Example 6.1. Double Pipe Benzene-Toluene Exchanger. It is desired to heat 9820 lb/hr of cold benzene from 80 to 120°F using hot toluene which is cooled from 160 to 100°F. The specific gravities at 68°F are 0.88 and 0.87, respectively. The other fluid properties will be found in the Appendix. A fouling factor of 0.001 should be provided for each stream, and the allowable pressure drop on each stream is 10.0 psi.

A number of 20-ft hairpins of 2- by 1¼-in. IPS pipe are available. How many hairpins are required?

Solution:

(1) Heat balance:

$$\text{Benzene, } t_{av} = \frac{80 + 120}{2} = 100°\text{F} \qquad c = 0.425 \text{ Btu/(lb)(°F)} \qquad \text{(Fig. 2)}$$

$$Q = 9820 \times 0.425(120 - 80) = 167{,}000 \text{ Btu/hr}$$

$$\text{Toluene, } T_{av} = \frac{160 + 100}{2} = 130°\text{F} \qquad c = 0.44 \text{ Btu/(lb)(°F)} \qquad \text{(Fig. 2)}$$

$$W = \frac{167{,}000}{0.44(160 - 100)} = 6330 \text{ lb/hr}$$

(2) LMTD, (see the method of Chap. 3):

Hot fluid		Cold fluid	Diff.	
160	Higher temp	120	40	Δt_2
100	Lower temp	80	20	Δt_1
			20	$\Delta t_2 - \Delta t_1$

$$\text{LMTD} = \frac{\Delta t_2 - \Delta t_1}{2.3 \log \Delta t_2/\Delta t_1} = \frac{20}{2.3 \log 40/20} = 28.8°\text{F} \qquad (5.14)$$

(3) Caloric temperatures: A check of both streams will show that neither is viscous at the cold terminal (the viscosities less than 1 centipoise) and the temperature ranges and temperature difference are moderate. The coefficients may accordingly be evaluated from properties at the arithmetic mean, and the value of $(\mu/\mu_w)^{0.14}$ may be assumed equal to 1.0.

$$T_{av} = \tfrac{1}{2}(160 + 100) = 130°\text{F} \qquad t_{av} = \tfrac{1}{2}(120 + 80) = 100°\text{F}$$

Proceed now to the inner pipe. A check of Table 6.2 indicates that the flow area of the inner pipe is greater than that of the annulus. Place the larger stream, benzene in the inner pipe.

Hot fluid: annulus, toluene

(4′) Flow area,

$D_2 = 2.067/12 = 0.1725$ ft

$D_1 = 1.66/12 = 0.138$ ft

$a_a = \pi(D_2^2 - D_1^2)/4$

$= \pi(0.1725^2 - 0.138^2)/4 = 0.00826$ ft²

Equiv diam, $D_e = (D_2^2 - D_1^2)/D_1$ ft [Eq (6.3)]

$D_e = (0.1725^2 - 0.138^2)/0.138$

$= 0.0762$ ft

Cold fluid: inner pipe, benzene

(4) $D = 1.38/12 = 0.115$ ft

Flow area, $a_p = \pi D^2/4$

$= \pi \times 0.115^2/4 = 0.0104$ ft²

Hot fluid: annulus, toluene

(5′) Mass vel, $G_a = W/a_a$

$= 6330/0.00826 = 767{,}000$ lb/(hr)(ft²)

(6′) At 130°F, $\mu = 0.41$ cp [Fig. 14]

$= 0.41 \times 2.42 = 0.99$ lb/(ft)(hr)

Reynolds no., $Re_a = \dfrac{D_e G_a}{\mu}$

$= 0.0762 \times 767{,}000/0.99 = 59{,}000$

(7′) $j_H = 167$ [Fig. 24]

(8′) At 130°F, $c = 0.44$ Btu/(lb)(°F) [Fig. 2]

$k = 0.085$ Btu/(hr)(ft²)(°F/ft) [Table 4]

$$\left(\frac{c\mu}{k}\right)^{1/3} = \left(\frac{0.44 \times 0.99}{0.085}\right)^{1/3} = 1.725$$

(9′) $h_o = j_H \dfrac{k}{D_e}\left(\dfrac{c\mu}{k}\right)^{1/3}\left(\dfrac{\mu}{\mu_w}\right)^{0.14}$ [Eq. (6.15*b*)]

$$= 167 \times \frac{0.085}{0.0762} \times 1.725 \times 1.0$$

$= 323$ Btu/(hr)(ft²)(°F)

Cold fluid: inner pipe, benzene

(5) Mass vel, $G_p = w/a_p$

$= 9820/0.0104 = 943{,}000$ lb/(hr)(ft²)

(6) At 100°F, $\mu = 0.50$ cp [Fig. 14]

$= 0.50 \times 2.42 = 1.21$ lb/(ft)(hr)

Reynolds no., $Re_p = \dfrac{DG_p}{\mu}$

$= 0.115 \times 943{,}000/1.21 = 89{,}500$

(7) $j_H = 236$ [Fig. 24]

(8) At 100°F, $c = 0.425$ Btu/(lb)(°F) [Fig. 2]

$k = 0.091$ Btu/(hr)(ft²)(°F/ft) [Table 4]

$$\left(\frac{c\mu}{k}\right)^{1/3} = \left(\frac{0.425 \times 1.21}{0.091}\right)^{1/3} = 1.78$$

(9) $h_i = j_H \dfrac{k}{D}\left(\dfrac{c\mu}{k}\right)^{1/3}\left(\dfrac{\mu}{\mu_w}\right)^{0.14}$ [Eq. (6.15*a*)]

$$= 236 \times \frac{0.091}{0.115} \times 1.78 \times 1.0$$

$= 333$ Btu/(hr)(ft²)(°F)

(10) Correct h_i to the surface at the *OD*

$h_{io} = h_i \times \dfrac{\text{ID}}{\text{OD}}$ [Eq. (6.5)]

$$= 333 \times \frac{1.38}{1.66} = 276$$

Now proceed to the annulus.

(11) Clean overall coefficient, U_C:

$$U_C = \frac{h_{io}h_o}{h_{io} + h_o} = \frac{276 \times 323}{276 + 323} = 149 \text{ Btu/(hr)(ft}^2\text{)(°F)} \tag{6.7}$$

(12) Design overall coefficient, U_D:

$$\frac{1}{U_D} = \frac{1}{U_C} + R_d \tag{6.10}$$

$R_d = 0.002$ (required by problem)

$$\frac{1}{U_D} = \frac{1}{149} + 0.002$$

$U_D = 115$ Btu/(hr)(ft²)(°F)

Summary

323	*h* outside	276
U_C	149	
U_D	115	

(13) Required surface:

$$Q = U_D A\,\Delta t \qquad A = \frac{Q}{U_D\,\Delta t}$$

$$\text{Surface} = \frac{167{,}000}{115 \times 28.8} = 50.5 \text{ ft}^2$$

From Table 11 for 1¼-in. IPS standard pipe there are 0.435 ft² of external surface per foot length.

$$\text{Required length} = \frac{50.5}{0.435} = 116 \text{ lin ft}$$

This may be fulfilled by connecting three 20-ft hairpins in series.

(14) The surface supplied will actually be $120 \times 0.435 = 52.2$ ft². The dirt factor will accordingly be greater than required. The actual design coefficient is

$$U_D = \frac{167{,}000}{52.2 \times 28.8} = 111 \text{ Btu/(hr)(ft}^2\text{)(°F)}$$

$$R_d = \frac{U_C - U_D}{U_C U_D} = \frac{149 - 111}{149 \times 111} = 0.0023 \text{ (hr)(ft}^2\text{)(°F)/Btu} \qquad (6.13)$$

Pressure Drop

(1′) D'_e for pressure drop differs from D_e for heat transfer.

$$D'_e = (D_2 - D_1) \qquad \text{[Eq. (6.4)]}$$
$$= (0.1725 - 0.138) = 0.0345 \text{ ft}$$

$$Re'_a = \frac{D'_e G_a}{\mu}$$
$$= 0.0345 \times 767{,}000/0.99 = 26{,}800$$

$$f = 0.0035 + \frac{0.264}{26{,}800^{0.42}} = 0.0071 \qquad \text{[Eq. (3.47b)]}$$

$s = 0.87$, $\rho = 62.5 \times 0.87 = 54.3$ [Table 6]

(2′) $$\Delta F_a = \frac{4fG_a^2L}{2g\rho^2D'_e}$$
$$= \frac{4 \times 0.0071 \times 767{,}000^2 \times 120}{2 \times 4.18 \times 10^8 \times 54.3^2 \times 0.0345}$$
$$= 23.5 \text{ ft}$$

(3′) $$V = \frac{G}{3600\rho} = \frac{767{,}000}{3600 \times 54.3} = 3.92 \text{ fps}$$

$$F_l = 3\left(\frac{V^2}{2g'}\right) = 3 \times \frac{3.92^2}{2 \times 32.2} = 0.7 \text{ ft}$$

$$\Delta P_a = \frac{(23.5 + 0.7)54.3}{144} = 9.2 \text{ psi}$$

Allowable $\Delta P_a = 10.0$ psi

(1) For $Re_p = 89{,}500$ in (6) above

$$f = 0.0035 + \frac{0.264}{(DG/\mu)^{0.42}} \qquad \text{[Eq. (3.47b)]}$$
$$= 0.0035 + \frac{0.264}{89{,}500^{0.42}} = 0.0057$$

$s = 0.88$, $\rho = 62.5 \times 0.88 = 55.0$ [Table 6]

(2) $$\Delta F_p = \frac{4fG_p^2L}{2g\rho^2D}$$
$$= \frac{4 \times 0.0057 \times 943{,}000^2 \times 120}{2 \times 4.18 \times 10^8 \times 55.0^2 \times 0.115}$$
$$= 8.3 \text{ ft}$$

$$\Delta P_p = \frac{8.3 \times 55.0}{144} = 3.2 \text{ psi}$$

Allowable $\Delta P_p = 10.0$ psi

A check of U_h and U_c gives 161 and 138, respectively, and $K_c = 0.17$. From Fig. 17 for $\Delta t_c/\Delta t_h = {}^{20}\!/_{40} = 0.5$, $F_c = 0.43$, whereas in the solution above the arithmetic mean temperatures were used. The arithmetic mean assumes $F_c = 0.50$. However, since the ranges are small for both fluids, the error is too small to be significant. If the ranges of the fluids or their viscosities were large, the error might be considerable for $F_c = 0.43$.

Example 11.3. Calculation of a Caustic Solution Cooler. 100,000 lb/hr of 15°Bé caustic solution (11 per cent sodium hydroxide, $s = 1.115$) leaves a dissolver at 190°F and is to be cooled to 120°F using water at 80°F. Use a combined dirt factor of 0.002 and pressure drops of 10 psi.

The viscosity of the 11 per cent sodium hydroxide may be approximated by the methods of Chap. 7, but is sirupy, and actual data should be used if possible. The viscosity at 100°F is 1.4 centipoises and at 210°F is 0.43 centipoises. For the specific heat assume the dry salt to have a value of 0.25 Btu/lb, giving a specific heat for the solution at the mean of 0.88.

Plant practice permits the use of triangular pitch with 1 in. OD tubes for solutions in which the scale may be boiled out.

Solution:

(1) Heat balance:

Caustic, $Q = 100{,}000 \times 0.88(190 - 120) = 6{,}160{,}000$ Btu/hr

Water, $Q = 154{,}000 \times 1(120 - 80) = 6{,}160{,}000$ Btu/hr

[1] An eight-pass exchanger would give a pressure drop of 10.8 psi.

(2) Δt:

Hot Fluid		Cold Fluid	Diff.
190	Higher Temp	120	70
120	Lower Temp	80	40
70	Differences	40	30

LMTD = 53.3°F　　Eq. (5.14)

$$R = \frac{70}{40} = 1.75 \qquad S = \frac{40}{190 - 80} = 0.364$$

$F_T = 0.815$　　(Fig. 18)

A 1-2 exchanger will be satisfactory.

$\Delta t = 0.815 \times 53.3 = 43.5$°F　　Eq. (7.42)

(3) T_c and t_c: The average temperatures T_a and t_a will be satisfactory because of the closeness of the ranges and the low viscosities.

Trial:

(*a*) Assume $U_D = 250$. From Table 8 this value is about the minimum for a 0.001 dirt factor and should be suitable for a trial when the required dirt factor is 0.0020.

$$A = \frac{6{,}160{,}000}{250 \times 43.5} = 567 \text{ ft}^2$$

$a'' = 0.2618$ ft²/lin ft (Table 10)

$$\text{Number of tubes, } N_t = \frac{567}{16'0'' \times 0.2618} = 136$$

(*b*) Assume four tube passes: For two tube passes $a_t = 0.258$ and $G_t = 598{,}000$ corresponding to a water velocity of only 2.65 fps.

From the tube counts (Table 9): 136 tubes, 4 passes, 1 in. OD on 1¼-in. triangular pitch

Nearest count: 140 tubes in a 19¼″ ID shell

(*c*) Corrected coefficient U_D:

$A = 140 \times 16'0'' \times 0.2618 = 586$ ft²

$$U_D = \frac{Q}{A\,\Delta t} = \frac{6{,}160{,}000}{586 \times 43.5} = 242$$

Hot fluid: shell side, caustic

(5′) $G_s = W/a_s$ [Eq. (7.2)]

$= 100{,}000/0.1875$

$= 533{,}000$ lb/(hr)(ft²)

(6′) At $T_a = 155°$F,

$\mu = 0.76 \times 2.42 = 1.84$ lb/(ft)(hr)

$D_e = 0.72/12 = 0.06$ ft [Fig. 28]

$Re_s = D_e G_s/\mu$ [Eq. (7.3)]

$= 0.06 \times 533{,}000/1.84 = 17{,}400$

(7′) $j_H = 75$ [Fig. 28]

(8′) At 155°F, $k = 0.9$ (k_{water}) [Table 4]

$= 0.9 \times 0.38$

$= 0.342$ Btu/(hr)(ft²)(°F/ft)

$(c\mu/k)^{1/3} = (0.88 \times 1.84/0.342)^{1/3} = 1.68$

(9′) $h_o = j_H \dfrac{k}{D_e}\left(\dfrac{c\mu}{k}\right)^{1/3} \phi_s$ [Eq. (6.15*b*)]

$\dfrac{h_o}{\phi_s} = 75 \times 0.342 \times 1.68/0.06 = 717$

Cold fluid: tube side, water

(5) $G_t = w/a_t$

$= 154{,}000/0.133$

$= 1{,}160{,}000$ lb/(hr)(ft²)

Vel, $V = G_t/3600\rho$

$= 1{,}160{,}000/3600 \times 62.5 = 5.16$ fps

(6) At $t_a = 100°$F,

$\mu = 0.72 \times 2.42 = 1.74$ lb/(ft)(hr) [Fig. 14]

$D = 0.834/12 = 0.0695$ ft [Table 10]

(Re_t is for pressure drop only)

$Re_t = DG_t/\mu$

$= 0.0695 \times 1{,}160{,}000/1.74 = 46{,}300$

(9) $h_i = 1240 \times 0.94 = 1165$ [Fig. 25]

(10) $h_{io} = h_i \times \text{ID/OD}$ [Eq. (6.5)]

$= 1165 \times 0.834/1.0$

$= 972$ Btu/(hr)(ft²)(°F)

(10′) (11′) (12′) $\phi_s = 1$ (low viscosity)

$h_o = \frac{h_o}{\phi_s} = 717$ Btu/(hr)(ft²)(°F)

Pressure Drop

(1′) For $Re_s = 17{,}400$,
$f = 0.0019$ ft²/in.² [Fig. 29]

(2′) No. of crosses, $N + 1 = 12L/B$ [Eq. (7.43)]

$= 12 \times 16/7 = 28$

$D_s = 19.25/12 = 1.60$ ft

(3′) $$\Delta P_s = \frac{fG_s^2 D_s(N+1)}{5.22 \times 10^{10} D_e s \phi_s} \quad \text{[Eq. (7.44)]}$$

$$= \frac{0.0019 \times 533{,}000^2 \times 1.60 \times 28}{5.22 \times 10^{10} \times 0.06 \times 1.115 \times 1.0} = 7.0 \text{ psi}$$

(1) For $Re_t = 46{,}300$,
$f = 0.00018$ ft²/in.² [Fig. 26]

(2) $$\Delta P_t = \frac{fG_t^2 Ln}{5.22 \times 10^{10} D s \phi_t} \quad \text{[Eq. (7.45)]}$$

$$= \frac{0.00018 \times 1{,}160{,}000^2 \times 16 \times 4}{5.22 \times 10^{10} \times 0.0695 \times 1.0 \times 1.0} = 4.3 \text{ psi} \quad \text{[Eq. (7.46)]}$$

(3) $$\Delta P_r = \frac{4n}{s}\frac{V^2}{2g'} \quad \text{[Fig. 27]}$$

$$= \frac{4 \times 4}{1} \times 0.18 = 2.9 \text{ psi}$$

(4) $$\Delta P_T = \Delta P_t + \Delta P_r \quad \text{[Eq. (7.47)]}$$

$$= 4.3 + 2.9 = 7.2 \text{ psi}$$

Now proceed to the shell side.

(13) Clean overall coefficient U_C:

$$U_C = \frac{h_{io}h_o}{h_{io} + h_o} = \frac{972 \times 717}{972 + 717} = 413 \text{ Btu/(hr)(ft}^2\text{)(°F)} \quad (6.38)$$

(14) Dirt factor R_d: U_D from (c) is 242.

$$R_d = \frac{U_C - U_D}{U_C U_D} = \frac{413 - 242}{413 \times 242} = 0.0017 \text{ (hr)(ft}^2\text{)(°F)/Btu} \quad (6.13)$$

Summary

717	h outside	972
U_C	413	
U_D	242	
R_d Calculated	0.0017	
R_d Required	0.0020	
7.0	Calculated ΔP	7.2
10.0	Allowable ΔP	10.0

Discussion. Adjustment of the baffle space to use the full 10 psi will still not permit the exchanger to make the 0.002 dirt factor. The value of U_D has been assumed too high. Try the next size shell.

Trial 2:

Try a $21\frac{1}{4}$ in. ID shell with four tube passes and a 6-in. baffle space. This corresponds to 170 tubes.

Summary

720	h outside	840
U_C	390	
U_D	200	
R_d Calculated 0.0024		
R_d Required 0.002		
9.8	Calculated ΔP	4.9
10.0	Allowable ΔP	10.0

The use of six tube passes exceeds the allowable tube side pressure drop.
The final exchanger will be

Shell side	*Tube side*
ID = $21\frac{1}{4}$ in.	Number and length = 170, 16′0″
Baffle space = 6 in.	OD, BWG, pitch = 1 in., 14 BWG, $1\frac{1}{4}$-in. tri.
Passes = 1	Passes = 4