

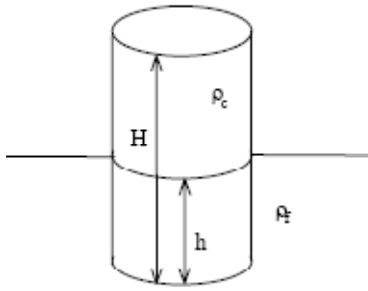
**CHEN200 Introduction to Chemical Engineering**  
**FINAL - SOLUTIONS**

9<sup>th</sup> August 2010

**P1. [20 marks, 2 marks for part (a), 4 marks for (b), 6 marks for (c) and 8 marks for (d)]**

(a) Convert density in  $\text{lb}_m/\text{ft}^3$  to  $\text{kg}/\text{m}^3 = 85.3/(2.2*2.832*10^{-2}) = 1369.1 \text{ kg}/\text{m}^3$   
Volume of pond =  $50*15*2 = 1,500 \text{ m}^3$ . Therefore the mass of the pond is =  **$2.05356*10^6 \text{ kg}$**   
Weight =  $9.81*2.05356*10^6 = \mathbf{20.15*10^6 \text{ N}}$

(b)



(i)

$$m_{\text{displaced fluid}} = m_{\text{cylinder}} \Rightarrow \rho_f V_f = \rho_c V_c \Rightarrow \rho_f h \pi r^2 = \rho_c H \pi r^2$$

$$\rho_c = \frac{\rho_f h}{H} = \frac{(30 \text{ cm} - 14.1 \text{ cm})(100 \text{ g}/\text{cm}^3)}{30 \text{ cm}} = \underline{\underline{0.53 \text{ g}/\text{cm}^3}}$$

(ii)

$$\rho_f = \frac{\rho_c H}{h} = \frac{(30 \text{ cm})(0.53 \text{ g}/\text{cm}^3)}{(30 \text{ cm} - 20.7 \text{ cm})} = \underline{\underline{1.71 \text{ g}/\text{cm}^3}}$$

(c)

5320 imp. gal	14 h	365 d	$10^6 \text{ cm}^3$	0.965 g	1 kg	1 tonne
plane · h	1 d	1 yr	220.83 imp. gal	1 $\text{cm}^3$	1000 g	1000 kg
$= 1.188 \times 10^5 \frac{\text{tonne kerosene}}{\text{plane} \cdot \text{yr}}$						
$4.02 \times 10^9$ tonne crude oil	1 tonne kerosene	plane · yr				
yr	7 tonne crude oil	$1.188 \times 10^5$ tonne kerosene				
$= 4834 \text{ planes} \Rightarrow \underline{\underline{5000 \text{ planes}}}$						

If US gallons were used the answer would be 5770 planes.

(d)

(i) 200 crystals/min.mm; 10 crystals/min.mm<sup>2</sup>.

(ii)

$$r = \frac{200 \text{ crystals}}{\text{min} \cdot \text{mm}} \left| \frac{0.050 \text{ in}}{\text{in}} \right| \frac{25.4 \text{ mm}}{\text{in}} - \frac{10 \text{ crystals}}{\text{min} \cdot \text{mm}^2} \left| \frac{0.050^2 \text{ in}^2}{\text{in}^2} \right| \frac{(25.4)^2 \text{ mm}^2}{\text{in}^2}$$

$$= 238 \text{ crystals} / \text{min} \Rightarrow \frac{238 \text{ crystals}}{\text{min}} \left| \frac{1 \text{ min}}{60 \text{ s}} \right| = \underline{\underline{4.0 \text{ crystals} / \text{s}}}$$

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(iii)

$$D(\text{mm}) = \frac{D'(\text{in}) \left| \frac{25.4 \text{ mm}}{1 \text{ in}} \right.}{1 \text{ in}} = 25.4D'; \quad r \left( \frac{\text{crystals}}{\text{min}} \right) = r' \frac{\text{crystals}}{\text{s}} \left| \frac{60 \text{ s}}{1 \text{ min}} \right. = 60r'$$

$$\Rightarrow 60r' = 200(25.4D') - 10(25.4D')^2 \Rightarrow r' = 84.7D' - 108(D')^2$$

**P2. [20 marks, 3 marks each for parts (a) and (b), 6 marks for (c) and 8 marks for (d)]**

(a)

- (i)  $2600 \times 1.934 \times 10^{-2} = \mathbf{50.284 \text{ psi}}$ ,
- (ii)  $(275/33.9) \times 101.325 = \mathbf{822 \text{ kPa}}$ ,
- (iii)  $(3.00 \times 1.01325 \times 10^5) / (100^2) = \mathbf{30.40 \text{ N/cm}^2}$ ,
- (iv)  $1 \text{ atm} - (20 \times 10 / 760) = \mathbf{0.737 \text{ atm}}$ ,
- (v)  $25.0 \times 51.71 = \mathbf{1292.75 \text{ mm Hg (gauge)}}$ ,
- (vi)  $(25.0 + 14.696) \times 51.71 = \mathbf{2052.68 \text{ mm Hg (absolute)}}$ .

(b) C

- (i)  $T = -10^\circ\text{F}$  to  $^\circ\text{R}$ ,  $^\circ\text{C}$ ,  $\text{K}$ ,  $T = -10^\circ\text{F} + 459.7 = \mathbf{449.7^\circ\text{R}}$ ,  $1.8 = \mathbf{249\text{K}}$ ,  $-273 = \mathbf{-23^\circ\text{C}}$
- (ii)  $\Delta T = 85^\circ\text{C} = \mathbf{85\text{K}}$ ,  $= 85^\circ\text{C} \times 1.8 = \mathbf{153^\circ\text{F}} = \mathbf{153^\circ\text{R}}$ ,
- (iii)  $\Delta T = 150^\circ\text{R} = \mathbf{150^\circ\text{F} / 1.8} = \mathbf{83.3^\circ\text{C}} = \mathbf{83.3\text{K}}$

(c)

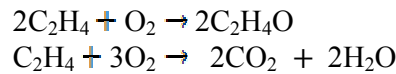
- (i)  $(P' + 14.32) \times V' = 10.45n'(T' + 459.4)$
- (ii)  $\mathbf{0.316 \text{ lb-mole}}$  of gas and  $\mathbf{2.65 \text{ lb}_m}$  of CO
- (iii)  $\mathbf{2735.5^\circ\text{F}}$ . The ideal gas equation is an approximation of the real behavior of gases where several simplifying assumptions are made (no interactions between the molecules, no interaction with the surface, etc.). The ideal gas equation does not apply at high temperatures and pressures when the conditions approach the critical point.

(d) Assumptions: Standard conditions, Density of water is  $1,000 \text{ kg/m}^3$ , Basis is  $1 \text{ m}^3$

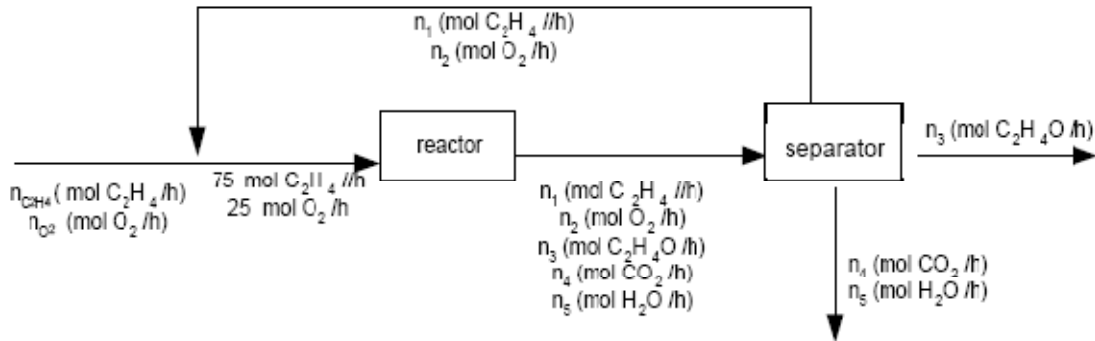
	Abu Dhabi				Kharg Island		
	MW	PPM (mg/L)	Weight F	Mol F	PPM (mg/L)	Weight F	Mol F
Chloride (Cl)	35.453	24,300	<b>0.55</b>	<b>0.50</b>	23,000	<b>0.56</b>	<b>0.50</b>
Sulfate (SO <sub>4</sub> )	96.064	3,420	<b>0.08</b>	<b>0.03</b>	3,100	<b>0.07</b>	<b>0.02</b>
Bicarbonate (HCO <sub>3</sub> )	61	200	<b>0.005</b>	<b>0.002</b>	171	<b>0.004</b>	<b>0.002</b>
Carbonate (CO <sub>3</sub> )	60	0	<b>0</b>	<b>0</b>	24	<b>0.001</b>	<b>0.0003</b>
Sodium (Na)	23	13,900	<b>0.32</b>	<b>0.44</b>	13,044	<b>0.32</b>	<b>0.44</b>
Magnesium (Mg)	54.94	1,560	<b>0.04</b>	<b>0.02</b>	1,500	<b>0.04</b>	<b>0.02</b>
Calcium (Ca)	40.08	600	<b>0.014</b>	<b>0.01</b>	520	<b>0.013</b>	<b>0.01</b>
SG		1.029			1.031		
No. of moles				<b>1,372</b>			<b>1,292</b>
<b>TDS</b>		<b>43,980</b>			<b>41,359</b>		
<b>Weight %</b>		<b>4.27%</b>			<b>4.01%</b>		

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**P3. [25 marks, 8 marks each for parts (a) and (b), 6 marks for (c) and 3 marks for (d)]**



(a) Basis: 100 mol fed to reactor/h  $\Rightarrow$  25 mol O<sub>2</sub>/h, 75 mol C<sub>2</sub>H<sub>4</sub>/h



Reactor

5 unknowns ( $n_1 - n_5$ )

-3 atomic balances

-1 - % yield

-1 - % conversion

0 D.F.

Strategy: 1. Solve balances around reactor to find  $n_1 - n_5$   
 2. Solve balances around mixing point to find  $n_{\text{O}_2}$ ,  $n_{\text{C}_2\text{H}_4}$

(1) % Conversion  $\Rightarrow n_1 = .800 * 75$

(2) % yield:  $(0.200)(75) \text{ mol C}_2\text{H}_4 \times \frac{90 \text{ mol C}_2\text{H}_4\text{O}}{100 \text{ mol C}_2\text{H}_4} = n_3$  (production rate of C<sub>2</sub>H<sub>4</sub>O)

(3) C balance (reactor):  $150 = 2 n_1 + 2 n_3 + n_4$

(4) H balance (reactor):  $300 = 4 n_1 + 4 n_3 + 2 n_5$

(5) O balance (reactor):  $50 = 2 n_2 + n_3 + 2 n_4 + n_5$

(6) O<sub>2</sub> balance (mix pt):  $n_{\text{O}_2} = 25 - n_2$

(7) C<sub>2</sub>H<sub>4</sub> balance (mix pt):  $n_{\text{C}_2\text{H}_4} = 75 - n_1$

Overall conversion of C<sub>2</sub>H<sub>4</sub>: 100%

(b) Calculate the quantities specified in part (b).

$n_1 = 60.0 \text{ mol C}_2\text{H}_4/\text{h}$ ,  $n_2 = 13.75 \text{ mol O}_2/\text{h}$ ,  $n_3 = 13.5 \text{ mol C}_2\text{H}_4\text{O}/\text{h}$

$n_4 = 3.00 \text{ mol CO}_2/\text{h}$ ,  $n_5 = 3.00 \text{ mol H}_2\text{O}/\text{h}$ ,  $n_{\text{O}_2} = 11.25 \text{ mol O}_2/\text{h}$

$n_{\text{C}_2\text{H}_4} = 15.0 \text{ mol C}_2\text{H}_4/\text{h}$ , 100% conversion of C<sub>2</sub>H<sub>4</sub>

(c)

$$\text{Scale factor} = \frac{2000 \text{ lbm C}_2\text{H}_4\text{O}}{\text{h}} \left| \frac{1 \text{ lb-mole C}_2\text{H}_4\text{O}}{44.05 \text{ lbm C}_2\text{H}_4\text{O}} \right| \frac{\text{h}}{13.5 \text{ mol C}_2\text{H}_4\text{O}} = 3.363 \frac{\text{lb-mol/h}}{\text{mol/h}}$$

$$n_{\text{C}_2\text{H}_4} = (3.363)(15.0) = \underline{\underline{50.4 \text{ lb-mol C}_2\text{H}_4/\text{h}}}$$

$$n_{\text{O}_2} = (3.363)(11.25) = \underline{\underline{37.8 \text{ lb-mol O}_2/\text{h}}}$$

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**P4. [15 marks, 6 marks parts (a) and 9 marks for part (b)]**

(a)

(i)  $P_{\text{final}} = 243 \text{ mm Hg}$ . Since liquid is still present, the pressure and temperature must lie on the vapor-liquid equilibrium curve, where by definition the pressure is the vapor pressure of the

(ii) Assuming ideal gas behavior for the vapor,

$$m(\text{vapor}) = \frac{(3.000 - 0.010) \text{ L}}{(30 + 273.2) \text{ K}} \left| \frac{\text{mol} \cdot \text{K}}{0.08206 \text{ L} \cdot \text{atm}} \right| \frac{243 \text{ mm Hg}}{760 \text{ mm Hg}} \left| \frac{1 \text{ atm}}{760 \text{ mm Hg}} \right| \frac{119.39 \text{ g}}{\text{mol}} = 4.59 \text{ g}$$

$$m(\text{liquid}) = \frac{10 \text{ mL}}{1 \text{ mL}} \left| \frac{1.489 \text{ g}}{\text{mL}} \right| = 14.89 \text{ g}$$

$$m_{\text{total}} = m(\text{vapor}) + m(\text{liquid}) = \underline{\underline{19.5 \text{ g}}}$$

$$x_{\text{vapor}} = \frac{4.59}{19.48} = \underline{\underline{0.235 \text{ g vapor / g total}}}$$

(b) Ethyl acetate has a vapour pressure of 118.3 mm Hg at 29.5°C and a normal boiling point of 77.0°C. Estimate the vapour pressure at 45°C using

(i) the Antoine equation:

$$\log_{10} p^* = 7.09808 - \frac{1238.71}{45 + 217} = 2.370 \Rightarrow p^* = 10^{2.370} = \underline{\underline{234.5 \text{ mm Hg}}}$$

(ii)

$$\ln p^* = -\frac{\Delta \hat{H}_v}{R} \frac{1}{T} + B \Rightarrow -\frac{\Delta \hat{H}_v}{R} = \frac{\ln(p_2^* / p_1^*)}{\frac{1}{T_2} - \frac{1}{T_1}} = \frac{\ln(760 / 118.3)}{\frac{1}{(77.0+273.2)\text{K}} - \frac{1}{(29.5+273.2)\text{K}}} = -4151 \text{ K}$$

$$B = \ln(p_1^*) + \frac{\Delta \hat{H}_v / R}{T_1} = \ln(118.3) + \frac{4151 \text{ K}}{(29.5 + 273.2)\text{K}} = 18.49$$

$$\ln p^*(45^\circ \text{C}) = -\frac{4151}{(45 + 273.2)} + 18.49 \Rightarrow \underline{\underline{p^* = 231.0 \text{ mm Hg}}}$$

$$\frac{231.0 - 234.5}{234.5} \times 100\% = \underline{\underline{-1.5\% \text{ error}}}$$

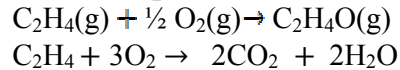
(iii)

$$p^* = \left( \frac{118.3 - 760}{29.5 - 77} \right) (45 - 29.5) + 118.3 = \underline{\underline{327.7 \text{ mm Hg}}}$$

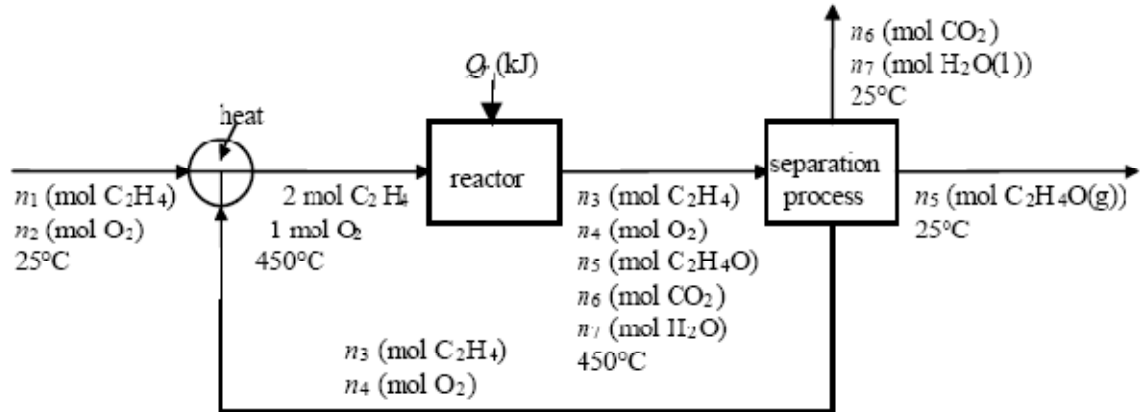
$$\frac{327.7 - 234.5}{234.5} \times 100\% = \underline{\underline{39.7\% \text{ error}}}$$

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P5. [20 marks, 8 marks part (a) and 12 marks for part (b)]



Basis: 2 mol C<sub>2</sub>H<sub>4</sub> fed to reactor



(a)

$$\text{70\% yield} \Rightarrow n_5 = \frac{0.500 \text{ mol C}_2\text{H}_4 \text{ consumed}}{1 \text{ mol C}_2\text{H}_4} \times 0.700 \text{ mol C}_2\text{H}_4\text{O} = \underline{\underline{0.350 \text{ mol C}_2\text{H}_4\text{O}}}$$

$$\text{C balance on reactor: } (2)(2) = (2)(1.50) + (2)(0.350) + n_6 \Rightarrow n_6 = \underline{\underline{0.300 \text{ mol CO}_2}}$$

$$\text{Water formed: } n_7 = \frac{0.300 \text{ mol CO}_2}{1 \text{ mol CO}_2} \times 1 \text{ mol H}_2\text{O} = \underline{\underline{0.300 \text{ mol H}_2\text{O}}}$$

$$\text{O balance on reactor: } (2)(1) = 2n_4 + 0.350 + (2)(0.300) + 0.300 \Rightarrow n_4 = \underline{\underline{0.375 \text{ mol O}_2}}$$

$$\text{Overall C balance: } 2n_1 = n_6 + 2n_5 = 0.300 + (2)(0.350) \Rightarrow n_1 = \underline{\underline{0.500 \text{ mol C}_2\text{H}_4}}$$

$$\text{Overall O balance: } 2n_2 = 2n_6 + n_7 + n_5 = (2)(0.300) + (0.300) + (0.350) \Rightarrow n_2 = \underline{\underline{0.625 \text{ mol O}_2}}$$

Feed stream: 44.4% C<sub>2</sub>H<sub>4</sub>, 55.6% O<sub>2</sub>      Reactor inlet: 66.7% C<sub>2</sub>H<sub>4</sub>, 33.3% O<sub>2</sub>

Recycle stream: 80.0% C<sub>2</sub>H<sub>4</sub>, 20.0% O<sub>2</sub>

Reactor outlet: 53.1% C<sub>2</sub>H<sub>4</sub>, 13.3% O<sub>2</sub>, 12.4% C<sub>2</sub>H<sub>4</sub>O, 10.6% CO<sub>2</sub>, 10.6% H<sub>2</sub>O

$$\text{Mass of ethylene oxide} = \frac{0.350 \text{ mol C}_2\text{H}_4\text{O}}{1 \text{ mol}} \times \frac{44.05 \text{ g}}{10^3 \text{ g}} = 0.0154 \text{ kg}$$

(b) References for enthalpy calculations :C (s) , H<sub>2</sub> (g) , O<sub>2</sub> (g) at 25 °C

$$\begin{aligned} \hat{H}_i(T) &= \Delta \hat{H}_f^\circ + \int_{25}^T C_p dT \text{ for C}_2\text{H}_4 \\ &= \Delta \hat{H}_f^\circ + \int_{298}^{T+273} C_p dT \text{ for C}_2\text{H}_4\text{O} \\ &= \Delta \hat{H}_f^\circ + \hat{H}_i(\text{table B.8}) \text{ for O}_2, \text{CO}_2, \text{H}_2\text{O}(\text{g}) \\ &= \Delta \hat{H}_f^\circ \text{ for H}_2\text{O}(\text{l}) \end{aligned}$$

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<u>Overall Process</u>					<u>Reactor</u>				
Substance	$n_{in}$ (mol)	$\hat{H}_{in}$ (kJ/mol)	$n_{out}$ (mol)	$\hat{H}_{out}$ (kJ/mol)	substance	$n_{in}$ (mol)	$\hat{H}_{in}$ (kJ/mol)	$n_{out}$ (mol)	$\hat{H}_{out}$ (kJ/mol)
C <sub>2</sub> H <sub>4</sub>	0.500	52.28	–	–	C <sub>2</sub> H <sub>4</sub>	2	79.26	1.50	79.26
O <sub>2</sub>	0.625	0	–	–	O <sub>2</sub>	1	13.37	0.375	13.37
C <sub>2</sub> H <sub>4</sub> O	–	–	0.350	–51.00	C <sub>2</sub> H <sub>4</sub> O	–	–	0.350	–19.99
CO <sub>2</sub>	–	–	0.300	–393.5	CO <sub>2</sub>	–	–	0.300	–374.66
H <sub>2</sub> O(l)			0.300	285.84	H <sub>2</sub> O(g)			0.300	226.72

Energy balance on process:  $Q = \Delta H = \sum_{out} n_i \hat{H}_i - \sum_{in} n_i \hat{H}_i = \underline{\underline{-248 \text{ kJ}}}$

Energy balance on reactor:  $Q = \Delta H = \sum_{out} n_i \hat{H}_i - \sum_{in} n_i \hat{H}_i = \underline{\underline{-236 \text{ kJ}}}$

**Bonus Problem [10 marks]**

void volume of bed:  $100 \text{ cm}^3 - (233.5 - 184) \text{ cm}^3 = 50.5 \text{ cm}^3$

porosity:  $50.5 \text{ cm}^3 \text{ void} / 184 \text{ cm}^3 \text{ total} = \underline{\underline{0.274 \text{ cm}^3 \text{ void} / \text{cm}^3 \text{ total}}}$

bulk density:  $600 \text{ g} / 184 \text{ cm}^3 = \underline{\underline{3.26 \text{ g} / \text{cm}^3}}$

absolute density:  $600 \text{ g} / (184 - 50.5) \text{ cm}^3 = \underline{\underline{4.49 \text{ g} / \text{cm}^3}}$