ChE 455
Fall 2002
Major 1

Drying Oil Production

You work in a new facility that produces 10,000 tonne/y of a drying oil. Drying oils are additives to paints and varnishes to aid in the drying process when these products are applied to surfaces. The facility manufactures drying oil (DO) from acetylated castor oil (ACO). Both of these compounds are mixtures. However, for simulation purposes, acetylated castor oil is modeled as palmitic (hexadecanoic) acid ($C_{15}H_{31}COOH$) and drying oil is modeled as 1-tetradecene ($C_{14}H_{28}$). In an undesired side reaction, a gum can be formed, which is modeled as 1-octacosene ($C_{28}H_{56}$).

Problems in the Drying Oil Facility

The following problems were encountered after the drying oil facility was started up in early August of this year.

1. Pump P-501 A/B has been noisy since start up and the noise (a high pitched whine) continues to get louder.

2. Beginning in early October, problems have been observed in T-501. Column performance has been below specification. Specifically, the flowrate of Dowtherm A through the reboiler, E-502 has had to be increased in order to keep the products at design specifications.

3. It has also been noted recently that production rates have fallen during the graveyard shift (12 p.m. – 8 a.m.). The head of operations believed that this was due to some of the operators not paying attention to the plant during this shift. However, after talking to all concerned, it appears that there might be a problem with the feed of ACO from the storage tank (not shown on the PFD) to the feed vessel, V-501. The design calculations for this line and some other information are included in Appendix 3 to this problem statement.

4. The pressure-relief valve on E-506 has been open from the start of production and steam has been venting to the atmosphere. This problem was more severe right after start-up; however, it is still occurring. Calculations for this exchanger are also provided in Appendix 3.

The first part of your assignment is to suggest causes for these problems, identify the most likely cause(s), and suggest potential remedies.

Possible Need for Scale-down in Drying Oil Plant

The business climate is not as good as projected when this plant was designed. Therefore, it is possible that production will have to be cut by up to 20%. The second part of your assignment is to provide a preliminary analysis of the operational consequences of a 20% production cut. This can be qualitative for now, but your analysis should be supported by the performance relationships for all equipment involved.

Cost Saving Strategies

Finally, an alternative to cutting production might be to sell our product for less than our competitors. Therefore, a qualitative discussion of cost cutting strategies and an approximate economic analysis should also be included.

Process Description

The process flow diagram is shown in Figure 1. ACO is fed from a holding tank where it is mixed with recycled ACO. The ACO is heated to reaction temperature in H-501. The reaction does not require a catalyst since it is initiated at high temperatures. The reactor, R-501, is simply a vessel with inert packing to promote radial mixing. The reaction is quenched in E-501. Any gum that has been formed is removed by filtration. There are two holding vessels, V-502 A/B, one of which is used to hold reaction products while the other one is feeding the filter (not shown). This allows a continuous flow of material into Stream 7. In T-501, the ACO is separated and recycled, and in T-502, the DO is purified from the acetic acid. The contents of Streams 11 and 12 are cooled (exchangers not shown) and sent to storage.

Tables 1 and 2 contain the stream and utility flows for the process as designed. Table 3 contains an equipment list. Other pertinent information and calculations are contained in the appendix.

V-501	P-501 A/B	H-501	R-501	E-501	V-502 A/B	T-501	E-502	E-503	P-502 A/B	V-503	T-502	E-504	E-505	P-503 A/B	V-504	E-506	P-504 A/B
Recycle Mixing Vessel	Feed Pump	Feed Fired Heater	Drying Oil Reactor	Reactor Effluent Cooler	Gum Filter Holding Vessel	ACO Recycle Tower	Recycle Tower Reboiler	Recyle Tower Condenser	Recycle Tower Reflux Pump	Recycle Tower Reflux Drum	Drying Oil Tower	Drying Oil Tower Reboiler	Drying Oil Tower Condenser	Drying Oil Tower Reflux Pump	Drying Oil Tower Reflux Drum	Recycle Cooler	Recycle Pump

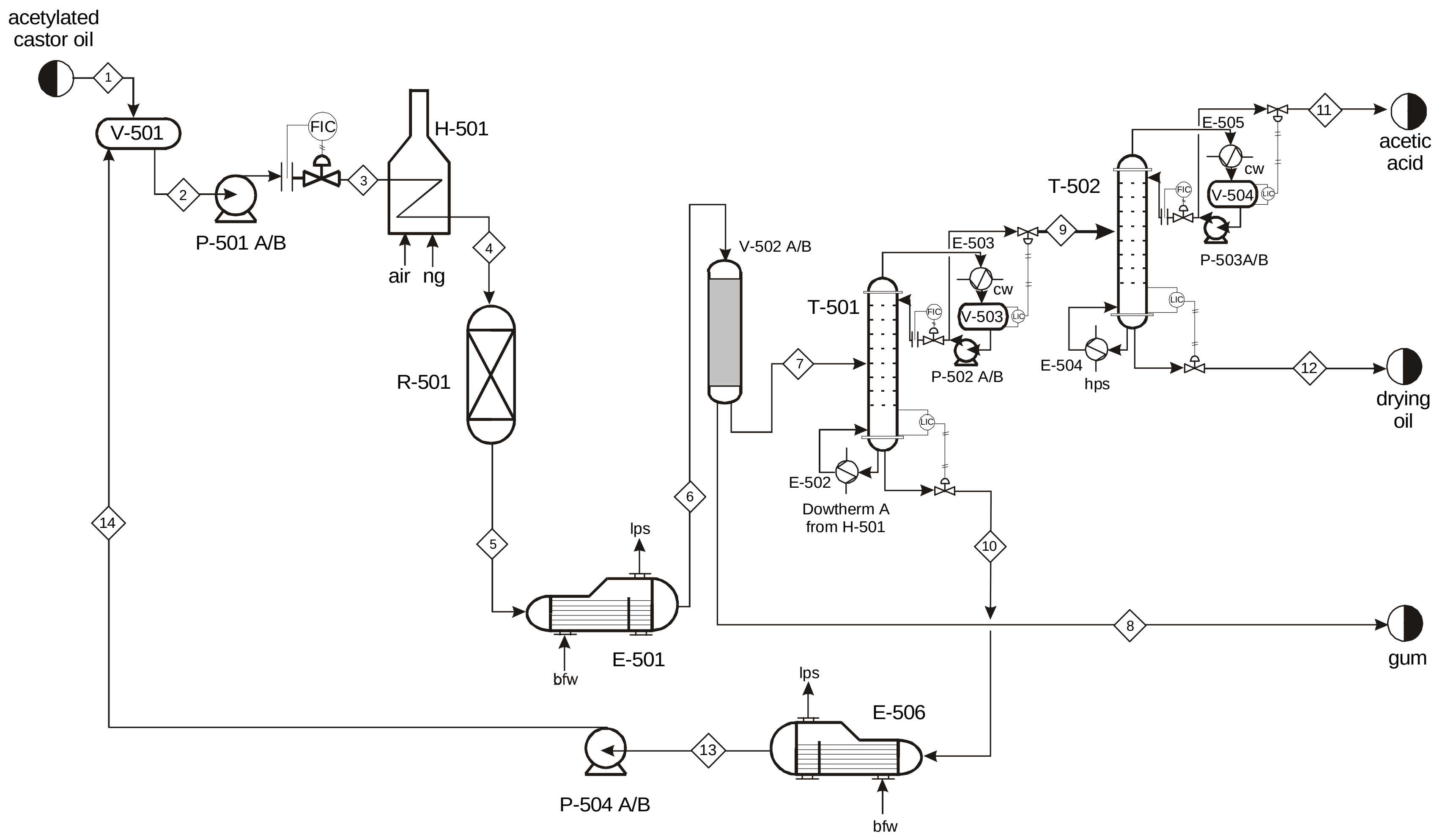


Figure 1: Drying Oil Production Process

Table 1
Stream Tables for Unit 500

Stream	**1**	**2**	**3**	**4**
Temp (°C)	25.00	151.03	151.13	380.00
Pres (kPa)	110.00	105.00	230.00	195.00
Vapor mole fraction	0.00	0.00	0.00	0.00
Flowrate (kg/h)	1628.70	10703.10	10703.10	10703.10
Flowrate (kmol/h)	6.35	41.75	41.75	41.75
Component Flowrates (kmol/h)				
Acetic Acid	0.00	0.00	0.00	0.00
1-Tetradecene (Drying Oil)	0.00	0.064	0.064	0.064
Hexadecanoic Acid (ACO)	6.35	41.69	41.69	41.69
Gum	0.00	0.00	0.00	0.00

Stream	**5**	**6**	**7**	**8**
Temp (°C)	342.81	175.00	175.00	175.00
Pres (kPa)	183.00	148.00	136.00	136.00
Vapor mole fraction	0.39	0.00	0.00	0.00
Flowrate (kg/h)	10703.10	10703.10	10703.08	0.02
Flowrate (kmol/h)	48.07	48.07	48.07	4.61×10^{-5}
Component Flowrates (kmol/h)				
Acetic Acid	6.32	6.32	6.32	0.00
1-Tetradecene (Drying Oil)	6.38	6.38	6.38	0.00
Hexadecanoic Acid (ACO)	35.38	35.38	35.38	0.00
Gum	4.61×10^{-5}	4.61×10^{-5}	0.00000	4.61×10^{-5}

Stream	**9**	**10**	**11**	**12**
Temp (°C)	107.96	344.75	119.19	252.83
Pres (kPa)	125.00	90.00	105.00	125.00
Vapor mole fraction	0.00	0.00	0.00	0.00
Flowrate (kg/h)	1628.68	9074.40	378.64	1250.04
Flowrate (kmol/h)	12.67	35.40	6.29	6.38
Component Flowrates (kmol/h)				
Acetic Acid	6.32	0.00	6.28	0.03
1-Tetradecene (Drying Oil)	6.32	0.06	0.01	6.31
Hexadecanoic Acid (ACO)	0.04	35.34	0.00	0.04
Gum	0.00	0.00	0.00	0.00

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

Stream	**13**	**14**
Temp (°C)	170.00	170.03
Pres (kPa)	65.00	110.00
Vapor mole fraction	0.00	0.00
Flowrate (kg/h)	9074.40	9074.40
Flowrate (kmol/h)	35.40	35.40
Component Flowrates (kmol/h)		
Acetic Acid	0.00	0.00
1-Tetradecene (Drying Oil)	0.06	0.06
Hexadecanoic Acid (ACO)	35.34	35.34
Gum	0.00	0.00

Table 2
Utility Stream Flow Summary for Unit 700

E-501	**E-502**	**E-503**
bfw→lps	Dowtherm A	cw
2664 kg/h	126,540kg/h	24,624 kg/h

E-504	**E-505**	**E-506**
hps	cw	bfw→lps
425 kg/h	5508 kg/h	2088 kg/h

Table 3
Partial Equipment Summary

Heat Exchangers

E-501 A = 26.2 m^2 1-2 exchanger, floating head, carbon steel process stream in tubes Q = 6329 MJ/h	**E-504** A = 64.8 m^2 1-2 exchanger, fixed head, carbon steel process stream in shell Q = 719 MJ/h
E-502 A = 57.5 m^2 1-2 exchanger, fixed head, carbon steel process stream in shell Q =5569 MJ/h	**E-505** A = 0.58 m^2 1-2 exchanger, floating head, carbon steel process stream in shell Q = 230 MJ/h
E-503 A = 2.95 m^2 1-2 exchanger, floating head, carbon steel process stream in shell Q = 1029 MJ/h	**E-506** A = 919 m^2 1-4 exchanger, floating head, stainless steel process stream in tubes Q = 4962 MJ/h

Towers

T-501 stainless steel 56 sieve trays plus reboiler and condenser 25% efficient trays total condenser feed on tray 32 reflux ratio = 0.15 12 in tray spacing, 2.2 in weirs column height = 17 m diameter = 2.1 m below feed and 0.65 m above feed	**T-502** stainless steel 35 sieve trays plus reboiler and condenser 52% efficient trays total condenser feed on tray 23 reflux ratio = 0.52 12 in tray spacing, 2.8 in weirs column height = 11 m diameter = 0.45 m

Reactors and Vessels

R-501 carbon steel pipe V = 1.15 m^3 5.3 m long, 0.53 m diameter	**V-501** stainless steel V = 2.3 m^3

Other Equipment

P-501 A/B carbon steel power = 0.9 kW (actual) 80% efficient $NPSH_R$ at design flow = 14 ft of liquid	**P-504 A/B** carbon steel power = 0.3 kW (actual) 80% efficient $NPSH_R$ at design flow = 12 ft of liquid
H-501 total heat duty required = 13219 MJ/h = 3672 kW design capacity = 4000 kW 85% thermal efficiency	

Economics

For process modifications, use a 15%, before-tax rate of return and a 5-year lifetime.

Deliverables

Specifically, you are to prepare the following by 9:00 a.m., Monday, November 18, 2002:

1. a diagnosis of potential causes for the operating problems with the plant, explanations of their relevance, and recommendations for solving the problems, including the modifications that might be required and the cost of such modifications.

2. an analysis of the processing consequences of a 20% cut in production, how this cut is to be accomplished, modifications that will have to be made, and the cost of such modifications.

3. a preliminary analysis of any cost cutting measures that you recommend for the plant. All recommendations should be accompanied by an economic analysis that accounts for the savings and cost of implementing the changes.

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

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

6. 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. 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. Reports that do not conform to the guidelines will receive severe deductions and will have to be rewritten to receive credit. Poorly written and/or organized written reports may also require re-writing. Be sure to follow the format outlined in the guidelines for written reports.

Oral Presentation

You will be expected to present and defend your results some time between November 18, 2002 and November 22, 2002. Your presentation should be 15-20 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 and hand it out before beginning the presentation.

Other Rules

You may not discuss this major with anyone other than the instructors. Discussion, collaboration, or any other interaction with anyone other than the instructors is prohibited. Violators will be subject to the penalties and procedures outlined in the University Procedures for Handling Academic Dishonesty Cases (begins on p. 48 of 2001-03 Undergraduate Catalog).

Consulting is available from the instructors. Chemcad consulting, *i.e.*, questions on how to use Chemcad, not how to interpret results, is unlimited and free, but only from the instructors. Each individual may receive five free minutes of consulting from the instructors. After five minutes of consulting, the rate is 2.5 points deducted for 15 minutes or any fraction of 15 minutes, on a cumulative basis. The initial 15-minute period includes the 5 minutes of free consulting.

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 1
Reaction Kinetics

The reactions and reaction kinetics are as follows:

$$\underset{\text{ACO}}{C_{15}H_{31}COOH(l)} \xrightarrow{k_1} \underset{\text{acetic acid}}{CH_3COOH(g)} + \underset{\text{DO}}{C_{14}H_{28}(l)} \tag{1}$$

$$\underset{\text{DO}}{2C_{14}H_{28}(l)} \xrightarrow{k_2} \underset{\text{gum}}{C_{28}H_{56}(s)} \tag{2}$$

where

$$-r_1 = k_1 C_{ACO} \tag{3}$$

$$-r_2 = k_2 C_{DO}^2 \tag{4}$$

and

$$k_1 = 5.538 \times 10^{13} \exp(-44{,}500 / RT) \tag{5}$$

$$k_2 = 1.55 \times 10^{26} \exp(-88{,}000 / RT) \tag{6}$$

The units of reaction rate, r_i, are kmol/m^{3}s, and the activation energy is in cal/mol (which is equivalent to kcal/kmol).

Appendix 2
Chemcad Hints

If you want to simulate any part of this process, it may be necessary for you to add gum as a compound to the Chemcad databank. This has already been done in room 453, and the simulation used for this process is also in the CC5data folder. However, if you save the job to a zip disk or floppy disk, it will not contain the new component. You must export the file rather than just saving or copying it for it to contain the new component information. Therefore, it may be beneficial for you to add this component to the databank on your home computer.

The procedure is as follows:

1. From the Thermophysical menu, click on databank and new component.

2. In the dialog box that is shown, enter a name for the compound (we used gum), the molecular weight (392) and the boiling point (431.6°C). Click on group contribution - Joback. This will use a group contribution method to estimate properties. Then, click OK.

3. In the next dialog box, you must put in the correct groups. There is 1 $–CH_3$ group, 25 $>CH_2$ groups, 1 $=CH_2$ group, and 1 =CH– group. Then, click OK.

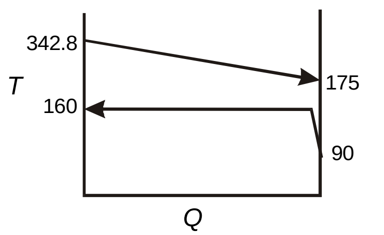
4. It will ask you if you want to save this component. Click yes. It will probably assign it as component number 8001.

5. If you want to check information or add more information, you can now go to Thermophysical, databank, view-edit. Then, type in the new component number. When the next menu list comes up, one thing you can do, for example, is add the chemical formula for gum or add the correct chemical name under synonyms. However, these are not necessary to run simulations using this new compound.

6. Be sure that the new compound, gum, is in your component list for the current job.

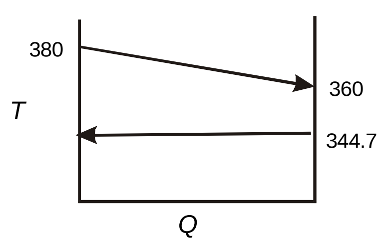
Appendix 3
Calculations and Other Pertinent Information

E-501



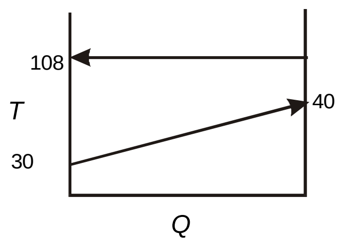
Q = 6329 MJ/h = 1758 kW
ΔT_{lm} = 67.11°C
process fluid h_i = 1200 W/m^{2}K
bfw vaporizing h_o = 6000 W/m^{2}K
assume all heat transfer in vaporizing zone
$U \approx 1/h_i + 1/h_o$ = 1000 W/m^{2}K
A = 26.2 m^2
$Q = \dot{m}\{C_p \Delta T + \lambda\} = \dot{m}$ {(4.184 kJ/kg°C)(70°C) + 2081.3}
bfw flow in Table 2

E-502



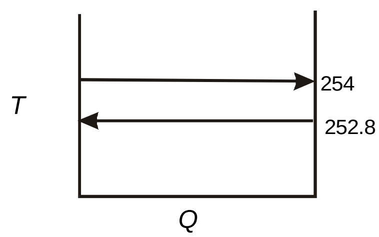
Q = 5569 MJ/h = 1547 kW
ΔT_{lm} = 23.92°C
process fluid boiling h_o = 4500 W/m^{2}K
Dowtherm A in tubes h_i = 1500 W/m^{2}K
$U \approx 1/h_i + 1/h_o$ = 1125 W/m^{2}K
A = 57.5 m^2
Dowtherm C_p = 0.526 BTU/lb°F = 2.2 kJ/kg°C
Dowtherm flow in Table 2

E-503



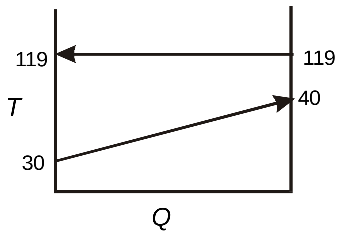
Q = 1029 MJ/h = 286 kW
ΔT_{lm} = 72.89°C
cw h_i = 2000 W/m^{2}K
condensing organic process stream h_o = 4000 W/m^{2}K
$U \approx$ 1333 W/m^{2}K
A = 2.95 m^2
cw flow in Table 2

E-504



Q = 719 MJ/h = 200 kW
ΔT_{lm} = 1.2°C
hps condensing h_i = 6000 W/m^{2}K
boiling process stream h_o = 4500 W/m^{2}K
$U \approx 1/h_i + 1/h_o$ = 2571 W/m^{2}K
A = 64.8 m^2
for condensing hps λ = 1694 kJ/kg
hps flow in Table 2

E-505



Q = 230 MJ/h = 64 kW
ΔT_{lm} = 84.00°C
cw h_i = 2000 W/m^{2}K
condensing organic process stream h_o = 4000 W/m^{2}K
$U \approx 1/h_i + 1/h_o$ = 1333 W/m^{2}K
A = 0.58 m^2
cw flow in Table 2

E-506

See detailed calculations at the end of this appendix.

H-501

required heat duty for process stream = 7656 MJ/h
required heat duty for E-502 = 5569 MJ/h
total heat duty = 13219 MJ/h = 3672 kW
design capacity = 4000 kW (energy available for process fluids)
thermal efficiency = 85%

R-701

V = 1.15 m^3

Choose L/D = 10 for plug flow considerations

$V = (\pi D^2/4)(10D) = 1.15$
$D = \{(4)(1.5)/[(\pi)(10)]\}^{1/3} = 0.53$ m
L = 5.3 m

T-501

from Chemcad, 14 ideal trays, feed at 9, plus partial reboiler and total condenser

above feed:
L = 200 kg/h, G = 1800 kg/h

ρ_L = 675 kg/m^3
ρ_G = 2.4 kg/m^3
$(L/V)(\rho_G/\rho_L)^{0.5}$ = 0.0066
from flooding graph for 12 in tray spacing (P. Wankat, *Equilibrium Staged Separations*, Prentice Hall, 1988, p. 387.)
C_{sb} = 0.24 (extrapolated)
u_{fl} = 4.02 ft/s
u_{act} = 3.02 ft/s = 0.92 m/s (75% of flooding)
if 75% active area
$A = (G/3600)/[(0.75)(\rho_G)(u_{act})]$ = 0.302 m^2
D = 0.62 m

below feed:
L = 29400 kg/h, G = 20300 kg/h
ρ_L = 650 kg/m^3
ρ_G = 4.5 kg/m^3
$(L/V)(\rho_G/\rho_L)^{0.5}$ = 0.12
from flooding graph for 12 in tray spacing (P. Wankat, *Equilibrium Staged Separations*, Prentice Hall, 1988, p. 387.)
C_{sb} = 0.19
u_{fl} = 2.28 ft/s
u_{act} = 1.71 ft/s = 0.52 m/s (75% of flooding)
if 75% active area
$A = (G/3600)/[(0.75)(\rho_G)(u_{act})]$ = 3.21 m^2
D = 2.02 m

25% overall column efficiency (O'Connell correlation)
$\Rightarrow$ 56 trays (so column about 56 ft tall ≈ 17 m)
$\Delta P = \rho g h N$
20000 Pa = (650 kg/m^3)(9.8 m/s^2)(h_{weir})(56)
h_{weir} = 0.056 m ≈ 2.2 in
go with 2.2 in weirs (0.056 m)

go with tapered column, 2.1 m diameter below feed, 0.65 m diameter above feed
height of 56 ft ≈ 17 m
h/D ratio 26 based on diameter above feed, 8.1 based on diameter below feed
32 trays above feed
24 trays below feed

T-502

from Chemcad, 18 ideal trays, feed at 12, plus partial reboiler and total condenser

above feed:
L = 195 kg/h, G = 575 kg/h
ρ_L = 920 kg/m^3

ρ_G = 2.1 kg/m^3
$(L/V)(\rho_G/\rho_L)^{0.5}$ = 0.016
from flooding graph for 12 in tray spacing (P. Wankat, *Equilibrium Staged Separations*, Prentice Hall, 1988, p. 387.)
C_{sb} = 0.22
u_{fl} = 4.6 ft/s
u_{act} = 3.45 ft/s = 1.05 m/s (75% of flooding)
if 75% active area
$A = (G/3600)/[(0.75)(\rho_G)(u_{act})]$ = 0.096 m^2
D = 0.35 m

below feed:
L = 2000 kg/h, G = 725 kg/h
ρ_L = 700 kg/m^3
ρ_G = 2.5 kg/m^3
$(L/V)(\rho_G/\rho_L)^{0.5}$ = 0.165
from flooding graph for 12 in tray spacing (P. Wankat, *Equilibrium Staged Separations*, Prentice Hall, 1988, p. 387.)
C_{sb} = 0.18
u_{fl} = 3.01 ft/s
u_{act} = 2.25 ft/s = 0.686 m/s (75% of flooding)
if 75% active area
$A = (G/3600)/[(0.75)(\rho_G)(u_{act})]$ = 0.157 m^2
D = 0.45 m

52% overall column efficiency (O'Connell correlation)
$\Rightarrow$ 35 trays (so column about 35 ft tall)
23 trays above feed
$\Delta P = \rho g h N$
20000 kg m/m^{2}s^2 = (920 kg/m^3)(9.8 m/s^2)(h_{weir})(23)
h_{weir} = 0.063 m ≈ 2.5 in
12 trays below feed
$\Delta P = \rho g h N$
20000 kg m/m^{2}s^2 = (920 kg/m^3)(9.8 m/s^2)(h_{weir})(12)
h_{weir} = 0.083 m ≈ 3.2 in
go with 2.8 in weirs (0.071 m) for entire column

go with 0.45 m diameter column
height of 35 ft ≈ 11 m
h/D ratio about 24.4

V-501

Use a 10 minute holding time for liquid to P-501
V = (10704)(10)/{(792)(60)} = 2.25 m^3
L/D = 3

$D = \{(4)(2.25)/[(\pi)(3)]\}^{1/3} = 1$ m
$L = 3$ m

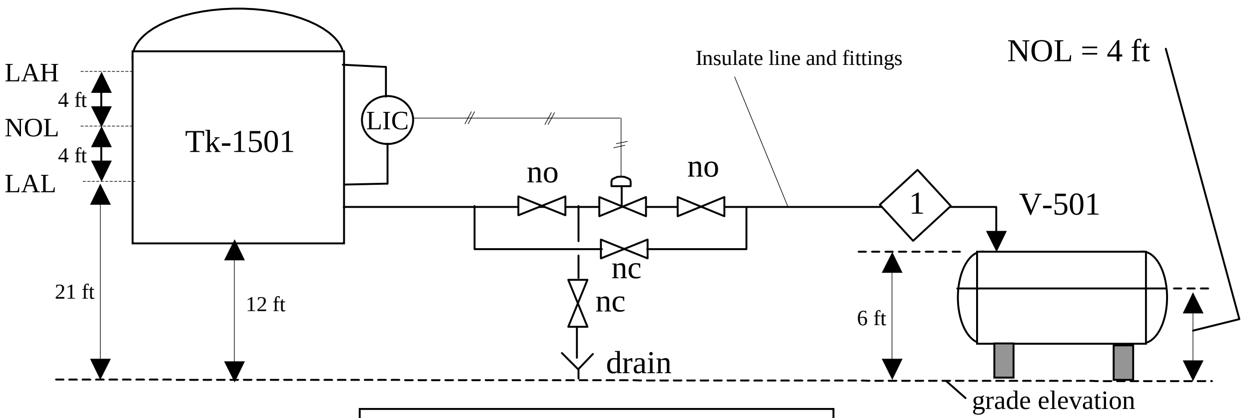
No calculations available for following equipment:

P 502 A/B
P 503 A/B
V-502 A/B and filtration equipment
V-503
V-504
two product cooling heat exchangers
pump for Dowtherm from H-501 to E-502

Design Calculations for Transfer Line from Tk-1501 (ACO storage tank) to V-501

By: KJG (03/04/02)

Process Sketch



LAH – Level Alarm High
NOL – Normal Operating Level
LAL – Level Alarm Low
no – normally open
nc – normally closed

Tk-1501 is situated at the north end of the plant and its base is at an elevation of 12 ft above the grade used for the design of the DO plant. Uninterrupted flow of ACO is crucial for the DO plant; therefore, use gravity feed of ACO to V-501.

Process sketch shows normal operation for ACO transfer, with bypass globe valve and bleed valves closed and isolation gate valves open. Design control valve with a 2 psi pressure drop at design flow of 1630 kg/h of ACO.

Physical properties of ACO

Density at 25°C = 874 kg/m^3
Volumetric flow, Q = (1630)/(874)/(3600) = 5.1805×10^{-4} m^3/s
Viscosity is given by the following equation for near ambient conditions:

$$\log \mu(\text{cP}) = 1.745 - 0.0144T(°\text{C})$$

at 25°C this gives viscosity, μ = 24.3 cP

Friction Loss Calculations

Mechanical Energy Balance

$$\Delta P_{12} + \rho g \Delta z_{12} + \cancel{\rho \Delta v_{12}^2 / 2} + \cancel{\rho w_s} + (-\Delta P_f) + \Delta P_{CV} = 0$$

now

$$\Delta P_{12} = (110 - 101) = 9 \text{ kPa}$$
$$\rho g \Delta z_{12} = (874)(9.81)(6 - 21)(0.3048) = -39.2 \text{ kPa}$$
$$\Delta P_{CV} = 2 \text{ psi} = 13.78 \text{ kPa}$$

Therefore,

$$9 - 39.2 + (-\Delta P_f) + 13.78 = 0$$
$$-\Delta P_f = 39.2 - 13.78 - 9 = 16.4 \text{ kPa}$$

Estimate pipe and fittings from R. Darby, *Chemical Engineering Fluid Mechanics (2nd ed.)*, Marcel-Dekker, 2001, pages 210-211

	Length/number	$(L/D)_{equiv}$
Straight pipe	250 ft = 76.2 m	$76.2/D$
Elbows (std 90°)	6	(6)(30)
Gate valves	4	(4)(8)
Ts	4	(4)(60)
Entrance, Exit, KE	negligible	0
Total $\Sigma(L/D)_{equiv}$		$452 + (76.2/D)$

Look at pipe diameters between 1" and 2.5" sch 40

Nominal D (inch)	Actual inside D (inch)	Actual inside D (m)	Velocity, v (m/s)	Re	$\Sigma(L/D)_{equiv}$	$-\Delta P_f$ kPa
1.0	1.049	0.0266	0.9322	892	3317	90.4
1.5	1.610	0.0409	0.3943	580	2315	17.4 ←
2.0	2.067	0.0525	0.2393	452	1903	6.75
2.5	2.469	0.0627	0.1678	378	1667	3.47

Since flow is laminar, use Hagen-Poiseuille equation: $-\Delta P_f = \dfrac{128 \mu Q L_{equiv}}{\pi D^4}$

Choose a 1.5" sch 40 pipe to run from Tk-1501 to V-501

Note: Above fittings, pipe length, and pipe diameter were checked against the as-built plant and found to be correct – SPL (06/22/02)

Design Calculations for E-506

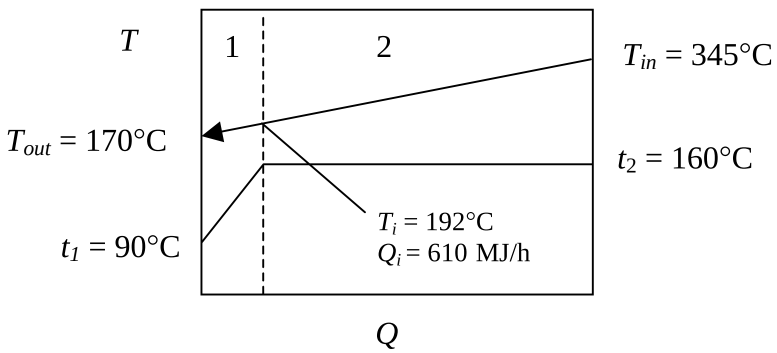
By: KJG (01/04/02)

Design flowrate (Stream 10) to E-506 is 9074 kg/h at a temperature of 345°C. The process stream is fed to the tube side of the exchanger and the boiler feed water is sent through the shell side.

Process stream properties are

ρ_l = 636 kg/m^3 inlet and 779 kg/m^3 outlet average = (636 + 779)/2 = 707.5 kg/m^3
μ_l = 0.32 cP inlet and 1.02 cP outlet average = (0.32 + 1.02)/2 = 0.67 cP
k_i = 0.1029 W/m K inlet and 0.1385 W/m K outlet
average = (0.1029 + 0.1385)/2 = 0.1207 W/m K

Q = 4960 MJ/h



2-Zone Heat Exchanger

Zone 1

Q_1 = 610 MJ/h = 169.5 kW

$\Delta T_{lm,1}$ = {(192-160)-(170-90)}/ln{192-160)/(170-90)} = (32-80)/ln(32/80) = 52.4°C
Assume flow will be laminar; therefore, for heat transfer with constant wall temperature, h_i is given by:

$Nu = h_i d_i/k_i = 3.66$ from O. Levenspiel, *Engineering Flow and Heat Exchange (2nd ed.)*, Plenum, New York, 1998, Equation (9.23), p 177.

Assuming exchanger is made from 18 BWG 1" diameter tubes (d_i = 22.91 mm) and using an average thermal conductivity, k_i, of 0.1207 W/m K, we get

$h_i = 3.66k_i/d_i$ = (3.66)(0.1207)/(0.02291) = 19.3 W/m^{2}K

Assuming a fouling coefficient of 500 W/m^{2}K, and ignoring the outside (boiling water) heat transfer coefficient that will be 2 to 3 orders of magnitude greater than h_i, we get:

U_1 = (1/19.3 + 1/500)$^{-1}$ = 18.6 W/m^{2}K

Area for zone 1 = $Q_1/U_1\Delta T_{lm,1}$ = (169500)/(18.6)/(52.4) = 173.9 m^2

<u>Zone 2</u>

Q_2 = (4960 – 610) = 4350 MJ/h = 1208 kW

$\Delta T_{lm,2}$ ={(345-160) – (192-160)}/ ln{(345-160)/(192-160)} = 87.2°C

U_2 = 18.6 W/m^{2}K

Area for zone 2 = $Q_2/U_2\Delta T_{lm,2}$ = (1208000)/(18.6)/(87.2) = 745.0 m^2

Total area = 173.9 + 745.0 = 918.9 m^2

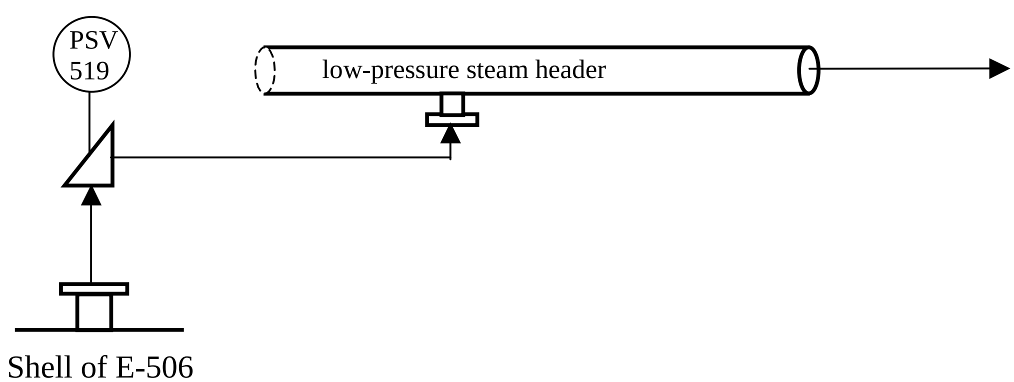
Assume we use 18 ft tubes, area per tube = $\pi d_i L$ = (π)(0.02291)(18)(0.3048) = 0.3949 m^2/tube
Therefore, we need (918.9)/(0.3949) = 2327 tubes arranged on a 1½" (0.0381 m) square pitch

Shell diameter $= \sqrt{\dfrac{(4)(2327)(0.0381)^2}{\pi}}$ = 2.074 m = 81.6 inch ⇒ use 84" shell

Check velocity in tubes – assume 4 tube passes.

Flow area on process side = (2327)/(4){(π/4)(0.02291)^2}= 0.2398 m^2
Velocity in tubes = (9074)/(707.5)/(3600)/(0.2398) = 0.0149 m/s
Re_{tube} = (0.0149)(707.5)(0.02291)/(0.00067) = 360 --- <u>Laminar</u>

<u>Look at piping arrangement for steam line from exchanger to header</u>



Flow of steam from E-506 to low-pressure header is 2088 kg/h. The pipe connecting the exchanger to the header will consist of 30 ft of straight pipe, one 90° standard elbow, and one wide-open angle valve. The angle valve is part of the pressure relief valve that will be set to protect the heat exchanger against overpressure.

Piping or Pipe Fitting	L/d
Straight pipe	$(30)(0.3048)/d = 9.144/d$
Elbows	30
Angle valve (open)	170

Calculation for pipe sizes 1" to 3" below:

diameter (sch 40)	1"	1.5"	2.0"	2.5"	3"	
actual diameter, in	1.049	1.61	2.067	2.469	3.068	
actual diameter, m	0.02665	0.04089	0.05250	0.06271	0.07792	
vel	3.29×10^2	1.39×10^2	0.847×10^2	0.593×10^2	0.384×10^2	m/s
Re	1.89×10^6	1.23×10^6	9.58×10^5	8.02×10^5	6.46×10^5	
e/d	0.00169	0.00110	0.000857	0.000718	0.000577	
f	0.005629	0.005084	0.004818	0.004657	0.004488	
Straight pipe L/D	343	224	174	146	117	
Elbows L_{eq}/D	30	30	30	30	30	
Angle valves L_{eq}/D	170	170	170	170	170	
Total (L_{eq}/D)	543	424	374	346	317	
$-\Delta P_f$	2,091,175	265,477	81,788	35,889	13,312	Pa

Use 2½" sch 40 pipe. Set relief valve (PSV-519) at 45 kPa above the low-pressure steam header.

Note: Due to problems with pipe arrangement and connection to header, an additional 20 feet of pipe and 2 more elbows were required for connection – this should not cause any problems since E-506 is rated for 750 kPa – SPL (06/17/02)