

UNIVERSITY  
OF  
JOHANNESBURG

**PROGRAM** : BACCALAUREUS TECHNOLOGIAE  
*CHEMICAL ENGINEERING*

**SUBJECT** : UNIT OPERATIONS IV

**CODE** : WARB432

**DATE** : WINTER EXAMINATION  
26 MAY 2018

**DURATION** : SESSION 2(12:30 – 15:30)

**WEIGHT** : 40 : 60

**TOTAL MARKS** : 100

**EXAMINER(S)** : MR G PAHLA

**MODERATOR** : DR A MAMVURA

**NUMBER OF PAGES** : 07 PAGES

**REQUIREMENTS** : Use of scientific (non-programmable) calculator is permitted  
(only one per candidate); graph paper

**HINTS AND INSTRUCTIONS TO CANDIDATE(S):**

- Purpose of assessment is to determine not only if you can write down an answer, but also to assess whether you understand the concepts, principles and expressions involved. Set out solutions in a logical and concise manner with justification for the steps followed.
- **ATTEMPT ALL QUESTIONS.** Please answer each question to the best of your ability.
- Write your details (module name and code, ID number, student number etc.) on script(s).
- Number each question clearly; questions may be answered in any order.
- Make sure that you read each question carefully before attempting to answer the question.
- Show all steps (and units) in calculations; this is a 'closed book' test.
- Ensure your responses are legible, clear and include relevant units (where appropriate).

**Question One (Multi-component Distillation)****[Total: 30 Marks]**

A feed(100 kmol/h) of saturated liquid containing 10 mole % LNK, 55 mole % LK, and 35 mole % HK is to be separated in a distillation column. The reflux ratio is 1.2 the minimum. It is desired to have 99.5 % recovery of the light key in the distillate. The mole fraction of the light key in the distillate should be 0.75. Equilibrium data:  $\alpha_{LNK} = 5.33$ ,  $\alpha_{LK} = 1.33$ ,  $\alpha_{HK} = 1.0$ . Find

- 1.1. Minimum number of stages required by Fenske method [11]
- 1.2. Minimum reflux ratio by Underwood method [6]
- 1.3. Number of ideal stages at  $R = 1.2 R_{min}$  by Gilliland method [7]
- 1.4. The number of ideal stages at rectifying section and the stripping section at the operating reflux ratio. [6]

**Question Two (Multi-Component Absorption)****[Total: 20 Marks]**

An absorption tower with 8 equilibrium stages is fed a gas mixture containing 88 mol%  $CH_4$ , 4%  $C_2H_6$ , 5%  $C_3H_8$  and 3%  $n-C_4H_{10}$ . It is operated isothermally at  $38^\circ C$  and 5 bar (abs). The aim is to remove 80% of the  $C_3H_8$ . Lean oil containing 0,5 mol%  $C_4H_{10}$  is to be used. The rest of the oil is non-volatile. Given that the flow ratio of inlet gas to lean oil is 0.5, determine the compositions of the exit gas and oil.

**Only show calculations for  $C_1$  and  $C_4$**

K values are as follows:  $CH_4 = 32$ ;  $C_2H_6 = 6,7$ ;  $C_3H_8 = 2,4$ ;  $n-C_4H_{10} = 0,74$ .

**Question Three (Evaporation)****[Total: 20 Marks]**

A continuous single-effect evaporator concentrates 9072 kg/h of a 1 wt % salt solution entering at  $37.8^\circ C$  (311.0K) to a final concentration of 1.5 wt %. The vapor space of the evaporator is at 1 bar(absolute) and the steam supplied is saturated at 143.3 kPa. The overall coefficient  $U = 1704 W/m^2.K$ . Calculate

- 3.1. The amounts of vapor and liquid product
- 3.2. The heat-transfer are required.
- 3.3. The steam economy

$$C_p(\text{solution}) = 4.14 \text{ kJ/kg.K}$$

$$H_v(373.2 \text{ K}) = 2257 \text{ kJ/kg}$$

$$\text{Latent heat}(373.2 \text{ K}) = 2230 \text{ kJ/k}$$

**Question Four (Crystallization)****[Total: 15 Marks]**

A hot aqueous solution of  $\text{Ba}(\text{NO}_3)_2$  contains 30.6 kg  $\text{Ba}(\text{NO}_3)_2$ /100 kg water. This stream is fed to a crystalliser where the solution is cooled and  $\text{Ba}(\text{NO}_3)_2$  crystallises. On cooling, 10% of the original water present evaporates.

For a feed solution of 100 kg calculate yield of crystals if the solution is cooled to 290 K where the solubility is 8.6 kg  $\text{Ba}(\text{NO}_3)_2$  /100 kg water

$\text{Ba}(\text{NO}_3)_2 = 261.337\text{g/mol}$

**Question Five (Fluidization)****[Total: 15 Marks]**

To promote an effective catalytic reaction, it is suggested to use a fluidized bed reactor. The catalyst are spherical pellets 3 mm in diameter and are to be fluidized with nitrogen at 101.3 kPa at 60°C. The density of the catalyst particles is 980 kg/m<sup>3</sup>. The molecular weight of nitrogen is 29 kg/kmol. If it is assumed that the point of incipient fluidization is reached at  $e_{mf} = 0.430$ , calculate the minimum fluidization velocity in the vessel. Nitrogen is considered here to be an Ideal Gas with  $\mu_{\text{nitrogen}} = 0.0000207 \text{ Ns/m}^2$ .

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**END****[Total: 100 Marks]**

Useful Formulae and Correlations

McCabe-Thiele Method:  $y_1 = \frac{\alpha_{1,2}(x_1)}{1 + (x_1)(\alpha_{1,2} - 1)}$

$$y_n = \frac{L_n}{V_n} x_{n+1} + \frac{D}{V_n} x_D \text{ or } y_n = \frac{R}{R+1} x_{n+1} + \frac{x_D}{R+1}, \quad y_m = \frac{L_m}{V_m} x_{m+1} + \frac{B}{V_m} x_B, \quad y_q = \frac{q}{q-1} x_q - \frac{z_f}{q-1}$$

Fenske's Equation(s):

$$N_{\min} + 1 = \frac{\log \left[ \left( \frac{x_{LK}}{x_{HK}} \right)_D \left( \frac{x_{HK}}{x_{LK}} \right)_B \right]}{\log \alpha_{LK, HK}}, \quad b_i = \frac{f_i}{1 + \left( \frac{d_r}{b_r} \right) (\alpha_{i,r})_m^{N_{\min}}}, \quad d_i = \frac{f_i \left( \frac{d_r}{b_r} \right) (\alpha_{i,r})_m^{N_{\min}}}{1 + \left( \frac{d_r}{b_r} \right) (\alpha_{i,r})_m^{N_{\min}}}$$

Minimum Reflux Ratio by Underwood's Equation(s):

$$\sum \frac{\alpha_i x_{iD}}{\alpha_i - \theta} = R_m + 1 \quad \alpha_{HK} < \theta < \alpha_{LK}$$

$$\sum \frac{\alpha_i x_{iF}}{\alpha_i - \theta} = 1 - q$$

Feed Plate Location by Kirkbride's Equation(s):

$$\log \left[ \frac{N_r}{N_s} \right] = 0.026 \log \left[ \frac{W}{D} \left( \frac{x_{HK}}{x_{LK}} \right)_F \left( \frac{x_{LK}}{x_{HK}} \right)_D \right]^2, \quad \frac{N_r}{N_s} = \left[ \left( \frac{Z_{j,F}}{Z_{j,D}} \right) \left( \frac{x_{i,B}}{x_{j,D}} \right)^2 \left( \frac{B}{D} \right) \right]^{0.206}$$

Erbar-Maddox correlation:  $\frac{R}{R+1}$  vs  $\frac{N_m}{N}$  with  $\frac{R_m}{R_m+1}$  as a parameter

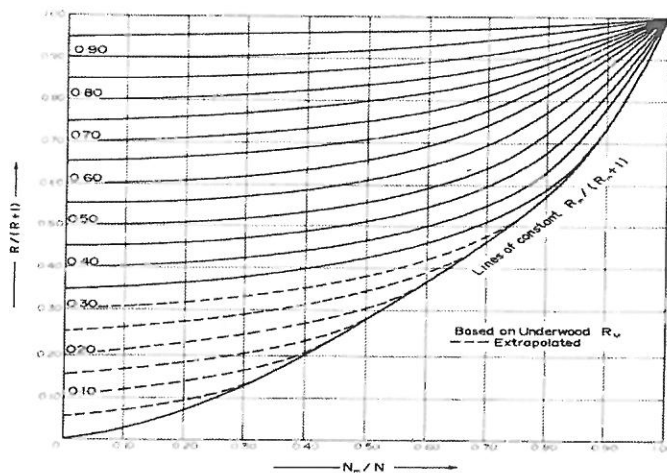


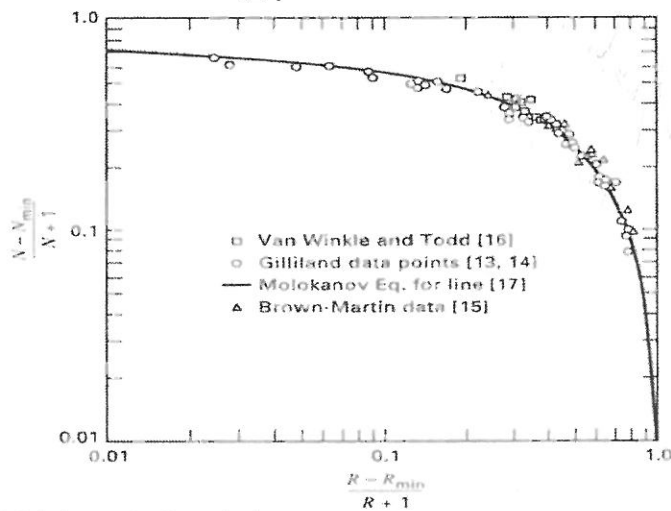
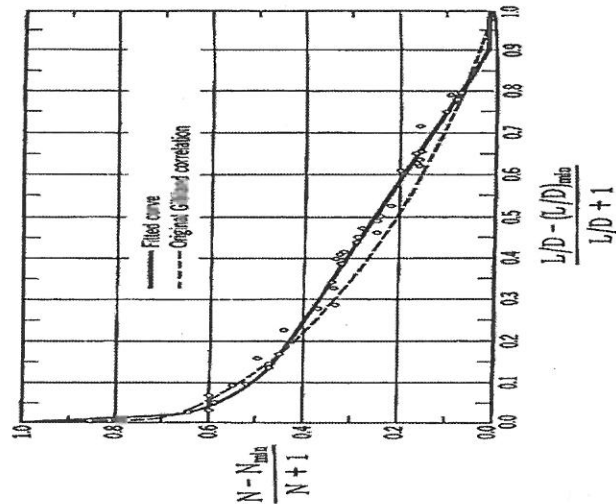
FIG. 11-11. Erbar-Maddox correlation (Erbar and Maddox, 1961)

Bubble and Dew point calculation(s):

$$\sum y_i = \sum K_i x_i = K_i \sum \alpha_i x_i = 1.0, \quad y_i = \frac{\alpha_i x_i}{\sum (\alpha_i x_i)}, \quad \sum_{i=1}^{N_i} y_i = \sum_{i=1}^{N_i} K_i x_i = 1.0, \quad (K_p)_{Trial2} = \frac{(K_p)_{Trial1}}{\sum K_i x_i}$$

$$\sum x_i = \sum \left( \frac{y_i}{K_i} \right) = \left( \frac{1}{K_i} \right) \sum \left( \frac{y_i}{\alpha_i} \right) = 0, \quad x_i = \frac{y_i / \alpha_i}{\sum (y_i / \alpha_i)}, \quad \sum_{i=1}^{N_i} x_i = \sum_{i=1}^{N_i} \frac{y_i}{K_i} = 1.0, \quad (K_i)_{Trial2} = (K_i)_{Trial1} \sum \frac{y_i}{K_i}$$

Gilliland correlation (number of ideal plates at the operating reflux):



Molokanov's Correlation:

$$\frac{N - N_{\min}}{N + 1} = 1 - \exp \left[ \left( \frac{1 + 54.4\Psi}{11 + 117.2\Psi} \right) \left( \frac{\Psi - 1}{\Psi^{0.5}} \right) \right] \quad \text{Where: } \Psi \equiv \frac{R - R_{\min}}{R + 1}; \quad R_m = \frac{1}{\alpha - 1} \left[ \frac{x_d}{x_f} - \alpha \frac{1 - x_d}{1 - x_f} \right]$$

$$\text{Slope of q-line: } -\left( \frac{f}{1-f} \right); \quad f = \frac{c_p(t_b - t_f)_{\text{Liquid}} + \Lambda_{\text{Feed}} + (c_p(t_b - t_f))_{\text{superheated vapour}}}{\Lambda}$$

$$\text{Number of transfer units is given by: } N_{OG} = \int_{Y_1}^{Y_2} \frac{dY}{Y_e - Y}; \quad N_{OG} = \frac{Z}{H_{OG}}; \quad N_{OL} = N_{OG} \left( \frac{m G_M}{L_M} \right)$$

$$\text{Height of transfer unit is given by: } H_{OG} = \frac{G_M}{K_G a P}$$

$$\text{Equilibrium partial pressure: } P_a = P_a^o \left\{ \frac{n_a}{n_a + n_b + n_c + \dots} \right\} = x_a P_a^o$$

$$\Delta T = T_{\text{steam}} - T_b$$

Heat balance:  $\{m_{\text{steam}} x h_{fg}\} = \{m_{\text{feed}} C_p \Delta T\} + \{m_v x h_{fg}\} + \{m_L C_p \Delta T\}$

$$Q = m_{\text{steam}} h_{fg} = m_{\text{feed}} C_p \Delta T + m_v h_{fg}$$

$$Q = m_{\text{feed}} C_p \Delta T + m_v h_{fg}$$

Start-up filter:  $\frac{t - t_s}{V - V_s} = \frac{K_1(V + V_s)}{2P} + \frac{K_2}{P}$

Rotary filter:  $\theta_f = k_f \theta_c$  ;  $\theta_f = \frac{K_1 V_f^2}{2P} + \frac{K_2 V_f}{P}$

Ergun equation:  $-\frac{\Delta P}{L} = \frac{150(1-\varepsilon)^2}{\varepsilon^3} \frac{\mu u_c}{d^2} + \frac{1.75(1-\varepsilon)}{\varepsilon^3} \frac{\rho u_c^2}{d}$ ;  $Ga = \frac{d^3 \rho (\rho_s - \rho) g}{\mu^2}$

Pressure drop:  $(-\Delta P) = (1 - e_{mf})(\rho_s - \rho)lg$ ;  $Re'_0 = (2.33Ga^{0.018} - 1.53Ga^{-0.016})^{13.3}$

$\frac{L_f}{L_p} = \frac{1 - e_p}{1 - e_f}$  ;  $(1 - e_{mf})(\rho_s - \rho)g = \frac{150(1 - e_{mf})^2}{e_{mf}^3} \frac{\mu u_{mf}}{d^2} + \frac{1.75(1 - e_{mf})}{e_{mf}^3} \frac{\rho u_{mf}^2}{d}$

Water balance:  $w_1 = w_2 + \left(y - \frac{y}{R}\right) + w_1 E$

Yield of crystals:  $y = \frac{Rw_1[c_1 - c_2(1 - E)]}{[1 - c_2(R - 1)]}$

$$\frac{1}{nF} \frac{V_w}{V_L} = \ln \frac{1 - F}{F}$$

Table A.1: Conversion Factors	
Quantity	Conversion
Length	1 m = 100 cm = 3.28084(ft) = 39.3701(in)
Mass	1 kg = 10 <sup>3</sup> g = 2.20462(lb <sub>m</sub> )
Force	1 N = 1 kg m s <sup>-2</sup> = 10 <sup>5</sup> (dyne) = 0.224809(lbf)
Pressure	1 bar = 10 <sup>5</sup> kg m <sup>-1</sup> s <sup>-2</sup> = 10 <sup>5</sup> N m <sup>-2</sup> = 10 <sup>5</sup> Pa = 10 <sup>2</sup> kPa = 10 <sup>6</sup> (dyne) cm <sup>-2</sup> = 0.986923(atm) = 14.5038(psia) = 750.061(torr)
Volume	1 m <sup>3</sup> = 10 <sup>6</sup> cm <sup>3</sup> = 10 <sup>3</sup> liters = 35.3147(ft) <sup>3</sup> = 264.172(gal)
Density	1 g cm <sup>-3</sup> = 10 <sup>3</sup> kg m <sup>-3</sup> = 62.4278(lb <sub>m</sub> )(ft) <sup>-3</sup>

Energy	1 J = 1 kg m <sup>2</sup> s <sup>-2</sup> = 1 N m = 1 m <sup>3</sup> Pa = 10 <sup>-5</sup> m <sup>3</sup> bar = 10 cm <sup>3</sup> bar = 9.86923 cm <sup>3</sup> (atm) = 10 <sup>7</sup> (dyne) cm = 10 <sup>7</sup> (erg) = 0.239006(cal) = 5.12197 × 10 <sup>-3</sup> (ft) <sup>3</sup> (psia) = 0.737562(ft)(lbf) = 9.47831 × 10 <sup>-4</sup> (Btu) = 2.77778 × 10 <sup>-7</sup> kWh
Power	1 kW = 10 <sup>3</sup> W = 10 <sup>3</sup> kg m <sup>2</sup> s <sup>-3</sup> = 10 <sup>3</sup> J s <sup>-1</sup> = 239.006(cal) s <sup>-1</sup> = 737.562(ft)(lbf) s <sup>-1</sup> = 0.947831(Btu) s <sup>-1</sup> = 1.34102(hp)

Table A.2: Values of the Universal Gas Constant	
$R = 8.314 \text{ J mol}^{-1} \text{ K}^{-1} = 8.314 \text{ m}^3 \text{ Pa mol}^{-1} \text{ K}^{-1}$ $= 83.14 \text{ cm}^3 \text{ bar mol}^{-1} \text{ K}^{-1} = 8.314 \text{ cm}^3 \text{ kPa mol}^{-1} \text{ K}^{-1}$ $= 82.06 \text{ cm}^3 (\text{atm}) \text{ mol}^{-1} \text{ K}^{-1} = 62.356 \text{ cm}^3 (\text{torr}) \text{ mol}^{-1} \text{ K}^{-1}$ $= 1.987 (\text{cal}) \text{ mol}^{-1} \text{ K}^{-1} = 1.986 (\text{Btu}) (\text{lb mole})^{-1} (\text{R})^{-1}$ $= 0.7302 (\text{ft})^3 (\text{atm}) (\text{lb mole})^{-1} (\text{R})^{-1} = 10.73 (\text{ft})^3 (\text{psia}) (\text{lb mole})^{-1} (\text{R})^{-1}$ $= 1.545 (\text{ft}) (\text{lbf}) (\text{lb mole})^{-1} (\text{R})^{-1}$	



