Heat Exchanger 2

Temperature profiles with length

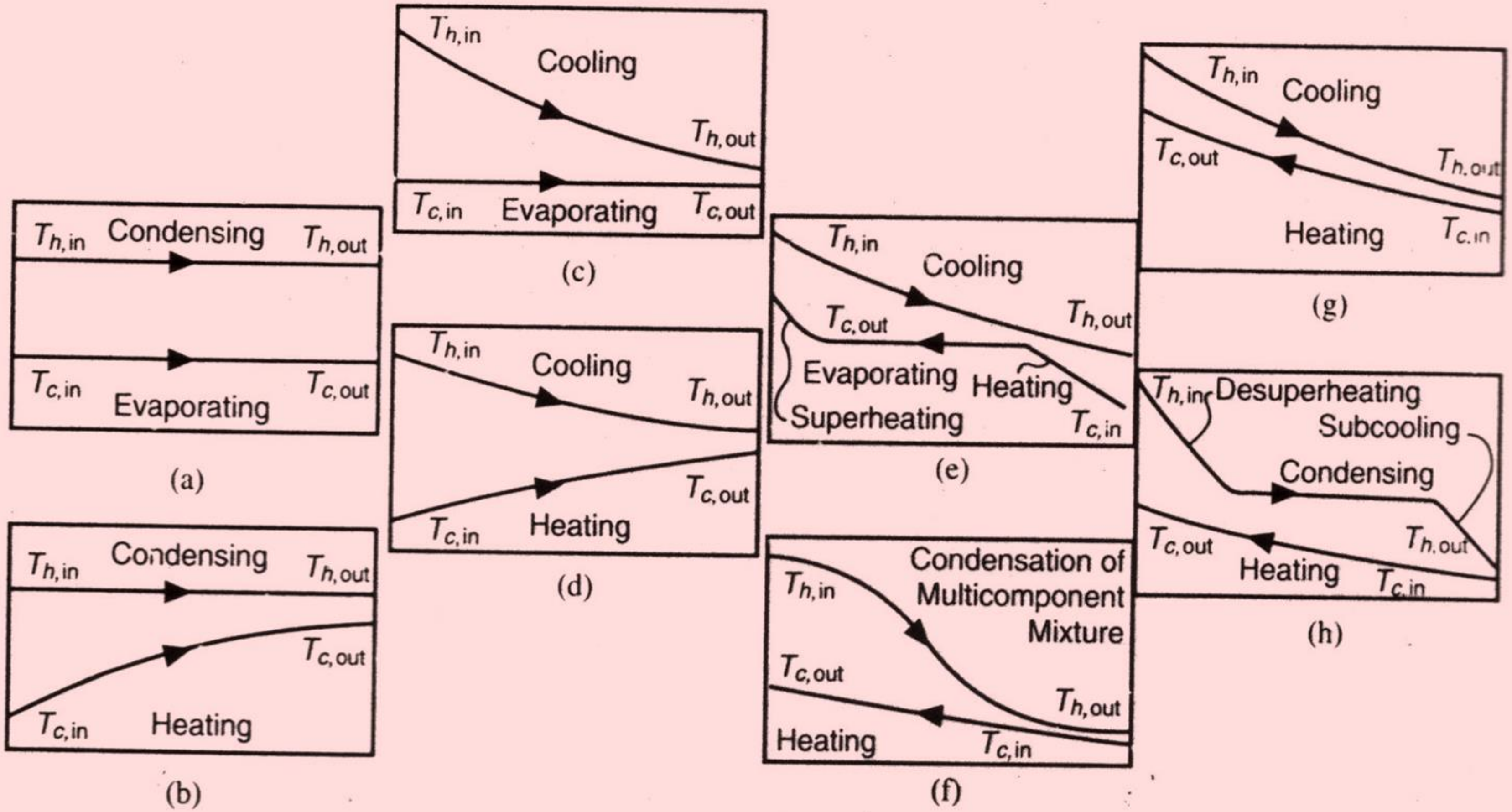
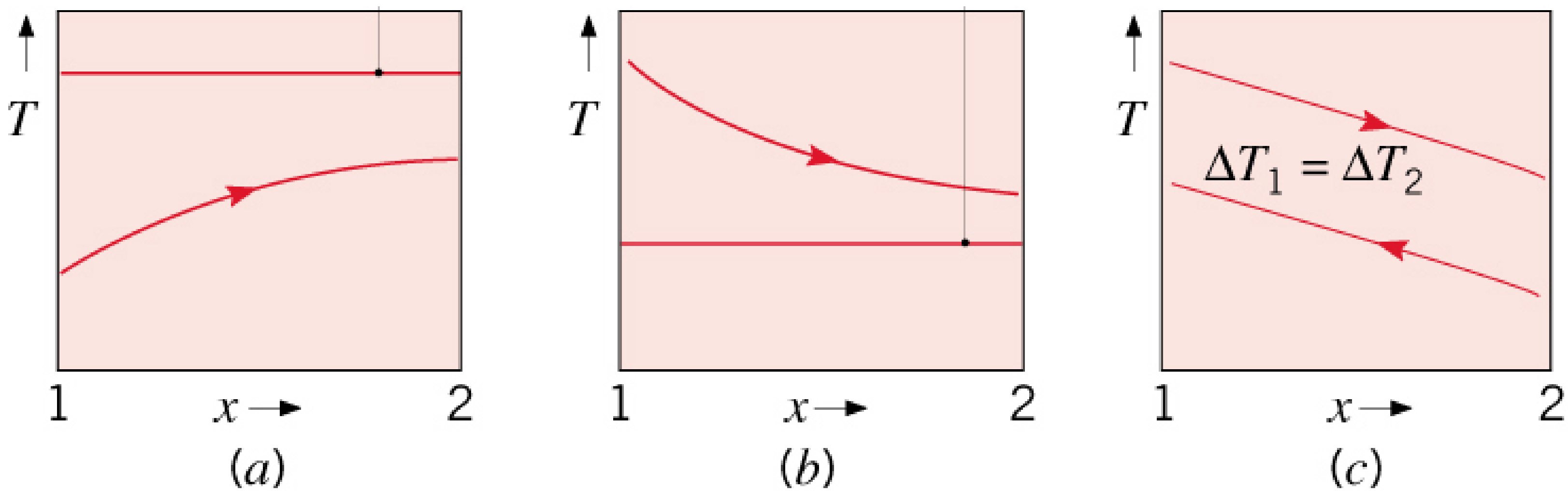


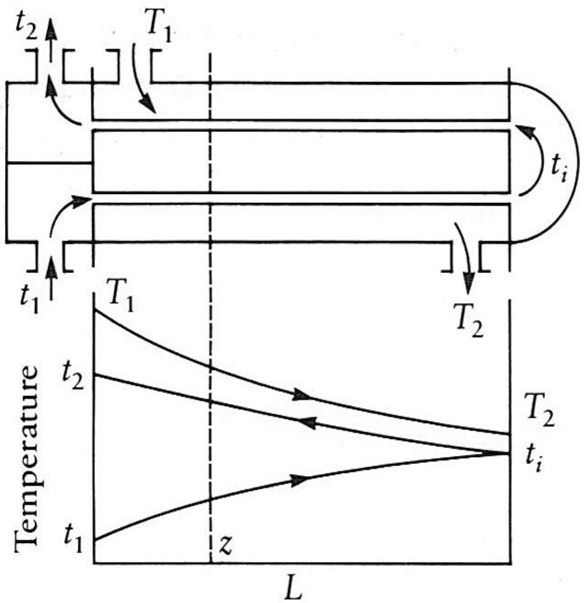
Fig. Variation of fluid temperature with length along the heat exchanger. (a) Both fluids changing phase; (b), (c), (e), (h) one fluid changing phase; (d) parallel flow, no phase change; (f) condensable and noncondensable components; (g) counterflow, no phase change. (Adapted from Walker, 1982. With permission).

Special Operating Conditions

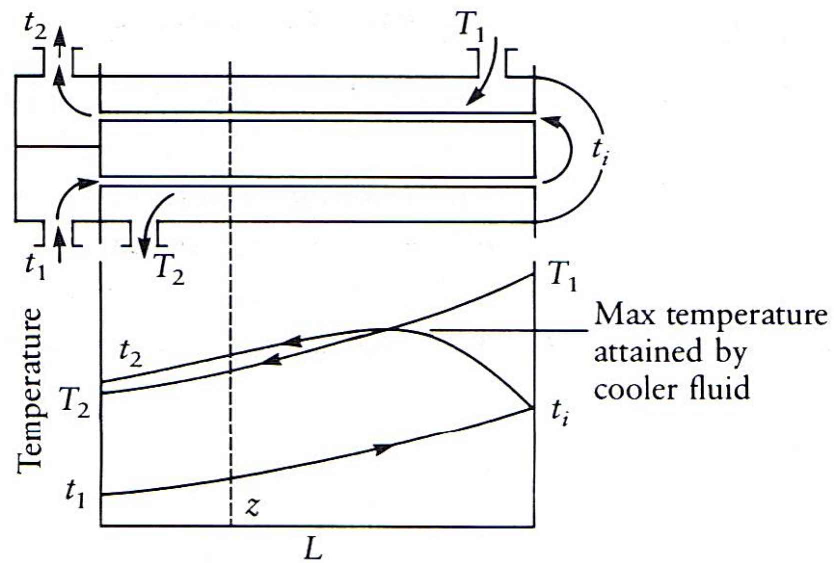


The LMTD Correction Factor

- Corrections are only for Multi-tube passes and multi-shell passes.
- Why corrections. Look to the following two figures.



(a) Warmer fluid inlet near cooler fluid outlet



(b) Warmer fluid outlet near cooler fluid inlet

Temperature variation with distance for both fluids in shell-and tube heat exchanger. Two possible flow arrangements are illustrated.

- ✓For this reason, the mean temperature difference is not equal to the logarithmic mean.
- ✓Therefore, it is convenient to retain the LMTD by introducing a correction factor, F, which is appropriately termed the LMTD correction factor:

$$\Delta T_m = F(\Delta T_{\ln})_{cf}$$

LMTD as if the flow were counter current

- ✓The correction factor can be computed analytically for any number of shell-side passes and any even number of tube-side passes as follows

let N = number of shell-side passes

$$R = \frac{T_a - T_b}{t_b - t_a}$$

$$P = \frac{t_b - t_a}{T_a - t_a}$$

where
T_a = inlet temperature of shell-side fluid
T_b = outlet temperature of shell-side fluid
t_a = inlet temperature of tube-side fluid
t_b = outlet temperature of tube-side fluid

- For R ≠ 1, compute

$$\alpha = \left(\frac{1 - RP}{1 - P}\right)^{1/N}$$

$$S = \frac{\alpha - 1}{\alpha - R}$$

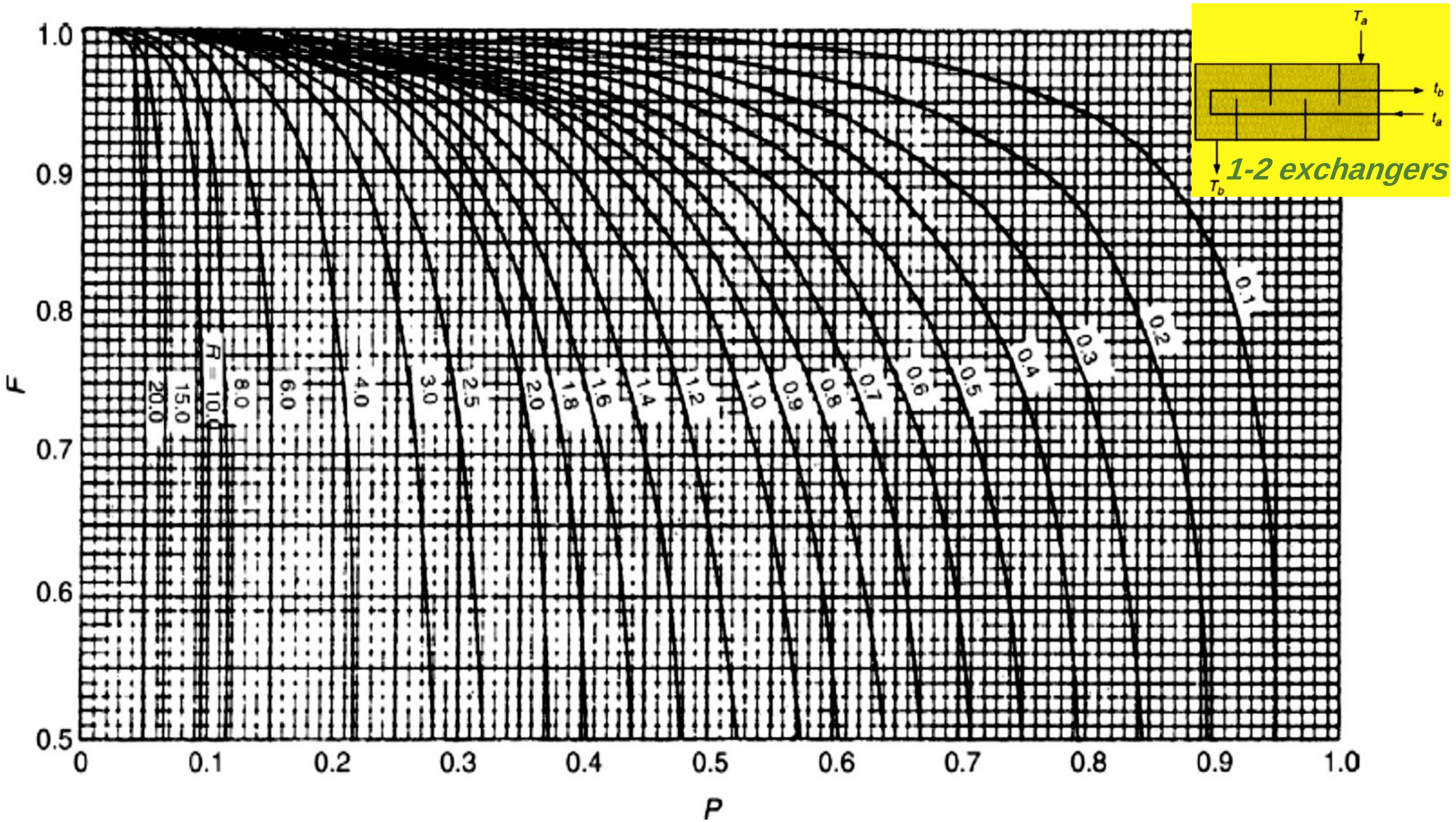
$$F = \frac{\sqrt{R^2 + 1}\ \ln\left(\frac{1 - S}{1 - RS}\right)}{(R - 1)\ln\left[\frac{2 - S(R + 1 - \sqrt{R^2 + 1})}{2 - S(R + 1 + \sqrt{R^2 + 1})}\right]}$$

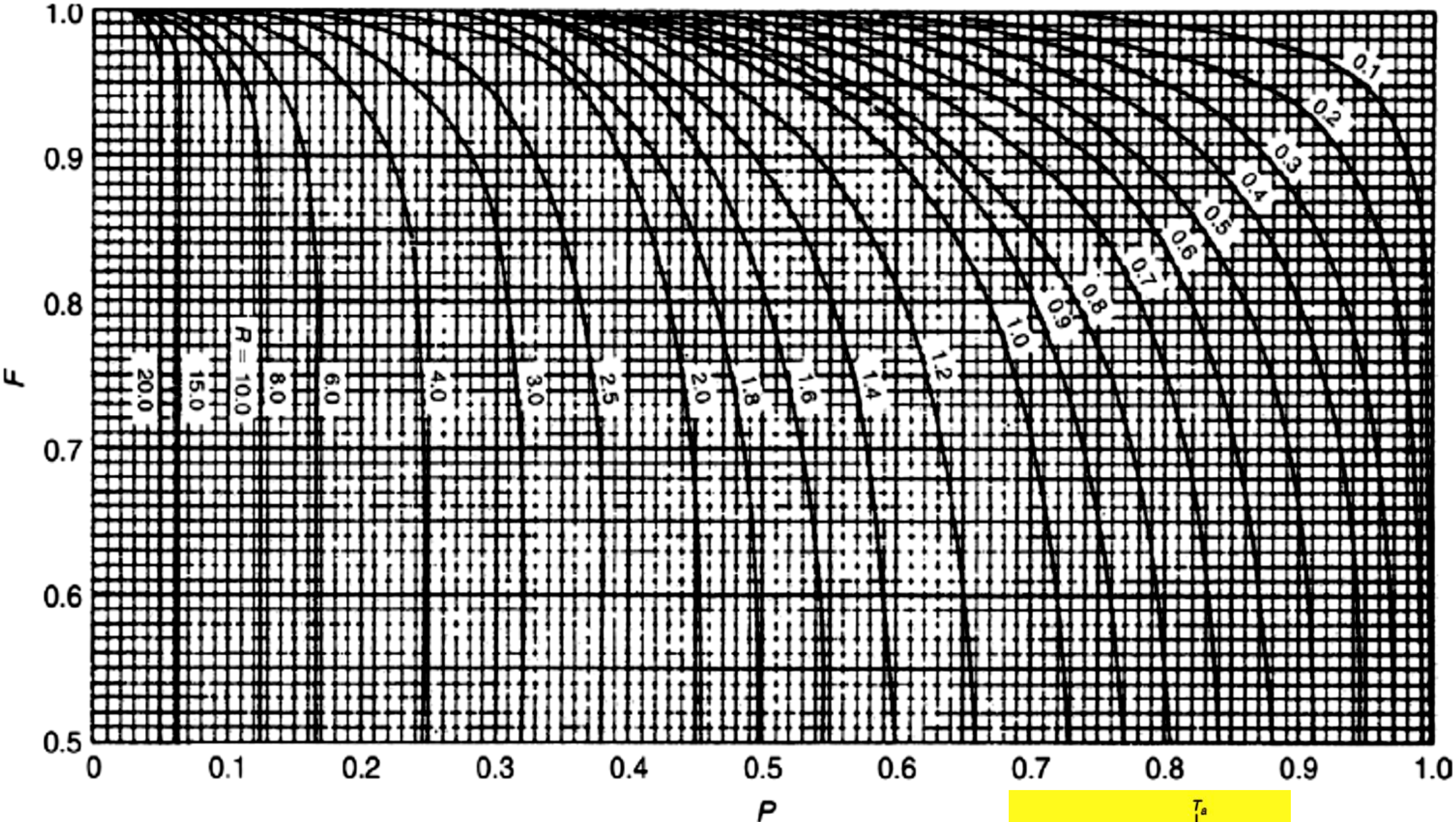
- For R = 1, compute

$$S = \frac{P}{N - (N - 1)P}$$

$$F = \frac{S\sqrt{2}}{(1 - S)\ln\left[\frac{2 - S(2 - \sqrt{2})}{2 - S(2 + \sqrt{2})}\right]}$$

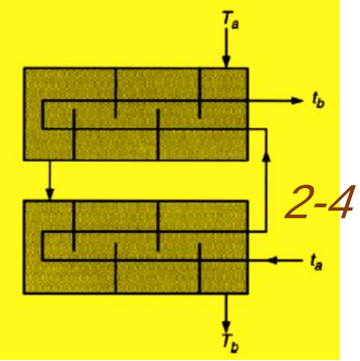
Graphs are convenient for making quick estimates to F



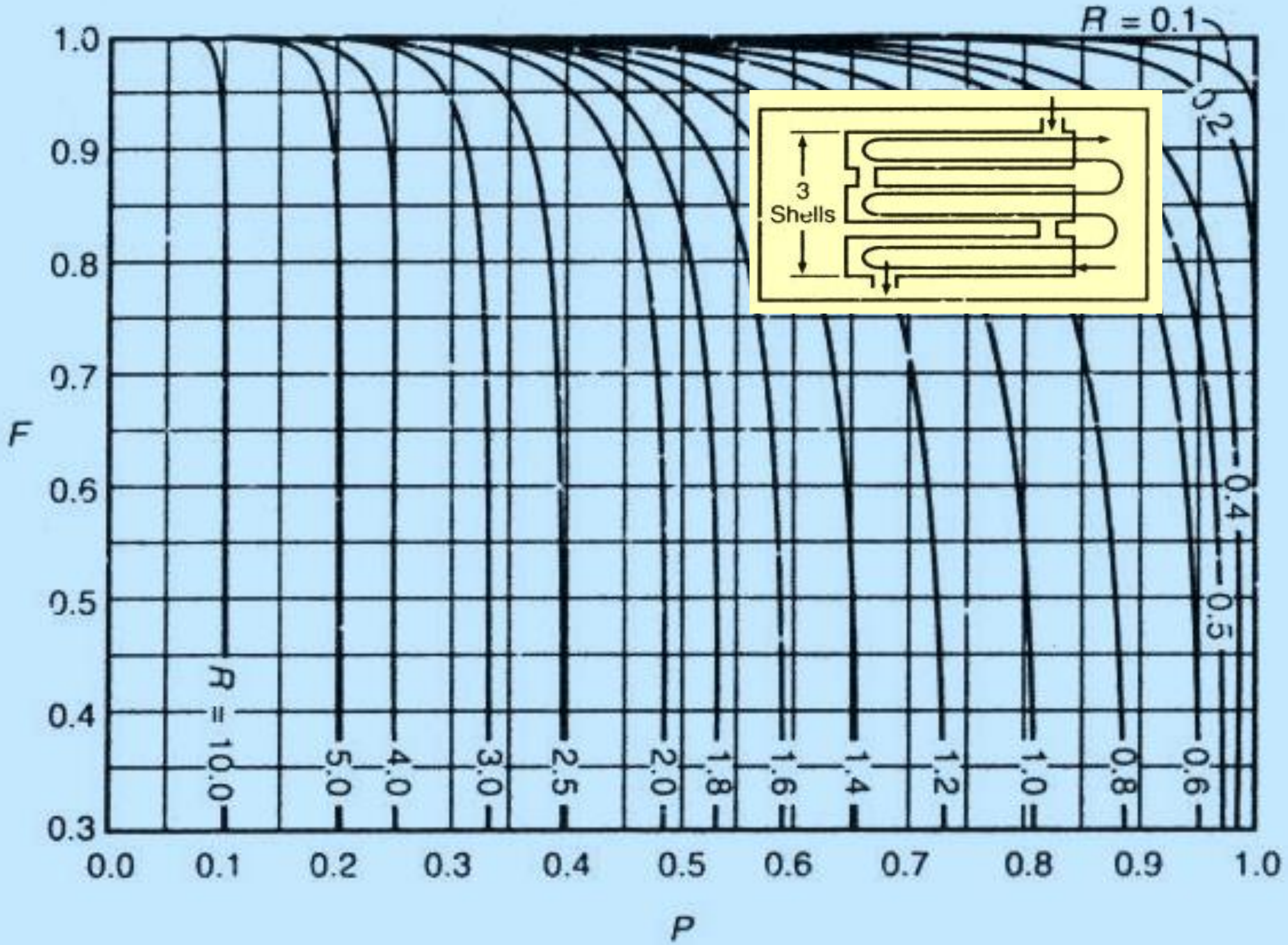


Note:

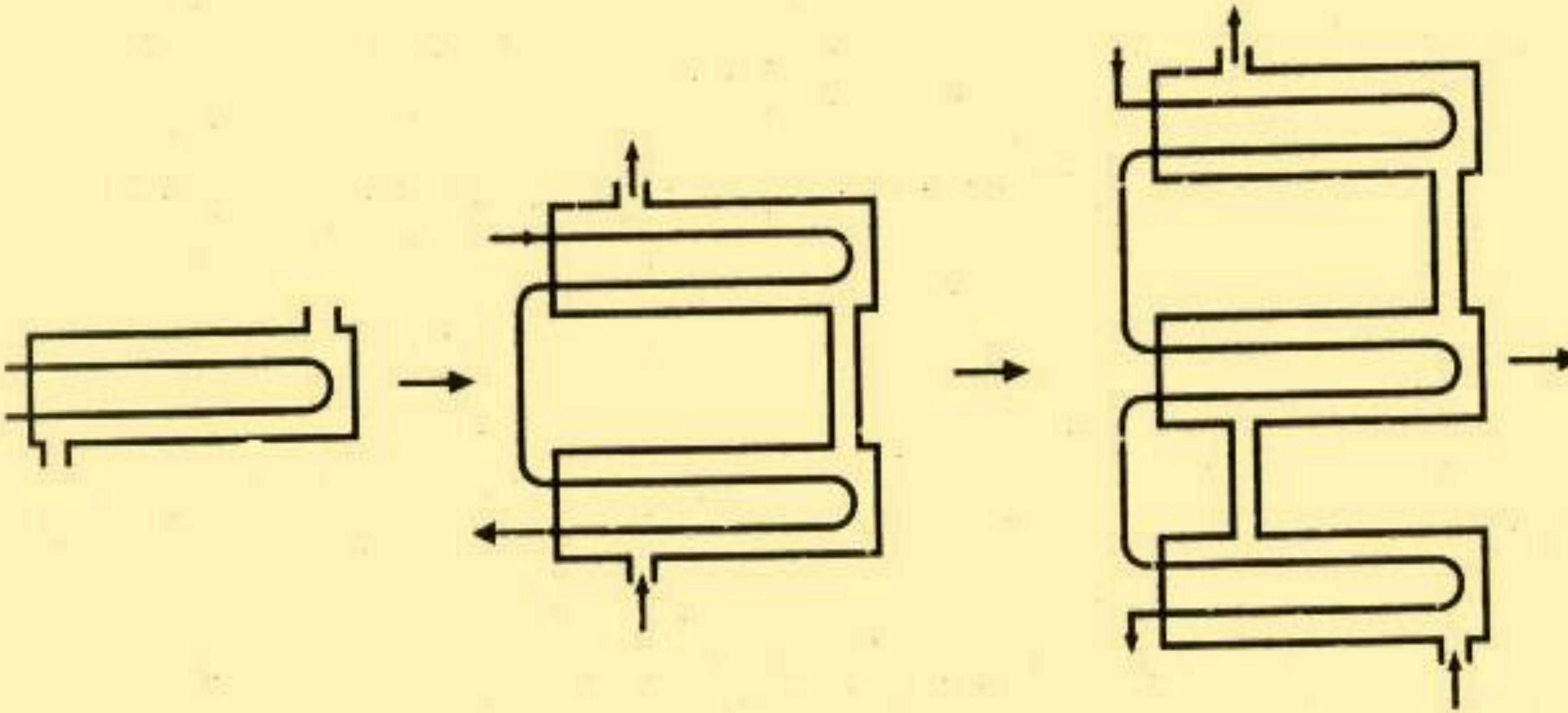
F must be not less than 0.8



2-4 exchangers


R = 0.1
0.2
0.4
0.5
R = 10.0
5.0
4.0
3.0
2.5
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
3 Shells
F
P
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0

Approaching counter flow operation by increasing the number of shells



Increasing F_T

Example 1

A fluid is to be heated from 100°F to 160°F by heat exchange with a hot fluid that will be cooled from 230°F to 150°F The heat-transfer rate will be 540,000 Btu/h and the hot fluid will flow in the tubes. Will a 1-2 exchanger (i.e., an exchanger with one shell pass and a multiple of two tube passes) be suitable for this service? Find the mean temperature difference in the exchanger.

Solution

$$R = \frac{T_a - T_b}{t_b - t_a} = \frac{100 - 160}{150 - 230} = 0.75$$

$$P = \frac{t_b - t_a}{T_a - t_a} = \frac{150 - 230}{100 - 230} = 0.615$$

- $F \cong 0.72$. Since F is less than 0.8, a 1-2 exchanger should not be used. Two shell passes, it is found from F Figure that $F \cong 0.94$.
- Hence, an exchanger with two shell passes and a multiple of four tube passes (2-4 exchanger) will be suitable.

Mean temperature difference calculations

$$\Delta T = 50^\circ\text{F} \begin{cases} 100^\circ\text{F} \longrightarrow 160^\circ\text{F} \\ 150^\circ\text{F} \longleftarrow 230^\circ\text{F} \end{cases} \quad \Delta T = 70^\circ\text{F}$$

$$(\Delta T_{\ln})_{cf} = \frac{\Delta T_2 - \Delta T_1}{\ln(\Delta T_2/\Delta T_1)} = \frac{70 - 50}{\ln(70/50)} = 59.6^\circ\text{F}$$

$$\Delta T_m = F(\Delta T_{\ln})_{cf} = 0.94 \times 59.6 = 56^\circ\text{F}$$

Double pipe thermal analysis

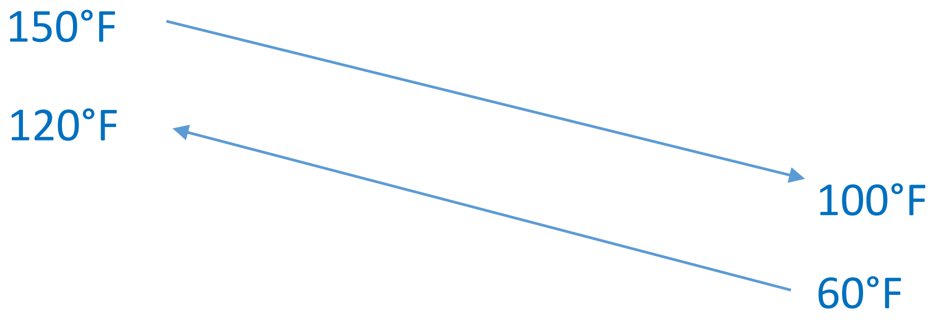
Thermal analysis of a double-pipe exchanger is illustrated in the following example:

10,000 lb/h of benzene is to be heated from 60°F to 120°F by heat exchange with an aniline stream that will be cooled from 150°F to 100°F A number of 16 ft hairpins consisting of 2 in. by 1.25 in. schedule 40 stainless steel pipe (type 316, k = 9.4 Btu/h. ft. °F are available and will be used for this service. how many hairpins will be required?

Basic Assumptions

- Assume heat from hot stream = cold stream.
- Assume benzene flows in the inner pipe.
- Properties at average properties or according to the correlation conditions.

Sketch T-x diagram



Solution _ Procesdure

Find properties for both streams

↓

find the heat load of the exchanger & unknown flow rate

↓

Calculate the LMTD

↓

Calculate h_i assuming ϕ_i = 1.0. firstly find D_i from tables, then Re, then Nu.

↓

Check entrance effect L/Di >60. In this example the length is not given, therefore assume one hair pin. Hence take L = 32 ft (one hairpin). If the ratio is greater than 60, you don't need to use entrance effects correction.

Calculate ho assuming ϕ_o = 1.0. Firstly find D_1, D_2 from tables. Then obtain D_e and A_f. Then find Re, Nu.

↓

Check entrance effect L/De > 60. **Note** in the annulus the flow is disrupted at the return bends, so it is appropriate to use the length of pipe in one leg of a hairpin to estimate entrance effects.

↓

Calculate wall pipe temperature T_w
See next slide.

↓

Find ϕ_i , ϕ_o .

↓

Correct the values of h_i and h_o

↓

Obtain fouling Factors

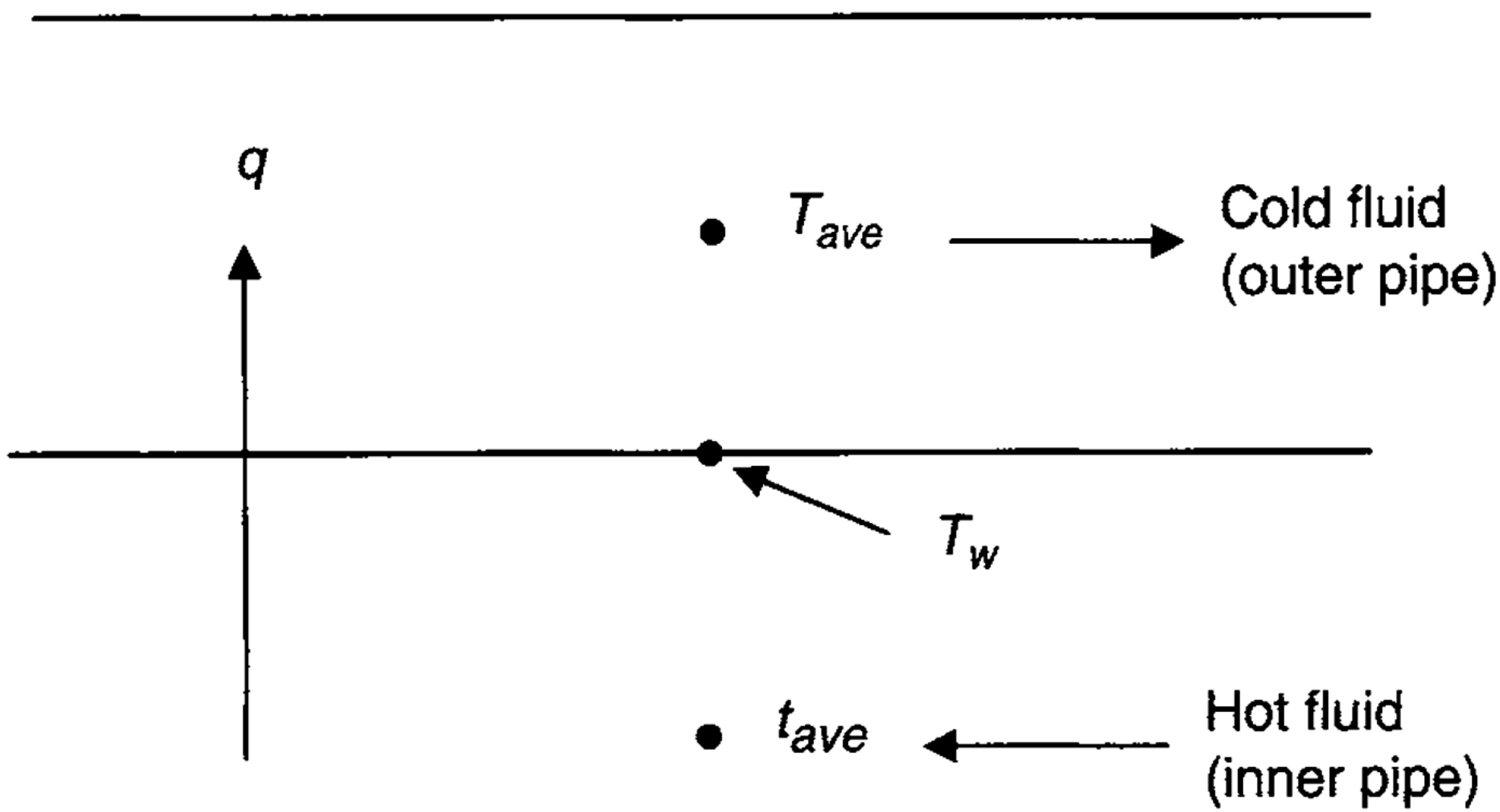
↓

Compute the O.H.T.C

↓

Calculate the required surface area. Then find L by using the table show in the next slides. Finally find the no. of hairpins.

How to calculate T_w



An energy balance gives:

$$q = h_i A_i (t_{ave} - T_w) = h_o A_o (T_w - T_{ave})$$

Solving for T_w yields:

$$T_w = \frac{h_i A_i t_{ave} + h_o A_o T_{ave}}{h_i A_i + h_o A_o}$$

Substituting $A = \pi DL$ for the areas and rearranging, we obtain:

$$T_w = \frac{h_i t_{ave} + h_o (D_o/D_i) T_{ave}}{h_i + h_o (D_o/D_i)}$$

Nominal pipe size (in.)	Outside diameter (in.)	Schedule No.	Wall thickness (in.)	Inside diameter (in.)	Cross-sectional area	
					Metal (in.^{2})	Flow (ft^2)
$\frac{1}{8}$	0.405	10S	0.049	0.307	0.055	0.00051
		40ST, 40S	0.068	0.269	0.072	0.00040
		80XS, 80S	0.095	0.215	0.093	0.00025
$\frac{1}{4}$	0.540	10S	0.065	0.410	0.097	0.00092
		40ST, 40S	0.088	0.364	0.125	0.00072
		80XS, 80S	0.119	0.302	0.157	0.00050
$\frac{3}{8}$	0.675	10S	0.065	0.545	0.125	0.00162
		40ST, 40S	0.091	0.493	0.167	0.00133
		80XS, 80S	0.126	0.423	0.217	0.00098
$\frac{1}{2}$	0.840	5S	0.065	0.710	0.158	0.00275
		10S	0.083	0.674	0.197	0.00248
		40ST, 40S	0.109	0.622	0.250	0.00211
		80XS, 80S	0.147	0.546	0.320	0.00163
		160	0.188	0.464	0.385	0.00117
		XX	0.294	0.252	0.504	0.00035
$\frac{3}{4}$	1.050	5S	0.065	0.920	0.201	0.00461
		10S	0.083	0.884	0.252	0.00426
		40ST, 40S	0.113	0.824	0.333	0.00371
		80XS, 80S	0.154	0.742	0.433	0.00300
		160	0.219	0.612	0.572	0.00204
		XX	0.308	0.434	0.718	0.00103
1	1.315	5S	0.065	1.185	0.255	0.00768
		10S	0.109	1.097	0.413	0.00656

Criteria for Fluid Placement, in Order of Priority

Tube-side fluid	Shell-side fluid
Corrosive fluid	Condensing vapor (unless corrosive)
Cooling water	Fluid with large ΔT (>100°F)
Fouling fluid	
Less viscous fluid	
Higher-pressure stream	
Hotter fluid	

Solution _ Numerical values

- Properties

Fluid property	Benzene ($t_{ave} = 90°F$)	Aniline ($T_{ave} = 125°F$)
μ (cp)	0.55	2.0
C_P (Btu /lbm · °F)	0.42	0.52
k (Btu/h · ft · °F)	0.092	0.100

- Energy balance

$$q = (\dot{m} C_P \Delta T)_B = 10{,}000 \times 0.42 \times 60 = 252{,}000 \text{ Btu/h}$$

$$252{,}000 = (\dot{m} C_P \Delta T)_A = \dot{m}_A \times 0.52 \times 50$$

$$\dot{m}_A = 9692 \text{ lb/h}$$

- LMTD

$$\Delta T = 40°\text{F} \begin{cases} 60°\text{F} \longrightarrow 120°\text{F} \\ 100°\text{F} \longleftarrow 150°\text{F} \end{cases} \Delta T = 30°\text{F}$$

$$\Delta T_{\ln} = \frac{40 - 30}{\ln(40/30)} = 34.76°\text{F}$$

- h_i calculation

$$D_i = \frac{1.38}{12} = 0.115\,\text{ft} \quad \text{(From Table B.2)}$$

$$Re = \frac{4\dot{m}}{\pi D_i \mu} = \frac{4 \times 10{,}000}{\pi \times 0.115 \times 0.55 \times 2.419} = 83{,}217 \Rightarrow \text{turbulent flow}$$

$$Nu = \frac{h_i D_i}{k} = 0.027\, Re^{0.8}\, Pr^{1/3}$$

$$h_i = \frac{k}{D_i} \times 0.027\, Re^{0.8}\, Pr^{1/3}$$

$$h_i = \frac{0.092}{0.115} \times 0.027\,(83{,}217)^{0.8} \left(\frac{0.42 \times 0.55 \times 2.419}{0.092}\right)^{1/3}$$

$$h_i = 340\,\text{Btu/h} \cdot \text{ft}^2 \cdot {}^\circ\text{F}$$

Check entrance effect

Entrance effect

- For the inner pipe, the effect of the return bends on the heat transfer is minor, so it is reasonable to use the entire length of the flow path in the correction term.
- Although this length is unknown in the present instance, the exchanger will have at least one hairpin containing 32 ft of pipe.

$$\frac{L}{D_i} \geq \frac{32}{0.115} = 278 > 60$$

$\therefore$ Entrance effects are negligible

- ho Calculation

$$\left.\begin{aligned} D_2 &= 2.067 \text{ in.} \\ D_1 &= 1.660 \text{ in.} \end{aligned}\right\} \quad \text{(From Table B.2)}$$

$$D_e = D_2 - D_1 = \frac{(2.067 - 1.660)}{12} = 0.0339 \text{ ft}$$

$$\text{Flow area} \equiv A_f = \frac{\pi}{4}(D_2^2 - D_1^2) = 0.00826 \text{ ft}^2$$

$$Re = \frac{D_e(\dot{m}/A_f)}{\mu} = \frac{0.0339 \times (9692/0.00826)}{2.0 \times 2.419} = 8222 \Rightarrow \text{transition flow}$$

$$Nu = \frac{h_o D_e}{k} = 0.116[Re^{2/3} - 125]\, Pr^{1/3}[1 + (D_e/L)^{2/3}]$$

Neglecting entrance effects,

$$h_o = \frac{k}{D_e} \times 0.116\,[Re^{2/3} - 125]Pr^{1/3}$$

$$= \frac{0.1}{0.0339} \times 0.116 \times [(8222)^{2/3} - 125]\left(\frac{0.52 \times 2.0 \times 2.419}{0.1}\right)^{1/3}$$

$$h_o = 283 \text{ Btu/h} \cdot \text{ft}^2 \cdot {}^\circ\text{F}$$

Entrance effect

In the annulus the flow is disrupted at the return bends, so it is appropriate to use the length of pipe in one leg of a hairpin to estimate entrance effects. Thus,

$$L/D_e = 16/0.0339 = 472 > 60$$

$\therefore$ Entrance effects are negligible

- Calculate the pipe-wall temperature.

$$T_w = \frac{h_i t_{ave} + h_o(D_o/D_i)T_{ave}}{h_i + h_o(D_o/D_i)}$$

$$T_w = \frac{340 \times 90 + 283 \times (1.66/1.38) \times 125}{340 + 283 \times (1.66/1.38)}$$

$$T_w = 108°\text{F}$$

- Calculate ϕ_i and ϕ_o, and corrected values of h_i and h_o.

At Tw = 108 °F

$$\mu_B = 0.47\text{cp and } \mu_A = 2.4\text{ cp}$$

$$\phi_i = \left(\frac{0.55}{0.47}\right)^{0.14} = 1.0222$$

$$\phi_o = \left(\frac{2.0}{2.4}\right)^{0.14} = 0.9748$$

- finally

$$h_i = 340(1.0222) = 348\,\text{Btu/h}\cdot\text{ft}^2\cdot{}^\circ\text{F}$$

$$h_o = 283(0.9748) = 276\,\text{Btu/h}\cdot\text{ft}^2\cdot{}^\circ\text{F}$$

- Obtain fouling factors

$$R_{Di} = R_{Do} = 0.001\,\text{h}\cdot\text{ft}^2\cdot{}^\circ\text{F/Btu}$$

- Calculate the O.H.T.C

$$U_D = \left[\frac{D_o}{h_i D_i} + \frac{D_o \ln(D_o/D_i)}{2k} + \frac{1}{h_o} + \frac{R_{Di} D_o}{D_i} + R_{Do}\right]^{-1}$$

$$U_D = \left[\frac{1.66}{348 \times 1.38} + \frac{(1.66/12)\ln(1.66/1.38)}{2 \times 9.4} + \frac{1}{276} + \frac{0.001 \times 1.66}{1.38} + 0.001\right]^{-1}$$

$$U_D = 94\,\text{Btu/h}\cdot\text{ft}^2\cdot{}^\circ\text{F}$$

- Calculate the required surface area

$$q = U_D A \, \Delta T_{\ln}$$

$$A = \frac{q}{U_D \, \Delta T_{\ln}}$$

$$A = \frac{252,000}{94 \times 34.76} = 77.12 \, \text{ft}^2$$

- Find the total length

$$L = \frac{77.12}{0.435} = 177.3 \, \text{ft}$$

- Find the number of hairpins assuming 32 ft hairpin

$$\text{Number of hairpins} = \frac{177.3}{32} = 5.5 \Rightarrow 6$$