

## PROBLEM SET 5

### Problem 14-15

The overhead vapor from the C<sub>2</sub> splitter in Fig. 3-3 is partially condensed in E-601. The process conditions for the vapor entering the condenser are:

Temperature	-30.1°C (sat.)
Pressure	1945.8 kPa (sat.) (changed from 2944 kPa)
Flow rate into condenser	
CH <sub>4</sub>	$3 \times 10^{-3}$ kg/s
C <sub>2</sub> H <sub>4</sub>	64.52 kg/s
C <sub>2</sub> H <sub>6</sub>	$6.26 \times 10^{-2}$ 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 °C 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 °C 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 °C while fixing the vapor fraction to 1 in CHEMCAD, giving the correct process stream pressure of 1945.806 kPa.

#### Solution:

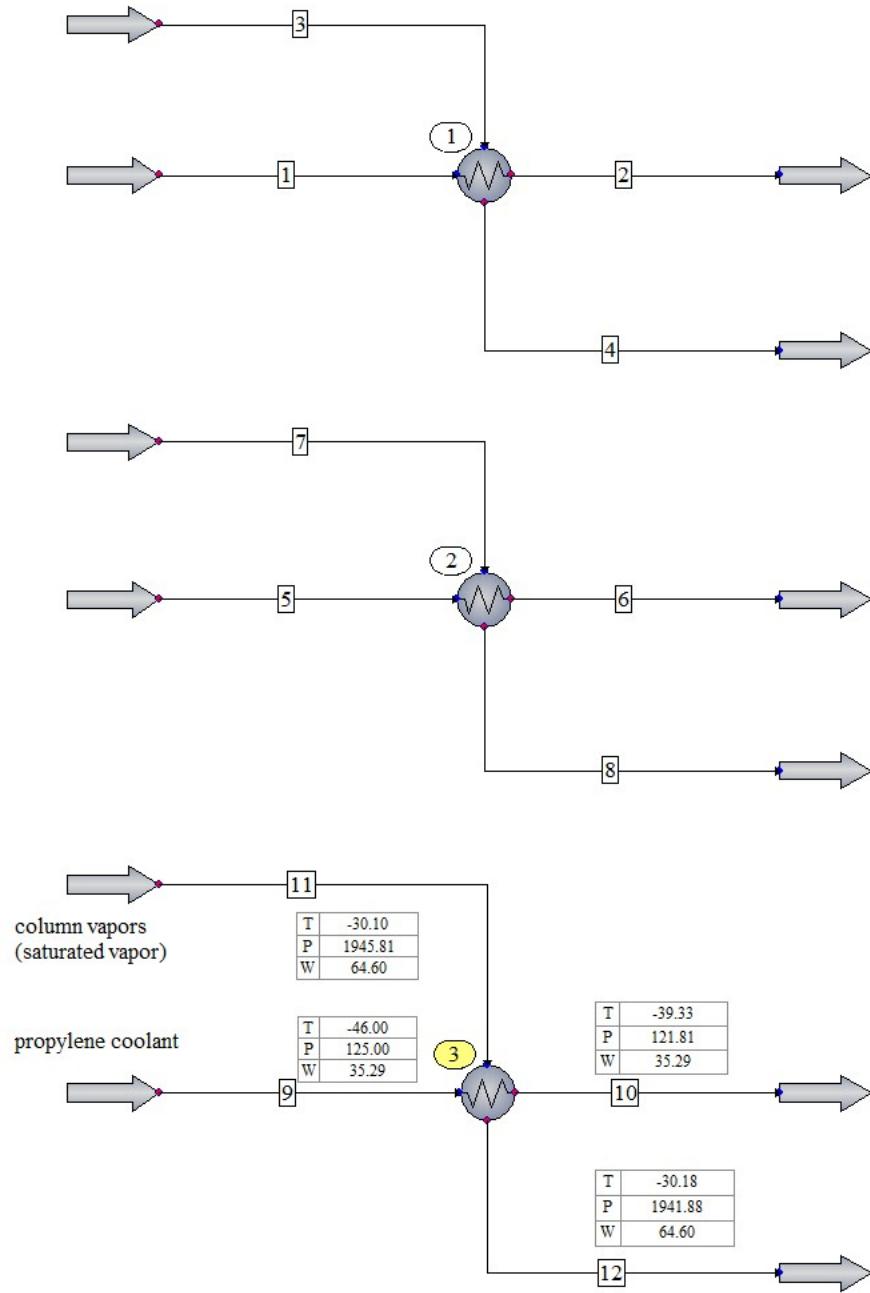
**The detailed procedure for this design is shown in the class notes for Lesson 9.**

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.

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The CHEMCAD flowsheet is shown below:



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

On the HTXR specs, propylene coolant should be nearly vaporized in stream 4 if it is being sent back to a refrigeration cycle. This is why the vapor fraction of stream 4 can be set to 0.995.

Stream	Property	Value
C	Delta temperature specification	
C	Minimum delta temperature	
	Hot outlet - cold inlet	
	Hot inlet - cold outlet	
C	Stream 2 - stream 4	
C	Stream 2 - stream 1	

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 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.

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### TABULATED ANALYSIS - DESIGN MODE

**Overall Data:**

Area Total	m <sup>2</sup>	2348.77	% Excess	5.97
<b>Area Required</b>	<b>m<sup>2</sup></b>	<b>2161.02</b>	U Calc. W/m <sup>2</sup> -K	566.06
Area Effective	m <sup>2</sup>	2290.05	U Service W/m <sup>2</sup> -K	534.16
Area Per Shell	m <sup>2</sup>	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/m <sup>2</sup> -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 <sup>3</sup>	3261.46	Press. Drop (Dirty)	kPa	4.35

**Tube-side Data:**

Film Coef. W/m <sup>2</sup> -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
<b>Shell I.D. m</b>	<b>3.66</b>	Shell in Series	1
Bonnet I.D. m	3.66	Shell in Parallel	1
Type	AEL	Max. Heat Flux Btu/ft <sup>2</sup> -hr	0.00
Imping. Plate	Impingement Plate	Sealing Strip	5

**Tubes:**

Number	19314	Tube Type	Bare
Length m	3.05	Free Int. Fl Area m <sup>2</sup>	0.00
Tube O.D. m	0.013	Fin Efficiency	0.000
Tube I.D. m	0.009	Tube Pattern	TRI60

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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	m <sup>2</sup> -K/W	0.00069
Shell-side Fouling	m <sup>2</sup> -K/W	0.00018
Tube Wall	m <sup>2</sup> -K/W	0.00004
Tube-side Fouling	m <sup>2</sup> -K/W	0.00018
Tube-side Film	m <sup>2</sup> -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 °C before entering the oxidation chamber. The heating is accomplished with the use of product gases, which cool from 380 to 200 °C. 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  $\text{area} = \pi \cdot D_o \cdot L \cdot N_T$ . 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,

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

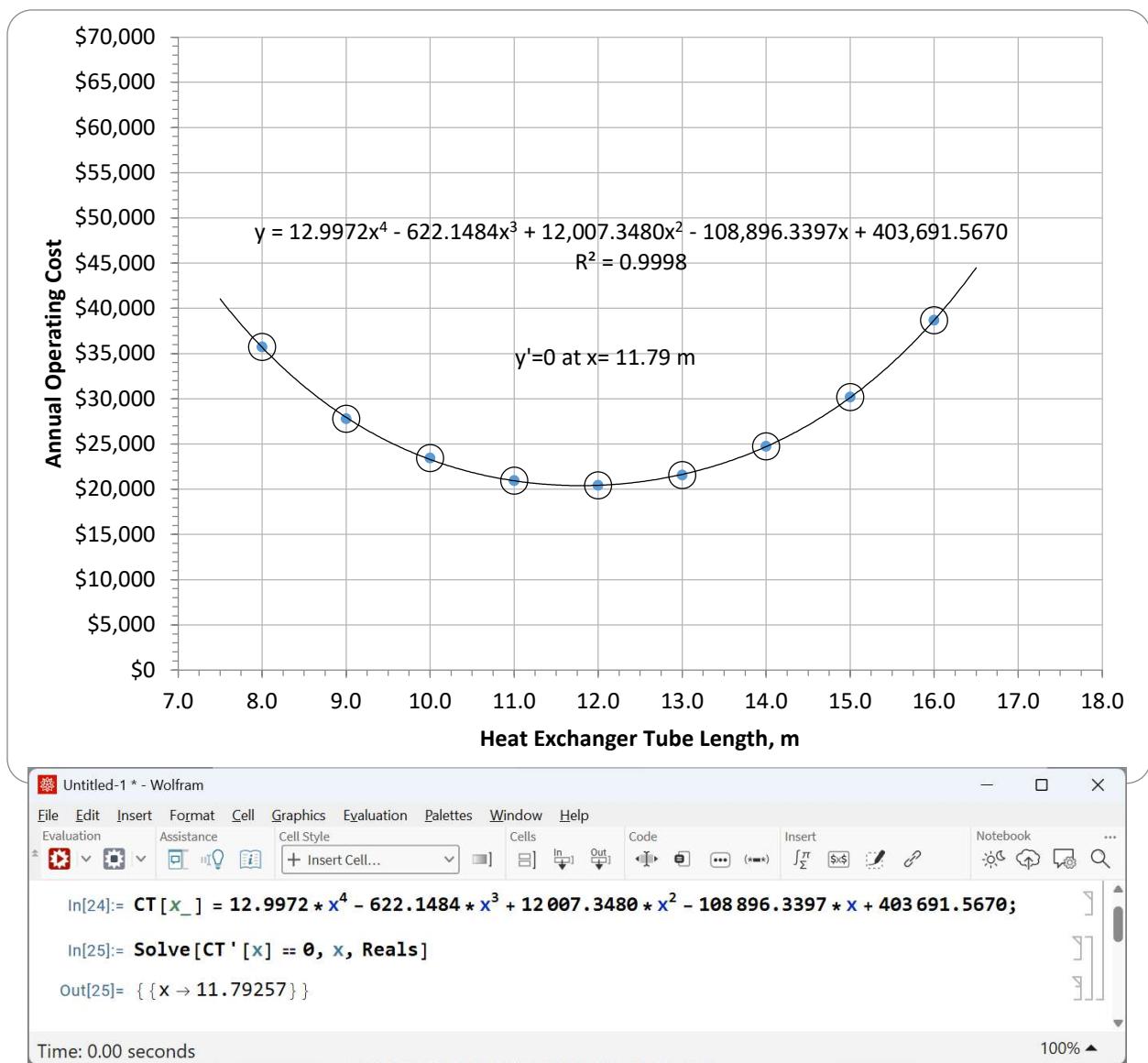
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**Answer:** In Mathematica, take the derivative of the operating cost function  $C_T(x)$  with respect to  $x$ , set it equal to zero, and solve for  $x$ , giving  $x=11.79$  m. The installed cost for the 11.79-m exchanger is \$47,326, obtained by 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.



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Problem 14-16. Cadet Template			"sizing" checks are required		Cadets complete this table								
Optimal Heat Exchanger Design					1.1295	0.8890	0.7220	0.5950	0.5100	0.4440	0.3930	0.3550	0.3280
Yellow - obtained from CHEMCAD simulations													
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 <sub>t</sub>	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 <sub>o</sub>	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 <sub>i</sub>	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 <sub>o</sub>	m <sup>2</sup>	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 <sub>Ao</sub>	\$/m <sup>2</sup>	\$366	\$366	\$350	\$359	\$373	\$392	\$411	\$432	\$454	\$474	\$492
Tube-side (hot gas) flow rate, CC	m <sub>i</sub>	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 <sub>ti</sub>	kg/m <sup>3</sup>	5.3956	5.3956	5.3956	5.3956	5.3956	5.3956	5.3956	5.3956	5.3956	5.3956	5.3956
Tube-side outlet fluid density, CC	r <sub>to</sub>	kg/m <sup>3</sup>	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	D <sub>p</sub> <sub>i</sub>	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 <sub>t</sub>	kg/m <sup>3</sup>	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 <sub>i</sub>	Nm/s per m <sup>2</sup>	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 <sub>o</sub>	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 <sub>si</sub>	kg/m <sup>3</sup>	12.3104	12.3104	12.3104	12.3104	12.3104	12.3104	12.3104	12.3104	12.3104	12.3104	12.3104
Shell-side outlet fluid density, CC	r <sub>so</sub>	kg/m <sup>3</sup>	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	D <sub>p</sub> <sub>o</sub>	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 <sub>s</sub>	kg/m <sup>3</sup>	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 <sub>o</sub>	Nm/s per m <sup>2</sup>	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 <sub>y</sub>	h/y	8000	8000	8000	8000	8000	8000	8000	8000	8000	8000	8000
Cost of pumping power	C <sub>i</sub>	\$/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 <sub>F</sub>	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 <sub>T</sub>	\$/y	\$25,538	\$25,538	\$35,737	\$27,784	\$23,436	\$20,949	\$20,418	\$21,546	\$24,740	\$30,179	\$38,675

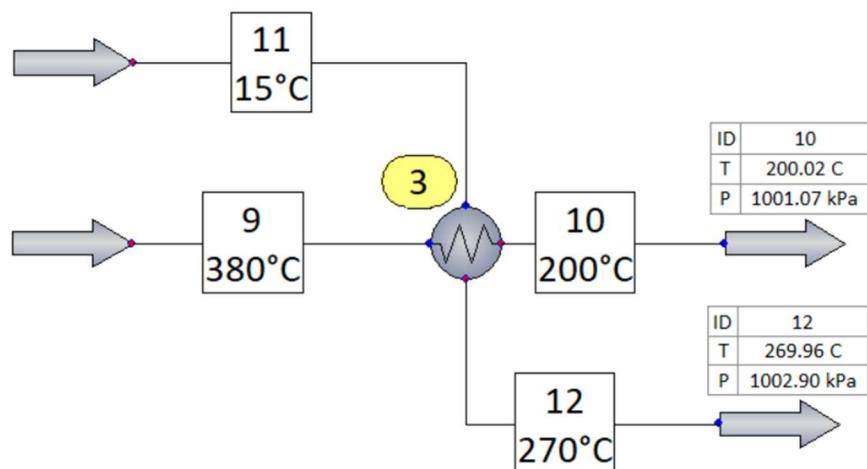
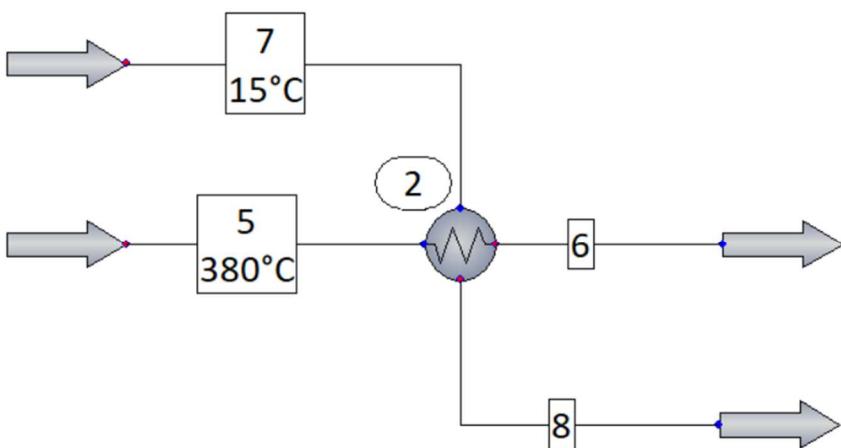
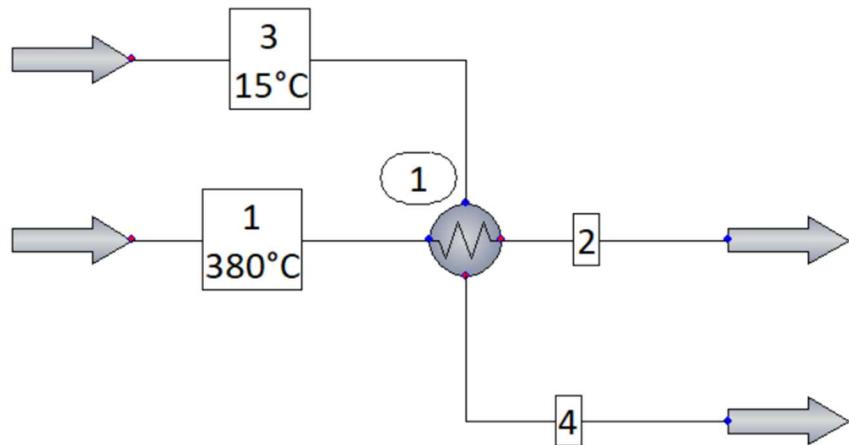
**Procedure:**

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 purchase 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

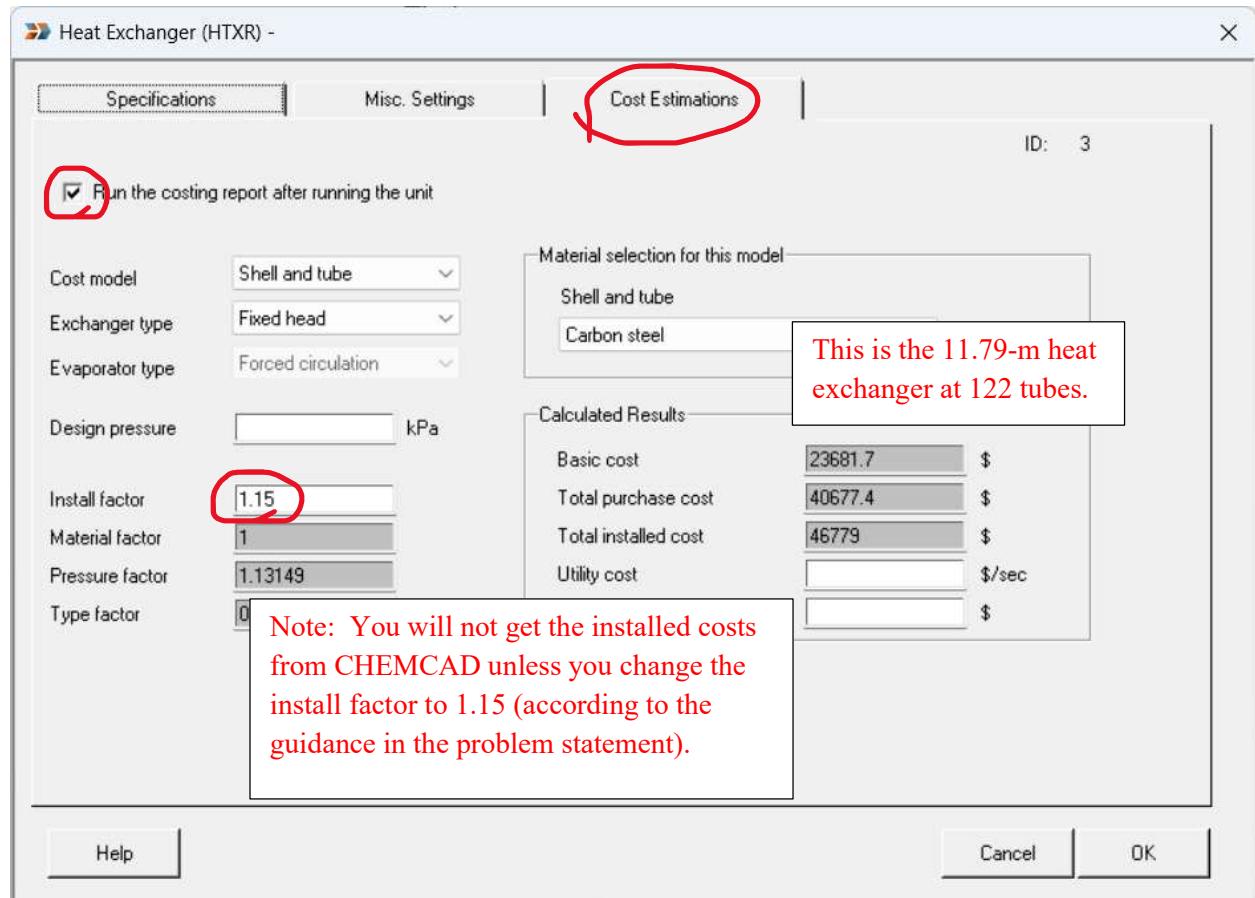
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**Purchased Cost: \$40,677**  
**Installed Cost: \$46,779,**  
**From CHEMCAD with 122 11.79-m tubes.**

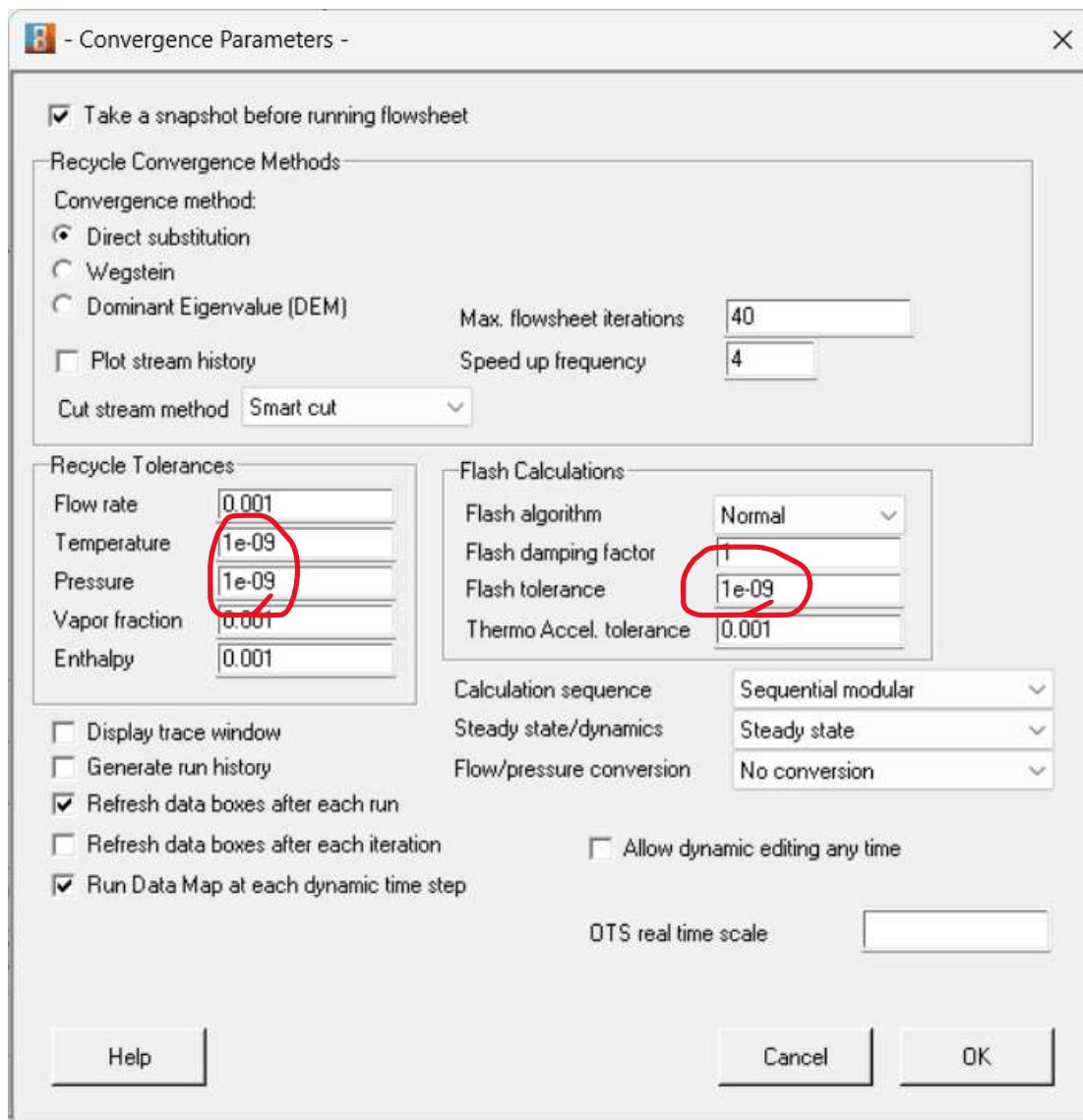
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Obtaining installed cost from CHEMCAD:



### 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.