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 2024.

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.

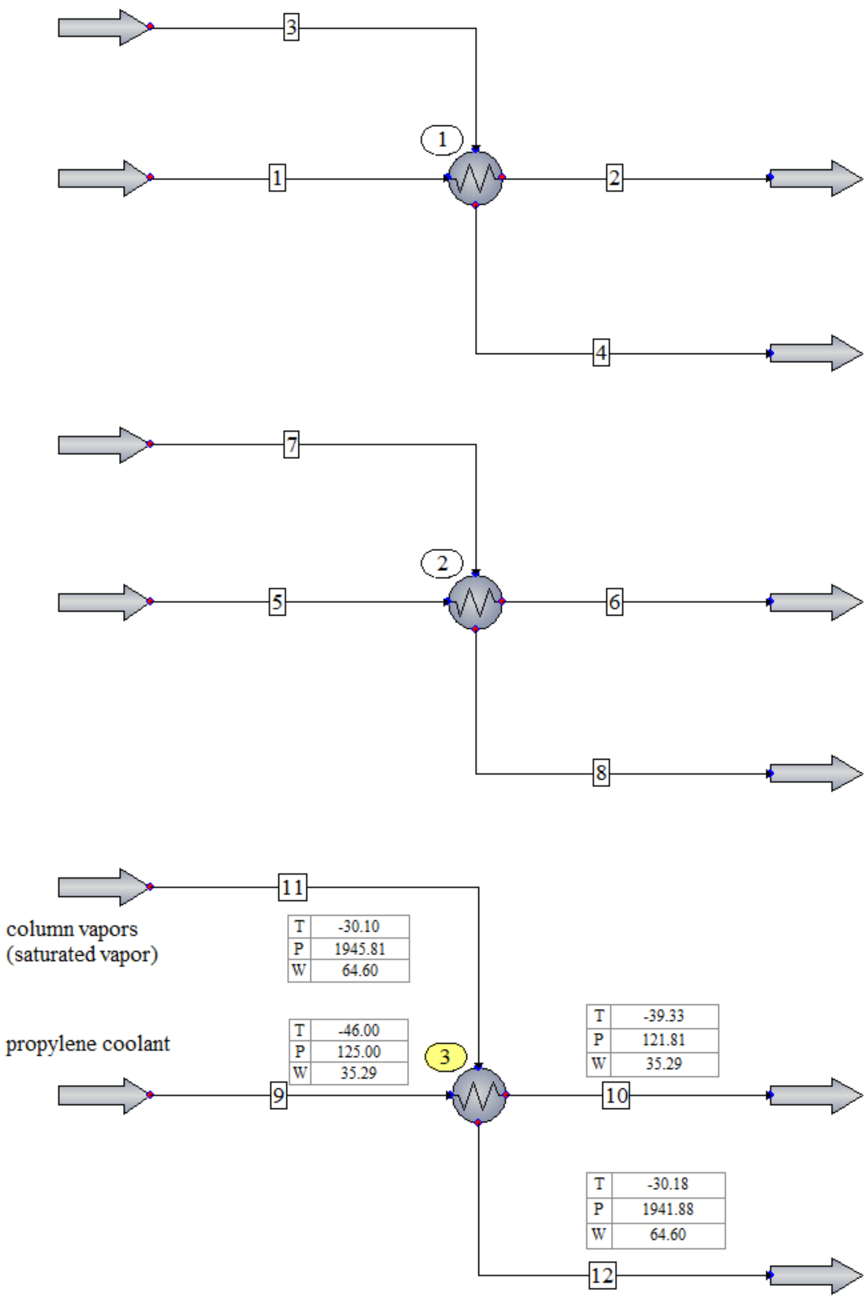
Solution:

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

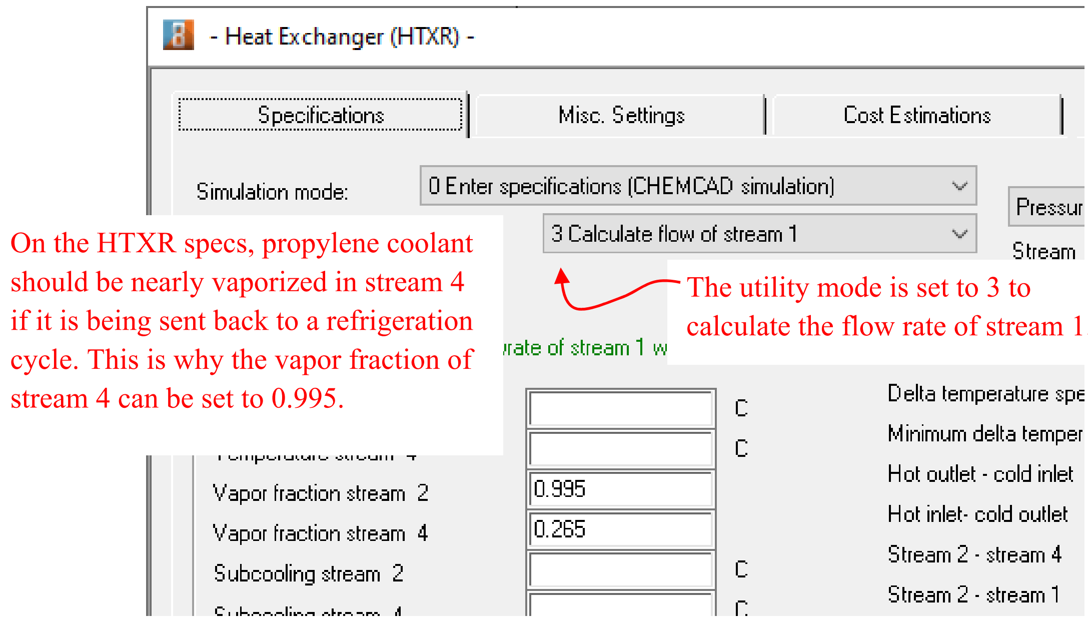
The propylene coolant pressure is unknown, so we need to assume a value. 125 kPa is reasonable since this is about 17 kPa higher than the pressure required to completely condense the coolant. This is an arbitrary assumption but is completely reasonable.

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 2024 is $945,744 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 2024 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 key equation is 14-91 on page 739 of PTW, and this is used to optimize the annual operating expenses in terms of tube length. The equation is best implemented in excel and there is an Excel template available for download from the course SharePoint. The Excel and CHEMCAD solutions are shown below.

- Step 1 of the 3-step method in CHEMCAD gives a hot gas flow rate of 2.64 kg/s.
- Step 2 of the 3-step method gives the "Sizing" results of 252 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 0.25 °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,

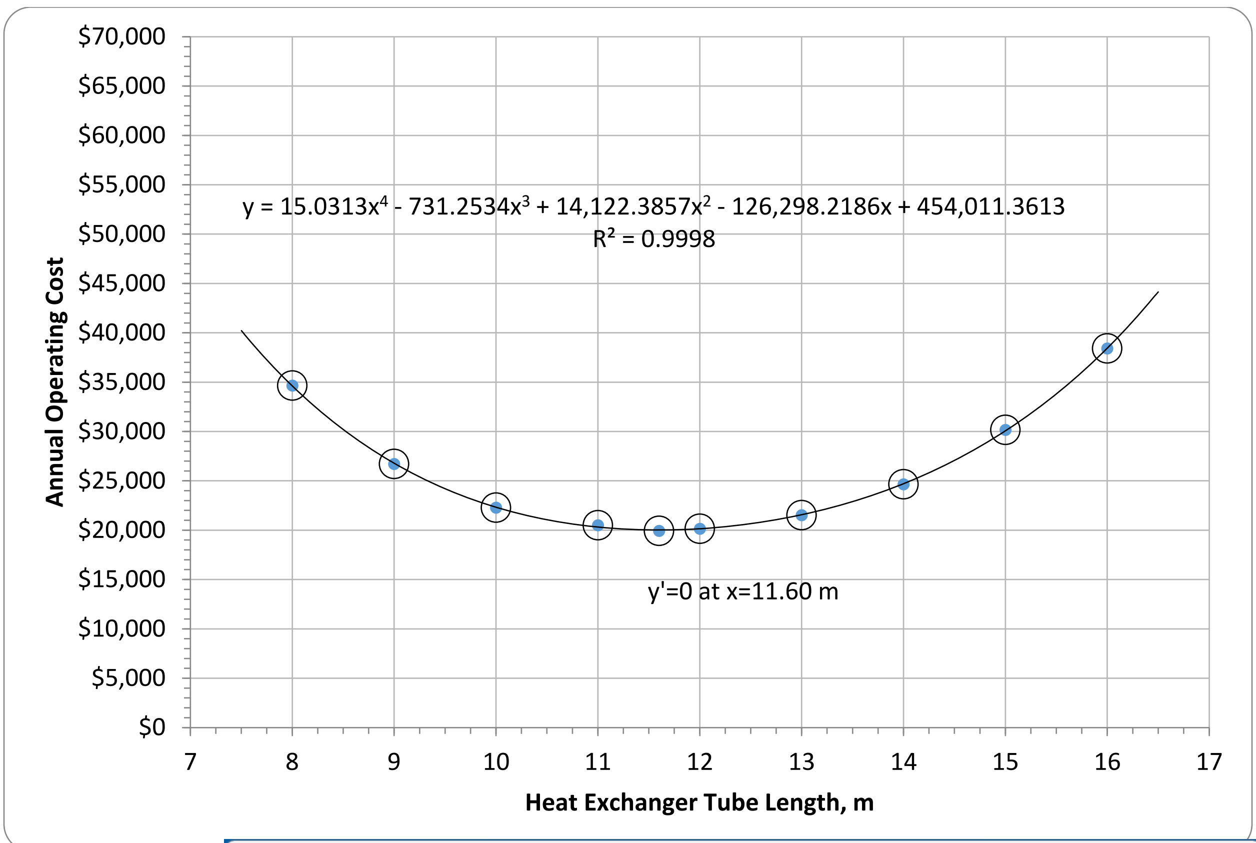
$$C_T(x) = 15.0313x^4 - 731.2534x^3 + 14{,}122.3857x^2 - 126{,}298.2186x + 454{,}011.3613$$

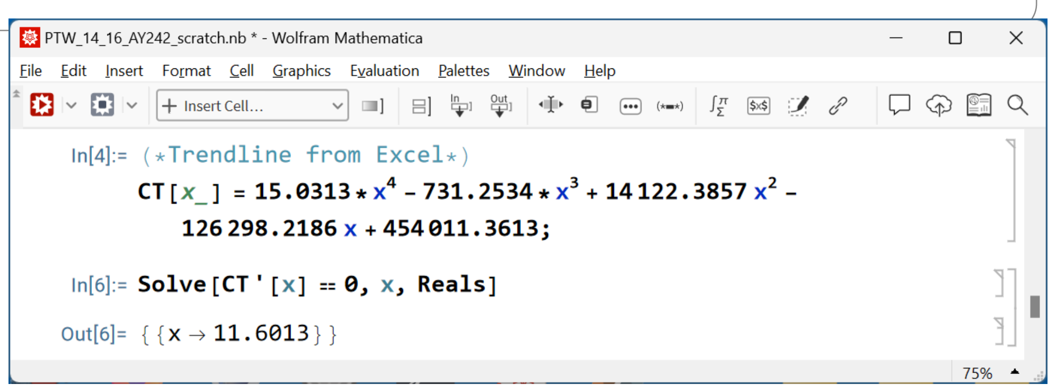
where x is the length of tubes in meters.

Answer: In Mathematica, take the derivative of $C_T(x)$ with respect to x, set it equal to zero, and solve for x, giving x=11.60 m. The annual operating costs of the 11.60-m exchanger is $C_T(11.60)$=$19,932. The installed cost for the 11.60-m exchanger is $45,611, obtained by running and iterating the 11.60-m exchanger with 126 tubes in CHEMCAD. This answer is circled in red in the spreadsheet below. This gives a purchased cost, after dividing by 1.15, of $39,622 //ANS.

Important Conclusion:

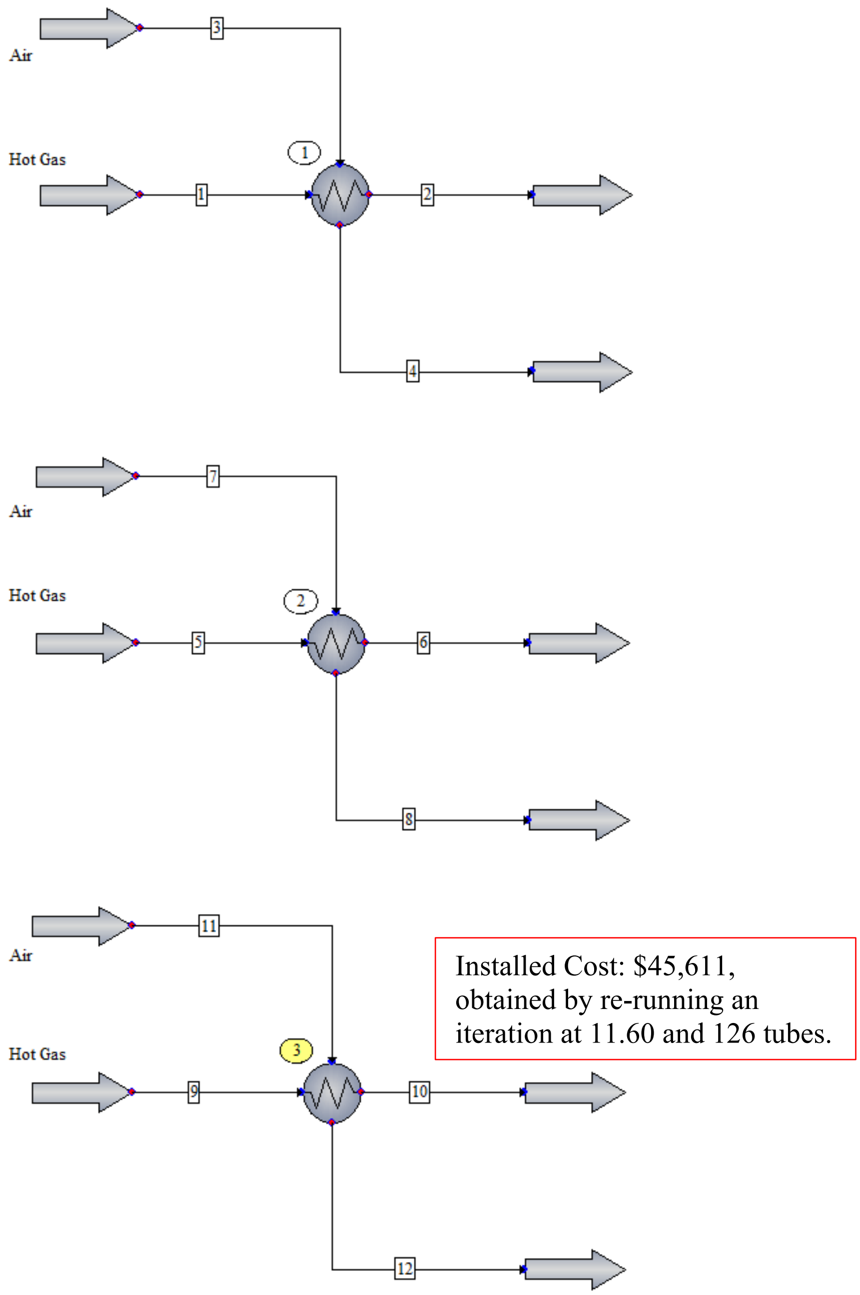
The optimized installed cost of $45,611 is significantly lower than the optimized cost determined by CHEMCAD of $78,955 using "Sizing" alone. This is because CHEMCAD sizing optimization does not account for operating costs.





	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P
1	**Problem 14-16. Cadet Template - Completed**			"checks" are required												
2	Optimimal Heat Exchanger Design						1.125	0.875	0.701	0.590	0.532	0.501	0.438	0.393	0.355	0.327
3	Yellow - CHEMCAD - you will obtain these from CHEMCAD (cadet input)															
4	Aqua - Specifications given in problem - page 753 in PTW															
5	White - short calculations - verify with "checks" (cadet enters an equation)										<---	iterations	--->			
6					"sizing"											
7	**Spreadsheet for evaluating Equation 14-91**				checks		**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
8	Number of tubes	N_t	dimensionless	288	288		600	358	226	157	126	111	83	65	52	43
9	Length of tubes	L	m	9.750	9.750		8	9	10	11	11.6	12	13	14	15	16
10	Installed cost, CC	C	$	$78,955	$78,955		$129,170	$89,220	$65,348	$52,187	$45,611	$42,386	$36,044	$31,754	$28,409	$26,009
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	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	0.0191
13	Tube wall thickness	x	m	0.0032	0.0032		0.0032	0.0032	0.0032	0.0032	0.0032	0.0032	0.0032	0.0032	0.0032	0.0032
14	Outside area of tubes	A_o	m^2	224.1	224.1		383.0	257.1	180.3	137.8	116.6	106.3	86.1	72.6	62.2	54.9
15	Installed cost per area	C_{Ao}	$\$/m^2$	$352	$352		$337	$347	$362	$379	$391	$399	$419	$437	$456	$474
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	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	5.3956
18	Tube-side oulet fluid density, CC	r_{to}	kg/m^3	7.3697	7.3697		7.3409	7.3417	7.3353	7.3234	7.3073	7.2939	7.2475	7.1748	7.0718	6.9232
19	Tube-side pressure drop, CC	Dp_i	kPa	13.9405	13.9405		13.9405	14.1216	14.8023	16.9051	18.7283	20.8501	27.3353	37.0705	51.9109	72.4675
20	Tube-side average density	r_t	kg/m^3	6.3827	6.3827		6.3683	6.3687	6.3655	6.3595	6.3515	6.3448	6.3216	6.2852	6.2337	6.1594
21	Tube-side power loss per area	E_i	Nm/s per m^2	25.7307	25.7307		15.0865	22.7658	34.0379	50.9182	66.7372	81.6132	132.5714	214.4070	353.1743	565.7016
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	1.9000
23	Shell-side inlet fluid density, CC	r_{si}	kg/m^3	12.3104	12.3100		12.3104	12.3104	12.3104	12.3104	12.3140	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		6.3872	6.3857	6.3848	6.3812	6.384	6.3818	6.3808	6.3827	6.3768	6.3752
25	Shell-side pressure drop, CC	Dp_o	kPa	16.7692	16.7692		16.7692	16.6697	17.0433	17.0672	17.1054	17.1076	17.1477	17.1814	17.3007	17.3981
26	Shell-side average density	r_s	kg/m^3	9.3340	9.3338		9.3488	9.3481	9.3476	9.3458	9.3490	9.3461	9.3456	9.3466	9.3436	9.3428
27	Shell-side power loss per area	E_o	Nm/s per m^2	15.2341	15.2344		8.8979	13.1781	19.2095	25.1781	29.8064	32.7208	40.4900	48.0990	56.5230	64.4475
28	Hours of operation per year	H_y	h/y	8000	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	0.12
30	Annual fixed charges factor	K_F	dimensionless	0.2	0.2		0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20
31																
32	Fixed charges		$/y	$15,791	$15,791		$25,834	$17,844	$13,070	$10,437	$9,122	$8,477	$7,209	$6,351	$5,682	$5,202
33	Tube-side pumping costs		$/y	$5,535	$5,535		$5,547	$5,619	$5,893	$6,736	$7,472	$8,328	$10,958	$14,946	$21,103	$29,815
34	Shell-side pumping costs		$/y	$3,277	$3,277		$3,272	$3,253	$3,326	$3,331	$3,337	$3,339	$3,347	$3,353	$3,377	$3,397
35	**Total annual cost**	C_T	**$/y**	**$24,603**	$24,603		$34,653	$26,716	$22,288	$20,505	$19,932	$20,144	$21,513	$24,650	$30,162	$38,413
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.								**Complete this table:**							
41	4. Complete column F for the "sizing" results								Tube Length, Optimized, m:			11.60				
42	5. Vary the tube number while adjusting tube length to keep stream temps on spec.								Installed Cost, Optimized, $:			$45,611				
43	6. Complete the "iterations" in columns G through Q								Purchased Cost, Optimized, $:			$39,662 //ANS				

3-Step Design Process



Stream No.	9	10	11	12
Name	hot gas		air	
- - Overall - -				
Temp C	380.0000	200.3113	15.0000	269.5630
Pres kPa	1020.0000	1001.2717	1020.0000	1002.8946
Mass flow kg/sec	2.6397	2.6397	1.9000	1.9000
Actual dens kg/m3	5.3956	7.3073	12.3104	6.3840

Obtaining installed cost from CHEMCAD: