9/17/99

ChE 182
Major 1

Styrene Production

Styrene is the monomer used to make polystyrene, which has a multitude of uses, the most common of which are in packaging and insulated styrofoam beverage cups. Styrene is produced by the dehydrogenation of ethylbenzene. Ethylbenzene is formed by reacting ethylene and benzene, and most benzene is made by hydrodealkylation of toluene, which is obtained as a byproduct of gasoline manufacture. There is very little ethylbenzene sold commercially. Most ethylbenzene manufacturers convert it directly into styrene.

The plant at which you are employed currently manufactures ethylbenzene, styrene, and polystyrene. The unit to which you are assigned, Unit 500, converts the ethylbenzene into styrene, producing around 100,000 metric tons per year of 99.8 wt % styrene.

Styrene Production Reactions

The reactions for styrene production are as follows:

$$\underset{\text{ethylbenzene}}{C_6H_5C_2H_5} \quad \underset{2}{\overset{1}{\rightleftarrows}} \quad \underset{\text{styrene}}{C_6H_5C_2H_3} \quad + \quad \underset{\text{hydrogen}}{H_2} \tag{1}$$

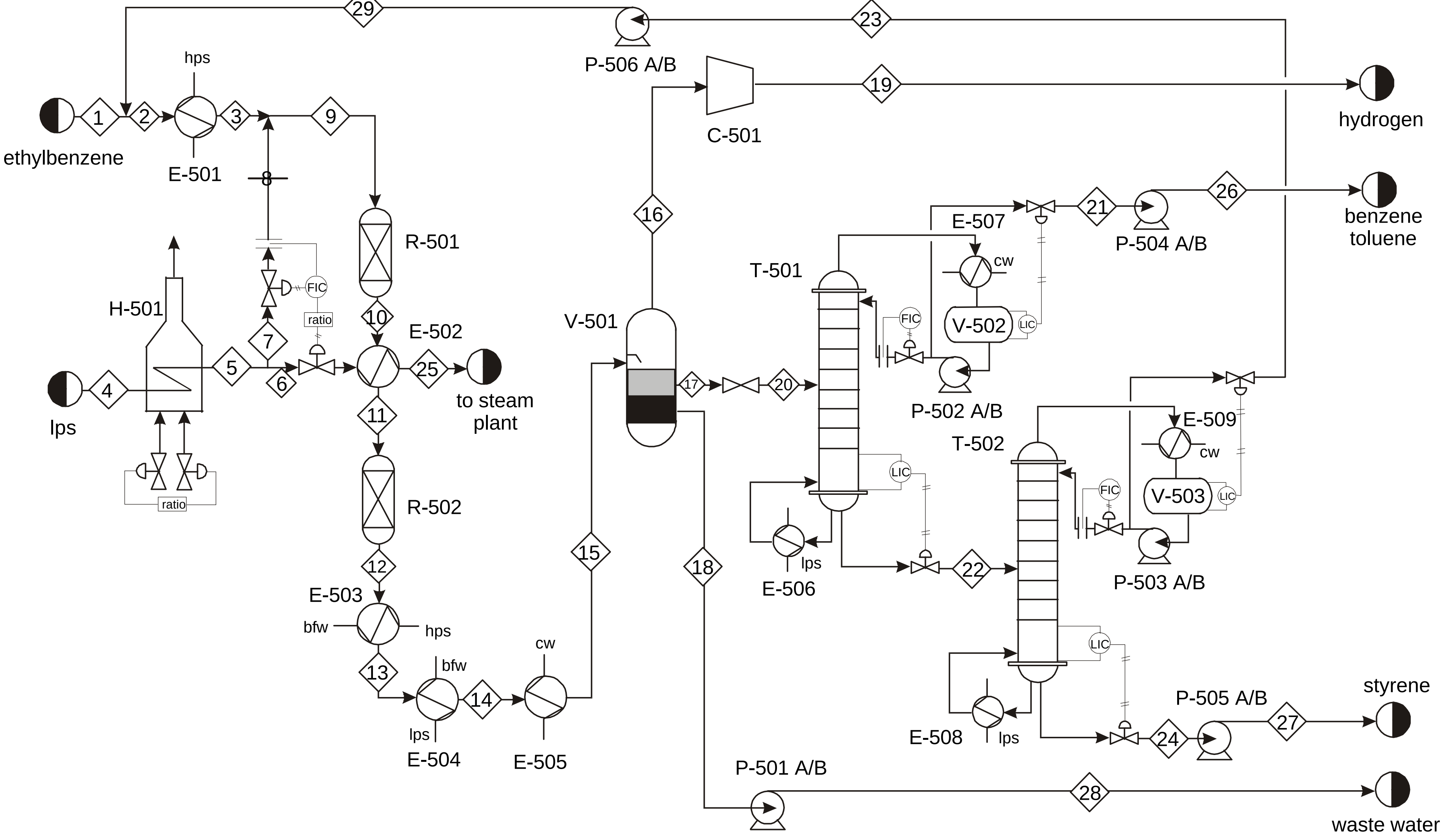
$$\underset{\text{ethylbenzene}}{C_6H_5C_2H_5} \quad \xrightarrow{3} \quad \underset{\text{benzene}}{C_6H_6} \quad + \quad \underset{\text{ethylene}}{C_2H_4} \tag{2}$$

$$\underset{\text{ethylbenzene}}{C_6H_5C_2H_5} \quad + \quad \underset{\text{hydrogen}}{H_2} \quad \xrightarrow{4} \quad \underset{\text{toluene}}{C_6H_5CH_3} \quad + \quad \underset{\text{methane}}{CH_4} \tag{3}$$

Process Description

The process flow diagram is shown in Figure 1. Ethylbenzene feed is mixed with recycled ethylbenzene, heated, and then mixed with high-temperature, superheated steam. Steam is an inert in the reaction, which drives the equilibrium shown in Equation (1) to the right by reducing the concentrations of all components. Since styrene formation is highly endothermic, the superheated steam also provides energy to drive the reaction. The reactants then enter two adiabatic packed beds with interheating. The products are cooled, producing steam from the high-temperature reactor effluent. The cooled product stream is sent to a three-phase separator, in which light gases (hydrogen, methane, ethylene), organic liquid, and water each exit in

H-501	steam heater
E-502	inter-heater
R-502	styrene reactor
E-503	product cooler
E-504	product cooler
E-505	product cooler
V-501	three-phase separator
C-501	compressor
P-501A/B	waste water pump
T-501	benzene toluene column
E-506	reboiler
E-507	condenser
P-502A/B	reflux pump
V-502	reflux drum
T-502	styrene column
E-508	reboiler
E-509	condenser
P-503 A/B	reflux pump
E-501	feed heater
R-501	styrene reactor
P-504 A/B	benzene toluene pump
P-505 A/B	styrene pump
P-506 A/B	recycle pump



Unit 500: Production of Styrene from Ethylbenzene

separate streams. The hydrogen stream is further purified as a source of hydrogen elsewhere in our plant. The benzene/toluene stream is currently returned as a feed stream to our petrochemical facility. The organic stream containing the desired product is distilled once to remove the benzene and toluene and distilled again to separate unreacted ethylbenzene for recycle from the styrene product.

The styrene product can spontaneously polymerize at higher temperatures. Since our product styrene is sent directly to the polymerization unit, experience suggests that as long its temperature is maintained below 125°C, there is no spontaneous polymerization problem. Since this is below styrene's normal boiling point, and since low pressure pushes the equilibrium in Equation (1) to the right, much of this process is run at vacuum.

Problem

Recently, Unit 500 has been periodically operating outside of standard conditions. There are significant process transients. Tables 1 and 2 show the design conditions for Unit 500. A survey of process conditions during an upset yielded the following observations:

1. The feed of ethylbenzene, Stream 1 is at design conditions. We have no information about Stream 4.

2. Production of styrene is reduced by up to 3%. The styrene that is produced is still within specifications.

3. The total flow of the recycle stream is reduced by up to 12%.

4. The total flow of the hydrogen effluent stream is approximately unchanged. An assay of this stream shows a decrease in hydrogen flowrate of up to 6%, an increase in methane flowrate of up to 3%, and an increase in ethylene flowrate of up to 13%.

5. The total flow of the benzene/toluene stream is increased by up to 7%. The ethylbenzene flowrate of this stream is reduced by up to 11%, the styrene flowrate is approximately constant, the toluene flowrate is increased by up to 2%, and the benzene flowrate is increased by up to 13%.

Your boss has solicited input from the operators with the following results. One operator says that the problem might be a new batch of catalyst. Another operator suggests that there is a problem with the ratio controller on H-501, since the problem goes away when he bangs the valve on the natural gas line with a wrench. (Your boss says this is nonsense.) Another operator says the problem is incorrect flow measurement downstream, and that styrene production has not actually been affected.

Clearly, operation this much outside of standard conditions is a cause for concern, especially if the problem should begin to occur more frequently and for longer durations. The first part of your assignment is to suggest causes for this periodic problem, identify the most likely cause,

Table 1
Stream Tables for Unit 500

Stream No.	1	2	3	4	5	6
Temperature (°C)	136	116	225	159	800	800
Pressure (kPa)	210	200	180	600	565	565
Vapor Mole Fraction	0	0	1	1	1	1
Total Flow (kg/h)	19417	54890	54890	227784	227784	83664
Total Flow (kmol/h)	183.6	517.8	517.8	12644	12644	4644
Component Flows						
Water				12644	12644	4644
Ethylbenzene	180	512.7	512.7			
Styrene		1.2	1.2			
Hydrogen						
Benzene	1.8	1.8	1.8			
Toluene	1.8	2.13	2.13			
Ethylene						
Methane						

Stream No.	7	8	9	10	11	12
Temperature (°C)	800	799	632	609	650	640
Pressure (kPa)	565	180	170	160	145	135
Vapor Mole Fraction	1	1	1	1	1	1
Total Flow (kg/h)	144120	144120	199010	199010	199010	199010
Total Flow (kmol/h)	8000	8000	8517.6	8614.7	8614.7	8662.7
Component Flows						
Water	8000	8000	8000	8000	8000	8000
Ethylbenzene			512.7	399.1	399.1	336.36
Styrene			1.2	86.8	86.8	120.67
Hydrogen				69.0	69.0	88.1
Benzene			1.8	13.1	13.1	27.5
Toluene			2.13	18.7	18.7	33.3
Ethylene				11.3	11.3	25.7
Methane				16.6	16.6	31.1

Table 1
Stream Tables for Unit 500 (cont'd)

Stream No.	13	14	15	16	17	18
Temperature (°C)	270	180	65	65	65	65
Pressure (kPa)	120	105	90	75	75	75
Vapor Mole Fraction	1	1	.025	1	0	0
Total Flow (kg/h)	199010	199010	199010	2682	53493	142715
Total Flow (kmol/h)	8662.7	8662.7	8662.7	216.3	517.8	7928.6
Component Flows						
Water	8000	8000	8000	71.4		7928.6
Ethylbenzene	336.36	336.36	336.36		336.36	
Styrene	120.67	120.67	120.67		120.67	
Hydrogen	88.1	88.1	88.1	88.1		
Benzene	27.5	27.5	27.5		27.5	
Toluene	33.3	33.3	33.3		33.3	
Ethylene	25.7	25.7	25.7	25.7		
Methane	31.1	31.1	31.1	31.1		

Stream No.	19	20	21	22	23	24
Temperature (°C)	197	65	66	119.5	105	124.5
Pressure (kPa)	240	60	40	60	210	60
Vapor Mole Fraction	1	0	0	0	0	0
Total Flow (kg/h)	2682	53493	5548	47905	35473	12432
Total Flow (kmol/h)	216.3	517.8	63.9	453.9	334.2	119.7
Component Flows						
Water	71.4					
Ethylbenzene		336.36	3.36	333.0	332.66	0.34
Styrene		120.67	0.1	120.53	1.20	119.3
Hydrogen	88.1					
Benzene		27.5	27.5			
Toluene		33.3	32.9	0.33	0.33	
Ethylene	25.7					
Methane	31.1					

Table 1
Stream Tables for Unit 500 (cont'd)

Stream No.	25	26	27	28	29
Temperature (°C)	700	66	124.5	65	105
Pressure (kPa)	565	200	200	200	210
Vapor Mole Fraction	1	0	0	0	0
Total Flow (kg/h)	83664	5548	12432	142715	35473
Total Flow (kmol/h)	4644	63.9	119.7	7928.6	334.2
Component Flows					
Water	4644			7928.6	
Ethylbenzene		3.36	0.34		332.66
Styrene		0.1	119.3		1.20
Hydrogen					
Benzene		27.5			
Toluene		32.9			0.33
Ethylene					
Methane					

Table 2
Utility Summary for Unit 500

E-501	**E-503**	**E-504**	**E-505**
hps	bfw → hps	bfw → lps	cw
17,566 kg/h	67,256 kg/h	14,790 kg/h	9,455,376 kg/h

E-506	**E-507**	**E-508**	**E-509**
lps	cw	lps	cw
15,878 kg/h	671,941 kg/h	163,505 kg/h	8,173,446 kg/h

and suggest potential remedies for this problem. We need your answer quickly, since a scheduled plant shut down occurs next month.

Current market conditions for polystyrene are very tight. Whatever we can do to improve the economic performance of Unit 500 will help the bottom line. Therefore, the second part of your assignment is to suggest process improvements that will enhance the profitability of Unit 500, especially ones that can reasonably be implemented during the upcoming shut down. Detailed economic calculations are not expected.

Other Information

Table 3 contains an equipment list. Other pertinent information and calculations are contained in the appendix.

Assignment

Specifically, you are to prepare the following by 9:00 am, Monday, September 27, 1999:

1. a diagnosis of the operating problems with the plant, explanations of their relevance, and recommendations for solving these problems

2. a list of suggested process improvements which can enhance the profitability of Unit 500

3. a written report, conforming to the guidelines, detailing the information in items 1 and 2, above

4. a legible, organized set of calculations justifying your recommendations, including any assumptions made

5. a signed copy of the attached confidentiality statement

Report Format

This report should be brief and should conform to the guidelines. It should be bound in a folder that is not oversized relative to the number of pages in the report. Most of the report should be an executive summary, which summarizes your diagnosis, recommendations, and rationale. Figures and tables should be included as appropriate. An appendix should be attached that includes items such as the requested calculations. These calculations should be easy to follow. The confidentiality statement should be the very last page of the report.

The written report is a very important part of the assignment. Poorly written and/or organized written reports may require re-writing. Be sure to follow the format outlined in the guidelines for written reports. Failure to follow the prescribed format may be grounds for a re-write.

Table 3
Partial Equipment Summary

E-501 carbon steel $A = 541\ \text{m}^2$ boiling in shell, condensing in tubes 1 shell – 2 tube passes $Q = 29695$ MJ/h	**E-503** 316 stainless steel $A = 2006\ \text{m}^2$ boiling in shell, process fluid in tubes 1 shell – 2 tube passes $Q = 162.8$ GJ/h
H-501 fired heater – refractory design $Q = 88.26$ MW max $Q = 100$ MW	**E-504** carbon steel $A = 2133\ \text{m}^2$ boiling in shell, process fluid in tubes 1 shell – 2 tube passes $Q = 35.16$ GJ/h
R-501 316 stainless steel, packed bed cylindrical catalyst pellet (1.6 mm×3.2 mm) void fraction = 0.4 $V = 1000\ \text{m}^3$ 5 reactors in parallel at 200 m^3 20 m tall, 3.6 m diameter	**R-502** 316 stainless steel, packed bed cylindrical catalyst pellet (1.6 mm×3.2 mm) void fraction = 0.4 $V = 700\ \text{m}^3$ 5 reactors in parallel at 140 m^3 20 m tall, 3.0 m diameter
E-505 carbon steel $A = 2904\ \text{m}^2$ cw in shell, process fluid in tubes 1 shell – 2 tube passes $Q = 395.9$ GJ/h	**V-501** carbon steel $V = 34.7\ \text{m}^3$
E-502 316 stainless steel $A = 456\ \text{m}^2$ steam in shell, process fluid in tubes 1 shell – 2 tube passes $Q = 19237$ MJ/h	**C-501** carbon steel $W = 364.2$ kW 80% adiabatic efficiency
P-501 carbon steel $W = 6.4$ kW (actual) 80% efficient	**P-505** carbon steel $W = 0.75$ kW (actual) 80% efficient
P-504 carbon steel $W = 0.38$ kW (actual) 80% efficient	**P-506** carbon steel W = 2.65 kW (actual) 80% efficient

Table 3 (cont'd)
Partial Equipment Summary

T-501 carbon steel 46 sieve trays 55% efficient total condenser (E-507) feed on tray 26 reflux ratio = 11.4 24 in tray spacing, 2 in weirs column height = 92 ft = 28 m top diameter = 3.6 m bottom diameter = 2.7 m tapered column	**T-502** carbon steel total condenser (E-509) feed at location equivalent to tray 36 reflux ratio = 25.8 structured packing $C_f = 1$ diameter = 4.1 m *HETP* = 0.3 m height = 34.5 m
E-506 carbon steel $A = 76.7\ \text{m}^2$ boiling in shell, condensing in tubes 1 shell – 2 tube passes $Q = 331.2$ GJ/h	**E-509** carbon steel $A = 680\ \text{m}^2$ condensing in shell, cw in tubes 1 shell – 2 tube passes $Q = 342.0$ GJ/h
E-507 carbon steel $A = 127\ \text{m}^2$ condensing in shell, cw in tubes 1 shell – 2 tube passes $Q = 281.1$ GJ/h	**E-508** carbon steel $A = 902\ \text{m}^2$ boiling in shell, condensing in tubes 1 shell – 2 tube passes $Q = 341.1$ GJ/h

Oral Presentation

You will be expected to present and defend your results some time between September 27 and October 2, 1999. Your presentation should be 10-15 minutes, followed by about a 30 minute question and answer period. Make certain that you prepare for this presentation since it is an important part of your assignment. You should bring at least one hard copy of your slides to the presentation.

Late Reports

Late reports are unacceptable. The following severe penalties will apply:

- late report on due date before noon: one letter grade (10 points)
- late report after noon on due date: two letter grades (20 points)
- late report one day late: three letter grades (30 points)
- each additional day late: 10 additional points per day

Appendix
Calculations and Other Pertinent Information

Reactor

Styrene reaction may be equilibrium limited

$$K = \left(\frac{y_{sty} y_{hyd} P}{y_{eb}} \right)$$

$$\ln K = 15.5408 - \frac{14852.6}{T}$$

where T is in K and P is in bar.

Equilibrium calculation:

$$\begin{array}{ccccc} C_6H_5C_2H_5 & \underset{2}{\overset{1}{\rightleftarrows}} & C_6H_5C_2H_3 & + & H_2 \\ 1 & & 0 & & 0 \\ 1 - x & & x & & x \end{array}$$

$$\text{total} = N + 1 + x \quad \text{includes } N \text{ moles of inert steam}$$

$$K = \frac{x^2 P}{(1 - x)(N + 1 + x)}$$

where P is in bar

can generate data for equilibrium conversion, x, versus P, T, and N

Kinetics (subscripts on r refer to reactions in Equation (1) – (3) (adapted from Snyder, J. D. and B. Subramaniam, *Chem. Engr. Sci.*, **49**, 5585-5601 (1994) – the positive activation energy can arise from non-elementary kinetics – perhaps these kinetics are an elementary approximation to non-elementary kinetics):

$$r_1 = 4.24 \times 10^6 \exp\left(-\frac{21708}{RT} \right) p_{eb}$$

$$r_2 = 0.755 \exp\left(\frac{7804}{RT} \right) p_{sty} p_{hyd}$$

$$r_3 = 7.21 \times 10^8 \exp\left(-\frac{49675}{RT}\right) p_{eb}$$

$$r_4 = 1723 \exp\left(-\frac{26857}{RT}\right) p_{eb}\, p_{hyd}$$

where p is in kPa, T is in K, R = 1.987 cal/mol K, and r_i is in mol/m^3 reactor s

other data:

bulk catalyst density = 1282 kg/m^3
void fraction = 0.4

Vessel (V-501)

assume 10 min residence time based on total liquid flow

organic liquid at 53493 kg/h = 892 kg/min, ρ = 835 kg/m^3, 892/835 = 1.07 m^3/min
water at 144120 kg/h = 2402 kg/min, ρ = 1000 kg/m^3, 2402/1000 = 2.40 m^3/min
total liquid flow = 3.47 m^3/min, 3.47(10) = 34.7 m^3
total volume = 69 m^3

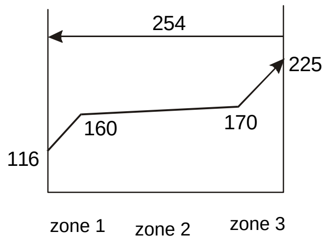
Heat Exchangers

key data:

latent heats
λ_{hps} = 1794 kJ/kg
λ_{mps} = 2002 kJ/kg
λ_{lps} = 2086 kJ/kg

sensible heats ($C_p\Delta T$)
hps 4.184 kJ/kg°C(254-90) = 686 kJ/kg
lps 4.184 kJ/kg°C(160-90) = 293 kJ/kg

E-501



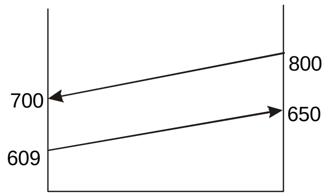
zone 1
Q_1 = 5200 MJ/h
ΔT_{lm} = 114.6°C
liquid organic h = 600 W/m^2K
condensing steam h = 6000 W/m^2K
$U \approx 1/h_i + 1/h_o$ = 545 W/m^2K
A = 23.1 m^2

zone 2
Q_2 = 19000 MJ/h
ΔT_{lm} = 88.9°C
boiling organic h = 6000 W/m^2K
condensing steam h = 6000 W/m^2K
$U \approx$3000 W/m^2K
A = 19.8 m^2

zone 3
Q_3 = 5500 MJ/h
ΔT_{lm} = 51.7°C
vapor organic h = 60 W/m^2K
condensing steam h = 6000 W/m^2K
$U \approx$ 59.4 W/m^2K
A = 497.5 m^2

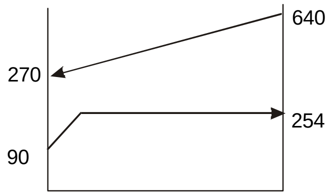
total A = 540 m^2
steam flow from Chemcad in Table 2

E-502



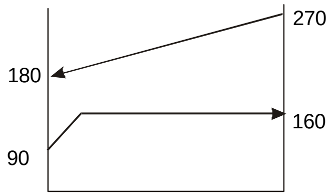
Q = 19237 MJ/h
ΔT_{lm} = 122°C
hot desuperheating steam h = 200 W/m^{2}K
hot vapor organic h = 200 W/m^{2}K
$U \approx$ 100 W/m^{2}K
LMTD corr factor – 1-2 exchanger = 0.96
A = 456 m^2

E-503



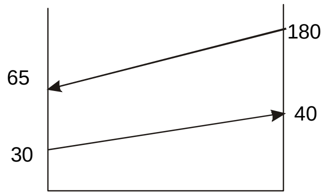
Q = 162767 MJ/h
ΔT_{lm} = 116.2°C
boiling water h = 6000 W/m^{2}K
hot vapor organic h = 200 W/m^{2}K
$U \approx$ 194 W/m^{2}K
A = 2006 m^2
$m = Q/(1794 + 686)$ = 61191 kg/h (denominator is $\lambda + C_p\Delta T$ in kJ/kg)

E-504



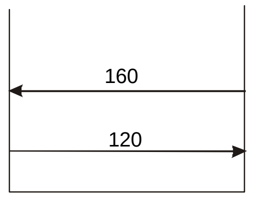
Q = 35163 MJ/h
ΔT_{lm} = 46.54°C
boiling water h = 6000 W/m^{2}K
warm vapor organic h = 100 W/m^{2}K
$U \approx$ 98.4 W/m^{2}K
A = 2133 m^2
$m = Q/(2086 + 293)$ = 14781 kg/h (denominator is $\lambda + C_p\Delta T$ in kJ/kg)

E-505



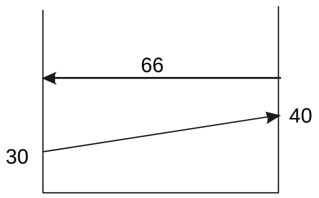
Q = 395921 MJ/h
ΔT_{lm} = 75.74°C
water h = 3000 W/m^{2}K
condensing organic h = 600 W/m^{2}K
$U \approx$ 500 W/m^{2}K
LMTD corr factor ≈ 1
A = 2904 m^2
$m = Q/[(4.184)(10)] = 9.46\times10^6$ kg/h (denominator is $C_p\Delta T$ of water in kJ/kg)

E-506



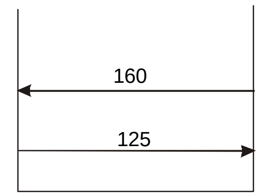
Q = 33122 MJ/h
ΔT_{lm} = 40°C
boling organic h = 6000 W/m^{2}K
condensing steam h = 6000 W/m^{2}K
$U \approx$ 3000 W/m^{2}K
A = 76.7 m^2
$m = Q/(2086)$ = 15878 kg/h (denominator is in kJ/kg)

E-507



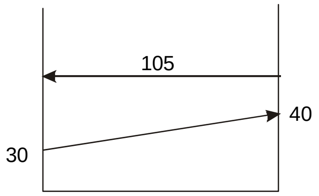
Q = 28114 MJ/h
ΔT_{lm} = 30.73°C
water h = 3000 W/m^{2}K
condensing organic h = 600 W/m^{2}K
$U \approx$ 500 W/m^{2}K
A = 508 m^2
$m = Q/[(4.184)(10)]$ = 671941 kg/h (denominator is $C_p\Delta T$ of water in kJ/kg)

E-508



Q = 341071 MJ/h
ΔT_{lm} = 35°C
boling organic h = 6000 W/m^{2}K
condensing steam h = 6000 W/m^{2}K
$U \approx$ 3000 W/m^{2}K
A = 902 m^2
$m = Q/(2086)$ = 163505 kg/h (denominator is in kJ/kg)

E-509



Q = 341977 MJ/h
ΔT_{lm} = 69.88°C
water h = 3000 W/m^{2}K
condensing organic h = 600 W/m^{2}K
$U \approx$ 500 W/m^{2}K
A = 2720 m^2
$m = Q/[(4.184)(10)] = 8.17\times10^6$ kg/h (denominator is $C_p\Delta T$ of water in kJ/kg)

T-501

from Chemcad 25 ideal stages, feed at 14
average flows above and below feed:
above feed: L = 65000 kg/h, V = 73000 kg/h
below feed: L = 140000 kg/h, V = 92000 kg/h
top T = 66°C, M = 85 kg/kmol; bottom T = 120°C, M = 105 kg/kmol
ρ_L = 835 kg/h
$\rho_G = PM/RT$

top: ρ_G = (40 kPa)(85 kg/kmol)/[(8.314 kPa m^3/kmol K)(339 K)] = 1.206 kg/m^3
bottom: ρ_G = (60 kPa)(105 kg/kmol)/[(8.314 kPa m^3/kmol K)(393 K)] = 1.92 kg/m^3
24 in tray spacing

calculations for top of column:
$(L/V)(\rho_G/\rho_L)^{0.5} = 0.034$
from flooding graph (C. J. King, *Separation Processes*, 2nd ed, McGraw-Hill, 1980, p. 594, which is similar to Fig. 6.24 in J. D. Seader and E. J. Henley, *Separation Process Principles*, Wiley, 1998)
$K_v = 0.37$
u_{fl} = 9.73 ft/s = 2.97 m/s
at 75% of flooding, u = 2.23 m/s
$A = (L/3600)/(\rho_G u)$ = 7.54 m^2
if 75% active area, A = 10.05 m^2
D = 3.58 m

calculations for bottom of column:
$(L/V)(\rho_G/\rho_L)^{0.5} = 0.073$
from flooding graph
$K_v = 0.35$
u_{fl} = 14.0 ft/s = 4.27 m/s
at 75% of flooding, u = 3.20 m/s
$A = (L/3600)/(\rho_G u)$ = 4.16 m^2
if 75% active area, A = 5.55 m^2
D = 2.67 m

use tapered column to avoid flooding at top and weeping at bottom
different diameters above and below feed as specified above

25 ideal stages
top α = 2.35, bottom α = 2.17, $[(2.35)(2.17)]^{0.5} = 2.26$
$\mu\alpha$ = 0.4 cp (2.26) = 0.9
from O'Connell correlation, 0.55 overall column efficiency
$\Rightarrow$ 46 stages (so column about 92 ft tall)
feed at 46(14/25) = 26
$\Delta P = \rho g h N$
20000 kg m/m^{2}s^2 = (835 kg/m^3)(9.8 m/s^2)(h_{weir})(46)
h_{weir} = 0.053 m = 2.1 in

T-502

from Chemcad 80 ideal stages, feed at 25
average flows above and below feed:
above feed: L = 920000 kg/h, V = 950000 kg/h
below feed: L = 970000 kg/h, V = 960000 kg/h
top T = 150°C, M = 106 kg/kmol; bottom T = 125°C, M = 145 kg/kmol

ρ_L = 800 kg/h
$\rho_G = PM/RT$
top: ρ_G = (40 kPa)(106 kg/kmol)/[(8.314 kPa m^3/kmol K)(378 K)] = 1.35 kg/m^3
bottom: ρ_G = (60 kPa)(104 kg/kmol)/[(8.314 kPa m^3/kmol K)(398 K)] = 2.32 kg/m^3

calculations for top of column:
$(L/G)(\rho_G/\rho_L)^{0.5} = 0.040$
from flooding graph
$K_v = 0.22$
u_{fl} = 7.58 ft/s = 2.31 m/s
at 75% of flooding, u = 1.73 m/s
$A = (V/3600)/(\rho_G u)$ = 113 m^2
if 75% active area, A = 151 m^2
D = 13.8 m – too large

calculations for bottom of column:
$(L/G)(\rho_G/\rho_L)^{0.5} = 0.054$
from flooding graph
$K_v = 0.21$
u_{fl} = 5.29 ft/s = 1.61 m/s
at 75% of flooding, u = 1.21 m/s
$A = (V/3600)/(\rho_G u)$ = 94.9 m^2
if 75% active area, A = 127 m^2
D = 12.7 m – too large

88 ideal stages
top and bottom α = 1.15
$\mu\alpha$ = 0.27 cp (1.15) = 0.3
from O’Connell correlation, 0.70 overall column efficiency
$\Rightarrow$ 115 stages (so column about 115 ft tall)
feed at 115(25/80) = 36
$\Delta P = \rho g h N$
20000 kg m/m^{2}s^2 = (800 kg/m^3)(9.8 m/s^2)(h_{weir})(115)
h_{weir} = 0.022 m = 0.87 in

try packed distillation column
structured packing, low pressure drop, high flooding capacity (choose packing so that C_f = 1.0)
use correlation in R. E. Treybal, *Mass Transfer Operations*, 3rd ed, McGraw-Hill, 1980, p. 195, which is similar to Fig. 6.36 in J. D. Seader and E. J. Henley, *Separation Process Principles*, Wiley, 1998

top of column
$(L/V)(\rho_G/(\rho_L - \rho_G))^{0.5} = 0.04$
$(G¢^{2}C_f\mu_L^{0.1})/(\rho_G(\rho_L - \rho_G)) = 0.3$
μ_L = 0.00027 kg/m s
solve for $G¢$ = 27.1 kg/m^{2}s

at 75% of flooding
$A = (V/3600)/[(0.75)(27.1)] = 12.98\ \text{m}^2$
$D = 4.06$ m

bottom of column
$(L/V)(\rho_G/(\rho_L - \rho_G))^{0.5} = 0.054$
$(G\text{¢}^{2}C_f\mu_L^{0.1})/(\rho_G(\rho_L - \rho_G)) = 0.29$
$\mu_L = 0.00027$ kg/m s
solve for $G\text{¢} = 34.93\ \text{kg/m}^2\text{s}$
at 75% of flooding
$A = (V/3600)/[(0.75)(34.93)] = 10.17\ \text{m}^2$
$D = 3.49$ m

make diameter 4.06 m
packing HETP = 0.3 m
column height = 0.3(115) = 34.5 m
feed at 34.5(36/115) = 10.8 m from top
column will be 5 m taller to allow room for distributors at feed location and throughout column
total column height = 39.5 m