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 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 2025.

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.

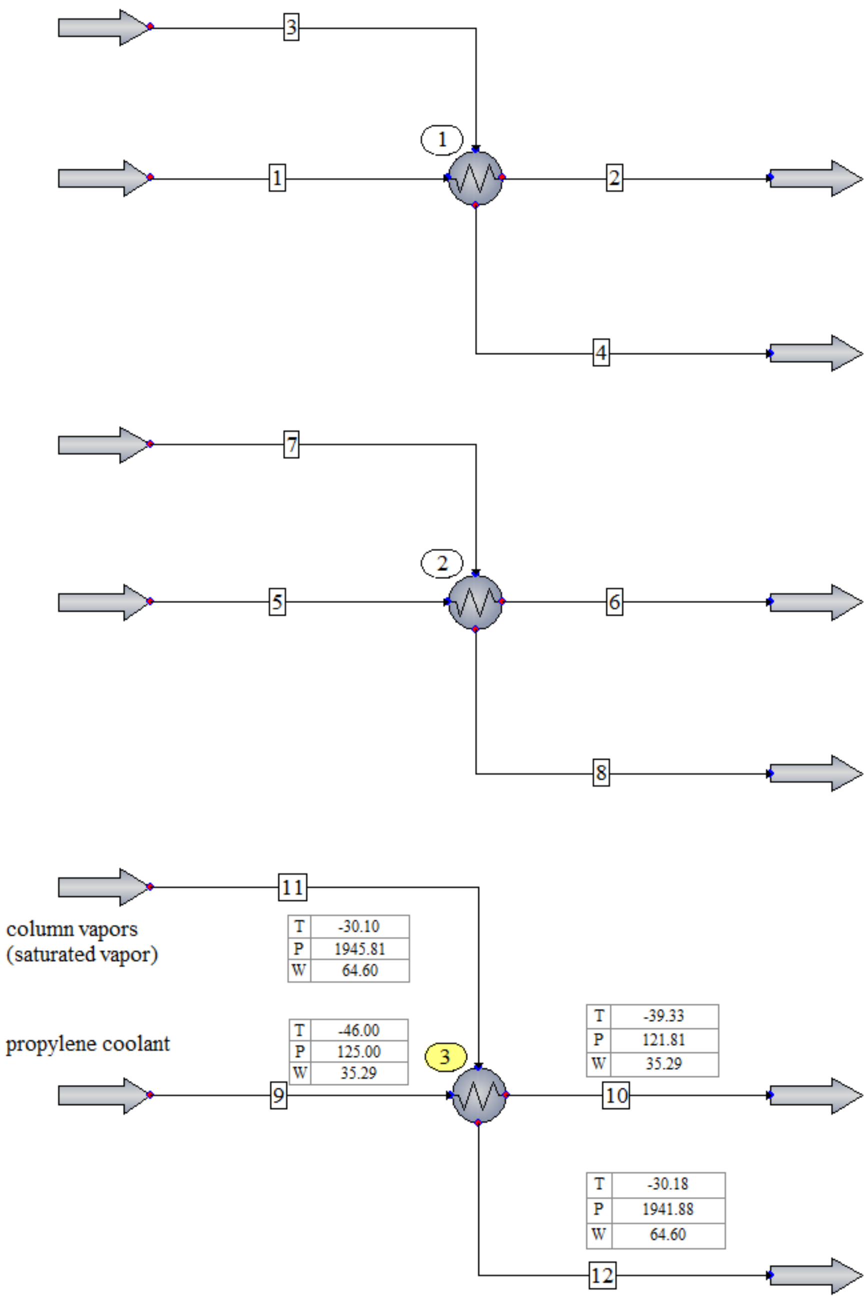
Solution:

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

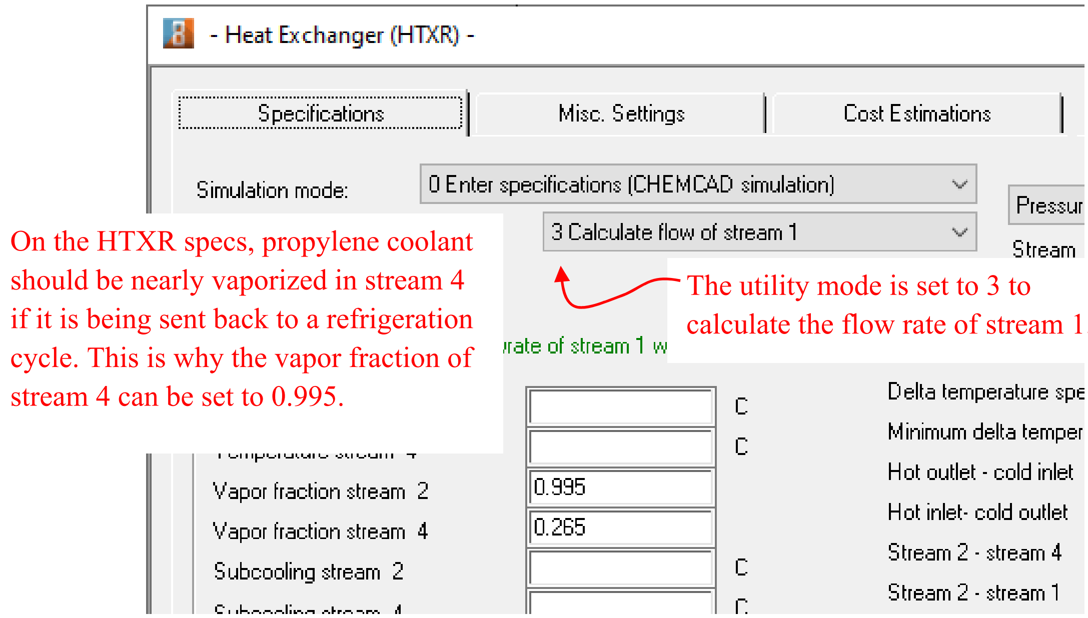
The propylene coolant pressure is unknown, so we need to assume a value. 125 kPa is reasonable since this is about 17 kPa higher than the pressure required to completely condense the coolant. This is an arbitrary assumption but is completely reasonable.

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."

Preferred method: In the "***design***" mode, CHEMCAD will do this calculation automatically. When the calculation mode is set to design, open the design options window. In this window, the tube length will need to be constrained. 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 needs to be increased to accommodate a shorter heat exchanger (resulting in more tubes).

The tabulated CHEMCAD results are shown below from the preferred method above. All answers are highlighted in YELLOW.

Total Purchased Cost:

The total purchased cost in February 2025 is $930,449 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 2025 for an accurate result.

TABULATED ANALYSIS - DESIGN MODE

Overall Data:

Area Total	m2	2758.72	% Excess		8.57
Area Required	m2	2482.72	U Calc.	W/m2-K	492.75
Area Effective	m2	2695.50	U Service	W/m2-K	453.85
Area Per Shell	m2	2695.50	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	0.52			
Film Coef.	W/m2-K	1102.64			
Allow Press. Drop	kPa	34.47	Calc. Press. Drop	kPa	3.30
Inlet Nozzle Size	m	0.49	Press. Drop/In Nozzle	kPa	3.61
Outlet Nozzle Size	m	0.44	Press. Drop/Out Nozzle	kPa	0.46
			Mean Temperature	C	-30.10
Rho V2 IN	kg/m-sec2	3260.83	Press. Drop (Dirty)	kPa	5.62

Tube-side Data:

Film Coef.	W/m2-K	2011.49			
Allow Press. Drop	kPa	34.47	Calc. Press. Drop	kPa	3.01
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	3.87	Mean Metal Temperature	C	-36.96

Clearance Data:

Baffle to shell	m	0.0063	Bundle diameter	m	3.9444
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	1.055
Center Space	m	0.867
Outlet Space	m	1.055
Baffle Cut, % Diameter		15.000
Baffle Overlap	m	0.000
Baffle Cut Direction		Vertical
Number of Int. Baffles		0
Baffle Thickness	m	0.016

Shell:

Shell O.D.	m	3.99	Orientation	H
Shell I.D.	m	3.96	Shell in Series	1
Bonnet I.D.	m	3.96	Shell in Parallel	1
Type		AEL	Max. Heat Flux Btu/ft2-hr	0.00
Imping. Plate		Impingement Plate	Sealing Strip	5

Tubes:

Number		22685	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	0.00091
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	0.00050

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	3.6127
Tube Entrance	kPa	0.0002	Impingement	kPa	2.1196
Tube	kPa	0.4311	Bundle	kPa	3.0558
Tube Exit	kPa	0.0878	Outlet Nozzle	kPa	0.4625
End	kPa	0.0000	Total Fric.	kPa	7.1310
Outlet Nozzle	kPa	0.3480	Total Grav.	kPa	-2.1003
Total Fric.	kPa	1.8539	Total Mome.	kPa	-1.7271
Total Grav.	kPa	1.3483	Total	kPa	3.3036
Total Mome.	kPa	-0.1922			
Total	kPa	3.0100			

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.

- 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,

$$C_T(x)=15.973x^4 - 772.05x^3 + 14{,}773x^2 - 130{,}899x + 466{,}356$$

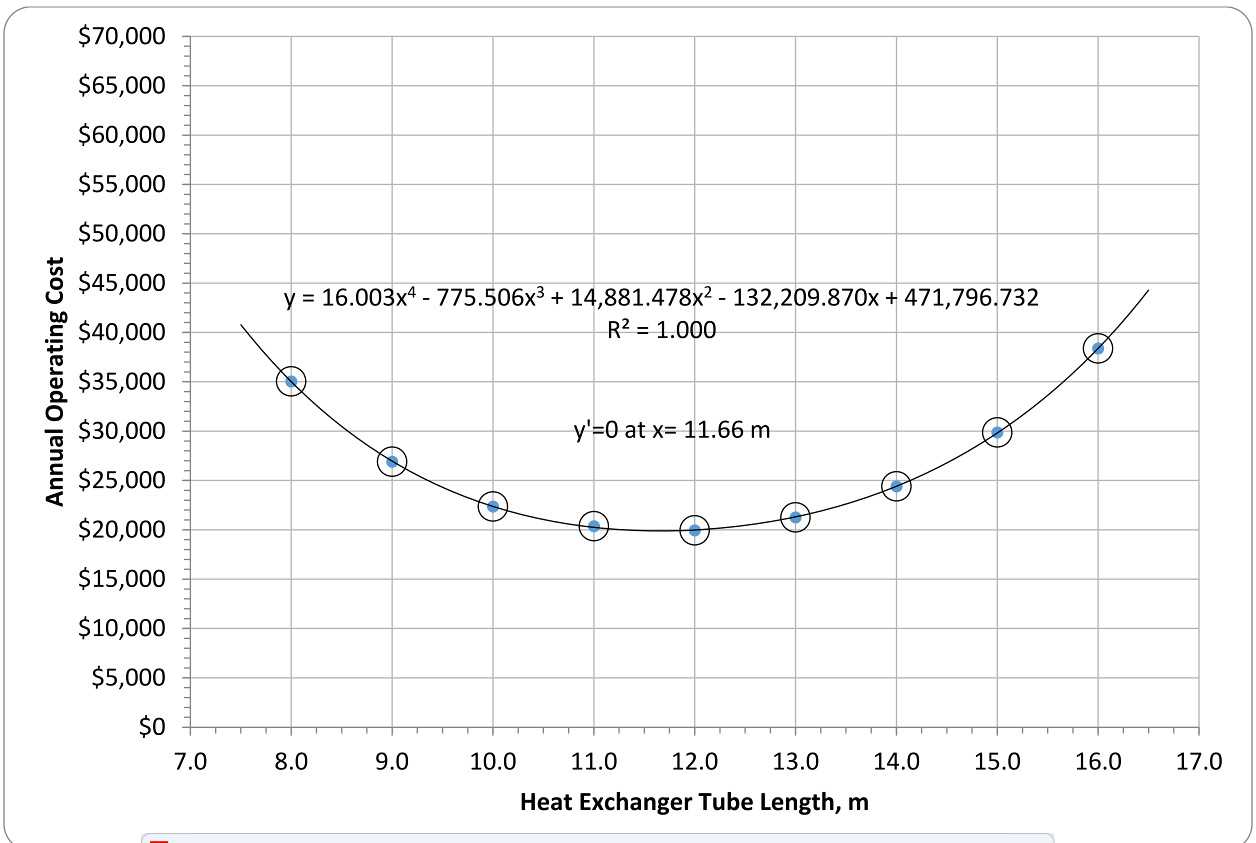
where x is the length of tubes in meters.

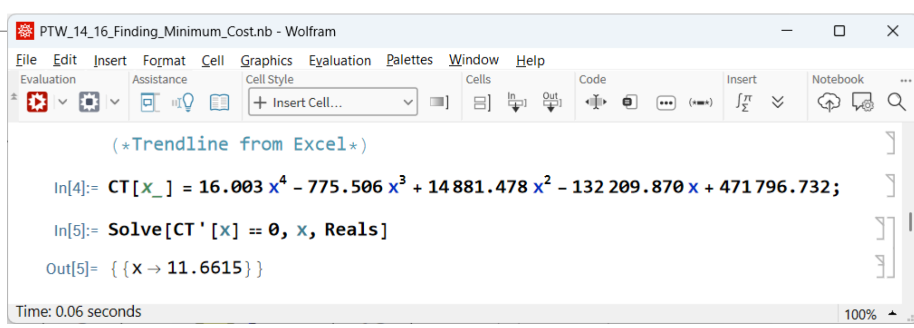
Answer: In Mathematica, take the derivative of the operating cost function $C_T(x)$ with respect to x, set it equal to zero, and solve for x, giving x=11.66 m. The installed cost for the 11.66-m exchanger is \$46,030, obtained by interpolating between 11 and 12 m. This gives a purchased cost, after dividing by 1.15, of \$40,026 //ANS

Cadets can also run and iterate the 11.66-m exchanger in CHEMCAD to calculate the purchased cost of \$39,182.

Important Conclusion:

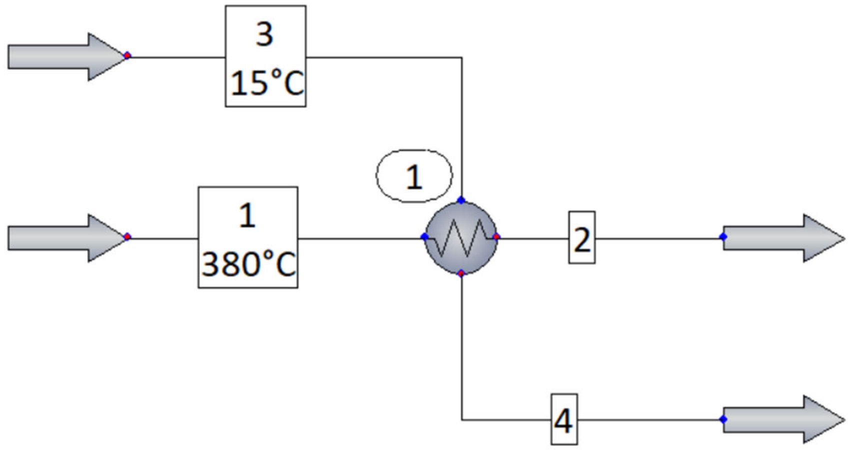
The optimized installed cost of \$45,674 is significantly lower than the optimized cost determined by CHEMCAD of \$78,955 using "Sizing" alone. This is because CHEMCAD sizing optimization does not account for operating costs.

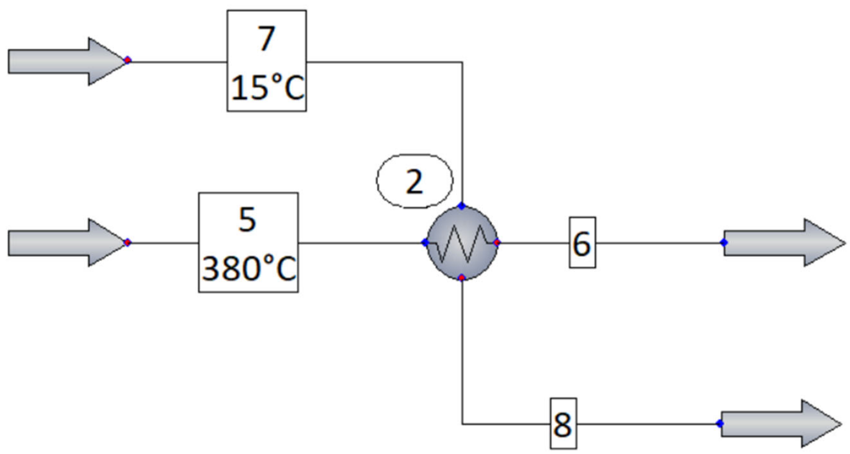


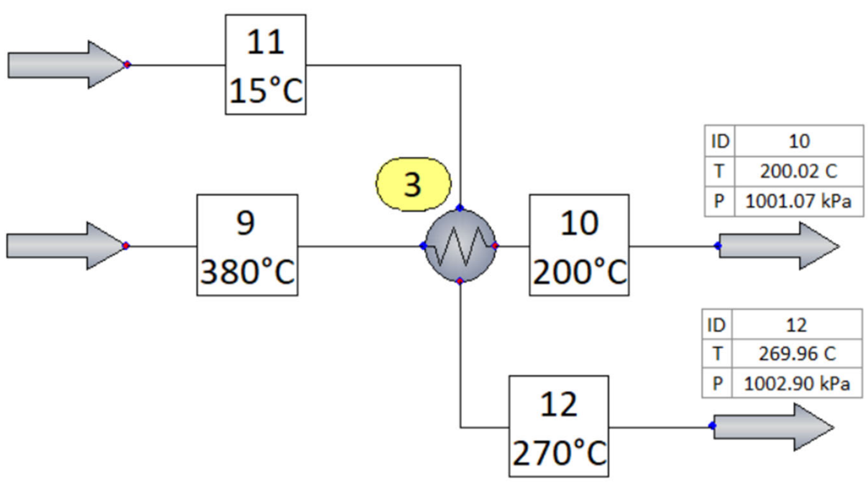


	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
1	**Problem 14-16. Cadet Template**			"sizing" checks are required					Cadets complete this table						
2	Optimimal Heat Exchanger Design						1.143	0.889	0.722	0.596	0.510	0.438	0.393	0.355	0.327
3	Yellow - obtained from CHEMCAD simulations						8	9	10	11	12	13	14	15	16
4	Light Blue - Specifications given in problem - page 753 in PTW textbook						620	370	240	160	115	83	65	52	43
5	White - excel calculations - verified with "checks" (results from CC design)									<---	iterations	--->			
6					"sizing"										
7	**Spreadsheet for evaluating Equation 14-91**				checks		**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
8	Number of tubes	N_t	dimensionless	288	288		620	370	240	160	115	83	65	52	43
9	Length of tubes	L	m	9.750	9.750		8.0	9.0	10.0	11.0	12.0	13.0	14.0	15	16
10	Installed cost, CC	C	$	$77,677	$77,677		$131,140	$90,436	$67,701	$52,147	$42,879	$35,461	$31,241	$27,949	$25,588
11	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
12	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
13	Tube wall thickness	x	m	0.00315	0.00315		0.0032	0.0032	0.0032	0.0032	0.3298	0.0032	0.0032	0.0032	0.0032
14	Outside area of tubes	A_o	m^2	224.1	224.1		395.8	265.7	191.5	140.4	110.1	86.1	72.6	62.2	54.9
15	Installed cost per area	C_{Ao}	$/$m^2$	$347	$347		$331	$340	$354	$371	$389	$412	$430	$449	$466
16	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
17	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
18	Tube-side oulet fluid density, CC	r_{to}	kg/m^3	7.3697	7.3697		7.3475	7.3498	7.3562	7.3277	7.3049	7.2501	7.1775	7.0751	6.9224
19	Tube-side pressure drop, CC	Dp_i	kPa	13.9405	13.9405		13.9405	13.9405	13.9405	16.5633	20.1127	26.9831	36.7011	51.4397	72.5865
20	Tube-side average density	r_t	kg/m^3	6.3827	6.3827		6.3716	6.3727	6.3759	6.3617	6.3503	6.3229	6.2866	6.2354	6.1590
21	Tube-side power loss per area	E_i	Nm/s per m^2	25.7307	25.7307		14.5923	21.7311	30.1368	48.9368	75.9227	130.8364	212.2249	349.8759	566.6674
22	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
23	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
24	Shell-side oulet fluid density, CC	r_{so}	kg/m^3	6.3576	6.3576		6.3804	6.3781	6.3751	6.3792	6.376	6.3807	6.3825	6.3771	6.3754
25	Shell-side pressure drop, CC	Dp_o	kPa	16.7692	16.7692		16.7692	16.7692	16.7692	17.0899	17.1076	17.1621	17.2014	17.2721	17.3742
26	Shell-side average density	r_s	kg/m^3	9.3340	9.3340		9.3454	9.3443	9.3428	9.3448	9.3432	9.3456	9.3465	9.3438	9.3429
27	Shell-side power loss per area	E_o	Nm/s per m^2	15.2341	15.2341		8.6140	12.8320	17.8072	24.7415	31.5925	40.5242	48.1555	56.4286	64.3583
28	Hours of operation per year	H_y	h/y	8000	8000		8000	8000	8000	8000	8000	8000	8000	8000	8000
29	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
30	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
31															
32	Fixed charges		$/y	$15,535	$15,535		$26,228	$18,087	$13,540	$10,429	$8,576	$7,092	$6,248	$5,590	$5,118
33	Tube-side pumping costs		$/y	$5,535	$5,535		$5,544	$5,543	$5,541	$6,598	$8,026	$10,814	$14,794	$20,906	$29,866
34	Shell-side pumping costs		$/y	$3,277	$3,277		$3,273	$3,273	$3,274	$3,336	$3,340	$3,350	$3,357	$3,372	$3,392
35	**Total annual cost**	C_T	**$/y**	**$24,347**	$24,347		$35,045	$26,904	$22,355	$20,363	$19,942	$21,256	$24,399	$29,867	$38,375
36															
37	**Procedure:**														
38	1. Repeat the "Check" calculations in column E.														
39	2. Run ChemCAD in utility mode to determine the necessary flow rate of the cold air.														
40	3. Run sizing in design mode to optimize total purcahe cost.														
41	4. Complete column F for the "sizing" results														
42	5. Vary the tube number while adjusting tube length to keep stream temps on spec.														
43	6. Complete the "iterations" in columns G through Q														
44	7. Add more iterations as necessary to minimize operating costs using equation 14-91														

Complete green cells in this table:		
Tube Length, Optimized, m:	11.66	//ANS
Installed Cost, Optimized, $:	$46,030	
Purchased Cost, Optimized, $:	$40,026	//ANS

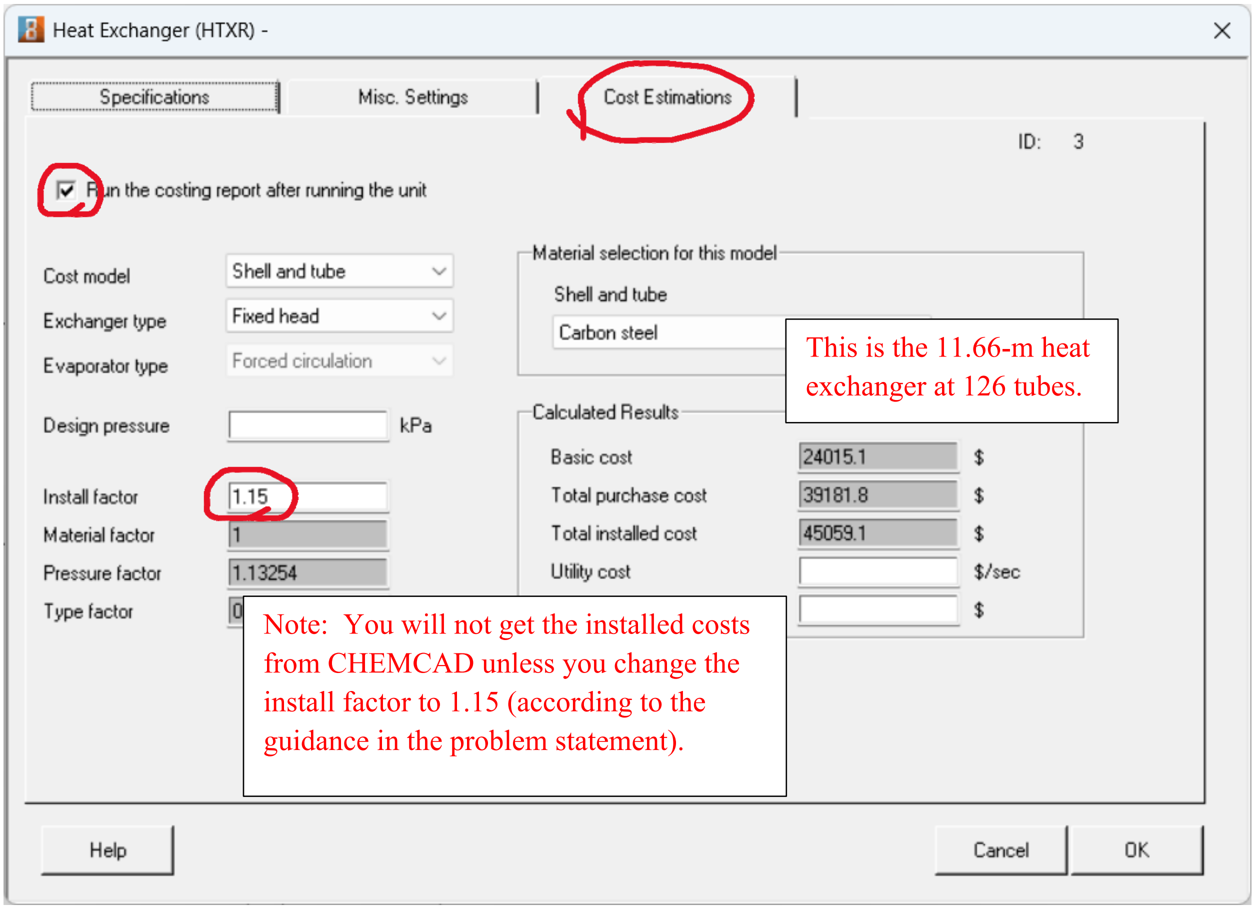




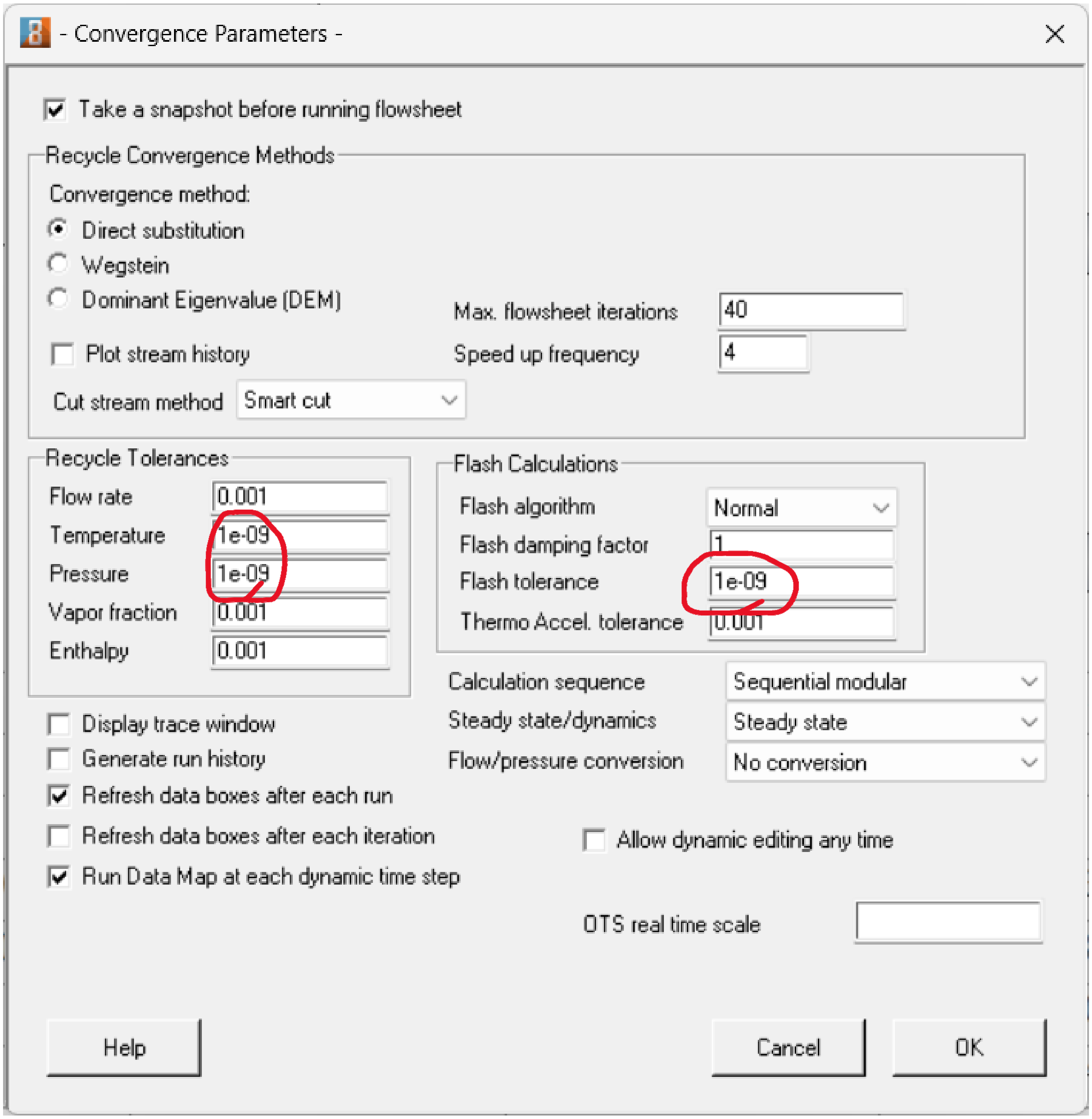


Purchased Cost: $39,182
Installed Cost: $45,059,
From CHEMCAD with 126 11.66-m tubes.

Obtaining installed cost from 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.