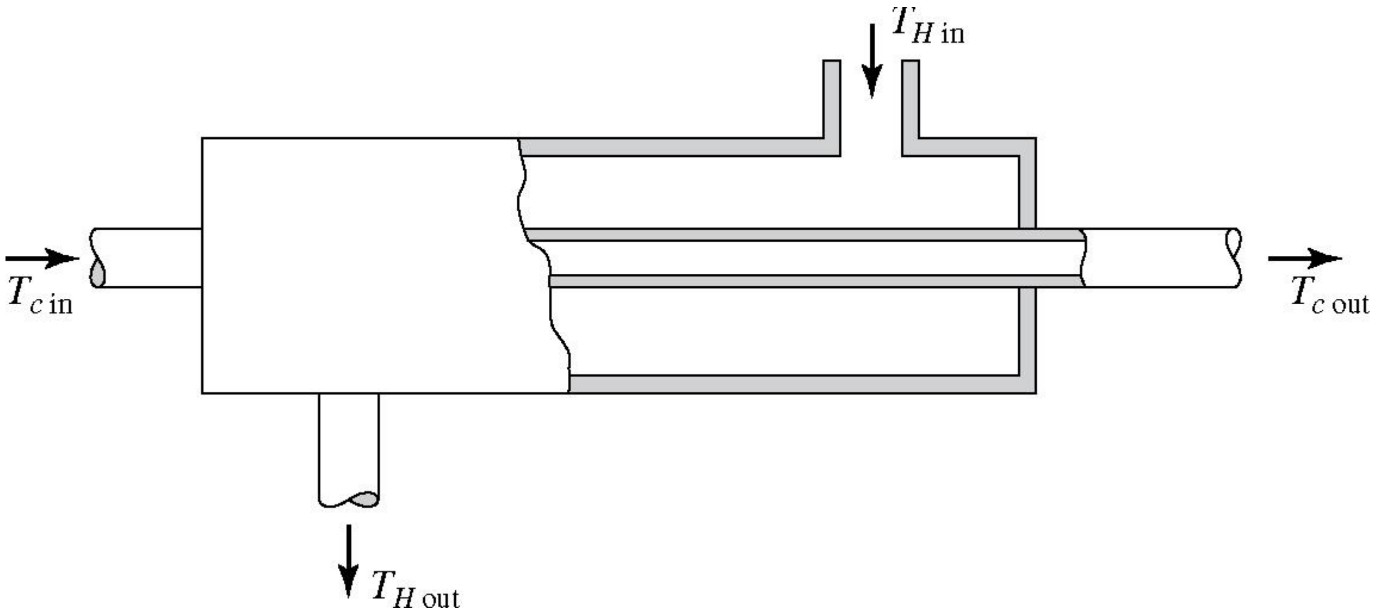
Heat Transfer equipment – (Chpt. 22)

Heat Exchangers

Open – Closed – Heaters



Heat Transfer Equipment

- Double-pipe exchanger, used for cooling or heating.
- Shell and tube heat exchangers, used for all applications.
- Plate-fin exchangers.
- Spiral heat exchangers.
- Air cooled: coolers and condensers.
- Direct contact: cooling and quenching.
- Agitated vessels.
- Fired heaters.

Heat Transfer Equipment

Usual terminology:

- Exchanger: heat exchange between two process streams.
- Heater or Cooler: a process stream is heated/cooled by a utility stream.
- Vaporizer: a process stream is completely vaporized.
- Reboiler: vaporizer associated with a distillation column.
- Evaporator: used to concentrate a solution.
- Fired heater: heating is done by combustion.

Heat Transfer Equipment – What do we want?

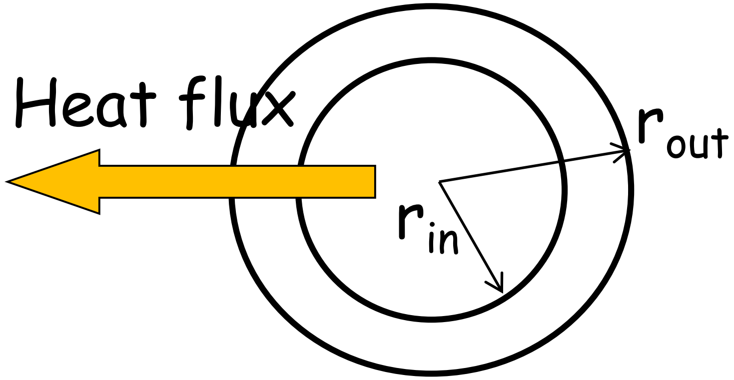
Design:

- Duty (how much heat/energy is exchanged)
- Stream conditions (T, flow rate, pressures, phase)
- Configuration (size, material of construction etc.)

Need: physical properties, need U (h and k)

Heat transport:

$$q = U\,A\Delta T_{tot}$$

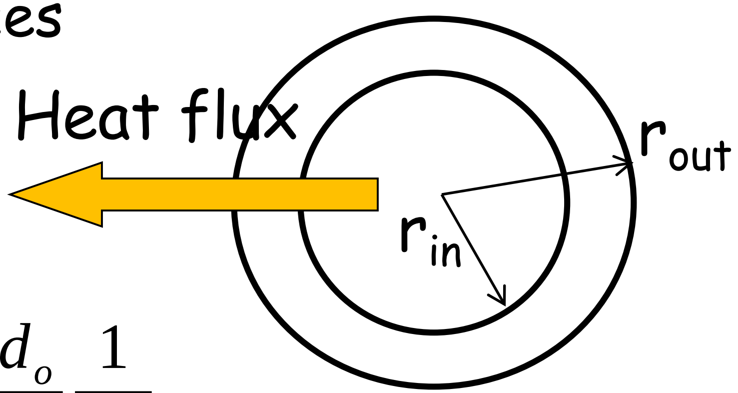


Overall resistance, *R=1/UA*

Overall Heat Transfer Coefficient

Resistances in series:

Overall resistance = Sum of resistances



In our case:

$$\frac{1}{U_o} = \frac{1}{h_o} + \frac{1}{h_{od}} + \frac{d_o \ln\left(d_o/d_i\right)}{2k_w} + \frac{d_o}{d_i}\frac{1}{h_i} + \frac{d_o}{d_i}\frac{1}{h_{id}}$$

U_o: overall heat transfer coefficient based on the outside area

h_o, h_i: outside/inside film heat transfer coefficient

d_o, d_i: outside/inside pipe diameter

k_w: wall thermal conductivity

h_{od}, h_{id}: outside/inside fouling heat transfer coefficient (Table 22.1)

Shell and Tube Heat Exchangers

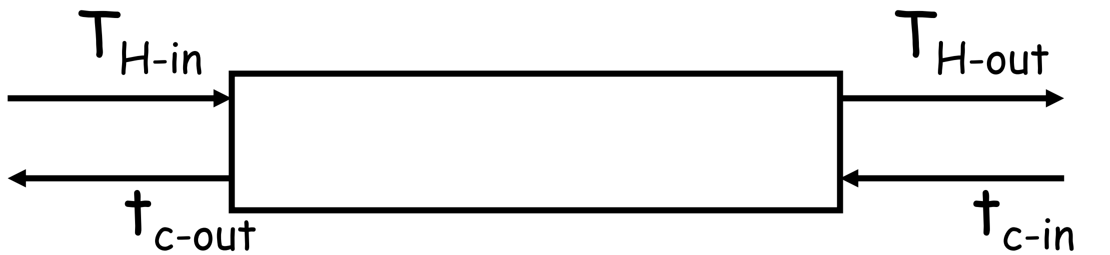
Most commonly used heat exchangers.

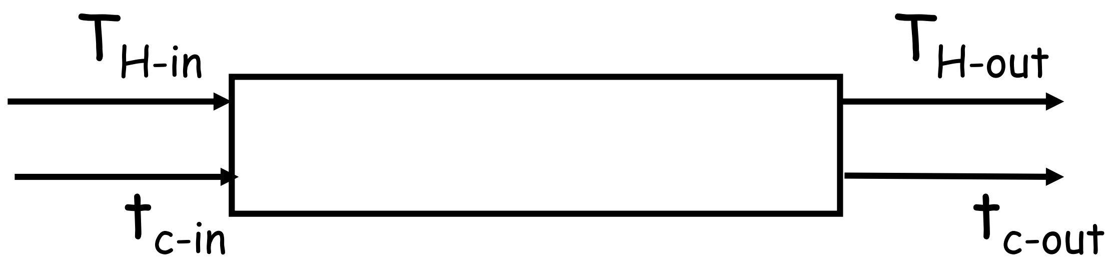
Advantages:

- Large surface area in a small volume.
- Good mechanical layout.
- Well-established fabrication methods.
- Can be constructed from a wide variety of materials.
- Easily cleaned and maintained.
- Well-established design procedures.

Shell and Tube Heat Exchangers

Single pass, co-current and countercurrent flow.





Heat Transfer Equipment

Tube and shell heat exchanger:

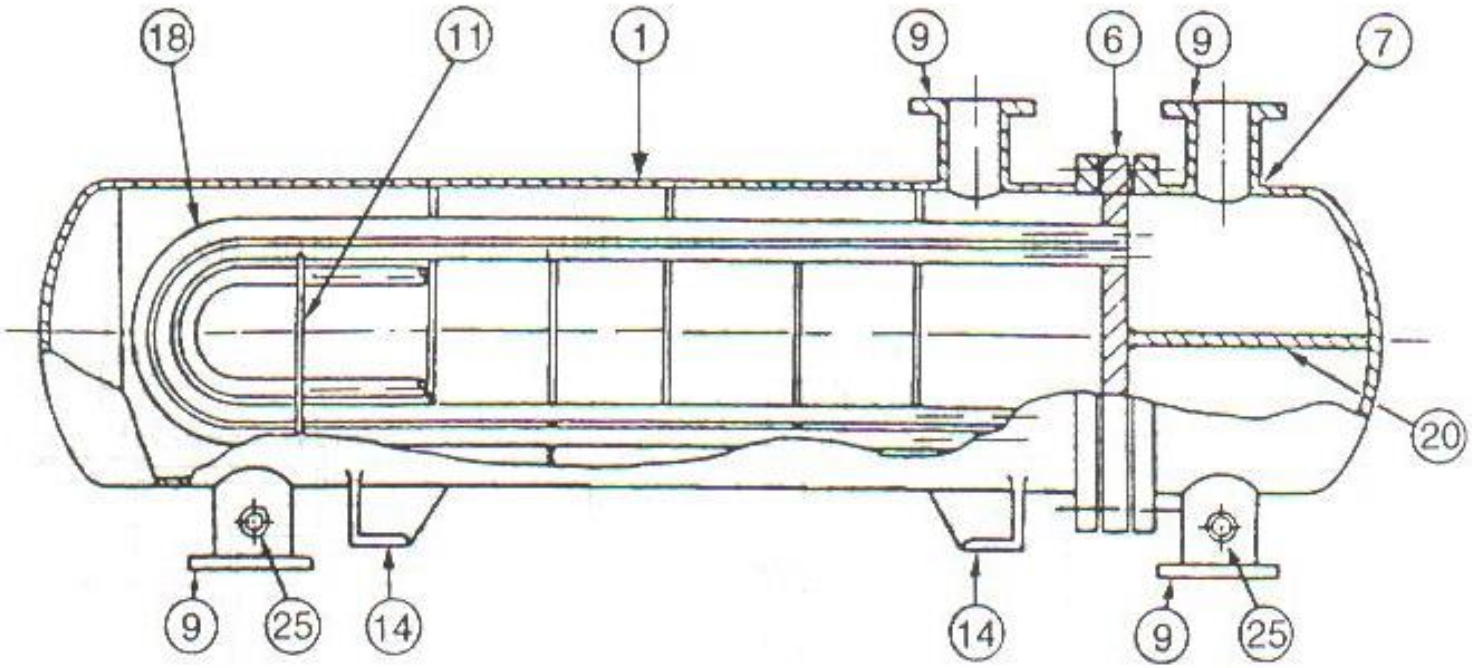


Figure 12.4. U-tube (based on figures from BS 3274: 1960)

Sinnott & Towler, Chemical Engineering Design, Elsevier, 5th edition, 2009

Heat Transfer Equipment

Tube and shell heat exchanger:

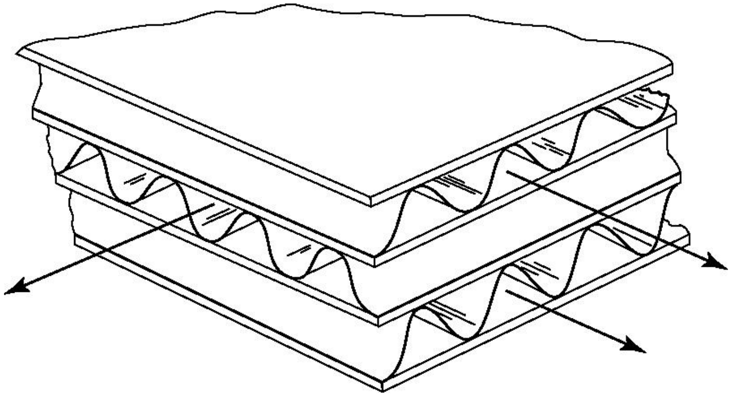
Nomenclature

Part number

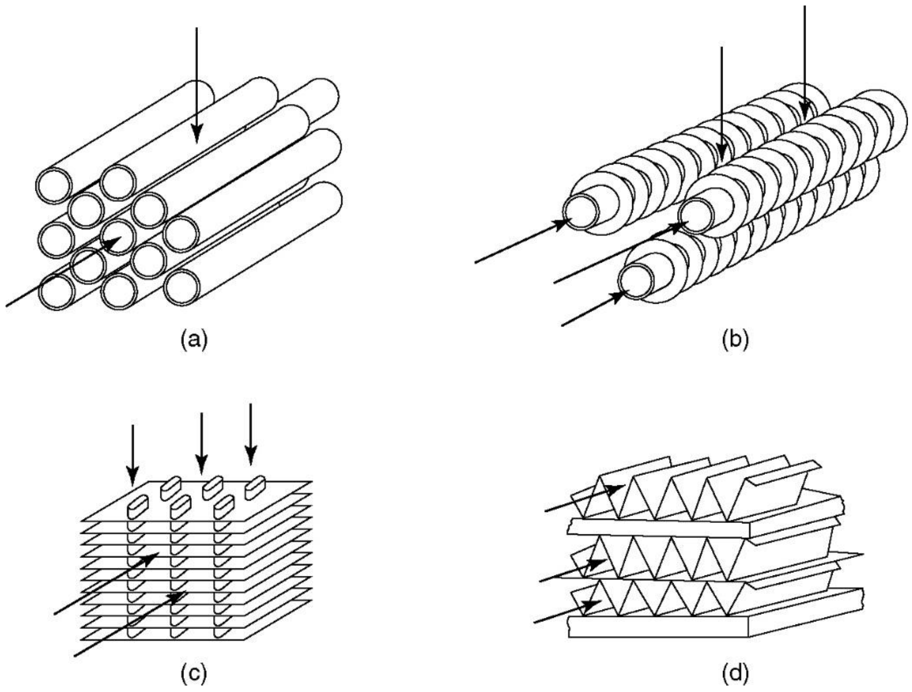
1. Shell
2. Shell cover
3. Floating-head cover
4. Floating-tube plate
5. Clamp ring
6. Fixed tube sheet (tube plate)
7. Channel (end-box or header)
8. Channel cover
9. Branch (nozzle)
10. Tie rod and spacer
11. Cross baffle or tube-support plate
12. Impingement baffle
13. Longitudinal baffle
14. Support bracket
15. Floating-head support
16. Weir
17. Split ring
18. Tube
19. Tube bundle
20. Pass partition
21. Floating-head gland (packed gland)
22. Floating-head gland ring
23. Vent connection
24. Drain connection
25. Test connection
26. Expansion bellows
27. Lifting ring

Heat Transfer Equipment

Cross-flow & compact H.E.:



Welty et al., Fig 22-2



Welty et al., Fig 22-4

Single pass heat exchangers: Analysis

- A T-Q diagram is a visual representation of the energy balance equation for each stream.

Single phase streams with constant C_p and no pressure effect on enthalpy:

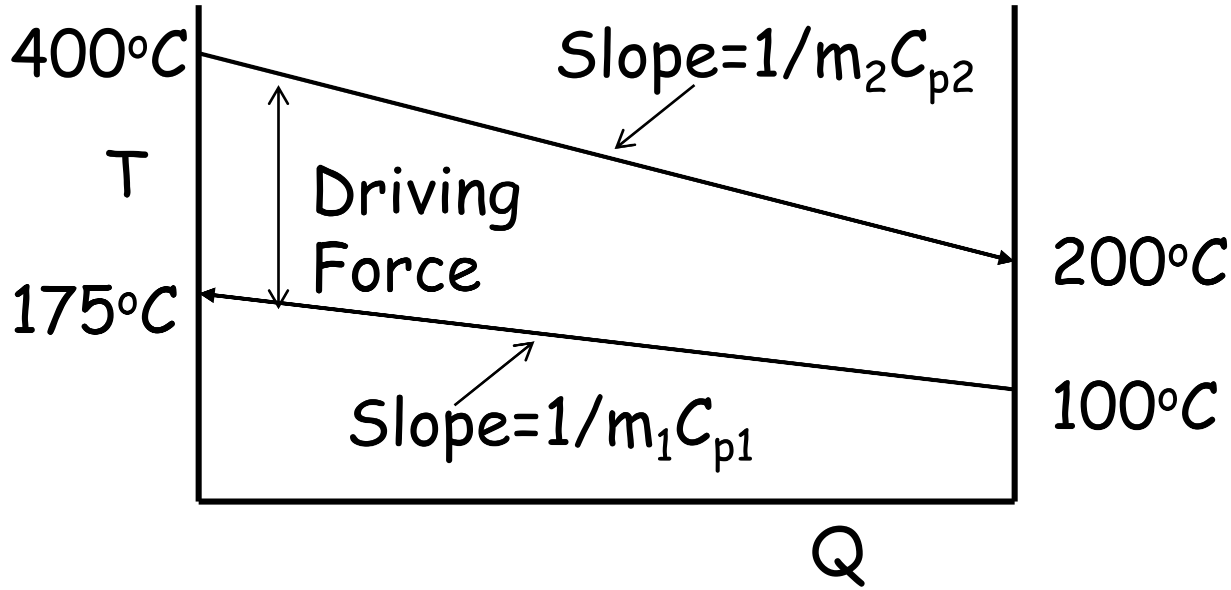
$$q = \dot{m} C_p \Delta T$$

Pure components undergoing phase change:

$$q = \dot{m} \lambda$$

Heat Exchangers: The T-Q Diagram

For the previous example:



The T-Q diagram reveals two important truths regarding heat transfer:

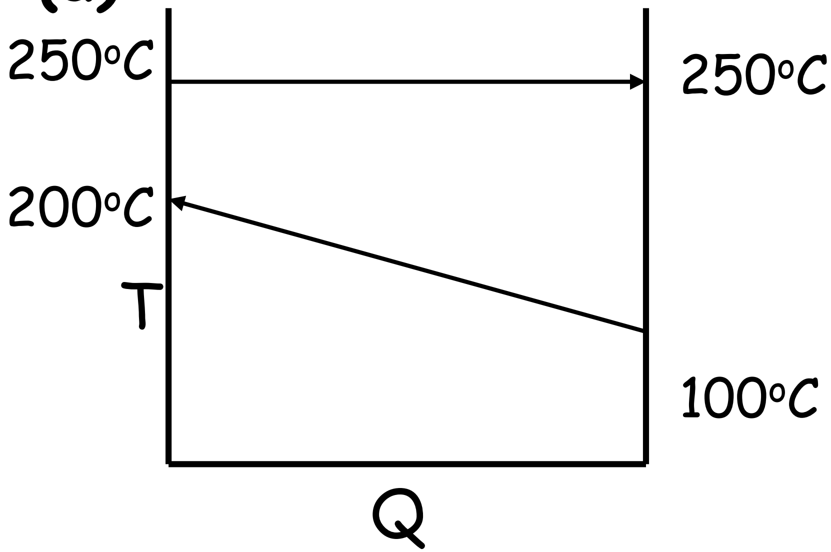
(1) T-lines for counter-current flows do not cross! It is impossible.

(2) T-lines should not approach each other too closely: As they approach, the area required for heat transfer goes to infinity. The point of closest approach is called ***pinch point***.

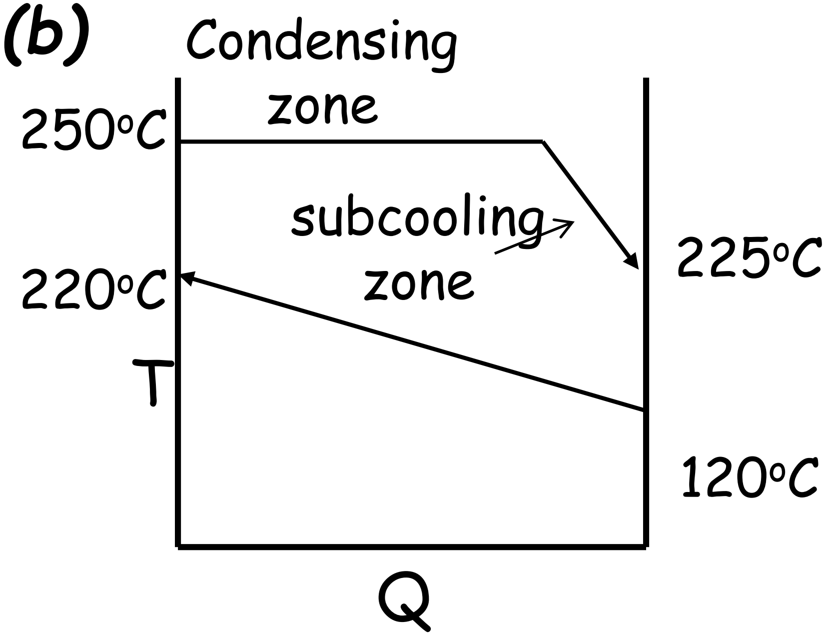
Heat Exchangers: The T-Q Diagram

Examples:

(a)



(b)

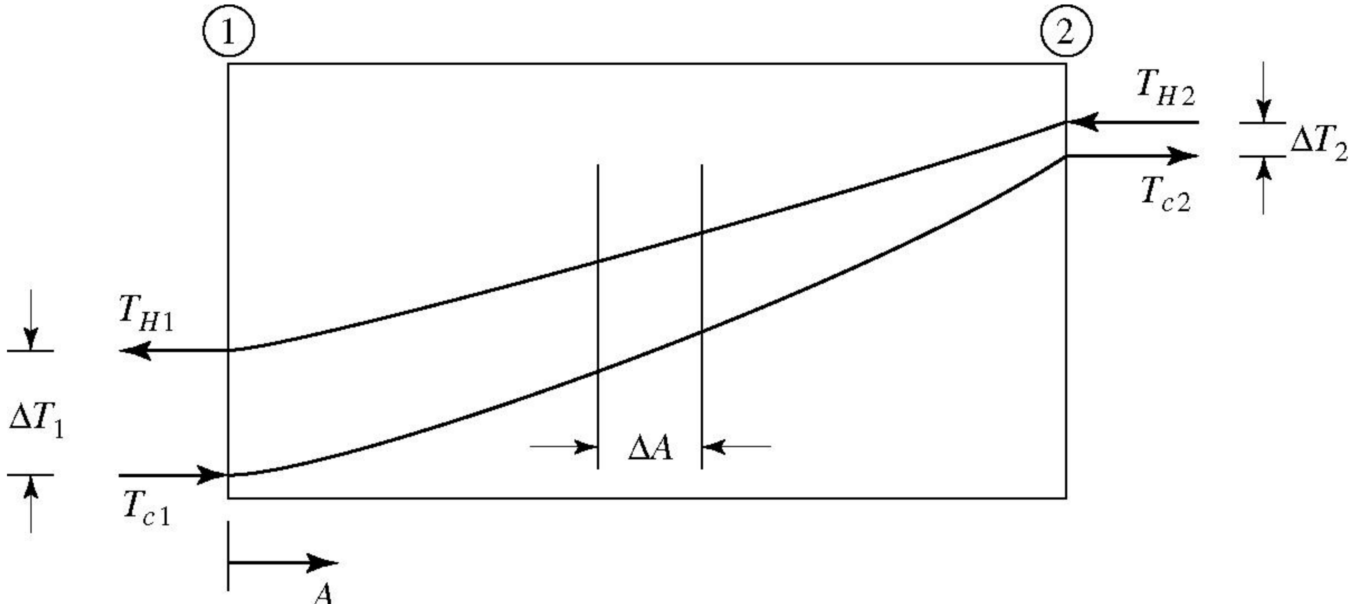


(a) A single-phase stream is heated from 100 to 200°C by condensing saturated steam to saturated liquid at 250°C in a countercurrent heat exchanger.

(b) A single-phase stream is heated from 120 to 220°C by condensation of saturated steam at 250°C and by subcooling the liquid to 225°C in a countercurrent heat exchanger.

Single pass heat exchangers: Analysis

- A T-A diagram is another visual representation of the energy transfer in a heat exchanger.



Energy balance (1st thermo law): $q = \dot{m} C_p \Delta T$

For a differential area

$$dq = (\dot{m}c_p)_H dT_H = C_H dT_H$$

$$dq = (mc_p)_c dT_c = C_c dT_c$$

Single pass heat exchangers: Analysis

$$dq = U\,dA(T_H - T_c)$$

Temperature difference: $\Delta T = (T_H - T_c)$

Differential $d(\Delta T) = dT_H - dT_c$

Substitute

$$d(\mathbf{\Delta}T) = dq\left(\frac{1}{C_H} - \frac{1}{C_c}\right) = \frac{dq}{C_H}\left(1 - \frac{C_H}{C_c}\right)$$

Heat lost from hot fluid is taken by cold fluid, so:

$$\frac{C_H}{C_c} = \frac{T_{c2} - T_{c1}}{T_{H2} - T_{H1}}$$

Single pass heat exchangers: Analysis

$$d(\Delta T) = \frac{dq}{C_H}\left(1 - \frac{T_{c2} - T_{c1}}{T_{H2} - T_{H1}}\right) = \frac{dq}{C_H}\left(\frac{T_{H2} - T_{H1} - T_{c2} + T_{c1}}{T_{H2} - T_{H1}}\right)$$

$$= \frac{dq}{C_H}\left(\frac{\Delta T_2 - \Delta T_1}{T_{H2} - T_{H1}}\right)$$

Recall: $\mathrm{d}q = U(dA)\Delta T$, and $q = C_H(T_{H2} - T_{H1})$

Then:

$$\int_{\Delta T_1}^{\Delta T_2} \frac{d(\Delta T)}{\Delta T} = \frac{U}{q}(\Delta T_2 - \Delta T_1)\int_0^A dA$$

Single pass heat exchangers: Analysis

Integrate:

$$\ln\frac{\Delta T_2}{\Delta T_1} = \frac{UA}{q}(\Delta T_2 - \Delta T_1)$$

And, by rearranging:

$$q = UA\frac{\Delta T_2 - \Delta T_1}{\ln\dfrac{\Delta T_2}{\Delta T_1}}$$

So that

$$q = UA\,\Delta T_{lm}$$

Single pass heat exchangers: Analysis

Log-mean temperature difference

$$q = UA\,\Delta T_{lm}$$

Important Assumptions:

U constant
No heat losses to ambient environment

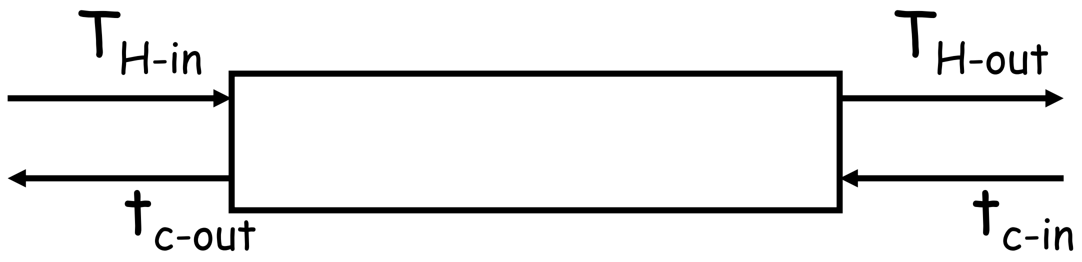
Can be used with U calculated at average conditions in the exchanger

Heat Exchangers - Typical design

1) Define duty: heat transfer rate, flows, temperatures.
2) Collect required physical properties (ρ, μ, k).
3) Decide on the type of exchanger.
4) Select a trial value for U.
5) Calculate the mean temperature difference, ΔT_m
6) Calculate area required.
7) Decide on the exchanger layout.
8) Calculate individual coefficients.
9) Calculate U. If significant difference from step (4), substitute in (4) and repeat.
10) Calculate the pressure drop. If it is not satisfactory, back to (7) or (4) or (3).
11) Optimise: repeat (4) to (10) to determine cheapest solution (usually smaller area).

Heat Exchangers

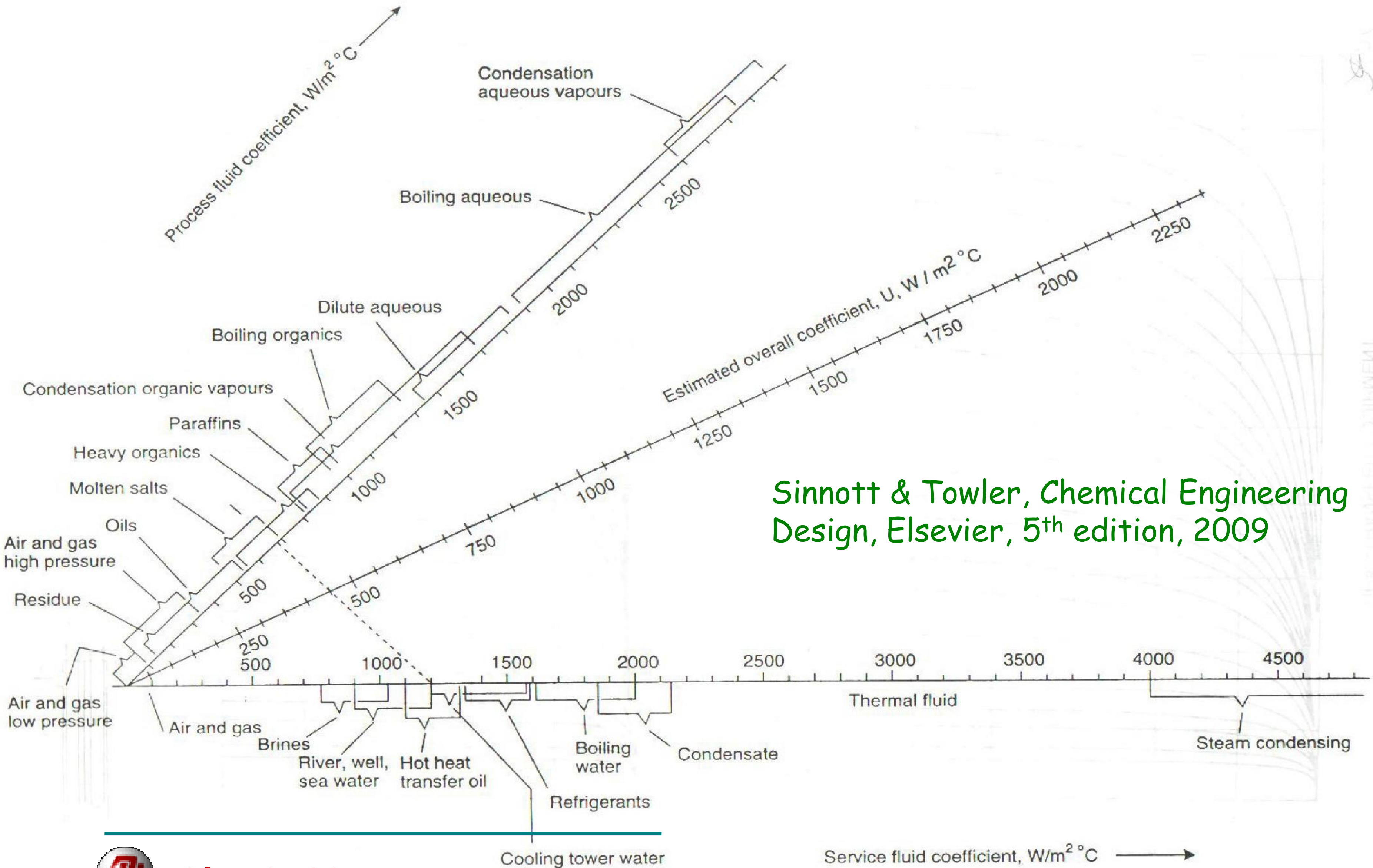
(4) Use first order approximations for *U*, such as table 22-2 pg. 385 in Welty et al.



Then we can use the simplified integral form (steps 5 & 6)

$$q = U\,A\Delta T_m$$

Overall Heat Transfer Coefficient



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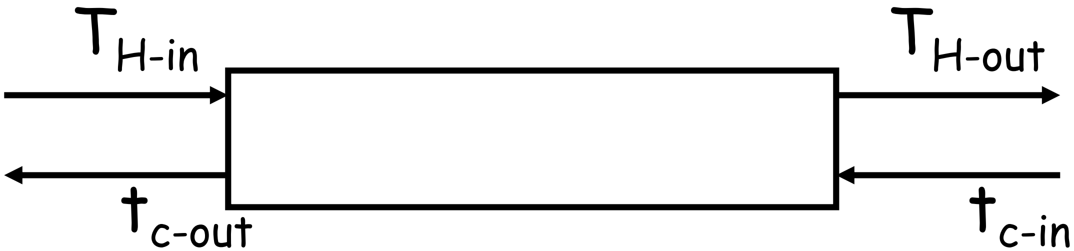
Heat Exchangers



(5) Mean temperature difference for counter-current flow:

$$\Delta T_m = \Delta T_{lm} = \frac{(T_{H-in} - t_{c-out}) - (T_{H-out} - t_{c-in})}{\ln \frac{(T_{H-in} - t_{c-out})}{(T_{H-out} - t_{c-in})}}$$

In reality, combination of co-current, countercurrent and cross flow.

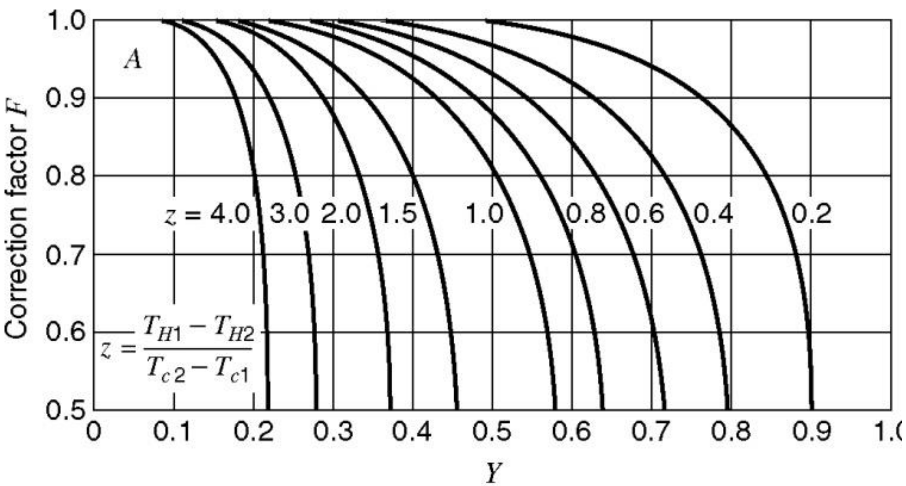
What do we do? Use a correction factor, F_t, (see figs 22-9 and 22-10 in Welty et al.)

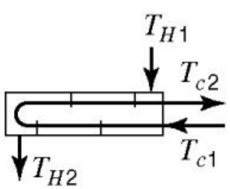
$$\Delta T_m = F_t \Delta T_{lm}$$

Parameters: $Z = R = \frac{(T_{H-in} - T_{H-out})}{(t_{c-out} - t_{c-in})}$, $\quad Y = S = \frac{(t_{c-out} - t_{c-in})}{(T_{H-in} - t_{c-in})}$

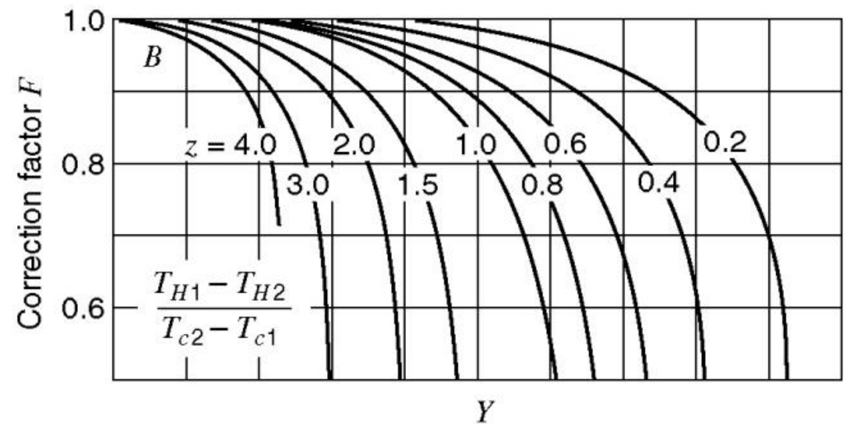
Heat Transfer Equipment

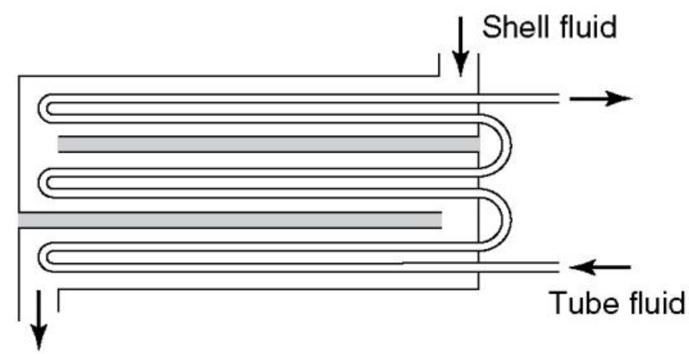
Correction factor:





Correction factor plot for exchanger with one shell pass and two, four, or any multiple of tube passes

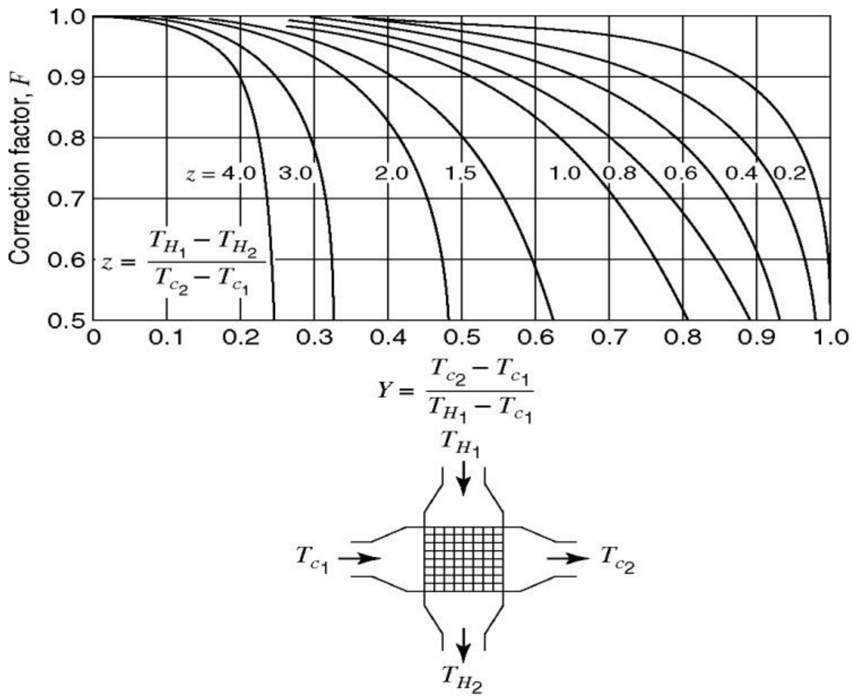




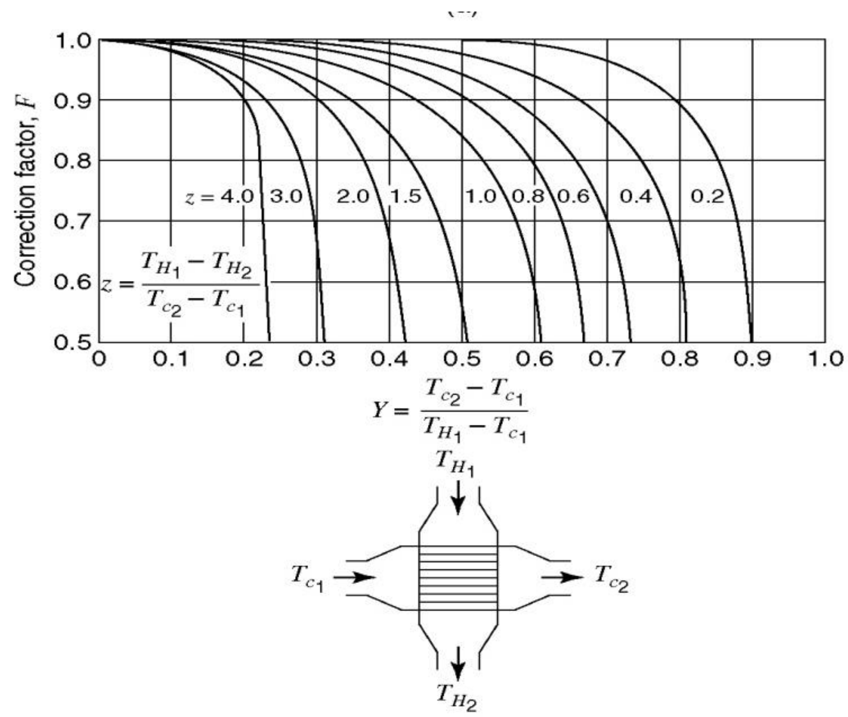
(b)

Heat Transfer Equipment

Correction factor:



(a)



(b)

Heat Transfer Equipment

Correction factor:

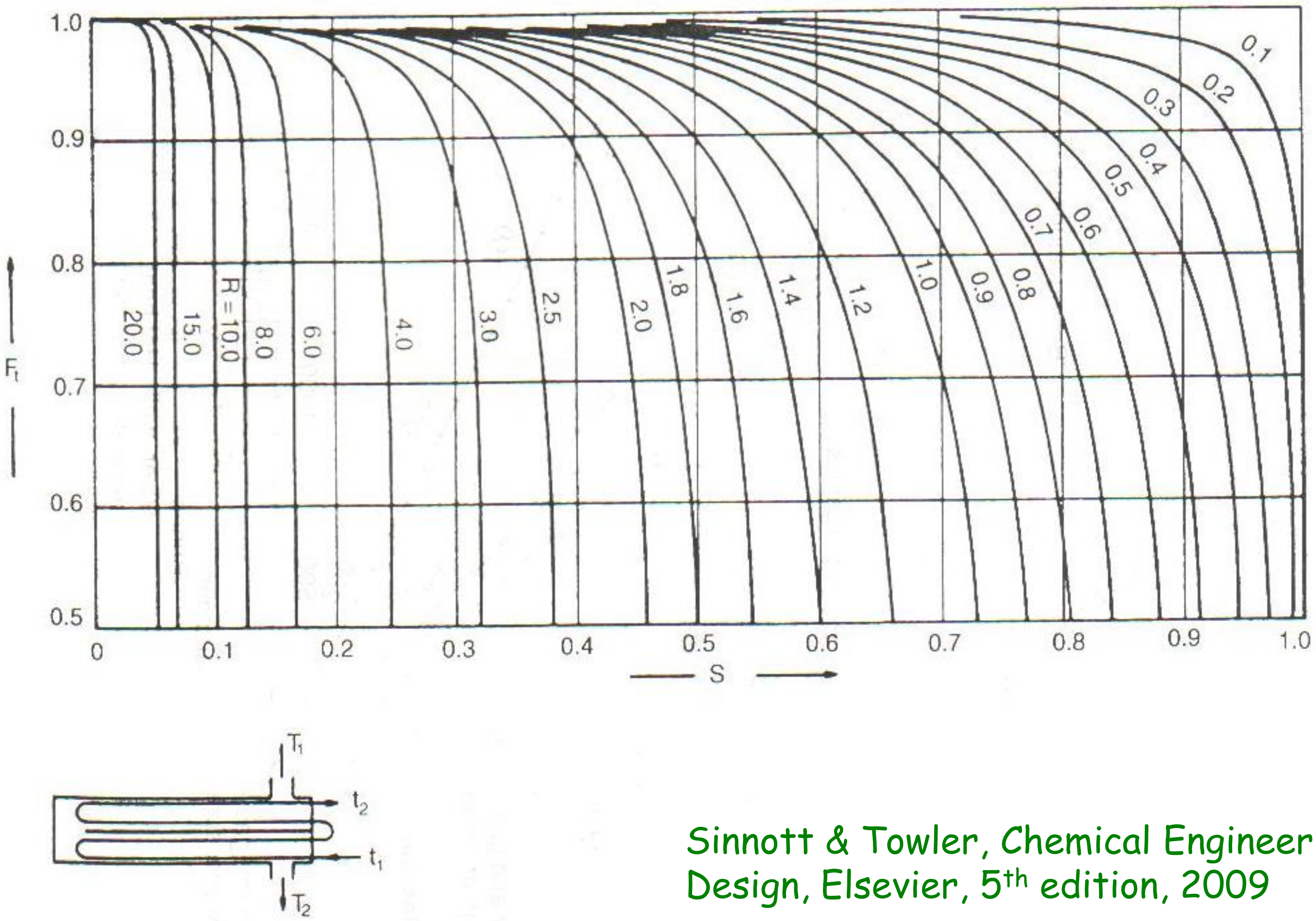


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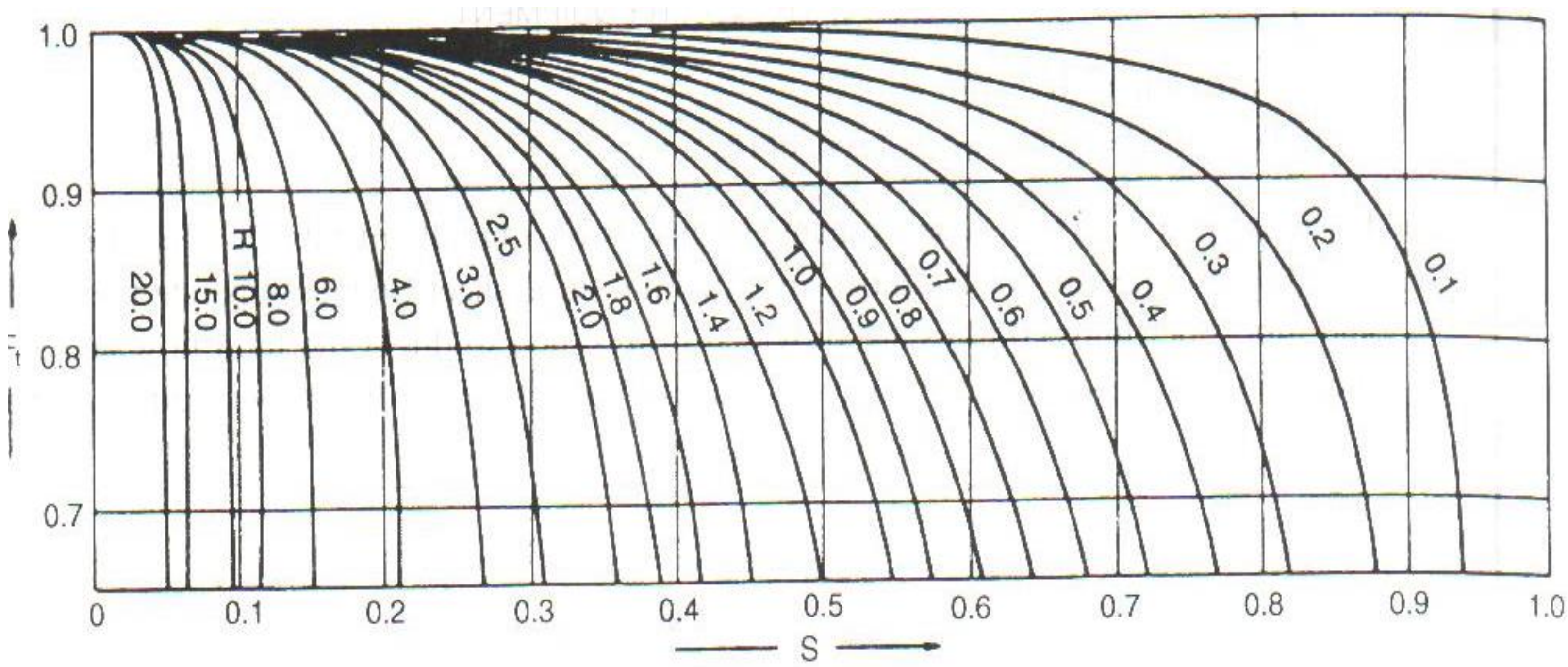
Figure 12.20. Temperature correction factor: two shell passes; four or multiples of four tube passes

Heat Transfer Equipment

Correction factor:



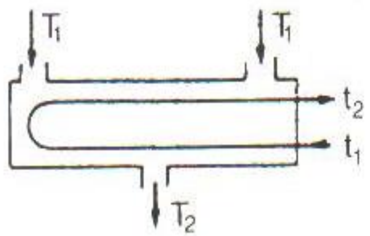


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Figure 12.21. Temperature correction factor: divided-flow shell; two or more even-tube passes

Heat Transfer Equipment

Correction factor:

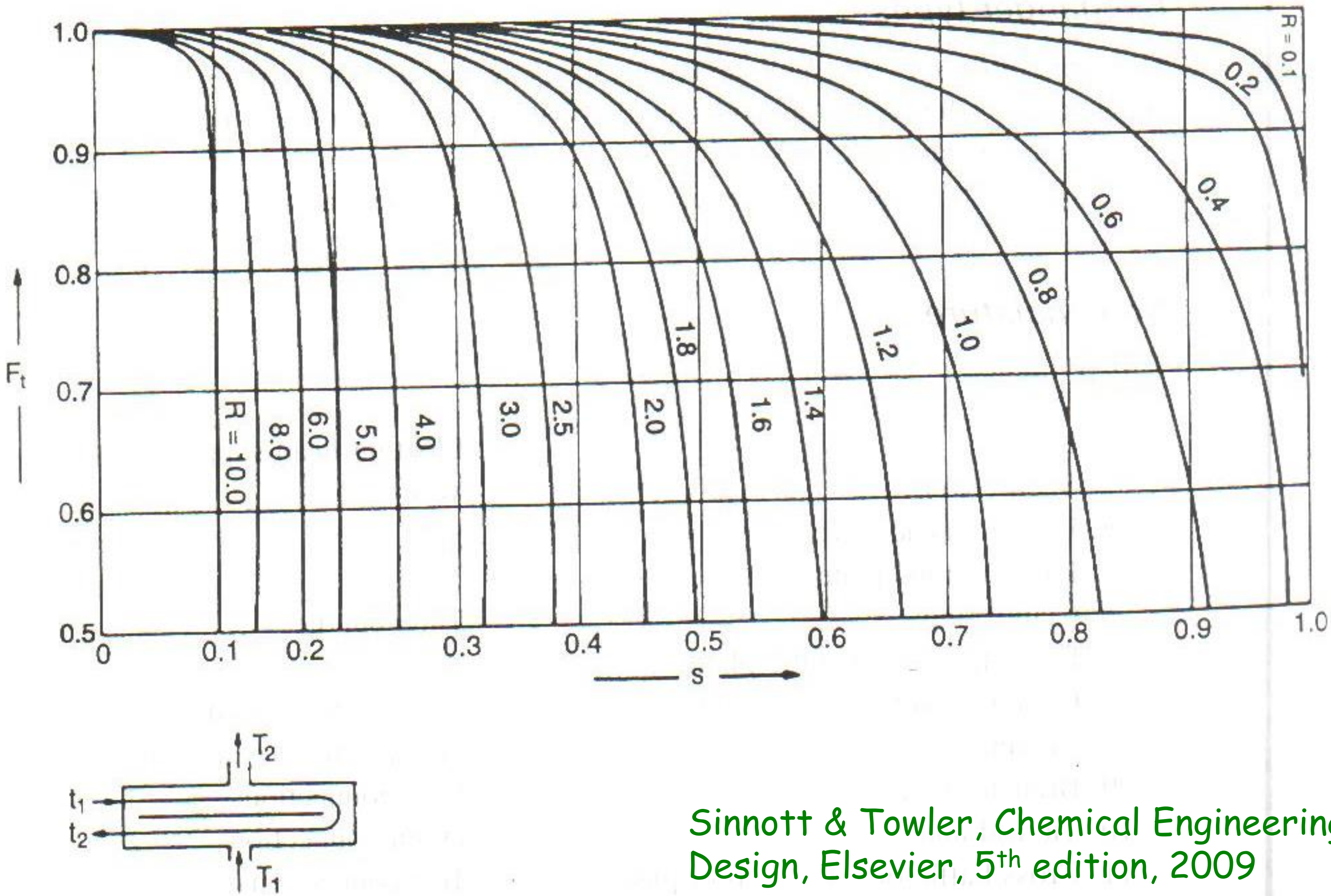

Figure 12.22. Temperature correction factor, split flow shell, 2 tube pass

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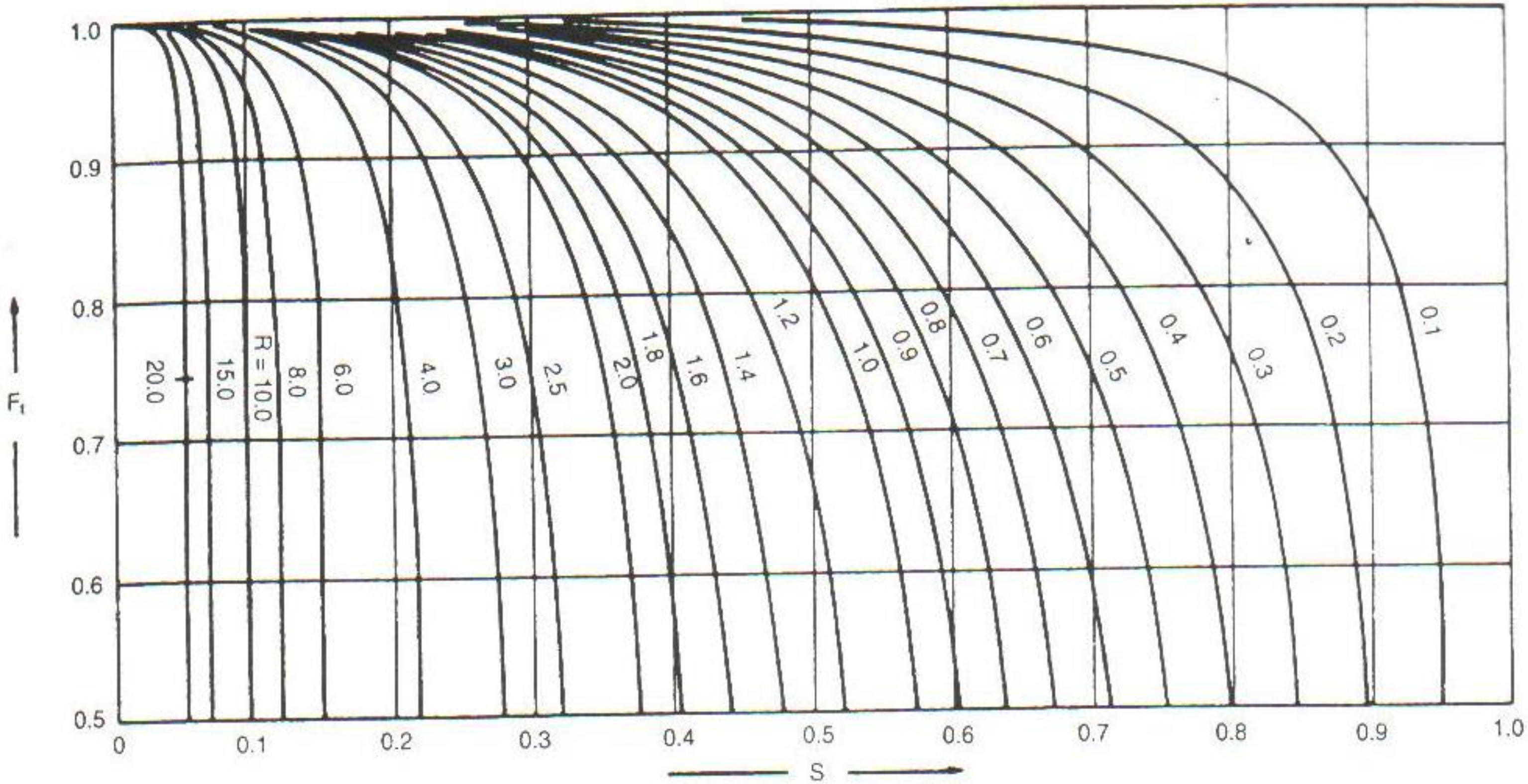
Heat Transfer Equipment

Correction factor:



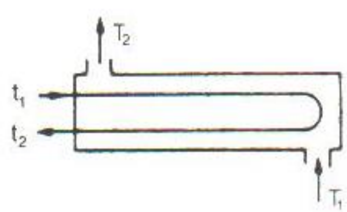


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Figure 12.19. Temperature correction factor: one shell pass; two or more even tube 'passes

Heat Exchangers - Typical design

1) Define duty: heat transfer rate, flows, temperatures.
2) Collect required physical properties (ρ, μ, k).
3) Decide on the type of exchanger.
4) Select a trial value for U.
5) Calculate the mean temperature difference, ΔT_m
6) Calculate area required.
7) Decide on the exchanger layout.
8) Calculate individual coefficients.
9) Calculate U. If significant difference from step (4), substitute in (4) and repeat.
10) Calculate the pressure drop. If it is not satisfactory, back to (7) or (4) or (3).
11) Optimise: repeat (4) to (10) to determine cheapest solution (usually smaller area).

Step (7): Shell and Tube Heat Exchangers

Tube size:

Length is standard, commonly 8, 12 or 16 ft.
Diameter: most common 3/4 or 1 in OD

Tube pitch and clearance:

Pitch is the shortest center-to-center distance between adjacent tubes. Commonly 1.25 to 1.5 time the tube diameter.

Clearance is the distance between tubes. It should be larger than 25% of the tube diameter.

Triangular or square arrangement of tubes are quite common.

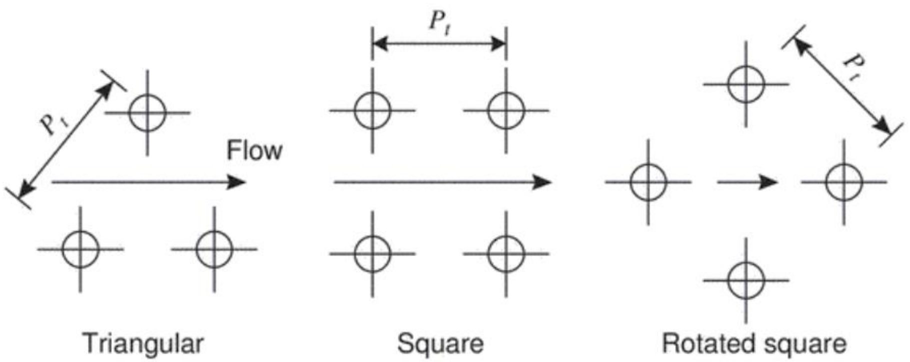
Baffles:

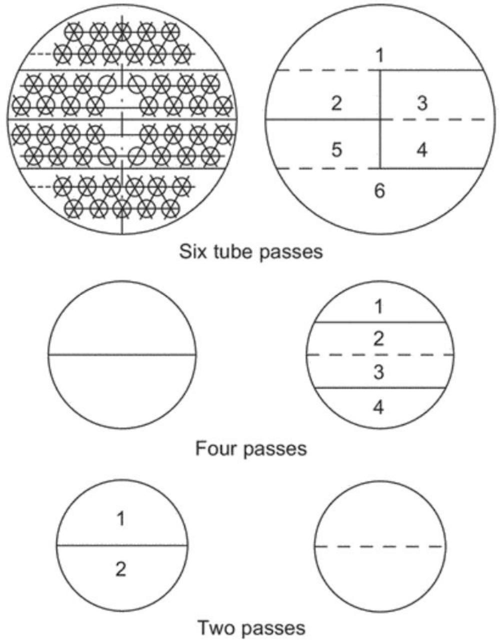
Baffles are usually spaced between 20% and 80% of the ID of the shell.

Step (7): Shell and Tube Heat Exchangers

Tube pitch and clearance:

Triangular or square arrangement of tubes are quite common.





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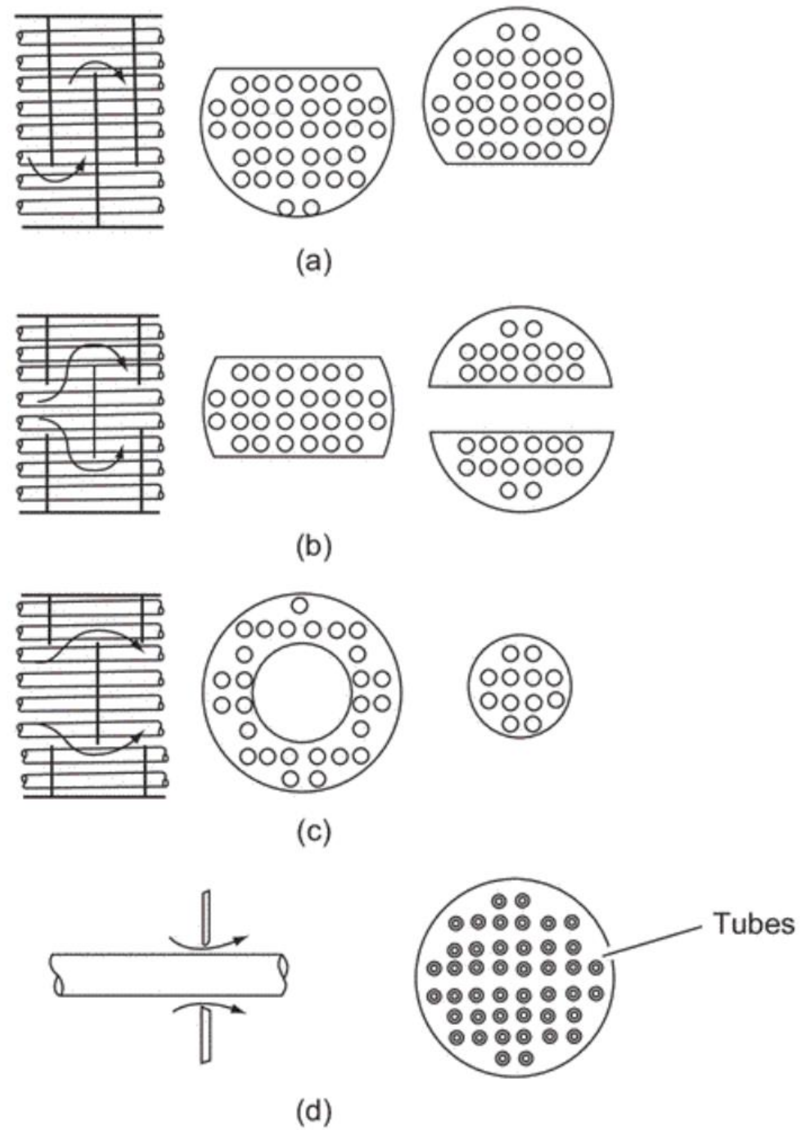
Shell and Tube Heat Exchangers

Shell:
Up to 24 in nominal size, use standard pipes.

Passes:
Most usual pass is one (type E according to TEMA – Tubular Exchangers Manufacturing Association standards).
Split flow arrangement (types G and J) are used for pressure drop reduction, when the pressure drop is the controlling factor in the design.

Shell and Tube Heat Exchangers

Shell - baffles



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Shell and Tube Heat Exchangers

Fluid location:

Corrosive fluids flow inside the tubes.
Fluid with higher fouling tendency inside the tubes.
High pressure fluid inside the tubes (if everything else the same).
Hot fluid inside the tubes.
Typical velocities:
Liquids: 1-2 m/s in tubes, max 4 m/s to reduce fouling.
0.3 to 1 m/s in shell
Vapors: 50-70 m/s (vacuum), 10-30 m/s (1 bar),
5-10 m/s (high P)

Shell and Tube Heat Exchangers - Design

• Tube side: Configuration (pitch, number of tubes, dimensions).
Heat transfer coefficient.
Pressure drop.

• Shell side: Configuration (dimensions, baffles).
Heat transfer coefficient.
Pressure drop.

Cost influenced by:

• Heat transfer area
• Tube diameter and length
• Pressure
• Material of construction
• Baffle type
• Special features, such as U bends, floating heads, fins etc.

Tube Side

1) Define duty: heat transfer rate, flows, temperatures.
2) Collect required physical properties (ρ, μ, k).
4) Select a value for U.
5) Calculate the mean temperature difference, ΔT_m. Use the correction factor, F_t.
6) Calculate area required.
7) Decide on the exchanger layout. Select one of the standard tube lengths and tube diameters. Calculate the number of tubes needed from the area estimated in (6). Decide on pitch.
Calculate bundle diameter from the following:

$$N_t = K_1 \left(\frac{D_b}{d_o} \right)^{n_1} \qquad D_b = d_o \left(\frac{N_t}{K_1} \right)^{1/n_1}$$

Tube Side

N_t is the number of tubes
D_b is the bundle diameter
d_o is the tube outside diameter

$$D_b = d_o \left(\frac{N_t}{K_1} \right)^{1/n_1}$$

Constants:

Triangular pitch, $p_t = 1.25 d_o$					
No. passes	1	2	4	6	8
K_1	0.319	0.249	0.175	0.0743	0.0365
n_1	2.142	2.207	2.285	2.499	2.675
Square pitch, $p_t = 1.25 d_o$					
No. passes	1	2	4	6	8
K_1	0.215	0.156	0.158	0.0402	0.0331
n_1	2.207	2.291	2.263	2.617	2.643

Heat Transfer Equipment

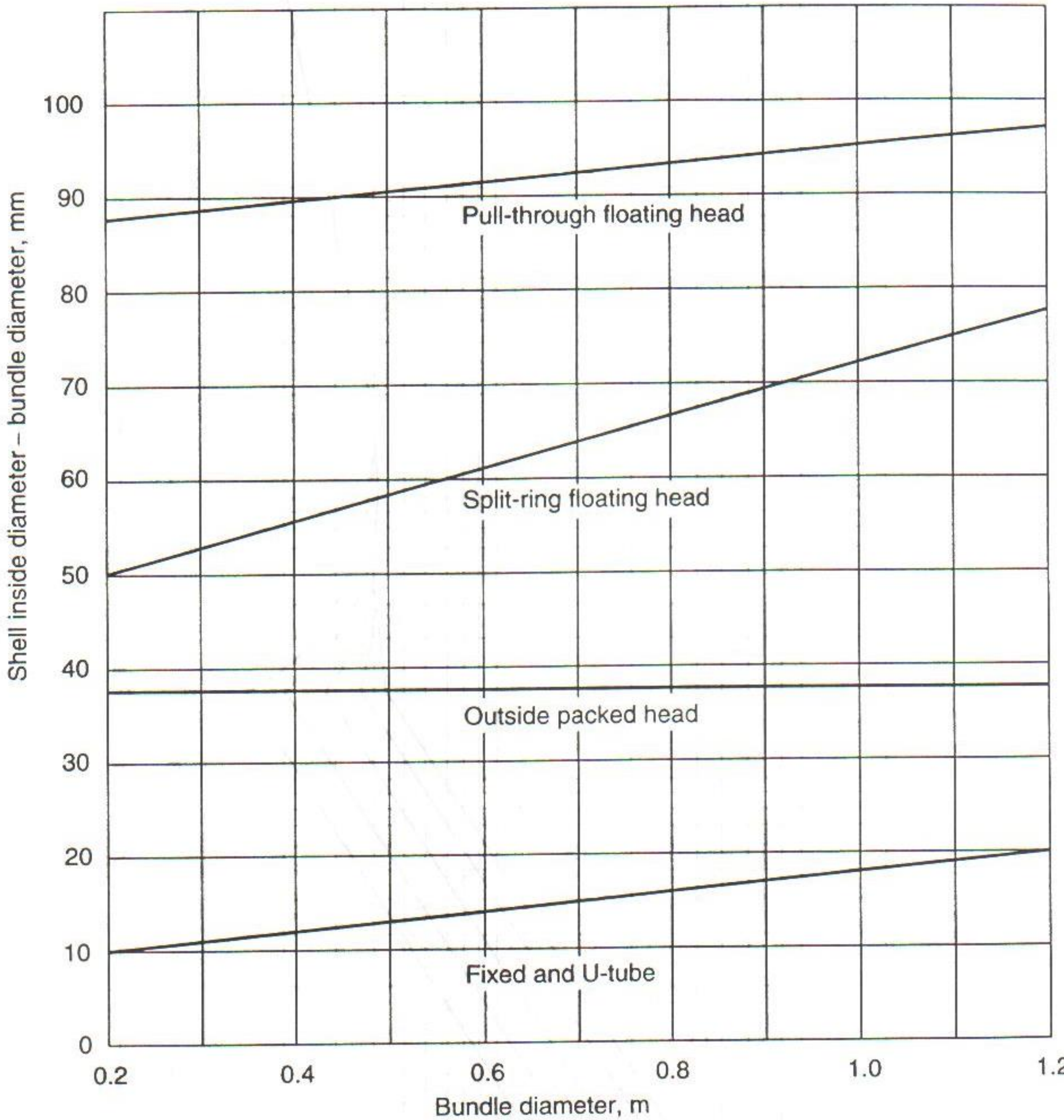

Figure 12.10. Shell-bundle clearance

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Heat Exchangers - Typical design

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2) Collect required physical properties (ρ, μ, k).
3) Decide on the type of exchanger.
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6) Calculate area required.
7) Decide on the exchanger layout.
8) Calculate individual coefficients.
9) Calculate U. If significant difference from step (4), substitute in (4) and repeat.
10) Calculate the pressure drop. If it is not satisfactory, back to (7) or (4) or (3).
11) Optimise: repeat (4) to (10) to determine cheapest solution (usually smaller area).

Tube Side

Use of the heat transfer factor, j_h, for transition and laminar flow:

$$Nu = j_h \, \mathrm{Re} \, \mathrm{Pr}^{0.33} \left(\frac{\mu}{\mu_w} \right)^{0.14}$$

See correlations in Chapter 20 of Welty et al. for internal forced convection.

9) Calculate pressure drop.
Use the friction factor, as for pipe flows, in the Fanning equation.

Heat Transfer Factor

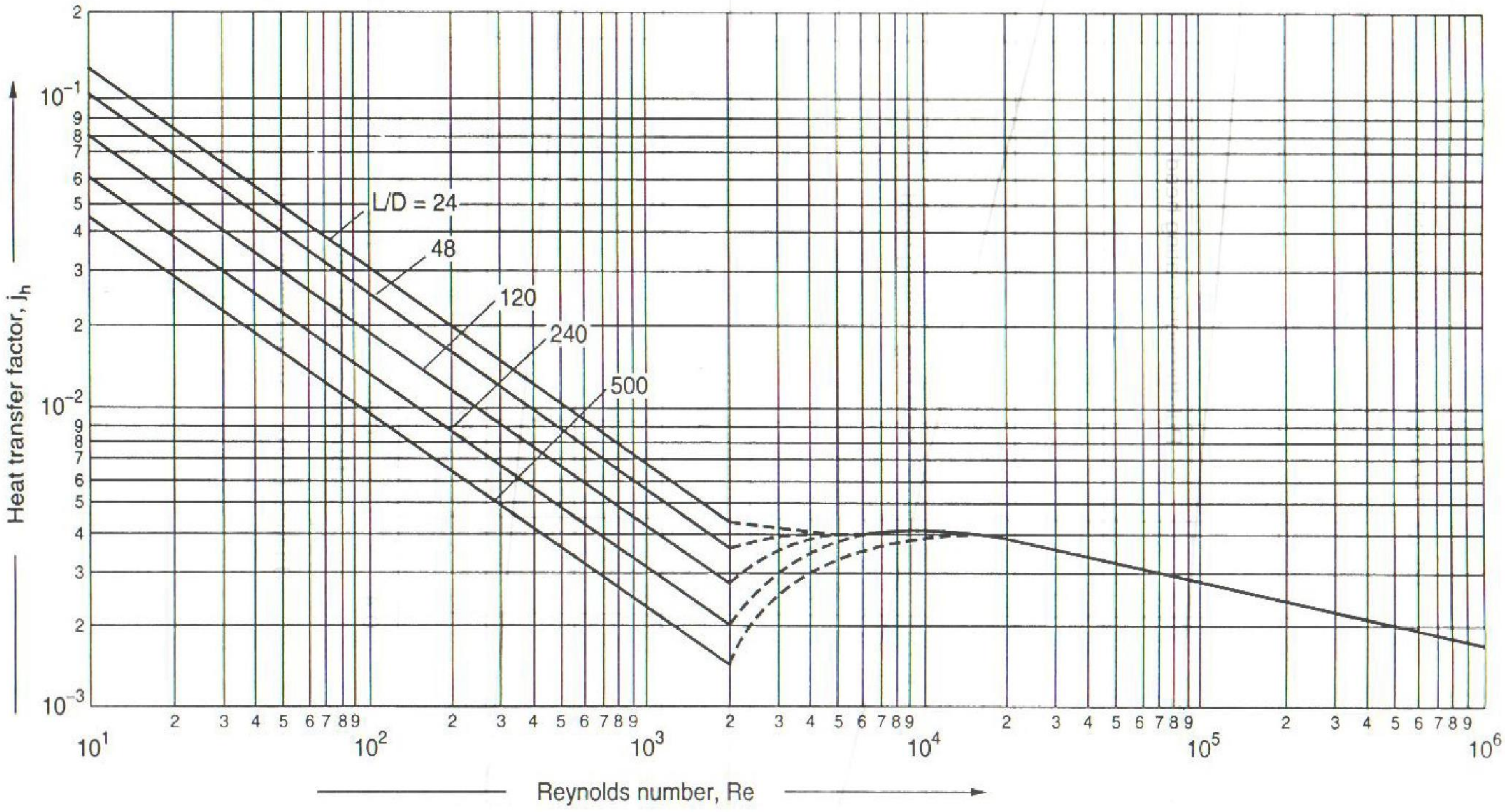

Figure 12.23. Tube-side heat-transfer factor

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Tube Side

9) Calculate pressure drop (Peters & Timmerhaus, 4th edition, 1991).

$$\Delta P_i = \frac{B_i 2 f_i G^2 L n_p}{g_c \rho_i d_i \phi_i}$$

f_i is the friction factor for isothermal flow at the mean temperature

n_p is the number of tube passes

g_c is the unit conversion factor

ϕ_i is a correction factor for non-isothermal flow

$$\phi_i = 1.1(\mu_i / \mu_w)^{0.25} \quad \text{for Re < 2100}$$

$$\phi_i = 1.02(\mu_i / \mu_w)^{0.14} \quad \text{for Re > 2100}$$

B_i is a correction factor for friction due to contraction, expansion and reversal of flow direction (B_i > 1, can use 1.2)

G is the mass velocity inside the tube (mass/area time)

Shell Side

From the bundle diameter we have the shell diameter (step 7)!

10) Calculate shell side heat transfer coefficient.
For turbulent flow outside the tubes:

$$Nu = \frac{a_o}{F_s} \mathrm{Re}^{0.6} \mathrm{Pr}^{0.33}$$

Nu is the Nusselt number, $Nu = h_o\, d_o / k_f$
Re is the shell side Reynolds number, $Re = G_s\, d_o / \mu$
Pr is the shell side Prandtl number, $Pr = C_p\, \mu / k_f$
a_o = 0.33 if the tubes are staggered and 0.26 if they are in line
F_s is a safety factor to account for bypassing (usually 1.6)
G_s is the mass velocity across tubes, based on the minimum free area between baffles.

Also see: Kern, "*Process heat transfer*", McGraw Hill, 1950

Shell Side

11) Calculate pressure drop.

$$\Delta P_o = \frac{B_o 2 f_o G_s^{\,2} N_r}{g_c \rho_o}$$

f_o is the friction factor for the shell side

$$f_o = b_o \left(\frac{d_o G_s}{\mu} \right)^{-0.15}$$

N_r is the number of rows of tubes
B_o is a correction factor for friction due to reversal of flow direction. It can be equal to the number of tube crossings (e.g., one when there are no baffles).

12) **Now we can recalculate *U* and make a decision.**

Heat Exchangers- On the Web!

Tubular Exchanger Manufacturing Association (TEMA),

Standards for H.E. design

http://www.tema.org/

Log-mean temperature difference

https://www.youtube.com/watch?v=AivvyYrPvtM

And:

https://www.youtube.com/watch?v=3DedKWNfM7Q

Also, other sites on YouTube.

MAIN POINTS

Heat transfer equipment

Concepts: Shell and tube heat exchangers
Log-mean temperature difference
T-Q heat exchanger diagrams
Design steps

Chapter 22