10} [H^+] \]

Where as:
- \( F_A \) = volumetric flow rate of acidic solution
- \( x_{1,i} \) = composition of acidic solution
- \( F_B \) = volumetric flow rate of alkaline solution
- \( x_{2,i} \) = composition of alkaline solution
- \( x_{3,i} \) = Buffer agent
- HA = Strong Acid
- BOH = Strong Base
- BX = Buffer Agent
- \( H^+ \) and \( OH^- \) = ions

**Q4**

Consider a non isothermal CSTR as shown in figure in which a first order exothermic irreversible chemical reaction takes place.

A \( \longrightarrow \) B

Reactant A is continuously supplied to reactor with a volumetric flow rate \( F_i \), a molar concentration \( C_{Af} \) and Temperature \( T_f \). An exit stream which contains a mixture of both reactant A and product B, is withdrawn from the reactor with a volumetric flow rate \( F_0 \), composition \( C_A \) and temperature \( T \). A coolant stream with volumetric flow rate \( F_j \) and an inlet temperature \( T_{jin} (<T) \) continuously takes out the heat to maintain the desired reaction temperature.

[CO-3]
Q1(a) 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  

[CO-2]

Q1(b) 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?

[CO-2]
Q1'(b)

Explain briefly the following models and their application in chemical engineering:

(i) Linear and nonlinear model
(ii) Static and dynamic model
(iii) Lumped parameter and distributed parameter model
(iv) Fundamental and empirical model

[CO-1]

Q2

A Newtonian fluid is in laminar flow in a narrow slit formed by two parallel walls at distance 2B apart. It is understood that B<<W, so that ‘edge’ effects are unimportant. Make a differential momentum balance and obtain the model equations for the following situation:
(a) Momentum flux and velocity distributions:

(i) \( r_{xx} = \left( \frac{P(0) - P(L)}{L} \right) x \)

(ii) \( v = \left( \frac{P(0) - P(L)}{2L\mu} \right) B^2 \left[ 1 - \left( \frac{x}{B} \right)^2 \right] \)

In these expressions \( P = p + \rho gh = \rho_g z \)

Where \( \rho \) = density of fluid

(b) Ratio of average velocity to the maximum velocity for the flow.

(c) The slit analogue of the Hagen-Poiseuille equation

OR

Q2

In a batch reactor the content is heated to reaction temperature with saturated steam supplied to the jacket at temperature \( T_j \). The reactor is stirred at fixed rpm and cooling water is passed through coil and exothermic heat is removed and desired temperature is maintained. Following consecutive reactions that take place in the reactor:

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

Assumed \( A \rightarrow B \) has second order kinetics whereas \( B \rightarrow C \) has first order kinetics. Where \( B \) is desired product and if the reaction goes on for long time the yield of undesired waste \( C \) will be high. If the reaction stops early conversion of \( A \) may be very low.

Mentioning the standard assumptions, derive the model to obtain following equations:

(i) \( \frac{dC_A}{dt} = -k_1 C_A^2 \)

(ii) \( \frac{dC_B}{dt} = k_1 C_A^2 - k_2 C_B \)

(iii) \( \frac{dT}{dt} = \frac{-\Delta H_1}{\rho C_p} k_1 C_A^2 + \frac{-\Delta H_2}{\rho C_p} k_2 C_B + \frac{U_A A_J}{\rho C_p V} (T_i - T) - \frac{U_c A_c}{\rho C_p V} (T - T_c) \)

cont'd
U_j and U_c= Overall heat transfer coefficients for heating jacket and cooling coil
ρ= mixture density
C_p= heat capacity of mixture
T_j= Jacket temperature
V= Mixture volume
h= enthalpy
A_j and A_c= Heat transfer areas of heating jacket and cooling coil
ΔH= heat of reaction
α= frequency factor
E= activation energy
N= number of moles
F_c= coolant flow rate

Q3 Derive the model for pH neutralization CSTR (Continuous stirred tank reactor) as shown in the following Figure.
Derive the process model and write the assumptions to obtain the following equations:

(i) \( \frac{dx_1}{dt} = \frac{F_A}{V} (x_{1,0} - x_1) - \frac{F_B}{V} x_1 \)

(ii) \( \frac{dx_2}{dt} = \frac{F_B}{V} (x_{2,0} - x_2) - \frac{F_A}{V} x_2 \)

(iii) \( \frac{dx_3}{dt} = \frac{F_B}{V} (x_{3,0} - x_3) - \frac{F_A}{V} x_3 \)

(iv) \( [H^+] x_2 + x_3 - x_1 - \frac{K_B}{[H^+]} \frac{x_3}{1 + \frac{K_B [H^+]}{K_B}} = 0 \)

and

\( pH = -\log_{10} [H^+] \)

Where as:
F_A = volumetric flow rate of acidic solution
x_{1,0} = composition of acidic solution
F_B = volumetric flow rate of alkaline solution
x_{2,0} = composition of alkaline solution
x_{3,0} = Buffer agent
HA = Strong Acid
BOH = Strong Base
BX = Buffer Agent
H^+ and OH^- = ions

Q4

Consider a non isothermal CSTR as shown in figure in which a first order exothermic irreversible chemical reaction takes place.

A \( \rightarrow \) B

Reactant A is continuously supplied to reactor with a volumetric flow rate F_A a molar concentration C_{Af} and Temperature T_f An exit stream which contains a mixture of both reactant A and product B, is withdrawn from the reactor with a volumetric flow rate F_0, composition C_A and temperature T. A coolant stream with volumetric flow rate F_j and an inlet temperature T_{jin} (< T) continuously takes out the heat to maintain the desired reaction temperature.
Mentioning the standard assumptions, derive the model to obtain following equations:

(i) \[
\frac{dC_A}{dt} = \frac{F_i}{A_i h} (C_{A_i} - C_A) - \alpha \exp\left(\frac{-E}{RT}\right) C_A
\]

(ii) \[
\frac{dT}{dt} = \frac{F_i}{A_i h} (T_f - T) + \left(\frac{-\Delta H}{\rho C_p}\right) \alpha \exp\left(\frac{-E}{RT}\right) C_A - \frac{U_i A_i}{\rho C_p A_i h} (T - T_j)
\]

U_i = Overall heat transfer coefficient
\(\rho\) = mixture density
C_p = heat capacity
T_j = Jacket temperature
A_i = Cross sectional area of reactor
h = height of reactor liquid
A_b = Heat transfer area
\(\Delta H\) = heat of reaction
\(\alpha\) = frequency factor
E = activation energy

[CO-4]
1(a). With the help of suitable temperature-enthalpy plots differentiate between a composite curve and its associated balanced composite curve. Which one of these require additional data and which one is used in the calculation of area targeting?

1(b). Plot the hot and cold composite curves to calculate the hot and cold utility targets and pinch temperature for the following problem at a global $\Delta T_{\text{min}}$ of 10°C.

Table 1 Stream data for four-stream problem

<table>
<thead>
<tr>
<th>Stream type</th>
<th>Supply temperature ($^\circ$C)</th>
<th>Target temperature ($^\circ$C)</th>
<th>Heat capacity Flow rate (kW/K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cold</td>
<td>20</td>
<td>135</td>
<td>2.0</td>
</tr>
<tr>
<td>Hot</td>
<td>170</td>
<td>60</td>
<td>3.0</td>
</tr>
<tr>
<td>Cold</td>
<td>80</td>
<td>140</td>
<td>4.0</td>
</tr>
<tr>
<td>Hot</td>
<td>150</td>
<td>30</td>
<td>1.5</td>
</tr>
</tbody>
</table>

OR

1'(a). Describe the following concepts frequently used in the optimal design of heat exchanger network:

- Grand Composite Curve
- The three golden rules of pinch study
1'b. Using Problem Table Algorithm (PTA) calculate the hot and cold utility and pinch point for the following stream data (Table 2). The value of global $\Delta T_{\text{min}}$ is 20°C.

Table 2 Stream data from a process plant

<table>
<thead>
<tr>
<th>Stream ID</th>
<th>Stream type</th>
<th>Supply temperature ($^\circ$C)</th>
<th>Target temperature ($^\circ$C)</th>
<th>Heat capacity (kW/K)</th>
<th>Heat load (kW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Hot</td>
<td>200</td>
<td>50</td>
<td>3</td>
<td>450</td>
</tr>
<tr>
<td>2</td>
<td>Hot</td>
<td>240</td>
<td>100</td>
<td>1.5</td>
<td>210</td>
</tr>
<tr>
<td>3</td>
<td>Hot</td>
<td>120</td>
<td>119</td>
<td>300</td>
<td>300</td>
</tr>
<tr>
<td>4</td>
<td>Cold</td>
<td>30</td>
<td>200</td>
<td>4</td>
<td>-680</td>
</tr>
<tr>
<td>5</td>
<td>Cold</td>
<td>50</td>
<td>250</td>
<td>2</td>
<td>-400</td>
</tr>
</tbody>
</table>

2. What are the basic principles of "pinch design method"? Using these principles, design a maximum energy recovery (MER) network for the four stream problem given in Table 1. Also find the number of heat exchangers needed in the so found MER network.

3(a). What is a spaghetti network and how is it constructed? Show that for a typical spaghetti network, the area target is given by the following equation:

$$A = \sum_{i} \left( \frac{1}{F LMTD} \right) \sum_{j} \left( \frac{Q_{j}}{h_{j}} \right)$$

Where $i$ and $j$ denotes the $i^{th}$ enthalpy interval and the number of streams in that interval, respectively.

**OR**

3(a'). What do you understand by "safe-side" linearization technique used to evaluate specific heats of process streams when these are not constants? Also show a typical composite curve when specific heats of process streams are variable.

Contd...3
3(b) Write a short note on the cost targeting with regard to that of a heat exchanger network.

3(b') What do you understand by the term supertargeting and how is it related to the choice of $\Delta T_{min}$?

4. Consider four processes involving a single contaminant with the following limiting water profile data:

<table>
<thead>
<tr>
<th>Process Label</th>
<th>$C_{in}$ (ppm)</th>
<th>$C_{out}$ (ppm)</th>
<th>$M_c$ (kg/h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>P1</td>
<td>0</td>
<td>200</td>
<td>4</td>
</tr>
<tr>
<td>P2</td>
<td>150</td>
<td>300</td>
<td>7.5</td>
</tr>
<tr>
<td>P3</td>
<td>200</td>
<td>600</td>
<td>16</td>
</tr>
<tr>
<td>P4</td>
<td>200</td>
<td>300</td>
<td>2</td>
</tr>
</tbody>
</table>

Table 3 Process limiting water profile data

Calculate the mass flow rate of water and graphically determine the minimum fresh water requirement without and with water reuse. Assume that dilute concentrations exist so that mass transfer rate is linearly proportional to the concentration difference.

***THE END***