CH402 Chemical Engineering Process Design

Class Notes L10

Heat Exchanger Design II

(Solution of 14-16 with Equation 14-91)

(These slides apply to CC NXT 1.2.0 only)

WPR 1 – L12– WARNO

Date – 9 February 2026, B&D Hours.

Coverage – Lessons 1-11 (Chapters 12 and 14 and Labs 1-3).

(1) Heat Exchangers – CHEMCAD 3-step method.

- *Simple mode,* including flow rates and exchanger specs.
- *Sizing mode,* including area, number and length of tubes, resistances, Reynolds numbers, and pressure drops.
- *Simulation mode,* including outlet temperatures and exchanger costs.
- Three different exchangers, one for each step.
- Apply equation 14-91 as in problem 14-16.

(2) Pumps and Pipe flow – static and dynamic losses, pump characteristics curve, CHEMCAD pipes, pumps, nodes, and compressors. Be able to explain static and dynamic head.

(3) CHEMCAD and textbook costing tools, especially for heat exchangers, pipes, pumps, compressors.

3 problems, 200 points (80/60/60), 55 minutes

Make sure you understand Problem Sets 1-5 and Labs 1-3.

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 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 gasses 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 Figure 14-19 (p. 682).

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

Annual cost of heat exchanger operation

Important!

$$C_T = \underbrace{A_0 \cdot K_F \cdot C_{A_0}}_{\text{Fixed annual costs}} + \underbrace{\dot{m}_u \cdot H_y \cdot C_u}_{\text{Utility fluid costs}} + \underbrace{A_0 \cdot E_i \cdot H_y \cdot C_i}_{\text{Tube-side pumping costs}} + \underbrace{A_0 \cdot E_0 \cdot H_y \cdot C_0}_{\text{Shell-side pumping costs}}$$

PTW Eq. 14-91, p. 739

C_T Total annual costs, dollars/yr

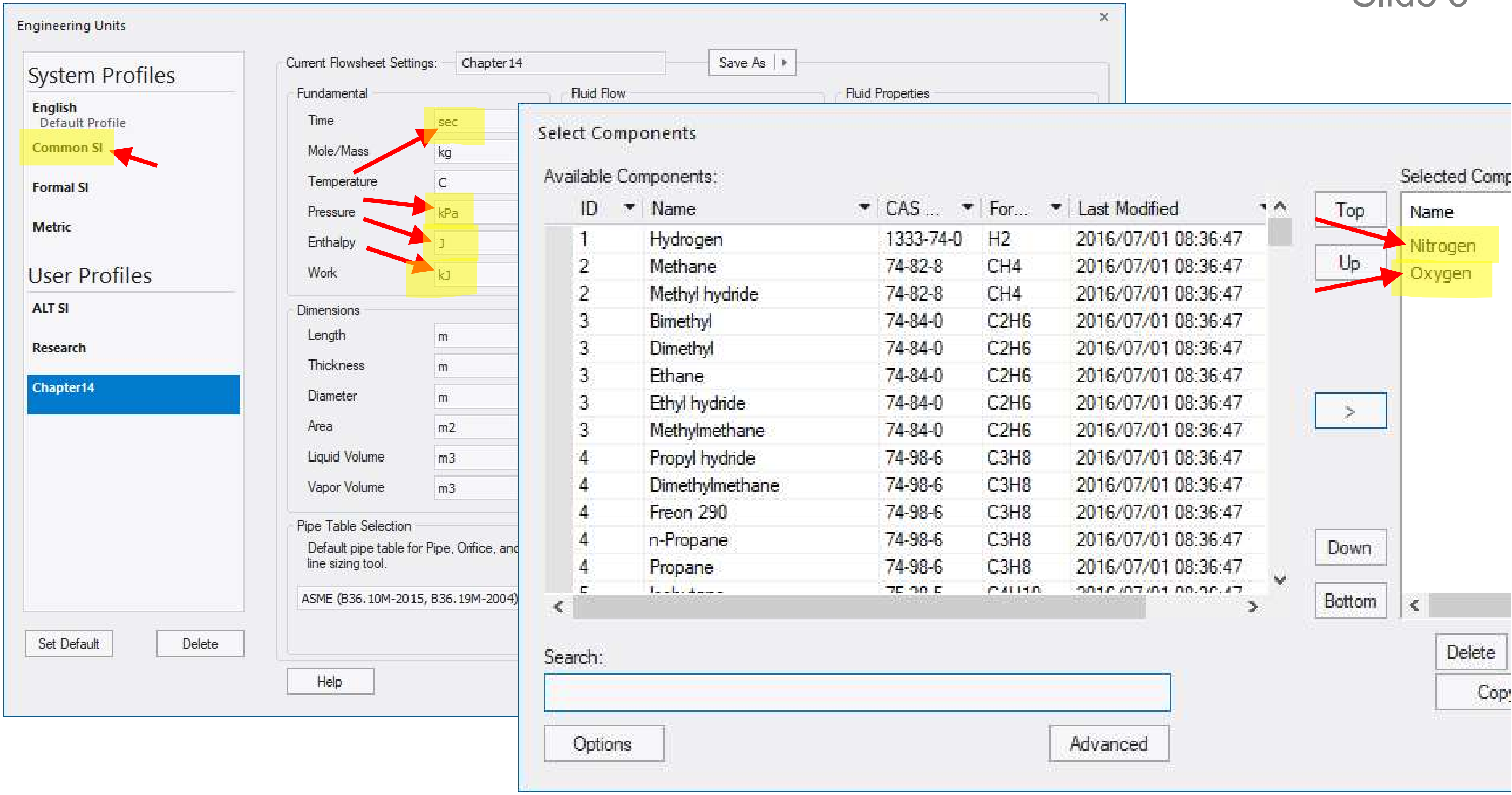
A_0 Outside tube area, m^2
K_F Annual fixed charges factor (maintenance, etc) as a fraction of installed cost, dimensionless
C_{A_0} Installed cost of the heat exchanger per unit outside tube area, dollars/m^2

$\dot{m}_u$ 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/$N \cdot m$

This will be explored in detail in Lesson 11. Today – CHEMCAD base “design” case.

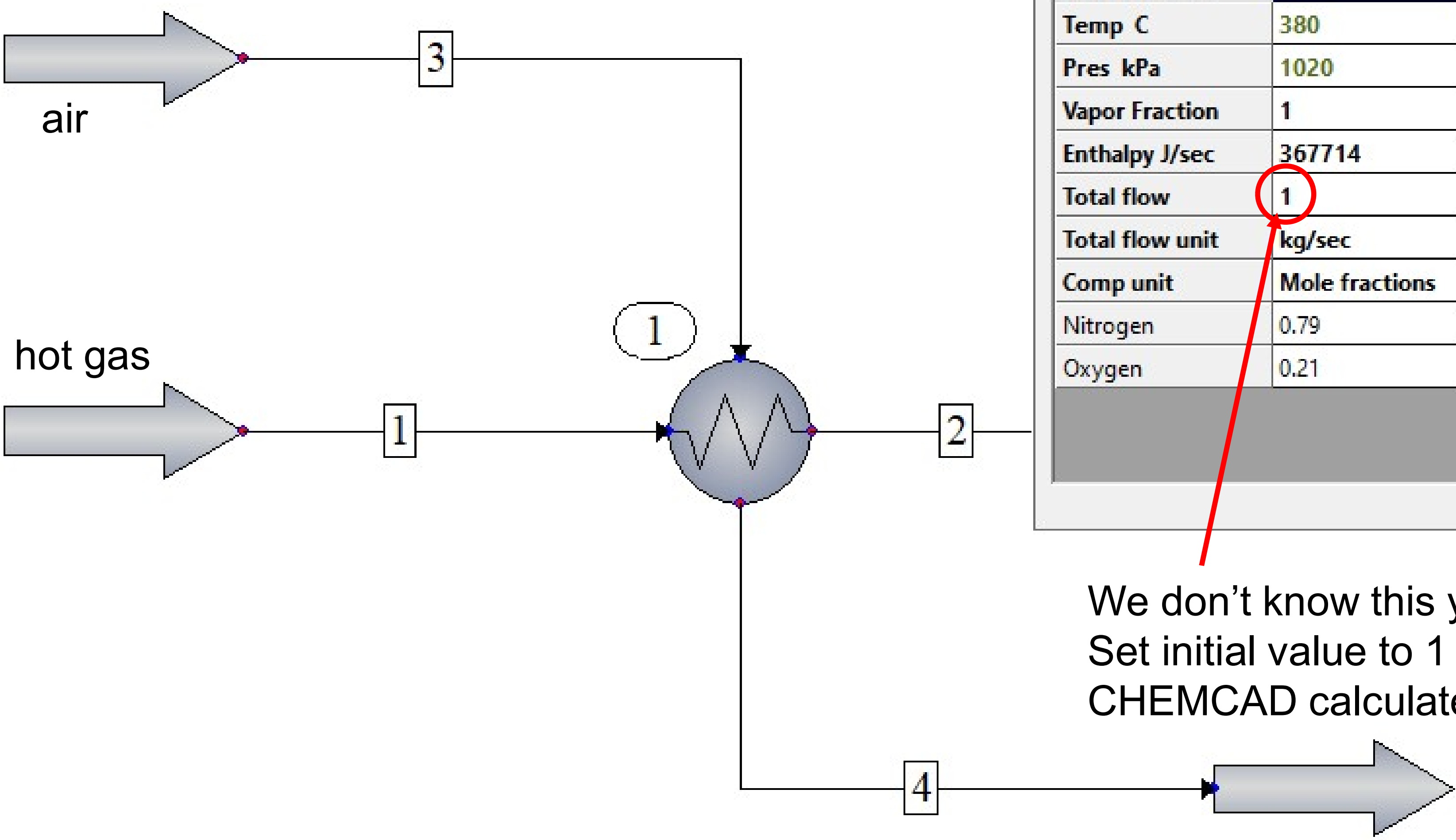


Format Engineering Units:
- Common SI
- Time – seconds
- Pressure – kPa
- Enthalpy – J
- Work – kJ

Thermophysical Select Components:
- Nitrogen and Oxygen
- (Do not use “Air”)

Thermodynamics Wizard:
- SRK for K and H

Level 1 Flowsheet



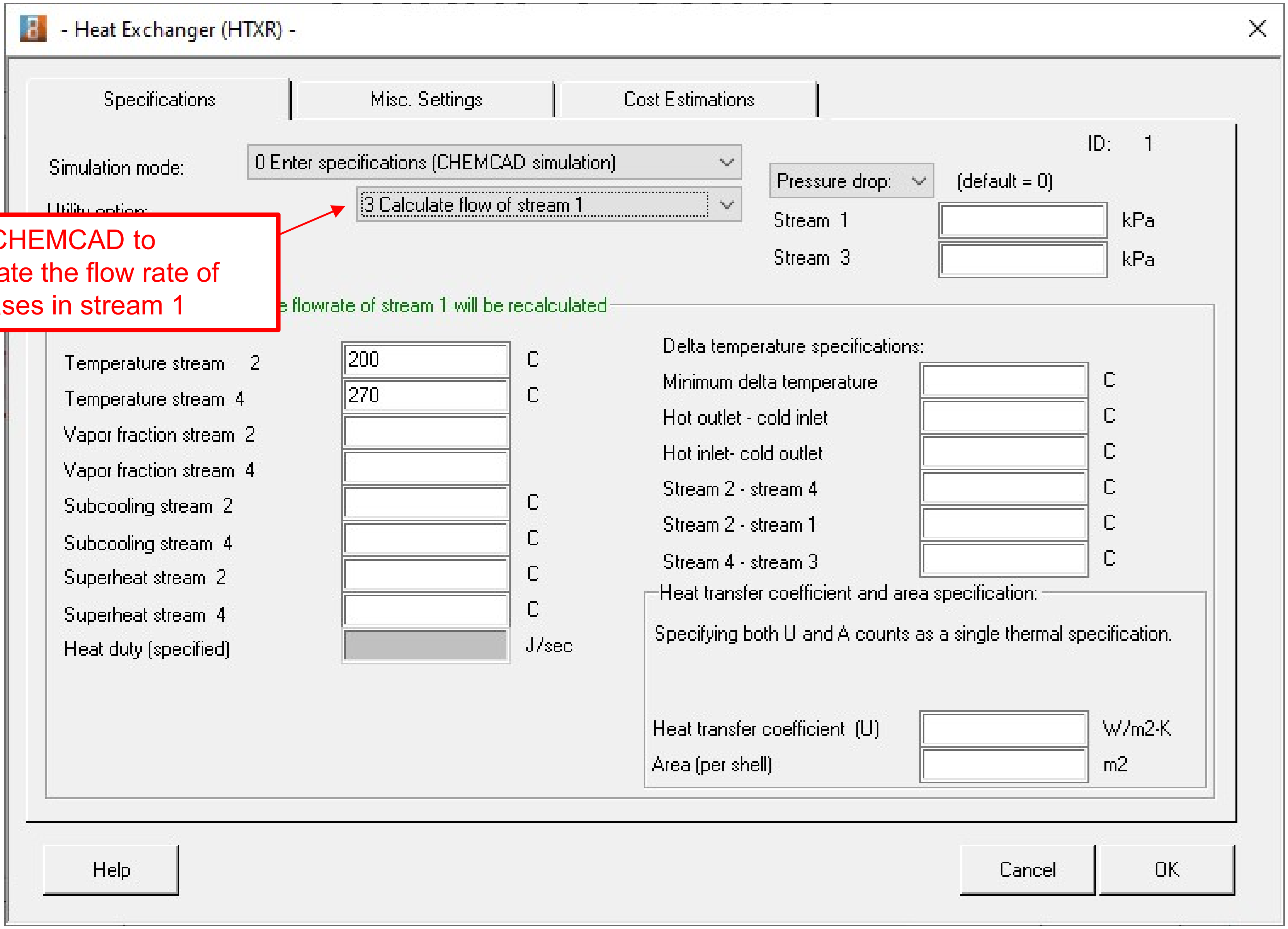
Edit Streams

Flash | Cancel | OK

Stream No.	1	3
Stream Name		
Temp C	380	15
Pres kPa	1020	1020
Vapor Fraction	1	1
Enthalpy J/sec	367714	-23977.57
Total flow	1	1.9
Total flow unit	kg/sec	kg/sec
Comp unit	Mole fractions	Mole fractions
Nitrogen	0.79	0.79
Oxygen	0.21	0.21

We don't know this yet.
Set initial value to 1 kg/s
CHEMCAD calculates it.

Level 1 Specs

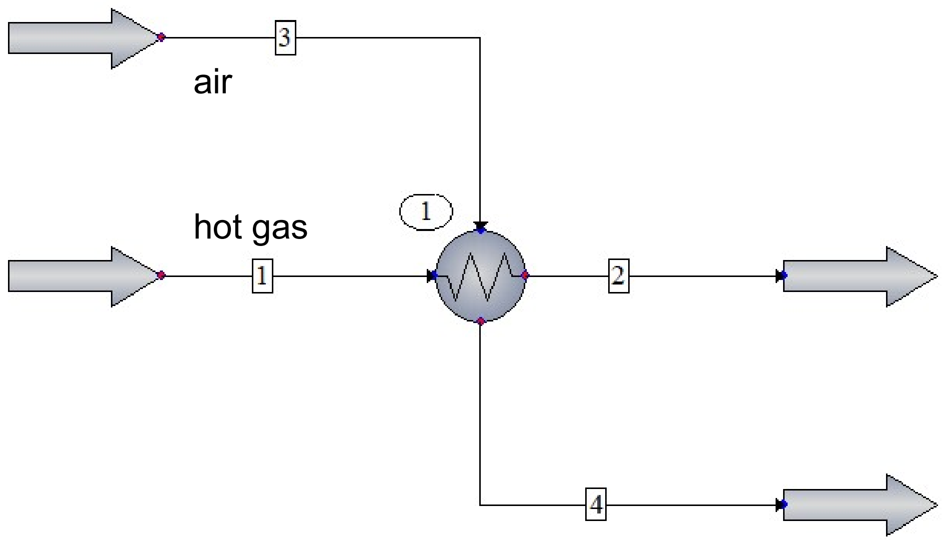


Tells CHEMCAD to calculate the flow rate of hot gases in stream 1

Click “OK” then “Run.” Verify that the flow rate of hot gas is 2.6397 kg/s in stream 1. This completes “Level 1” design.

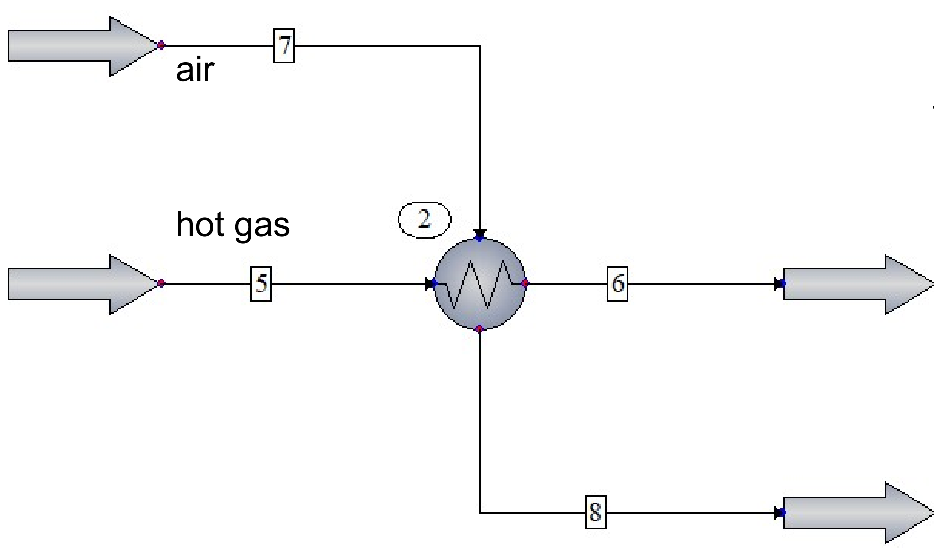
Level 2 Design

Step 1



In Step 1, CHEMCAD solved mass and energy balances and determined unknown hot gas flow rate.

Step 2 – Copy and Paste

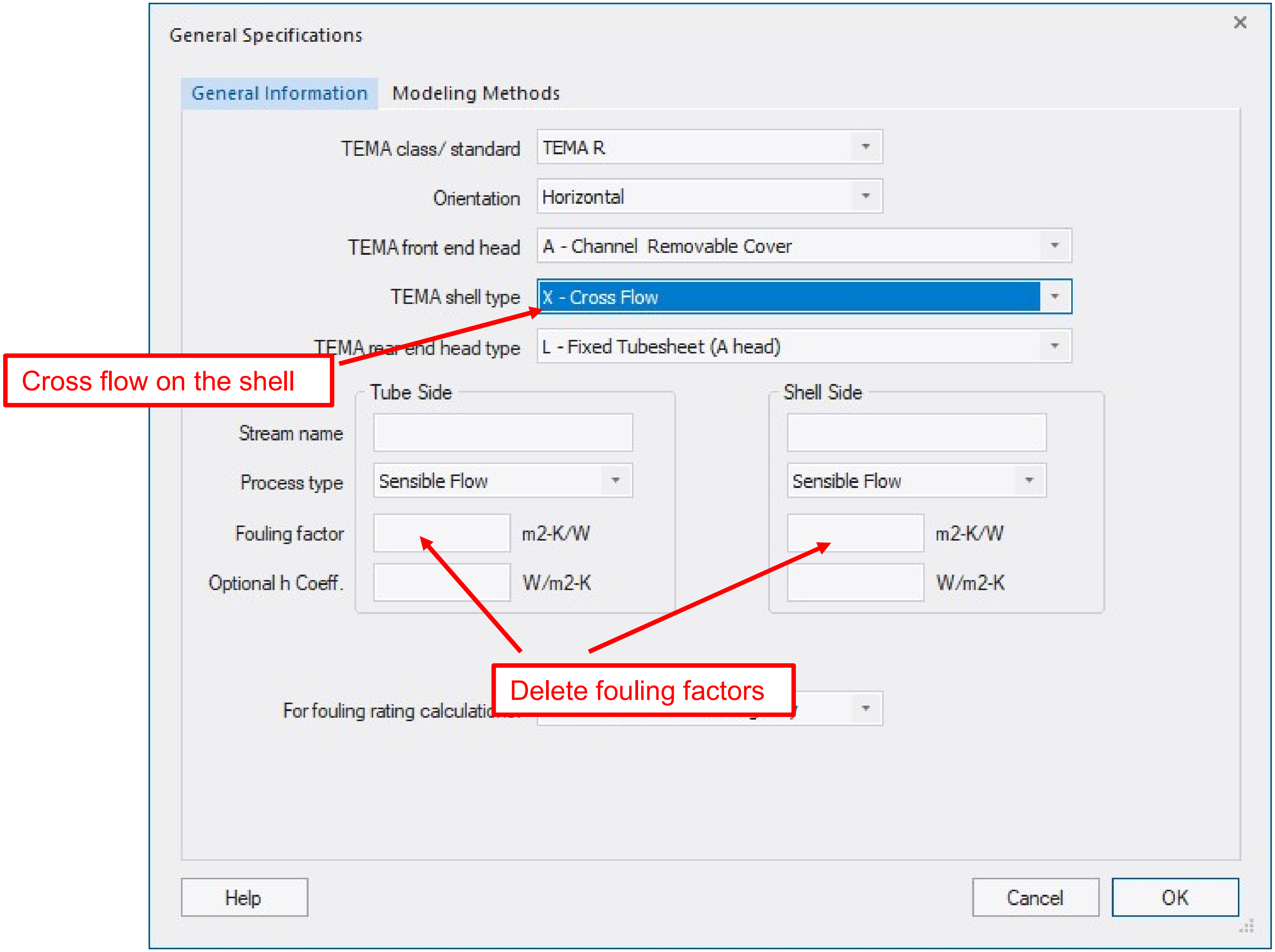


In Step 2, CHEMCAD uses mechanical details to optimize the exchanger in terms of total purchased cost.

Proceed to Sizing -> Shell and Tube, and enter unit 2

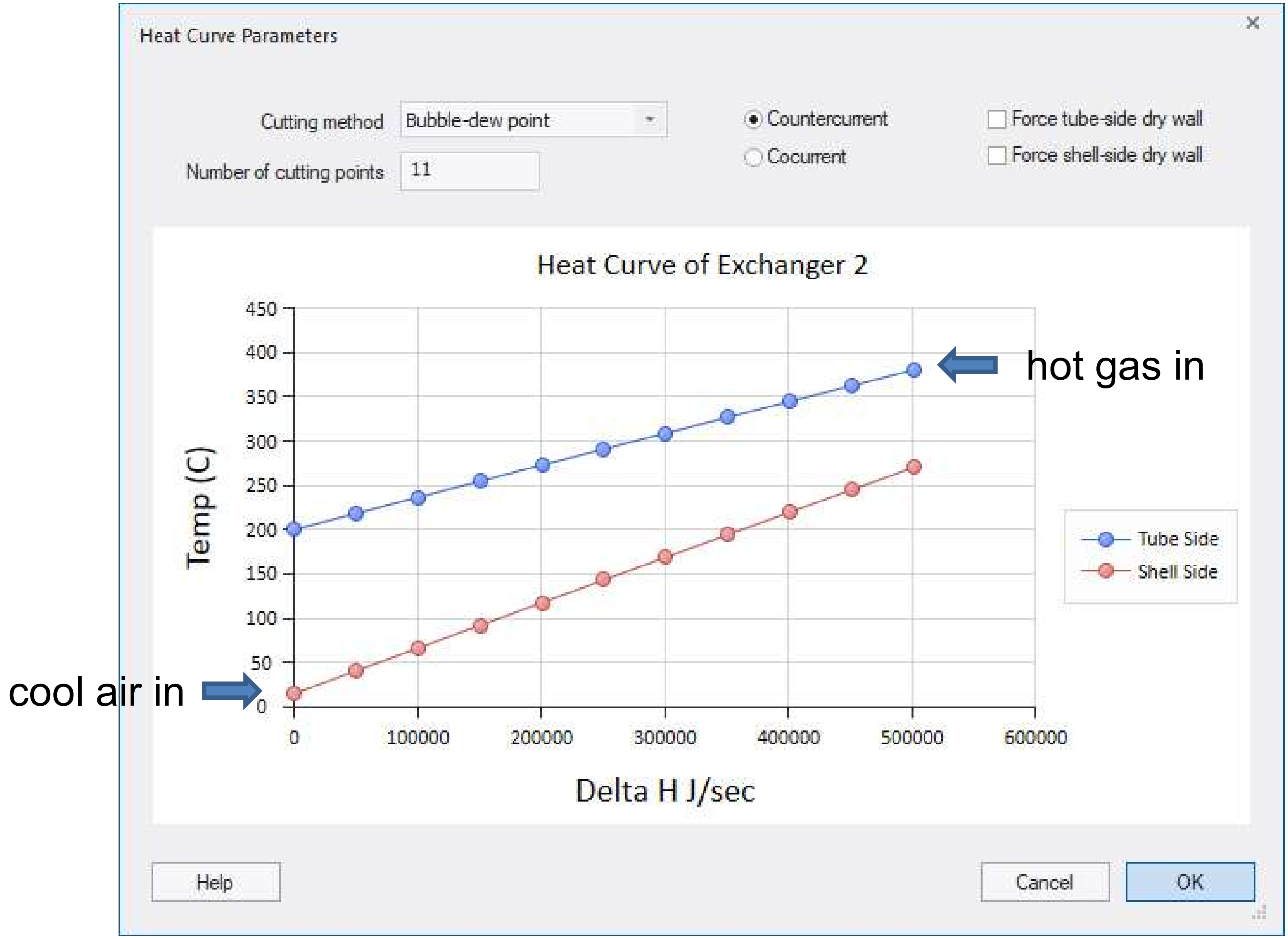
General Specs

In the CCTherm tab, in the Configuration Group, click “General,” and then enter “5” for the stream entering tube side. This opens the General Specs window.

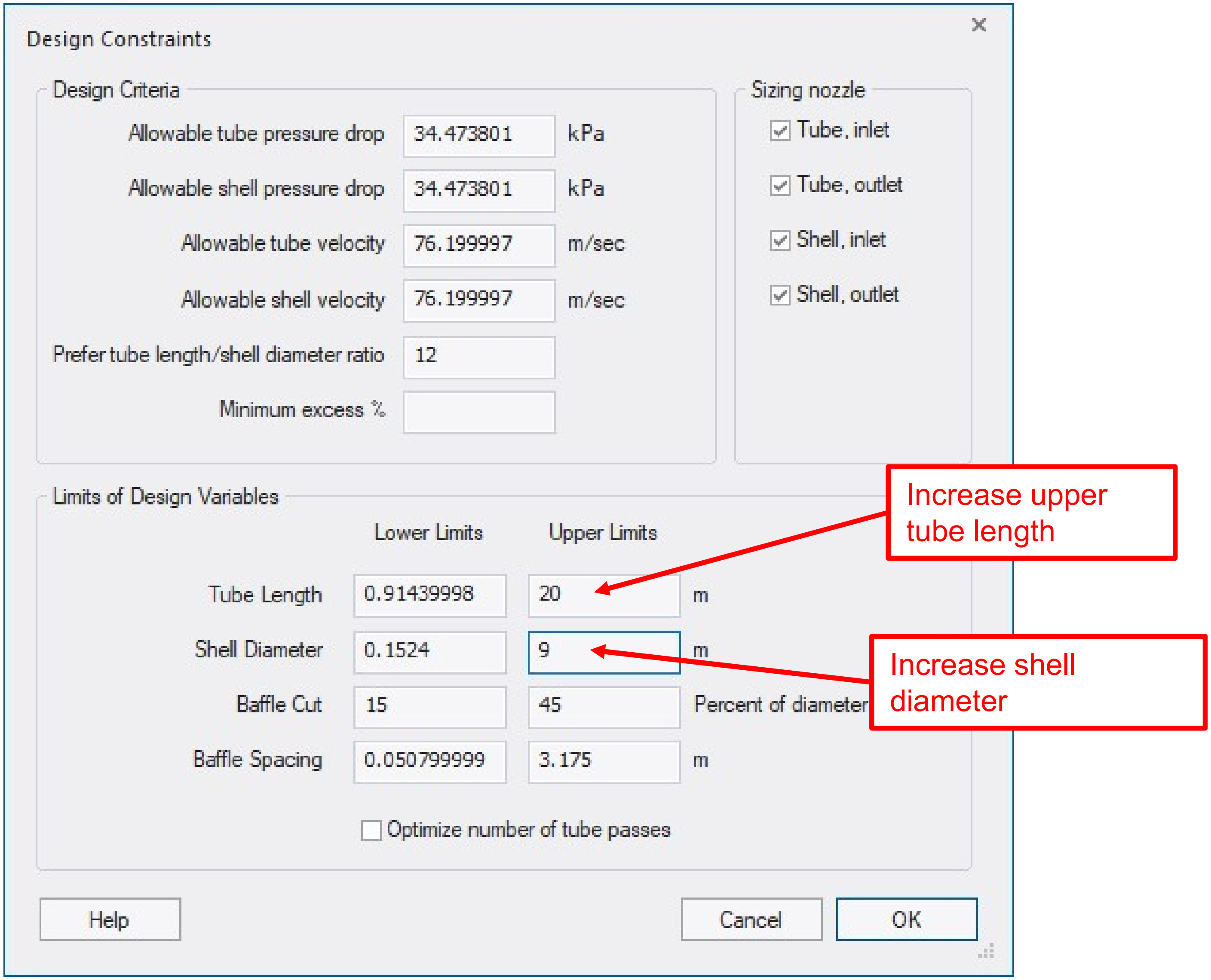


Heat Curves

It is a good idea to look at the heating-cooling curves. Proceed to CCTherm Configuration Group -> Heat Curve Specification

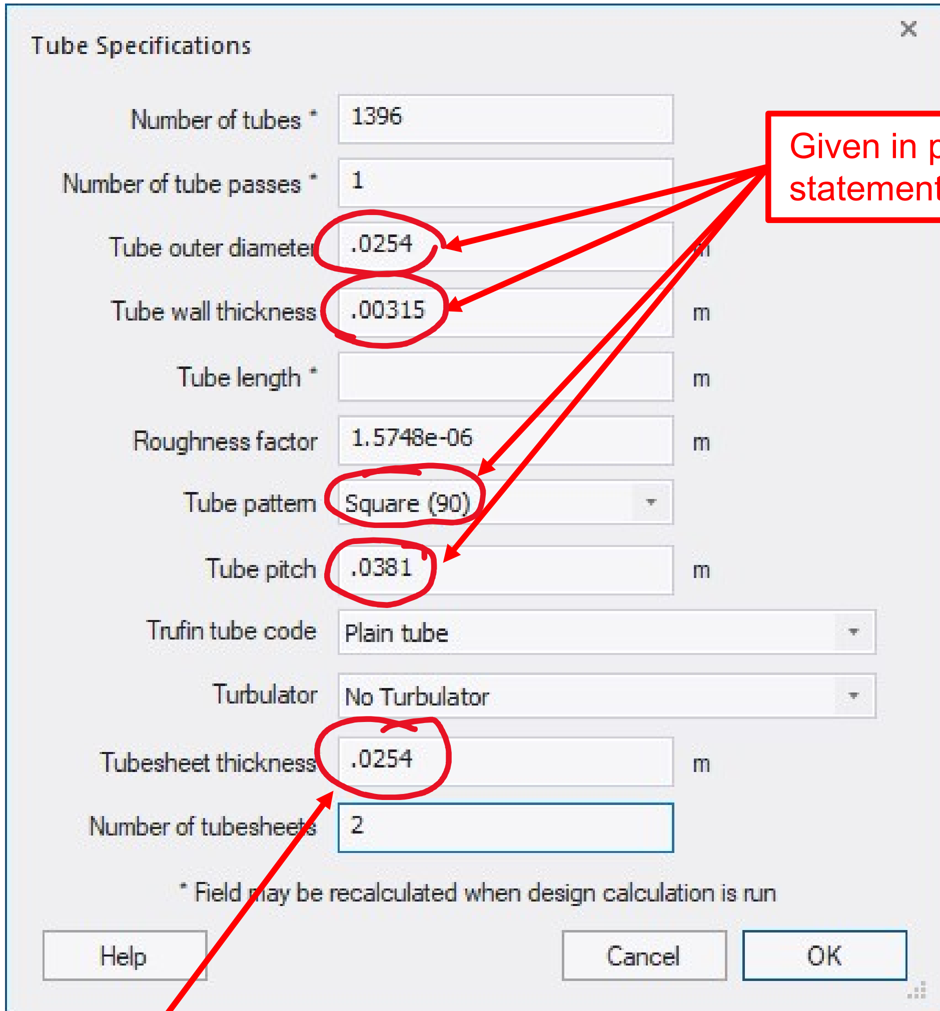


Design Constraints



CCTherm Configuration Group -> General Dropdown -> Design Constraints

Tube Specs

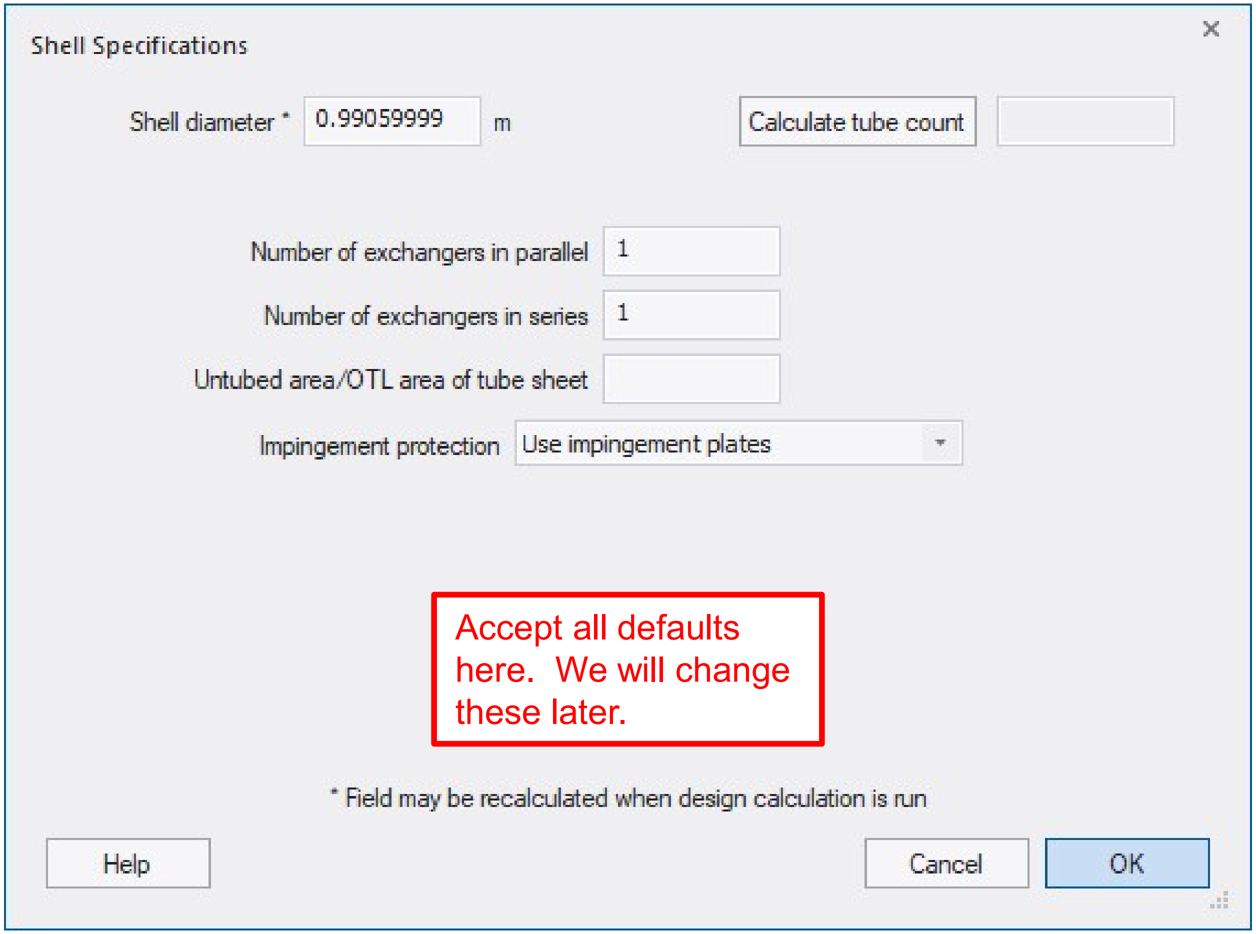


Given in problem statement

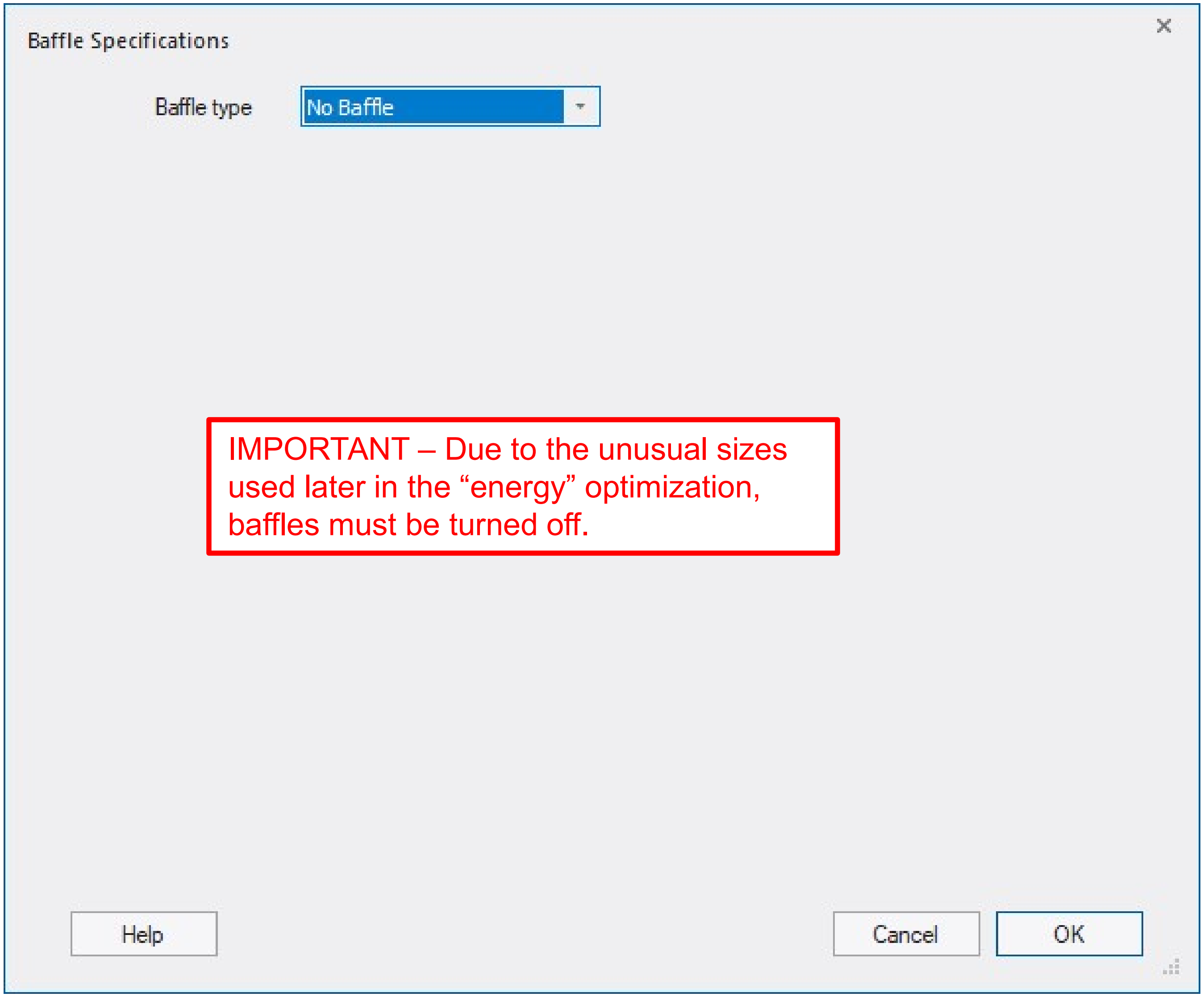
Increase tubesheet thickness to 0.0254 m

This is a TEMA spec on tubesheet thickness. Generally, it must match the tube OD.

Shell Specs

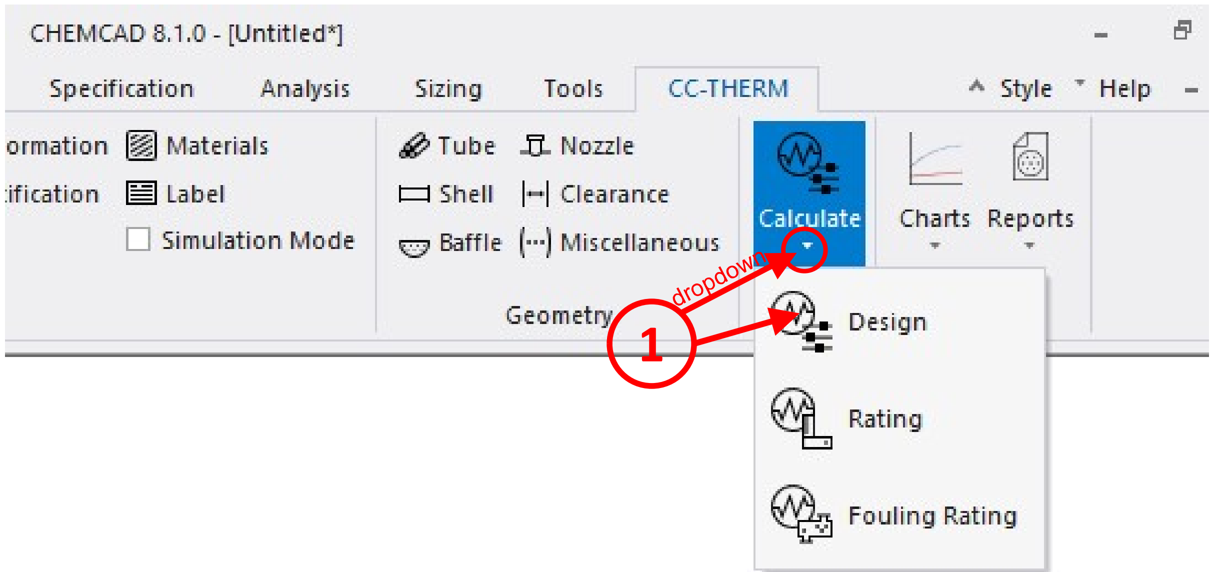

Shell Specifications
Shell diameter *
0.99059999
m
Calculate tube count
Number of exchangers in parallel
1
Number of exchangers in series
1
Untubed area/OTL area of tube sheet
Impingement protection
Use impingement plates
Accept all defaults here. We will change these later.
* Field may be recalculated when design calculation is run
Help
Cancel
OK

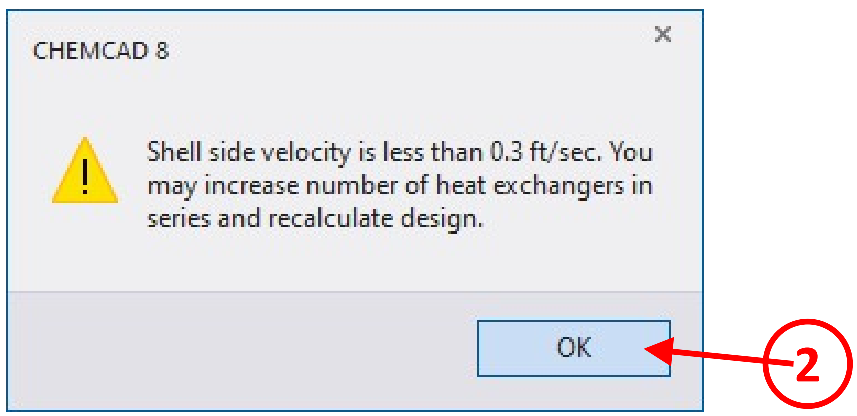
Baffle Specs



IMPORTANT – Due to the unusual sizes used later in the "energy" optimization, baffles must be turned off.

Calculate: Design





TABULATED ANALYSIS

Overall Data:

Area Total	m2	224.15	% Excess		2.72
Area Required	m2	217.08	U Calc.	W/m2-K	19.61
Area Effective	m2	222.98	U Service	W/m2-K	19.09
Area Per Shell	m2	222.98	Heat Duty	J/sec	5.01E+05

Weight LMTD C 144.27 LMTD CORR Factor 0.8154 CORR LMTD C 117.63

Shell-side Data:

Film Coef.	W/m2-K	24.55	Reynolds No.		1502
Allow Press. Drop	kPa	34.47	Calc. Press. Drop	kPa	16.32
Inlet Nozzle Size	m	0.13	Press. Drop/In Nozzle	kPa	1.82
Outlet Nozzle Size	m	0.09	Press. Drop/Out Nozzle	kPa	2.63
			Mean Temperature	C	142.50
Rho V2 IN	kg/m-sec2	1760.30	Press. Drop (Dirty)	kPa	27.74

Low Reynolds Number.

Tube-side Data:

Film Coef.	W/m2-K	130.72	Reynolds No.		20904
Allow Press. Drop	kPa	34.47	Calc. Press. Drop	kPa	13.94
Inlet Nozzle Size	m	0.13	Press. Drop/In Nozzle	kPa	3.72
Outlet Nozzle Size	m	0.10	Press. Drop/Out Nozzle	kPa	2.87
Interm. Nozzle Size	m	0.00			
Velocity	m/sec	5.06			

Shell:

Shell O.D.	m	0.81
Shell I.D.	m	0.79
Bonnet I.D.	m	0.79
Type		AXL
Imping. Plate		Impingement Plate

Tubes:

Number		288
Length	m	9.75
Tube O.D.	m	0.025
Tube I.D.	m	0.019
Tube Wall Thk.	m	0.003
No. Tube Pass		1
Inner Roughness	m	0.0000016
Number of tubesheets		2

Resistances:

Shell-side Film	m2-K/W	0.04073
Shell-side Fouling	m2-K/W	0.00000
Tube Wall	m2-K/W	0.00008
Tube-side Fouling	m2-K/W	0.00000
Tube-side Film	m2-K/W	0.00765

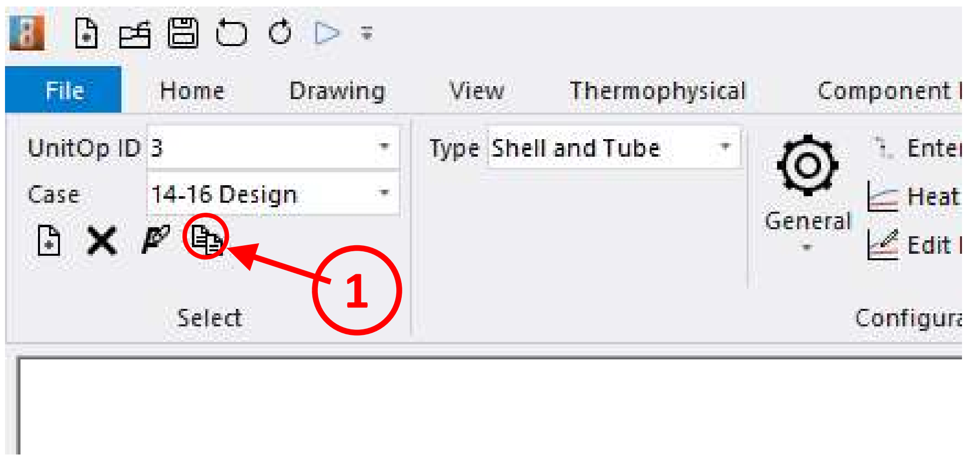
Reference Factor (Total outside area/inside area based on tube ID) 1.330

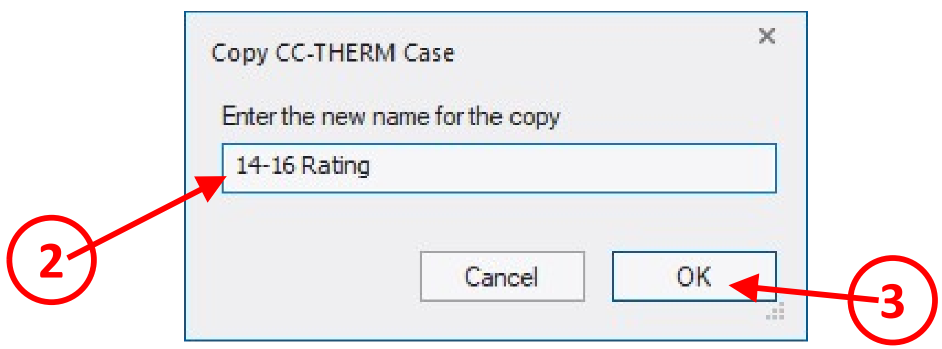
Pressure Drop Distribution:

Tube Side			Shell Side		
Inlet Nozzle	kPa	3.7201	Inlet Nozzle	kPa	1.8239
Tube Entrance	kPa	0.0389	Impingement	kPa	1.1442
Tube	kPa	1.0672	Bundle	kPa	0.0136
Tube Exit	kPa	0.0686	Outlet Nozzle	kPa	2.6325
End	kPa	0.0000	Total Fric.	kPa	4.4700
Outlet Nozzle	kPa	2.8731	Total Grav.	kPa	-0.0713
Total Fric.	kPa	7.7678	Total Mome.	kPa	11.9172
Total Grav.	kPa	0.0559	Total	kPa	16.3159
Total Mome.	kPa	6.1167			
Total	kPa	13.9405			

Create a Copy of Your CCTherm Design

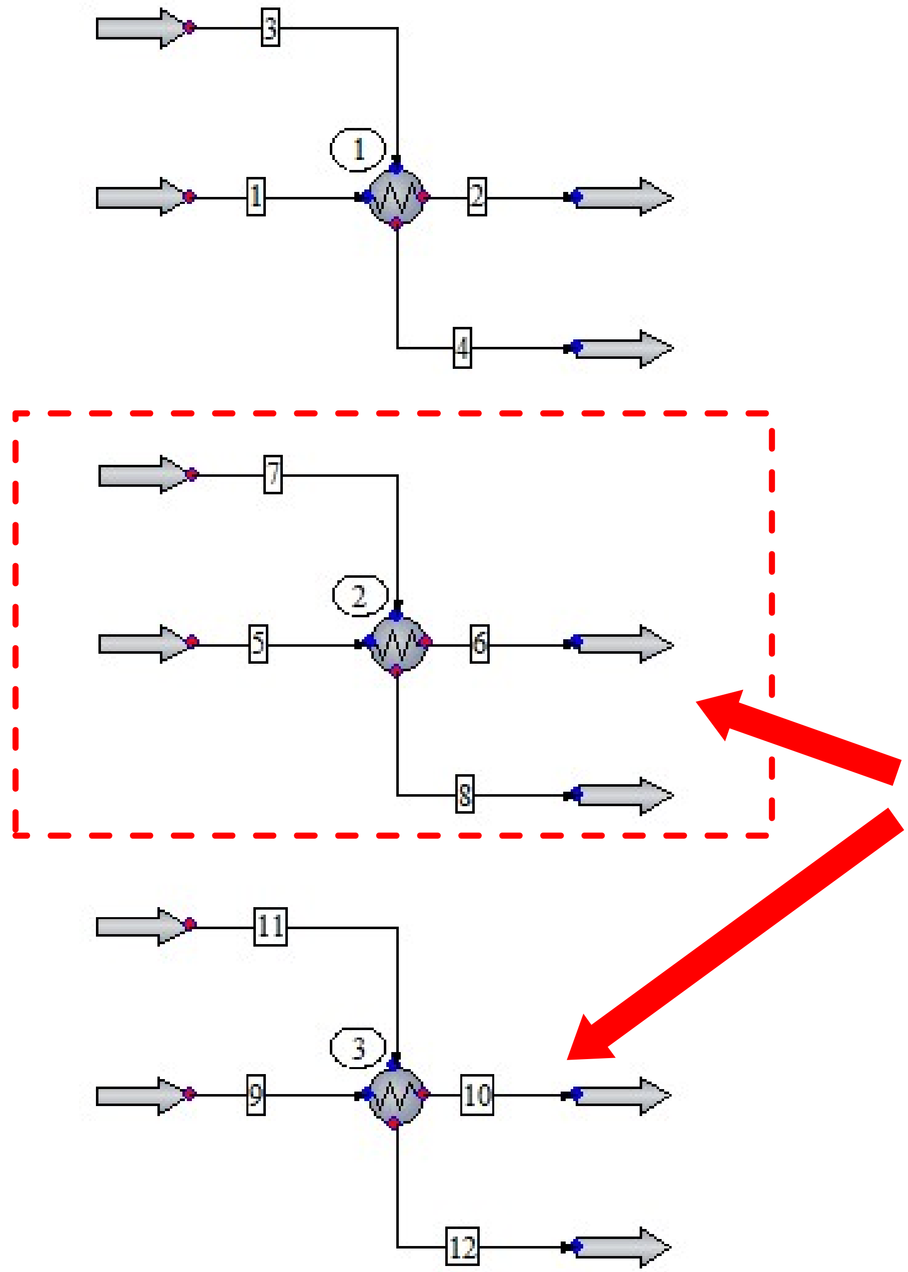
Create a copy of your CCTherm design. This guards against loosing your work through mistakes. In the CCTherm "Select" Group -> Click "Copy CCTherm Case"





Level 3 – Shell and Tube Simulation

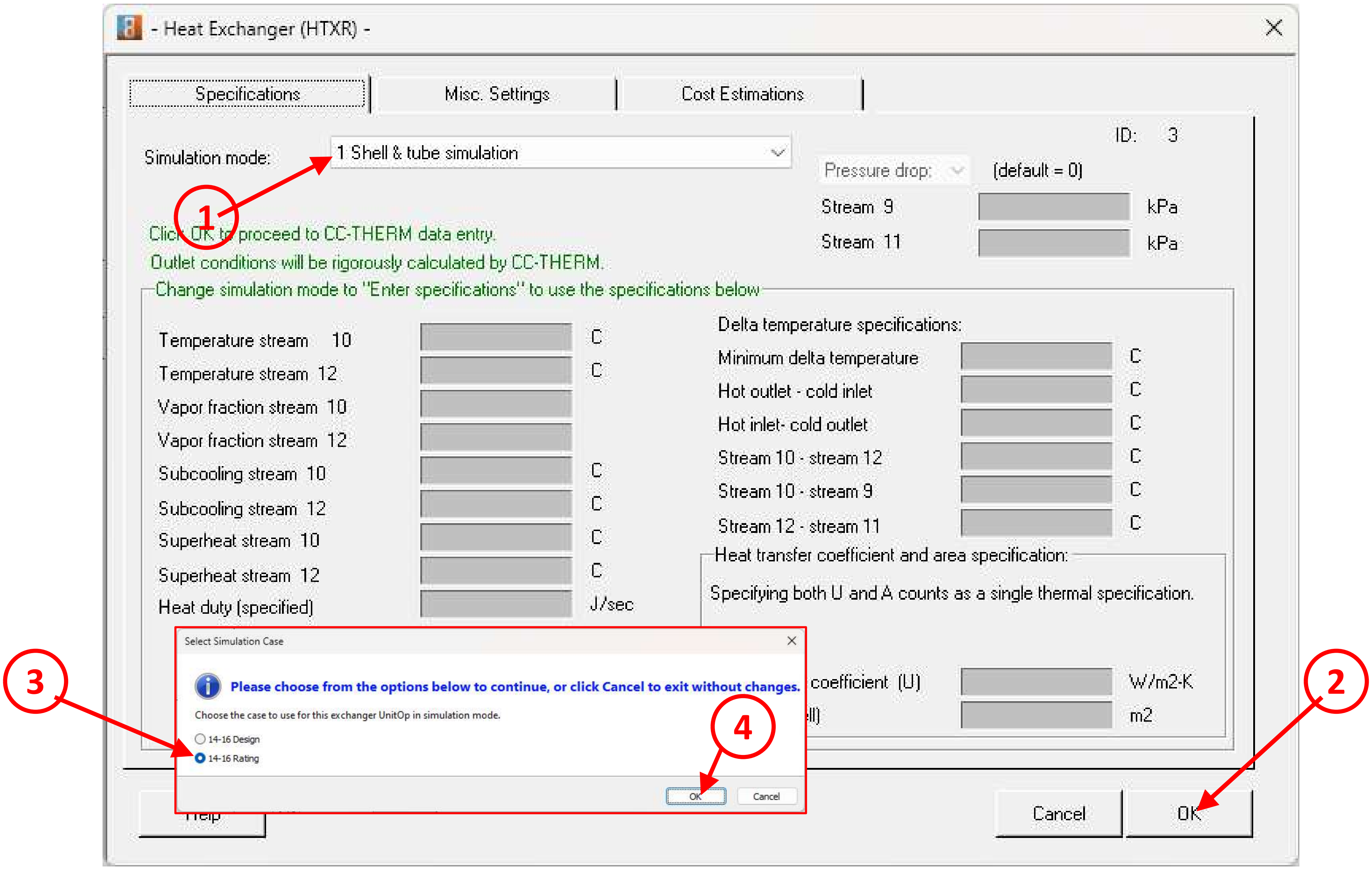
Copy and Paste Exchanger 2 (creating exchanger 3)



Copy this exchanger
and past it here.

Change Mode to Simulation

Copy and Paste Exchanger 2 (creating exchanger 3), double-click the exchanger, and change simulation mode to “1 Shell & tube simulation”

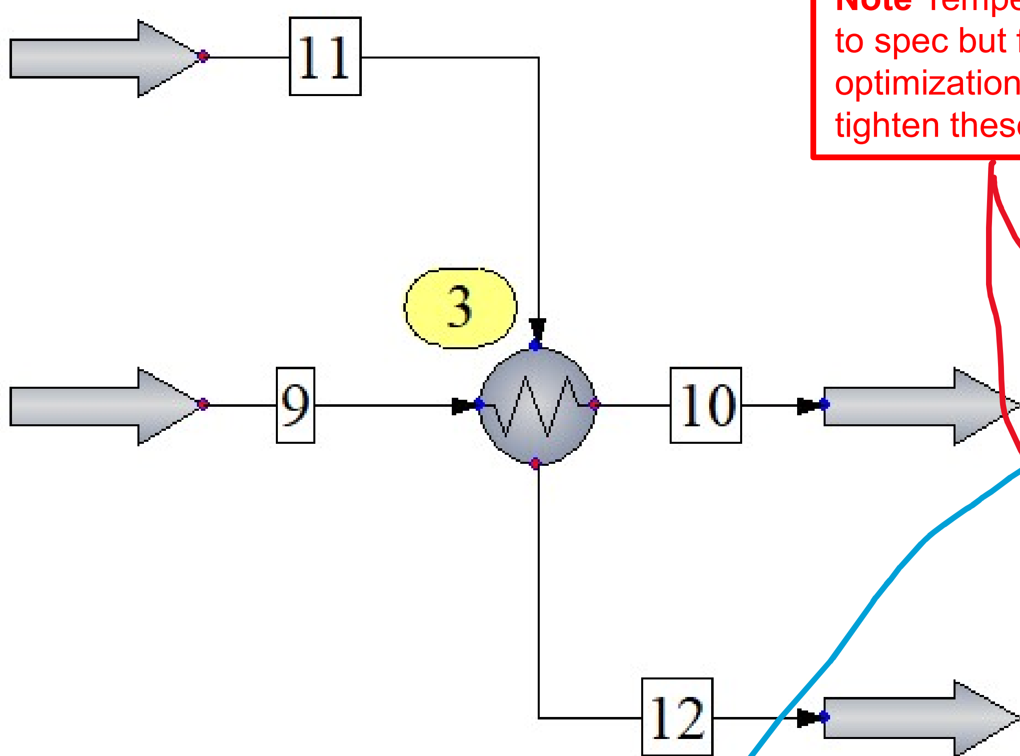


Run the Simulation

Checking results shows that outlet streams are slightly off spec based on percent excess safety factor.

ID	11
T	15.00 C
P	1020.00 kPa
W	1.90 kg/sec

ID	9
T	380.00 C
P	1020.00 kPa
W	2.64 kg/sec



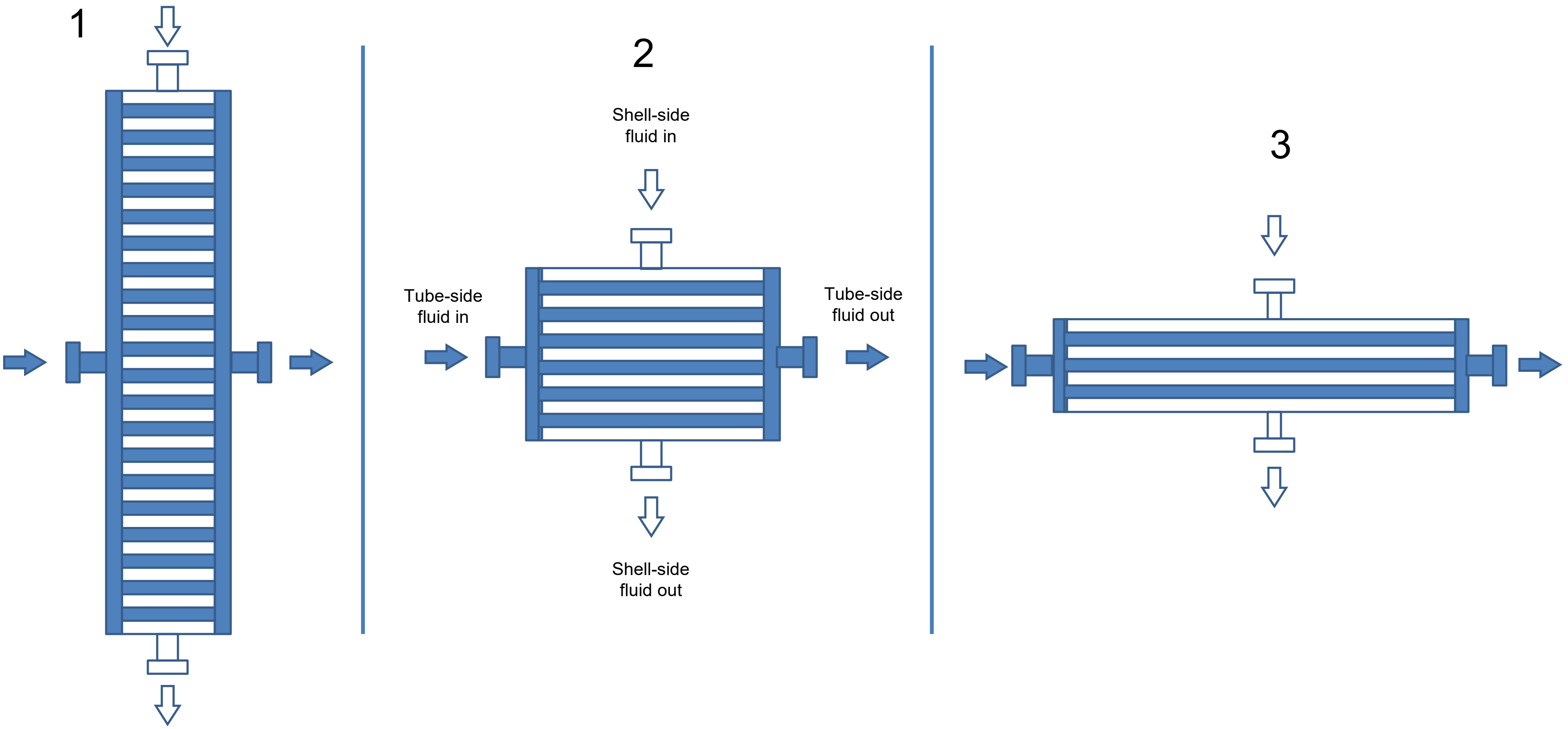
Note Temperatures are close to spec but for more precise optimization, we will need to tighten these up.

ID	10
T	198.54 C
P	1006.06 kPa
W	2.64 kg/sec

ID	12
T	272.00 C
P	1003.23 kPa
W	1.90 kg/sec

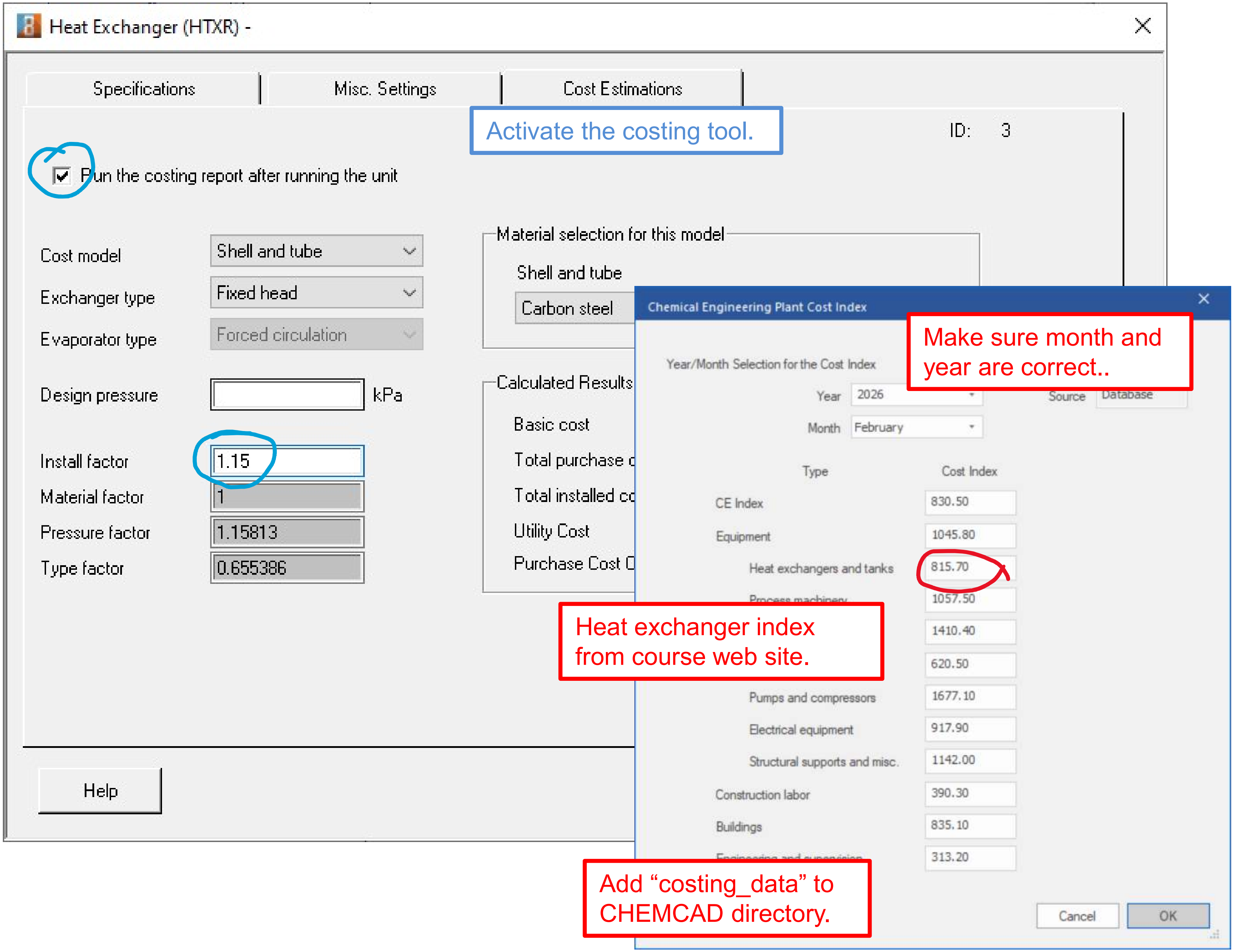
Note Outlet pressures give average pressure close to spec. Recall from problem statement that the average absolute pressure on both the tube side and the shell side is 1010 kPa.

What happens to P-drop when we go from 1 to 2 to 3?

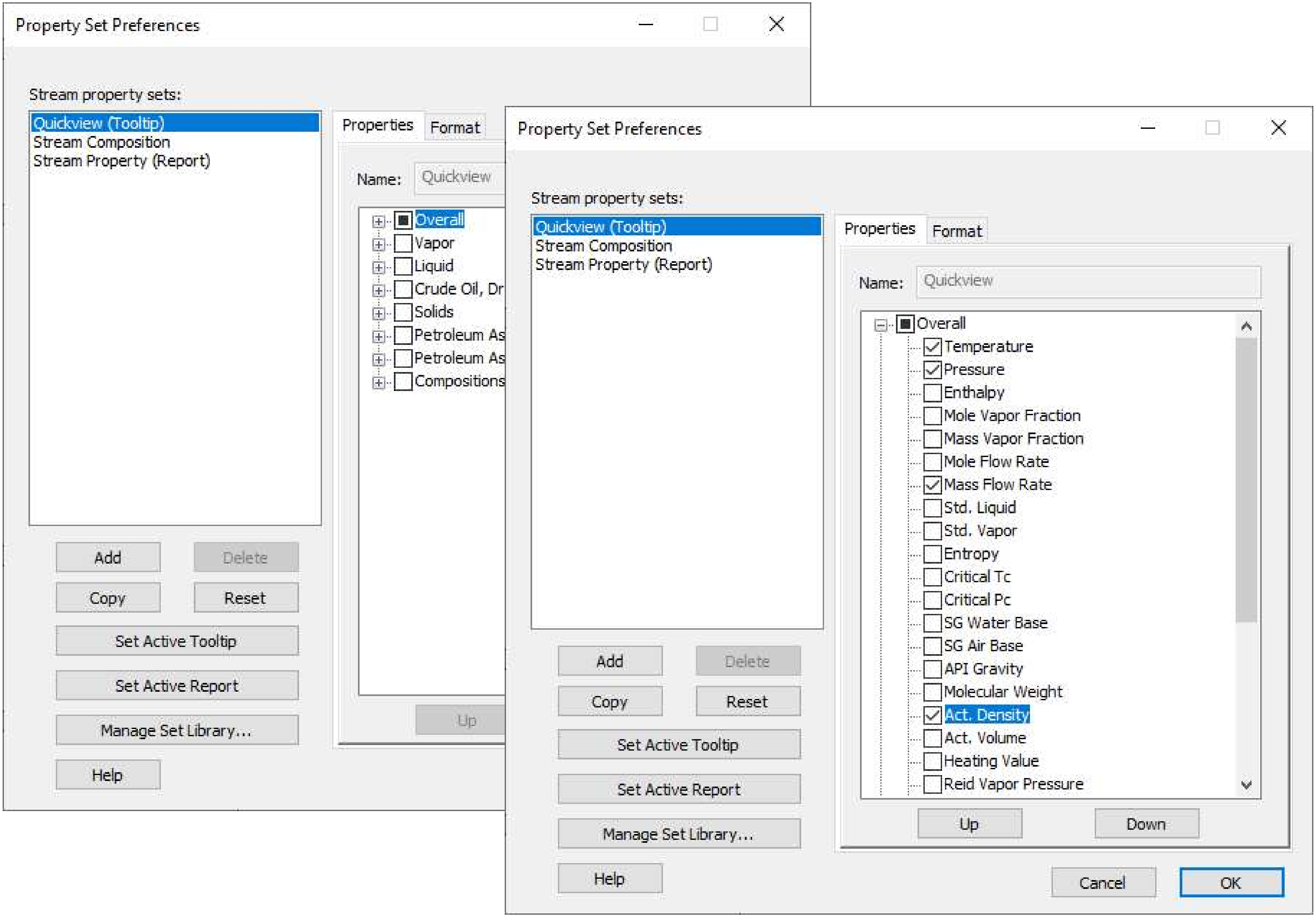


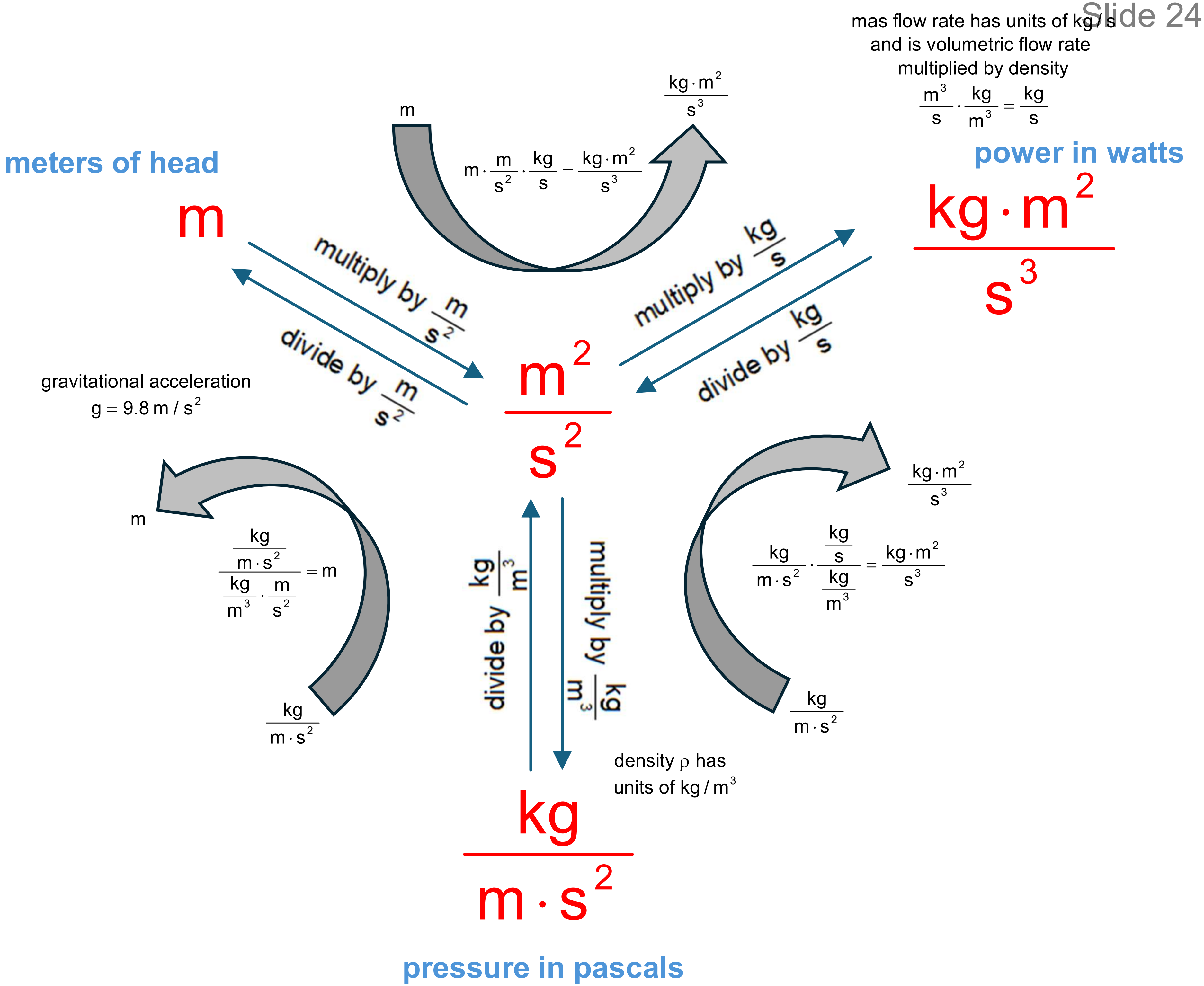
This affects cost to push fluids.

Update Cost Index and Run Costing



In the Home tab, in the Results Group, click (property sets)




mas flow rate has units of kg / s
and is volumetric flow rate
multiplied by density
$\frac{m^3}{s} \cdot \frac{kg}{m^3} = \frac{kg}{s}$
power in watts
$\frac{kg \cdot m^2}{s^3}$
meters of head
m
m
$\frac{kg \cdot m^2}{s^3}$
$m \cdot \frac{m}{s^2} \cdot \frac{kg}{s} = \frac{kg \cdot m^2}{s^3}$
multiply by $\frac{m}{s^2}$
divide by $\frac{m}{s^2}$
multiply by $\frac{kg}{s}$
divide by $\frac{kg}{s}$
$\frac{m^2}{s^2}$
gravitational acceleration
$g = 9.8\, m / s^2$
m
$\frac{\frac{kg}{m \cdot s^2}}{\frac{kg}{m^3} \cdot \frac{m}{s^2}} = m$
$\frac{kg}{m \cdot s^2}$
divide by $\frac{kg}{m^3}$
multiply by $\frac{kg}{m^3}$
$\frac{kg \cdot m^2}{s^3}$
$\frac{kg}{m \cdot s^2} \cdot \frac{\frac{kg}{s}}{\frac{kg}{m^3}} = \frac{kg \cdot m^2}{s^3}$
$\frac{kg}{m \cdot s^2}$
density ρ has
units of kg / m^3
$\frac{kg}{m \cdot s^2}$
pressure in pascals

Problem 14-16. Cadet Template			"sizing" checks are required	
Optimimal Heat Exchanger Design				
Yellow - obtained from CHEMCAD simulations				
Light Blue - Values are derived from specs and do not change.				
White - excel calculations - verified with "checks" (results from CC design)				
				"sizing"
Spreadsheet for evaluating Equation 14-91				checks
Number of tubes	N_t	dimensionless	288	
Length of tubes	L	m	9.750	
Installed cost, CC	C	$	$82,011	
Tube outer diameter	D_o	m	0.0254	
Tube inner diameter	D_i	m	0.0191	
Tube wall thickness	x	m	0.00315	
Outside area of tubes	A_o	m^2	224.1	
Installed cost per area	C_{Ao}	$\$/m^2$	$366	
Tube-side (hot gas) flow rate, CC	m_i	kg/s	2.6397	
Tube-side inlet fluid density, CC	r_{ti}	kg/m^3	5.3956	
Tube-side oulet fluid density, CC	r_{to}	kg/m^3	7.3697	
Tube-side pressure drop, CC	Dp_i	kPa	13.9405	
Tube-side average density	r_t	kg/m^3	6.3803	
Tube-side power loss per area	E_i	Nm/s per m^2	25.7402	
Shell-side (air) flow rate	m_o	kg/s	1.9000	
Shell-side inlet fluid density, CC	r_{si}	kg/m^3	12.3104	
Shell-side oulet fluid density, CC	r_{so}	kg/m^3	6.3576	
Shell-side pressure drop, CC	Dp_o	kPa	16.7692	
Shell-side average density	r_s	kg/m^3	9.3340	
Shell-side power loss per area	E_o	Nm/s per m^2	15.2341	
Hours of operation per year	H_y	h/y	8000	
Cost of pumping power	C_i	$/kWh	0.12	
Annual fixed charges factor	K_F	dimensionless	0.2	
Fixed charges		$/y	$16,402	
Tube-side pumping costs		$/y	$5,537	
Shell-side pumping costs		$/y	$3,277	
Total annual cost	C_T	**$/y**	**$25,216**	

Complete this portion of the template.

Values in column D are checks to confirm your work.

Blue rows are specs or calculated from the specs from the problem and are typed in as is. These numbers do not change.

Yellow rows (red font) come from CHEMCAD exchanger 3. These numbers will change in the optimization, but not yet.

White rows are formula entries. Calculation of cells E21 and E21 (power losses) are calculated from the methods in slide 24.

Formulas are shown in slide 26.

Problem 14-16. Cadet Template			"sizing" checks are required	
Optimimal Heat Exchanger Design				
Yellow - obtained from CHEMCAD simulations				
Light Blue - Values are derived from specs and do not change.				
White - excel calculations - verified with "checks" (results from CC design)				
				"sizing"
Spreadsheet for evaluating Equation 14-91				checks
Number of tubes	N_t	dimensionless	288	288
Length of tubes	L	m	9.750	9.750
Installed cost, CC	C	$	$82,011	$82,011
Tube outer diameter	D_o	m	0.0254	0.0254
Tube inner diameter	D_i	m	0.0191	0.0191
Tube wall thickness	x	m	0.00315	=(E11-E12)/2
Outside area of tubes	A_o	m^2	224.1	=PI()*E11*E8*E9
Installed cost per area	C_{Ao}	$\$/m^2$	$366	=E10/E14
Tube-side (hot gas) flow rate, CC	m_i	kg/s	2.6397	2.6397
Tube-side inlet fluid density, CC	r_{ti}	kg/m^3	5.3956	5.3956
Tube-side oulet fluid density, CC	r_{to}	kg/m^3	7.3697	7.3697
Tube-side pressure drop, CC	Dp_i	kPa	13.9405	13.9405
Tube-side average density	r_t	kg/m^3	6.3803	=AVERAGE(E17:E18)
Tube-side power loss per area	E_i	Nm/s per m^2	25.7402	=1000*E19*E16/E20/E14
Shell-side (air) flow rate	m_o	kg/s	1.9000	1.9000
Shell-side inlet fluid density, CC	r_{si}	kg/m^3	12.3104	12.3104
Shell-side oulet fluid density, CC	r_{so}	kg/m^3	6.3576	6.3576
Shell-side pressure drop, CC	Dp_o	kPa	16.7692	16.7692
Shell-side average density	r_s	kg/m^3	9.3340	=AVERAGE(E23:E24)
Shell-side power loss per area	E_o	Nm/s per m^2	15.2341	=1000*E25*E22/E26/E14
Hours of operation per year	H_y	h/y	8000	8000
Cost of pumping power	C_i	$/kWh	0.12	0.12
Annual fixed charges factor	K_F	dimensionless	0.2	0.2
Fixed charges		$/y	$16,402	=E30*E15*E14
Tube-side pumping costs		$/y	$5,537	=E21*E14*E28*E29/1000
Shell-side pumping costs		$/y	$3,277	=E27*E14*E28*E29/1000
Total annual cost	C_T	**$/y**	**$25,216**	=SUM(E32:E34)

Good Luck!