

CH402 Chemical Engineering Process Design

Class Notes L10

Heat Exchanger Design II

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

(These slides apply to CC v8.1 only)

WPR 1 – L12– WARNO

Date – 9 February 2024, C&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.

(2) Pumps and Pipe flow – static and dynamic losses, pump characteristics curve, CHEMCAD pipes, pumps, 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, especially problems 14-15 and 14-16.

Be prepared to apply equation 14-91.

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, m²

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/m²

\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 · m/s per m²

C_i Cost of supplying 1 N · m to pump fluid through the inside of the tubes, dollars/N · m

E_0 Power loss experienced on the shell side per unit outside tube area, N · m/s per m²

C_0 Cost of supplying 1 N · m to pump fluid through the shell side, dollars/N · m

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

The screenshot shows two overlapping dialog boxes from a software application. The 'Engineering Units' dialog is in the background, and the 'Select Components' dialog is in the foreground.

Engineering Units Dialog:

- System Profiles:** 'Common SI' is selected under the 'English' profile.
- Current Flowsheet Settings:** 'Chapter 14' is selected.
- Fundamental:**
 - Time: sec
 - Mole/Mass: kg
 - Temperature: C
 - Pressure: kPa
 - Enthalpy: J
 - Work: kJ
- Dimensions:**
 - Length: m
 - Thickness: m
 - Diameter: m
 - Area: m²
 - Liquid Volume: m³
 - Vapor Volume: m³
- Pipe Table Selection:** 'ASME (B36.10M-2015, B36.19M-2004)' is selected.

Select Components Dialog:

- Available Components Table:**

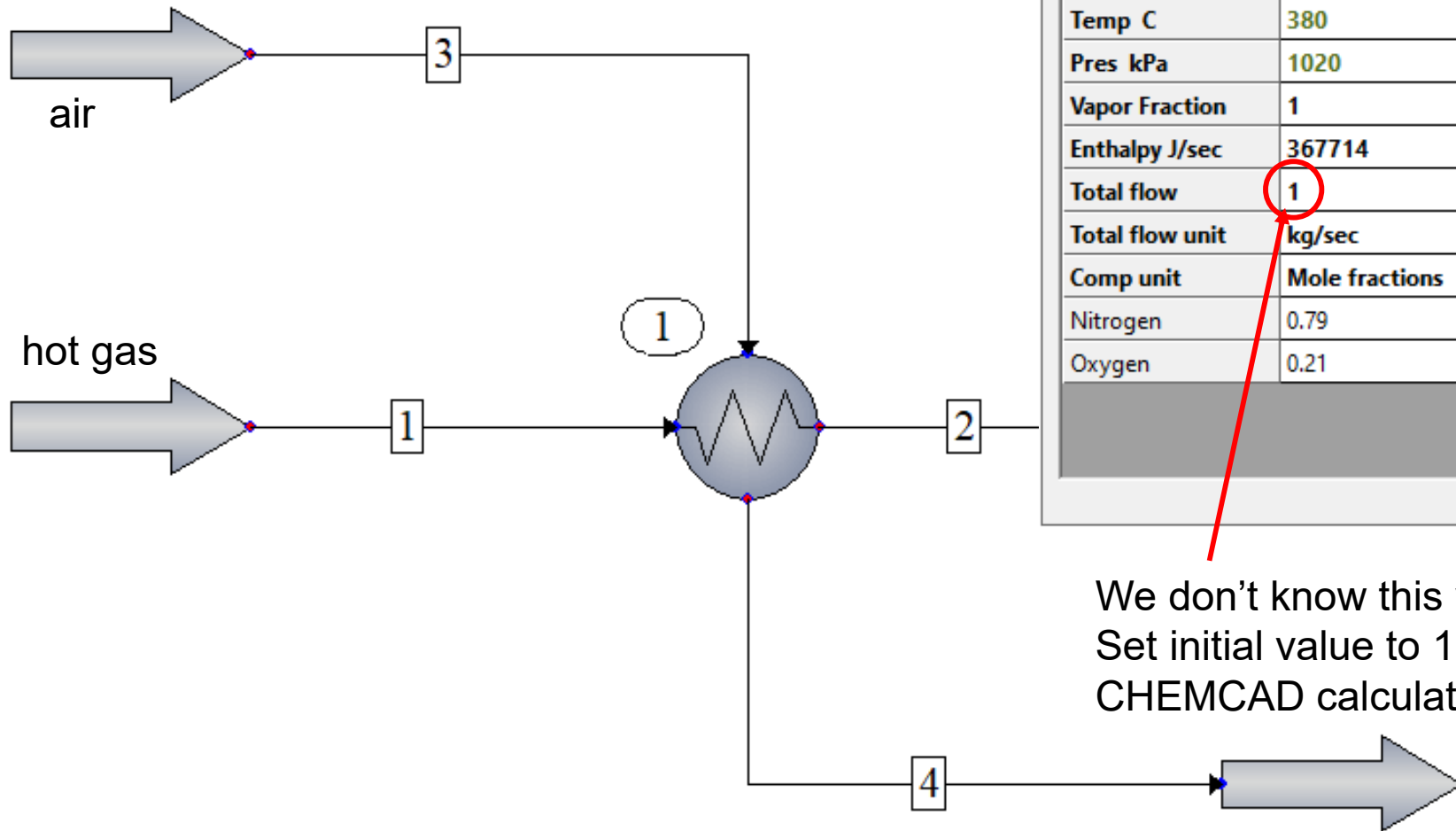
ID	Name	CAS ...	For...	Last Modified
1	Hydrogen	1333-74-0	H2	2016/07/01 08:36:47
2	Methane	74-82-8	CH4	2016/07/01 08:36:47
2	Methyl hydride	74-82-8	CH4	2016/07/01 08:36:47
3	Bimethyl	74-84-0	C2H6	2016/07/01 08:36:47
3	Dimethyl	74-84-0	C2H6	2016/07/01 08:36:47
3	Ethane	74-84-0	C2H6	2016/07/01 08:36:47
3	Ethyl hydride	74-84-0	C2H6	2016/07/01 08:36:47
3	Methylmethane	74-84-0	C2H6	2016/07/01 08:36:47
4	Propyl hydride	74-98-6	C3H8	2016/07/01 08:36:47
4	Dimethylmethane	74-98-6	C3H8	2016/07/01 08:36:47
4	Freon 290	74-98-6	C3H8	2016/07/01 08:36:47
4	n-Propane	74-98-6	C3H8	2016/07/01 08:36:47
4	Propane	74-98-6	C3H8	2016/07/01 08:36:47
5	Isobutane	75-28-5	C4H10	2016/07/01 08:36:47
- Selected Components:** 'Nitrogen' and 'Oxygen' are listed.
- Buttons:** Top, Up, Down, Bottom, Search, Options, Advanced, Delete, Copy.

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

Heat Exchanger (HTXR) -

Specifications | Misc. Settings | Cost Estimations

Simulation mode: 0 Enter specifications (CHEMCAD simulation) ID: 1

Utility option: 3 Calculate flow of stream 1 Pressure drop: (default = 0)

Stream 1 kPa

Stream 3 kPa

Temperature stream 2 200 C

Temperature stream 4 270 C

Vapor fraction stream 2

Vapor fraction stream 4

Subcooling stream 2 C

Subcooling stream 4 C

Superheat stream 2 C

Superheat stream 4 C

Heat duty (specified) J/sec

Delta temperature specifications:

Minimum delta temperature C

Hot outlet - cold inlet C

Hot inlet - cold outlet C

Stream 2 - stream 4 C

Stream 2 - stream 1 C

Stream 4 - stream 3 C

Heat transfer coefficient and area specification:

Specifying both U and A counts as a single thermal specification.

Heat transfer coefficient (U) W/m²-K

Area (per shell) m²

Help Cancel OK

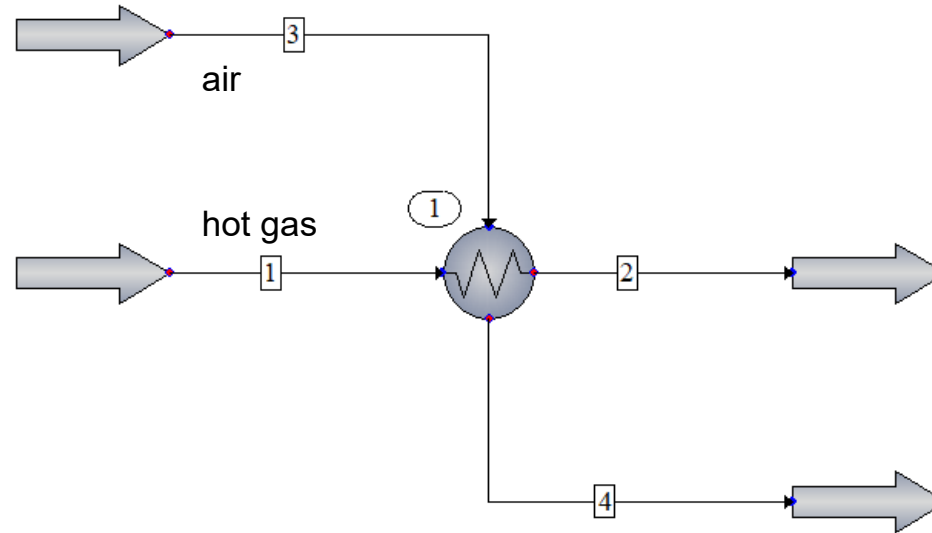
The flowrate of stream 1 will be recalculated

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.

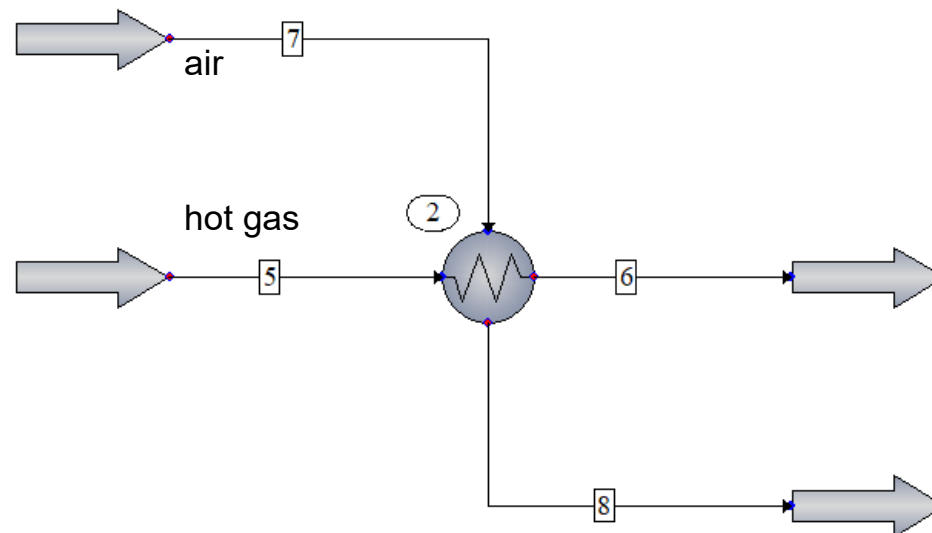
Level 2 Design

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.

General Specifications

General Information Modeling Methods

TEMA class/ standard TEMA R

Orientation Horizontal

TEMA front end head A - Channel Removable Cover

TEMA shell type X - Cross Flow

TEMA rear end head type L - Fixed Tubesheet (A head)

Cross flow on the shell

Tube Side

Stream name

Process type Sensible Flow

Fouling factor m2-K/W

Optional h Coeff. W/m2-K

Shell Side

Stream name

Process type Sensible Flow

Fouling factor m2-K/W

Optional h Coeff. W/m2-K

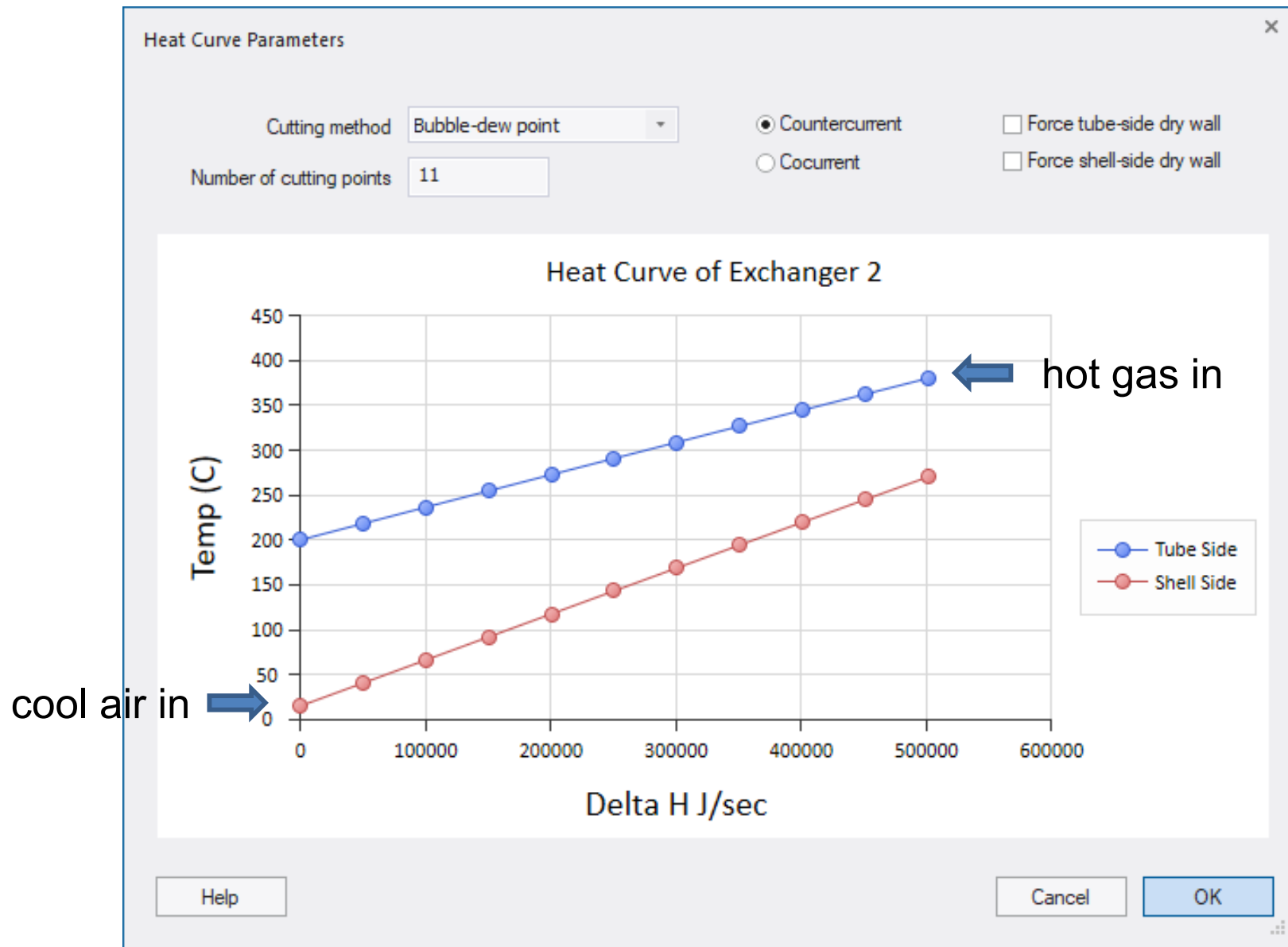
Delete fouling factors

For fouling rating calculation

Help Cancel OK

Heat Curves

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



Design Options

Design Constraints

Design Criteria

Allowable tube pressure drop	34.473801	kPa
Allowable shell pressure drop	34.473801	kPa
Allowable tube velocity	76.199997	m/sec
Allowable shell velocity	76.199997	m/sec
Prefer tube length/shell diameter ratio	12	
Minimum excess %		

Sizing nozzle

- ☒ Tube, inlet
- ☒ Tube, outlet
- ☒ Shell, inlet
- ☒ Shell, outlet

Limits of Design Variables

	Lower Limits	Upper Limits	
Tube Length	0.91439998	20	m
Shell Diameter	0.1524	9	m
Baffle Cut	15	45	Percent of diameter
Baffle Spacing	0.050799999	3.175	m

☐ Optimize number of tube passes

Help Cancel OK

Increase upper
tube length

Increase shell
diameter

CCTherm Configuration Group -> General Dropdown -> Design Constraints

Tube Specs

Tube Specifications

Number of tubes * 1396

Number of tube passes * 1

Tube outer diameter .0254 m

Tube wall thickness .00315 m

Tube length * m

Roughness factor 1.5748e-06 m

Tube pattern Square (90)

Tube pitch .0381 m

Trufin tube code Plain tube

Turbulator No Turbulator

Tubesheet thickness .0254 m

Number of tubesheets 2

* Field may be recalculated when design calculation is run

Help Cancel OK

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

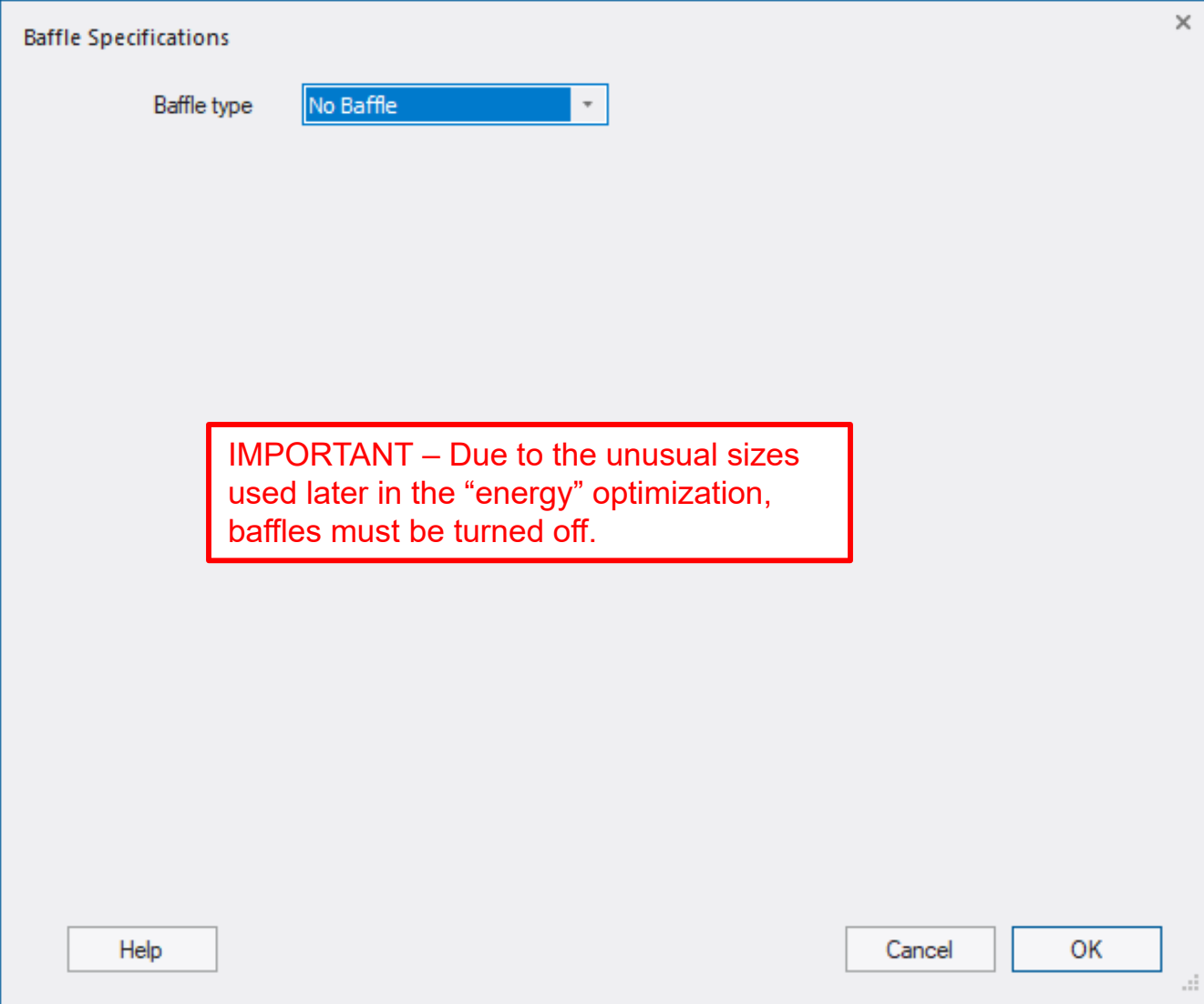
Impingement protection Use impingement plates

Accept all defaults here. We will change these later.

* Field may be recalculated when design calculation is run

Help Cancel OK

Baffle Specs



A screenshot of a software dialog box titled "Baffle Specifications". The dialog has a light gray background and a blue border. At the top left is the title "Baffle Specifications" and a close button (X) at the top right. Below the title is a label "Baffle type" followed by a dropdown menu showing "No Baffle". In the center, a red-bordered box contains the text: "IMPORTANT – Due to the unusual sizes used later in the “energy” optimization, baffles must be turned off." At the bottom, there are three buttons: "Help" on the left, and "Cancel" and "OK" on the right. A small icon of three dots is visible in the bottom right corner of the dialog area.

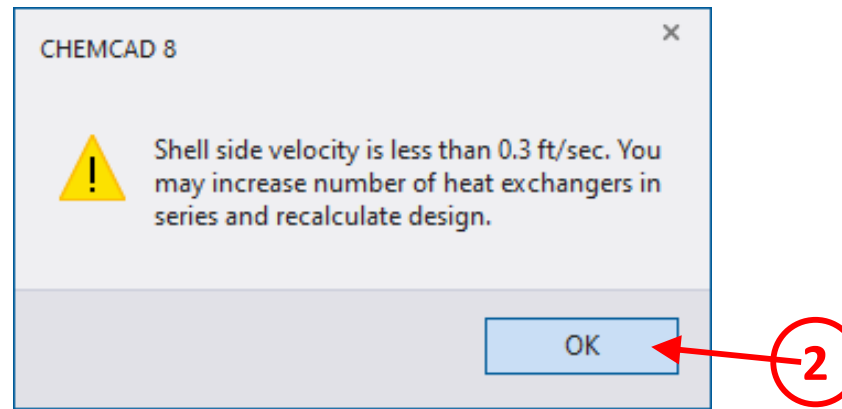
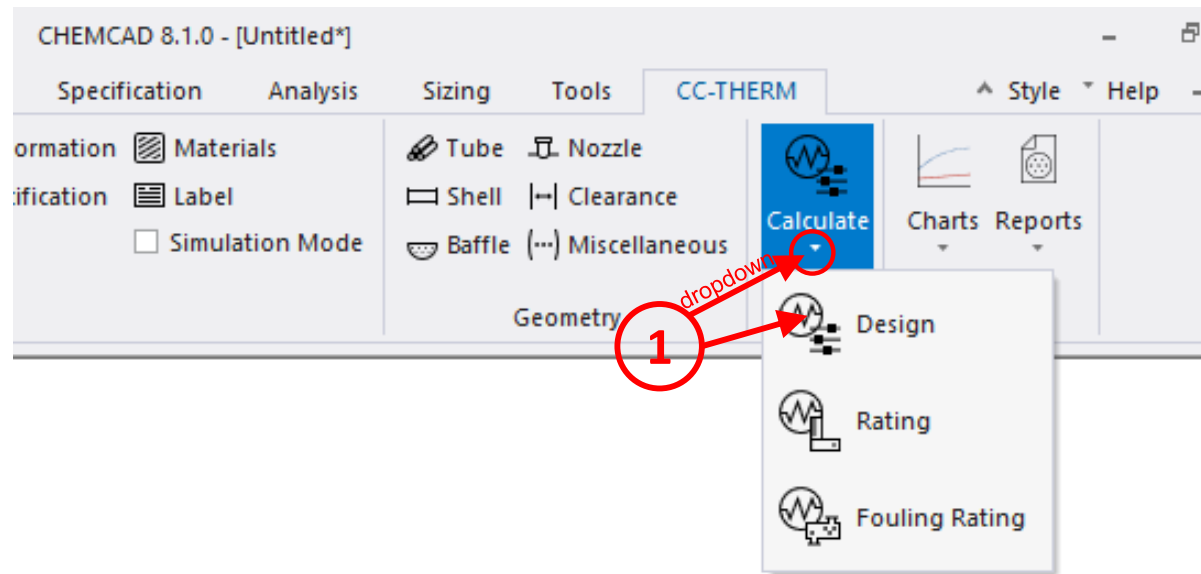
Baffle Specifications

Baffle type No Baffle

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

Help Cancel OK

Design Run



TABULATED ANALYSIS

Overall Data:

Area Total	m2	196.13	% Excess		0.09
Area Required	m2	194.94	U Calc.	W/m2-K	21.84
Area Effective	m2	195.11	U Service	W/m2-K	21.82
Area Per Shell	m2	195.11	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	27.35	Reynolds No.		1605
Allow Press. Drop	kPa	34.47	Calc. Press. Drop	kPa	16.29
Inlet Nozzle Size	m	0.13	Press. Drop/In Nozzle	kPa	1.81
Outlet Nozzle Size	m	0.09	Press. Drop/Out Nozzle	kPa	2.62
			Mean Temperature	C	142.50
Rho V2 IN	kg/m-sec2	1760.30	Press. Drop (Dirty)	kPa	27.69

Low Reynolds Number.

Tube-side Data:

Film Coef.	W/m2-K	145.46	Reynolds No.		23890
Allow Press. Drop	kPa	34.47	Calc. Press. Drop	kPa	14.22
Inlet Nozzle Size	m	0.13	Press. Drop/In Nozzle	kPa	3.69
Outlet Nozzle Size	m	0.10	Press. Drop/Out Nozzle	kPa	2.87
Interm. Nozzle Size	m	0.00			
Velocity	m/sec	5.79			

Shell:

Shell O.D.	m	0.76
Shell I.D.	m	0.74
Bonnet I.D.	m	0.74
Type		AXL
Imping. Plate		Impingement Plate

Resistances:

Shell-side Film	m2-K/W	0.03656
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	0.00687
Reference Factor (Total outside area/inside area based on tube ID)		1.330

Pressure Drop Distribution:

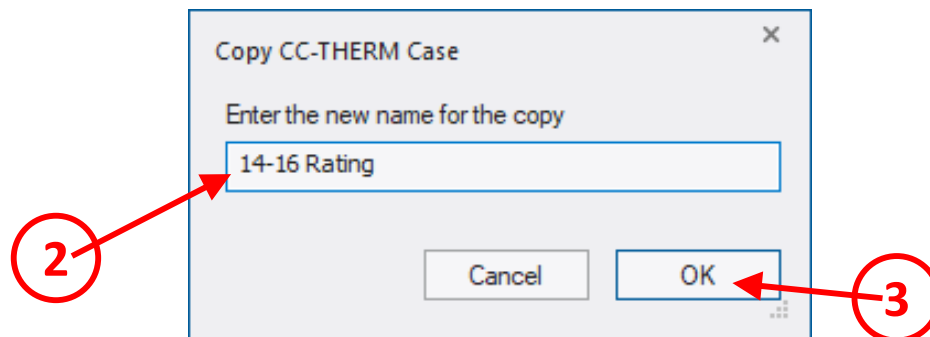
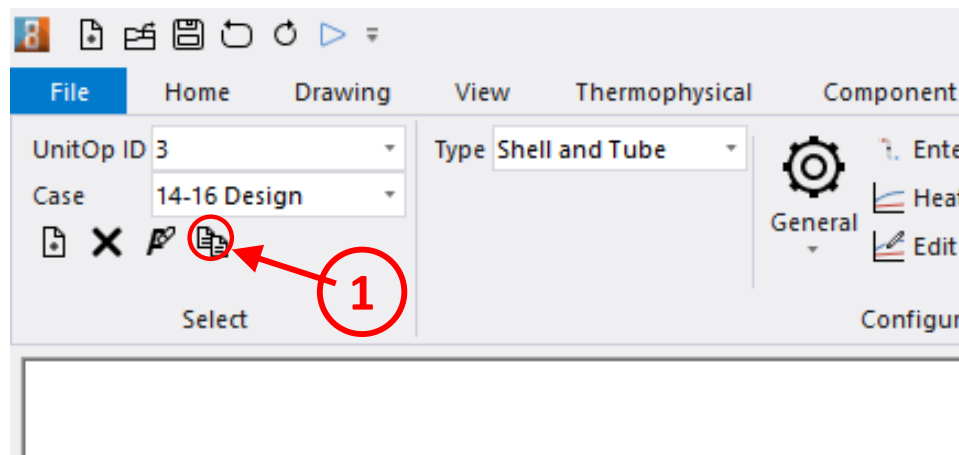
Tube Side		Shell Side		
Inlet Nozzle	kPa	Inlet Nozzle	kPa	1.8104
Tube Entrance	kPa	Impingement	kPa	1.1442
Tube	kPa	Bundle	kPa	0.0134
Tube Exit	kPa	Outlet Nozzle	kPa	2.6151
End	kPa	Total Fric.	kPa	4.4389
Outlet Nozzle	kPa	Total Grav.	kPa	-0.0681
Total Fric.	kPa	Total Mome.	kPa	11.9172
Total Grav.	kPa	Total	kPa	16.2880
Total Mome.	kPa			
Total	kPa			

Tubes:

Number		252
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

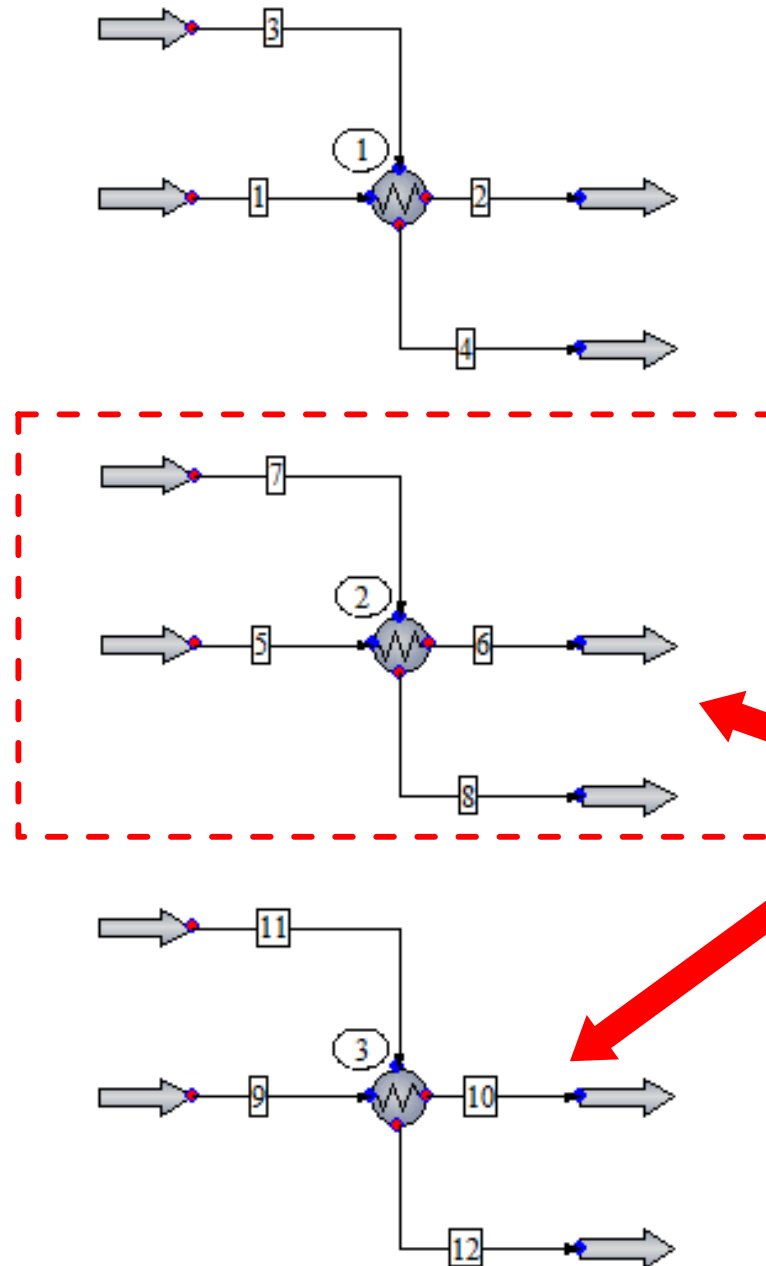
Create a Copy of Your CCTherm Design

Create a copy of your CCTherm design. This guards against losing 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”

The screenshot shows the 'Heat Exchanger (HTXR)' dialog box with the 'Specifications' tab selected. The 'Simulation mode' dropdown is set to '1 Shell & tube simulation', indicated by a red circle with the number 1. Below this, green text instructs the user to click OK to proceed to CC-THERM data entry. The dialog contains various input fields for temperature, vapor fraction, subcooling, superheat, and heat duty for streams 10 and 12. It also includes a section for 'Delta temperature specifications' and 'Heat transfer coefficient and area specification'. A 'Select Simulation Case' sub-dialog box is open, showing two options: '14-16 Design' and '14-16 Rating', with '14-16 Rating' selected. This sub-dialog is indicated by a red circle with the number 3. The 'OK' button in the sub-dialog is indicated by a red circle with the number 4. The main dialog has 'Cancel' and 'OK' buttons at the bottom right, with the 'OK' button indicated by a red circle with the number 2. The 'Pressure drop' dropdown is set to '(default = 0)'. The 'ID' of the exchanger is 3.

Heat Exchanger (HTXR) -

Specifications Misc. Settings Cost Estimations

Simulation mode: 1 Shell & tube simulation ID: 3

Pressure drop: (default = 0)

Stream 9 kPa

Stream 11 kPa

Click OK to proceed to CC-THERM data entry.
Outlet conditions will be rigorously calculated by CC-THERM.
Change simulation mode to "Enter specifications" to use the specifications below

Temperature stream 10 C

Temperature stream 12 C

Vapor fraction stream 10

Vapor fraction stream 12

Subcooling stream 10 C

Subcooling stream 12 C

Superheat stream 10 C

Superheat stream 12 C

Heat duty (specified) J/sec

Delta temperature specifications:

Minimum delta temperature C

Hot outlet - cold inlet C

Hot inlet - cold outlet C

Stream 10 - stream 12 C

Stream 10 - stream 9 C

Stream 12 - stream 11 C

Heat transfer coefficient and area specification:

Specifying both U and A counts as a single thermal specification.

coefficient (U) W/m2-K

A m2

Select Simulation Case

Please choose from the options below to continue, or click Cancel to exit without changes.

Choose the case to use for this exchanger UnitOp in simulation mode.

☐ 14-16 Design

☒ 14-16 Rating

OK Cancel

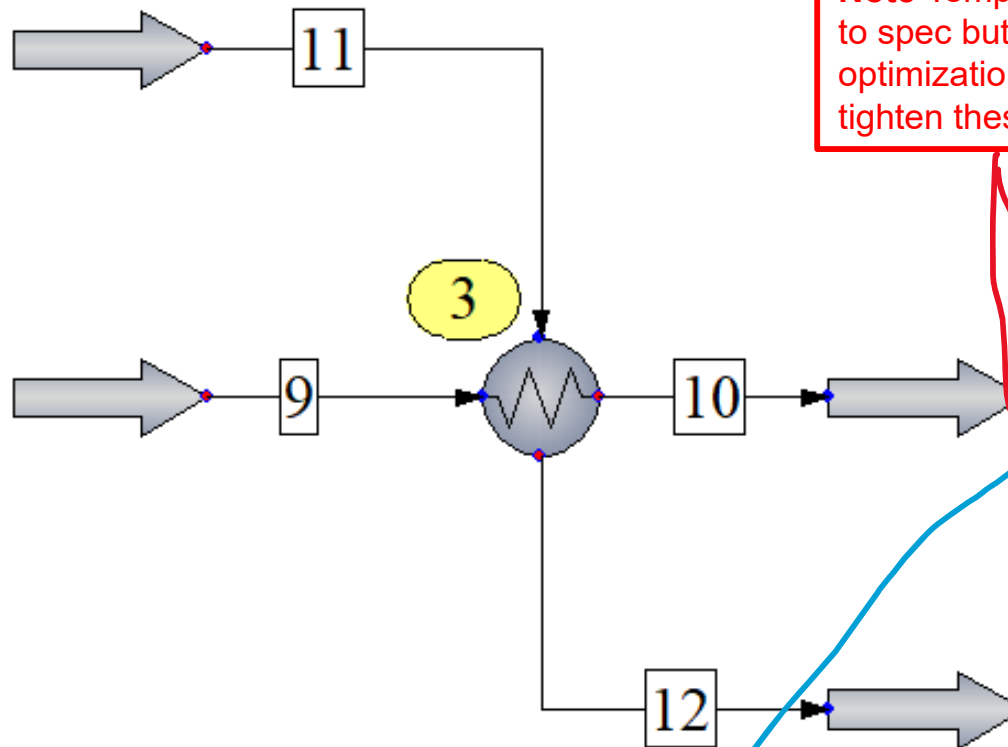
Cancel OK

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



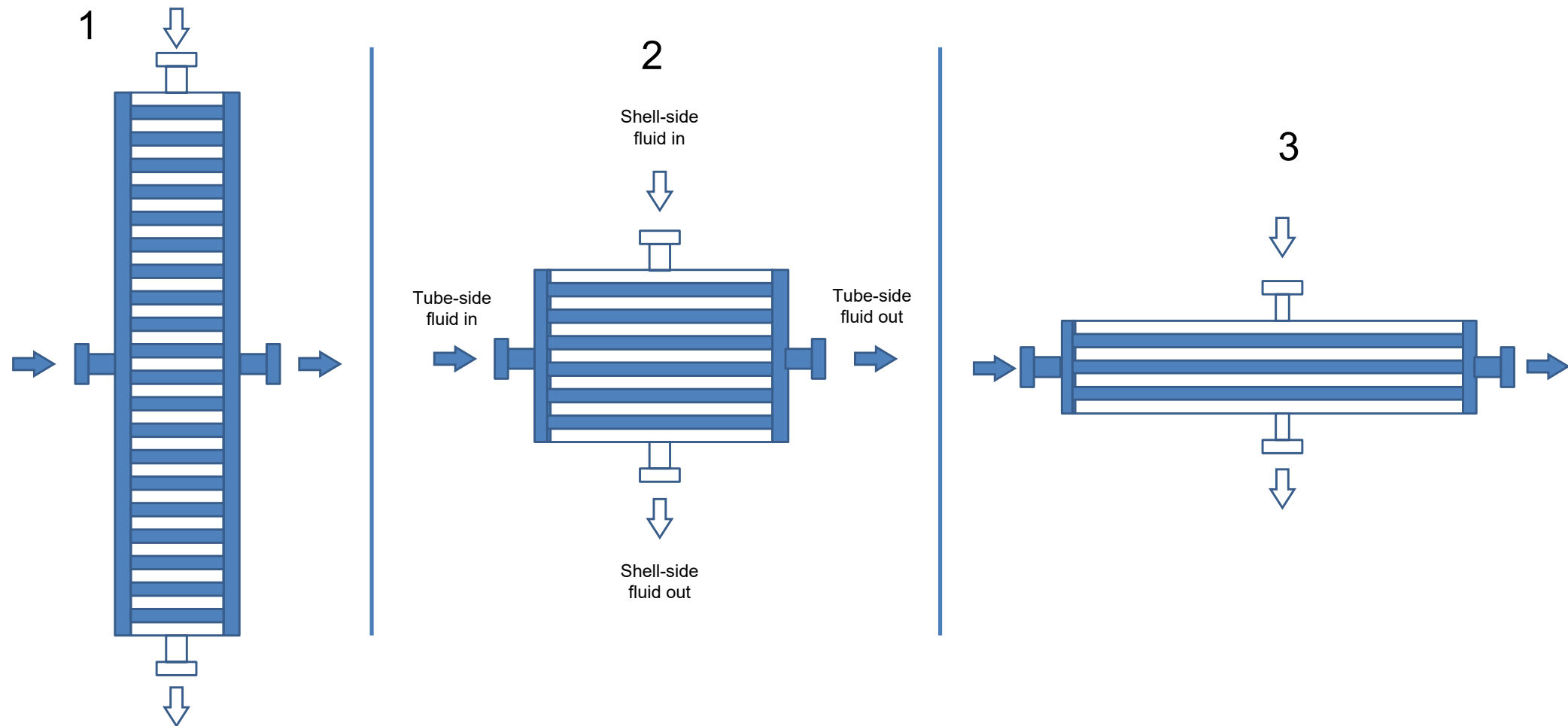
Note Temperatures are close to spec but for more precise optimization, we will need to tighten these up.

ID	10
T	198.84 C
P	1006.93 kPa
W	2.64 kg/sec

ID	12
T	271.59 C
P	1003.24 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

Heat Exchanger (HTXR) -

Specifications | Misc. Settings | Cost Estimations

Activate the costing tool.

☒ Run the costing report after running the unit

Cost model: Shell and tube

Exchanger type: Fixed head

Evaporator type: Forced circulation

Design pressure: kPa

Install factor: 1.15

Material factor: 1

Pressure factor: 1.15813

Type factor: 0.655386

Material selection for this model: Shell and tube, Carbon steel

Calculated Results:

- Basic cost
- Total purchase cost
- Total installed cost
- Utility Cost
- Purchase Cost Override

Year/month for the cost index:

Year: 2022

Month: February

Type: CE INDEX

Equipment: Heat exchangers and tanks

Process machinery

Electrical equipment

Structural supports and misc.

Construction labor

Buildings

Engineering and supervision

Cost Index:

CE INDEX	801.3
Equipment	1015.3
Heat exchangers and tanks	837.9
Process machinery	1007.8
Electrical equipment	1470.3
Structural supports and misc.	558.1
Construction labor	1226.9
Buildings	726.9
Engineering and supervision	1118.8

Make sure month and year are correct..

Heat exchanger index from course web site.

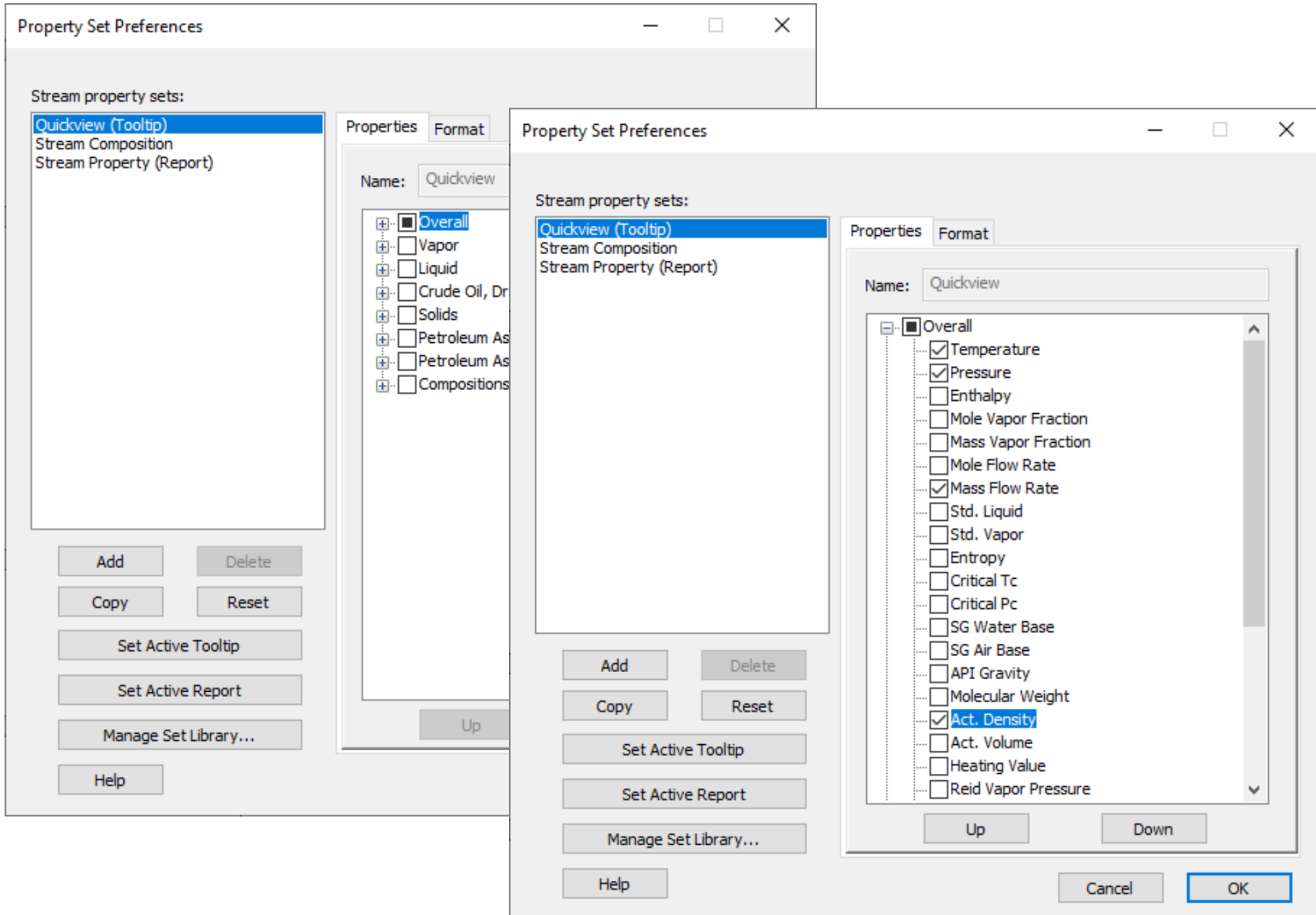
Add "costing_data" to CHEMCAD directory.

Help

Cancel OK

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

Slide 23



Questions?