Troubleshooting Design Project

Production of Ethanol via the Vapor-Phase Hydration of Ethylene

Background

"This design is not worth the value of the paper it is written on," which started the worst meeting of your former boss's career. The irate client was complaining about a recent design for a 30,000 tonne/yr plant to convert ethylene to ethanol that our company (FD Engineering and Construction Company or FD E&C Co.) has proposed. The client mentioned a list of errors that the current design has and also made the statement that the current design would never work as required. Needless to say, our company is embarrassed by this apparently poor design and has assured the client that all the problems and errors will be rectified by the next time we meet. However, there is one tiny problem. It appears that in management's haste to assuage our client's anger, your former boss has been sent has been sent to oversee construction of our ozone-hole monitoring facility in Antarctica. He cannot be contacted for several weeks, and apparently the meeting minutes and other pertinent information have also gone missing. Thus, it is not clear what exactly the problems are with the design.

As a junior engineer with the FD Engineering and Construction Company, you have been assigned the task to investigate and "fix" the current design, which is a tremendous opportunity to impress management. To help you with your task, a copy of the preliminary design and design basis specifications are provided. The Chemcad simulation on which the original design was based is also available. There is a trickle-down effect of the poor initial design, namely, information has gone out to equipment suppliers for detailed engineering estimates and price quotes. Most of this information has been received or is in the mail. Because this project is a high priority to the client, who wants to move quickly to the construction phase, further delays will be costly. Minimizing such delays by using equipment already specified and priced will be beneficial. However, the technical feasibility and the overall efficiency of the conversion process are the primary concerns.

Process Description

A PFD for the ethanol production process (the "bad" design) is shown in Figure 1. A flow table, tables of utility consumption, and equipment specifications are included as Tables 1-3. Referring to Figure 1 and Table 1, the raw ethylene feed for this process is supplied to the plant via a pipeline at a pressure of 50 atm and ambient temperature. The fresh ethylene is first mixed with recycled ethylene-rich gas, Steam 20, prior to mixing with boiler feed water, Stream 3. The resulting stream, Stream 4, is then sent to heat exchanger E-201 where the stream is vaporized and heated to approximately 227°C. Stream 5 leaving this exchanger is sent to a gas-phase adiabatic reactor containing a bed of 100 m^3 of zirconium tungstate catalyst. The reactor effluent, Stream 6, is then cooled and partially condensed in heat exchanger E-202 prior to being throttled to a pressure of 500 kPa and sent to the high-pressure separator, V-201. The liquid leaving V-201 Stream 10, is flashed to a pressure of250 kPa and fed to the low-pressure separator. The vapor from the low-pressure

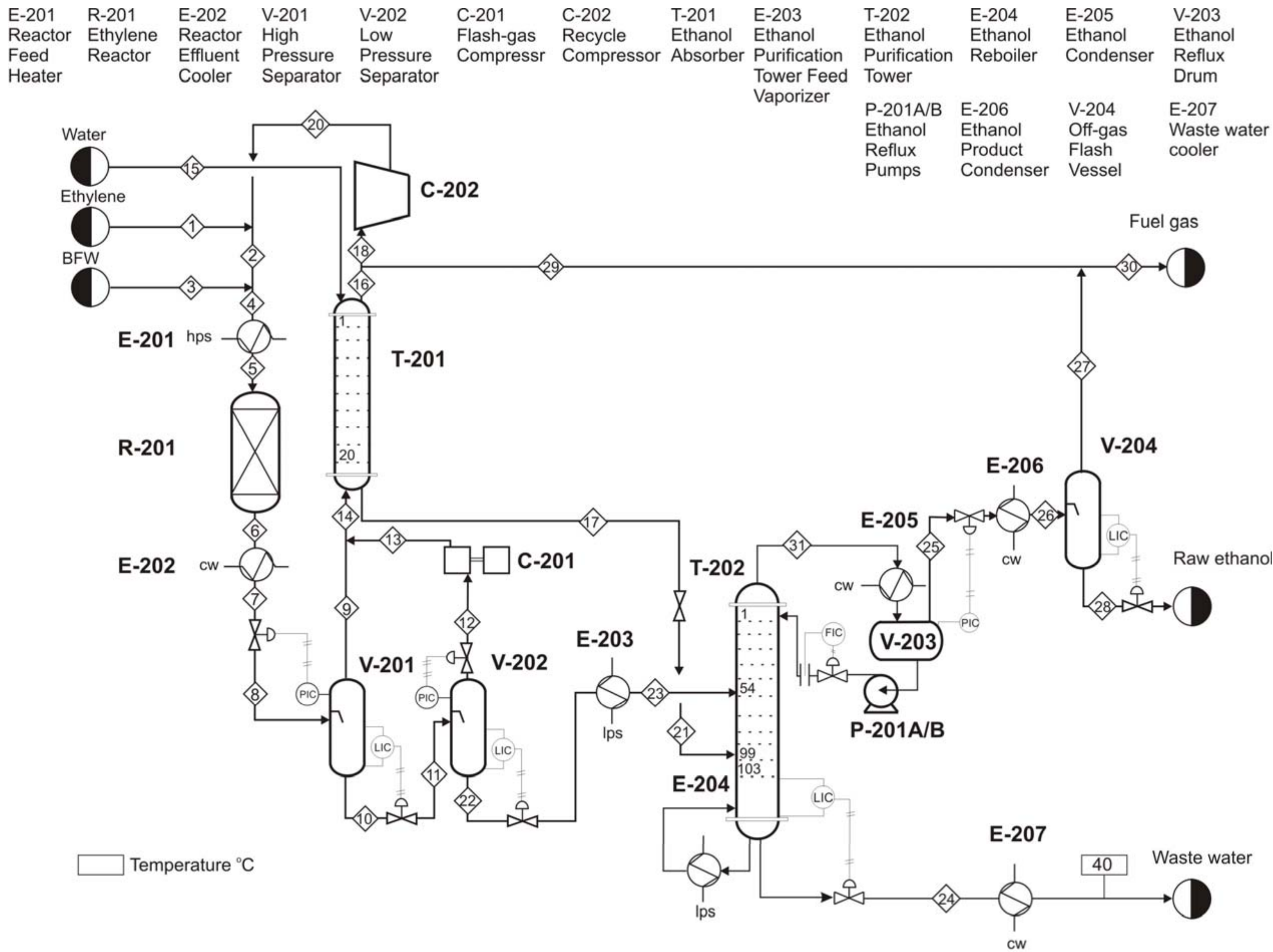


Figure 1: Process Flow Diagram for Unit 200 - Ethylene Hydration to Ethanol

Table 1: Stream Table for Ethylene Hydration Process – Unit 200

Stream No.	1	2	3	4	5	6	7
Temp °C	25	202	25	85	229	264	50
Pres kPa	5,000	5,000	5,000	5,000	4,975	4,925	4,915
Vapor mole fraction	1.00	1.00	-	0.39	1.00	1.00	0.35
Total kg/h	2,384.54	18,266.46	18,015.00	36,281.45	36,282.11	36,282.11	36,282.11
Total kmol/h	85.00	653.86	1,000.00	1,653.86	1,653.89	1,574.84	1,574.84
Flowrates in kmol/h							
Methane	0.0042	0.51	-	0.51	0.51	0.51	0.51
Acetylene	0.0001	0.0001	-	0.0001	0.0001	-	-
Ethylene	84.9958	644.18	-	644.18	644.20	565.15	565.15
Acetaldehyde	-	0.00	-	0.00	0.00	0.00	0.00
Ethanol	-	0.76	-	0.76	0.76	79.80	79.80
Water	-	8.41	1,000.00	1,008.41	1,008.41	929.37	929.37

Stream No.	8	9	10	11	12	13	14
Temp °C	36	36	36	35	35	87	36
Pres kPa	500	500	500	250	250	500	500
Vapor mole fraction	0.37	1.00	-	0.00	1.00	1.00	1.00
Total kg/h	36,282.11	16,162.52	20,119.60	20,119.60	37.75	37.75	16,200.26
Total kmol/h	1,574.84	575.36	999.48	999.48	1.34	1.34	576.70
Flowrates in kmol/h							
Methane	0.51	0.51	0.00	0.00	0.00	0.00	0.51
Acetylene	-	-	-	-	-	-	-
Ethylene	565.15	562.62	2.54	2.54	1.29	1.29	563.90
Acetaldehyde	0.00	0.00	0.00	0.00	-	-	0.00
Ethanol	79.80	5.36	74.45	74.45	0.02	0.02	5.38
Water	929.37	6.87	922.49	922.49	0.03	0.03	6.90

Table 1: Stream Table for Ethylene Hydration Process – Unit 200 (cont'd)

Stream No.	15	16	17	18	19	20	21
Temp °C	30	39	37	39	228	228	37
Pres kPa	500	500	520	500	5,000	5,000	230
Vapor mole fraction	-	1.00	-	1.00	1.00	1.00	0.00
Total kg/h	1,801.50	16,010.00	1,991.77	15,881.92	15,881.92	15,881.92	1,991.77
Total kmol/h	100.00	573.45	103.25	568.86	568.86	568.86	103.25
Flowrates in kmol/h							
Methane	-	0.51	-	0.51	0.51	0.51	-
Acetylene	-	-	-	-	-	-	-
Ethylene	-	563.69	0.21	559.18	559.18	559.18	0.21
Acetaldehyde	-	0.00	-	0.00	0.00	0.00	-
Ethanol	-	0.76	4.62	0.76	0.76	0.76	4.62
Water	100.00	8.48	98.42	8.41	8.41	8.41	98.42

Stream No.	22	23	24	25	26	27	28
Temp °C	35	123	127	99	50	50	50
Pres kPa	250	235	250	230	220	220	220
Vapor mole fraction	-	1.00	-	1.00	0.01	1.00	-
Total kg/h	20,081.85	20,081.85	18,280.14	3,793.48	3,793.48	27.23	3,766.25
Total kmol/h	998.13	998.13	1,012.26	89.13	89.13	0.90	88.23
Flowrates in kmol/h							
Methane	-	-	-	-	-	-	-
Acetylene	-	-	-	-	-	-	-
Ethylene	1.25	1.25	-	1.46	1.46	0.77	0.69
Acetaldehyde	0.00	0.00	-	0.00	0.00	-	0.00
Ethanol	74.42	74.42	1.58	77.46	77.46	0.12	77.35
Water	922.46	922.46	1,010.67	10.21	10.21	0.01	10.20

Table 1: Stream Table for Ethylene Hydration Process – Unit 200 (cont'd)

Stream No.	29	30
Temp C	39	38
Pres kPa	500	220
Vapor mole fraction	1.00	1.00
Total kg/h	128.08	155.31
Total kmol/h	4.59	5.49
Flowrates in kmol/h		
Methane	0.00	0.00
Acetylene	-	-
Ethylene	4.51	5.28
Acetaldehyde	-	-
Ethanol	0.01	0.12
Water	0.07	0.08

Table 2: Utilities Summary for Unit 200

	E-201	E-202	E-203	E-204	E-205	E-206	E-207
Utility	hps	cw	lps	lps	cw	cw	cw
Duty (MJ/h)	49,360	57,210	46,300	6,516	41,580	4,014	6,699
Utility flowrate (kg/h)	29.2×10^3	1.37×10^6	22.2×10^3	2.95×10^3	9.95×10^5	9.60×10^4	16.03×10^4

Table 3: Preliminary Equipment Summary for Unit 200

Heat Exchangers

E-201 *A* = 214 m^2 1-2 exchanger, floating head, carbon steel process stream in shell *Q* = 49,360 MJ/h maximum pressure rating of 5,500 kPa	**E-205** *A* = 164 m^2 1-2 exchanger, floating head, carbon steel process stream in shell *Q* = 41,580 MJ/h maximum pressure rating of 350 kPa
E-202 *A* = 442 m^2 1-2 exchanger, floating head, carbon steel process stream in shell *Q* = 57,210 MJ/h maximum pressure rating of 5,500 kPa	**E-206** *A* = 28 m^2 1-2 exchanger, floating head, carbon steel process stream in tubes *Q* = 4,014 MJ/h maximum pressure rating of 350 kPa
E-203 *A* = 187 m^2 1-2 exchanger, floating head, carbon steel process stream in shell *Q* = 46,300 MJ/h maximum pressure rating of 350 kPa	**E-207** *A* = 73 m^2 1-2 exchanger, floating head, carbon steel process stream in tubes *Q* = 6,699 MJ/h maximum pressure rating of 350 kPa
E-204 *A* = 55 m^2 1-2 exchanger, kettle reboiler, carbon steel process stream in shell *Q* = 6,516 MJ/h maximum pressure rating of 350 kPa	

Pumps and Compressors

C-201 carbon steel power = 1 kW 70% efficient Reciprocating	**P-201 A/B** carbon steel power = 1.9 kW 80% efficient Centrifugal
C-202 carbon steel power = 1,550 kW 75% efficient Centrifugal	

Reactors

R-201 *L* = 23.5 m^2 *D* = 2.35 m carbon steel adiabatic reactor with 100 m^3 of catalyst maximum pressure rating of 5,500 kPa maximum temperature rating = 300°C

Towers

T-201 carbon steel absorber – no reboiler or condenser 20 sieve 50% efficient 18" tray spacing diameter = 1.24 m column height = 9.14 maximum pressure rating of 550 kPa	**T-202** carbon steel 103 sieve trays plus reboiler and partial condenser 33% efficient trays feed on trays 54 and 99 reflux ratio = 12.22 0.6096 m tray spacing, 0.091 m weirs column height 63.1 m diameter = 2.44 m maximum pressure rating of 350 kPa

Vessels

V-201 Carbon Steel D = 1.15 m L = 3.45 m Orientation – Vertical pressure rating 650 kPa	**V-203** Carbon Steel D = 1.65 m L = 5.00 m Orientation – Horizontal pressure rating 300 kPa
V-202 Carbon Steel D = 1.15 m L = 3.45 m Orientation – Vertica1 pressure rating 350 kPa	**V-204** Carbon Steel D = 0.70 m L = 2.10 m Orientation – Vertical pressure rating 300 kPa

separator, Stream12, is compressed in C-201 and mixed with the vapor from the high-pressure separator prior to being fed to the ethanol absorber, T-201. Process water is fed to the top of the absorber to scrub out small amounts of ethanol. The liquid stream from the low-pressure separator, Stream 22, contains most of the ethanol and is fed to a heat exchanger, E-203, where it is vaporized prior to being fed to a tray tower, T-202. In this tower, an ethanol-rich stream, containing approximately 90 mol% of ethanol is taken as a top product. The stream leaving the bottom of the absorber, T-201, is also sent to the ethanol purification tower to recover ethanol. The bottom stream from T-202 is water containing a small amount of ethanol that is cooled to 40°C in heat exchanger

E-207 prior to being sent to waste water treatment. It should be noted that the overhead of T-202 uses a partial condenser because there is a small amount of ethylene in the feed to the column that cannot be totally condensed. The overhead vapor stream is sent to a heat exchanger, E-206, where it is cooled to 50°C, and most of the stream is condensed. The non-condensable portion is mixed with the ethylene recycle purge, Stream 29, and this combined stream is sent to the boiler house as fuel gas that is used to raise steam.

The vapor leaving the absorber, Stream 16, is split, with the majority being sent to the recycle-gas compressor, C-202, where it is pressurized and recycled to mix with fresh ethylene feed. A small portion of the absorber overhead product is purged, in Stream 29, to control the build up of non-condensables in the recycle loop. This purge is combined with the off-gas from T-202 to produce a fuel-gas stream.

Assignment

Your assignment is to provide a comprehensive list of changes that need to be made to the existing ("bad") design. Specifically, you are to prepare the following by 9:00 a.m., Monday, November 12, 2007:

1. Prepare a written report detailing your diagnosis, recommended equipment changes, and a comparison of operating costs for the existing ("bad") design and your new (proposed) design. The report should:

    a. Include an analysis of all equipment and process changes needed in Unit 200.

    b. Include an analysis of equipment that does not need to be changed for the new design, clearly showing modifications (if any) to the operating conditions that are needed to make this equipment operate correctly.

    c. Include a list of all utility and raw material costs for the old and new designs.

    e. Include a PFD that illustrates any/all modifications recommended for the process.

2. Prepare a list of new equipment to be sent to the appropriate vendors, including size, design specifications, and materials of construction.

3. Include a converged Chemcad report for your proposed design – do not include a full list of stream properties, but do include stream flows, unit operations, convergence results, and any other data relevant to your design.

Deliverables

Specifically, you are to prepare the following by 9:00 a.m., Monday, November 12, 2007:

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

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

3. Attach 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 and the Chemcad report for the converged simulation for the new case. 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 rewriting. 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 12, 2007, and November 15, 2007. 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 (see p. 48 of 2007-09 Undergraduate Catalog or follow the link http://www.arc.wvu.edu/rightsa.html).

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 – Design Criteria for Unit 200

- Feed ethylene specifications
  - available from pipeline at a pressure of 5,000 kPa and ambient temperature
  - composition
    - ≤ 1 ppm acetylene
    - ≤ 0.05 mole % of methane
    - balance is ethylene
- Design basis = 30,000 tonne/yr of ethanol – this should be contained in a crude ethanol stream with an ethanol content >94 wt% at a pressure of 200 kPa and as a saturated liquid.
- Final purification and dehydration of ethanol will be performed by client
- Stream Factor = 0.965
- Cooling water is available at 30°C and 5 bar, should be returned at 40°C for design conditions, and never should the return temperature exceed 45°C. The cost of cooling water is $0.354/GJ.
- Fuel gas should be used for all fired heaters (assume natural gas content = 100% methane) at a cost of $10/GJ (based on lower heating value).
- Steam available for process heating:
  - High pressure – saturated at 42 bar available at a cost of $9.83/GJ
  - Medium pressure – saturated at 11 bar available at a cost of $8.22/GJ
  - Low pressure – saturated at 6 bar available at a cost of $7.78/GJ
- Wastewater, at a temperature ≤ 40°C and containing organics with a total concentration of less than 5000 ppm, is sent to a centralized treatment facility at a cost of $100/1000m^3.
- Selling price for ethanol is $2.90/gal
- Cost of ethylene is $0.35/lb

Appendix 2 – Information on Reaction Kinetics

Most ethanol (approximately 85%) manufactured in the U.S. comes from some form of fermentation process. However, a small amount is manufactured via the catalytic, gas-phase hydration of ethylene. The main reaction is

$$C_2H_4 + H_2O \underset{r_2}{\overset{r_1}{\leftrightarrow}} C_2H_5OH \qquad (1)$$

ethylene *ethanol*

Where r_1 and r_2 are the forward and reverse rates, respectively. Experimental analysis of the performance of this catalyst [1], gives the following expressions for these reaction rates:

$$r_1 = \frac{k_1 p_W p_E}{\left(1 + K_W p_W + K_E p_E + \cancel{K_A p_A}\right)^2} \qquad (2)$$

and

$$r_2 = \frac{k_2 p_A}{\left(1 + K_W p_W + K_E p_E + \cancel{K_A p_A}\right)^2} \qquad (3)$$

where

$$k_1[\text{kmol/m}^3\text{cat/h/atm}^2] = 1.7723 \times 10^{-9} \exp\left(\frac{91{,}130}{RT[\text{K}]}\right)$$

$$k_2[\text{kmol/m}^3\text{cat/h/atm}] = 1.3865 \times 10^{-2} \exp\left(\frac{43{,}915}{RT[\text{K}]}\right)$$

$$K_W[\text{atm}^{-1}] = 1.2328 \times 10^{-17} \exp\left(\frac{162{,}730}{RT[\text{K}]}\right)$$

$$K_E[\text{atm}^{-1}] = 2.0850 \times 10^{-4} \exp\left(\frac{35{,}368}{RT[\text{K}]}\right)$$

and the activation energy is given in kJ/kmol, and p_i is measured in atmospheres.

Under the conditions used in commercial reactors, the last term in the denominator is negligible and may be ignored. Also note that the exponential terms in the numerator and denominator are all positive. This is an artifact of the lumping together of reaction rate constants and adsorption equilibrium constants in Equations (2)-(3). However, the net effect of temperature on the overall forward and reverse reactions is that the overall rates increase with increasing temperature, which is consistent with Arrhenius-type behavior.

Along with the desired, forward, reaction shown in Equation (1), ethanol can also dehydrate to form diethyl ether as follows:

$$\underset{\textit{ethanol}}{C_2H_5OH} \leftrightarrow H_2O + \underset{\textit{diethyl ether}}{(CH_3CH_2)_2O} \tag{4}$$

The catalyst used in the process of interest is zirconium tungstate, and it effectively suppresses the diethyl ether reaction shown in Equation (4).

In addition, any in the ethylene feed may be converted to acetaldehyde, which is tolerable in the final ethanol product at only very low concentrations (< 1ppm).

$$\underset{\textit{acetylene}}{C_2H_2} + H_2O \xrightarrow{r_3} \underset{\textit{acetaldehyde}}{CH_3CHO} \tag{5}$$

The rate for this reaction is given by:

$$r_3 = k_3[\text{kmol/m}^3\text{cat/h/atm}]p_{Acet}[\text{atm}] \tag{6}$$

where

$$k_3 = 1\times10^{-4}\exp\left[-\frac{25{,}000[\text{kJ/kmol}]}{\text{RT}[K]}\right] \tag{7}$$

Reference

1. Momose, H., Kusumoto, K., Izumi, Y., and Y. Mizutani, Vapor-phase direct hydration of ethylene over zirconium tungstate catalyst, *J. Catalysis*, 77, 23-31 (1982)

Appendix 3– Equipment Sizing Calculations

C-201 – Flash-Gas Compressor

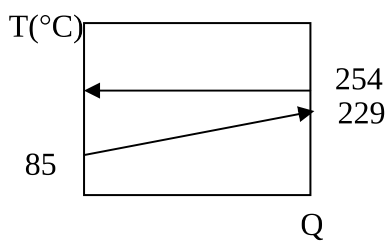
ΔP = 250 kPa
Q = 13.5 m^3/h (at inlet conditions)
$\dot{m} = 37.7$ kg/h
$\dot{W}_s$ = 1 kW
Positive displacement - Electric Drive

C-202 – Recycle Compressor

ΔP = 4500 kPa
Q = 2,794 m^3/h (at inlet conditions)
$\dot{m} = 16,455$ kg/h
$\dot{W}_s$ = 1550 kW
Centrifugal - Electric Drive

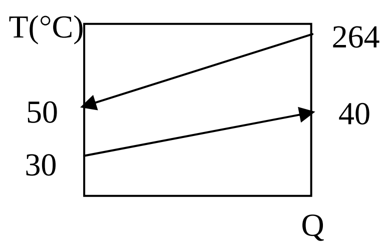
Note: All overall heat transfer coefficients are taken from existing exchangers with similar services.

E-201 – Reactor Feed Heater



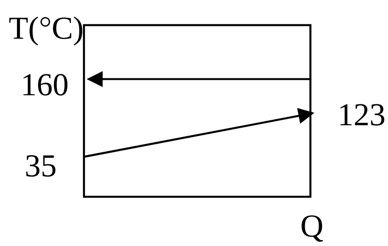
Q = 49,360 MJ/h
U = 850 W/m^2°C
ΔT_{LM} = (229-85)/ln{(254-85)/(254-229)}=75.4°C
A = 49,360×10^6/(3600)/(850)/(75.4) = 214 m^2

E-202 – Reactor Effluent Cooler



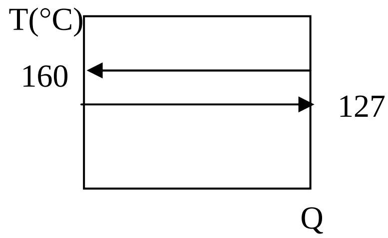
Q = 57,210 MJ/h
U = 425 W/m^2°C
ΔT_{LM} = (224-20)/ln{(224)/(20)}=84.4°C
A = 57,210×10^6/(3600)/(425)/(84.4) = 442 m^2

E-203 – Ethanol Purification Tower Feed Vaporizer



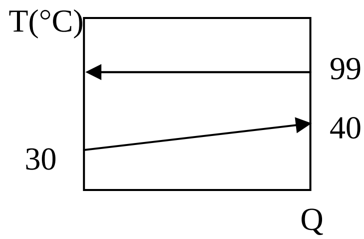
Q = 46,300 MJ/h
U = 950 W/m^2°C
ΔT_{LM} = (125-37)/ln{(125)/(37)}=72.3°C
A = 46,300×10^6/(3600)/(950)/(72.3) = 187 m^2

E-204 – Ethanol Reboiler



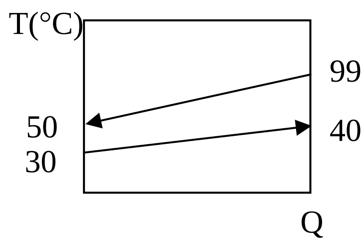
Q = 6,516 MJ/h
U = 1000 W/m^2°C
ΔT_{LM} =33°C
A = 6,516×10^6/(3600)/(1000)/(33) = 55 m^2

E-205 – Ethanol Condenser



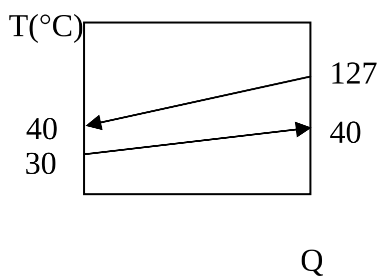
Q = 41,580 MJ/h
U = 1100 W/m^2°C
ΔT_{LM} = (10)/ln{(69)/(59)}=63.9°C
A = 41,580×10^6/(3600)/(1100)/(63.9) = 164 m^2

E-206 – Ethanol Product Condenser



Q = 4,014 MJ/h
U = 1100 W/m^2°C
ΔT_{LM} = (59-20)/ln{(59)/(20)}=36.1°C
A = 4,004×10^6/(3600)/(1100)/(36.1) = 28 m^2

E-207 – Waste water cooler



Q = 6,699 MJ/h
U = 900 W/m^2°C
F = 0.8
ΔT_{LM} = (87-10)/ln{(87)/(10)}=35.6°C
A = 6,699×10^6/(3600)/(900)/(36.1)/(0.8) = 73 m^2

P-201A/B Ethanol Reflux Pumps

Reflux rate = 63.4 m^3
$-\Delta P_f$ = 50 ft of liquid = ρhg = (722)(50)(0.3048)(9.81) = 108 kPa
Efficiency = 65%

$$-\dot{W}_s = Q\Delta P = \frac{(63.4)(108{,}000)}{3600} = 1902 \text{ W} = 1.9 \text{ kW}$$

R-201 Ethylene Reactor

Volume of Catalyst = 100 m^3
Catalyst diameter = 1 cm, voidage = 0.5
L/D = 10/1

$$\frac{\pi D^2(10D)}{4} = 100 \Rightarrow D = 2.35\,\text{m}$$

L = 23.5 m
assume ΔP = 50 kPa

T-201 Ethanol Absorber

Limiting condition at top of column
L = 1837 kg/h, G = 16,045 kg/h
ρ_L = 981 kg/m^3
ρ_G = 5.537 kg/m^3
$(L/G)(\rho_G/\rho_L)^{0.5}$ = 0.0086
from flooding graph for 18 in tray spacing (P. Wankat, *Separation Processes in Engineering, 2nd ed.*, Prentice Hall, 2007, p. 315.)
C_{sb} = 0.295
u_{fl} = 3.92 ft/s
u_{act} = 0.897 m/s (75% of flooding)
if 75% active area
$A = (G/3600)/[(0.75)(\rho_G)(u_{act})]$ = 1.24 m^2
D = 1.26 m

Efficiency from O'Connell equation

$$\log E_o = 1.597 - 0.199\log\left(\frac{KM_L\mu_L}{\rho_L}\right) - 0.0896\left[\log\left(\frac{KM_L\mu_L}{\rho_L}\right)\right]^2$$

Where K = K-value for ethanol = 0.159
M_L = MW of liquid = 19.3
μ_L = viscosity of liquid = 0.72 cP
ρ_L = density of liquid = 59.5 lb/ft^3

$$\frac{KM_L\mu_L}{\rho_L} = \frac{(0.159)(19.3)(.7)}{59.5} = 0.0361$$

$$\log E_o = 1.597 - 0.199\log(0.0361) - 0.0896\left[\log(0.0361)\right]^2 = 50\%$$

Number of theoretical Stages = 10
Number of actual Stages = 20
Tray spacing = 0.457 m (1.5 ft)
Tan-tan height = 9.14 m
Column diameter = 1.24 m

T-202 Ethanol Purification Column

Limiting condition at top of column

L = 45,526 kg/h, *G* = 49,319 kg/h
ρ_L = 723 kg/m^3
ρ_G = 3.262 kg/m^3
$(L/G)(\rho_G/\rho_L)^{0.5}$ = 0.0620
from flooding graph for 24 in tray spacing (P. Wankat, *Separation Processes in Engineering, 2nd ed.*, Prentice Hall, 2007, p. 315.)
C_{sb} = 0.355
u_{fl} = 5.27 ft/s
u_{act} =1.204 m/s (75% of flooding)
if 75% active area
$A = (G/3600)/[(0.75)(\rho_G)(u_{act})]$ = 4.68 m^2
D = 2.44 m

Efficiency from O'Connell equation

$$\log E_o = 1.597 - 0.199\log\left(\frac{KM_L\mu_L}{\rho_L}\right) - 0.0896\left[\log\left(\frac{KM_L\mu_L}{\rho_L}\right)\right]^2$$

Where *K* = *K*-value for ethanol = 3.77
M_L = MW of liquid = 42.7
μ_L = viscosity of liquid = 0.659 cP
ρ_L = density of liquid = 47.48 lb/ft^3

$$\frac{KM_L\mu_L}{\rho_L} = \frac{(3.77)(42.7)(.659)}{(47.48)} = 2.234$$

$$\log E_o = 1.597 - 0.199\log(2.234) - 0.0896\left[\log(2.234)\right]^2 = 33\%$$

Number of theoretical Stages = 34
Number of actual Stages = 103
Tray spacing = 0.609 m (2 ft)
Tan-tan height = 63.1 m
Column diameter = 2.44 m

V-201 High Pressure Separator

Liquid Flowrate = 21.5 m^3/h
Vertical
L/*D* = 3/1
Liquid hold-up = 10 mins

$$\frac{\pi D^2(3D)}{4} = \frac{21.5}{6} \Rightarrow D = 1.15\text{m}$$

L = 3.45 m

V-202 Low Pressure Separator

Liquid Flowrate = 21.3 m^3/h
Vertical
L/D = 3/1
Liquid hold-up = 10 mins

$$\frac{\pi D^2(3D)}{4} = \frac{21.3}{6} \Rightarrow D = 1.15\text{m}$$

L = 3.45 m

V-203 Ethanol Reflux Drum

Liquid Flowrate = 63.4 m^3/h
Vapor Flow = 15202 m^3/h
Horizontal
L/D = 3/1
Liquid hold-up = 10 mins

$$\frac{\pi D^2(3D)}{4} = \frac{63.4}{6} \Rightarrow D = 1.65\text{m}$$

L = 5.0 m

Vapor Velocity = $\frac{15,202}{(1.65)(5)(3600)} = 0.51$ m/s - OK

V-204 Off-Gas Flash Vessel

Liquid Flowrate = 4.94 m^3/h
Vertical
L/D = 3/1
Liquid hold-up = 10 mins

$$\frac{\pi D^2(3D)}{4} = \frac{4.94}{6} \Rightarrow D = 0.70\text{m}$$

L = 2.1 m