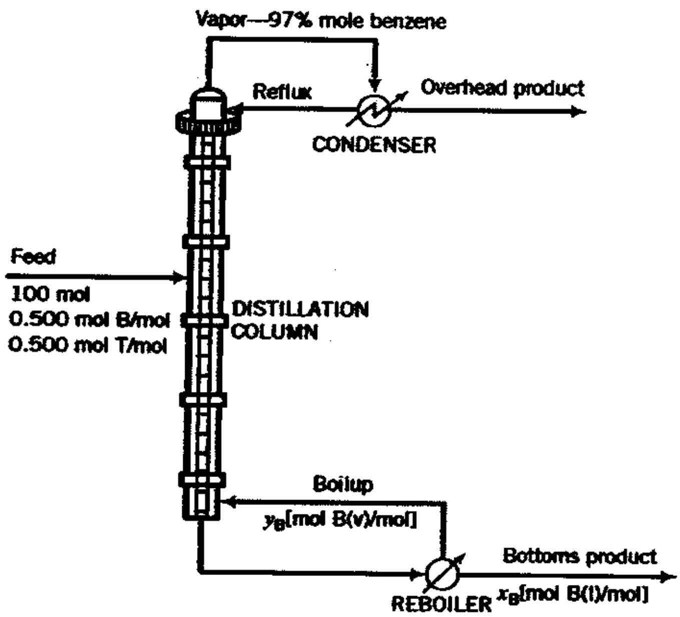
INDIAN INSTITUTE OF TECHNOLOGY KHARAGPUR
Mid-Autumn Semester 2018-19

Date of Examination: 20/09/2018 **Session (FN/AN)** AN **Duration** 2 hrs **Full Marks:** 30
Subject No.: CH21103 **Subject:** CHEMICAL PROCESS CALCULATIONS
Department: CHEMICAL ENGINEERING
Specific charts, graph paper, log book etc., required: NO.
Special Instructions (if any): Answer all questions. Assume, if necessary, clearly stating them. No queries will be entertained during the examination.

PART A

1. An equimolar liquid mixture of benzene and toluene is separated into two product streams by distillation. A process flowchart and a somewhat oversimplified description of what happens in the process are as follows:



Inside the column a liquid stream flows downward and a vapor stream rises. At each point in the column some of the liquid vaporizes and some of the vapor condenses. The vapor leaving the top of the column, which contains 97 mole% benzene, is completely condensed and split into two equal fractions: one is taken off as the overhead product stream, and the other (the **reflux**) is recycled to the top of the column. The overhead product stream contains 89.2% of the benzene fed to the column. The liquid leaving the bottom of the column is fed to a partial reboiler in which 45% of it is vaporized. The vapor generated in the reboiler (the **boilup**) is recycled to become the rising vapor stream in the column, and the residual reboiler liquid is taken off as the bottom product stream. The compositions of the streams leaving the reboiler are governed by the relation: $\frac{y_B/(1-y_B)}{x_B/(1-x_B)} = 2.25$ where y_B and x_B are the mole fractions of benzene in the vapor and liquid streams, respectively.

(a) Take a basis of 100 mole fed to the column. Draw and completely label a flowchart, and for each of four systems (overall process, column, condenser, and reboiler), do the degree-of-freedom analysis and identify a system with which the process analysis might appropriately begin. **(4)**

(b) Write in order the equations you would solve to determine all unknown variables on the flowchart, circling the variable for which you would solve in each equation. Do not do the calculations in this part. **(2)**

(c) Calculate the molar amounts of the overhead and bottoms products, the mole fraction of benzene in the bottoms product, and the percentage recovery of toluene in the bottoms product. **(2)**

2. An evaporation–crystallization process, consists of an evaporator and then a crystallization unit in series, is used to obtain solid K_2SO_4 from an aqueous solution of this salt. The fresh feed to the process contains 19.6 wt% K_2SO_4. The wet filter cake (product from crystallization unit) consists of solid K_2SO_4 crystals and a 40.0 wt% K_2SO_4 solution, in a ratio 10 kg crystals/kg solution. The filtrate (from crystallization unit), also a 40.0% solution, is recycled to join the fresh feed. Of the water fed to the evaporator, 45.0% is evaporated. The evaporator has a maximum capacity of 175 kg water evaporated/s.

(a) Assume the process is operating at maximum capacity. Draw and label a flowchart and do the degree-of-freedom analysis for the overall system, the recycle–fresh feed mixing point, the evaporator, and the crystallizer. Then write in an efficient order the equations you would solve to determine all unknown stream variables. In each equation, circle the variable for which you would solve, but don't do the calculations. **(3)**

(b) Calculate the maximum production rate of solid K_2SO_4, and the ratio kg recycle/kg fresh feed. **(2)**

(c) Calculate the composition and feed rate of the stream entering the crystallizer if the process is scaled to 75% of its maximum capacity. **(2)**

PART B

For answering Questions 3 and 4, use the Steam Table data given in Page 3 of the Question Paper. Please detach it from the question paper and attached to your answer script. Write your name and Roll Number on it.

3. (a) Find the density of steam at **100°C** which has quality Q = **60%**. (2)
   (b) Find the specific enthalpy of steam at **430°C** temperature and **675 KPa** pressure. (2)

4. Initially, 3 Kg of steam is there in a tank at **600 Kpa** pressure and **650°C** temperature. The steam is cooled inside the tank to 120 °C. Using the attached steam table, please answer the following:
   (a) The nature of the steam in its initial and final states.
   (b) Calculate the heat transferred during the process.
   (2+4=6)

5. (a) Why heat of vaporization is much higher that heat of fusion? (1)
   (b) What is critical Temperature? Why a gas can never be liquefied by applying pressure above it's critical temperature? (0.5+1)
   (c) What is molar heat capacity of a substance ($\hat{C}$)? From it's fundamental expression, Show that $\hat{C}_P = \hat{C}_V + R$ (1+1.5)

Roll Number: **Name:**

Steam Table related data (Detach this sheet and attach to answer script)

Please Mark the data that you are using.

TABLE B.1 Saturated Water: Temperature Table

T °C	P kPa, MPa	$\hat{v}_l$ m³/kg	$\hat{v}_v$ m³/kg	$\hat{u}_l$ kJ/kg	$\Delta\hat{u}_{vap}$ kJ/kg	$\hat{u}_v$ kJ/kg	$\hat{h}_l$ kJ/kg	$\Delta\hat{h}_{vap}$ kJ/kg	$\hat{h}_v$ kJ/kg
50	12.350	0.001012	12.032	209.30	2234.2	2443.5	209.31	2382.7	2592.1
55	15.758	0.001015	9.568	230.19	2219.9	2450.1	230.20	2370.7	2600.9
60	19.941	0.001017	7.671	251.09	2205.5	2456.6	251.11	2358.5	2609.6
65	25.033	0.001020	6.197	272.00	2191.1	2463.1	272.03	2346.2	2618.2
70	31.188	0.001023	5.042	292.93	2176.6	2469.5	292.96	2333.8	2626.8
75	38.578	0.001026	4.131	313.87	2162.0	2475.9	313.91	2321.4	2635.3
80	47.390	0.001029	3.407	334.84	2147.4	2482.2	334.88	2308.8	2643.7
85	57.834	0.001032	2.828	355.82	2132.6	2488.4	355.88	2296.0	2651.9
90	70.139	0.001036	2.361	376.82	2117.7	2494.5	376.90	2283.2	2660.1
95	84.554	0.001040	1.982	397.86	2102.7	2500.6	397.94	2270.2	2668.1
100	0.10135	0.001044	1.6729	418.91	2087.6	2506.5	419.02	2257.0	2676.0
105	0.12082	0.001047	1.4194	440.00	2072.3	2512.3	440.13	2243.7	2683.8
110	0.14328	0.001052	1.2102	461.12	2057.0	2518.1	461.27	2230.2	2691.5
115	0.16906	0.001056	1.0366	482.28	2041.4	2523.7	482.46	2216.5	2699.0
120	0.19853	0.001060	0.8919	503.48	2025.8	2529.3	503.69	2202.6	2706.3
125	0.2321	0.001065	0.77059	524.72	2009.9	2534.6	524.96	2188.5	2713.5
130	0.2701	0.001070	0.66850	546.00	1993.9	2539.9	546.29	2174.2	2720.5
135	0.3130	0.001075	0.58217	567.34	1977.7	2545.0	567.67	2159.6	2727.3
140	0.3613	0.001080	0.50885	588.72	1961.3	2550.0	589.11	2144.8	2733.9
145	0.4154	0.001085	0.44632	610.16	1944.7	2554.9	610.61	2129.6	2740.2

TABLE B.2 Saturated Water: Pressure Table

P MPa	T °C	$\hat{v}_l$ m³/kg	$\hat{v}_v$ m³/kg	$\hat{u}_l$ kJ/kg	$\Delta\hat{u}_{vap}$ kJ/kg	$\hat{u}_v$ kJ/kg	$\hat{h}_l$ kJ/kg	$\Delta\hat{h}_{vap}$ kJ/kg	$\hat{h}_v$ kJ/kg
0.100	99.62	0.001043	1.6940	417.33	2088.7	2506.1	417.44	2258.0	2675.5
0.125	105.99	0.001048	1.3749	444.16	2069.3	2513.5	444.29	2241.1	2685.3
0.150	111.37	0.001053	1.1593	466.92	2052.7	2519.6	467.08	2226.5	2693.6
0.175	116.06	0.001057	1.0036	486.78	2038.1	2524.9	486.97	2213.6	2700.5
0.200	120.23	0.001061	0.8857	504.47	2025.0	2529.5	504.68	2202.0	2706.6
0.225	124.00	0.001064	0.7933	520.45	2013.1	2533.6	520.69	2191.3	2712.0
0.250	127.43	0.001067	0.7187	535.08	2002.1	2537.2	535.34	2181.5	2716.9
0.275	130.60	0.001070	0.6573	548.57	1992.0	2540.5	548.87	2172.4	2721.3
0.300	133.55	0.001073	0.6058	561.13	1982.4	2543.6	561.45	2163.9	2725.3
0.325	136.30	0.001076	0.5620	572.88	1973.5	2546.3	573.23	2155.8	2729.0
0.350	138.88	0.001079	0.5243	583.93	1965.0	2548.9	584.31	2148.1	2732.4
0.375	141.32	0.001081	0.4914	594.38	1956.9	2551.3	594.79	2140.8	2735.6
0.40	143.63	0.001084	0.4625	604.29	1949.3	2553.6	604.73	2133.8	2738.5
0.45	147.93	0.001088	0.4140	622.75	1934.9	2557.6	623.24	2120.7	2743.9
0.50	151.86	0.001093	0.3749	639.66	1921.6	2561.2	640.21	2108.5	2748.7
0.55	155.48	0.001097	0.3427	655.30	1909.2	2564.5	655.91	2097.0	2752.9
0.60	158.85	0.001101	0.3157	669.88	1897.5	2567.4	670.54	2086.3	2756.8
0.65	162.01	0.001104	0.2927	683.55	1886.5	2570.1	684.26	2076.0	2760.3
0.70	164.97	0.001108	0.2729	696.43	1876.1	2572.5	697.20	2066.3	2763.5

TABLE B.4 Superheated Water Vapor

P = 500 kPa				
T °C	$\hat{v}$ m³/kg	$\hat{u}$ kJ/kg	$\hat{h}$ kJ/kg	$\hat{s}$ kJ/kg K
sat	0.37489	2561.2	2748.7	6.8213
200	0.42492	2642.9	2855.4	7.0592
250	0.47436	2723.5	2960.7	7.2709
300	0.52256	2802.9	3064.2	7.4599
350	0.57012	2882.6	3167.6	7.6329
400	0.61728	2963.2	3271.8	7.7937
500	0.71093	3128.4	3483.8	8.0872
600	0.80406	3299.6	3701.7	8.3521
700	0.89691	3477.5	3926.0	8.5952
800	0.98959	3662.2	4157.0	8.8211
900	1.08217	3853.6	4394.7	9.0329
1000	1.17460	4051.8	4639.1	9.2328
1100	1.26718	4256.3	4889.9	9.4224
1200	1.35964	4466.8	5146.6	9.6029
1300	1.45210	4682.5	5408.6	9.7749

P = 600 kPa				
T °C	$\hat{v}$ m³/kg	$\hat{u}$ kJ/kg	$\hat{h}$ kJ/kg	$\hat{s}$ kJ/kg K
sat	0.31567	2567.4	2756.8	6.7600
200	0.35202	2638.9	2850.1	6.9665
250	0.39383	2720.9	2957.2	7.1816
300	0.43437	2801.0	3061.6	7.3723
350	0.47424	2881.1	3165.7	7.5463
400	0.51372	2962.0	3270.2	7.7078
500	0.59199	3127.6	3482.7	8.0020
600	0.66974	3299.1	3700.9	8.2673
700	0.74720	3477.1	3925.4	8.5107
800	0.82450	3661.8	4156.5	8.7367
900	0.90188	3853.2	4394.4	8.9485
1000	0.97882	4051.5	4638.8	9.1484
1100	1.05584	4256.1	4889.6	9.3381
1200	1.13282	4466.5	5146.2	9.5185
1300	1.21000	4682.3	5408.3	9.6906

P = 800 kPa				
T °C	$\hat{v}$ m³/kg	$\hat{u}$ kJ/kg	$\hat{h}$ kJ/kg	$\hat{s}$ kJ/kg K
sat	0.24043	2576.8	2769.1	6.6627
200	0.26080	2630.6	2839.2	6.8158
250	0.29314	2715.5	2950.0	7.0384
300	0.32411	2797.1	3056.4	7.2327
350	0.35439	2878.2	3161.7	7.4088
400	0.38426	2959.7	3267.1	7.5716
500	0.44331	3125.9	3480.6	7.8672
600	0.50184	3297.9	3699.4	8.1332
700	0.56007	3476.2	3924.3	8.3770
800	0.61813	3661.1	4155.7	8.6032
900	0.67610	3852.8	4393.6	8.8152
1000	0.73401	4051.0	4638.2	9.0152
1100	0.79188	4255.6	4889.1	9.2048
1200	0.84974	4466.1	5145.8	9.3854
1300	0.90758	4681.8	5407.9	9.5575