

CH402 Chemical Engineering Process Design

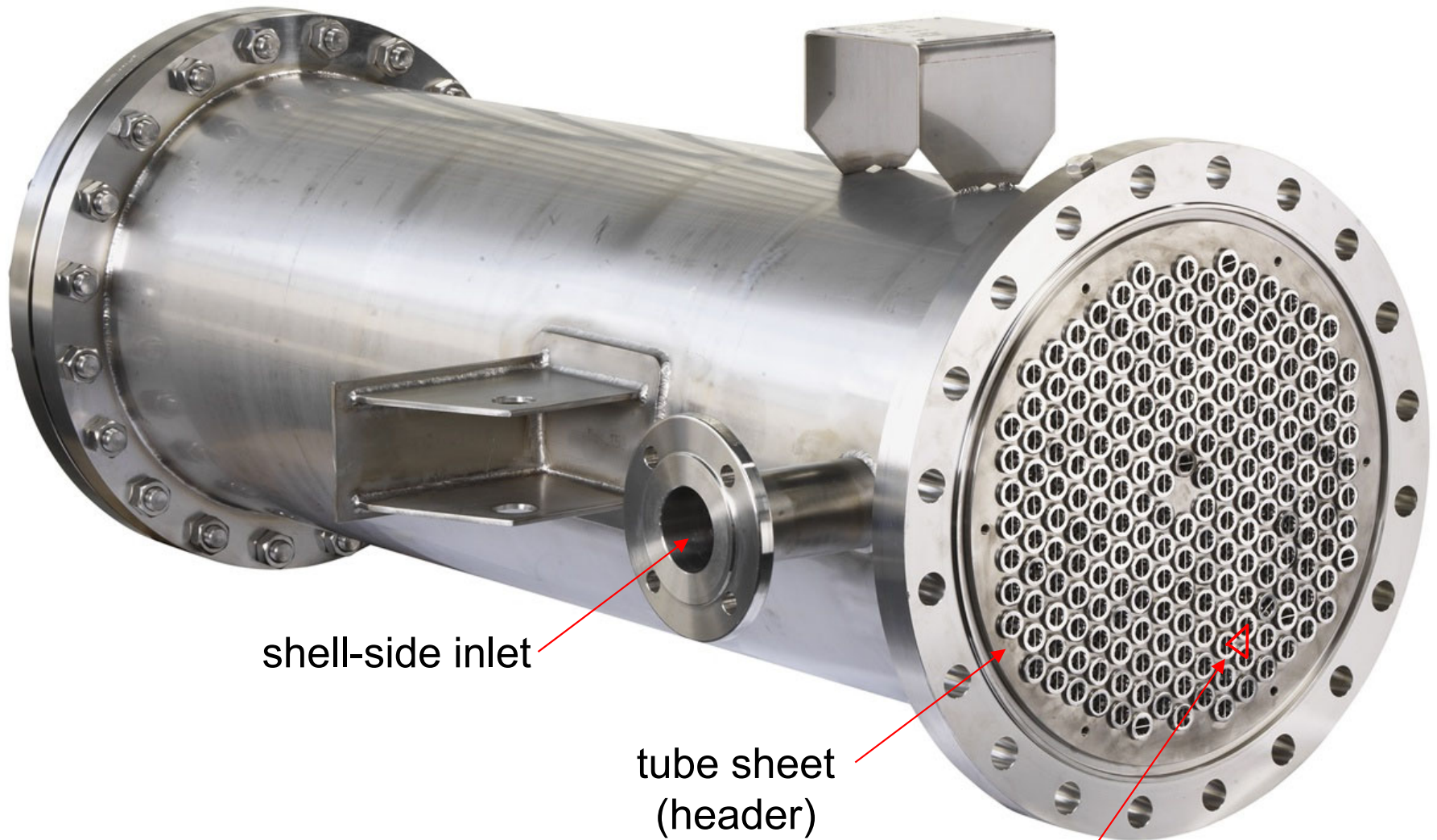
Class Notes L7

Heat Exchanger Theory

Agenda for Today's Class

- design and cost factors (slides 3-7)
- heat transfer and LMTD (slides 8-11)
- resistance to heat transfer (slides 12-18)
- pressure drop (slides 19-21)

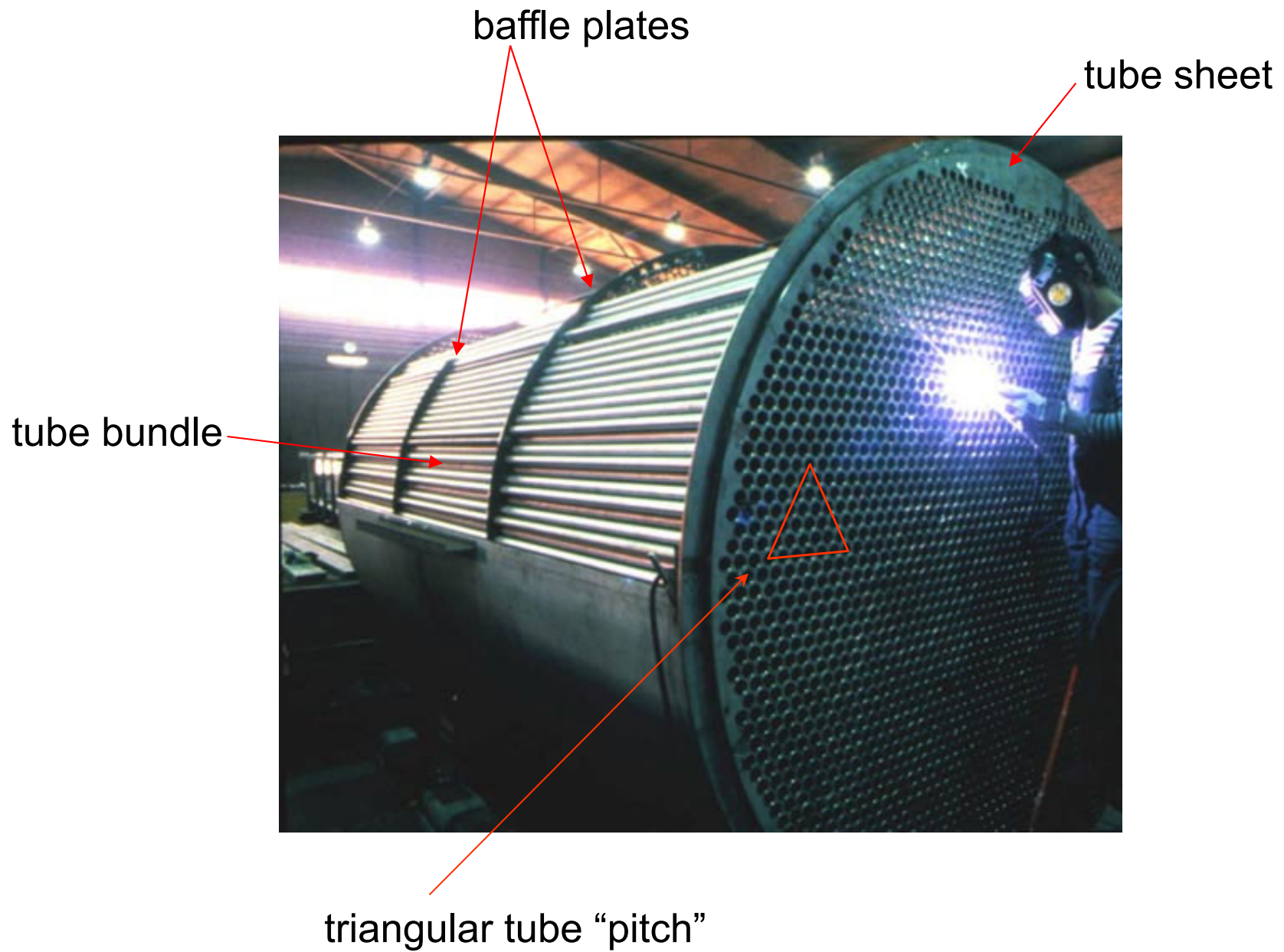
Basic “shell-and-tube” design



shell-side inlet

tube sheet
(header)

notice the triangular pattern or “pitch” of the tubes



4 tube-side “passes”

shell-side baffle plates

tube sheet
(header)

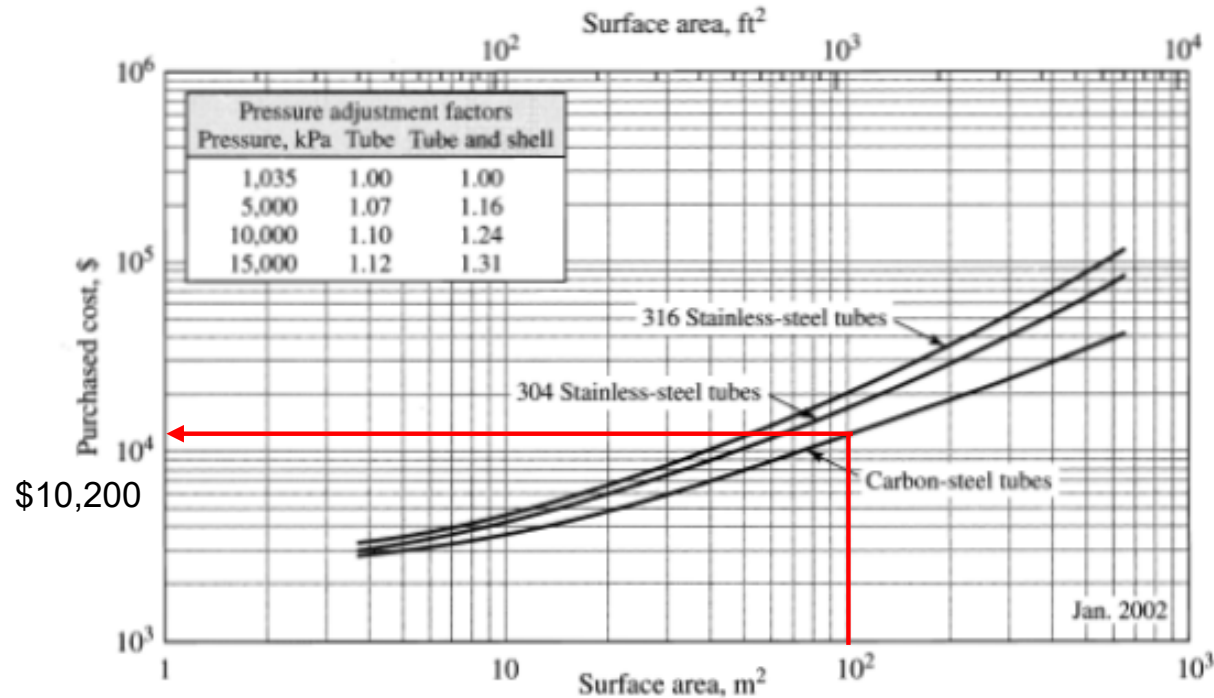


notice the square pattern
or “pitch” of the tubes

What cost factors are most important?

Slide 6

Heat transfer area and material



p. 682

Figure 14-18

Purchased cost of fixed-tube-sheet heat exchangers with 0.019-m ($\frac{3}{4}$ -in.) OD \times 0.025-m (1-in.) square pitch and 4.88- or 6.10-m (16- or 20-ft) bundles and carbon-steel shell operating at 1035 kPa (150 psia)

carbon steel, 100 m²: \$10,200

$\frac{3}{4}$ -in tubes, 1-inch square-pitch fixed tube sheet, 4.88 m or 6.10 m in length at 150 psia

What if we change design to 1.5-inch tubes, 4 m in length, 500 psia, stainless 316L, in Jan 2024?

1.5-in tubes, multiply by 1.37, figure 14-21: \$13,974

4-m length, multiply by 1.07, figure 14-22: \$14,952

500 psia, multiply by 1.39, figure 14-23: \$20,784

Stainless 316L, multiply by 2.2, table 14-8: \$45,724

Jan 2024, multiply by 786.6/356.9, CEPCI: \$100,774 // ANS

Summary of cost factors and Adjustments

All cost charts located on pages 680 – 692 **Very Important!**

Basic shell-and-tube heat exchangers, Figures 14-18 and 14-19, page 682

0.019-m x 4.88-m, fixed-tube-sheet, Figure 14-18, p. 682

0.019-m x 4.88-m, floating-head, Figure 14-19, p. 682

Adjustments

Tube diameter, Figure 14-21, p. 683

Tube length, Figure 14-22, p. 684

Pressure, Figure 14-23, p. 684

Material, Table 14-8 and Figure 14-24, p. 685

Agenda for Today's Class

- design and cost factors (slides 3-7)
- **heat transfer and LMTD (slides 8-11)**
- resistance to heat transfer (slides 12-18)
- pressure drop (slides 19-21)

FE Reference Manual – pp. 215-216

FEE Manual, pp. 215-216; recommend review of entire heat transfer section, pp. 204-219; very well written.

Heat Exchangers

The rate of heat transfer associated with either stream in a heat exchanger in which incompressible fluid or ideal gas with constant specific heats flows is

$$\dot{Q} = \dot{m}c_p(T_{\text{exit}} - T_{\text{inlet}})$$

c_p = specific heat (at constant pressure)

\dot{m} = mass flow rate

The rate of heat transfer in a heat exchanger is

$$\dot{Q} = UAF\Delta T_{lm}$$

A = any convenient reference area (m^2)

F = correction factor for log mean temperature difference for more complex heat exchangers (shell and tube arrangements with several tube or shell passes or cross-flow exchangers with mixed and unmixed flow); otherwise $F = 1$.

U = overall heat-transfer coefficient based on area A and the log mean temperature difference [$\text{W}/(\text{m}^2\cdot\text{K})$]

ΔT_{lm} = log mean temperature difference (K)

Log Mean Temperature Difference (LMTD)

For *counterflow* in tubular heat exchangers

$$\Delta T_{lm} = \frac{(T_{Ho} - T_{Ci}) - (T_{Hi} - T_{Co})}{\ln\left(\frac{T_{Ho} - T_{Ci}}{T_{Hi} - T_{Co}}\right)}$$

For *parallel flow* in tubular heat exchangers

$$\Delta T_{lm} = \frac{(T_{Ho} - T_{Co}) - (T_{Hi} - T_{Ci})}{\ln\left(\frac{T_{Ho} - T_{Co}}{T_{Hi} - T_{Ci}}\right)}$$

ΔT_{lm} = log mean temperature difference (K)

T_{Hi} = inlet temperature of the hot fluid (K)

T_{Ho} = outlet temperature of the hot fluid (K)

T_{Ci} = inlet temperature of the cold fluid (K)

T_{Co} = outlet temperature of the cold fluid (K)

Overall Heat-Transfer Coefficient for Concentric Tube and Shell-and-Tube Heat Exchangers

$$\frac{1}{UA} = \frac{1}{h_i A_i} + \frac{R_{fi}}{A_i} + \frac{\ln\left(\frac{D_o}{D_i}\right)}{2\pi k L} + \frac{R_{fo}}{A_o} + \frac{1}{h_o A_o}$$

A_i = inside area of tubes (m^2)

A_o = outside area of tubes (m^2)

D_i = inside diameter of tubes (m)

D_o = outside diameter of tubes (m)

h_i = convection heat-transfer coefficient for inside of tubes [$\text{W}/(\text{m}^2\cdot\text{K})$]

h_o = convection heat-transfer coefficient for outside of tubes [$\text{W}/(\text{m}^2\cdot\text{K})$]

k = thermal conductivity of tube material [$\text{W}/(\text{m}\cdot\text{K})$]

R_i = fouling factor for inside of tube [$(\text{m}^2\cdot\text{K})/\text{W}$]

R_{fo} = fouling factor for outside of tube [$(\text{m}^2\cdot\text{K})/\text{W}$]

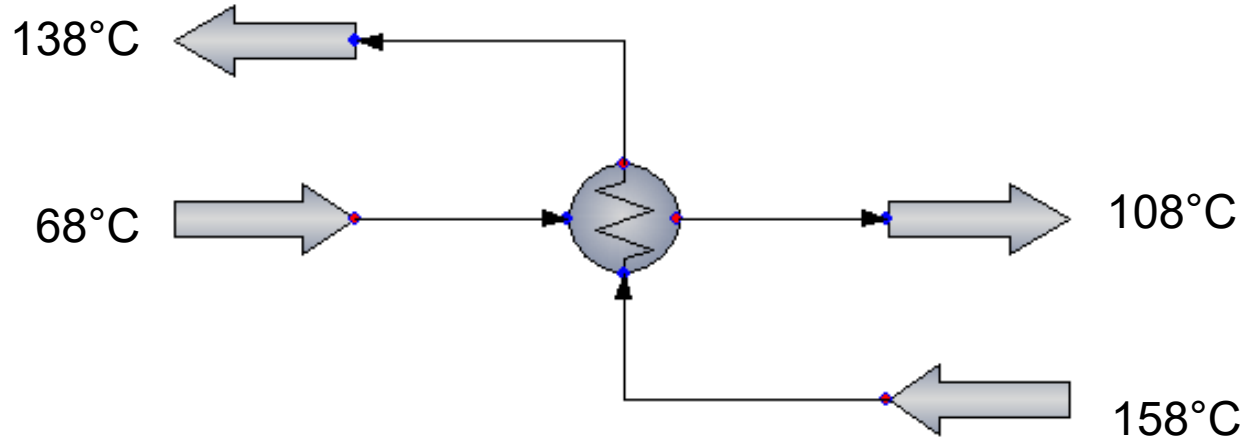
A is calculated from the geometry

$$A = \pi \cdot D \cdot L \cdot N_t$$

Log mean temperature difference - example Slide 10

Calculate the log mean temperature difference for countercurrent and co-current flow.

FE Reference Manual,
page 215



countercurrent
(counterflow)

$$\Delta T_{lm} = \frac{(T_{Ho} - T_{Ci}) - (T_{Hi} - T_{Co})}{\ln((T_{Ho} - T_{Ci}) / (T_{Hi} - T_{Co}))} = \frac{(138 - 68) - (158 - 108)}{\ln((138 - 68) / (158 - 108))} = 59.44^{\circ}\text{C}$$

average temperature difference:

$$\Delta T_{mean} = \frac{70 + 50}{2} = 60$$

co-current
(parallel flow)

$$\Delta T_{lm} = \frac{(T_{Ho} - T_{Co}) - (T_{Hi} - T_{Ci})}{\ln((T_{Ho} - T_{Co}) / (T_{Hi} - T_{Ci}))} = \frac{(138 - 108) - (158 - 68)}{\ln((138 - 108) / (158 - 68))} = 54.61^{\circ}\text{C}$$

average temperature difference:

$$\Delta T_{mean} = \frac{30 + 90}{2} = 60$$

(Recall that the LMTD comes from integration of the difference between the stream enthalpies.)

Multiple Passes

Use correction factor F ; FEE manual defines it on page 215 but does not explain how to calculate it. Used in CHEMCAD.

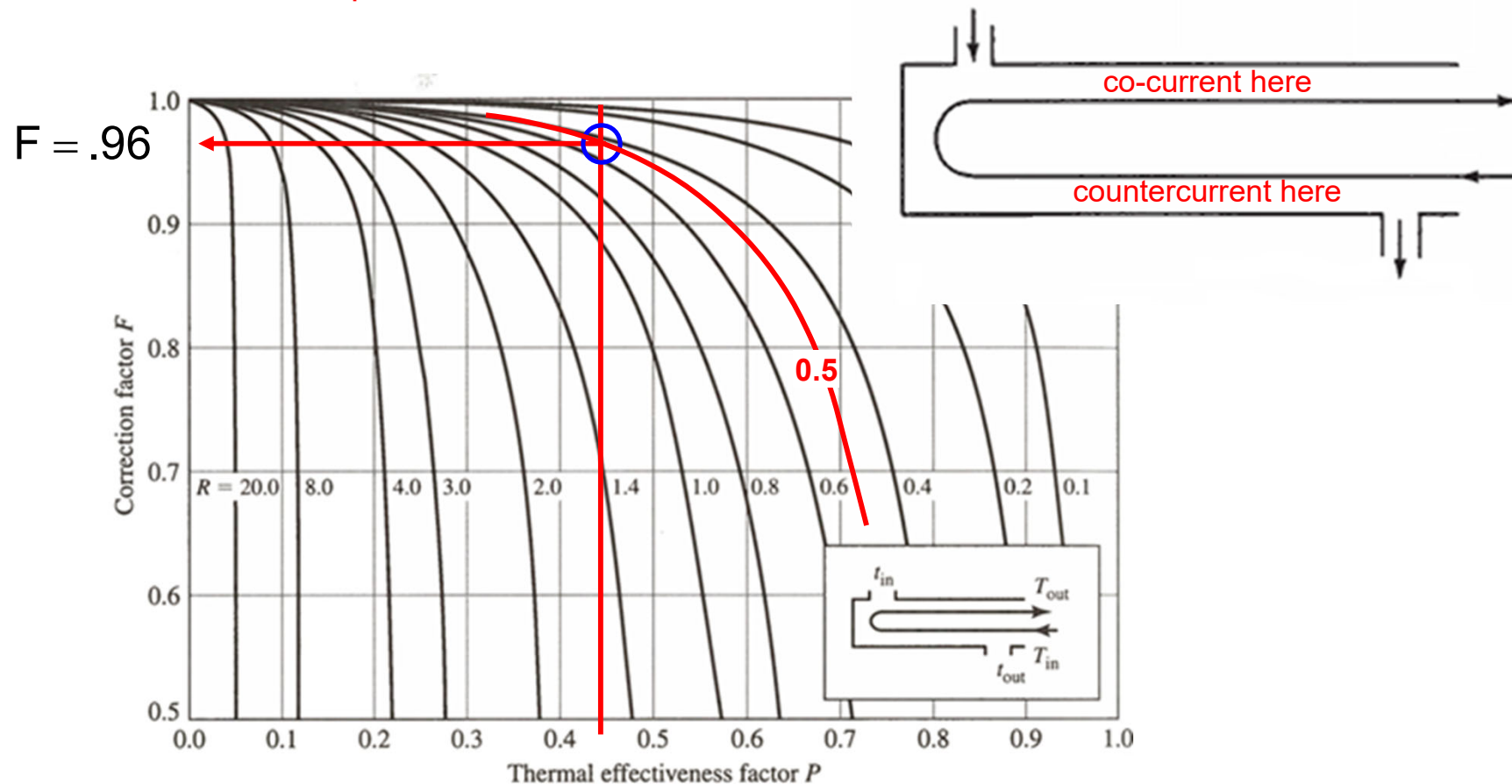


Figure 14-4. One shell pass and 2 or more tube passes.

Figure 14-5. Other contact patterns.

$$R = \frac{T_{Hi} - T_{Ho}}{T_{Co} - T_{Ci}} = \frac{158 - 138}{108 - 68} = 0.5$$

(14-9a, p.648)

$$P = \frac{T_{Co} - T_{Ci}}{T_{Hi} - T_{Ci}} = \frac{108 - 68}{158 - 68} = 0.44$$

(14-9b)

$$F = \frac{(R^2 + 1)^{1/2} \cdot \ln\left(\frac{1-P}{1-R \cdot P}\right)}{(R-1) \cdot \ln\left(\frac{2-P \cdot [(R+1) - (R^2+1)^{1/2}]}{2-P \cdot [(R+1) + (R^2+1)^{1/2}]}\right)} = 0.96$$

(14-9)

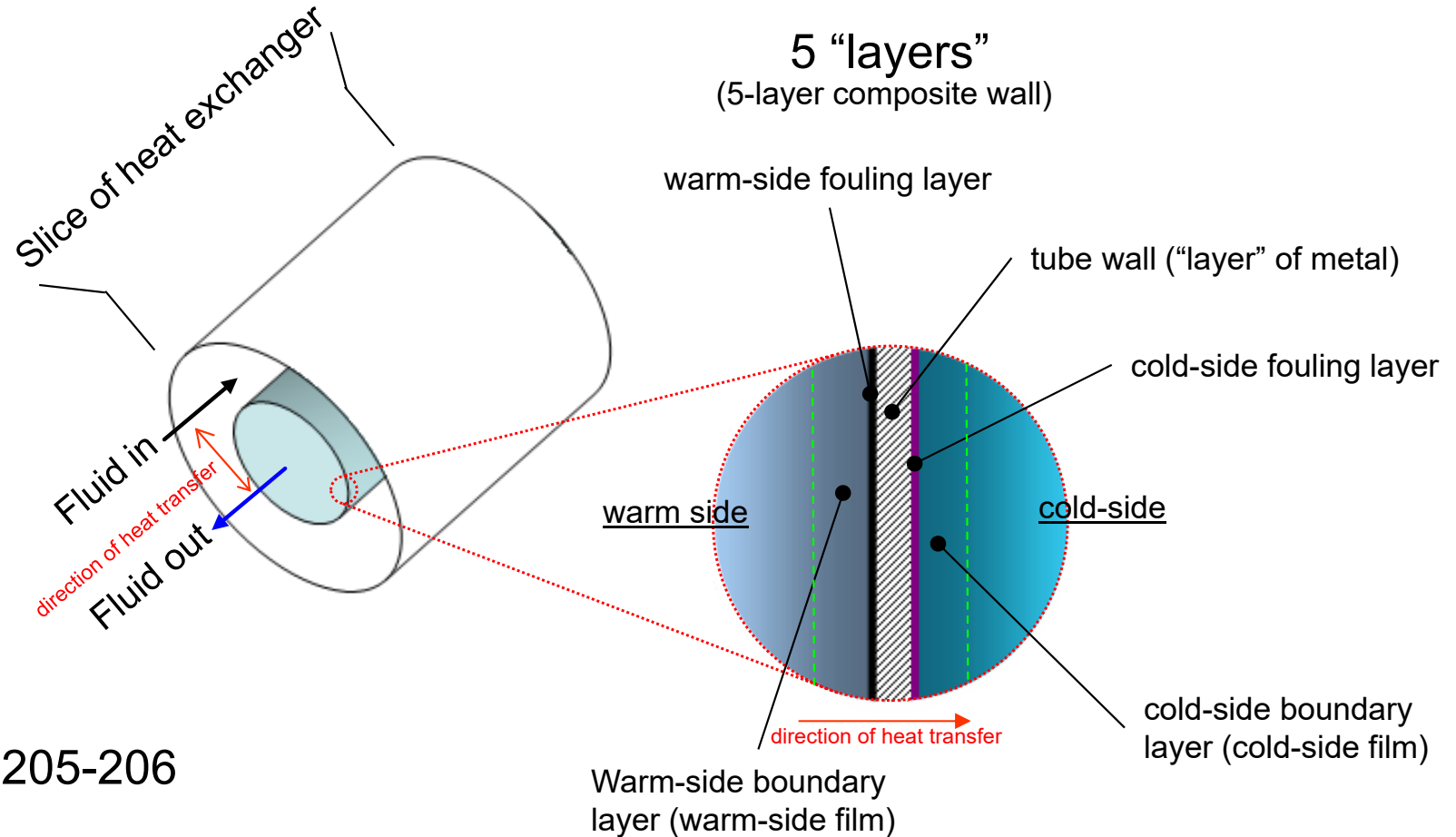
$$\Delta T_{o,m} = F \cdot \Delta T_{o,\log \text{ mean}} = .96 \cdot 54.61 = \underline{52.42} \text{ } ^\circ\text{C}$$

Agenda for Today's Class

- design and cost factors (slides 3-7)
- heat transfer and LMTD (slides 8-11)
- **resistance to heat transfer (slides 12-18)**
- pressure drop (slides 19-21)

Thermal Resistances in Series Model

Slide 13



FE Manual, pp. 205-206

Total resistance = sum of resistances of individual layers

$$R_{\text{tot}} = \frac{1}{U} = \overbrace{\left(\frac{1}{h_{\text{warm}}} \right)}^{\text{warm-side film}} + \overbrace{\left(R_{\text{warm,fouling}} \right)}^{\text{warm-side fouling}} + \overbrace{\left(\frac{x_{\text{wall}}}{k_w} \right)}^{\text{wall}} + \overbrace{\left(R_{\text{cold,fouling}} \right)}^{\text{cold-side fouling}} + \overbrace{\left(\frac{1}{h_{\text{cold}}} \right)}^{\text{cold-side film}}$$

Different forms for total resistance

“Overall Heat Transfer Coefficient for Concentric Tube and Shell-and-Tube Heat Exchangers”

FEE manual, page 216.

$$\frac{1}{UA} = \frac{1}{h_i \cdot A_i} + \frac{R_{fi}}{A_i} + \frac{\ln\left(\frac{D_o}{D_i}\right)}{2\pi kL} + \frac{R_{fo}}{A_o} + \frac{1}{h_o A_o}$$

$A = A_i \text{ or } A_o$ —————→

$A_i = \pi \cdot D_i \cdot L$ (inside area)

$A_o = \pi \cdot D_o \cdot L$ (outside area)

L = length

FE Reference Manual,
page 216 (222/502)

Example:

$$A = A_o \quad \frac{1}{U_o} = \frac{A_o}{h_i \cdot A_i} + \frac{A_o R_{fi}}{A_i} + \frac{A_o \ln\left(\frac{D_o}{D_i}\right)}{2\pi kL} + R_{fo} + \frac{1}{h_o}$$

Local Heat Transfer Coefficients for Flow Inside Tubes

FE Prep: Heat Transfer Section, FE Manual, p. 211

Needed for
problem 14-2

Laminar (viscous) fluid flow inside tubes, $Re < 2100$:

$$\frac{h_i \cdot D_i}{k} = 1.86 \cdot \left(\frac{D_i \cdot G_i}{\mu} \right)^{1/3} \cdot \left(\frac{C_p \cdot \mu}{k} \right)^{1/3} \cdot \left(\frac{D_i}{L} \right)^{1/3} \cdot \left(\frac{\mu}{\mu_w} \right)^{.14}$$

14-17, p. 657
FE Reference Manual,
page 210

$$h_i = 1.86 \cdot \left(\frac{4 \cdot \dot{m}_i \cdot C_p}{\pi \cdot k \cdot L} \right)^{1/3} \cdot \left(\frac{\mu}{\mu_w} \right)^{.14}$$

$$G = \text{mass velocity in } \frac{\text{kg}}{\text{m}^2 \text{ sec}} = \text{velocity} \times \text{density} = v \times \rho$$

$\frac{\text{m}}{\text{sec}} \quad \frac{\text{kg}}{\text{m}^3}$

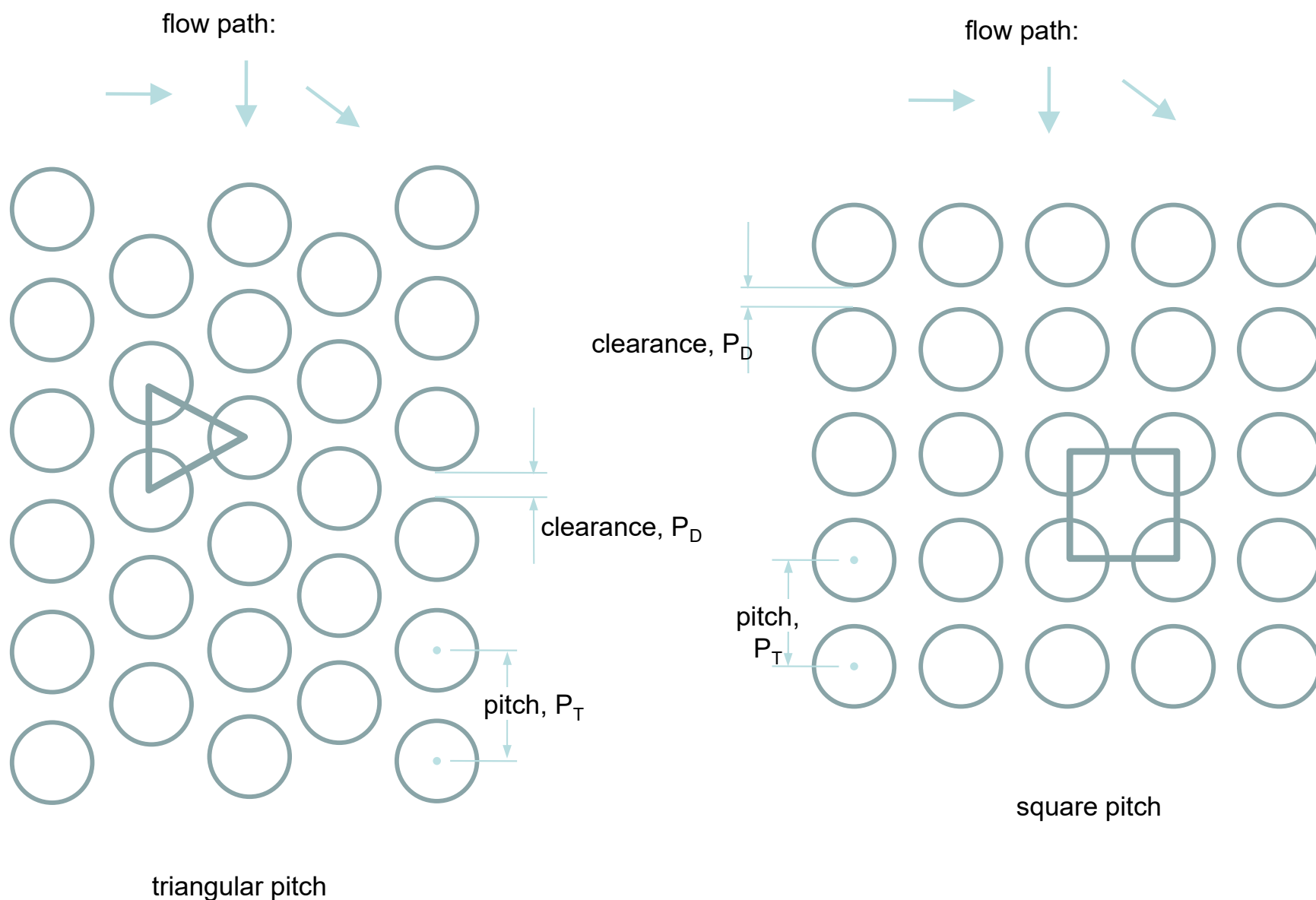
Turbulent, fully developed fluid flow inside tubes,
 $Re > 10000$, $0.7 < Pr < 160$, and $L/D_i > 10$

book typo here

$$\underbrace{\frac{h_i \cdot D_i}{k}}_{\text{Nusselt number}} = .023 \cdot \underbrace{\left(\frac{D_i \cdot G_i}{\mu} \right)^{4/5}}_{\text{Reynolds number}} \cdot \underbrace{\left(\frac{C_p \cdot \mu}{k} \right)^{1/3}}_{\text{Prandtl number}} \cdot \left(\frac{\mu}{\mu_w} \right)^{.14}$$

14-18, p. 657
Sieder-Tate Equation

Tube Bank Patterns in Shell-and-Tube Heat Exchangers



Film Coefficients for Flow Outside Banks of Tubes

Shell-side Nusselt number:

$$Nu = \frac{h_o \cdot D_o}{k} = a \cdot Re^m \cdot Pr^{0.34} \cdot F_1 \cdot F_2$$

Eq. 14-22, p. 660

$$v_{max} = \frac{\dot{m}_T}{\rho \cdot N_T \cdot (P_T - D_o) \cdot L}$$

Eq. 14-22c, p. 661

$$Re = \frac{D_o \cdot v_{max} \cdot \rho}{\mu}$$

Eq. 14-22a, p. 660

Constants a and m are in Table 14-1 and depend on shell-side Reynolds number:

Calculate F_1 :

$$F_1 = \left(\frac{Pr_{bulk}}{Pr_{wall}} \right)^{.26} \quad \text{for } Pr < 600$$

Eq. 14-22b, p. 660

Look up F_2 Table 14-2

(Not found in FE Manual – inside tubes only)

Table 14-1. Values of a and m for eq. 14-22

Re	Inline banks $1.2 < P_T/D_o < 4$		Staggered banks ($Re > 100$)	
	a	m	a	m
10-300	0.742	0.431	1.309	0.360
300- 2×10^5	0.211	0.651	0.273	0.635
2×10^5 - 2×10^6	0.116	0.700	0.124	0.700

Table 14-2. Correction factor F_2 for eq 14-22

Number of tube rows	F_2 , inline banks ($Re > 2100$)	F_2 , staggered banks ($Re > 100$)
3	0.86	0.85
4	0.90	0.90
6	0.94	0.95
8	0.98	0.985
10+	0.99	0.99

TABLE 11-3 Typical Overall Heat-Transfer Coefficients in Tubular Heat Exchangers

$$U = \text{Btu}/(^{\circ}\text{F} \cdot \text{ft}^2 \cdot \text{h})$$

Shell side	Tube side	Design U	Includes total dirt	Shell side	Tube side	Design U	Includes total dirt
Liquid-liquid media				Dowtherm vapor	Dowtherm liquid	80–120	.0015
Aroclor 1248	Jet fuels	100–150	.0015	Gas-plant tar	Steam	40–50	.0055
Cutback asphalt	Water	10–20	.01	High-boiling hydrocarbons V	Water	20–50	.003
Demineralized water	Water	300–500	.001	Low-boiling hydrocarbons A	Water	80–200	.003
Ethanol amine (MEA or DEA) 10–25% solutions	Water or DEA, or MEA solutions	140–200	.003	Hydrocarbon vapors (partial condenser)	Oil	25–40	.004
Fuel oil	Water	15–25	.007	Organic solvents A	Water	100–200	.003
Fuel oil	Oil	10–15	.008	Organic solvents high NC, A	Water or brine	20–60	.003
Gasoline	Water	60–100	.003	Organic solvents low NC, V	Water or brine	50–120	.003
Heavy oils	Heavy oils	10–40	.004	Kerosene	Water	30–65	.004
Heavy oils	Water	15–50	.005	Kerosene	Oil	20–30	.005
Hydrogen-rich reformer stream	Hydrogen-rich reformer stream	90–120	.002	Naphtha	Water	50–75	.005
Kerosene or gas oil	Water	25–50	.005	Naphtha	Oil	20–30	.005
Kerosene or gas oil	Oil	20–35	.005	Stabilizer reflux vapors	Water	80–120	.003
Kerosene or jet fuels	Trichlorethylene	40–50	.0015	Steam	Feed water	400–1000	.0005
Jacket water	Water	230–300	.002	Steam	No. 6 fuel oil	15–25	.0055
Lube oil (low viscosity)	Water	25–50	.002	Steam	No. 2 fuel oil	60–90	.0025
Lube oil (high viscosity)	Water	40–80	.003	Sulfur dioxide	Water	150–200	.003
Lube oil	Oil	11–20	.006	Tall-oil derivatives, vegetable oils (vapor)	Water	20–50	.004
Naphtha	Water	50–70	.005	Water	Aromatic vapor-stream azeotrope	40–80	.005
Naphtha	Oil	25–35	.005	Gas-liquid media			
Organic solvents	Water	50–150	.003	Air, N ₂ , etc. (compressed)	Water or brine	40–80	.005
Organic solvents	Brine	35–90	.003	Air, N ₂ , etc., A	Water or brine	10–50	.005
Organic solvents	Organic solvents	20–60	.002	Water or brine	Air, N ₂ (compressed)	20–40	.005
Tall oil derivatives, vegetable oil, etc.	Water	20–50	.004	Water or brine	Air, N ₂ , etc., A	5–20	.005
Water	Caustic soda solutions (10–30%)	100–250	.003	Water	Hydrogen containing natural-gas mixtures	80–125	.003
Water	Water	200–250	.003	Vaporizers			
Wax distillate	Water	15–25	.005	Anhydrous ammonia	Steam condensing	150–300	.0015
Wax distillate	Oil	13–23	.005	Chlorine	Steam condensing	150–300	.0015
Condensing vapor-liquid media				Chlorine	Light heat-transfer oil	40–60	.0015
Alcohol vapor	Water	100–200	.002	Propane, butane, etc.	Steam condensing	200–300	.0015
Asphalt (450°F.)	Dowtherm vapor	40–60	.006	Water	Steam condensing	250–400	.0015
Dowtherm vapor	Tall oil and derivatives	60–80	.004				

NC = noncondensable gas present.

V = vacuum.

A = atmospheric pressure.

Dirt (or fouling factor) units are $(\text{h} \cdot \text{ft}^2 \cdot ^{\circ}\text{F})/\text{Btu}$.

To convert British thermal units per hour-square foot-degrees Fahrenheit to joules per square meter-second-kelvins, multiply by 5.6783; to convert hours per square foot-degree Fahrenheit-British thermal units to square meters per second-kelvin-joules, multiply by 0.1761.

See Tables 14-3 to 14.5, pages 661-663 in PTW

Agenda for Today's Class

- design and cost factors (slides 3-7)
- heat transfer and LMTD (slides 8-11)
- resistance to heat transfer (slides 12-18)
- pressure drop (slides 19-21)

Needed for
problem 14-2

Pressure Drop – Tube-side

pages 664-665 and footnote on page 665

$$\Delta p_i = \frac{2 \cdot \beta_i \cdot f_i \cdot G_i^2 \cdot L \cdot n_p}{\rho_i \cdot D_i \cdot \Phi_i}$$

Eq 14-23, p. 664

$$f_i = \begin{cases} 0.079 \text{Re}^{-0.25} & \text{for } \text{Re} \leq 2100 \\ 0.046 \text{Re}^{-0.20} & \text{for } \text{Re} > 2100 \end{cases}$$

Eq 14-23a,b

$$\Phi_i = \begin{cases} 1.10 (\mu_i / \mu_w)^{0.25} & \text{for } \text{Re} \leq 2100 \\ 1.02 (\mu_i / \mu_w)^{0.14} & \text{for } \text{Re} > 2100 \end{cases}$$

$$\beta_i = \begin{cases} 1 + \frac{F_e + F_c + F_r}{2 \cdot f_i \cdot G_i^2 \cdot L / (\rho_i^2 \cdot D_i \cdot \Phi_i)} \\ 1 + \frac{0.51 \cdot K_1 \cdot n_p \cdot \Delta T_{f,i} \cdot (\mu_i / \mu_w)^{0.28}}{(T_{i, \text{in}} - T_{i, \text{out}}) \cdot \text{Pr}^{2/3}} \end{cases}$$

Eq 14-23c,d, p. 665

$$F_e = \frac{(V_1 - V_2)^2}{2} \quad \text{expansion}$$

see T12.1, pp. 490-491
for V_1 , V_2 , and K_c

$$F_c = \frac{K_c V_2^2}{2} \quad \text{contraction}$$

$$F_r = \frac{0.5 V_2^2 \cdot (n_p - 1)}{2 \cdot n_p} \quad \text{flow reversal}$$

$$K_1 = (1 - S_i / S_H)^2 + K_c + 0.5 \cdot (n_p - 1) / n_p$$

S_i / S_H = area ratio (cr-sect, tubes to header)

f_i = fanning friction factor based on average T

Φ_i = correction factor for nonisothermal flow

μ_i = viscosity at average T

μ_w = viscosity at wall T

n_p = number of tubes

G_i = mass velocity, $\text{kg/s} \cdot \text{m}^2$

L = length

β_i = correction factor for sudden expansion and contraction

Pressure Drop – Shell-side

$$\Delta p_o = \frac{2 \cdot B_o \cdot f' \cdot N_{tr} \cdot G_s^2}{\rho_o}$$

B_o = num. of tube crossings

N_{tr} = num. of tube rows

$$f' = b_o \left(\frac{D_o \cdot G_s}{\mu_o} \right)^{-0.15} \quad \text{for } 2000 < Re < 40000$$

$$b_o = \begin{cases} 0.44 + \frac{0.08 \cdot x_L}{(x_T - 1)^{(0.43 - 1.13)/x_L}} & \text{for inline tubes} \\ 0.23 + \frac{0.11}{(x_T - 1)^{1.08}} & \text{for staggered tubes} \end{cases}$$

x_T is “pitch” or center to center distance

x_L is ratio of pitch to outside tube diameter

Questions