1. Work Text Problem 12.4

2. Work Text Problem 12.21

3. A counterflow heat exchanger has an area of 270 ft². Heat exchangers in similar service in your plant have overall heat transfer coefficients of 150 Btu/hr ft² F. A process fluid must be heated in the exchanger from 150 F. A heating medium is available at 350 F. To what temperature can the process fluid be raised?

Data:

Flowrate of cold fluid - 100,000 lb/hr
Flowrate of hot fluid - 150,000 lb/hr

Heat capacity - 0.45 Btu/lb F
Heat capacity - 0.40 Btu/lb F

4. Work Text Problem 15.2

5. Work Text Problem 15.15

Assume \( \frac{\mu}{\mu_w} = 0.25 \)
Evaluate the oil coefficients at both the inlet and exit temperatures.
Equations 12.14, 12.25, and 15.6 might be useful.
12.4 Use Eq. (11.32). $h_o = 300 \text{ Btu/h-ft}^2\text{-oF}$

For steel, $k = 26 \text{ Btu/h-ft}^\circ\text{F}$ (Appendix 10)

Tube dimensions (Appendix 4)

$$X_w = 0.065/12 = 0.0054 \text{ ft}$$
$$D_0 = 0.75/12 = 0.0625 \text{ ft}$$
$$D_i = 0.0620/12 = 0.0517 \text{ ft}$$

$$\bar{D}_l = (0.0625 - 0.0517)/\ln(0.0625/0.0517)$$

$$= 0.0569 \text{ ft}$$

For the inside coefficient:

$$\rho = 0.805 \times 62.3 = 50.2 \text{ lb/ft}^3$$
$$C_p = 0.583 \text{ Btu/lb}^\circ\text{F}$$
$$k = 0.0875 \text{ Btu/h-ft}^\circ\text{F}$$
$$\mu = 1.5 \times 2.42 = 3.63 \text{ lb/ft-h}$$

$$\bar{V} = 8 \text{ ft/s}$$

$$G = 8 \times 50.2 \times 3600 = 1.446 \times 10^6 \text{ lb/h-ft}^2$$

Use Eqs. (12.49) and (12.52).

$$\text{Re} = 0.0517 \times 1.446 \times 10^6 / 3.63$$

$$= 20590$$

$$\text{Pr} = 0.583 \times 3.63 / 0.0875 = 24.19$$

$$h_i = \frac{0.023 \times 0.583 \times 1.446 \times 10^6}{20590^{0.2} \times 24.19^{2/3}}$$

$$= 318 \text{ Btu/h-ft}^2\text{-oF}$$

From Eq. (11.32)

$$U_0 = \frac{1}{\frac{0.0625}{318 \times 0.0517} + \frac{0.0054 \times 0.0625}{26 \times 0.0569} + \frac{1}{300}}$$

$$= 1/(0.0003802 + 0.000228 + 0.003333)$$

$$= 135.8 \text{ Btu/h-ft}^2\text{-oF}$$
12.21 (a) \[ u_o = 10 \text{ m/s}, T_o = 20^\circ \text{C} \]
\[ T_w = 80^\circ \text{C} \]
\[ x_i = 1.6 \text{ m} \]

Evaluate \[ k, \rho, \mu \] at 20\(^\circ\) C or 68\(^\circ\) F

App. 12
\[ k = 0.014 \text{ at } 32^\circ \text{F}, \ 0.0184 \text{ at } 212^\circ \text{F} \]

at 60\(^\circ\) F,
\[ k = 1.49 \times 10^{-2} \text{ Btu/ft \cdot h \cdot F} = 2.58 \times 10^{-2} \text{ W/m \cdot }^\circ \text{C} \]
\[ \mu = 1.79 \times 10^{-2} \text{ c_p} \]
\[ \rho = 1.206 \text{ kg/m}^3 \]

\[ \text{Re}_x = \left( \frac{1.6(10)(1.206)}{1.79 \times 10^{-5}} \right) = 1.08 \times 10^6 \]
\[ \text{Pr} = 0.69 \]

Eq. (12.7)
\[ N_u_x = 0.332(0.69)^3 \left(1.08 \times 10^6\right)^{1/2} = 305 \]

\[ h_x = \frac{305(2.58 \times 10^{-2})}{1.6} = 4.92 \text{ W/m}^2\cdot^\circ \text{C} \]
local flux \[ = 4.92 \times 60 = 295 \text{ W/m}^2 \]
\[ h = 2h_x = 9.84 \text{ W/m}^2\cdot^\circ \text{C} \]
average flux \[ = 9.84 \times 60 = 590 \text{ W/m}^2 \]

(b) Thickness of thermal boundary layer \[ \frac{k}{h} = \frac{2.58 \times 10^{-2}}{4.92} = 5.24 \times 10^{-3} \text{ m} \]
Problem No 3

100,000 lb/hr, \( T = 150^\circ F \), \( CP = 0.45 \frac{BTU}{lb^\circ F} \)

\[
\begin{align*}
T &= 275^\circ F \\
Q &= 100,000 \frac{lb}{hr} \left( 0.45 \frac{BTU}{lb^\circ F} \right) \left( 250 - 150 \right) \\
\bar{Q} &= 4.5 \times 10^6 \frac{BTU}{hr} = 150,000 \frac{lb}{hr} \left( 0.40 \right) \left( 550 - x \right) \\
T &= 275^\circ F \\
\Delta T_{lm} &= \frac{125 - 100}{0.125} = 112 \text{ F} \\
A &= \frac{4.5 \times 10^6 \frac{BTU}{hr}}{150 \frac{BTU}{hr^\circ F} \left( 112 \right)} = 270 \text{ ft}^2
\end{align*}
\]
15.2. Use Eq. (15.6). Put the bottom product in the shell. Assume \( f_b = 0.1955 \) (see Example 15.3).

**Shell side**

\[
N_b = 324 \times 0.1955 = 63 \text{ tubes}
\]

\[
S_b = \frac{0.1955 \pi (23.25)^2}{4} - \frac{63 \pi (0.75)^2}{4}
\]

\[
= 0.3831 \text{ ft}^2 (0.03559 \text{ m}^2)
\]

From Eq. (15.4), since \( P = 9/12 = 0.75 \text{ ft}, p = 1 \text{ in.}, \) and \( D_0 = 0.75 \text{ in.} : \)

\[
S_e = \frac{0.75 \times 23.25}{12} \left(1 - \frac{0.75}{1}\right)
\]

\[
= 0.3633 \text{ ft}^2 (0.03375 \text{ m}^2)
\]

\( G_b = \frac{129,000}{(3600 \times 0.03559)} = 1007 \text{ kg/m}^2\cdot\text{s} \)

\( G_c = \frac{129,000}{(3600 \times 0.03375)} = 1062 \text{ kg/m}^2\cdot\text{s} \)

\( G_e = (1007 \times 1062)^{1/2} = 1034 \text{ kg/m}^2\cdot\text{s} \)

\( \mu = 5.2 \times 10^{-3} \text{ kg/m-s} \)

\( D_0 = 0.75/39.37 = 0.01905 \text{ m} \)

\[\text{Re} = \frac{0.01905 \times 1034}{5.2 \times 10^{-3}} = 3788\]

\[\text{Pr} = \frac{2.20 \times 5.2}{0.119} = 96.1\]

From Eq. (15.6), neglecting \( (\mu/\mu_0)^{0.14} \),

\[h_0 = \frac{0.119 \times 0.2 \times 3788^{0.6} \times 96.1^{0.33}}{0.01905} = 790 \text{ W/m}^2\cdot^\circ\text{C} \]

**Tube side**

Inside sectional area per pass:

\[(324/2) \times 0.00186 = 0.301 \text{ ft}^2 \text{ or } 0.0280 \text{ m}^2\]

\[\text{Pr}^{2/3} = (1.99 \times 2.9/0.137)^{2/3} = 12.11\]

\( G = \frac{150,000}{(3600 \times 0.0280)} = 1488 \text{ kg/m}^2\cdot\text{s} \)

\( D_i = 0.584/39.37 = 0.01483 \text{ m} \) (Appendix 4)

\[\left(\frac{D_i G}{\mu}\right)^{0.2} = \left(\frac{0.01483 \times 1488}{2.9 \times 10^{-3}}\right)^{0.2} = 5.97\]

From Eqs. (12.51) and (5.53),

\[h_i = \frac{0.023 \times 1.99 \times 1488 \times 10^3}{5.97 \times 12.11} = 942 \text{ W/m}^2\cdot^\circ\text{C} \]
Metal wall

\[ k = 26 \times 1.73073 = 45 \text{ W/m}^{-\circ\text{C}} \]

\[ x_w = 0.083/39.37 = 0.00211 \text{ m (Appendix 4)} \]

\[ \bar{D}_t = \frac{0.75 - 0.584}{\ln (0.75/0.584)} = 0.664 \text{ in. or } 0.0169 \text{ m} \]

With clean tubes, from Eq. (11.34),

\[ \frac{1}{U_o} = \frac{0.01905}{0.01483 \times 942} + \frac{0.00211 \times 0.01905}{45 \times 0.0169} + \frac{1}{790} \]

\[ U_o = \frac{1}{0.002676} = 374 \text{ W/m}^2\cdot\circ\text{C} \]

Coefficient needed to transfer desired heat:

\[ \bar{\Delta}t_L = \frac{(146 - 57) - (107 - 20)}{\ln (89/87)} = 88\circ\text{C} \]

\[ Z = \frac{146 - 107}{57 - 20} = 1.05 \text{ [Eq. (15.1)]} \]

\[ \gamma_H = \frac{57 - 20}{146 - 20} = 0.294 \text{ [Eq. (15.2)]} \]

From Fig. 15.6a.

\[ F_g = 0.96 \]

\[ A = 324 \times 0.1963 \times 12 = 763 \text{ ft}^2 \text{ or } 70.9 \text{ m}^2 \]

\[ q_{\text{crude}} = 1.99 \times 10^3 (57 - 20)(150,000/3600) \]
\[ = 3.068 \times 10^6 \text{ W} \]

\[ q_{\text{product}} = 2.20 \times 10^3 (146 - 107)(129,000/3600) \]
\[ = 3.075 \times 10^6 \text{ W} \]

\[ \bar{q} = 3.0715 \times 10^6 \text{ W} \]

\[ U_o \text{ needed} = 3.0715 \times 10^6/(70.9 \times 88 \times 0.96) \]
\[ = 513 \text{ W/m}^2\cdot\circ\text{C} \]

The exchanger would not be suitable, since even with clean tubes \( U_o \) is only 374 W/m²-°C.
For oil in tubes, \( Re = \left( \frac{0.834}{12} \times 0.3048 \right) \left( \frac{0.30 \times 710}{3.1 \times 10^{-3}} \right) = 1456 \), laminar flow at 120°C

\( c_p = 2100 \text{ J/kg\cdot°C} \)

\( Pr = \frac{2100(3.1 \times 10^{-3})}{0.104} = 62.6 \)

Eq. (12.14),

\[
G_z = \frac{\pi}{4} Re Pr \frac{D}{L}
\]

assume \( L = 16 \text{ ft}, \quad \frac{L}{D} = \frac{16 \times 12}{1} = 192 \)

\[
G_z = \frac{\pi}{4} \left( \frac{1456(62.6)}{192} \right) = 373
\]

Eq. (12.25),

\[
Nu \cong 2.0 G_z^{1/3} = 14.4 = hD/k
\]

For oil outside of tubes, \( Re = D_o \frac{u p}{\mu}, \quad D_o = 1.0 \text{ in} \)

if \( u = 30 \text{ cm/s} \quad Re = 1456 \left( \frac{1.0}{0.834} \right) = 1746 \)

Eq. (15.6) \( Nu = 0.2(1746)^{0.6}(62.6)^{0.33} (\mu/\mu_p)^{0.14} \)

\[
Nu = 69(\mu/\mu_p)^{0.14}
\]

if \( \mu_p = 4 \mu \quad Nu = 57 \)
The oil-film coefficient is about 4 time greater for flow outside the tube.

For oil in the tubes at 50°C

\[ \text{Re} = \left( \frac{0.834}{12} \times 0.3048 \right) \times 0.30 \left( \frac{780}{12 \times 10^{-3}} \right) = 413 \]

\[ \text{Pr} = \frac{2100 \left(12 \times 10^{-3}\right)}{0.104} = 242 \]

\[ G_{\varepsilon} = \frac{\pi \left( \frac{413 \times 242}{192} \right)}{4} = 409 \]

\[ Nu \cong 14.8 \quad \text{(slightly higher because of higher density)} \]

For oil outside the tubes at 50°C, if \( \mu_o = 4\mu \)

\[ \text{Re} = 413 \left( \frac{1.0}{0.834} \right) = 495 \]

\[ Nu = 0.2 \left( 495^{0.6} \times 242^{0.33} \right)^{0.14} \left( \frac{1}{4} \right) \]

\[ Nu = 42 \]

The advantage for flow outside the tubes is about a 3-fold increase in film coefficient.

(b) If the velocity in the tubes was high enough to ensure turbulent flow, the difference in film coefficients would be reduced, but not by enough to favor internal flow.