1) Check the heat balance

Benzene, $t_{avg} = \frac{5}{9}(80°F - 32) + \frac{5}{9}(120°F - 32)/2$

$= 26.6667 + 48.8889/2 = 37.7778\ °C$

$C = 0.425 \frac{Btu}{lb_m °F} * \left(\frac{4.1869 \frac{kJ}{kg°C}}{1 \frac{Btu}{lb_m °F}} \right) = 1.779432 \frac{kJ}{kg°C}$

$q = 5130 * 1.7794 * (48.8889 - 26.6667)$

$= 202851.39 \frac{kJ}{hr}$

Toluene, $T_{avg} = \frac{5}{9}(160°F - 32) + \frac{5}{9}(100°F - 32)/2$

$= 71.1111 + 37.7778/2 = 54.4444\ °C$

$C = 0.44 \frac{Btu}{lb_m °F} * \left(\frac{4.1869 \frac{kJ}{kg°C}}{1 \frac{Btu}{lb_m °F}} \right) = 1.8422 \frac{kJ}{kg°C}$

$W = \frac{202851.39}{1.8422(71.1111 - 37.7778)} = 3303.41 \frac{kg}{hr}$

2) Calculate LMTD

Hot fluid		Cold fluid	Diff	
71.11	High temp	48.8889	22.2222	Δt_2
37.7778	Lower temp	26.6667	11.1111	Δt_1
			11.1111	$\Delta t_2 - \Delta t_1$

$$LMTD = (\Delta t_2 - \Delta t_1)/\ln(\Delta t_2/\Delta t_1)$$

$$= (22.2222 - 11.1111)/\ln\left(\frac{22.2222}{11.1111}\right) = 16.0299^{\circ}C$$

3) The viscosities of both streams at the cold terminal are less than 1cP and the temp ranges and temp diff are moderate. The coefficient may accordingly be evaluated from properties at the arithmetic mean & the value $(\mu/\mu_w)^{0.4}$ may be assumed equal to unity.

The hot fluid is placed in the tube side in order to minimize the heat losses to the environment which are of course dependent on the temp gradient.

Hot fluid : annulus toluene | Cold fluid : inner pipe Benzene

(4') Flow area

$D_2 = 3.068/12 = 0.2557\ ft \left(\frac{0.3048m}{1\ ft}\right)$

$= 0.0779\ m$

$D_1 = 2.38/12 = 0.1983\ ft \left(\frac{0.3048m}{1\ ft}\right)$

$= 0.0604\ m$

$a_a = \frac{\pi}{4}(D_2^2 - D_1^2) = \frac{\pi}{4}(0.0779^2 - 0.0604^2)$

$= 1.9008 * 10^{-3}\ m^2$

(4) Flow area

$D = 2.067/12 = 0.1725\ ft \left(\frac{0.3048m}{1\ ft}\right)$

$= 0.05258\ m$

$a_p = \frac{\pi D^2}{4}$

$= \frac{\pi(0.05258)^2}{4}$

$= 2.17135 * 10^{-3}\ m^2$

Fluids flowing in annuli

Its convenient to express heat transfer coefficient & friction factors by the same type of eqns & curves used for pipes & tubes. To permit this type of representation for annulus heat transfer, it has been advantageous to employ an equivalent diameter, D_e.

$D_e = (D_2^2 - D_1^2)/D_1 = 0.04007 m$

(5') Mass Vel

$G_a = W/a_a$

$= 3308.41/1.9008 \times 10^{-3}$

$= 1737905.095 \frac{kg}{hr\,m^2}$

(6') At 54.4444 °c, $\mu = 0.45 cP$

$= 0.45 \times 2.42 = 1.089 \; lb/ft \cdot hr$

$\times \left(\frac{1 kg/m.s}{2419.2 \frac{lb_m}{ft.hr}} \right) = 4.50148 \times 10^{-4} \frac{kg}{m.s}$

Reynolds no. $Re_a = (D_e G_a)/\mu$

$= \frac{(0.04007 \times 1737905.095)}{4.50148 \times 10^{-4} \times \left(\frac{1 s}{\frac{1}{3600} hr}\right)}$

$= 42972.19845$

3600 s/hr

(5) Mass Vel

$G_p = W/a_p$

$= 5130 / 2.17135 \times 10^{-3}$

$= 2362585.488 \frac{kg}{hr.m}$

(6) At 37.7778 °c, $\mu = 0.53$

$= 0.53 \times 2.42 = 1.2826 \frac{lb}{ft.h}$

$\times \left(\frac{1 kg/m.s}{2419.2 \frac{lb_m}{ft.hr}} \right)$

$= 5.3017 \times 10^{-4} \frac{kg}{m.s}$

Reynolds no. $Re_p = \frac{DG_p}{\mu}$

$= \frac{(0.05258 \times 2362585.488)}{5.3017 \times 10^{-4} \times \left(\frac{1 s}{\frac{1}{3600} hr}\right)}$

$= 65086.4319$

(7)' $j_H = 180$

(8)' At 54.4444°C, $C = 1.842 \frac{kJ}{kg°C}$

$k = 0.085 \frac{Btu}{hr\,ft^2)(°F/ft)} \left(\frac{1.7307 \frac{W}{m°C}}{1\ Btu/h \cdot ft \cdot °F} \right)$

$= 0.1471095 \frac{W}{m°C}$

$\left(\frac{C\mu}{k}\right)^{1/3} = \left(\frac{1.8422 \times 10^3 \times 4.50148 \times 10^{-4}}{0.1471095}\right)^{1/3}$

$= 1.7797$

(9)' $h_o = j_H \frac{k}{D_e} \left(\frac{C\mu}{k}\right)^{1/3} \left(\frac{\mu}{\mu_w}\right)^{0.14}$

$= 180 \times \frac{0.1471095}{0.04007} \times 1.7797 \times 1.0$

$= 849.398 \frac{W}{m^2 °C}$

(11) Clean overall Coefficient, U_C:

$U_C = \frac{h_{io} h_o}{h_{io} + h_o}$

$= \frac{991.4738 \times 849.398}{991.4738 + 849.398}$

$= 457.4766 \frac{W}{m^2 °C}$

(12) Design overall coefficient, U_D

$\frac{1}{U_D} = \frac{1}{U_c} + R_d$

$R_d = 0.002$

(7) $j_H = 210$

(8) At 57.7778°C, $C = 1.7791 \frac{kJ}{kg°C}$

$k = 0.091 \frac{Btu}{hr \cdot ft \cdot °F} \times \left(\frac{1.7307 \frac{W}{m°C}}{\frac{1\ Btu}{h \cdot ft \cdot °F}} \right)$

$= 0.1574 \frac{W}{m°C}$

$\left(\frac{C\mu}{k}\right)^{1/3}$

$= \left(\frac{1.7791 \times 10^3 \times 5.3017 \times 10^{-4}}{0.1574}\right)^{1/3}$

$= 1.816$

(9) $h_i = j_H \frac{k}{D} \left(\frac{C\mu}{k}\right)^{1/3} \left(\frac{\mu}{\mu_w}\right)^{0.14}$

$= 210 \times \frac{0.1574}{0.05258} \times 1.816 \times 1.0$

$= 1141.61 \frac{W}{m^2 °C}$

(10) $h_{io} = h_i \times \frac{ID}{OD}$

$= 1141.61 \times \frac{2.067}{2.38}$

$= 991.4738 \frac{W}{m^2 °C}$

Now Proceed to the column

$$\frac{1}{U_D} = \frac{1}{457.4766} + 0.002$$

$= 238.897 \frac{W}{m^2\,^\circ C}$

(13) Required surface

$q = U_D A \Delta t \qquad A = \frac{q}{U_D \Delta t}$

$$\text{Surface} = \frac{202851.39 \times 10^3 \left(\frac{J}{hr}\right) * \left(\frac{1\,hr}{3600\,s}\right)}{238.897 \left(\frac{J}{s\,m^2\,^\circ C}\right) * 16.02992 (^\circ C)}$$

$= 14.71409\ m^2$

From table 11 for 2 in IPS Standard Pipe there are 0.622 ft^2 of external surface per foot length

$$\text{Required length} = \frac{14.71409}{0.0604 * \pi} = 77.543 \text{ lin m}$$

15   2.7432 m

This may be filled by connecting
9 ft = 2.7432 m
hairpins in series

14) The surface applied will actually be 2.7432 $* 30 * \pi * 0.0604 = 15.6158\ m^2$. The dirt factor will accordingly be greater than required.
The actual design coefficient is:

$$U_D = \frac{202851.39 \times 10^3 * \frac{1}{3600}\left(\frac{J}{s}\right)}{15.6158 (m^2) * 16.02992 (^\circ C)} = 225.10 \frac{J}{s\,m^2\,^\circ C}$$

$$R_d = \frac{U_c - U_D}{U_c U_D} = \frac{457.4766 - 225.1022}{457.4766 * 225.1022}$$

$= 0.00225$ (s) (m²) (°C) / J

Pressure Drop

(1') D_e' for pressure drop differs from D_e for heat transfer

$D_e' = (D_2 - D_1)$

$= (0.0779 - 0.0604)$

$= 0.0175$ m

$$Re_a' = \frac{D_e' G_a}{\mu}$$

$$= \frac{0.0175 \times 1737905.093}{4.50148 \times 10^{-4} \times 3600}$$

$= 18767.49$

$$f = 0.0035 + \frac{0.264}{18767.49^{0.42}}$$

$= 0.00773$

$\rho = s *$

$s = 0.87$ $998 = 868.26 \ \frac{kg}{m^3}$

For Pressure drop in the annulus side

$$\Delta F_a = \frac{4 f G_a^2 L}{2 g \rho^2 D_e'}$$

$g = 9.81456 \ \frac{m}{s^2} = 127196698$ m

(1) For $Re_p = 65086.431$

$$f = 0.0035 + \frac{0.264}{(DG/\mu)^{0.42}}$$

$$= 0.0035 + \frac{0.264}{65086.431^{0.42}}$$

$= 0.00601$

$s = 0.88$, $\rho = 998 * 0.88$

$= 878.24 \ \frac{kg}{m^3}$

(2) $\Delta F_p = \frac{4 f G_p^2 L}{2 g \rho^2 D}$

$$= \frac{(4 * 0.00601 * 6258.488^{2} * 2.7432 * 36)}{2 * 127196698 * 878.24^2 * 0.0525}$$

$= 1.07037$ m

$= 1.$ ~~07037~~ psi ~~522~~

$$\Delta F_a = \frac{4 * 0.00773 * 17379005.093^2 * (2.7432 \times 30)}{2 * 127196698 * 868.26^2 * 0.0175}$$

$$= 2.2899\,m = 3.256\ \text{PSI}$$