Heat Transfer Equipment
1. Heat Exchangers

Heat Exchangers

- **Heat Transfer Basics**
- Tubular Exchangers
- Heat Exchanger Design
- Compact Heat Exchangers

Three Mechanisms of Heat Transfer

- Conduction

$$Q = A\,k\,\frac{dT}{dx}$$

  - Affects wall resistances, which are usually negligible for heat transfer equipment

- Convection

$$Q = U\,A\,\Delta T$$

  - Usually the governing mechanism in most process applications

- Radiation

$$Q = A\,\sigma\,\varepsilon\,(\Delta T^4)$$

  - Important in fired heaters

Q = heat duty
A = area
T = absolute temperature
k = thermal conductivity
U = heat transfer coefficient
σ = Stefan Boltzman const.
ε = transmission factor

Convective Heat Transfer in a Tube

Dittus-Boelter Equation:

$$Nu = \frac{h_i \, d_i}{k} = 0.023 \left(\frac{C_p \, \mu}{k}\right)^{1/3} \left(\frac{\rho \, v \, d_i}{\mu}\right)^{0.8}$$

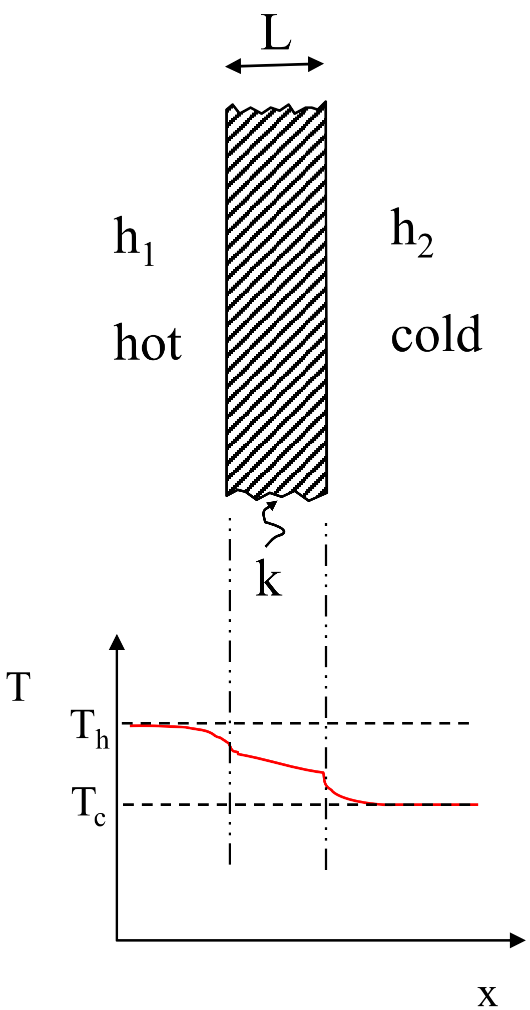
(for inside h.t.c. h_i based on inside diameter d_i)

Collect variables:

$$h_i = 0.023 \, \frac{k^{2/3}}{d_i^{0.2}} \, C_p^{1/3} \, \mu^{-0.467} \, (v \, \rho)^{0.8}$$

So if we increase	then h_i will:
Fluid thermal conductivity, k	
Fluid heat capacity, C_p	
Fluid density, ρ	
Velocity, v	
Fluid viscosity, μ	
Pipe diameter, d_i	

Combined Conduction and Convection



- For a flat plate, overall resistance is the sum of the individual resistances

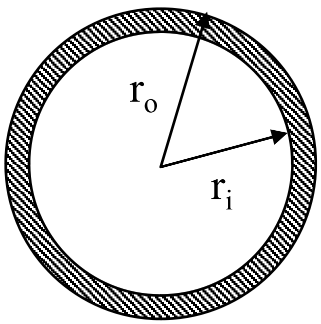
$$\frac{Q}{A}\left(\frac{1}{h_1}+\frac{L}{k}+\frac{1}{h_2}\right) = T_h - T_c$$

- Hence overall heat transfer coefficient, U is given by

$$Q = U A \left(T_h - T_c\right)$$

$$\frac{1}{U} = \frac{1}{h_1}+\frac{L}{k}+\frac{1}{h_2}$$

Cylindrical Geometry (Tubes)



- By convention, U is based on outside diameter

$$Q = U\,A\left(T_h - T_c\right)$$

$$\frac{1}{r_o\,U} = \frac{1}{r_o\,h_o} + \frac{\ln\left(r_o / r_i\right)}{k} + \frac{1}{r_i\,h_i}$$

- Add terms for fouling:

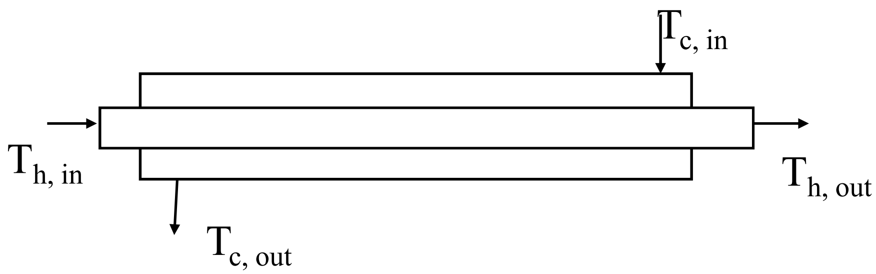
$$\frac{1}{r_o\,U} = \frac{1}{r_o\,h_o} + \frac{1}{r_o f_o} + \frac{\ln\left(r_o / r_i\right)}{k} + \frac{1}{r_i f_i} + \frac{1}{r_i\,h_i}$$

Outside h.t.c. h_o depends strongly on equipment type: see Chapter 12 for correlations

Counter Current Heat Transfer

Hot End

$\Delta T_h = T_{h,in} - T_{c,out}$



Cold End

$\Delta T_c = T_{h,out} - T_{c,in}$

- $Q = U\,A\,\Delta T_m$

- For perfect counter current flow, ΔT_m is the log mean temperature difference:

$$\Delta T_{lm} = \frac{\left(\left(T_{h,in} - T_{c,out}\right) - \left(T_{h,out} - T_{c,in}\right)\right)}{\ln\left(\frac{\left(T_{h,in} - T_{c,out}\right)}{\left(T_{h,out} - T_{c,in}\right)}\right)}$$

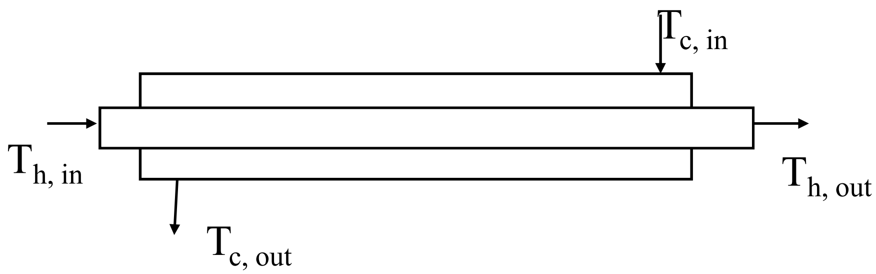
- Easiest to remember as:

$$\Delta T_{lm} = \frac{\left(\Delta T_h - \Delta T_c\right)}{\ln\left(\frac{\Delta T_h}{\Delta T_c}\right)}$$

Counter Current Heat Transfer

Hot End

$\Delta T_h = T_{h,in} - T_{c,out}$



Cold End

$\Delta T_c = T_{h,out} - T_{c,in}$

$$\Delta T_{lm} = \frac{(\Delta T_h - \Delta T_c)}{\ln\left(\frac{\Delta T_h}{\Delta T_c}\right)}$$

A useful shortcut to know:

$\Delta T_h/\Delta T_c$	1.0	1.5	2.0	3.0	4.0
$\Delta T_{lm} / \Delta T_c$	1.0	1.2	1.4	1.8	2.2

$\Delta T_{geom\ mean} = \sqrt{(\Delta T_c \times \Delta T_h)}$

$\Delta T_{geom\ mean} / \Delta T_c$	1.0	1.22	1.41	1.73	2.0

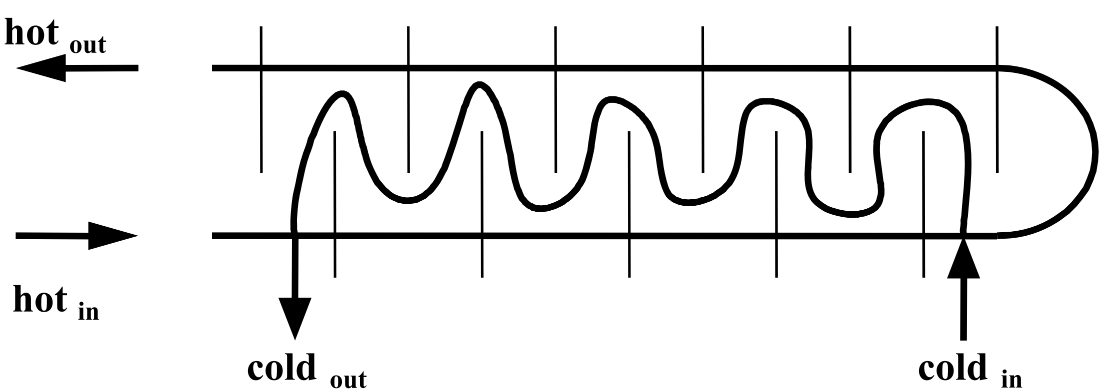
So $\Delta T_{lm} \approx \Delta T_{geom\ mean}$ if ratio is 3 or less!

Counter-current Flow in Real Exchangers

- Most real heat exchangers do not have pure counter-current flow
- We apply a correction factor for this in design

$$Q = U\ A\ F\ \Delta T_{lm}$$

- F is usually > 0.8 unless the design is poor (see later)
- F is sometimes called F_t

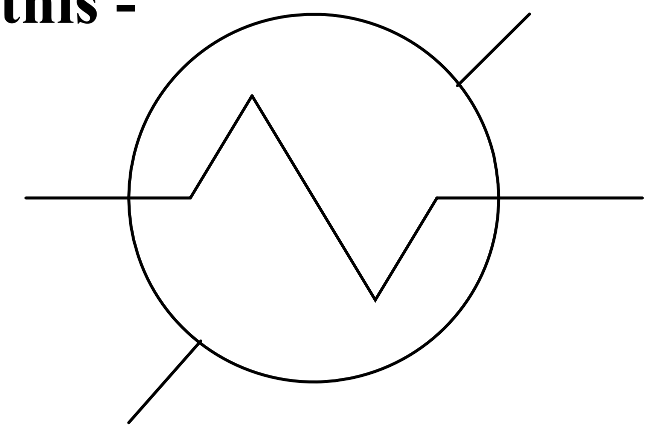


Heat Exchangers

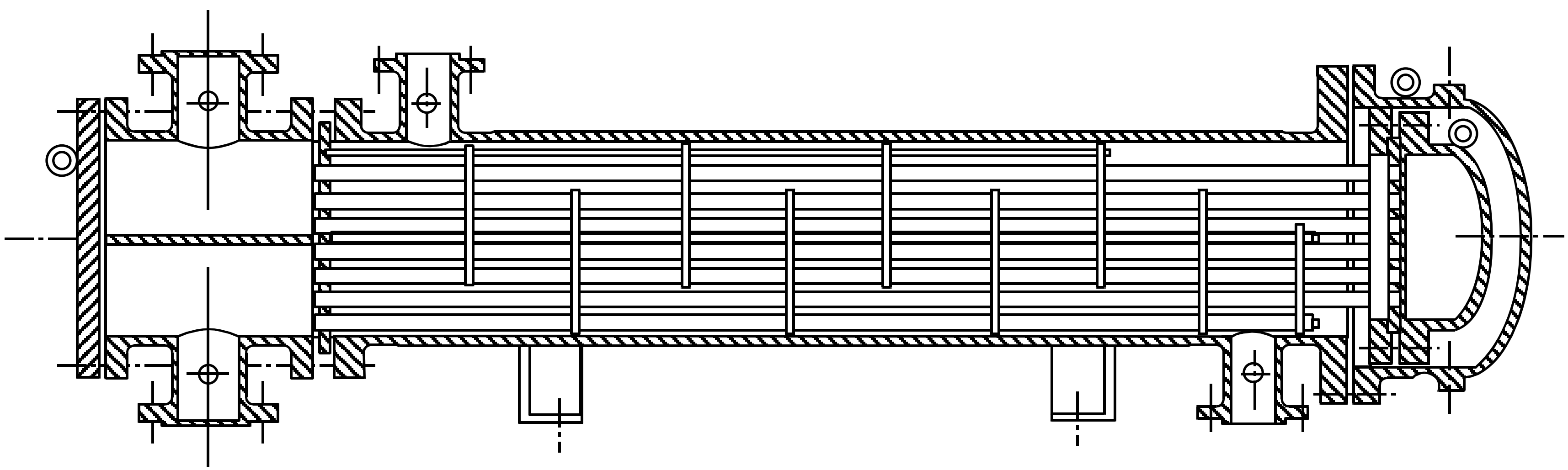
- Heat Transfer Basics
- **Tubular Exchangers**
- Heat Exchanger Design
- Compact Heat Exchangers

Shell and Tube Heat Exchangers

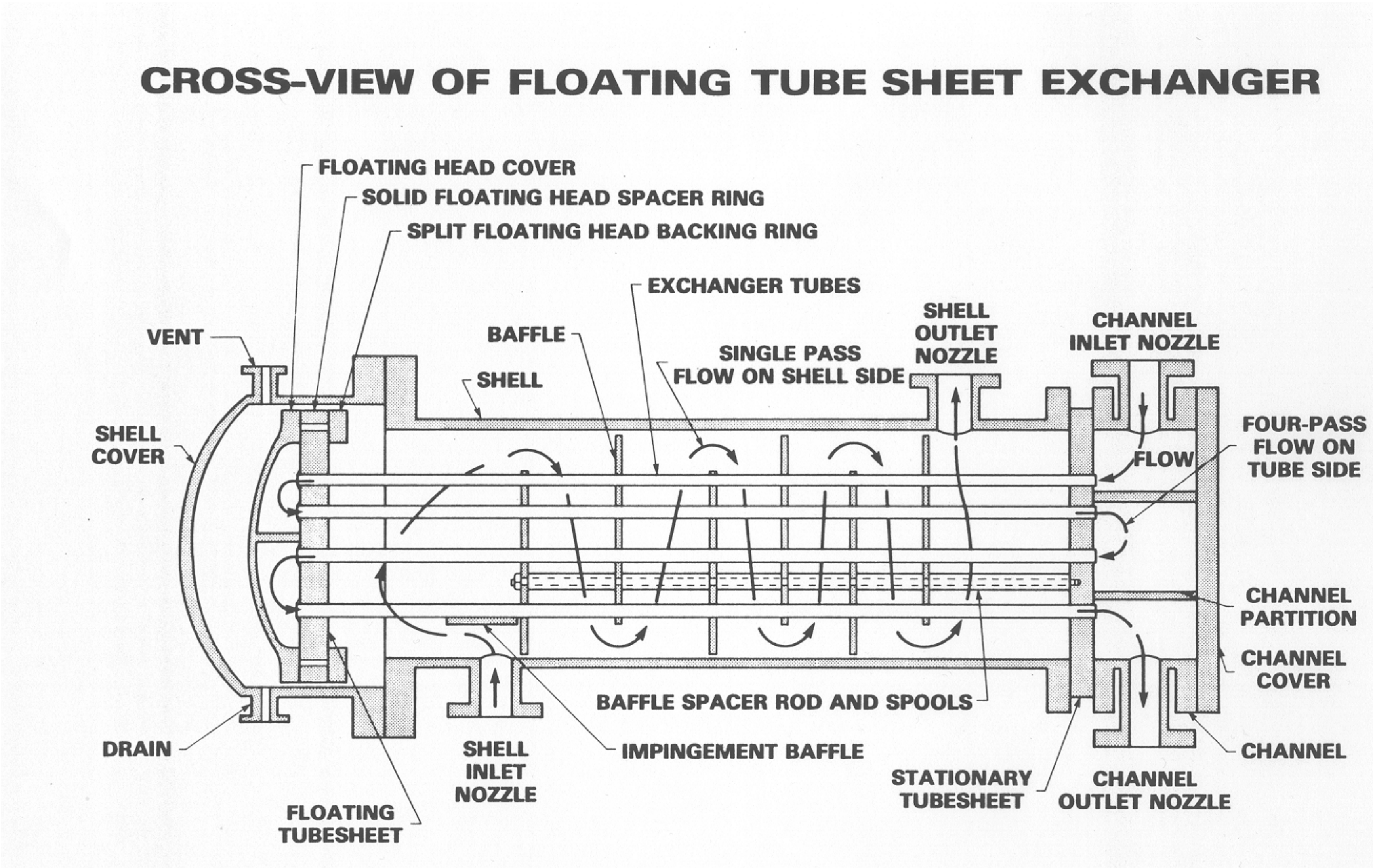
How do we turn this -



Into this -

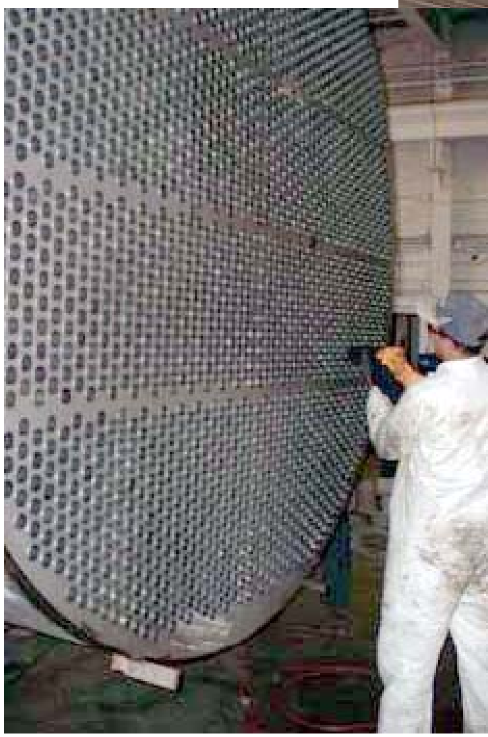


Shell and Tube Heat Exchangers



Source: Perry's Chemical Engineers Handbook, McGraw-Hill

Shell and Tube Exchangers



Source: Riggins Company:
www.rigginscompany.com

S&T Exchanger Construction

Welding the shell

Baffle assembly

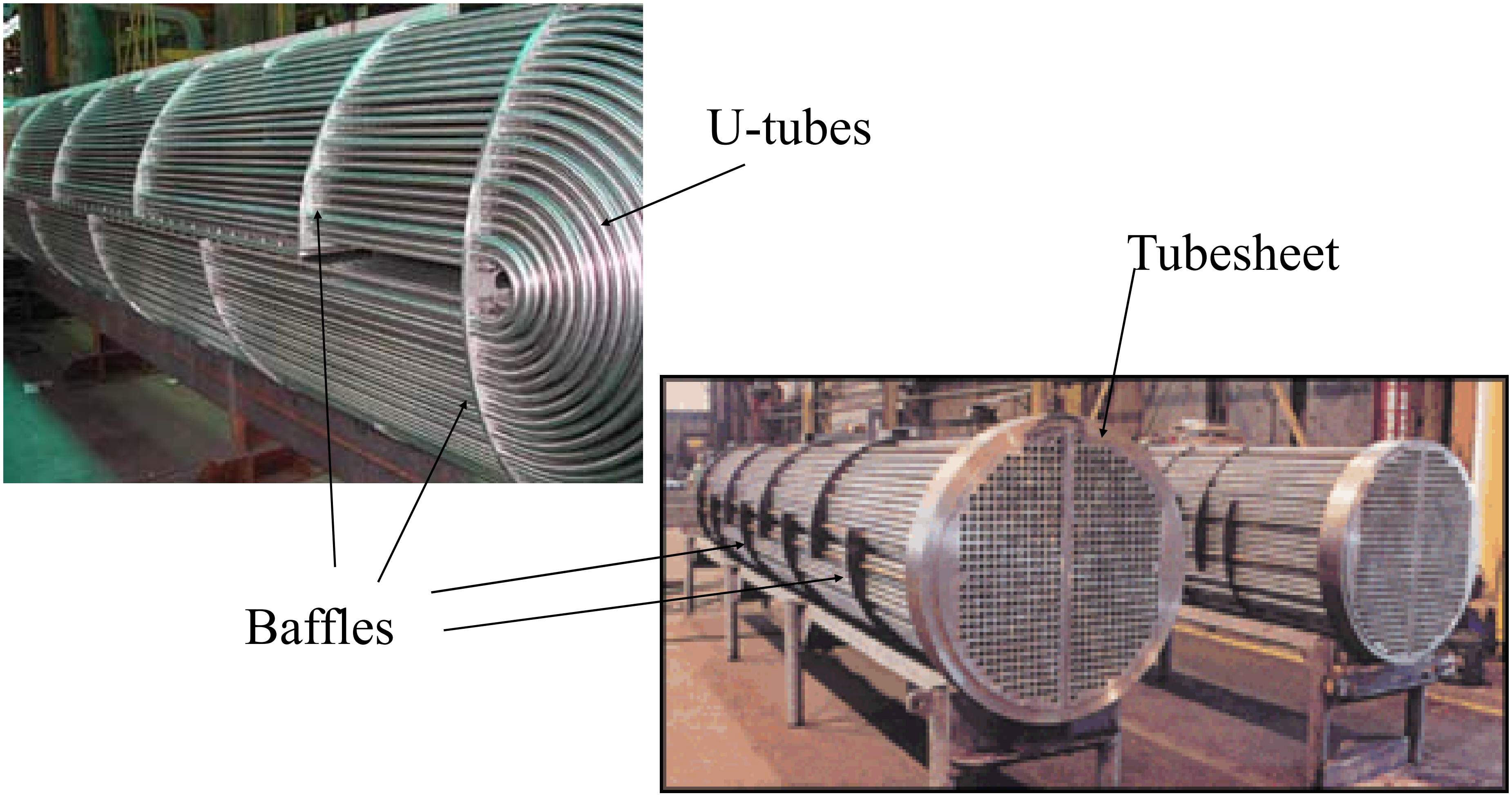
Inserting tubes

Tubesheet

Final product

Source: Bos-Hatten Inc.: www.Bos-Hatten.com

Tube Bundles

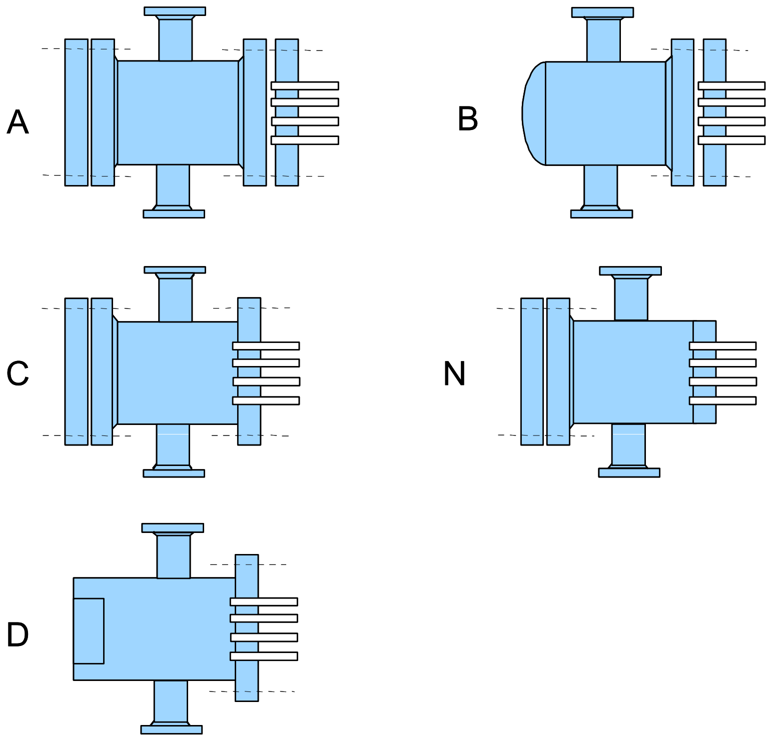


Source: UOP

Heat Exchanger Design

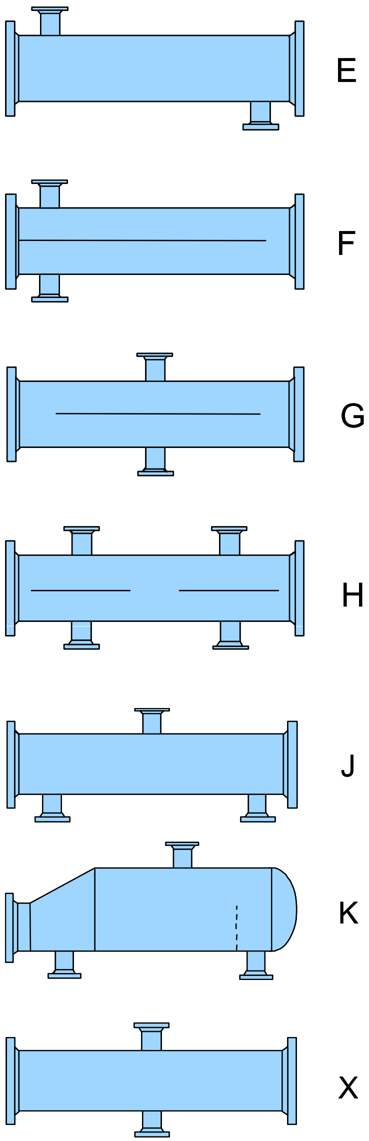
- Heat exchange design must:
  - Provide required area
  - Contain process pressure
  - Prevent leaks from shell to tubes or tubes to shell
  - Allow for thermal expansion
  - Allow for cleaning if fouling occurs
  - Allow for phase change (some cases)
  - Have reasonable pressure drop
- S&T heat exchangers are built to standards set by the Thermal Exchanger Manufacturers Association (TEMA)

TEMA Nomenclature: Front Heads



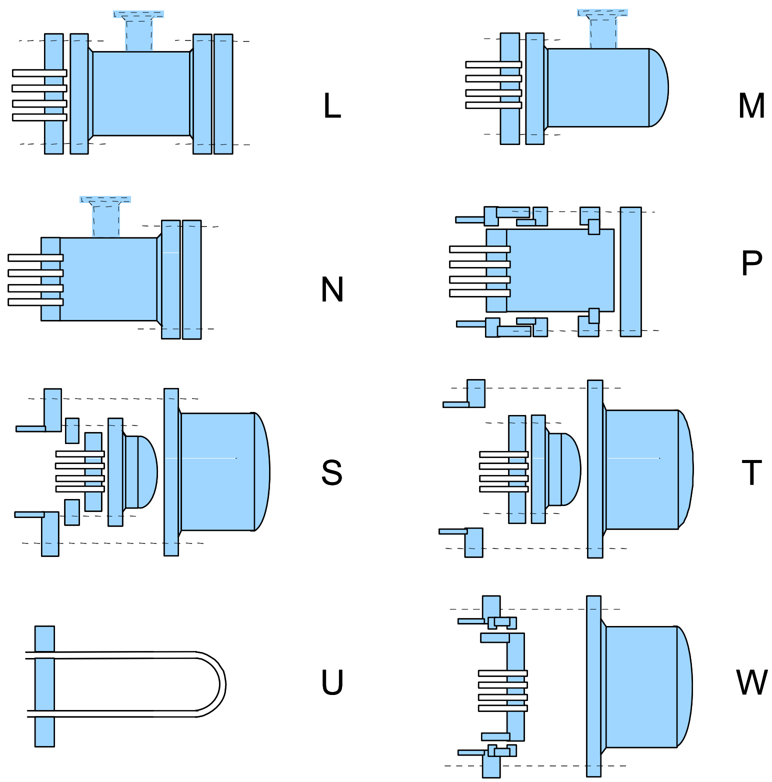
- A Type
  - Easy to open for tubeside access
  - Extra tube side joint
- B Type
  - Must break piping connections to open exchanger
  - Single tube side joint
- C Type
  - Channel to tubesheet joint eliminated
  - Bundle integral with front head
- N Type
  - Fixed tubesheet with removable cover plate
- D Type
  - Special closures for high pressure applications

TEMA Nomenclature: Shells



- E Type
  - Most common configuration without phase change
- F Type
  - Counter current flow obtained. Baffle leakage problems.
- G Type
  - Lower pressure drop
- H Type
  - Horizontal thermosyphon reboilers
- J Type
  - Older reboiler designs
- K Type
  - Phase separation integral to exchanger
- X Type
  - Lowest pressure drop, low F factor

TEMA Nomenclature: Rear Heads



- L Type
  - Same as A type front head
- M Type
  - Same as B type front head
- N Type
  - Same as N type front head
- P & W Types
  - Rarely used
- S Type
  - Floating head with backing ring
- T Type
  - Floating head pulls through shell
- U Type
  - Removable bundle without floating head

Selection of Exchanger Type: Examples

1) Feed preheater

Low pressure

Tubeside - Steam

Shellside – Naphtha

2) Crude preheat train

Low pressure

Tubeside – Vacuum Residue

Shellside – Crude oil

3) Reboiler

Medium pressure

Tubeside - Steam

Shellside - Kerosene

4) Sterilizer Preheat

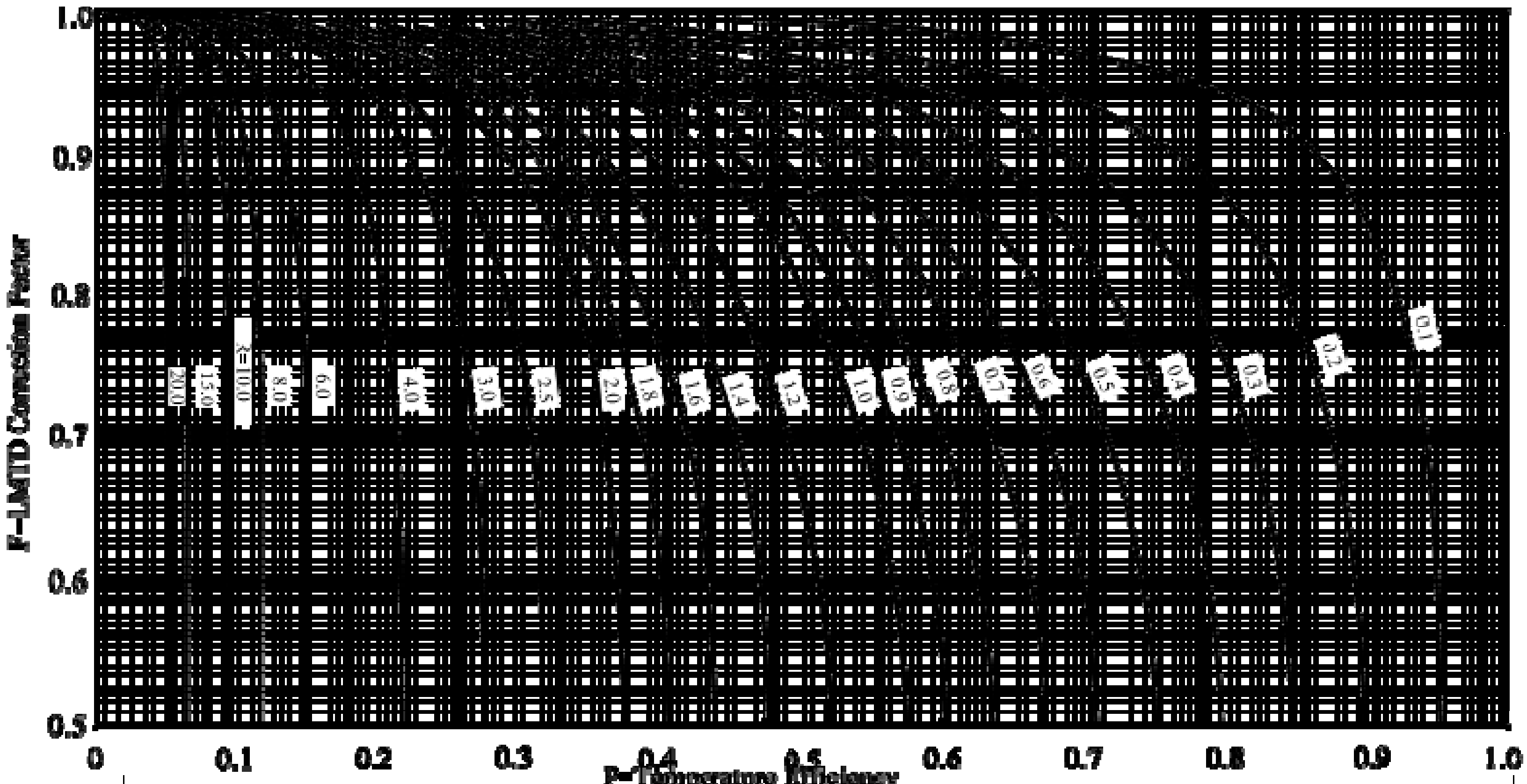
Low pressure

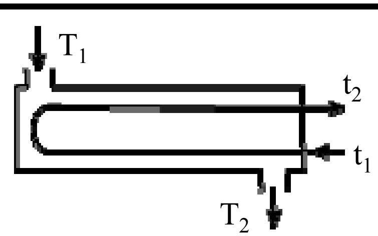
Tubeside - Milk

Shellside - Steam

Lmtd Correction Factors

E Shell - 1 Shell Pass: Similar correlations exist for other shell arrangements





LMTD Correction Factor

1 Shell Pass — **Even Number Of Tube Passes**

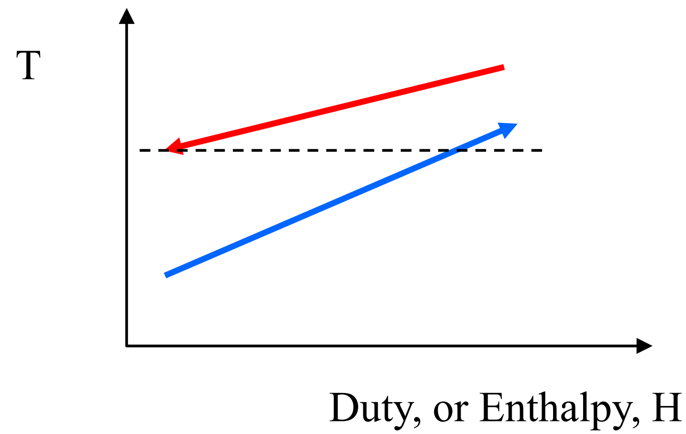
$$R = \frac{(T_1 - T_2)}{(t_2 - t_1)}$$

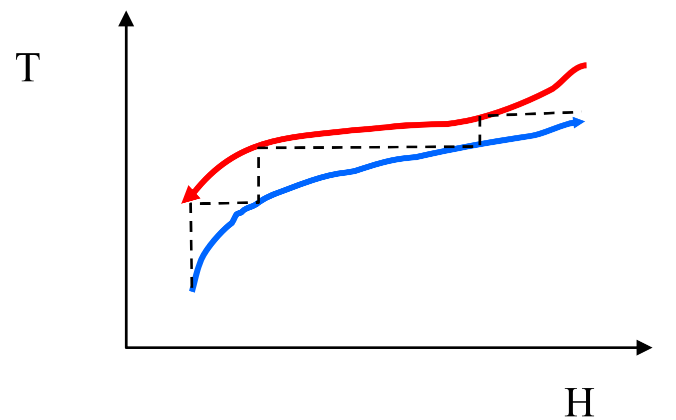
$$P = \frac{t_2 - t_1}{T_1 - t_1}$$

Source: Perry's Chemical Engineers Handbook, McGraw-Hill

Temperature Cross

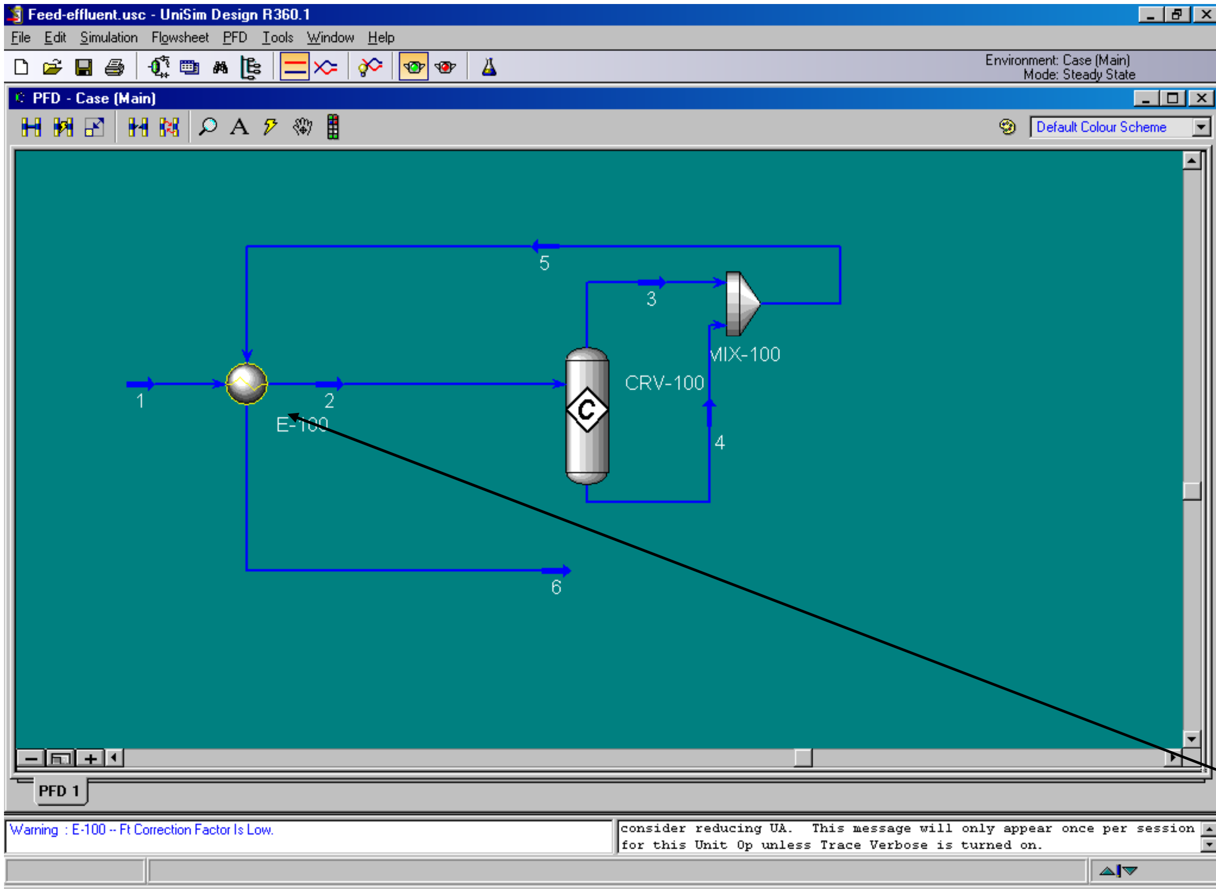
- When $T_{h,\ out} < T_{c,\ out}$ we have a "temperature cross"
- Temperature cross causes problems if exchanger is not counter-current and gives low F factors
- If $T_{c,out} – T_{h,out} >$ 5% of Lmtd then F < 0.8 and it is usually best to split the exchanger into multiple shells in series
- Number of shells can be estimated by stepping off on T-H diagram





Note:
- Real exchangers can have non-constant Cp
- Size & duty of HX in series is not necessarily the same
- Large number of shells in series approximates pure counter-current exchange

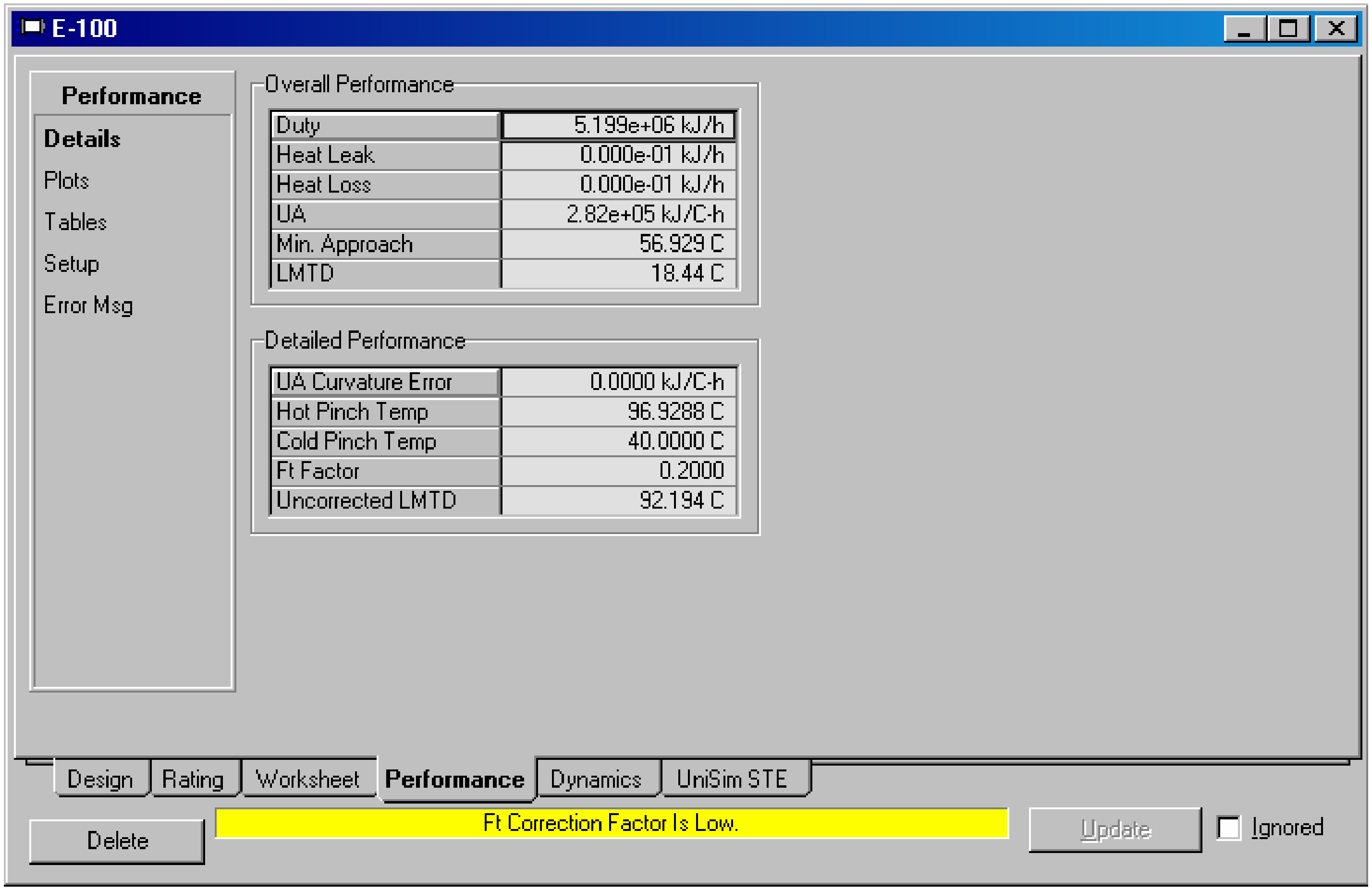
Temperature Cross in Simulation



- Most simulators show an error if there is a low F factor
- For example, in UniSim Design the exchanger shows up yellow

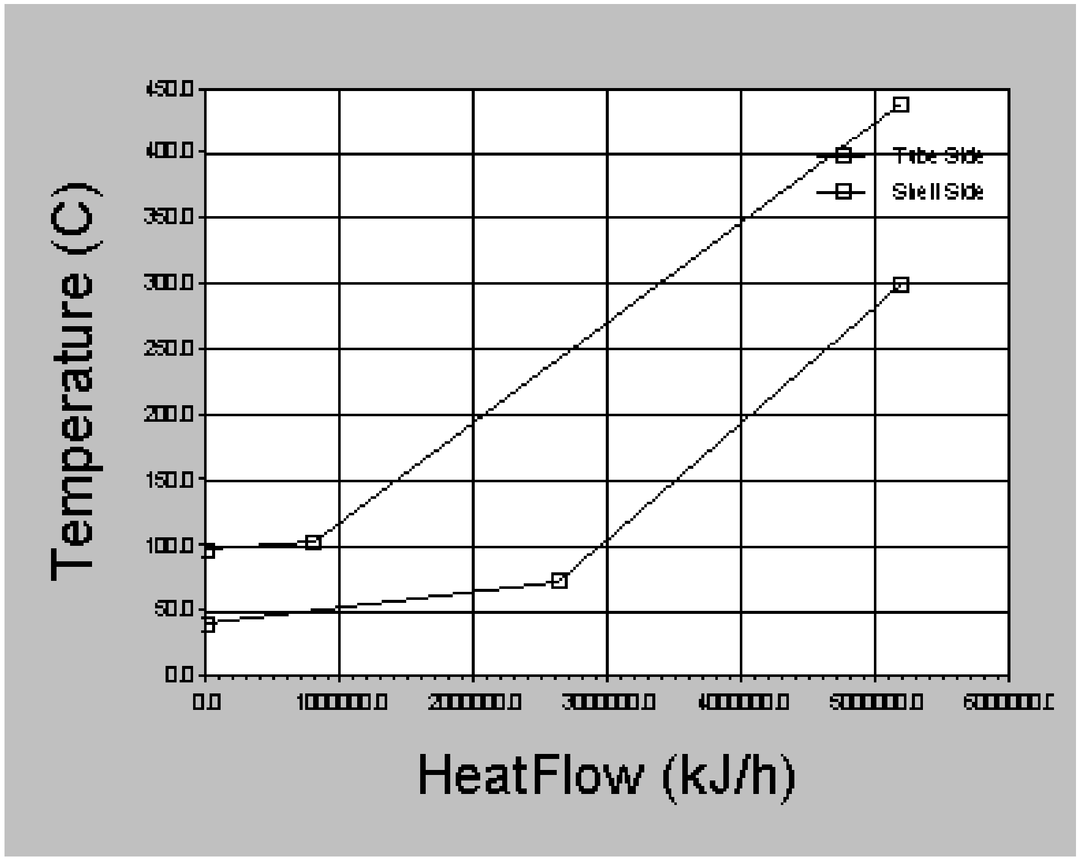
- Details of the example are in Ch 4

Temperature Cross in Simulation



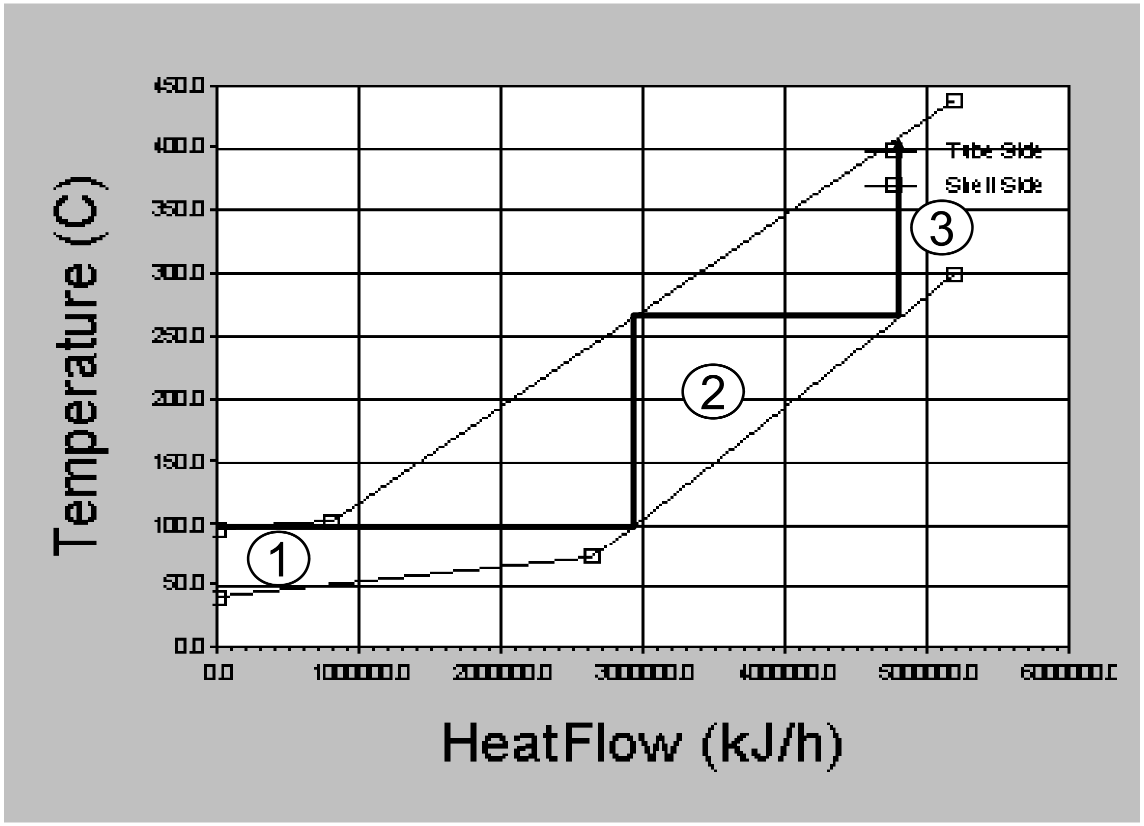
- Opening the exchanger shows the low F factor

Temperature Cross in Simulation



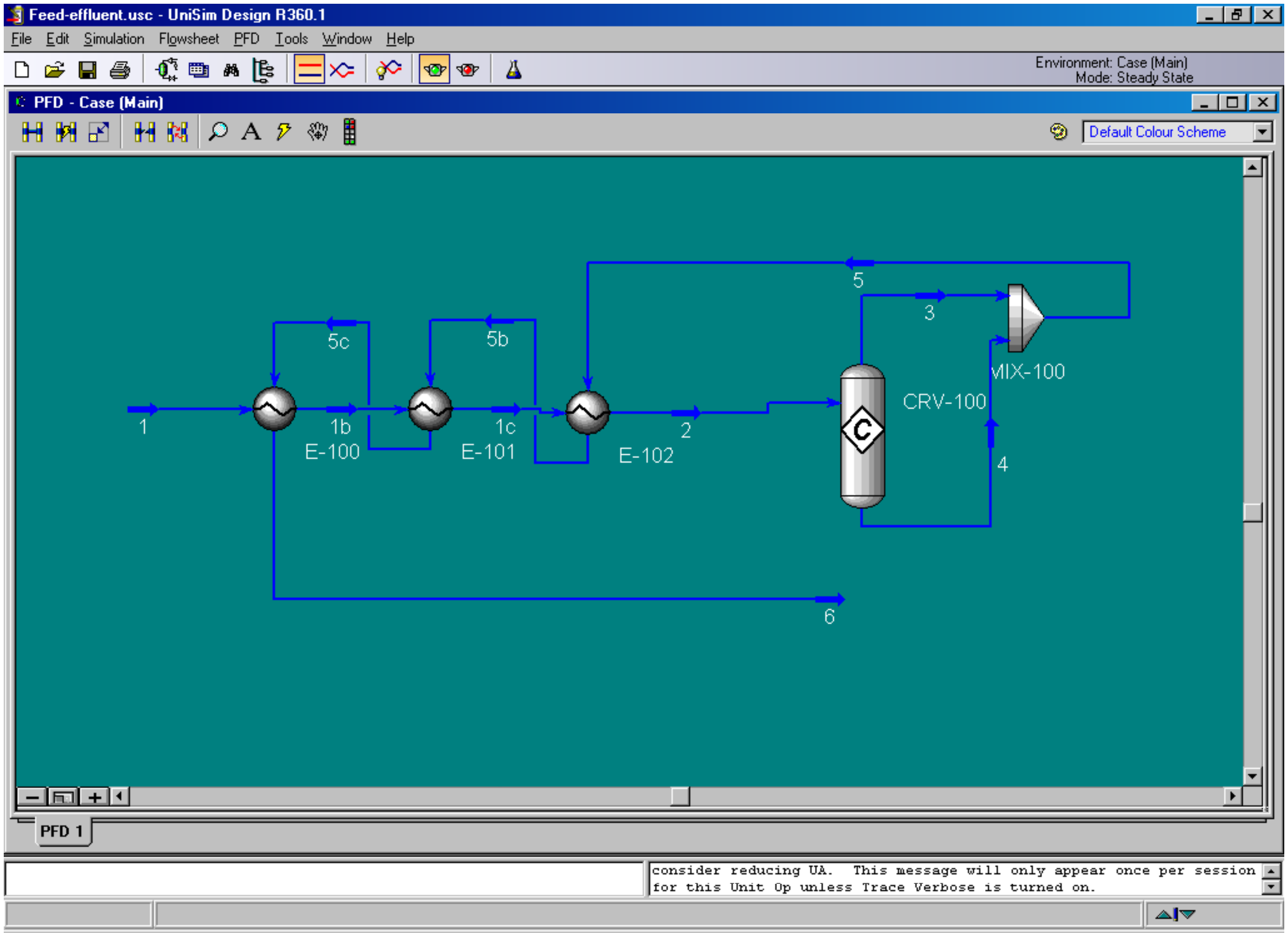
- Can use the “plots” tab to plot temperature against heat flow and visualize the temperature cross

Temperature Cross in Simulation

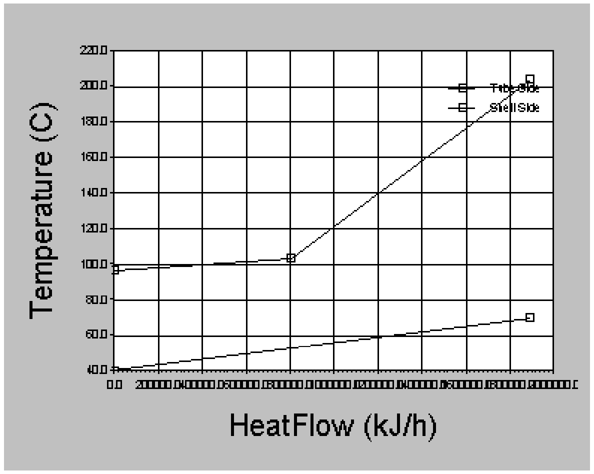


- Stepping off between profiles suggests we need three exchangers and gives target inlet and outlet temperatures

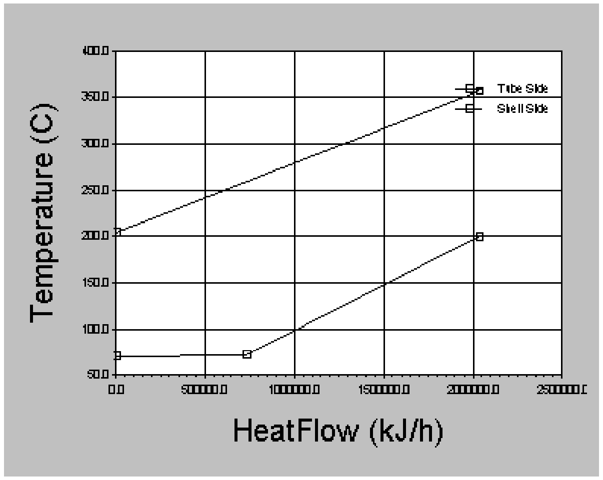
New design with temperature cross eliminated



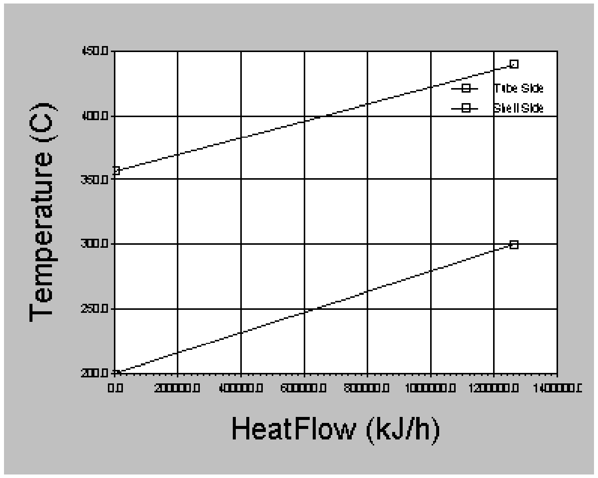
Profiles for the New Exchangers



(*a*) E100

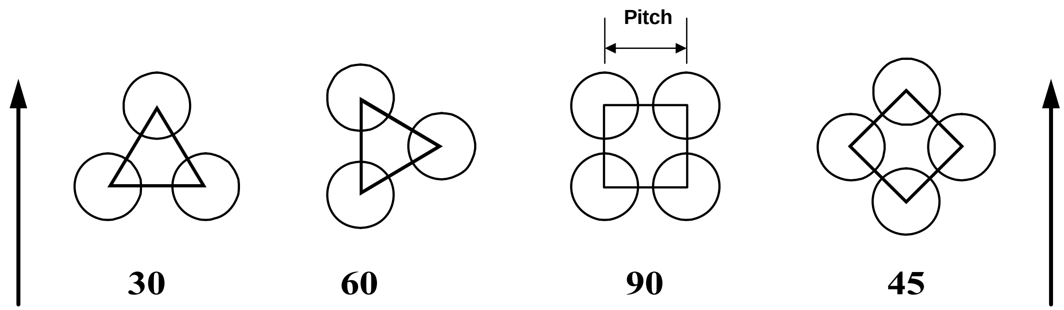


(*b*) E101



(*c*) E102

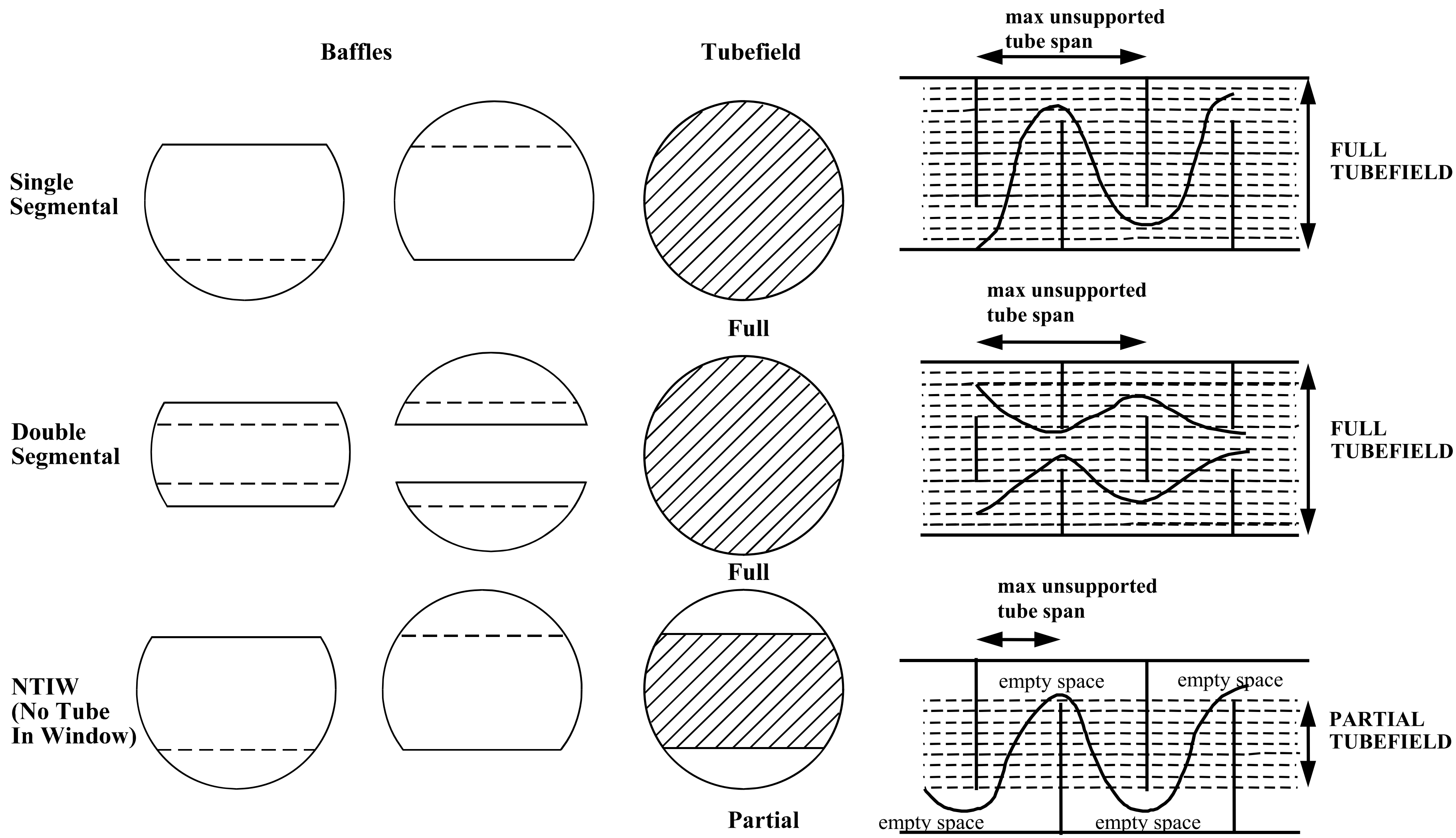
Tube Pitch



- Triangular or square pitch, each with two orientations
- TEMA minimum pitch is 1.25 x tube outside diameter
- Sometimes use larger pitch for easier cleaning (but bigger shell, lower shellside h.t.c.)

FEATURE	USE PATTERN:
lower ΔP on shellside	square (effective only at low Re number)
shellside fouling	square - easier cleaning
horizontal shellside boiling	square - prevent vapor blanketing
decrease shell size	fit 15% more tubes if triangular pitch used

Baffle Types & Shell Flow Patterns



Selection of Sides

Process Fluid	Side Selection	Reason
Fouling fluid		
Viscous fluid		
Suspended solids		
Highest T		
Highest pressure		
Cooling water		
Corrosive fluid		
Much larger flow		
Condensing fluid		

Heat Exchangers

- Heat Transfer Basics
- Tubular Exchangers
- **Heat Exchanger Design**
- Compact Heat Exchangers

Heat Exchanger Design

1. Determine duty, check for temp cross

$$Q = (m\ C_p\ \Delta T) + (\delta m\ \Delta H_{vap})$$

2. Estimate U and hence calculate area

$$Q = U\ A\ F\ \Delta T_{lm}$$

3. Determine exchanger type and tube layout
4. Pick d, L and calculate number of tubes, hence shell diameter
5. Calculate h_i, h_o and confirm U. Return to 2 if needed.
6. Calculate Δp. Return to 3 if needed.

Approximate Heat Transfer Coefficients

More examples (in metric units) in Chapter 12

Fluid	h (Btu/(hr.ft^2.F))	
	Shell-side	Tube-side
<u>**Liquids**</u>		
Water solutions, 50% water or more	300	300
Alcohols, organic solvents	200	200
Light Hydrocarbons (naphtha, gasoline)	190	190
Medium Hydrocarbons (kerosene, diesel)	130	120
Heavy oils (gas oils, crude oil)	30	20
<u>**Vapors**</u>		
Air, 10 psig	10	10
Hydrogen, 50 psig	100	100
Hydrogen, 300 psig	300	300
Hydrogen, 500 psig	400	400
Hydrocarbon vapor, 50 psig	60	60
Noncondensible gas, 2 psig	5	5

Note: Coefficients are based on 3/4 inch diameter tubes. For Tube side flows, correct by multiplying by 0.75/Actual OD. Estimated accuracy is 25%. For 50% hydrogen in vapor, reduce h to 2/3 of pure H_2 value.

Approximate Fouling Factors

Fluid	f (Btu/(hr.ft^2.F))
River water	300
Sea water	1000
Cooling tower water	400
Town water (soft)	700
Town water (hard)	300
Flue gas	800
Steam	1000
Steam condensate	1000
Light & medium hydrocarbons	400
Heavy oils	150
Boiling organics	400
Aqueous salt solutions	600
Fermentation broths	300

Hydraulics & Pressure Drop

- Heat exchanger design is a trade off between better heat transfer (high velocity, low diameter) and pressure drop
- In early stages of design, we usually allow for a "typical" pressure drop:
    - 5 psi shell-side
    - 10 psi tube-side
  – But we have to calculate Δp rigorously where it is critical to performance, e.g. thermosyphon reboilers
- In detailed design, use correlations or simulation programs to more rigorously optimize if pressure drop is important to process performance – see Chapter 12 for examples

Example: S&T HX Design

- What size of exchanger is needed to heat 375,000 lb/h of naphtha from 150F to 300F using medium pressure steam at 360F?

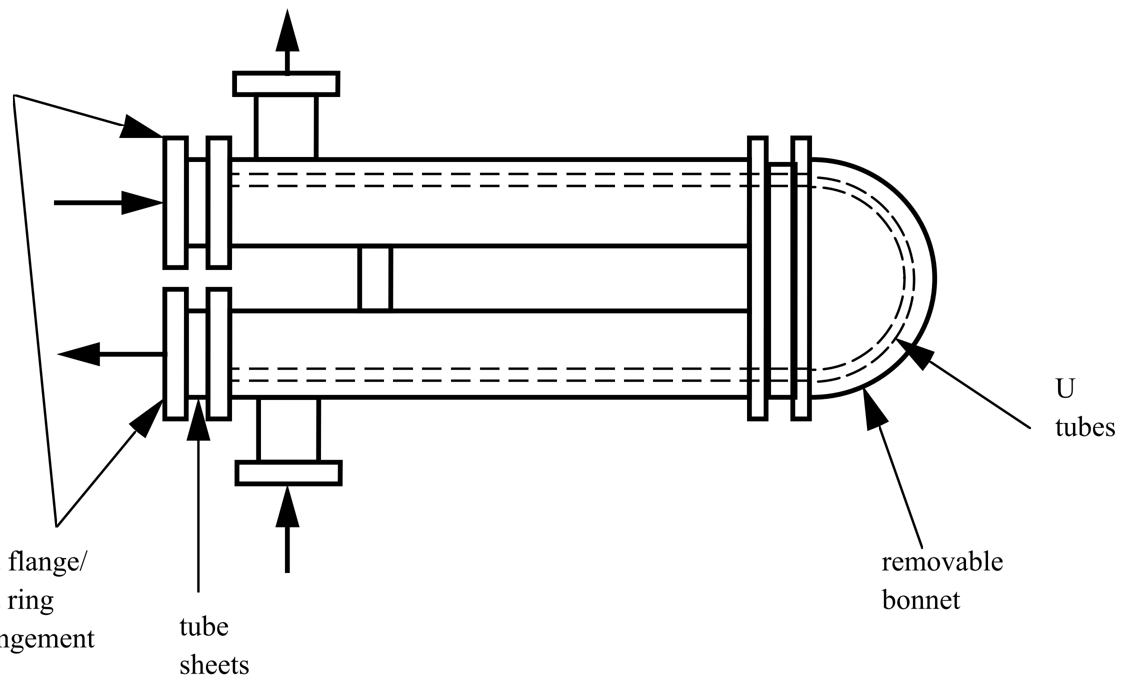
- We can now use correlations to confirm design and check hydraulics

Heat Exchangers

- Heat Transfer Basics
- Tubular Exchangers
- Heat Exchanger Design
- **Compact Heat Exchangers**

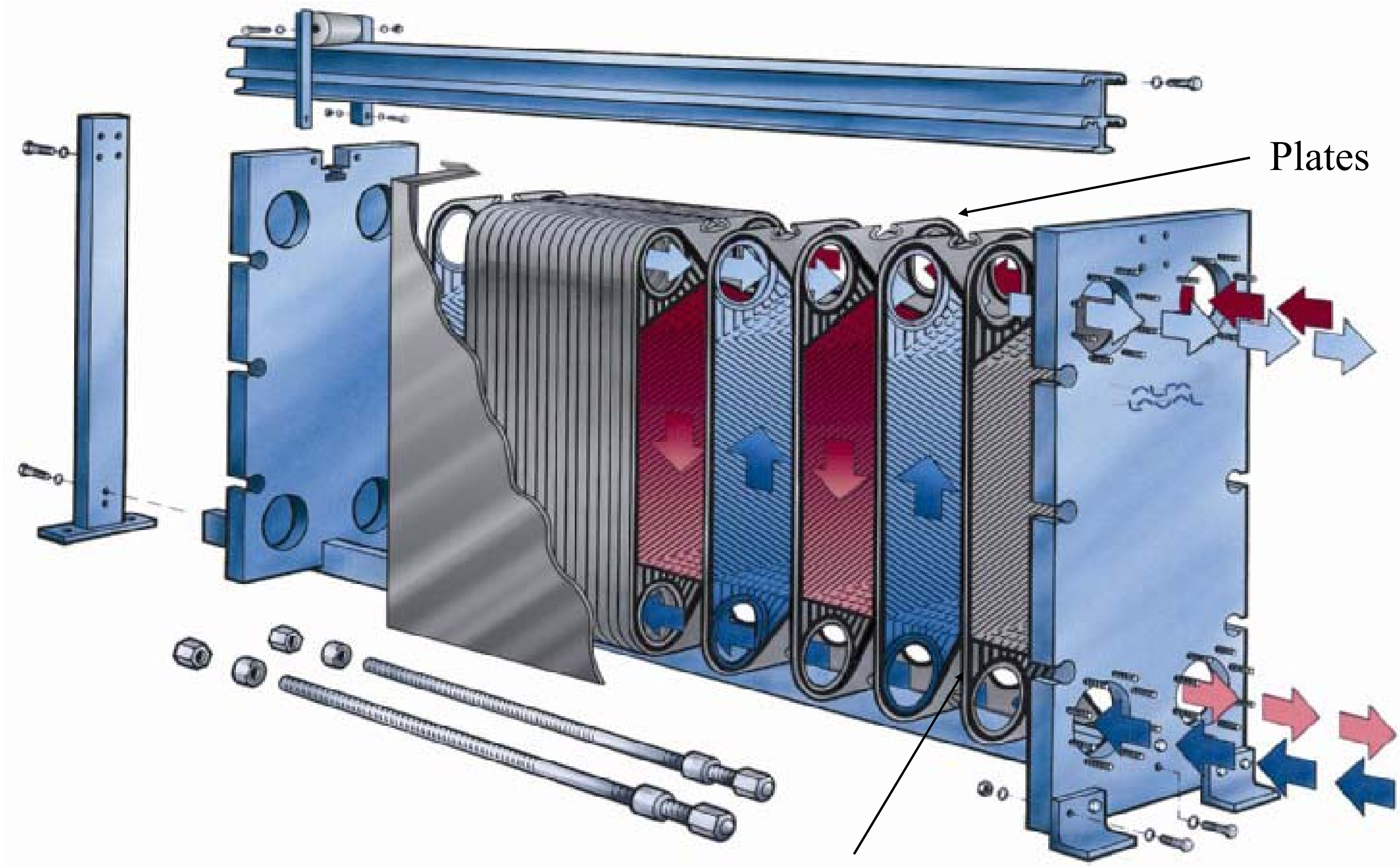
Hairpin Exchangers

- When small duties are required, hairpin exchangers are specified:
  - cheaper than very small shell and tube
  - highly effective (single pass, true countercurrent)
  - 75 → 1500 ft^2 surface area
  - 4 → 16" shell diameter, 20 ft long



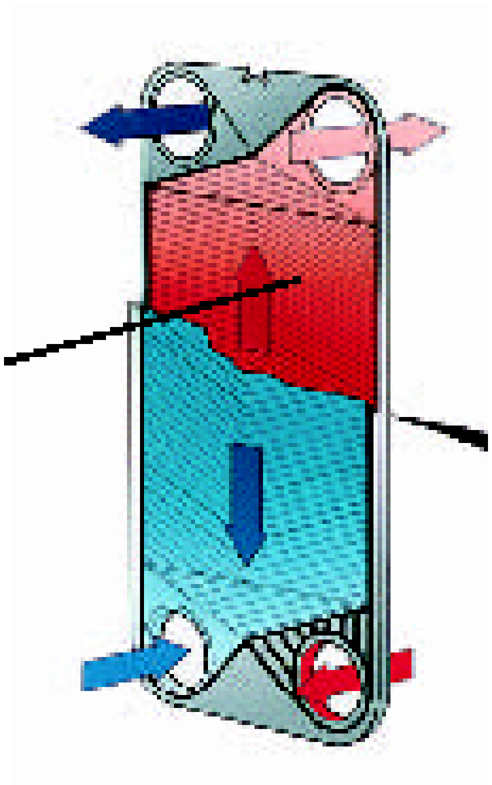
This design is used for double-pipe and multi-tube exchangers.

Plate & Frame Exchangers



Source: Alfa-Laval, www.AlfaLaval.com

Plate & Frame Exchangers



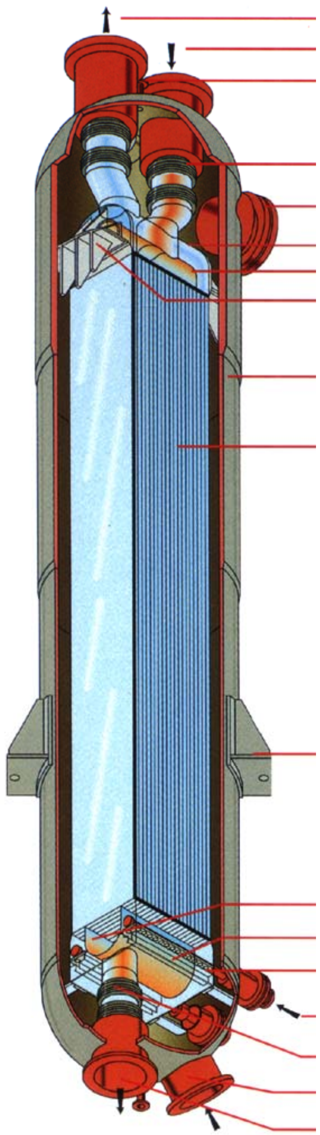
- Advantages
  - Close to counter-current heat transfer, so high F factor allows temperature cross and close temperature approach
  - Easy to add area
  - Compact size
  - Relatively inexpensive for high alloy
  - Can be designed for quick cleaning in place
- Disadvantages
  - Lots of gaskets
  - Lower design pressure, temperature
  - External leakage if gaskets fail
- Applications
  - Food processing, brewing, biochemicals, etc.
- Design method: see Chapter 12

Source: Alfa-Laval, www.AlfaLaval.com

Plate & Frame Exchangers

Source: Alfa-Laval, www.AlfaLaval.com

Welded Plate Heat Exchangers



Source: Alfa-Laval Packinox

- Advantages
  - Higher thermal efficiency
  - Single unit can replace multiple shell & tube units
  - Closer approach to hot inlet temperature
  - Low pressure drop
  - Little chance of vibration problems
  - Excellent distribution of two phase flows
- Disadvantages
  - Single alloy material for plates
  - Difficult to clean
  - Few manufacturers at large scale (Alfa Laval Packinox)
- Used in large scale clean services that need close temperature approach

Questions ?