CADET SECTION TIME OF DEPARTURE	
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#### DEPARTMENT OF CHEMISTRY & LIFE SCIENCE

CH402, AY2023-2024 WRITTEN PARTIAL REVIEW I 55 Minutes, C-Hour 9 February 2024 TEXT: Peters, Timmerhaus & West SCOPE: CHAPTERS: 12, 14

References Permitted: Open note and open book; Mathematica; Excel; CHEMCAD.

#### **INSTRUCTIONS**

- 1. You will have 55 minutes for the exam.
- 2. Do not mark this exam or open it until "begin work" is given.
- 3. Solve the problems in the space provided. Show all work to receive full credit.
- 4. There are 3 problems on 4 pages in this exam (not including the cover page).
- 5. Write your name on the top of each sheet.
- 6. Save all work and save it frequently.
- 7. Final CHEMCAD file must be saved in Canvas to receive partial credit.

(TOTAL WEIGHT: 200 POINTS)

#### DO NOT WRITE IN THIS SPACE

PROBLEM	VALUE	CUT
A	80	
В	60	
С	60	
TOTAL CUT		
GRADE	200	

#### THE FOLLOWING INFORMATION IS REQUIRED FOR QUESTIONS A, B, & C

Air used in a catalytic oxidation process is to be heated from 15 to 470  $^{\circ}$ C before entering the process. The heating is accomplished with the use of product gases, which cool from 480 to 200  $^{\circ}$ C.

A one-pass shell-and-tube TEMA type AEL exchanger with single-segmental baffles has been proposed. The tubes are type 316 stainless-steel, with type A-240-316 stainless steel used for the tube sheet, shell, channel material, and baffles.

The properties of the hot gases can be considered identical to those of air.

Both streams enter the exchanger at 1020 kPa.

The hot gasses are sent through the tubes at a flow rate of 5.6 kg/s.

The air is sent through the shell.

The shell-side and tube-side fouling factors are zero.

The inside and outside diameters for the tubes are 0.0191 and 0.0254 m, respectively. The tubes will be arranged in line with a square pitch of 0.0381 m with fixed tube sheets. The tubesheet thickness is equal to the outside diameter of the tubes.

Baffles are single segmental.

The exchanger operates for 8000 h/yr.

Installation costs are 15% of purchased cost, and annual fixed charges including maintenance are 20% of the installed cost.

The energy cost is \$0.16/kWh.

No utility fluid is used so the annual cost of utility fluid may be ignored.

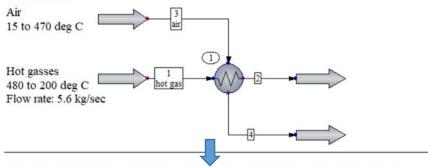
Design Constraints: The upper limit on the tube length is 20 m and the upper limit on the shell diameter is 6 m.

Use CHEMCAD to perform a 3-step *design* analysis on the proposed heat exchanger and answer the following questions: (1) Determine the number and length of tubes, the inside diameter of the shell, and the required area of the exchanger. (2) Determine the largest resistance to heat transfer in the exchanger. (3) Determine the February 2024 total installed cost of the heat exchanger.

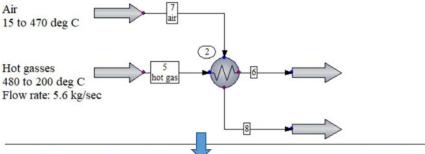
#### **SOLUTION:**

Blue arrows indicate the 1-2-3 heat exchanger design process.

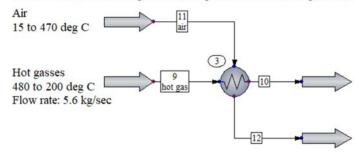
Step 1 (CH485 Level 1). Basic heat exchanger design. Specify or calculate steam flow rates, temperatures, and heat duties. Utility option in exchanger used to calculate flow rate of stream 3.



Step 2 (CH485 Level 2). Detailed internal design. Calculation performed in "design" mode using "Sizing." Enter specs. CHEMCAD optimizes number and length of tubes, baffle spacings and cuts, and calculates pressure drops, area, and heat transfer coefficient from resistance model.



Step 3 (CH485 Level 3). Simulation. Calculation performed in "shell-and-tube simulation mode 1." Uses shell- and tube-side pressure drops, area, and heat transfer coefficient to calculate outlet stream temperatures and pressures and exchanger costs.



# TABULATED ANALYSIS - DESIGN (LEVEL 2)

Overall Data:         Area Totoal         m2         286.32         % Excess         -4.60           Area Required         m2         291.96         U Calc.         W/m2-K         94.35           Area Effective         m2         278.53         U Service         W/m2-K         98.90           Area Per Shell         m2         278.53         Heat Duty         J/sec         1.65E+06           Weight LMTD C         59.98         LMTD CORR Factor         1.0000         CORR LMTD C         59.98           Shell-side Data:         Crossflow Vel.         m/sec         4.7E+00         Endzone         Vel. 4.7E+00         Window Vel.         3.1E+00           Film Coef.         W/m2-K         205.67         Reynolds No.         32721         Allow Press.         Drop         kPa         3.06           Outlet Nozzle Size         m         0.15         Press.         Drop/Out Nozzle kPa         3.06           Rho V2 IN         kg/m-sec         2841.99         Press.         Drop/Out Nozzle kPa         3.06           Stream Analysis:         SA Factors:         12.78         B 75.38         C 2.53         E 9.31         F 0.00           Stream Analysis:         SA Factors:         12.78         B 75.38         C 2.5				
Area Required   m2   291.96   U Calc.   W/m2-K   94.35   Area Effective   m2   278.53   U Service   W/m2-K   94.35   Area Effective   m2   278.53   U Service   W/m2-K   1.65E+06   Weight LMTD C 59.98   LMTD CORR Factor   1.0000   CORR LMTD C 59.98   LMTD C 59.98   LMTD CORR LMTD C 59.98   LMTD CORR LMTD C 59.98   LMTD CORR LMTD C 59.98   LMTD C 5	Overall Data:			
Area Required   m2   291.96   U Calc.   W/m2-K   94.35   Area Effective   m2   278.53   U Service   W/m2-K   94.35   Area Effective   m2   278.53   U Service   W/m2-K   1.65E+06   Weight LMTD C 59.98   LMTD CORR Factor   1.0000   CORR LMTD C 59.98   LMTD C 59.98   LMTD CORR LMTD C 59.98   LMTD CORR LMTD C 59.98   LMTD CORR LMTD C 59.98   LMTD C 5	Area Total m2	286.32	% Excess	-4.60
Area Effective m2 278.53 U Service W/m2-K 1.65E+06	Area Required m2			
Area Per Shell   m2	-			
Shell-side Data:   Crossflow Vel. m/sec			·	
Shell-side Data:   Crossflow Vel. m/sec 4.7E+00    EndZone Vel. 4.7E+00    Window Vel. 3.1E+00      Film Coef. W/m2-K			<b>4</b> '	
Crossflow Vel. m/sec	Weight LMTD C 59.98	LMTD CORR Fa	ctor 1.0000 CORR LMTD C	59.98
Film Coef. W/m2-K   205.67   Reynolds No.   32721   Allow Press. Drop   KPa   34.47   Calc. Press. Drop   KPa   3.06   Outlet Nozzle Size   m   0.13   Press. Drop/In Nozzle   KPa   3.06   Mean Temperature   C   242.50   Mean Mean Metal Temperature   C   242.50   Mean Temperature   C   242.50   Mean Temperature   C   242.50   Mean Mean Metal Temperature   C   242.50   Mean Mean Mean Mean Mean Mean Mean Mean		7F+00 Fnd7o	one Vel 4 7F+00 Window Ve	1 3 1⋤±∩∩
The Nozzle Size m	•			
Outlet Nozzle Size m Rho V2 IN kg/m-sec2  2841.99 Press. Drop/Out Nozzle kPa 242.50 Rho V2 IN kg/m-sec2  2841.99 Press. Drop (Dirty) kPa 71.40  Stream Analysis: SA Factors: A 12.78 B 75.38 C 2.53 E 9.31 F 0.00 Ideal Cross Vel. m/sec 6.20 Ideal Window Vel. m/sec 3.94  Tube-side Data: Film Coef, W/m2-K 240.38 Reynolds No. 37203 Inlet Nozzle Size m 0.20 Press. Drop/In Nozzle kPa 15.38 Inlet Nozzle Size m 0.15 Press. Drop/In Nozzle kPa 2.48 Outlet Nozzle Size m 0.15 Press. Drop/Out Nozzle kPa 2.45 Interm. Nozzle Size m 0.00 Mean Temperature C 340.00 Velocity m/sec 10.16 Mean Metal Temperature C 340.00 Velocity m/sec 10.16 Mean Metal Temperature C 287.11  Clearance Data: Baffle to shell m 0.0008 Bundle diameter m 0.08202 Tube hole clear. m 0.0008 Outer tube clear. m 0.0180 Bundle btm space m 0.0000 In-line pass clear. m 0.0180 Bundle btm space m 0.0000 Pass clearance m 0.0159  Eaffle Parameters: Number of Baffles	Allow Press. Drop kPa	34.47	Calc. Press. Drop kPa	a 42.00
Outlet Nozzle Size m         0.13 Mean Temperature         C 242.50 Mean Temperature         C 245.30 Mean Temperature         C 253 Mean Temperature         E 9.31 Mean Temperature         F 0.00 Mean Temperature         Temperature         Temperature         C 2.53 Mean Temperature         E 9.31 Mean Temperature         F 0.00 Mean Mean Mean Mean Mean Mean Mean Mean	Inlet Nozzle Size m	0.15	Press. Drop/In Nozzle kPa	a 3.06
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Stream Analysis: SA Factors: A 12.78	_1 1	0044 00		
SA Factors: A 12.78	Rho V2 IN kg/m-sec2	2841.99	Press. Drop (Dirty) kPa	a 71.40
Tube-side Data:         Film Coef. W/m2-K         240.38 Reynolds No.         37203           Allow Press. Drop kPa         34.47 Calc. Press. Drop kPa         15.38           Inlet Nozzle Size m         0.20 Press. Drop/In Nozzle kPa         2.88           Outlet Nozzle Size m         0.15 Press. Drop/Out Nozzle kPa         2.45           Interm. Nozzle Size m         0.00 Mean Temperature         C 340.00           Velocity m/sec         10.16 Mean Metal Temperature         C 340.00           Velocity m/sec         0.0008 Outer tube clear         0.0180           Baffle to shell m         0.0008 Outer tube clear         0.0180           Bundle top space m         0.0000 In-line pass clear         0.0180           Bundle btm space m         0.0000 In-line pass clear         0.0180           Baffle Parameters:         Number of Baffles         38           Baffle Space def.         Edge-Edge         0.403           Center Space m         <		D 75 20	C 2 52 F 0 21	E 0 00
Tube-side Data: Film Coef. W/m2-K				
Film Coef. W/m2-K         240.38         Reynolds No.         37203           Allow Press. Drop kPa         34.47         Calc. Press. Drop kPa         15.38           Inlet Nozzle Size m         0.20         Press. Drop/In Nozzle kPa         2.88           Outlet Nozzle Size m         0.15         Press. Drop/In Nozzle kPa         2.45           Interm. Nozzle Size m         0.00         Mean Temperature         C         340.00           Velocity m/sec         10.16         Mean Metal Temperature         C         340.00           Velocity m/sec         0.0008         Bundle diameter m         0.8202           Tube hole clear. m         0.0008         Outle clear. m         0.0180           Bundle top space m         0.0000         In-line pass clear. m         0.0000           Baffle Parameters:         Number of Baffles         38         Single Segmental </td <td>ideal Cross Vel. m/sec</td> <td>6.20 I</td> <td>deal window vel. m/sec</td> <td>3.94</td>	ideal Cross Vel. m/sec	6.20 I	deal window vel. m/sec	3.94
Allow Press. Drop kPa 34.47 Calc. Press. Drop kPa 15.38 Inlet Nozzle Size m 0.20 Press. Drop/In Nozzle kPa 2.88 Outlet Nozzle Size m 0.15 Press. Drop/Out Nozzle kPa 2.45 Interm. Nozzle Size m 0.00 Mean Temperature C 340.00 Velocity m/sec 10.16 Mean Metal Temperature C 287.11  Clearance Data:  Baffle to shell m 0.0063 Bundle diameter m 0.8202 Tube hole clear. m 0.0008 Outer tube clear. m 0.0180 Bundle top space m 0.0000 In-line pass clear. m 0.0180 Bundle btm space m 0.0000 In-line pass clear. m 0.0159  Baffle Parameters: Number of Baffles 38 Baffle Type Single Segmental Edge-Edge Inlet Space m 0.267 Outlet Space m 0.403 Baffle Cut, % Diameter 19.000 Baffle Cut, % Diameter 19.000 Baffle Cut Direction Horizontal Number of Int. Baffles Death of Int. Baffles Baffle Thickness m 0.086 Orientation Horizontal Number of Int. Baffles Baffle Thickness m 0.84 Shell in Series Bonnet I.D. m 0.84 Shell in Parallel 1 Type AEL Max. Heat Flux Btu/ft2-hr 0.000	Tube-side Data:			
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Inlet Nozzle Size m	Allow Press Drop kPa		1	
Outlet Nozzle Size m         0.15         Press. Drop/Out Nozzle kPa         2.45           Interm. Nozzle Size m         0.00         Mean Temperature         C         340.00           Velocity         m/sec         10.16         Mean Metal Temperature         C         340.00           Velocity         m/sec         10.16         Mean Metal Temperature         C         287.11           Clearance Data:         Baffle to shell m         0.0008         Bundle diameter m         0.8202           Tube hole clear. m         0.0008         Outer tube clear. m         0.0180           Bundle top space m         0.0000         In-line pass clear. m         0.0180           Bundle top space m         0.0000         In-line pass clear. m         0.0000           Baffle Parameters:         Number of Baffles         38         Salegamental         Salegamental         Edge-Edge           Inlet Space         m         0.267         0.403         Outer Space         Mean Metal Temperature C         2.84           Saffle Type         Single Segmental         Bege-Edge         Salegamental         Bege-Edge         Bege-Edge         Salegamental         Bege-Edge         Salegamental         Bege-Edge         Bege-Edge         Bege-Edge         Bege-Edge         Salegam				
Interm. Nozzle Size m				
Velocity         m/sec         10.16         Mean Metal Temperature C         287.11           Clearance Data:         Baffle to shell m         0.0063         Bundle diameter m         0.8202           Tube hole clear. m         0.0008         Outer tube clear. m         0.0180           Bundle top space m         0.0000         In-line pass clear. m         0.0000           Bundle btm space m         0.0000         Pass clearance m         0.0005           Baffle Parameters:         Number of Baffles         38         38           Baffle Type         Single Segmental         58         58         69           Baffle space def.         Edge-Edge         60<			<del>-</del>	
Clearance Data:   Baffle to shell   m	Interm. Nozzle Size m	0.00	Mean Temperature C	340.00
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Type AEL Max. Heat Flux Btu/ft2-hr 0.00				
11				
Imping. Plate Impingement Plate Sealing Strip 5				r 0.00
	Imping. Plate Imping	ement Plate	Sealing Strip	5

Tubes:

Number		327	Tube Type		Bare
<b>Length</b>	m	10.97	Free Int. Fl A	rea m2	0.00
Tube O.D.	m	0.025	Fin Efficiency		0.000
Tube I.D.	m	0.019	Tube Pattern		SQUAR
Tube Wall Thk.	m	0.003	Tube Pitch	m	0.038
No. Tube Pass		1			
Inner Roughnes	s m	0.0000016			
Number of tube	sheets	2	Tubesheet thic	kness, m	0.025
Resistances:					
Shell-side Fil			m2-K/W	0.00486	
Shell-side Fou	ling		m2-K/W	0.00000	
Tube Wall			m2-K/W	0.00020	
Tube-side Foul	_		m2-K/W	0.00000	
Tube-side Film			m2-K/W	0.00416	
Reference Fact	or (Total	outside area/i	nside area base	d on tube ID)	1.330
Pressure Drop D	istributi	on:			
Tube Side			Shell Side		
Inlet Nozzle	kPa	2.8773	Inlet Nozzle	kPa	3.0568
Tube Entrance	kPa	0.1441	Impingement	kPa	1.8473
Tube	kPa	3.9437	Bundle	kPa	23.3859
Tube Exit	kPa	0.2386	Outlet Nozzle	kPa	3.0647
End	kPa	0.0000	Total Fric.	kPa	29.5074
Outlet Nozzle	kPa	2.4548	Total Grav.	kPa	-0.0638
Total Fric.	kPa	9.6585	Total Mome.	kPa	12.5575
Total Grav.	kPa	0.0593	Total	kPa	42.0010
Total Mome.	kPa	5.6606			
Total	kPa	15.3783			

The completed CHEMCAD flowsheet is shown on page 2 and the detailed tabulated results on pages 3-4, with answers to questions (1) and (2) are highlighted in yellow.

Number of tubes: 327 //ANS

Length of the tubes: 10.97 m //ANS

Inside diameter of the shell: 0.84 m //ANS

Required area of the exchanger: 291.96 m<sup>2</sup> //ANS

Largest resistance to heat transfer in the exchanger: 0.00486 m<sup>2</sup>K/W Shell-side //ANS

The installed cost is determined by activating the "costing report" in the Cost Estimations tab in the Level 3 heat exchanger.

February 2024 total installed cost: \$263,008 //ANS

# Cadet: APPROVED SOLUTION

Problem: Weight: 60

Use equation 14-91 to determine the total annual operating costs for the shell-and-tube exchanger as designed in Problem A assuming utility costs are zero. Do not optimize.

#### **SOLUTION:**

Equation 14-91 is found in the PTW textbook on page 739, and the stream properties are shown in the stream box from CHEMCAD:

$$C_{T} = A_{0} \cdot K_{F} \cdot C_{A_{0}} + m_{u} \cdot H_{y} \cdot C_{u} + A_{0} \cdot E_{i} \cdot H_{y} \cdot C_{i} + A_{0} \cdot E_{0} \cdot H_{y} \cdot C_{0}$$

C<sub>T</sub> Total annual costs, dollars/yr

A<sub>0</sub> Outside tube area, m<sup>2</sup>

K<sub>E</sub> Annual fixed charges factor (maintenance, etc) as a fraction of installed cost, dimensionless

 $C_{\mbox{\scriptsize A}_0}$  Installed cost of the heat exchanger per unit outside tube area, dollars/m²

m<sub>u</sub> Mass flow rate of utility fluid, kg/hr

H<sub>v</sub> Hours of operation per year

C<sub>u</sub> Cost of utility fluid, dollars/kg

E<sub>1</sub> Power loss due to fluid flow inside heat exchanger tubes per unit outside tube area, N·m/s per m<sup>2</sup>

 $C_i$  Cost of supplying  $1 \ N \cdot m$  to pump fluid through the inside of the tubes, dollars/ $N \cdot m$ 

 $E_0$  Power loss experienced on the shell side per unit outside tube area,  $N \cdot m/s$  per  $m^2$ 

 $C_0$  Cost of supplying  $1 \text{ N} \cdot \text{m}$  to pump fluid through the shell side, dollars/N  $\cdot$  m

Stream No.	9	10	11	12
Name	hot gas		air	
Overall				
Temp C	480.0000	200.9785	15.0000	468.5166
Pres kPa	1020.0000	1004.3643	1020.0000	977.6427
Mass flow kg/sec	5.6000	5.6000	3.4950	3.4950
Actual dens kg/m3	4.6984	7.3505	12.3721	4.5736

Tube-side pressure drop = 1020 - 1004.3643 = 15.6357 kPa = 15,635.7 Pa

Tube-side average density =  $(4.6984 + 7.3505)/2 = 6.02445 \text{ kg/m}^3$ 

Tube-side mass flow rate = 5.6000 kg/s

Shell-side pressure drop = 1020 - 977.6427 = 42.3573 kPa = 42,357.3 Pa

Shell-side average density =  $(12.3721 + 4.5736)/2 = 8.47285 \text{ kg/m}^3$ 

Shell-side mass flow rate = 3.4950 kg/s

$$A_0 = \pi \cdot D_0 \cdot L \cdot N_P = \pi \cdot 0.0254 \,\text{m} \cdot 10.97 \,\text{m} \cdot 327 = 286.245 \,\text{m}^2$$

$$C_{A_0} = \$263,008 / 286.245 \,\text{m}^2 = \$918.821 / \,\text{m}^2$$

$$K_{\rm F} = 0.2$$

$$C_{n} = 0$$

$$H_v = 8,000 \, hrs$$

$$C_i = $0.16 / kWh$$

$$E_{i} = \frac{15,635.7 \frac{N}{m^{2}} \cdot 5.6000 \frac{kg}{s} \cdot \frac{1 m^{3}}{6.02445 \, kg}}{286.245 \, m^{2}} = 50.7750 \, \frac{W}{m^{2}} = 0.0507750 \, \frac{kW}{m^{2}}$$

$$E_0 = \frac{42,357.3 \frac{N}{m^2} \cdot 3.4950 \frac{kg}{s} \cdot \frac{1 \, m^3}{8.47285 \, kg}}{286.245 \, m^2} = 61.0391 \, \frac{W}{m^2} = 0.0610391 \, \frac{kW}{m^2}$$

$$C_{T} = 286.245 \,\mathrm{m}^{2} \cdot 0.2 \cdot \frac{\$918.821}{\mathrm{m}^{2}}$$

$$+ 286.245 \,\mathrm{m}^{2} \cdot 0.05077750 \frac{\mathrm{kW}}{\mathrm{m}^{2}} \cdot 8,000 \,\mathrm{h} \cdot \frac{\$0.16}{\mathrm{kWh}}$$

$$+ 286.245 \,\mathrm{m}^{2} \cdot 0.0610391 \frac{\mathrm{kW}}{\mathrm{m}^{2}} \cdot 8,000 \,\mathrm{h} \cdot \frac{\$0.16}{\mathrm{kWh}}$$

$$= \$93,570$$

$$= \$93,570$$

$$= \$93,570$$

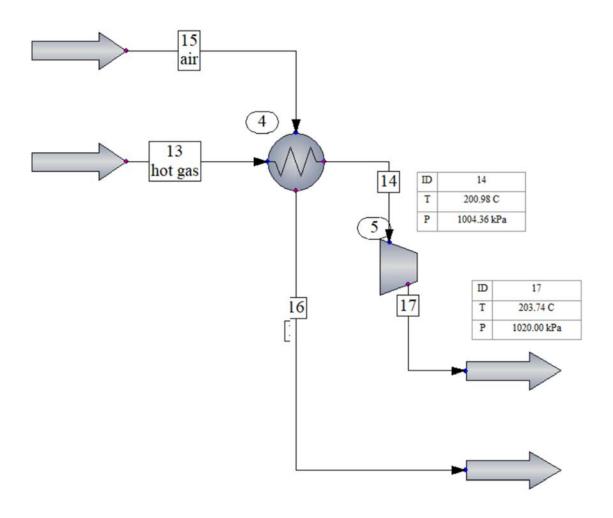
$$= \$93,570$$

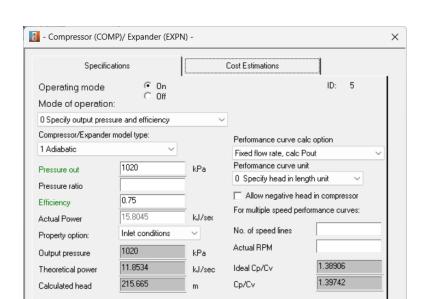
(1) Determine the total purchased cost in February 2024 of a compressor designed to increase the tube-side hot gasses from the outlet pressure at the exchanger back to 1020 kPa. The compressor is centrifugal with an open drip-proof 1200 RPM motor and a variable speed drive coupling.

(2) If the air temperature must be within 0.5 degrees of 200 °C at the outlet of the compressor, how does the addition of the compressor impact the design of the heat exchanger? (No simulation, explain only.)

#### **SOLUTION:**

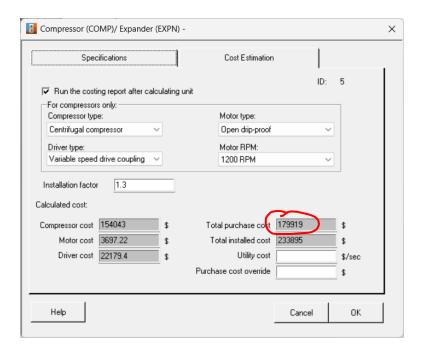
The CHEMCAD flowsheet is shown below with temperatures and pressures indicated in the TP boxes. The unit op cost specifications and cost estimation windows follow on the next page. The total purchase cost is \$179,919 in February 2024.





Cancel

Help



A screenshot of the pump cost estimation window is shown above. The purchased cost is obtained <u>after</u> cadets check the button "Run the costing report after calculating the unit." Cadets must also update the pump/compressor cost index to 1505.0 for February 2024.

- (1) The purchased cost in February 2024 is \$179,919 and is circled in red. //ANS
- (2) The compressor heats the hot gas ~2 degrees, so more heat must be removed from the hot gas to compensate. Either the area of the heat exchanger or the flow rate in stream 15 could be increased. //ANS

CADET SECTIONTIME OF DEPARTURE	
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#### DEPARTMENT OF CHEMISTRY & LIFE SCIENCE

CH402, AY2023-2024 WRITTEN PARTIAL REVIEW I 55 Minutes, D-Hour 9 February 2024

SCOPE: CHAPTERS: 12, 14

TEXT: Peters, Timmerhaus & West

References Permitted: Open note and open book; Mathematica; Excel; CHEMCAD.

#### **INSTRUCTIONS**

- 1. You will have 55 minutes for the exam.
- 2. Do not mark this exam or open it until "begin work" is given.
- 3. Solve the problems in the space provided. Show all work to receive full credit.
- 4. There are 3 problems on 4 pages in this exam (not including the cover page).
- 5. Write your name on the top of each sheet.
- 6. Save all work and save it frequently.
- 7. Final CHEMCAD file must be saved in Canvas to receive partial credit.

(TOTAL WEIGHT: 200 POINTS)

#### DO NOT WRITE IN THIS SPACE

PROBLEM	VALUE	CUT
A	80	
В	60	
С	60	
TOTAL CUT		
GRADE	200	

#### THE FOLLOWING INFORMATION IS REQUIRED FOR QUESTIONS A, B, & C

Air used in a catalytic oxidation process is to be heated from 15 to 270 °C before entering the process. The heating is accomplished with the use of product gases, which cool from 480 to 20 °C.

A one-pass shell-and-tube TEMA type AEL exchanger with single-segmental baffles has been proposed. The tubes are type 316 stainless-steel, with type A-240-316 stainless steel used for the tube sheet, shell, channel material, and baffles.

The properties of the hot gases can be considered identical to those of air.

Both streams enter the exchanger at 1020 kPa.

The hot gasses are sent through the tubes at a flow rate of 5.6 kg/s.

The air is sent through the shell.

The shell-side and tube-side fouling factors are zero.

The inside and outside diameters for the tubes are 0.0191 and 0.0254 m, respectively. The tubes will be arranged in line with a square pitch of 0.0381 m with fixed tube sheets. The tubesheet thickness is equal to the outside diameter of the tubes.

Baffles are single segmental.

The exchanger operates for 8000 h/yr.

Installation costs are 15% of purchased cost, and annual fixed charges including maintenance are 20% of the installed cost.

The energy cost is \$0.16/kWh.

No utility fluid is used so the annual cost of utility fluid may be ignored.

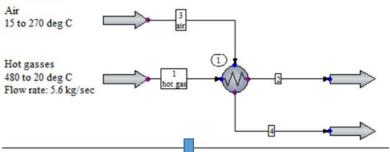
Design Constraints: The upper limit on the tube length is 20 m and the upper limit on the shell diameter is 6 m.

Use CHEMCAD to perform a 3-step *design* analysis on the proposed heat exchanger and answer the following questions: (1) Determine the number and length of tubes, the inside diameter of the shell, and the required area of the exchanger. (2) Determine the largest resistance to heat transfer in the exchanger. (3) Determine the February 2024 total installed cost of the heat exchanger.

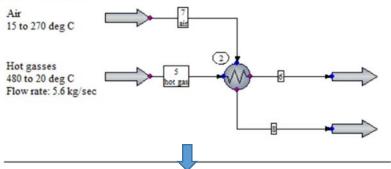
### **SOLUTION:**

Blue arrows indicate the 1-2-3 heat exchanger design process.

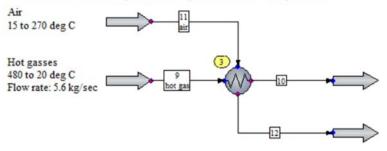
Step 1 (CH485 Level 1). Basic heat exchanger design. Specify or calculate steam flow rates, temperatures, and heat duties. Utility option in exchanger used to calculate flow rate of stream 3.



Step 2 (CH485 Level 2). Detailed internal resign. Calculation performed in "design" mode using "Sizing." Enter specs. CHEMCAD optimizes number and length of tubes, baffle spacings and cuts, and calculates pressure drops, area, and heat transfer coefficient from resistance model.



Step 3 (CH485 Level 3). Simulation. Calculation performed in "shell-and-tube simulation mode 1." Uses shell- and tube-side pressure drops, area, and heat transfer coefficient to calculate outlet stream temperatures and pressures and exchanger costs.



# TABULATED ANALYSIS - DESIGN (LEVEL 2)

Overall Data:						
Area Total	m2	663.50	% Excess			1.41
Area Required	m2	643.73		W/m2-K		75.89
=				•		
Area Effective	m2	652.82	U Service	•		74.83
Area Per Shell	m2	652.82	-			2.68E+06
Weight LMTD C	54.85	LMTD CORR Fa	ctor 1.000	O CORR LMT	D C	54.85
Shell-side Data: Crossflow Vel. 1	m/sec 5.	2E+00 EndZo	ne Vel. 3.5	E+00 Window	Vel.	. 3.8E+00
Film Coef. W/m	2-K	228.11	Reynolds N	Ο.		50223
Allow Press. Dro	op kPa	34.47	Calc. Pres	s. Drop	kPa	42.22
Inlet Nozzle Si	_	0.25		p/In Nozzle	kPa	3.61
Outlet Nozzle S:		0.20		p/Out Nozzle		
Oddice NOZZIE B.	120 111	0.20			C	142.50
-10 1 /	0	2005 51	Mean Tempe			
Rho V2 IN kg/m	-sec2	3297.71	Press. Dro	p (Dirty)	kPa	71.77
Stream Analysis: SA Factors: A Ideal Cross Vel		в 81.71 6.39 I	C 1.97 deal Window	E 5.55 Vel. m/sec	F	0.00 4.57
Tube-side Data:						
Film Coef. W/m	2-K	155.23	Reynolds N	ο.		22002
Allow Press. Dro	op kPa	34.47	_		kPa	16.70
Inlet Nozzle Si		0.20		p/In Nozzle		3.04
Outlet Nozzle S		0.13		p/Out Nozzle		3.21
Interm. Nozzle	Size m	0.00	Mean Tempe		С	250.00
Velocity	m/se	c 4.29	Mean Metal	Temperature	С	177.95
<b>6</b> 1 <b>5</b>						
Clearance Data:						
Baffle to shell	m	0.0063	Bundle dia	meter m		1.1250
Tube hole clear	. m	0.0008	Outer tube	clear. m		0.0180
Bundle top space	e m	0.0000	In-line pa	ss clear. m		0.0000
Bundle btm space		0.0000	Pass clear			0.0159
Baffle Parameters	s:			0.6		
Number of Baffle	28			26		
Baffle Type			ngle Segmen	tal		
Baffle space de:	f.	Ed	ge-Edge			
Inlet Space		m	0.	710		
Center Space		m	0.	471		
Outlet Space		m		710		
Baffle Cut, % D:	iamotor	•••		.000		
	Tailleter					
Baffle Overlap		m		000		
Baffle Cut Dire			Horizon	tal		
Number of Int. 1	Baffles			0		
Baffle Thickness	S	m	0.	006		
Shell:						
Shell O.D.	m	1.17	Orientat			H
Shell I.D.	m	1.14	Shell in	Series		1
Bonnet I.D.	m	1.14	Shell in	Parallel		1
Type		AEL	Max. Heat	Flux Btu/ft	2-hr	0.00
Imping. Plate	Impina	ement Plate	Sealing	•		5
1 3	1 -2	<del>-</del>		-		•

Tubes:

Number		620	Tube Type		Bare
<mark>Length                                    </mark>	m	13.41	Free Int. Fl A	rea m2	0.00
Tube O.D.	m	0.025	Fin Efficiency	•	0.000
Tube I.D.	m	0.019	Tube Pattern		SQUAR
Tube Wall Thk.	m	0.003	Tube Pitch	m	0.038
No. Tube Pass		1			
Inner Roughnes	s m	0.0000016			
Number of tube	sheets	2	Tubesheet thic	kness, m	0.025
Resistances:					
Shell-side Fil			m2-K/W	0.00438	
Shell-side Fou	ling		m2-K/W	0.00000	
Tube Wall			m2-K/W	0.00023	
Tube-side Foul			m2-K/W	0.00000	
Tube-side Film			m2-K/W	0.00644	
Reference Fact	or (Total	outside area/:	inside area base	d on tube ID)	1.330
D D D.		•			
Pressure Drop D Tube Side	ISCIIDUCIO	11.	Shell Side		
Inlet Nozzle	kPa	3.0427	Inlet Nozzle	kPa	3.6082
Tube Entrance	kPa kPa	0.0433	Impingement	kPa kPa	2.1435
Tube Entrance Tube	kPa	1.2097	Bundle	kPa	23.3191
Tube Tube Exit	kPa kPa	0.0409	Outlet Nozzle	kPa kPa	3.1424
End	kPa kPa	0.0409	Total Fric.	kPa kPa	30.0696
Outlet Nozzle	kPa	3.2101	Total Grav.	kPa	-0.1168
Total Fric.					12.2643
Total Fric.	kPa	7.5467 0.0773	Total Mome.	kPa kPa	42.2171
Total Mome.	kPa kPa	9.0803	Total	rrd	44.41/1
Total Mome. Total	кра kPa	9.0803 16.7044			

The completed CHEMCAD flowsheet is shown on page 2 and the detailed tabulated results on pages 3-4, with answers to questions (1) and (2) are highlighted in yellow.

Number of tubes: 620 //ANS

Length of the tubes: 13.41 m //ANS

Inside diameter of the shell: 1.14 m //ANS

Required area of the exchanger: 643.73 m<sup>2</sup> //ANS

Largest resistance to heat transfer in the exchanger: 0.00644 m<sup>2</sup>K/W Tube-side //ANS

The installed cost is determined by activating the "costing report" in the Cost Estimations tab in the Level 3 heat exchanger.

February 2024 total installed cost: \$645,337 //ANS

# Cadet: APPROVED SOLUTION

Problem: Weight: 8

Use equation 14-91 to determine the total annual operating costs for the shell-and-tube exchanger as designed in Problem A assuming utility costs are zero. Do not optimize.

#### **SOLUTION:**

Equation 14-91 is found in the PTW textbook on page 739, and the stream properties are shown in the stream box from CHEMCAD:

$$C_{T} = A_{0} \cdot K_{F} \cdot C_{A_{0}} + m_{u} \cdot H_{y} \cdot C_{u} + A_{0} \cdot E_{i} \cdot H_{y} \cdot C_{i} + A_{0} \cdot E_{0} \cdot H_{y} \cdot C_{0}$$

C<sub>T</sub> Total annual costs, dollars/yr

A<sub>0</sub> Outside tube area, m<sup>2</sup>

K<sub>F</sub> Annual fixed charges factor (maintenance, etc) as a fraction of installed cost, dimensionless

C<sub>A<sub>0</sub></sub> Installed cost of the heat exchanger per unit outside tube area, dollars/m<sup>2</sup>

m<sub>u</sub> Mass flow rate of utility fluid, kg/hr

H<sub>v</sub> Hours of operation per year

C<sub>u</sub> Cost of utility fluid, dollars/kg

 $E_i$  Power loss due to fluid flow inside heat exchanger tubes per unit outside tube area,  $N \cdot m/s$  per  $m^2$ 

 $\boldsymbol{C}_{_{i}}$  Cost of supplying 1  $N\cdot m$  to pump fluid through the inside of the tubes, dollars/N  $\cdot$  m

 ${\bf E}_0$  Power loss experienced on the shell side per unit outside tube area,  ${\bf N}\cdot{\bf m}/{\bf s}$  per  ${\bf m}^2$ 

 $\boldsymbol{C}_0$  Cost of supplying 1 N  $\cdot$  m to pump fluid through the shell side, dollars/N  $\cdot$  m

Stream No.	9	10	11	12
Name	hot gas		air	
Overall				
Temp C	480.0000	19.7409	15.0000	270.1087
Pres kPa	1020.0000	1002.9738	1020.0000	976.5488
Mass flow kg/sec	5.6000	5.6000	10.2759	10.2759
Actual dens kg/m3	4.6984	11.9621	12.3721	6.2360

Tube-side pressure drop = 1020 - 1002.9738 = 17.0262 kPa = 17,026.2 PaTube-side average density =  $(4.6984 + 11.9621)/2 = 8.33025 \text{ kg/m}^3$ 

Tube-side mass flow rate = 5.6000 kg/s

Shell-side pressure drop = 1020 - 976.5488 = 43.4512 kPa = 43,451.2 PaShell-side average density =  $(12.3721 + 6.2360)/2 = 9.30405 \text{ kg/m}^3$ Tube-side mass flow rate = 10.2759 kg/s

$$A_0 = \pi \cdot D_0 \cdot L \cdot N_P = \pi \cdot 0.0254 \,\text{m} \cdot 13.41 \,\text{m} \cdot 620 = 663.444 \,\text{m}^2$$

$$C_{A_0} = $645,337 / 663.444 \text{ m}^2 = $972.708 / \text{ m}^2$$

$$K_{\rm F} = 0.2$$

$$C_{ij} = 0$$

$$H_v = 8,000 \, hrs$$

$$C_i = $0.16 / kWh$$

$$E_{i} = \frac{17,026.2 \frac{N}{m^{2}} \cdot 5.6000 \frac{kg}{s} \cdot \frac{1 \, m^{3}}{8.33025 \, kg}}{663.444 \, m^{2}} = 17.2522 \, \frac{W}{m^{2}} = 0.0172522 \, \frac{kW}{m^{2}}$$

$$E_0 = \frac{43,451.2 \frac{N}{m^2} \cdot 10.2759 \frac{kg}{s} \cdot \frac{1 \, m^3}{9.30405 \, kg}}{663.444 \, m^2} = 72.3345 \, \frac{W}{m^2} = 0.0723345 \, \frac{kW}{m^2}$$

$$C_{T} = 663.444 \,\mathrm{m}^{2} \cdot 0.2 \cdot \frac{\$972.708}{\mathrm{m}^{2}}$$

$$+ 663.444 \,\mathrm{m}^{2} \cdot 0.0172522 \,\frac{\mathrm{kW}}{\mathrm{m}^{2}} \cdot 8,000 \,\mathrm{h} \cdot \frac{\$0.16}{\mathrm{kWh}}$$

$$+ 663.444 \,\mathrm{m}^{2} \cdot 0.0723345 \,\frac{\mathrm{kW}}{\mathrm{m}^{2}} \cdot 8,000 \,\mathrm{h} \cdot \frac{\$0.16}{\mathrm{kWh}}$$

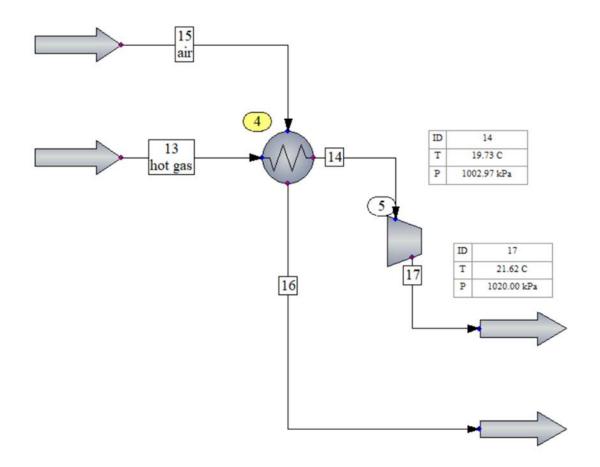
$$= \$205,145 \,\frac{}{\mathrm{m}^{2}} \,\mathrm{ans}$$

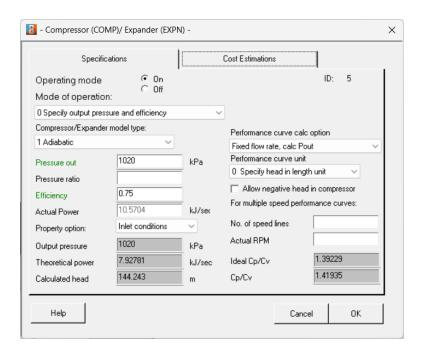
(1) Determine the total purchased cost of a compressor designed to increase the tube-side hot gasses from the outlet pressure at the exchanger back to 1020 kPa. The compressor is centrifugal with an explosion-proof 1800 RPM motor and a chain-drive coupling. Determine the cost must be in February 2024.

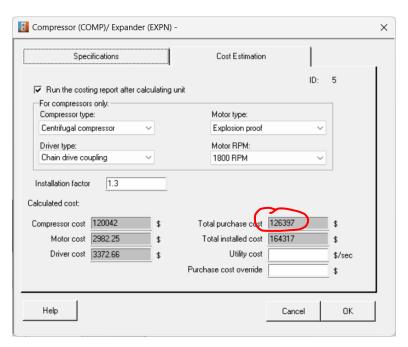
(2) If the air temperature must be within 0.5 degrees of 20 °C at the outlet of the compressor, how does the addition of the compressor impact the design of the heat exchanger? (No simulation, explain only.)

#### **SOLUTION:**

The CHEMCAD flowsheet is shown below with temperatures and pressures indicated in the TP boxes. The unit op cost specifications and cost estimation windows follow on the next page. The total purchase cost is \$126,397 in February 2024.







A screenshot of the pump cost estimation window is shown above. The purchased cost is obtained after cadets check the button "Run the costing report after calculating the unit." Cadets must also update the pump/compressor cost index to 1505.0 for February 2024.

- (1) The purchased cost in February 2024 is \$126,397 and is circled in red. //ANS
- (2) The compressor heats the hot gas ~2 degrees, so more heat must be removed from the hot gas to compensate. Either the area of the heat exchanger or the flow rate in stream 15 could be increased. //ANS