Problem 14-15

The overhead vapor from the C_2 splitter in Fig. 3-3 is partially condensed in E-601. The process conditions for the vapor entering the condenser are:

Temperature	-30.1ºC (sat.)
Pressure	1945.8 kPa (sat.) (changed from 2944 kPa)
Flow rate into condenser	
CH_4	3×10^{-3} kg/s
C_2H_4	64.52 kg/s
C_2H_6	6.26×10^{-2} kg/s

A shell-and-tube exchanger has been selected for this heat transfer process to condense 73.5% of the overhead vapor. Use an appropriate software package (based on TEMA guidelines) to obtain the overall heat-transfer coefficient and the area required for the condensation if the tubes have an outside diameter of 0.0127 m and an inside diameter of 0.0094 m. Assuming that the maximum length of the tubes is 3.05 m, how many tubes will be required and what shell diameter is recommended? Propylene at -46 ºC and 125 kPa serves as the coolant for the condensation process. Additional Questions: Identify the largest resistance to heat transfer in the exchanger and determine the total purchase cost of the exchanger in Feb 2026.

Important Note: There is a typo in the process conditions listed in the book. At -30.1 ºC and 2944 kPa the overhead vapor would be completely condensed, and this is not feasible for overhead vapors leaving a distillation column. To fix this issue, we flash the stream at -30.1 ºC while fixing the vapor fraction to 1 in CHEMCAD, giving the correct process stream pressure of 1945.806 kPa.

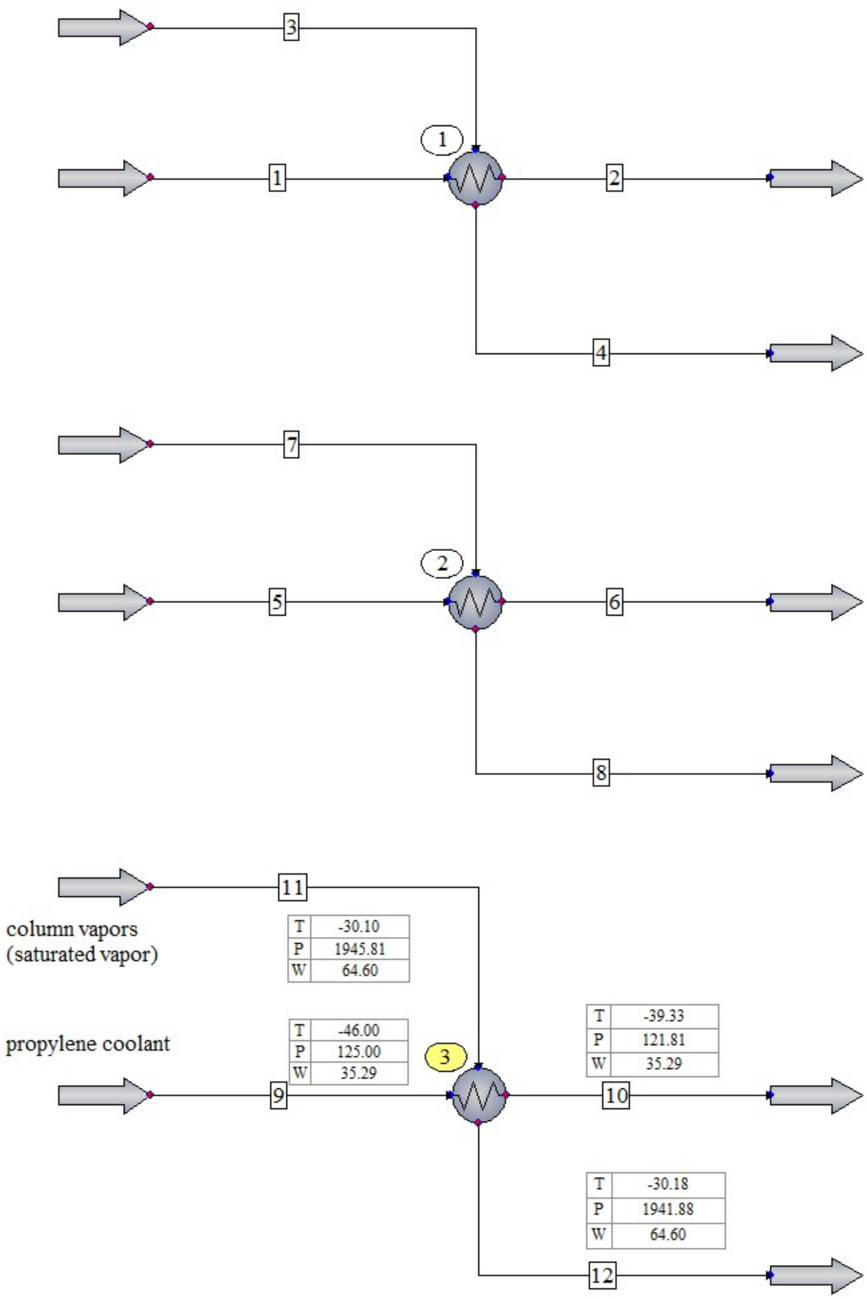
Solution:

The detailed procedure for this design is shown in the class notes for Lesson 9.

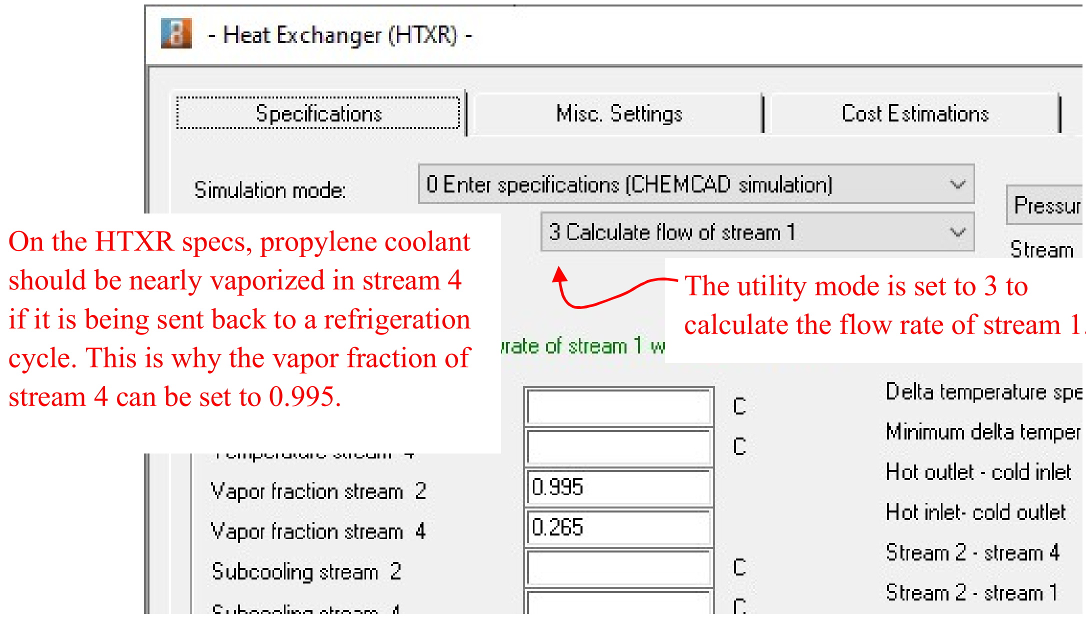
The propylene coolant pressure is unknown, so we need to assume a value. 125 kPa is reasonable since this is about 17 kPa higher than the pressure required to completely condense the coolant. This is an arbitrary assumption but is completely reasonable.

The propylene coolant flow rate is also unknown. This is calculated in CHEMCAD by using the "utility option" in the heat exchanger specifications. (This is utility option 3 in CHEMCAD.) This requires us to make an additional specification on the propylene coolant. We assume that it is 99.5% vaporized in the condenser, allowing us to use its heat of vaporization to absorb the heat released by the condensing overhead vapors. This is an arbitrary specification but is reasonable since propylene can be recovered by using it as the working fluid in a refrigeration cycle. Note also that when using the utility option, we must use a guess for the flow rate, such as 1 kg/s.

The CHEMCAD flowsheet is shown below:



The specifications for the first heat exchanger (unit 1 above) are shown below:



This gives the propylene coolant flow rate. After determining the propylene coolant flow rate (35.29 kg/s using the specifications above), the next step is to use heat exchanger sizing in CHEMCAD, also referred to as "CCTherm," accessed through the "Sizing" tab.

The tube length will need to be constrained in the "***design constraints***" dropdown. The CHEMCAD defaults for the lower and upper tube lengths are 0.914 and 6.096 m. This should be set to a lower limit of 3 m and an upper limit of 3.1 m. This will constrain CHEMCAD to 3.05 m during the optimization. The upper limit on the shell diameter also needs to be increased to accommodate a shorter heat exchanger (resulting in more tubes).

The tabulated results report is shown below. All answers are highlighted in YELLOW.

Total Purchased Cost:

The total purchased cost in February 2026 is $810,750 from CHEMCAD. This is determined by running the "shell-and-tube simulation" and checking the box labelled "Run the costing report after running the unit" in the "Cost Estimations" tab. Note: The CEPCI index in CHEMCAD needs to be updated to February 2026 for an accurate result.

```
                    TABULATED ANALYSIS - DESIGN MODE
                    --------------------------------
Overall Data:
 Area Total          m2       2348.77   % Excess                      5.97
 Area Required       m2       2161.02   U Calc.    W/m2-K           566.06
 Area Effective      m2       2290.05   U Service  W/m2-K           534.16
 Area Per Shell      m2       2290.05   Heat Duty  J/sec          1.57E+07
 Weight LMTD C   12.80   LMTD CORR Factor  1.0000   CORR LMTD C   12.80

Shell-side Data:
 Avg. SS Vel. m/sec          0.75
 Film Coef.  W/m2-K        1457.30
 Allow Press. Drop   kPa     34.47   Calc. Press. Drop      kPa      2.56
 Inlet Nozzle Size   m        0.49   Press. Drop/In Nozzle  kPa      3.55
 Outlet Nozzle Size  m        0.44   Press. Drop/Out Nozzle kPa      0.45
                                     Mean Temperature       C      -30.10
 Rho V2 IN  kg/m-sec2      3261.46   Press. Drop (Dirty)    kPa      4.35

Tube-side Data:
 Film Coef.  W/m2-K        2146.02
 Allow Press. Drop   kPa     34.47   Calc. Press. Drop      kPa      3.15
 Inlet Nozzle Size   m        0.20   Press. Drop/In Nozzle  kPa      0.99
 Outlet Nozzle Size  m        0.79   Press. Drop/Out Nozzle kPa      0.35
 Interm. Nozzle Size m        0.00   Mean Temperature       C      -42.90
 Velocity            m/sec    4.55   Mean Metal Temperature C      -36.96

Clearance Data:
 Baffle to shell   m        0.0063   Bundle diameter     m         3.6396
 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         0.0159

Baffle Parameters:
 Number of Baffles                             2
 Baffle Type                    Single Segmental
 Baffle space def.              Edge-Edge
 Inlet Space             m                 1.114
 Center Space            m                 0.756
 Outlet Space            m                 1.114
 Baffle Cut, % Diameter                   15.000
 Baffle Overlap          m                 0.000
 Baffle Cut Direction                   Vertical
 Number of Int. Baffles                        0
 Baffle Thickness        m                 0.013

Shell:
 Shell O.D.        m             3.68    Orientation                    H
 Shell I.D.        m             3.66    Shell in Series                1
 Bonnet I.D.       m             3.66    Shell in Parallel              1
 Type                            AEL   Max. Heat Flux Btu/ft2-hr    0.00
 Imping. Plate     Impingement Plate     Sealing Strip                  5

Tubes:
 Number                         19314     Tube Type                   Bare
 Length            m             3.05    Free Int. Fl Area   m2       0.00
 Tube O.D.         m            0.013    Fin Efficiency            0.000
 Tube I.D.         m            0.009    Tube Pattern              TRI60
```

Tube Wall Thk.	m	0.002	Tube Pitch	m	0.024
No. Tube Pass		1			
Inner Roughness	m	0.0000016			
Number of tubesheets		2	Tubesheet thickness, m		0.019

Resistances:

Shell-side Film	m2-K/W	0.00069
Shell-side Fouling	m2-K/W	0.00018
Tube Wall	m2-K/W	0.00004
Tube-side Fouling	m2-K/W	0.00018
Tube-side Film	m2-K/W	0.00047

Reference Factor (Total outside area/inside area based on tube ID) 1.351

Pressure Drop Distribution:

Tube Side			Shell Side		
Inlet Nozzle	kPa	0.9868	Inlet Nozzle	kPa	3.5489
Tube Entrance	kPa	0.0002	Impingement	kPa	2.1200
Tube	kPa	0.5485	Bundle	kPa	2.2924
Tube Exit	kPa	0.1211	Outlet Nozzle	kPa	0.4534
End	kPa	0.0000	Total Fric.	kPa	6.2947
Outlet Nozzle	kPa	0.3454	Total Grav.	kPa	-1.9950
Total Fric.	kPa	2.0012	Total Mome.	kPa	-1.7381
Total Grav.	kPa	1.3395	Total	kPa	2.5616
Total Mome.	kPa	-0.1922			
Total	kPa	3.1485			

Problem 14-16

Air used in a catalytic oxidation process is to be heated from 15 to 270 ºC before entering the oxidation chamber. The heating is accomplished with the use of product gases, which cool from 380 to 200 ºC. A steel one-pass shell-and-tube heat exchanger with cross-flow on the shell side has been proposed. The average absolute pressure on both the tube side and the shell side is 1010 kPa, with the hot gases being sent through the tubes. The flow rate for the air has been set at 1.9 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. The exchanger operates for 8000 h/yr. The properties of the hot gases can be considered identical to those of air. The cost data for the exchanger are given in Fig. 14-19.

Installation costs are 15 percent of the purchased cost, and annual fixed charges including maintenance are 20 percent of the installed cost. The cost for power delivered is $0.12/kWh. Under these conditions, determine the most appropriate tube length and the purchased cost for the optimum heat exchanger.

Solution:

The problem follows example 14-9 very closely. The most appropriate tube length is the optimum tube length. The optimum is calculated from equation 14-91 on page 739 of PTW, but this equation is based on area. However, area is related to tube length since area=$\pi \cdot D_o \cdot L \cdot N_T$. So equation 14-91 is used to optimize the annual operating expenses in terms of tube length. Excel is used for plotting and an Excel template available CANVAS. The Excel and CHEMCAD solutions are shown below.

- Answers may differ slightly from cadets. See comments on page 11.
- Step 1 of the 3-step method in CHEMCAD gives a hot gas flow rate of 2.6397 kg/s.
- Step 2 of the 3-step method gives the "Sizing" results of 288 tubes and 9.75 m.
- Step 3 of the 3-step method shows that the outlet streams are somewhat off-spec. Cadets should iterate to get these within 0.5 °C of specified values.
- In subsequent iterations shown in the excel sheet, this exchanger is re-optimized using equation 14-91, by changing the tube length and then iterating the number of tubes to adjust the area and bring the exchanger back on spec.
- All installed costs, and shell-side and tube-side densities and pressure drops are carried forward from the CHEMCAD simulation result to the Excel spreadsheet.
- The cost components in eq. 14-91 are calculated in Excel, with the total annual cost being plotted as a function of tube length.
- From the trend-line in the plot, where x is the length of tubes in meters,

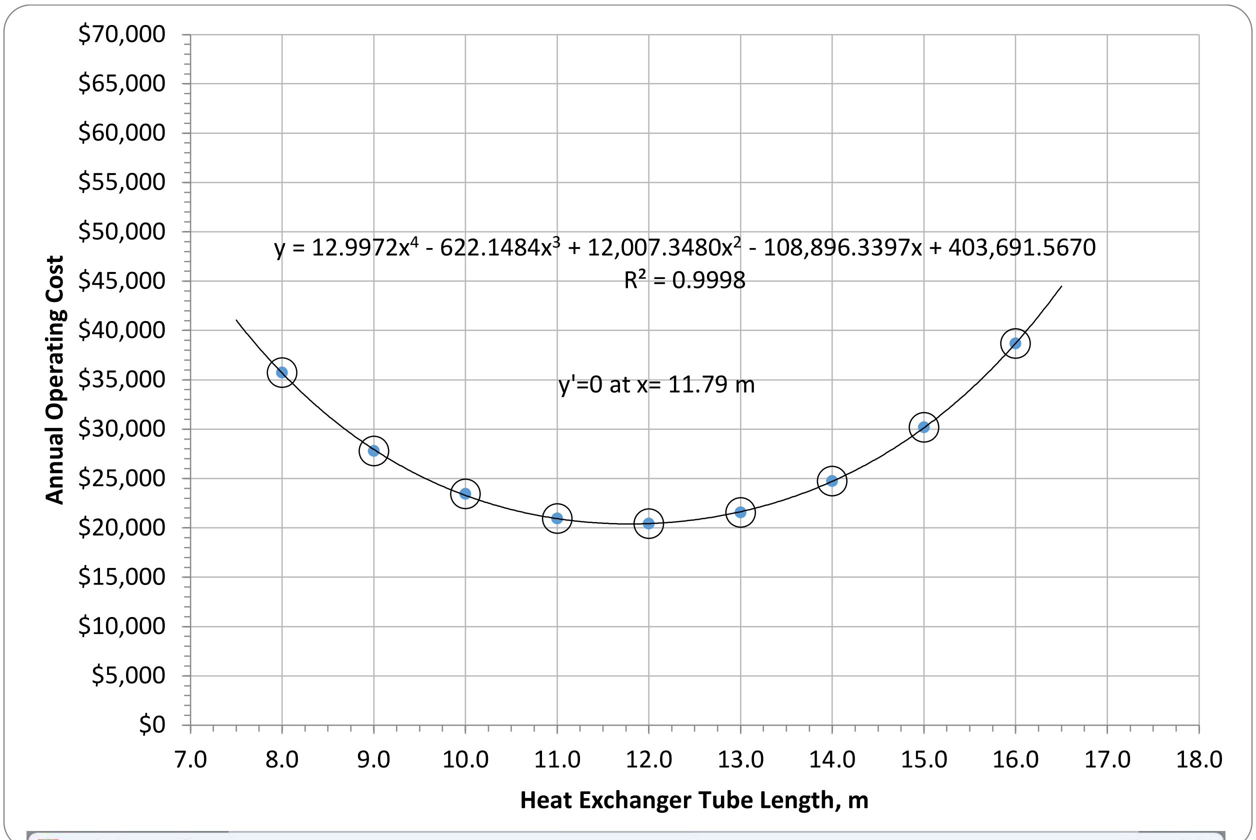
$$C_T(x)=12.9972\ x^4 - 622.1484\ x^3 + 12{,}0007.3480\ x^2 - 108{,}896.3397\ x + 403{,}691.5670$$

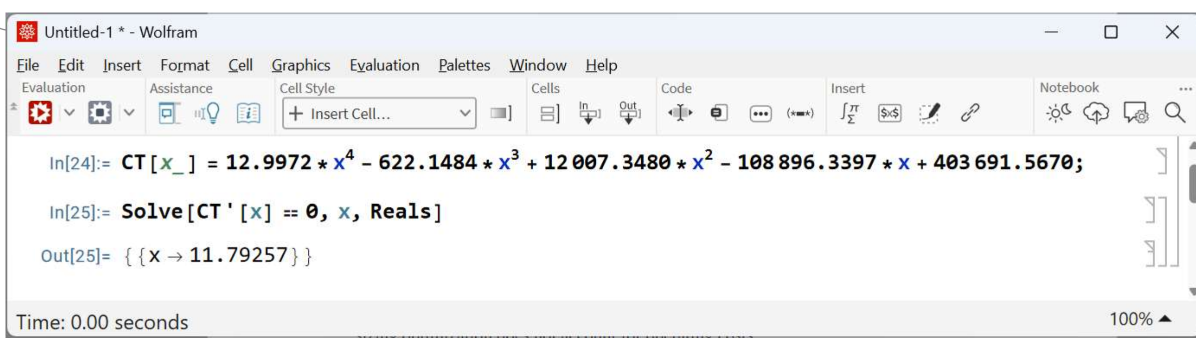
Answer: In Mathematica, take the derivative of the operating cost function $C_T(x)$ with respect to x, set it equal to zero, and solve for x, giving x=11.79 m. The installed cost for the 11.79-m exchanger is $47,326, obtained by interpolating between 11 and 12 m. This gives a purchased cost, after dividing by 1.15, of $41,153. //ANS

Cadets can also run and iterate the 11.79-m exchanger in CHEMCAD to calculate the purchased cost of $40,677.

Important Conclusion:

The optimized installed cost of $47,326 is significantly lower than the optimized cost determined by CHEMCAD of $82,011 using "Sizing" alone. This is because CHEMCAD sizing optimization does not account for operating costs.





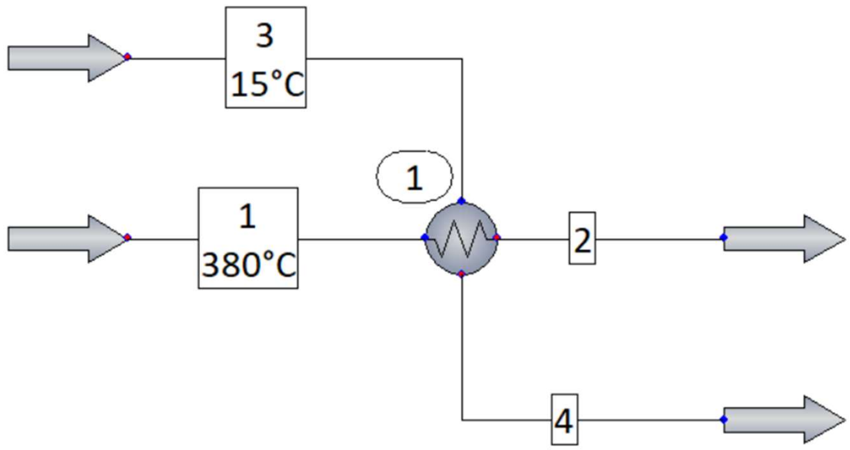
PROBLEM SET 5

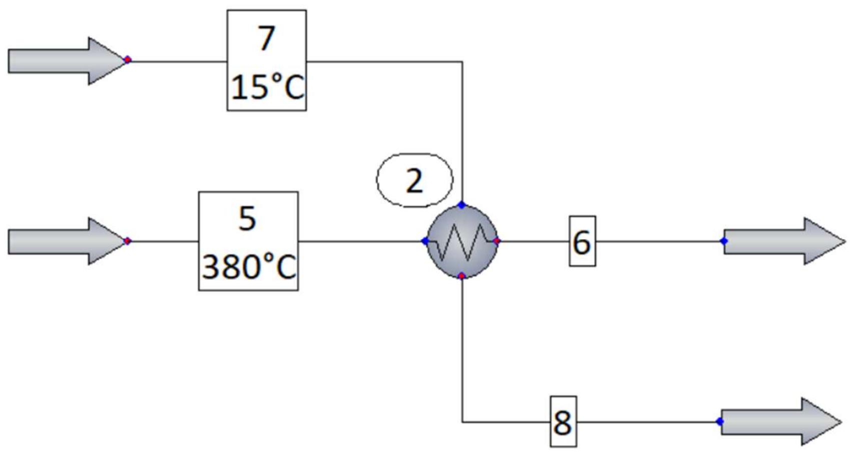
Problem 14-16. Cadet Template				"sizing" checks are required				Cadets complete this table					
Optimimal Heat Exchanger Design													
Yellow - obtained from CHEMCAD simulations					1.1295	0.8890	0.7220	0.5950	0.5100	0.4440	0.3930	0.3550	0.3280
Light Blue - Specifications given in problem - page 753 in PTW textbook													
White - excel calculations - verified with "checks" (results from CC design)							<---	iterations	--->				
Spreadsheet for evaluating Equation 14-91				"sizing" checks	1	2	3	4	5	6	7	8	9
Number of tubes	N_t	dimensionless	288	288	605	370	240	160	115	85	65	52	43
Length of tubes	L	m	9.750	9.750	8.0	9.0	10.0	11.0	12.0	13.0	14.0	15.0	16.0
Installed cost, CC	C	$	$82,011	$82,011	$135,240	$95,482	$71,478	$55,056	$45,271	$38,121	$32,984	$29,509	$27,016
Tube outer diameter	D_o	m	0.0254	0.0254	0.0254	0.0254	0.0254	0.0254	0.0254	0.0254	0.0254	0.0254	0.0254
Tube inner diameter	D_i	m	0.0191	0.0191	0.0191	0.0191	0.0191	0.0191	0.0191	0.0191	0.0191	0.0191	0.0191
Tube wall thickness	x	m	0.00315	0.00315	0.0032	0.0032	0.0032	0.0032	0.0032	0.0032	0.0032	0.0032	0.0032
Outside area of tubes	A_o	m^2	224.1	224.07	386.2	265.7	191.5	140.4	110.1	88.2	72.6	62.2	54.9
Installed cost per area	C_{Ao}	$\$/m^2$	$366	$366	$350	$359	$373	$392	$411	$432	$454	$474	$492
Tube-side (hot gas) flow rate, CC	m_i	kg/s	2.6397	2.6397	2.6397	2.6397	2.6397	2.6397	2.6397	2.6397	2.6397	2.6397	2.6397
Tube-side inlet fluid density, CC	r_{ti}	kg/m^3	5.3956	5.3956	5.3956	5.3956	5.3956	5.3956	5.3956	5.3956	5.3956	5.3956	5.3956
Tube-side oulet fluid density, CC	r_{to}	kg/m^3	7.3650	7.3650	7.3460	7.3530	7.3478	7.3309	7.3052	7.2550	7.1777	7.0751	6.9169
Tube-side pressure drop, CC	Dp_i	kPa	14.6039	14.6039	13.4926	13.4926	14.6039	16.5743	20.1036	26.3911	36.6807	51.4390	72.5951
Tube-side average density	r_t	kg/m^3	6.3803	6.3803	6.3708	6.3743	6.3717	6.3633	6.3504	6.3253	6.2867	6.2354	6.1563
Tube-side power loss per area	E_i	Nm/s per m^2	26.9651	26.9651	14.4753	21.0276	31.5917	48.9570	75.8865	124.9065	212.1035	349.8711	566.9877
Shell-side (air) flow rate	m_o	kg/s	1.9000	1.9000	1.9000	1.9000	1.9000	1.9000	1.9000	1.9000	1.9000	1.9000	1.9000
Shell-side inlet fluid density, CC	r_{si}	kg/m^3	12.3104	12.3104	12.3104	12.3104	12.3104	12.3104	12.3104	12.3104	12.3104	12.3104	12.3104
Shell-side oulet fluid density, CC	r_{so}	kg/m^3	6.3556	6.3556	6.3838	6.3765	6.3733	6.3758	6.3756	6.3801	6.3825	6.3771	6.3813
Shell-side pressure drop, CC	Dp_o	kPa	17.0649	17.0649	17.0248	17.0248	17.0649	17.0953	17.1166	17.1574	17.2030	17.2722	17.3670
Shell-side average density	r_s	kg/m^3	9.3330	9.3330	9.3471	9.3435	9.3419	9.3431	9.3430	9.3453	9.3465	9.3438	9.3459
Shell-side power loss per area	E_o	Nm/s per m^2	15.5044	15.5044	8.9604	13.0287	18.1230	24.7539	31.6098	39.5611	48.1600	56.4289	64.3113
Hours of operation per year	H_y	h/y	8000	8000	8000	8000	8000	8000	8000	8000	8000	8000	8000
Cost of pumping power	C_i	$/kWh	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12
Annual fixed charges factor	K_F	dimensionless	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Fixed charges		$/y	$16,402	$16,402	$27,048	$19,096	$14,296	$11,011	$9,054	$7,624	$6,597	$5,902	$5,403
Tube-side pumping costs		$/y	$5,800	$5,800	$5,367	$5,364	$5,808	$6,601	$8,022	$10,573	$14,786	$20,905	$29,882
Shell-side pumping costs		$/y	$3,335	$3,335	$3,322	$3,324	$3,332	$3,337	$3,342	$3,349	$3,357	$3,372	$3,389
Total annual cost	C_T	**$/y**	**$25,538**	$25,538	$35,737	$27,784	$23,436	$20,949	$20,418	$21,546	$24,740	$30,179	$38,675

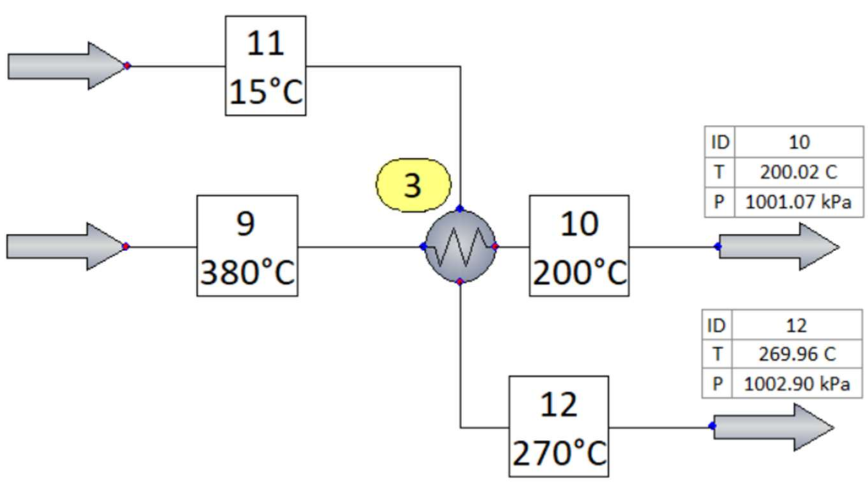
Procedure:

1. Repeat the "Check" calculations in column E.
2. Run ChemCAD in utility mode to determine the necessary flow rate of the cold air.
3. Run sizing in design mode to optimize total purcahe cost.
4. Complete column F for the "sizing" results
5. Vary the tube number while adjusting tube length to keep stream temps on spec.
6. Complete the "iterations" in columns G through Q
7. Add more iterations as necessary to minimize operating costs using equation 14-91

Complete green cells in this table:		
Tube Length, Optimized, m:	11.79	//ANS
Installed Cost, Optimized, $:	$47,326	
Purchased Cost, Optimized, $:	$41,153	//ANS

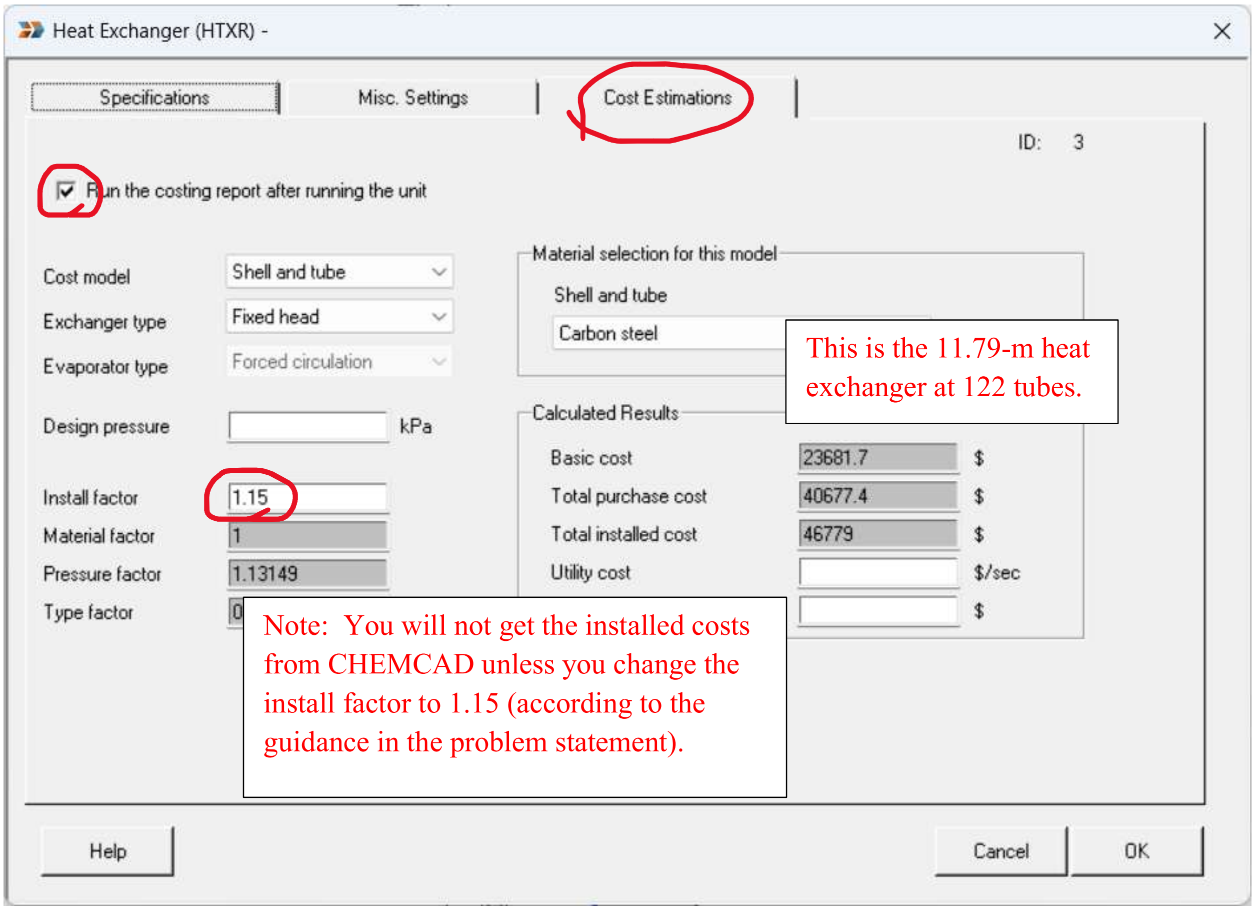






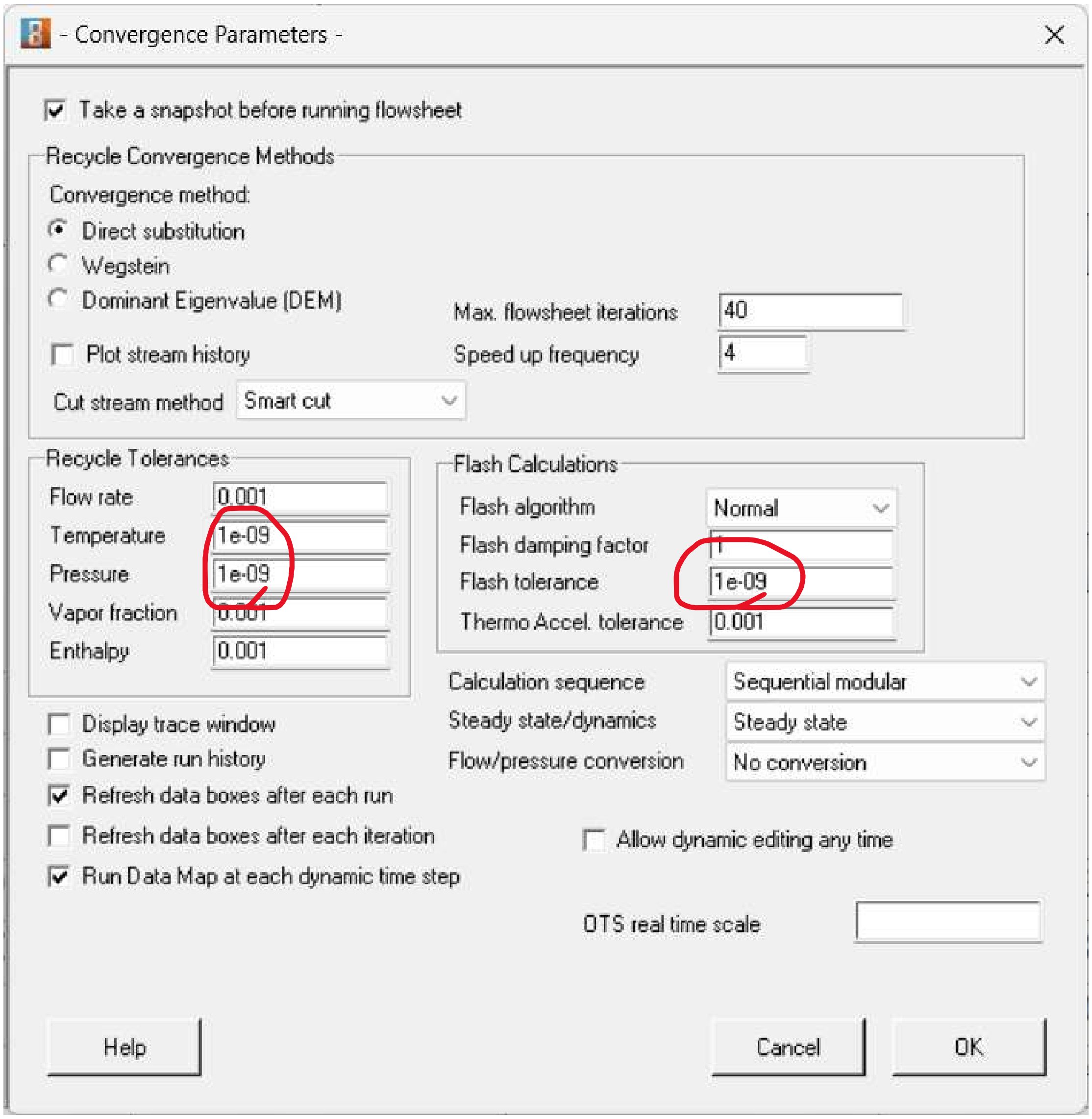
Purchased Cost: $40,677
Installed Cost: $46,779,
From CHEMCAD with 122 11.79-m tubes.

Obtaining installed cost from CHEMCAD:



Comments on Numerical Solutions in CHEMCAD:

Cadet answers can vary somewhat and may not be exactly the same as the instructor answers. While the equations and methods are the same, the order of operations can vary from person to person. Variations can be reduced by the tolerances on the temperature, pressure, and flash, as shown below.



Here is an illustrating example of how different results can arise: Cadet Jones designs correctly, switches to simulation mode and switches to 620 8-m tubes. Cadet Smith also designs correctly, switches to 43 16-m tubes, then to 620 and 8 m. Since the path is different, CHEMCAD's starting values for its numerical methods are different, and the final solutions can be different within the allowed tolerances.