APPROVED SOLUTION

CADET ____________________ SECTION ______TIME OF DEPARTURE ________

DEPARTMENT OF CHEMISTRY & LIFE SCIENCE

CH402, AY2022-2023
WRITTEN PARTIAL REVIEW I
55 Minutes, C-Hour
16 February 2023

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 SharePoint to receive partial credit.

(TOTAL WEIGHT: 200 POINTS)

DO NOT WRITE IN THIS SPACE

PROBLEM	VALUE	CUT
A	80	
B	60	
C	60	
TOTAL CUT		
GRADE	200	

Cadet: APPROVED SOLUTION

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 °C before entering the process. The heating is accomplished with the use of product gases, which cool from 480 to 200 °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 and the air is sent through the shell.

The flow rate for the air (shell-side flow rate) has been set at 5.6 kg/s.

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.

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

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 10 m.

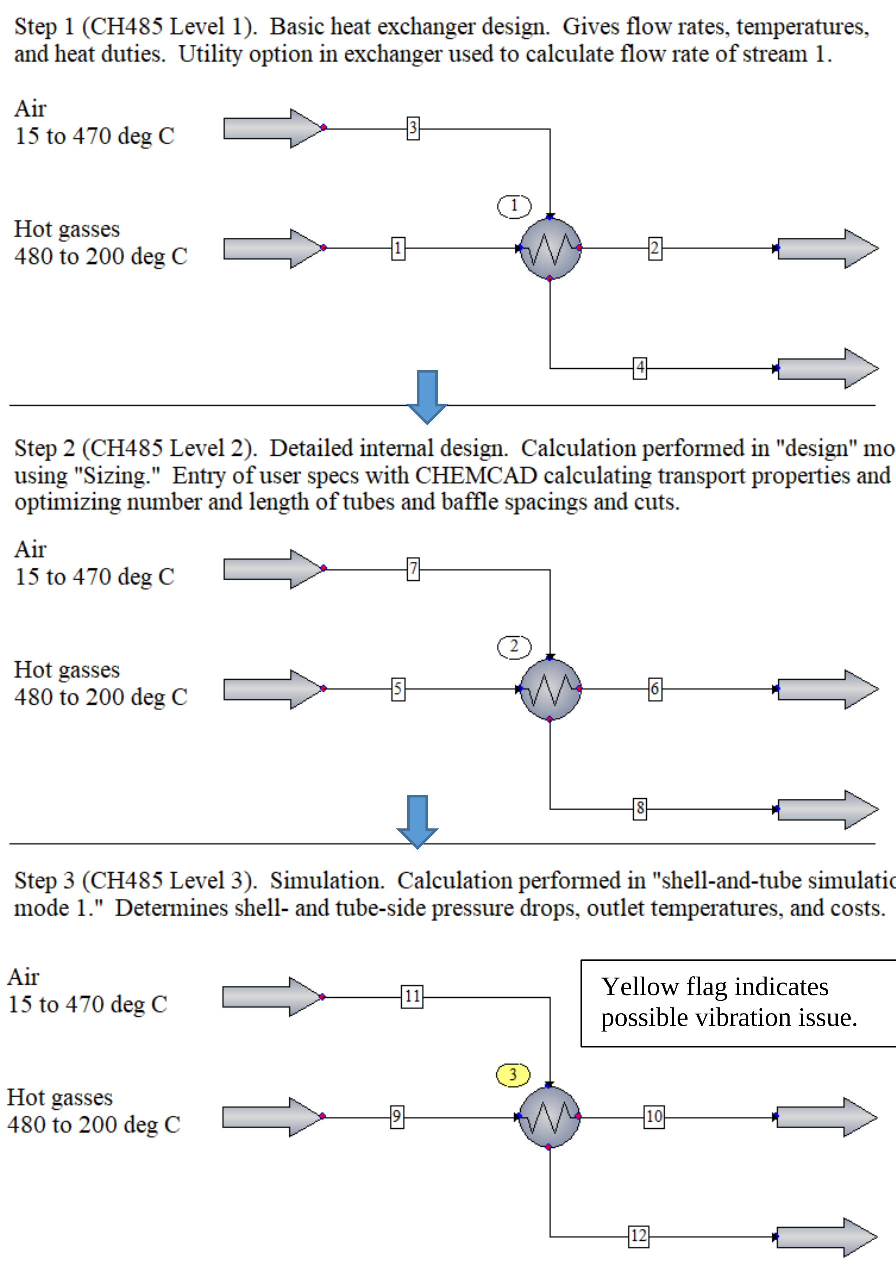
Cadet: **APPROVED SOLUTION**

Problem:	Weight:
A	80

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. (2) Determine the February 2023 total installed cost of the heat exchanger.

SOLUTION:

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



Yellow flag indicates possible vibration issue.

TABULATED ANALYSIS - DESIGN (LEVEL 2)

```
Overall Data:
 Area Total          m2       452.39  % Excess                        0.06
 Area Required       m2       442.94  U Calc.    W/m2-K              97.14
 Area Effective      m2       443.20  U Service  W/m2-K              97.08
 Area Per Shell      m2       443.20  Heat Duty  J/sec            2.67E+06
 Weight LMTD C    62.04    LMTD CORR Factor  1.0000    CORR LMTD C    62.04

Shell-side Data:
 Crossflow Vel. m/sec  5.1E+00  EndZone Vel. 3.4E+00  Window Vel. 3.7E+00
 Film Coef.  W/m2-K           217.18  Reynolds No.                   34741
 Allow Press. Drop   kPa       34.47  Calc. Press. Drop       kPa    47.47
 Inlet Nozzle Size   m          0.20  Press. Drop/In Nozzle   kPa     2.68
 Outlet Nozzle Size  m          0.15  Press. Drop/Out Nozzle  kPa     4.06
                                      Mean Temperature        C     241.94
 Rho V2 IN  kg/m-sec2        2445.46  Press. Drop (Dirty)     kPa    80.69

Stream Analysis:
 SA Factors:    A 12.54     B 79.75     C  1.90     E  5.82     F  0.00
 Ideal Cross Vel.  m/sec       6.39  Ideal Window Vel. m/sec      4.49

Tube-side Data:
 Film Coef.  W/m2-K           242.41  Reynolds No.                   41497
 Allow Press. Drop   kPa       34.47  Calc. Press. Drop       kPa    15.03
 Inlet Nozzle Size   m          0.25  Press. Drop/In Nozzle   kPa     2.94
 Outlet Nozzle Size  m          0.20  Press. Drop/Out Nozzle  kPa     2.13
 Interm. Nozzle Size m          0.00  Mean Temperature        C     340.38
 Velocity            m/sec     11.59  Mean Metal Temperature  C     285.89

Clearance Data:
 Baffle to shell   m          0.0048  Bundle diameter     m         0.9756
 Tube hole clear.  m          0.0008  Outer tube clear.   m         0.0150
 Bundle top space  m          0.0000  In-line pass clear. m         0.0000
 Bundle btm space  m          0.0000  Pass clearance      m         0.0159

Baffle Parameters:
 Number of Baffles                                   31
 Baffle Type                           Single Segmental
 Baffle space def.                     Edge-Edge
 Inlet Space              m                       0.546
 Center Space             m                       0.362
 Outlet Space             m                       0.546
 Baffle Cut, % Diameter                          21.000
 Baffle Overlap           m                       0.038
 Baffle Cut Direction                        Horizontal
 Number of Int. Baffles                               0
 Baffle Thickness         m                       0.006

Shell:
 Shell O.D.       m             1.02    Orientation                      H
 Shell I.D.       m             0.99    Shell in Series                  1
 Bonnet I.D.      m             0.99    Shell in Parallel                1
 Type                           AEL   Max. Heat Flux Btu/ft2-hr     0.00
 Imping. Plate     Impingement Plate    Sealing Strip                    5

Tubes:
```

Number		465	Tube Type		Bare
Length	m	12.19	Free Int. Fl Area	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 Roughness	m	0.0000016			
Number of tubesheets		2	Tubesheet thickness, m		0.025

Resistances:

Shell-side Film	m2-K/W	0.00460
Shell-side Fouling	m2-K/W	0.00000
Tube Wall	m2-K/W	0.00020
Tube-side Fouling	m2-K/W	0.00000
Tube-side Film	m2-K/W	0.00413
Reference Factor (Total outside area/inside area based on tube ID)		1.330

Pressure Drop Distribution:

Tube Side			Shell Side		
Inlet Nozzle	kPa	2.9362	Inlet Nozzle	kPa	2.6835
Tube Entrance	kPa	0.1836	Impingement	kPa	1.5896
Tube	kPa	5.5017	Bundle	kPa	23.3226
Tube Exit	kPa	0.3093	Outlet Nozzle	kPa	4.0553
End	kPa	0.0000	Total Fric.	kPa	30.0614
Outlet Nozzle	kPa	2.1257	Total Grav.	kPa	-0.0753
Total Fric.	kPa	11.0565	Total Mome.	kPa	17.4793
Total Grav.	kPa	0.0717	Total	kPa	47.4654
Total Mome.	kPa	3.9018			
Total	kPa	15.0300			

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: 465 //ANS
Length of the tubes: 12.19 m //ANS
Inside diameter of the shell: 0.99 m //ANS
Required area of the exchanger: 442.94 m^2 //ANS
Largest resistance to heat transfer in the exchanger: 0.00460 m^2K/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 2023 total installed cost: $452,477 //ANS

Cadet: **APPROVED SOLUTION**

Problem: B   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 stream box from CHEMCAD:

$$C_T = A_0 \cdot K_F \cdot C_{A_0} + \cancelto{0}{m_u \cdot H_y \cdot C_u} + A_0 \cdot E_i \cdot H_y \cdot C_i + A_0 \cdot E_0 \cdot H_y \cdot C_0$$

C_T Total annual costs, dollars/yr

A_0 Outside tube area, m^2
K_F Annual fixed charges factor (maintenance, etc) as a fraction of installed cost, dimensionless
C_{A_0} Installed cost of the heat exchanger per unit outside tube area, dollars/m^2

m_u Mass flow rate of utility fluid, kg/hr
H_y Hours of operation per year
C_u 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
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 $N \cdot m$ to pump fluid through the shell side, dollars/$N \cdot m$

Stream No.	9	10	11	12
Name				
- - Overall - -				
Temp C	480.0000	200.7530	15.0000	468.8719
Pres kPa	1020.0000	1005.0000	1020.0000	972.5267
Mass flow kg/sec	8.9728	8.9728	5.6000	5.6000
Actual dens kg/m3	4.6808	7.3275	12.3104	4.5305

Tube-side pressure drop = 1020 – 1005.000 = 15.000 kPa = 15,000.0 Pa
Tube-side average density = (4.6808 + 7.3275)/2 = 6.00415 kg/m^3
Tube-side mass flow rate = 8.9728 kg/s

Shell-side pressure drop = 1020 – 972.5267 = 47.4733 kPa = 47,473.3 Pa
Shell-side average density = (12.3104 + 4.5305)/2 = 8.42045 kg/m^3

$$A_0 = \pi \cdot D_O \cdot L \cdot N_P = \pi \cdot 0.0254\,\text{m} \cdot 12.19\,\text{m} \cdot 465 = 452.314\,\text{m}^2$$

$$C_{A_0} = \$452,477 / 452.314\,\text{m}^2 = \$1,000.360 / \text{m}^2$$

$$K_F = 0.2$$

$$C_u = 0$$

$$H_y = 8,000\,\text{hrs}$$

$$C_i = \$0.16 / \text{kWh}$$

$$E_i = \frac{15,000.0\dfrac{\text{N}}{\text{m}^2} \cdot 8.9728\dfrac{\text{kg}}{\text{s}} \cdot \dfrac{1\,\text{m}^3}{6.00415\text{kg}}}{452.314\,\text{m}^2} = 49.560\,\frac{\text{W}}{\text{m}^2} = 0.049560\,\frac{\text{kW}}{\text{m}^2}$$

$$E_0 = \frac{47,473.3\dfrac{\text{N}}{\text{m}^2} \cdot 5.600\dfrac{\text{kg}}{\text{s}} \cdot \dfrac{1\,\text{m}^3}{8.42045\,\text{kg}}}{452.314\,\text{m}^2} = 69.801\,\frac{\text{W}}{\text{m}^2} = 0.069801\,\frac{\text{kW}}{\text{m}^2}$$

$$C_T = 452.314\,\text{m}^2 \cdot 0.2 \cdot \frac{\$1,000.360}{\text{m}^2}$$
$$+ 452.314\,\text{m}^2 \cdot 0.049560\frac{\text{kW}}{\text{m}^2} \cdot 8,000\,\text{h} \cdot \frac{\$0.16}{\text{kWh}}$$
$$+ 452.314\,\text{m}^2 \cdot 0.049560\frac{\text{kW}}{\text{m}^2} \cdot 8,000\,\text{h} \cdot \frac{\$0.16}{\text{kWh}}$$

$$= \underline{\underline{\$147,882}}_{\text{ans}}$$

Cadet: APPROVED SOLUTION

Problem: C   Weight: 60

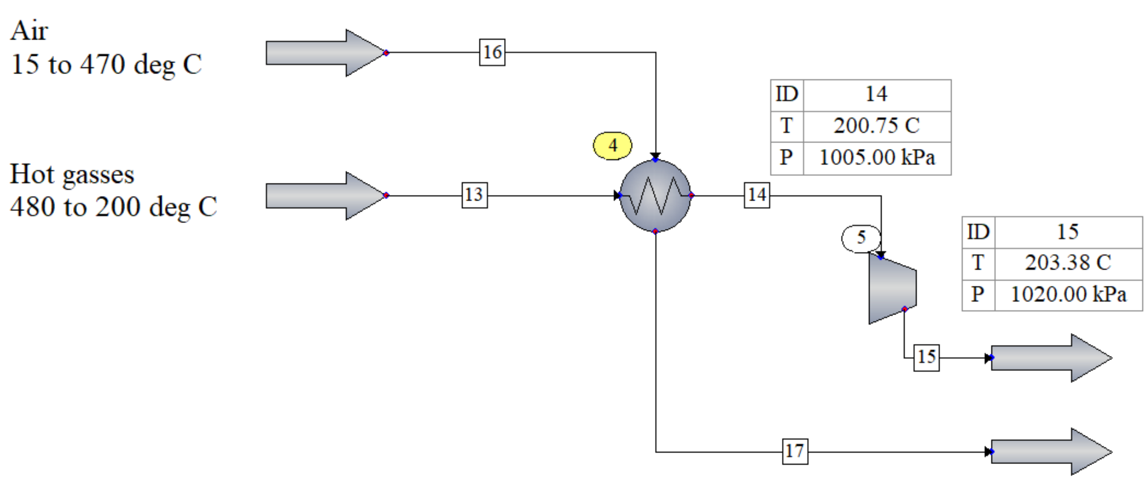
(1) Determine the total purchased cost of a compressor designed to increase the tube-side hot gasses from the outlet pressure at the exchanger back to 1020 kPa. The compressor is centrifugal with an open drip-proof 1200 RPM motor and a variable sped drive coupling. Determine the cost must be in February 2023.

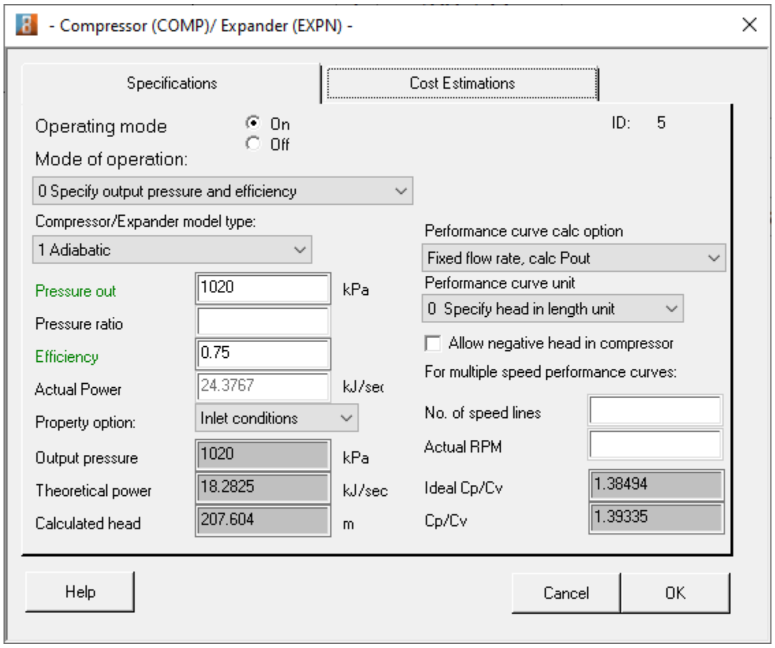
(2) If the air temperature must be within 0.5 degrees of 470 ºC at the outlet of the compressor, how does the addition of the compressor impact the design of the heat exchanger? (No simulation, explain only.)

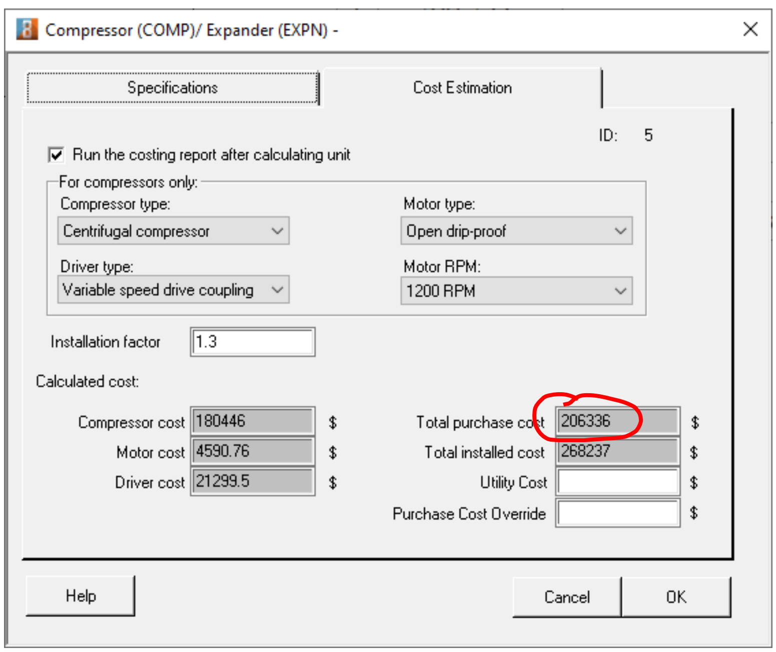
Should be: If the air temperature must be within 0.5 degrees of 200 ºC at the outlet of the compressor, how does the addition of the compressor impact the design of the heat exchanger? (No simulation, explain only.)

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 $88,939 in February 2023.







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 1347.6 for February 2023.

(1) The purchased cost in February 2023 is $206,336 and is circled in red. **//ANS**

(2) The question was worded incorrectly. It should have been: "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.)"

The answer for the intended question is that the compressor heats the gasses ~2.6 degrees so the area of the heat exchanger can be reduced, saving money on the cost of the heat exchanger. **//ANS**

As a result of the instructor error, cadets receive credit for any reasonable answer.

APPROVED SOLUTION

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DEPARTMENT OF CHEMISTRY & LIFE SCIENCE

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WRITTEN PARTIAL REVIEW I
55 Minutes, D-Hour
16 February 2023

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.
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4. There are 3 problems on 4 pages in this exam (not including the cover page).
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(TOTAL WEIGHT: 200 POINTS)

DO NOT WRITE IN THIS SPACE

PROBLEM	VALUE	CUT
A	80	
B	60	
C	60	
TOTAL CUT		
GRADE	200	

Cadet: APPROVED SOLUTION

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 and the air is sent through the shell.

The flow rate for the air (shell-side flow rate) has been set at 5.6 kg/s.

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.

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

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 10 m.

Cadet: **APPROVED SOLUTION**

<u>Problem:</u> A

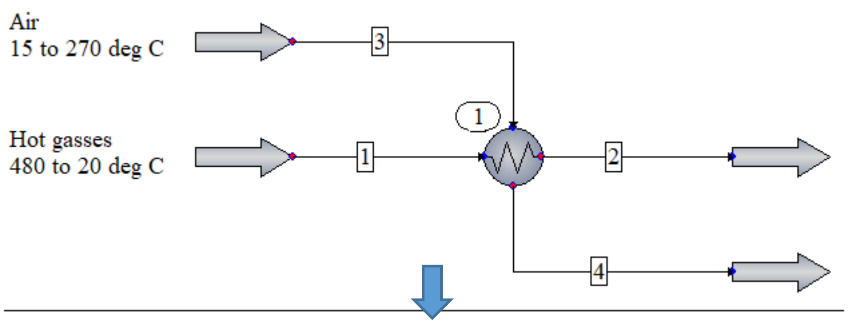
<u>Weight:</u> 80

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. (2) Determine the February 2023 total installed cost of the heat exchanger.

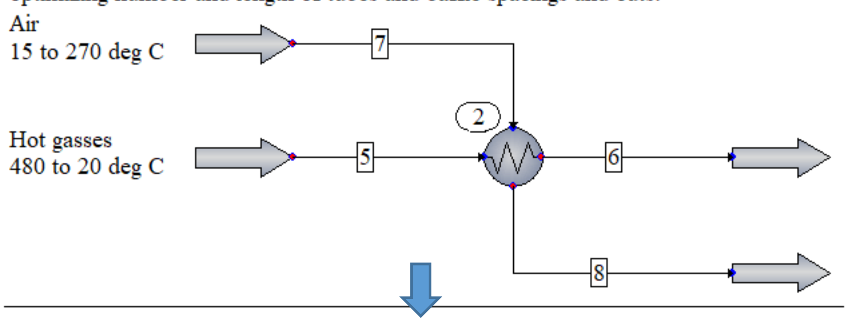
SOLUTION:

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

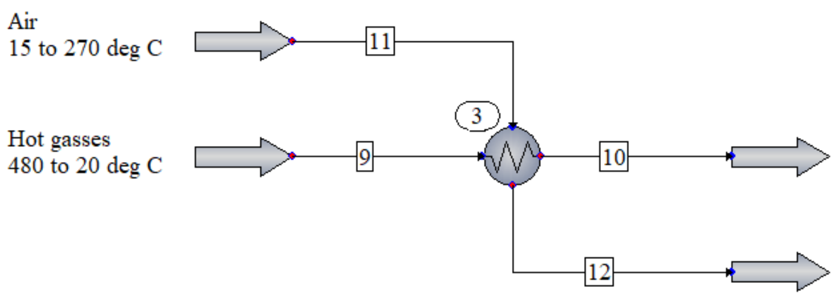
Step 1 (CH485 Level 1). Basic heat exchanger design. Gives flow rates, temperatures, and heat duties. Utility option in exchanger used to calculate flow rate of stream 1.



Step 2 (CH485 Level 2). Detailed internal design. Calculation performed in "design" mode using "Sizing." Entry of user specs with CHEMCAD calculating transport properties and optimizing number and length of tubes and baffle spacings and cuts.



Step 3 (CH485 Level 3). Simulation. Calculation performed in "shell-and-tube simulation mode 1." Determines shell- and tube-side pressure drops, outlet temperatures, and costs.



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                 TABULATED ANALYSIS - DESIGN (LEVEL 2)
                 -------------------------------------
Overall Data:
 Area Total          m2       578.96  % Excess                    2.48
 Area Required       m2       552.36  U Calc.    W/m2-K          48.73
 Area Effective      m2       566.08  U Service  W/m2-K          47.55
 Area Per Shell      m2       566.08  Heat Duty  J/sec        1.48E+06
 Weight LMTD C   54.85   LMTD CORR Factor  1.0000   CORR LMTD C   54.85

Shell-side Data:
 Crossflow Vel. m/sec  4.3E+00  EndZone Vel. 2.8E+00  Window Vel. 2.5E+00
 Film Coef.  W/m2-K           196.81  Reynolds No.                 41132
 Allow Press. Drop   kPa       34.47  Calc. Press. Drop       kPa  41.61
 Inlet Nozzle Size   m          0.20  Press. Drop/In Nozzle   kPa   2.68
 Outlet Nozzle Size  m          0.15  Press. Drop/Out Nozzle kPa   2.82
                                      Mean Temperature        C   142.50
 Rho V2 IN  kg/m-sec2        2445.46  Press. Drop (Dirty)     kPa  70.73

Stream Analysis:
 SA Factors:    A 14.72     B 77.27     C  1.69     E  6.33     F  0.00
 Ideal Cross Vel.  m/sec      5.55  Ideal Window Vel. m/sec      3.21

Tube-side Data:
 Film Coef.  W/m2-K            87.42  Reynolds No.                 13662
 Allow Press. Drop   kPa       34.47  Calc. Press. Drop       kPa  20.56
 Inlet Nozzle Size   m          0.15  Press. Drop/In Nozzle   kPa   2.78
 Outlet Nozzle Size  m          0.09  Press. Drop/Out Nozzle kPa   3.95
 Interm. Nozzle Size m          0.00  Mean Temperature        C   250.00
 Velocity            m/sec      2.69  Mean Metal Temperature C    168.37

Clearance Data:
 Baffle to shell   m          0.0048  Bundle diameter     m       1.0518
 Tube hole clear.  m          0.0008  Outer tube clear.   m       0.0150
 Bundle top space  m          0.0000  In-line pass clear. m       0.0000
 Bundle btm space  m          0.0000  Pass clearance      m       0.0159

Baffle Parameters:
 Number of Baffles                          39
 Baffle Type                   Single Segmental
 Baffle space def.             Edge-Edge
 Inlet Space              m              0.483
 Center Space             m              0.320
 Outlet Space             m              0.483
 Baffle Cut, % Diameter                 21.000
 Baffle Overlap           m              0.038
 Baffle Cut Direction               Horizontal
 Number of Int. Baffles                      0
 Baffle Thickness         m              0.006

Shell:
 Shell O.D.       m              1.09    Orientation                    H
 Shell I.D.       m              1.07    Shell in Series                1
 Bonnet I.D.      m              1.07    Shell in Parallel              1
 Type                            AEL   Max. Heat Flux Btu/ft2-hr     0.00
 Imping. Plate     Impingement Plate    Sealing Strip                  5

Tubes:
```

Number		541	Tube Type		Bare
Length	m	13.41	Free Int. Fl Area	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 Roughness	m	0.0000016			
Number of tubesheets		2	Tubesheet thickness, m		0.025

Resistances:

Shell-side Film	m2-K/W	0.00508
Shell-side Fouling	m2-K/W	0.00000
Tube Wall	m2-K/W	0.00023
Tube-side Fouling	m2-K/W	0.00000
Tube-side Film	m2-K/W	0.01144
Reference Factor (Total outside area/inside area based on tube ID)		1.330

Pressure Drop Distribution:

Tube Side			Shell Side		
Inlet Nozzle	kPa	2.7814	Inlet Nozzle	kPa	2.6767
Tube Entrance	kPa	0.0170	Impingement	kPa	1.5896
Tube	kPa	0.5322	Bundle	kPa	24.7382
Tube Exit	kPa	0.0160	Outlet Nozzle	kPa	2.8247
End	kPa	0.0000	Total Fric.	kPa	30.2395
Outlet Nozzle	kPa	3.9483	Total Grav.	kPa	-0.1021
Total Fric.	kPa	7.2948	Total Mome.	kPa	11.4696
Total Grav.	kPa	0.0667	Total	kPa	41.6070
Total Mome.	kPa	13.2014			
Total	kPa	20.5629			

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: 541 //ANS
Length of the tubes: 13.41 m //ANS
Inside diameter of the shell: 1.07 m //ANS
Required area of the exchanger: 552.36 m^2 //ANS
Largest resistance to heat transfer in the exchanger: 0.01144 m^2K/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 2023 total installed cost: $588,633 //ANS

Cadet: APPROVED SOLUTION

Problem: B

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 stream box from CHEMCAD:

$$C_T = A_0 \cdot K_F \cdot C_{A_0} + \cancelto{0}{m_u \cdot H_y \cdot C_u} + A_0 \cdot E_i \cdot H_y \cdot C_i + A_0 \cdot E_0 \cdot H_y \cdot C_0$$

C_T Total annual costs, dollars/yr

A_0 Outside tube area, m^2

K_F Annual fixed charges factor (maintenance, etc) as a fraction of installed cost, dimensionless

C_{A_0} Installed cost of the heat exchanger per unit outside tube area, dollars/m^2

m_u Mass flow rate of utility fluid, kg/hr

H_y Hours of operation per year

C_u 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

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 $N \cdot m$ to pump fluid through the shell side, dollars/$N \cdot m$

Stream No.	9	10	11	12
Name	Tube In	Tube Out	Shell In	Shell Out
- - Overall - -				
Temp C	480.0000	19.5527	15.0000	270.2131
Pres kPa	1020.0000	998.9630	1020.0000	977.2355
Mass flow kg/sec	3.0520	3.0520	5.6000	5.6000
Actual dens kg/m3	4.6808	11.8632	12.3104	6.2139

Tube-side pressure drop = 1020 – 998.9630 = 21.0370 kPa = 21,037.0 Pa
Tube-side average density = (4.6808 + 11.8632)/2 = 8.2720 kg/m^3
Tube-side mass flow rate = 3.0520 kg/s

Shell-side pressure drop = 1020 – 977.2355 = 42.7645 kPa = 42,764.5 Pa
Shell-side average density = (12.3104 + 6.2139)/2 = 9.26215 kg/m^3

$$A_0 = \pi \cdot D_O \cdot L \cdot N_P = \pi \cdot 0.0254\,m \cdot 13.41\,m \cdot 541 = 578.908\,m^2$$

$$C_{A_0} = \$588,633 / 578.908\,m^2 = \$1,016.799 / m^2$$

$$K_F = 0.2$$

$$C_u = 0$$

$$H_y = 8,000\,hrs$$

$$C_i = \$0.16 / kWh$$

$$E_i = \frac{21,037.0\frac{N}{m^2} \cdot 3.0520\frac{kg}{s} \cdot \frac{1\,m^3}{8.2720\,kg}}{578.908\,m^2} = 13.408\,\frac{W}{m^2} = 0.013408\,\frac{kW}{m^2}$$

$$E_0 = \frac{42764.5\frac{N}{m^2} \cdot 5.600\frac{kg}{s} \cdot \frac{1\,m^3}{9.26215\,kg}}{578.908\,m^2} = 44.663\,\frac{W}{m^2} = 0.044663\,\frac{kW}{m^2}$$

$$C_T = 578.908\,m^2 \cdot 0.2 \cdot \frac{\$1,016.799}{m^2} + 578.908\,m^2 \cdot 0.013408\frac{kW}{m^2} \cdot 8,000\,h \cdot \frac{\$0.16}{kWh} + 578.908\,m^2 \cdot 0.044663\frac{kW}{m^2} \cdot 8,000\,h \cdot \frac{\$0.16}{kWh}$$

$$= \underline{\underline{\$160,757}}\ \text{ans}$$

Cadet: APPROVED SOLUTION

Problem: C
Weight: 60

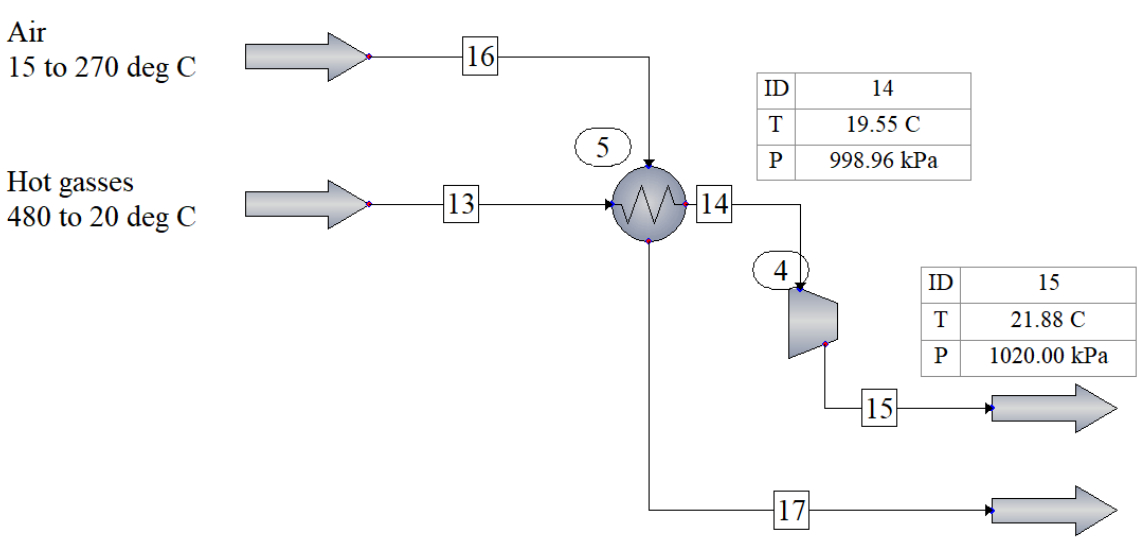
(1) Determine the total purchased cost of a compressor designed to increase the tube-side hot gasses from the outlet pressure at the exchanger back to 1020 kPa. The compressor is centrifugal with an explosion-proof 1800 RPM motor and a chain-drive coupling. Determine the cost must be in February 2023.

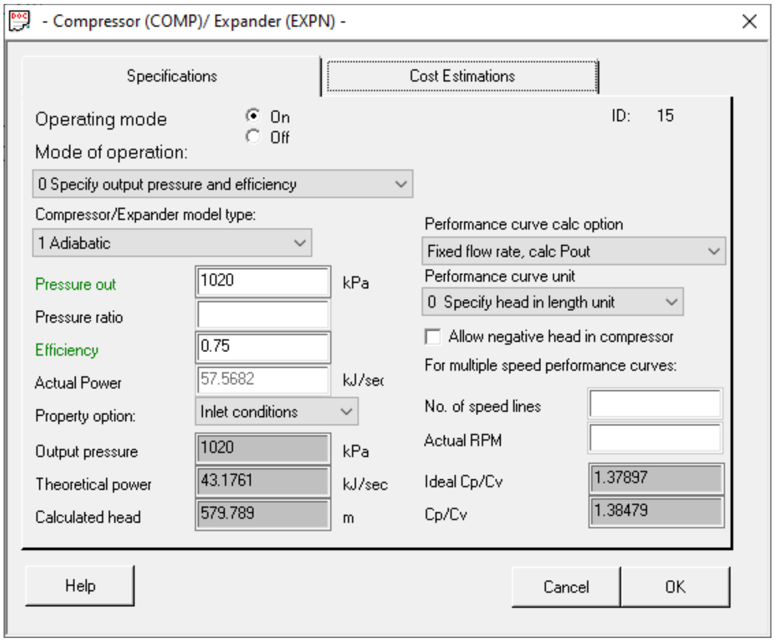
(2) If the air temperature must be within 0.5 degrees of 270 °C at the outlet of the compressor, how does the addition of the compressor impact the design of the heat exchanger? (No simulation, explain only.)

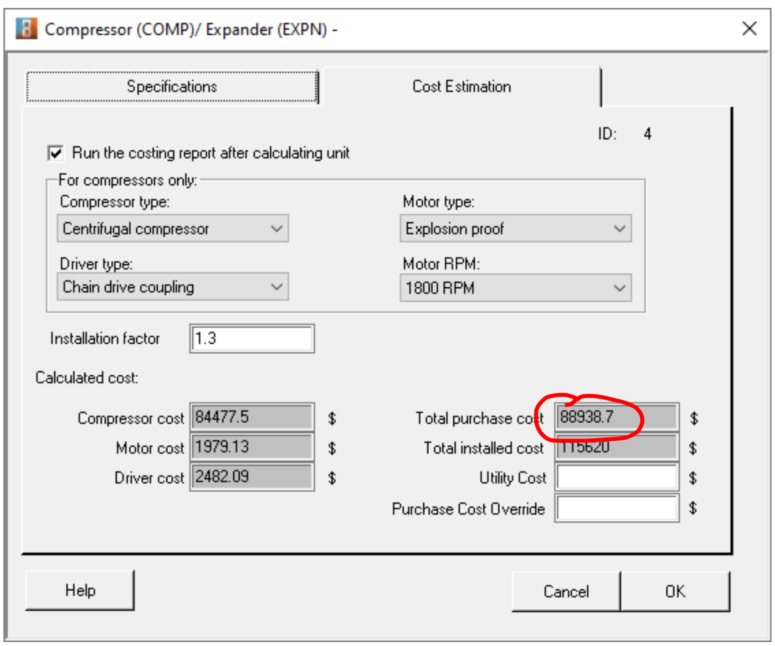
Should be: If the air temperature must be within 0.5 degrees of 20 °C at the outlet of the compressor, how does the addition of the compressor impact the design of the heat exchanger? (No simulation, explain only.)

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 $88,939 in February 2023.







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 1347.6 for February 2023.

(1) The purchased cost in February 2023 is $88,939 and is circled in red. //**ANS**

(2) The question was worded incorrectly. It should have been: "If the air temperature must be within 0.5 degrees of 20 ºC at the outlet of the compressor, how does the addition of the compressor impact the design of the heat exchanger? (No simulation, explain only.)"

The answer for the intended question is that the compressor heats the gasses ~2.3 degrees so the area of the heat exchanger can be reduced, saving money on the cost of the heat exchanger. **//ANS**

As a result of the instructor error, cadets receive credit for any reasonable answer.

APPROVED SOLUTION

CADET ____________________ SECTION ______TIME OF DEPARTURE ________

DEPARTMENT OF CHEMISTRY & LIFE SCIENCE

CH402, AY2022-2023
WRITTEN PARTIAL REVIEW I
55 Minutes, Make-up
21 February 2023

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 work must be saved in SharePoint to receive partial credit.

(TOTAL WEIGHT: 200 POINTS)

DO NOT WRITE IN THIS SPACE

PROBLEM	VALUE	CUT
A	80	
B	60	
C	60	
TOTAL CUT		
GRADE	200	

Cadet: APPROVED SOLUTION

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

Methane used in a catalytic gas-to-liquids synfuel process is to be heated from 15 to 300 °C before entering the reactor. The heating is accomplished with the use of hot product gases, which cool from 380 to 35 °C.

A stainless-steel (type A-240-316) one-pass shell-and-tube TEMA type AEL exchanger with single-segmental baffles has been proposed.

Both streams enter the exchanger at 1020 kPa.

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

The hot gasses are sent through the tubes and the methane is sent through the shell.

The flow rate for the methane has been set at 7.6 kg/s.

The inside and outside diameters for the tubes are 0.0191 and 0.0254 m, respectively. The tubes will be arranged in a diamond (45º) pitch of 0.0381 m with fixed tube sheets. The tubesheet thickness is equal to the outside diameter of the tubes.

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

The exchanger operates for 8000 h/yr.

Installation costs are 18% of purchased cost, and annual fixed charges including maintenance are 23% of the installed cost.

The energy cost is $0.17/kWh.

The annual cost of utility fluid may be ignored.

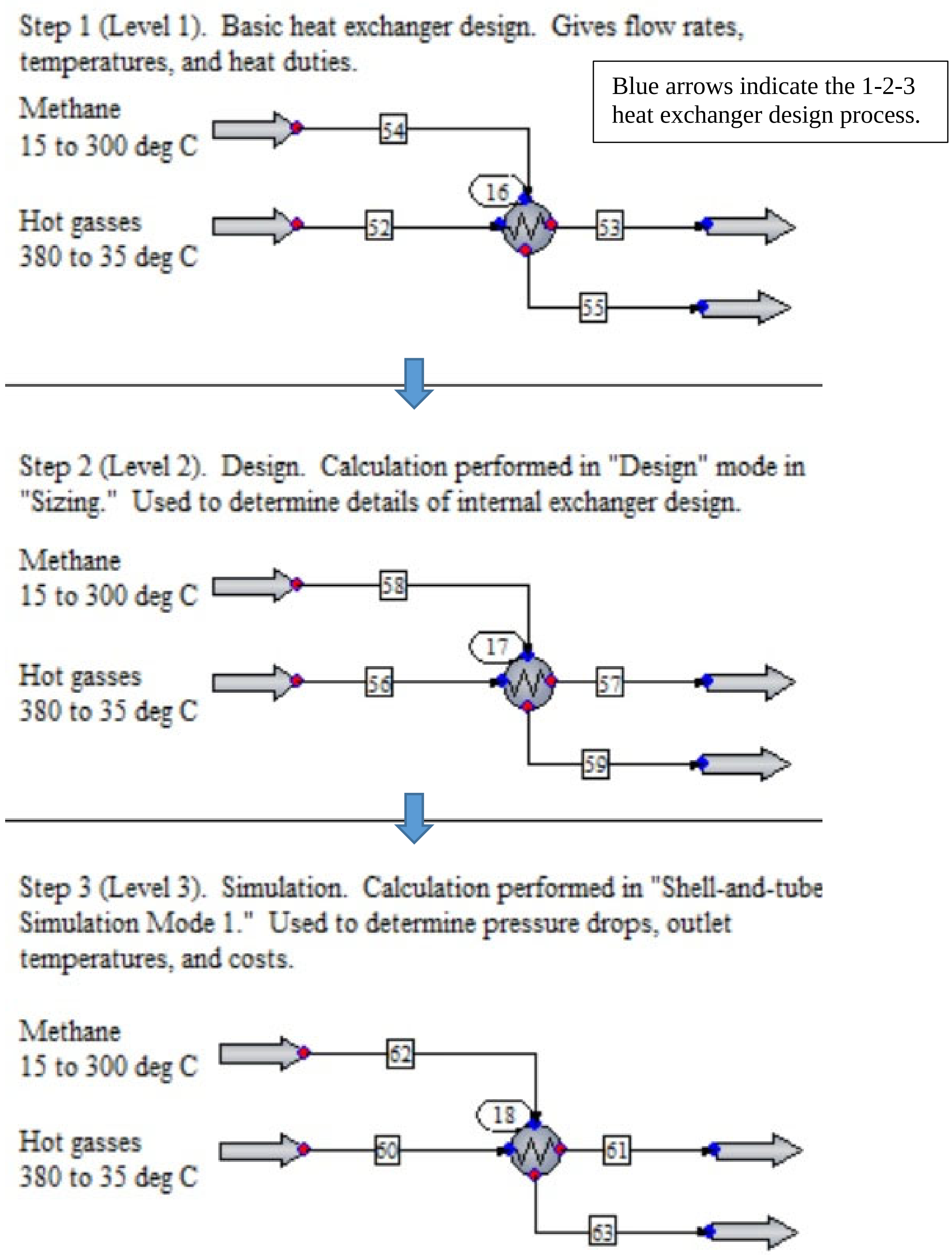
Design Constraints: The upper limit on the tube length is 20 m and the upper limit on the shell diameter is 10 m.

Cadet: APPROVED SOLUTION

Problem: Weight:
A 80

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. (2) Determine the February 2023 total installed cost of the heat exchanger.

SOLUTION:



Cadet: APPROVED SOLUTION

TABULATED ANALYSIS – DESIGN (LEVEL 2)

Simulation: CH402 WPR1 AY22-23 Makeup   Case: WPR1 - Rating

TABULATED ANALYSIS

Overall Data:

Area Total	m2	1229.91	% Excess		-0.01
Area Required	m2	1209.38	U Calc.	W/m2-K	110.42
Area Effective	m2	1209.32	U Service	W/m2-K	110.43
Area Per Shell	m2	1209.32	Heat Duty	J/sec	5.82E+06

Weight LMTD C 43.58 LMTD CORR Factor 1.0000 CORR LMTD C 43.58

Shell-side Data:

Crossflow Vel. m/sec 4.8E+00 EndZone Vel. 3.2E+00 Window Vel. 4.0E+00

Film Coef.	W/m2-K	374.67	Reynolds No.		37517
Allow Press. Drop	kPa	34.47	Calc. Press. Drop	kPa	44.68
Inlet Nozzle Size	m	0.25	Press. Drop/In Nozzle	kPa	3.52
Outlet Nozzle Size	m	0.20	Press. Drop/Out Nozzle	kPa	3.43
			Mean Temperature	C	157.39
Rho V2 IN	kg/m-sec2	3203.15	Press. Drop (Dirty)	kPa	75.95

Stream Analysis:

SA Factors: A 13.27 B 81.33 C 1.05 E 4.35 F 0.00

Ideal Cross Vel. m/sec 5.92 Ideal Window Vel. m/sec 4.85

Tube-side Data:

Film Coef.	W/m2-K	215.84	Reynolds No.		45987
Allow Press. Drop	kPa	34.47	Calc. Press. Drop	kPa	11.11
Inlet Nozzle Size	m	0.30	Press. Drop/In Nozzle	kPa	4.17
Outlet Nozzle Size	m	0.25	Press. Drop/Out Nozzle	kPa	1.81
Interm. Nozzle Size	m	0.00	Mean Temperature	C	207.63
Velocity	m/sec	8.14	Mean Metal Temperature	C	178.43

Clearance Data:

Baffle to shell	m	0.0048	Bundle diameter	m	1.3566
Tube hole clear.	m	0.0008	Outer tube clear.	m	0.0150
Bundle top space	m	0.0000	In-line pass clear.	m	0.0000
Bundle btm space	m	0.0000	Pass clearance	m	0.0159

Baffle Parameters:

Number of Baffles		37
Baffle Type		Single Segmental
Baffle space def.		Edge-Edge
Inlet Space	m	0.648
Center Space	m	0.430
Outlet Space	m	0.648
Baffle Cut, % Diameter		23.000
Baffle Overlap	m	0.038
Baffle Cut Direction		Horizontal
Number of Int. Baffles		0
Baffle Thickness	m	0.006

Shell:

Shell O.D.	m	1.40	Orientation	H
Shell I.D.	m	1.37	Shell in Series	1

Bonnet I.D.	m	1.37	Shell in Parallel		1
Type		AEL	Max. Heat Flux Btu/ft2-hr		0.00
Imping. Plate		Impingement Plate	Sealing Strip		5

Tubes:

Number		903	Tube Type		Bare
Length	m	17.07	Free Int. Fl Area	m2	0.00
Tube O.D.	m	0.025	Fin Efficiency		0.000
Tube I.D.	m	0.019	Tube Pattern		SQU45
Tube Wall Thk.	m	0.003	Tube Pitch	m	0.038
No. Tube Pass		1			
Inner Roughness	m	0.0000016			
Number of tubesheets		2	Tubesheet thickness, m		0.025

Resistances:

Shell-side Film	m2-K/W	0.00267
Shell-side Fouling	m2-K/W	0.00000
Tube Wall	m2-K/W	0.00023
Tube-side Fouling	m2-K/W	0.00000
Tube-side Film	m2-K/W	0.00463
Reference Factor (Total outside area/inside area based on tube ID)		1.330

Pressure Drop Distribution:

Tube Side			Shell Side		
Inlet Nozzle	kPa	4.1698	Inlet Nozzle	kPa	3.5209
Tube Entrance	kPa	0.1375	Impingement	kPa	2.0821
Tube	kPa	4.9148	Bundle	kPa	24.0874
Tube Exit	kPa	0.1723	Outlet Nozzle	kPa	3.4261
End	kPa	0.0000	Total Fric.	kPa	31.0344
Outlet Nozzle	kPa	1.8063	Total Grav.	kPa	-0.0680
Total Fric.	kPa	11.2008	Total Mome.	kPa	13.7123
Total Grav.	kPa	0.1170	Total	kPa	44.6787
Total Mome.	kPa	-0.2062			
Total	kPa	11.1117			

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

Number of tubes: 903 //ANS
Length of the tubes: 17.07 m //ANS
Inside diameter of the shell: 1.37 m //ANS
Required area of the exchanger: 1,209.38 m^2 //ANS
Largest resistance to heat transfer in the exchanger: 0.00463 m^2K/W (tube-side) //ANS

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

February 2023 total installed cost: $1,434,290 //ANS

Cadet: APPROVED SOLUTION

Problem: Weight:
B 60

Determine the total annual operating costs for the shell-and-tube exchanger as designed in Problem A.

SOLUTION:

Use Equation 14-91 in the PTW textbook on page 739 with the stream box from CHEMCAD:

$$C_T = A_0 \cdot K_F \cdot C_{A_0} + \cancelto{0}{m_u \cdot H_y \cdot C_u} + A_0 \cdot E_i \cdot H_y \cdot C_i + A_0 \cdot E_0 \cdot H_y \cdot C_0$$

C_T Total annual costs, dollars/yr

A_0 Outside tube area, m^2
K_F Annual fixed charges factor (maintenance, etc) as a fraction of installed cost, dimensionless
C_{A_0} Installed cost of the heat exchanger per unit outside tube area, dollars/m^2

m_u Mass flow rate of utility fluid, kg/hr
H_y Hours of operation per year
C_u 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
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 $N \cdot m$ to pump fluid through the shell side, dollars/$N \cdot m$

Stream No.	9	10	12	11
Name	HG		CH4	
- - Overall - -				
Temp C	380.0000	35.2623	15.0000	299.7734
Pres kPa	1020.0000	1008.9029	1020.0000	975.3494
Mass flow kg/sec	16.1900	16.1900	7.6000	7.6000
Std liq m3/h	67.3659	67.3659	91.2001	91.2001
Actual dens kg/m3	5.3956	11.3559	6.9673	3.2779

Tube-side pressure drop = 1020 – 1008.9029 = 11.0971 kPa = 11,097.1 Pa
Tube-side average density = (5.3964 + 11.3559)/2 = 8.37615 kg/m^3
Tube-side mass flow rate = 16.1900 kg/s from level 1

Shell-side pressure drop = 1020 – 975.3494 = 44.6506 kPa = 44,650.6 Pa
Shell-side average density = (6.9673 + 3.2779)/2 = 5.1226 kg/m^3
Shell-side mass flow rate = 7.6000 kg/s from level 1

$$A_0 = \pi \cdot D_O \cdot L \cdot N_P = \pi \cdot 0.0254\,\text{m} \cdot 17.07\,\text{m} \cdot 9003 = 1230.00\,\text{m}^2$$

$$C_{A_0} = \$1,434,290 / 1230.00\,\text{m}^2 = \$1,166.089 / \text{m}^2$$

$$K_F = 0.23$$

$$C_u = 0$$

$$H_y = 8,000\,\text{hrs}$$

$$C_i = \$0.17 / \text{kWh}$$

$$E_i = \frac{11,097.1\dfrac{\text{N}}{\text{m}^2} \cdot 16.1900\dfrac{\text{kg}}{\text{s}} \cdot \dfrac{1\,\text{m}^3}{8.37165\,\text{kg}}}{1230.00\,\text{m}^2} = 17.4384\,\frac{\text{W}}{\text{m}^2} = 0.0174384\,\frac{\text{kW}}{\text{m}^2}$$

$$E_0 = \frac{44,650.6\dfrac{\text{N}}{\text{m}^2} \cdot 7.600\dfrac{\text{kg}}{\text{s}} \cdot \dfrac{1\,\text{m}^3}{5.1226\,\text{kg}}}{1230.00\,\text{m}^2} = 53.8574\,\frac{\text{W}}{\text{m}^2} = 0.0538574\,\frac{\text{kW}}{\text{m}^2}$$

$$\begin{aligned}C_T = {} & 1230.00\,\text{m}^2 \cdot 0.23 \cdot \frac{\$1166.089}{\text{m}^2} \\ & + 1230.00\,\text{m}^2 \cdot 0.0174384\frac{\text{kW}}{\text{m}^2} \cdot 8,000\,\text{h} \cdot \frac{\$0.17}{\text{kWh}} \\ & + 1230.00\,\text{m}^2 \cdot 0.0538574\frac{\text{kW}}{\text{m}^2} \cdot 8,000\,\text{h} \cdot \frac{\$0.17}{\text{kWh}}\end{aligned}$$

$$= \$449,150$$

ans

Problem: C

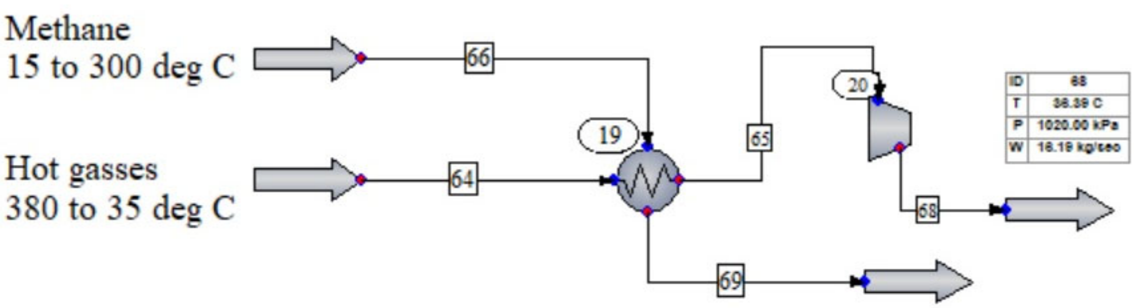
Weight: 60

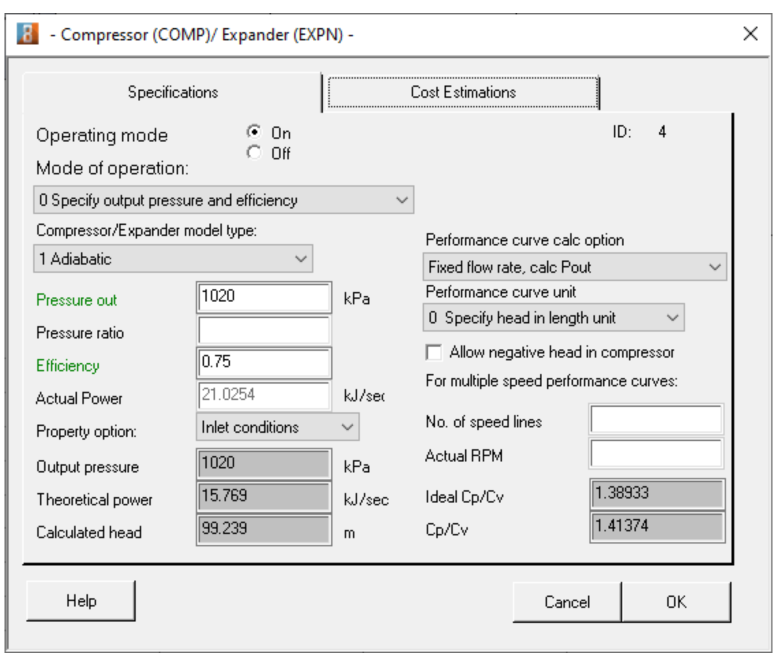
(1) Determine the total purchased cost of a compressor designed to increase the tube-side hot gasses from the outlet pressure at the exchanger back to 1020 kPa. The compressor is centrifugal with an explosion-proof 3600 RPM motor and a belt-drive coupling. Determine the cost must be in February 2023.

(2) If the hot gas air temperature must be within 0.5 degrees of 35 ºC at the outlet of the compressor, how does the addition of the compressor impact the design of the heat exchanger? (No simulation, explain only.)

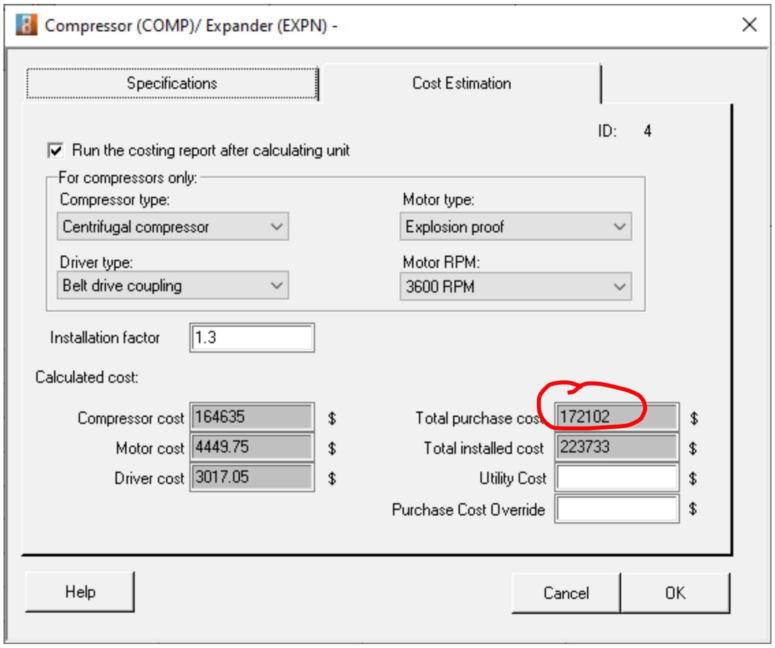
SOLUTION:

The CHEMCAD flowsheet is shown below with temperatures and pressures indicated in the TP box. Unit Ops Cost estimation windows follow below. The total purchase cost is $172,102 in February 2023.





Cadet: **APPROVED SOLUTION**



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 1347.6 and the cost index year to February 2023.

(1) The purchased cost in February 2023 is circled in red and is equal to $172,102. **//ANS**

(2) Compression of a gas causes heating, thus the compressor will heat the gasses somewhat. This means the flow rate of the air can be reduced somewhat or the area of the heat exchanger can be reduced somewhat. **//ANS**