UNIVERSITI TEKNOLOGI PETRONAS

FINAL EXAMINATION
JANUARY 2025 SEMESTER

COURSE	**:**	**CFB2063 - SEPARATION PROCESS II**
DATE	**:**	**17 APRIL 2025 (THURSDAY)**
TIME	**:**	**9.00 AM - 12.00 NOON (3 HOURS)**

INSTRUCTIONS TO CANDIDATES

1. Answer **ALL** questions in the Answer Booklet.
2. Begin **EACH** answer on a new page in the Answer Booklet.
3. Indicate clearly answers that are cancelled, if any.
4. Where applicable, show clearly steps taken in arriving at the solutions and indicate **ALL** assumptions, if any.
5. **DO NOT** open this Question Booklet until instructed.

Note :

i. There are **ELEVEN (11)** pages in this Question Booklet including the cover page and appendices.

ii. **DOUBLE-SIDED** Question Booklet.

1. a. Ms. Krypton from EcoGreen Sdn. Bhd. was tasked to scale up a continuous fixed-bed adsorption column for the removal of residual drug (paracetamol) from pharmaceutical effluent over molecular sieve ZIX (ρ = 897 kg/m^3). Her intern, Ms. Gerald run the lab-scale adsorption process using a packed bed column (diameter: 5 cm & length: 12 cm). The feed solution having a solute concentration of 520 ppm paracetamol and a density of 938 kg/m^3 entered the bed at a flow rate of 0.03 m^3/min. Through computational fluid dynamics analysis, the height associated to non-idealities in the lab-scale adsorption is 1.3 cm. By analyzing the breakthrough curve of the lab-scale adsorption, the break point occurred at 9 min, while the ratio of usable capacity to total capacity was 0.57. Considering the capital cost, the desirable actual height and cross-sectional area of the upscaled column were respectively 97 cm and 50 cm^2. Later, Gerald realized that she wrongly applied the regenerated ZIX as fresh ZIX in her lab-scale study. Regenerated ZIX contained an initial solute concentration of 0.05 kg paracetamol/kg ZIX.

i. Discuss **TWO (2)** contributing factors to the non-idealities of a continuous fixed-bed adsorption column.

[4 marks]

ii. Determine the break point of the upscaled column if the non-idealities contribute to an additional column height of 7.7 cm.

[8 marks]

iii. Determine the saturation loading capacity of the ZIX adsorbent bed.

[5 marks]

b. A microalgae cultivation wastewater has sodium (Na^+) and chloride (Cl^-) ions with a respective ion concentration of 0.03 M and 0.04 M. To comply with the discharge standard, the effluent should be treated by a strong base-anion (SBA) exchanger. The ion exchanger is packed with polystyrene resin with 8% divinyzlbenzene (DVB) cross-linking, where the sulfate (SO_4^{2-}) ions initially present as the exchangeable counterions on their surface functional groups. The total ion exchange capacity of resin and the total equivalent concentration of solution are about 2.3 eq/L of wet bed volume and 0.8 eq/L of solution, separately. SBA exchanger is unreactive towards the aqueous co-ions, so their attachment onto the resin is impossible. Evaluate the equivalent concentrations of aqueous counterions and aqueous co-ions in the resin at equilibrium, individually.

[8 marks]

2. A hot solution from an evaporator containing 130 kg of trisodium phosphate (Na_3PO_4) solution at 55°C. The aforesaid solution serves as the feed stream to an isothermal cooling crystallizer at 25°C for the crystallization of Na_3PO_4 dodecahydrate ($Na_3PO_4 \cdot 12H_2O$) crystals. For anhydrous Na_3PO_4 salt, its solubility in water (c_s in g solute/100 g solvent) is positively correlated with temperature (T in °C) by the $c_s = 0.0051T^2+0.6007T-1.1455$ relation. The supersaturated feed solution has a relative supersaturation of 15% whereas the mother liquor exists in saturated solution state after the crystallization. The average heat capacity of the feed solution is assumed as 2.71 kJ/kg·K. The heat of solution for $Na_3PO_4 \cdot 12H_2O$ at 25°C is 62.76 kJ/mol. Throughout the crystallization process, 7% of the original water evaporates on cooling. Given the molar mass of compounds (in kg/kmol): Na_3PO_4 (163.94) and $Na_3PO_4 \cdot 12H_2O$ (380.12).

   a. Calculate the water solubilities of Na_3PO_4 in both supersaturated feed solution and saturated mother liquor using the relative supersaturation concept and the solubility-temperature relation.

   [5 marks]

   b. Determine the yield of $Na_3PO_4 \cdot 12H_2O$ crystals.

   [10 marks]

   c. Determine the heat change of the crystallization process.

   [10 marks]

3. The increasing demand for high-purity oxygen (O_2) in medical, industrial, and emerging energy applications requires efficient and cost-effective separation technologies. Membrane-based separation offers a promising alternative to conventional methods like cryogenic distillation. For this evaluation, five (5) membrane materials have been selected to separate O_2 from atmospheric air. The feed air composition is 21 vol% O_2 and 79 vol% nitrogen (N_2) at a pressure of 400 cm Hg, with a flow rate of 10000 cm^3 (STP)/s. **TABLE Q3** provides the permeability data of the membrane materials, all with a thickness of 10 nm.

TABLE Q3: Permeability data of membrane materials for N_2 and O_2

Membrane	N_2 permeability (cm³(STP)cm/(cm²·s·cm Hg))	O_2 permeability (cm³(STP)cm/(cm²·s·cm Hg))
Material A	4.9×10^{-5}	5.0×10^{-5}
Material B	3.0×10^{-5}	1.5×10^{-5}
Material C	2.5×10^{-5}	2.0×10^{-5}
Material D	1.0×10^{-5}	2.0×10^{-4}
Material E	1.2×10^{-5}	4.2×10^{-4}

a. Evaluate which membrane is feasible to achieve N_2 purity in the retentate of at least 90 vol% with the smallest possible membrane area, if the permeate pressure is set at 20 cm Hg. Provide appropriate calculation and justification for your selection.

[18 marks]

b. With the aid of a labelled diagram, describe the membrane mechanism involved in the separation process. Suggest **ONE (1)** potential membrane material for this specific application.

[7 marks]

4. a. An evaporator is used to manufacture 2500 kg/h of concentrated grape juice with 25 wt% of solids. The raw juice having a concentration of 9 wt% solids is used for this purpose. The feed enters at 37.8°C and the maximum allowable temperature for the grape juice is 57.2°C, which will be the temperature of the product. Saturated steam at 172.3 kPa with a latent heat of 2216 kJ/kg is used for heating. The heat capacity of the feed is 4.14 kJ/kg·°C. The enthalpy of saturated vapor is 2365 kJ/kg and neglect boiling point rise, if any.

i. The plant engineer proposed to fabricate an evaporator with the heat transfer coefficient of 1704 W/m²·°C. Based on the given details, determine the feed rate required, steam economy and the area required for the proposed process.

[10 marks]

ii. After a few years, the management decided to reduce the cost involved in the fabrication of the evaporator. The plant engineer planned to modify and use the existing film type evaporator with the proposed new overall heat transfer coefficient of 1260 W/m²·°C. Determine the heat transfer area required for the given duty with same operating conditions. The steam economy is maintained as constant. Compare the results obtained in **part (a)(i)** with respect to the heat transfer area and the heat transfer coefficient.

[6 marks]

iii. For further modification of the evaporation process in the future, state **TWO (2)** important factors to be considered for maximum steam efficiency.

[4 marks]

b. A solution with a negligible boiling point rise is being evaporated in a triple effect evaporator using saturated steam at 121.1°C. The pressure in the vapor of the last evaporator is 25 kPa. The heat transfer coefficients are given as U_1, U_2, and U_3, respectively. Assume the areas in all effects are equal, sketch a diagram of forward feed evaporator with proper labelling.

[5 marks]

– END OF PAPER –

APPENDIX I

Table A.1: Relative-molar-selectivity coefficients of polystyrene ion exchangers with 8% divinyzlbenzene (DVB) cross-linking

Strong-base anion exchange (Relative to Cl^- as 1.0)		Strong-acid cation exchanger (Relative to Li^+ as 1.0)	
Cl^-	1.0	Li^+	1.0
I^-	8.7	H^+	1.27
NO_3^-	3.8	Na^+	1.98
CH_3COO^-	0.2	NH_4^+	2.55
SO_4^{2-}	0.15	K^+	2.90
OH^-	0.05 – 0.07	Mg^{2+}	3.29
		Cu^{2+}	3.85
		Ca^{2+}	5.16

APPENDIX II

Table A.2: Properties of saturated water

Properties of saturated water

Temp. T, °C	Saturation Pressure P_{sat}, kPa	Density ρ, kg/m³ Liquid	Density ρ, kg/m³ Vapor	Enthalpy of Vaporization h_{fg}, kJ/kg	Specific Heat c_p, J/kg·K Liquid	Specific Heat c_p, J/kg·K Vapor	Thermal Conductivity k, W/m·K Liquid	Thermal Conductivity k, W/m·K Vapor	Dynamic Viscosity μ, kg/m·s Liquid	Dynamic Viscosity μ, kg/m·s Vapor	Prandtl Number Pr Liquid	Prandtl Number Pr Vapor	Volume Expansion Coefficient β, 1/K Liquid
0.01	0.6113	999.8	0.0048	2501	4217	1854	0.561	0.0171	1.792×10^{-3}	0.922×10^{-5}	13.5	1.00	-0.068×10^{-3}
5	0.8721	999.9	0.0068	2490	4205	1857	0.571	0.0173	1.519×10^{-3}	0.934×10^{-5}	11.2	1.00	0.015×10^{-3}
10	1.2276	999.7	0.0094	2478	4194	1862	0.580	0.0176	1.307×10^{-3}	0.946×10^{-5}	9.45	1.00	0.733×10^{-3}
15	1.7051	999.1	0.0128	2466	4185	1863	0.589	0.0179	1.138×10^{-3}	0.959×10^{-5}	8.09	1.00	0.138×10^{-3}
20	2.339	998.0	0.0173	2454	4182	1867	0.598	0.0182	1.002×10^{-3}	0.973×10^{-5}	7.01	1.00	0.195×10^{-3}
25	3.169	997.0	0.0231	2442	4180	1870	0.607	0.0186	0.891×10^{-3}	0.987×10^{-5}	6.14	1.00	0.247×10^{-3}
30	4.246	996.0	0.0304	2431	4178	1875	0.615	0.0189	0.798×10^{-3}	1.001×10^{-5}	5.42	1.00	0.294×10^{-3}
35	5.628	994.0	0.0397	2419	4178	1880	0.623	0.0192	0.720×10^{-3}	1.016×10^{-5}	4.83	1.00	0.337×10^{-3}
40	7.384	992.1	0.0512	2407	4179	1885	0.631	0.0196	0.653×10^{-3}	1.031×10^{-5}	4.32	1.00	0.377×10^{-3}
45	9.593	990.1	0.0655	2395	4180	1892	0.637	0.0200	0.596×10^{-3}	1.046×10^{-5}	3.91	1.00	0.415×10^{-3}
50	12.35	988.1	0.0831	2383	4181	1900	0.644	0.0204	0.547×10^{-3}	1.062×10^{-5}	3.55	1.00	0.451×10^{-3}
55	15.76	985.2	0.1045	2371	4183	1908	0.649	0.0208	0.504×10^{-3}	1.077×10^{-5}	3.25	1.00	0.484×10^{-3}
60	19.94	983.3	0.1304	2359	4185	1916	0.654	0.0212	0.467×10^{-3}	1.093×10^{-5}	2.99	1.00	0.517×10^{-3}
65	25.03	980.4	0.1614	2346	4187	1926	0.659	0.0216	0.433×10^{-3}	1.110×10^{-5}	2.75	1.00	0.548×10^{-3}
70	31.19	977.5	0.1983	2334	4190	1936	0.663	0.0221	0.404×10^{-3}	1.126×10^{-5}	2.55	1.00	0.578×10^{-3}
75	38.58	974.7	0.2421	2321	4193	1948	0.667	0.0225	0.378×10^{-3}	1.142×10^{-5}	2.38	1.00	0.607×10^{-3}
80	47.39	971.8	0.2935	2309	4197	1962	0.670	0.0230	0.355×10^{-3}	1.159×10^{-5}	2.22	1.00	0.653×10^{-3}
85	57.83	968.1	0.3536	2296	4201	1977	0.673	0.0235	0.333×10^{-3}	1.176×10^{-5}	2.08	1.00	0.670×10^{-3}
90	70.14	965.3	0.4235	2283	4206	1993	0.675	0.0240	0.315×10^{-3}	1.193×10^{-5}	1.96	1.00	0.702×10^{-3}
95	84.55	961.5	0.5045	2270	4212	2010	0.677	0.0246	0.297×10^{-3}	1.210×10^{-5}	1.85	1.00	0.716×10^{-3}
100	101.33	957.9	0.5978	2257	4217	2029	0.679	0.0251	0.282×10^{-3}	1.227×10^{-5}	1.75	1.00	0.750×10^{-3}
110	143.27	950.6	0.8263	2230	4229	2071	0.682	0.0262	0.255×10^{-3}	1.261×10^{-5}	1.58	1.00	0.798×10^{-3}
120	198.53	943.4	1.121	2203	4244	2120	0.683	0.0275	0.232×10^{-3}	1.296×10^{-5}	1.44	1.00	0.858×10^{-3}
130	270.1	934.6	1.496	2174	4263	2177	0.684	0.0288	0.213×10^{-3}	1.330×10^{-5}	1.33	1.01	0.913×10^{-3}
140	361.3	921.7	1.965	2145	4286	2244	0.683	0.0301	0.197×10^{-3}	1.365×10^{-5}	1.24	1.02	0.970×10^{-3}
150	475.8	916.6	2.546	2114	4311	2314	0.682	0.0316	0.183×10^{-3}	1.399×10^{-5}	1.16	1.02	1.025×10^{-3}
160	617.8	907.4	3.256	2083	4340	2420	0.680	0.0331	0.170×10^{-3}	1.434×10^{-5}	1.09	1.05	1.145×10^{-3}
170	791.7	897.7	4.119	2050	4370	2490	0.677	0.0347	0.160×10^{-3}	1.468×10^{-5}	1.03	1.05	1.178×10^{-3}
180	1,002.1	887.3	5.153	2015	4410	2590	0.673	0.0364	0.150×10^{-3}	1.502×10^{-5}	0.983	1.07	1.210×10^{-3}
190	1,254.4	876.4	6.388	1979	4460	2710	0.669	0.0382	0.142×10^{-3}	1.537×10^{-5}	0.947	1.09	1.280×10^{-3}
200	1,553.8	864.3	7.852	1941	4500	2840	0.663	0.0401	0.134×10^{-3}	1.571×10^{-5}	0.910	1.11	1.350×10^{-3}
220	2,318	840.3	11.60	1859	4610	3110	0.650	0.0442	0.122×10^{-3}	1.641×10^{-5}	0.865	1.15	1.520×10^{-3}
240	3,344	813.7	16.73	1767	4760	3520	0.632	0.0487	0.111×10^{-3}	1.712×10^{-5}	0.836	1.24	1.720×10^{-3}
260	4,688	783.7	23.69	1663	4970	4070	0.609	0.0540	0.102×10^{-3}	1.788×10^{-5}	0.832	1.35	2.000×10^{-3}
280	6,412	750.8	33.15	1544	5280	4835	0.581	0.0605	0.094×10^{-3}	1.870×10^{-5}	0.854	1.49	2.380×10^{-3}
300	8,581	713.8	46.15	1405	5750	5980	0.548	0.0695	0.086×10^{-3}	1.965×10^{-5}	0.902	1.69	2.950×10^{-3}
320	11,274	667.1	64.57	1239	6540	7900	0.509	0.0836	0.078×10^{-3}	2.084×10^{-5}	1.00	1.97	
340	14,586	610.5	92.62	1028	8240	11,870	0.469	0.110	0.070×10^{-3}	2.255×10^{-5}	1.23	2.43	
360	18,651	528.3	144.0	720	14,690	25,800	0.427	0.178	0.060×10^{-3}	2.571×10^{-5}	2.06	3.73	
374.14	22,090	317.0	317.0	0	—	—	—	—	0.043×10^{-3}	4.313×10^{-5}			

Note 1: Kinematic viscosity ν and thermal diffusivity α can be calculated from their definitions, $\nu = \mu/\rho$ and $\alpha = k/\rho c_p = \nu/\text{Pr}$. The temperatures 0.01°C, 100°C, and 374.14°C are the triple-, boiling-, and critical-point temperatures of water, respectively. The properties listed above (except the vapor density) can be used at any pressure with negligible error except at temperatures near the critical-point value.

Note 2: The unit kJ/kg·°C for specific heat is equivalent to kJ/kg·K, and the unit W/m·°C for thermal conductivity is equivalent to W/m·K.

Source: Viscosity and thermal conductivity data are from J. V. Sengers and J. T. R. Watson, *Journal of Physical and Chemical Reference Data* 15 (1986), pp. 1291–1322. Other data are obtained from various sources or calculated.