# Calculation sheet for rating shell and tube heat exchangers

| No | Symbol | Description | Source | Value | Units |
|---|---|---|---|---|---|
| 51 | $D_{otl}$ | diameter passing through the outer tubes | $D_s$-$L_{bb}$<br>$\langle 1\rangle - \langle 21\rangle$ |  | m |
| 52 | $D_{ctl}$ | Diameter passing through center of tubes | $D_{otl}$-$d_o$<br>$\langle 51\rangle - \langle 2\rangle$ |  | m |
| 53 | $N_{tt}$ | Number of tubes | Input data table item # 15 or see note on Item #53 & Fig. R1 |  | -- |
| 54 | $S_m$ | Cross flow area at shell center line | See notes on item # 54 & Eq. (2) |  | $m^2$ |
| 55 | $G_s$ | Maximum shell side mass velocity | $\dot{m}_s/S_m$ |  | kg/($m^2$.s) |
| 56 | $\mathrm{Re}_s$ | Shell side Reynolds number | $G_s d_o/\mu_s$ |  | - |
| 57 | $\Delta T_1$ | Temperature difference, | see note on item #57 & Fig. R2 |  | ° C |
| 58 | $\Delta T_2$ | Temperature difference | see note on item #58 & Fig. R2 |  | ° C |
| 59 | $\Delta T_{LM,CF}$ | Log mean temperature difference for counter flow arrangement | $\dfrac{\Delta T_1 - \Delta T_2}{ln\,(\Delta T_1/\Delta T_2)}$ |  | ° C |
| 60 | $F$ | Temperature correction factor | See notes on item #60 |  | - |
| 61 | $\Delta T_{LM}$ | Mean temperature difference | $\Delta T_{LM,CF}F$ |  | ° C |
| 62 | $A_o$ | Heat transfer area based on shell side | $\pi d_o L_{ta} N_{tt}$ |  | $m^2$ |
| 63 | $\theta_{ds}$ | Angle intersecting the inside shell wall with baffle edge | $2\cos^{-1}[1 - 2\,B_c/100] = 2\cos^{-1}[1 - 2\langle 11\rangle/100]$<br>See note on Items 63-67 |  | deg. |
| 64 | $\theta_{ctl}$ | Angle intersecting the centers of the outmost tubes with baffle edge | $2\cos^{-1}\{(D_s/D_{ctl})[1 - 2\,B_c/100]\}$<br>See note on Items 63-67 |  | deg. |
| 65 | $\theta_{otl}$ | Angle intersecting the outer surface of the outmost tubes with baffle edge, | $2\cos^{-1}\{(D_s/D_{otl})[1 - 2(B_c/100)]\}$<br>See note on Items 63-67 |  | deg. |
| 66 | $S_{wg}$ | Gross window flow area, See note on item 63-67 | $(\pi/4)(D_s^2)[(\theta_{ds}/360) - \sin\,(\theta_{ds})/2\pi]$ |  | $m^2$ |
| 67 | $F_w$ | Fraction of number of tubes in one window | $(\theta_{ctl}/360) - \sin\,(\theta_{ctl})/2\pi$ |  | - |
| 68 | $F_c$ | Fraction of tubes in pure cross flow | $1 - 2F_w$ |  | - |
| 69 | $S_{wt}$ | Area occupied by tubes in the window | $N_{tt}F_w\,(\pi/4)\,d_o^2$ |  | $m^2$ |
| 70 | $S_w$ | Cross flow area through one baffle windows | $S_{wg} - S_{wt}$ |  | $m^2$ |
| 71 | $L_{pp}$ | Layout geometry length, See note on item # 72 | See input data sheet & notes on item 72 |  | m |
| 72 | $N_{tcc}$ | Number of effective rows crossed in one cross flow section between baffle tips | $(D_s/L_{pp})[1 - 2(B_c/100)]$ |  | - |
| 73 | $N_{tcw}$ | Effective number of rows crossed in baffle window | $(0.8/L_{pp})\,[D_S(B_c/100) - (D_s - D_{ctl})/2]$ |  | - |
| 74 | $N_b$ | Number of baffles | $(L_{ti}/L_{bc} - 1)$ |  | - |
| 75 | $L_{pl}$ | A dimension to express the effect the tube lane partition | 0 or $L_p/2$ See the input data sheet |  | m |
| 76 | $S_b$ | Shell to bundle by pass area | $L_{bc}\big[(D_s - D_{otl}) + N_{tp} * L_{pl}\,\big]$ |  | $m^2$ |
| 77 | $F_{spb}$ | Ratio of $S_b$ to $S_m$ | $S_b/S_m$ |  |  |
| 78 | $L_{sb}$ | Clearance between shell and baffle (Dimeteral) | Data or $L_{sb} = 3.1 + 0.004D_s\ \ in\ mm$ |  | m |
| 79 | $S_{sb}$ | Shell to baffle leakage area | $\pi D_s(L_{sb}/2)[(360 - \theta_{ds})/360]$ |  | $m^2$ |
| 80 | $S_{tb}$ | Tube to baffle leakage area | $(\pi/4)[(d_o + L_{tb})^2 - d_o^2]N_{tt}(1 - F_w)$ |  | $m^2$ |
| 81 | $J_c$ | Segmental baffle window correction factor | $0.55 + 0.72F_c$ |  | - |
|  |  |  |  |  |  |
|  |  |  |  |  |  |

| No | Symbol | Description | Source | Value | Units |
|---|---|---|---|---|---|
| 82 | $r_{lm}$ | Parameter for finding the leakage correction factor | $(S_{sb}+S_{tb})/S_m$ | | - |
| 83 | $r_s$ | Parameter for finding the leakage correction factor | $S_{sb}/(S_{sb}+S_{tb})$ | | - |
| 84 | $J_l$ | Heat transfer correction factor due to leakage , see Note on item 85 | See Eq. (10) & Fig. R3 | | - |
| 85 | $R_l$ | Pressure drop correction factor due to leakage, see notes on item # 86 | See Eq. (11) & Fig. R4 | | - |
| 86 | $r_{ss}$ | Sealing strips factor | $N_{ss}/N_{tcc}$ | | - |
| 87 | $J_b$ | Heat transfer correction factor due to shell to bundle by pass | Eq. (12) & Fig. R5<br>See Notes on item 87 | | - |
| 88 | $R_b$ | Pressure drop correction factor due to shell to bundle by pass | Eq. (13) & Fig. R6<br>See notes on item 88 | | - |
| 89 | $N_c$ | Total number of tube rows crossed | $(N_{tcc}+N_{tcw})*(N_b-1)$ | | - |
| 90 | $J_r$ | Heat transfer correction factor due adverse temperature gradient in laminar flow | See Eq. (14-16) and Fig. R7 | | - |
| 91 | $L_i^*$ | Dimensionless inlet baffle spacing | $L_{bi}/L_{bc}$ | | - |
| 92 | $L_o^*$ | Dimensionless outlet baffle spacing | $L_{bo}/L_{bc}$ | | - |
| 93 | $J_s$ | Heat transfer correction factor due to unequal inlet and outlet baffle spacing | Eq. (17) & Fig. R8<br>See notes on item 93 | | - |
| 94 | $R_s$ | Pressure drop correction factor due to unequal inlet and outlet baffle spacing | See notes on item 94 | | - |
| 95 | $\phi_s^r$ | Shell side viscosity effect correction factor | See notes on item 95 | | |
| 96 | $j_i$ | Ideal tube bank heat transfer *j* factor | Eq. (23-24) & Fig. (R9) & table R1 | | - |
| 97 | $f_i$ | Ideal tube bank *f* pressure friction factor | Eq. (25-26) & Fig. (R9) & table R1 | | - |
| 98 | $h_i$ | Ideal heat transfer coefficient | $j_i C_{ps} G_s P_r^{-2/3} \phi_s^r$ | | $W/(m^2.K)$ |
| 99 | $J_{tot}$ | Total heat transfer correction factor | $J_c J_l J_b J_r J_s$ | | |
| 100 | $h_s$ | Shell side heat transfer coefficient | $h_i\, j_{tot}$ | | $W/(m^2.K)$ |
| **101** | $\Delta p_{bi}$ | Ideal pressure drop for tube bank in one baffle compartment | $4 f_i\, N_{tcc}(G_s^2/2\rho_s)\phi_s^{-r}$ | | $Pa$ |
| 102 | $\Delta p_c$ | Pressure drop in cross flow between baffle tips | $\Delta p_{bi} * (N_b - 1) R_b R_l$ | | $Pa$ |
| 103 | $D_w$ | Window hydraulic diameter | $\dfrac{4S_w}{\pi d_o N_{tw} + \pi D_s\, \theta_{ds}/360}$ | | $m$ |
| **104** | $G_w$ | Window mass flow velocity | $\dot{m}_s/\sqrt{(S_m\, S_w}$ | | $kg/(m^2.s)$ |
| 105 | $\Delta p_w$ | Pressure drop in baffle window, see note on item #105 | Eq. (27-30), & Fig. R10 | | $Pa$ |
| 106 | $\Delta p_e$ | Pressure drop in the two end zones, See note on item #106 | $2\,\Delta p_{bi}(1 + N_{tcw}/N_{tcc}) R_b R_s$ | | $Pa$ |
| 107 | $\Delta p_s$ | Shell side pressure drop. See notes on item # 107 | $\Delta p_c + \Delta p_w + \Delta p_e$ | | $Pa$ |
| 108 | $h_t$ | Tube side heat transfer coefficient | Input sheet estimated or calculated | | $W/(m^2.K)$ |
| 109 | $A_o/A_i$ | Ratio of shell side to tube side heat transfer areas | $d_o/d_i$ ( no fins) | | - |
| 110 | $R_w A_o$ | Wall thermal resistance | $\dfrac{d_o \ln\,(d_o/d_i)}{2k_w}$ | | $m^2K/W$ |
| 111 | $1/U_o$ | Overall thermal resistance for the heat exchanger | $\frac{1}{h_s} + R_{fo} + R_w A_o + R_{fi}\frac{A_o}{A_i} + \frac{A_o/A_i}{h_t}$ | | $m^2K/W$ |
| | $U_o$ | Shell side overall heat transfer coefficient | | | $W/(m^2.K)$ |
| 112 | $\dot{Q}_{act}$ | Actual heat transfer rate | $A_o U_o \Delta T_{LM}$ | | $W$ |
| 113 | $\dot{Q}_{req}$ | Required heat transfer rate | Given or $\dot{m}_s C_{ps}\lvert(T_{si} - T_{so})\rvert$ | | $W$ |
| | | | | | |

**Item # 53**

$$N_{tt} = (N_{tt})_1 = \frac{0.78\, D_{ctl}^2}{C_1\, L_{tp}^2} \tag{1a}$$

C₁=0.866 for $\theta_{tp}$=30° or 1 for $\theta_{tp} = 45°$ or 90°

Correction if some tubes have to be omitted

$$N_{tt} = (N_{tt})_1(1 - \psi_c) \tag{1b}$$

$$\theta_{ctl} = 2\cos^{-1}\left[\frac{D_s}{D_{ctl}}\left(1 - \frac{2B_c^*}{100}\right)\right] \tag{1c}$$

$L_{bch}^*$ is the cut height due tube omission, and related to $B_c^*$ as follows

$$B_c^* = 100\frac{L_{bch}^*}{D_s} \tag{1d}$$

Which is similar to baffle cut

$$\psi_c = \frac{\theta_{ctl}}{360} - \frac{\sin(\theta_{ctl})}{2\pi} \tag{1e}$$

If tube field on both sides of the shell is cut, then use $2\psi_c$.

- Correction for multiple tube passes (i.e. $N_{tp}$>1)

$$N_{tt} = (N_{tt})_1(1 - \psi_n) \tag{1f}$$

$\psi_c$ can be found from the following figure

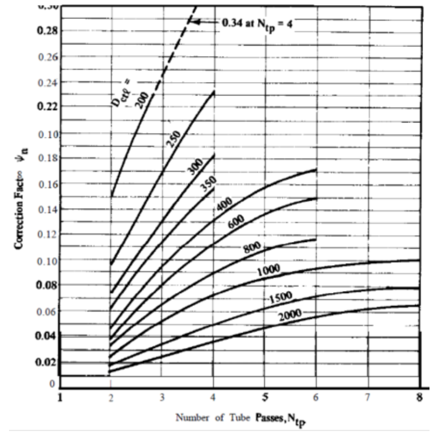


Fig. R-1 Correction factor $\psi_n$ for estimation of number of tubes for tube bundles with number of tube passes $N_{tp}$ = 2-8. Best range of application for $d_o$ = 16-25 mm.

**Item # 54**

$$S_m = L_{bc}\left[L_{bb} + \frac{D_{ctl}}{L_{tp,eff}}(L_{tp} - d_o)\right] \qquad (2)$$

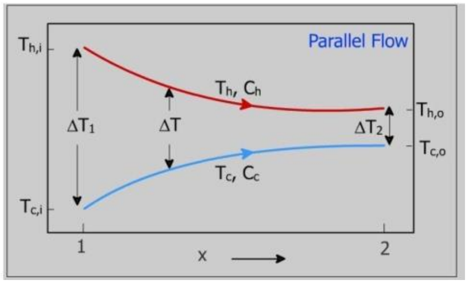
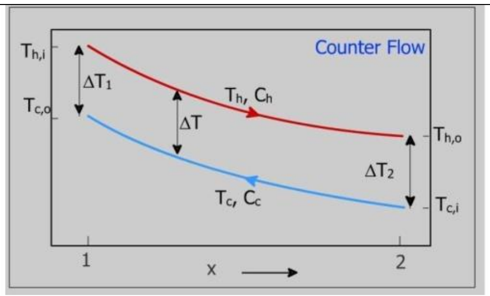
Where

$L_{bb}= D_s-D_{otl}$

$L_{tp,eff} = L_{tp}$ for $\theta_{tp} = 30°$ or $90°$ layout

$L_{tp,eff}=0.707L_{tp}$ for 45° staggered layout

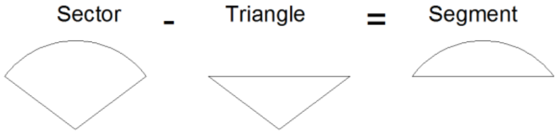
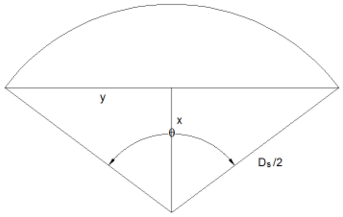
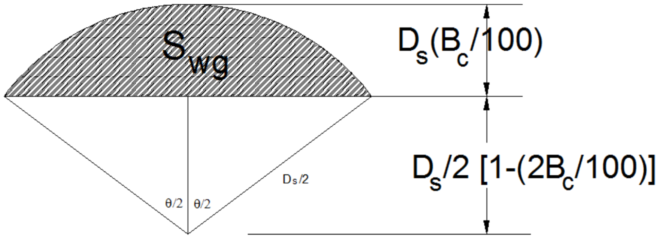
**Item # 57 & 58**

| | |
|---|---|
|  |  |
| Fig. R2a Temperature profile for pure parallel flow arrangement | Fig. R2b Temperature profile for counter low arrangement |

**Item # 60**

F=1 for pure parallel, counter flow HX, and for phase change heat exchangers. F should be around 0.75 to 0.8 or above

**Item # 63 though 67**

| | |
|---|---|
|  <br>Segment area=Sector area-Triangle area |  |
|  | |
| Fig. R2c Baffle window geometry | |

$$\cos\left(\theta_{ds}/2\right) = \frac{(1/2)D_S(1-2B_c/100)}{D_s/2} \tag{3a}$$

$$\theta_{ds} = 2\cos^{-1}(1-2B_c/100) \tag{3b}$$

Similarly one can find expression for $\theta_{ctl}$ and $\theta_{otl}$.

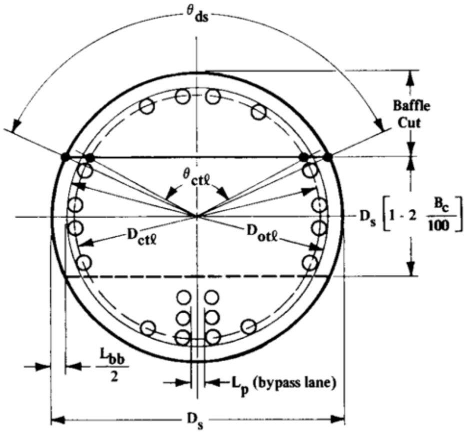


Fig. R2d Basic baffle geometry

$$x = D_s/2\cos(\theta/2) \tag{4a}$$

$$y = D_s/2\sin(\theta/2) \tag{4b}$$

Triangle area

$$2\left[\frac{1}{2}x\,y\right] = 2\left[\frac{1}{2}\frac{D_S}{2}\cos\left(\frac{\theta}{2}\right)*\frac{D_S}{2}\sin\left(\frac{\theta}{2}\right)\right] = \frac{D_S^2}{4}\cos\left(\frac{\theta}{2}\right)*\sin\left(\frac{\theta}{2}\right) = \frac{D_S^2}{4}\frac{1}{2}\sin(\theta) \tag{5}$$

Using

$$\sin(2\alpha) = \sin(\alpha)\cos(\alpha) \tag{6}$$

Segment area

$$S_{wg} = Sector\ area - Triangle\ area \tag{7}$$

$$S_{wg} = \pi\frac{D_S^2}{4}\frac{\theta}{360} - \frac{D_S^2}{4}\frac{1}{2}\sin(\theta) = \pi\frac{D_S^2}{4}\left(\frac{\theta_{ds}}{360} - \frac{\sin(\theta_{ds})}{2\pi}\right) \tag{8}$$

The fraction of tubes in the baffle window is the ratio of the segmented area divide by the cross-section area of the shell i.e.

$$F_w = \frac{\theta_{ctl}}{360} - \frac{\sin(\theta_{ctl})}{2\pi}$$

**Item # 71**

$L_{pp}$ Layout geometry length:

$L_{pp}=0.866L_{tp}$ *for* $\theta_{tp}=30°$

$L_{pp}=L_{tp}$ *for* $\theta_{tp}=90°$

$L_{pp}=0.707L_{tp}$ *for* $\theta_{tp}=45°$

**Item # 75**

$L_{pl}$ =0 or $L_p/2$. $L_p$ can be assumed to be equal to $d_o$

**Item # 76**

Shell to bundle by pass area

According to Shah, Fundamentals of Heat Exchanger Design, Wiley, 2003.

$$S_b = L_{bc}\left[(D_s - D_{otl}) + N_{tp} * L_{pl}\right] \tag{9}$$

Where $N_{tp}$ is the number of tube passes.

**Item #84**

$J_l$: Baffle leakage heat transfer coefficient correction factor

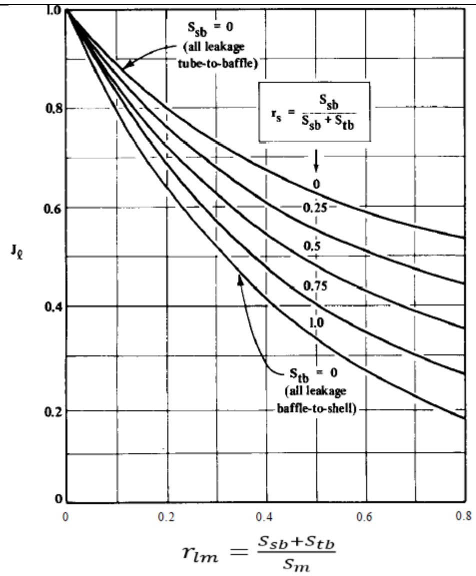
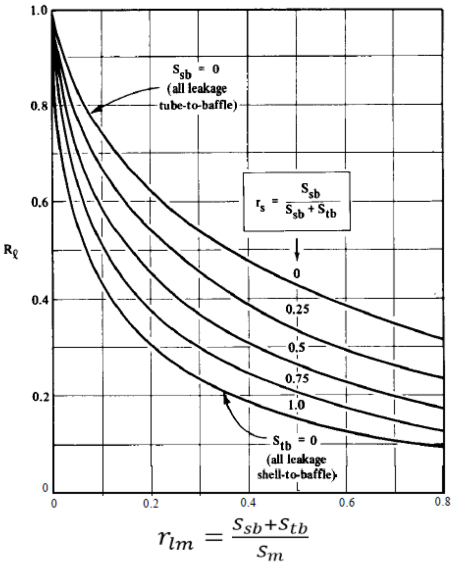
$$J_l = 0.44(1 - r_s) + [(1 - 0.44(1 - r_S)] * \exp(-2.2 r_{lm}) \tag{10}$$

**Item #85**

$R_l$: Baffle leakage pressure drop correction factor

$$R_l = exp\left[(-1.33)(1 + r_s) r_{lm}^{p}\right] \tag{11a}$$

$$p = [-0.15(1 + r_s) + 0.8] \tag{11b}$$

| | |
|---|---|
|  |  |
| Fig. R3 Baffle leakage heat transfer correction factor $J_l$ as a function of $r_{lm}$ and $r_s$ | Fig. R4 Baffle leakage pressure drop correction factor $R_l$ as a function of $r_{lm}$ and $r_s$ |

**Item # 87** $J_b$: Heat transfer correction factor due to bundle bypass

$$J_b = exp\left[-C_{bh} F_{sbp}\left(1 - \sqrt[3]{2 r_{ss}}\right)\right] \tag{12}$$

With the limits

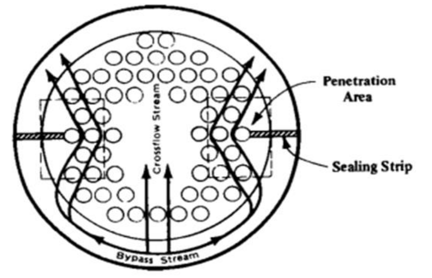
$J_b$=1 for $r_{ss} \geq ½$ and

$C_{bh}$=1.35 for $Re_s \leq 100$ and

$C_{bh}$=1.25 for $Re_s$>100

$$r_{ss} = N_{ss}/N_{tcc}$$

$$F_{sbp} = S_b/S_m$$



Effect of sealing strips on flow ($N_{ss}$=1)

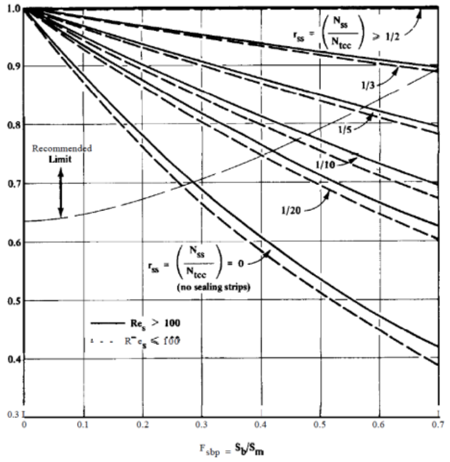


Fig. R5 Heat transfer correction factor $J_b$ due to shell-bundle by pass

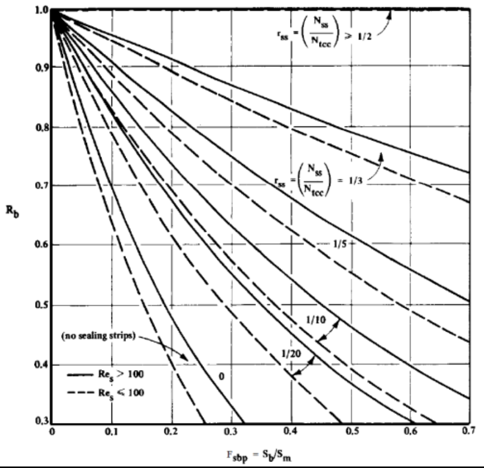


Fig. R6 Pressure drop correction factor $R_b$ due to shell-bundle by pass

**Item # 88**

$R_b$: pressure drop correction factor due to bundle by pass

$$R_b = exp\left[-C_{bp}F_{sbp}(1 - \sqrt[3]{2r_{ss}}\ )\right] \tag{13}$$

With the limit

$R_b$=1 at $r_{ss} \geq ½$

And

$C_{bp}$=4.5 if $R_s \leq 100$ and

$C_{bp}$=3.7 if $R_s > 100$

**Item # 90**

$J_r$: heat transfer correction factor for adverse temperature gradient in laminar flow

For $Re_s \leq 20$

$$J_r = (J_r)_r = \left(\frac{10}{N_c}\right)^{0.18} \tag{14}$$

Where $N_c$ is the total number of tube rows crossed i.e.

$$N_c = (N_{tcc} + N_{tcw})(N_b + 1) \tag{15}$$

For 20 < $Re_s$ <100

$$J_r = (J_r)_r + \left(\frac{20-Re_s}{80}\right)\ ((J_r)_r - 1\ ) \tag{16}$$

With the limits

$$J_r = 1\ for\ Re_s > 100$$

$$J_r = (J_r)_r\ for\ Re_s < 100\ ; J_r \geq 0.4$$

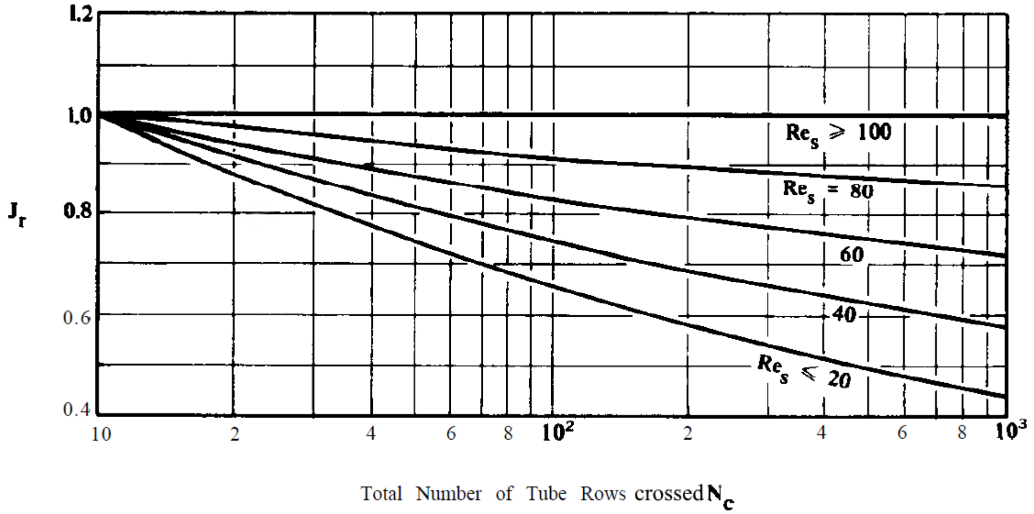


Fig. R7 Heat transfer correction factor $J_r$ for laminar flow ($Re_s$ < 100)

**Item # 93** $J_s$: Heat transfer correction factor for unequal inlet/outlet baffle spacing

$$J_s = \frac{(N_b-1)+(L_i^*)^{1-n}+(L_o^*)^{1-n}}{(N_b-1)+L_i^*+L_o^*} \tag{17}$$

Where

n= 0.6 for turbulent flow

n=1/3 for laminar flow

$$L_i^* = L_{bi}/L_{bc}$$

$$L_o^* = L_{bo}/L_{bc}$$

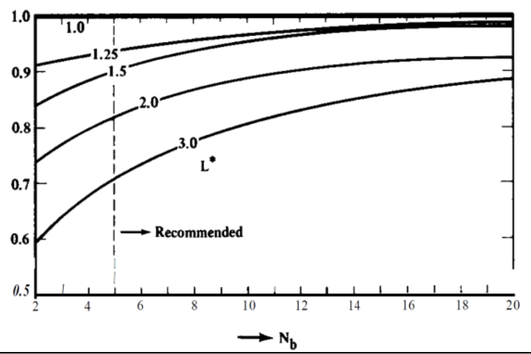


Fig. R8 $J_s$ correction factor

**Item # 94**

$R_s$: shell side pressure drop correction factor for unequal inlet/outlet baffle spacing

$$R_s = \left(\frac{L_{bc}}{L_{bo}}\right)^{2-n} + \left(\frac{L_{bc}}{L_{bi}}\right)^{2-n} \tag{18}$$

Where

n=1 for laminar flow

n=0.2 for turbulent flow

with the following limits

- For $L_{bc}=L_{bo}=L_{bi}$ $R_s=2$
- For $L_{bo}=L_{bi}=2L_{bc}$ $R_s=1$ for laminar flow, and $R_s=0.57$ for turbulent flow.
- For typical U tube HX $L_{bi}=L_{bc}$ and $L_{bo}=2L_{bc}$; $R_s=1.5$ for laminar flow, and $R_s=1.3$ for turbulent flow.

**Item # 95**

$\phi_s^r$ is a correction factor that accounts for viscosity variation between the average (bulk) and wall value.

1-For liquids

$$\phi_s^r = \left(\frac{\mu_s}{\mu_{sw}}\right)^{0.14} \tag{19}$$

2-For gas being cooled

$$\phi_s^r = 1.0 \tag{20}$$

3-For gas being heated

$$\phi_s^r = \left(\frac{T_{s_{avg}}+273}{T_w+273}\right)^{0.25} \tag{21}$$

A first estimate for the wall temperature $T_w$ can be assumed as the average temperature of the fluids in the shell and in the tubes. If an estimate for the shell side and tube heat transfer coefficient are known then

$$T_w = T_{t,avg} + \frac{T_{s,avg}-T_{t,avg}}{1+h_t/h_s} \tag{22}$$

**Item #96 &97** Ideal heat transfer and friction coefficients

$$j_i = a_1 \left(\frac{1.33}{L_{tp}/d_o}\right)^{a} (R_{es})^{a_2} \tag{23}$$

$$a = \frac{a_3}{1+0.14\, R_{es}^{a_4}} \tag{24}$$

$$f_i = b_1 \left(\frac{1.33}{L_{tp}/d_o}\right)^{b} R_{es}^{b_2} \tag{24}$$

$$b = \frac{b_3}{1+0.14\, R_{es}^{b_4}} \tag{26}$$

Table R1 Constants for $f_i$ and $j_i$ expressions for deal flow over bank of tubes

| Layout Angle | Res | $a_1$ | $a_2$ | $a_3$ | $a_4$ | $b_1$ | $b_2$ | $b_3$ | $b_4$ |
|---|---|---|---|---|---|---|---|---|---|
| **30°** | $10^5-10^4$ | 0.321 | -0.388 | 1.450 | 0.519 | 0.372 | -0.123 | 7.000 | 0.500 |
| | $10^4-10^3$ | 0.321 | -0.388 | | | 0.486 | -0.152 | | |
| | $10^3-10^2$ | 0.593 | -0.477 | | | 4.570 | -0.476 | | |
| | $10^2-10$ | 1.360 | -0.657 | | | 45.100 | -0.973 | | |
| | <10 | 1.40 | -0.667 | | | 48.000 | -1.000 | | |
| **45°** | $10^5-10^4$ | 0.370 | -0.396 | 1.930 | 0.500 | 0.303 | -0.126 | 6.59 | 0.520 |
| | $10^4-10^3$ | 0.370 | -0.396 | | | 0.333 | -0.136 | | |
| | $10^3-10^2$ | 0.730 | -0.500 | | | 3.500 | -0.476 | | |
| | $10^2-10$ | 1.300 | -0.656 | | | 26.200 | -0.913 | | |
| | <10 | 1.550 | -0.667 | | | 32.000 | -1.000 | | |
| **90°** | $10^5-10^4$ | 0.370 | -0.395 | 1.187 | 0.370 | 0.391 | -0.148 | 6.30 | 0.378 |
| | $10^4-10^3$ | 0.107 | -0.266 | | | 0.0815 | 0.022 | | |
| | $10^3-10^2$ | 0.408 | -0.460 | | | 6.0900 | -0.602 | | |
| | $10^2-10$ | 0.900 | -0.631 | | | 32.100 | -0.963 | | |
| | <10 | 0.970 | -0.667 | | | 35.000 | -1.000 | | |

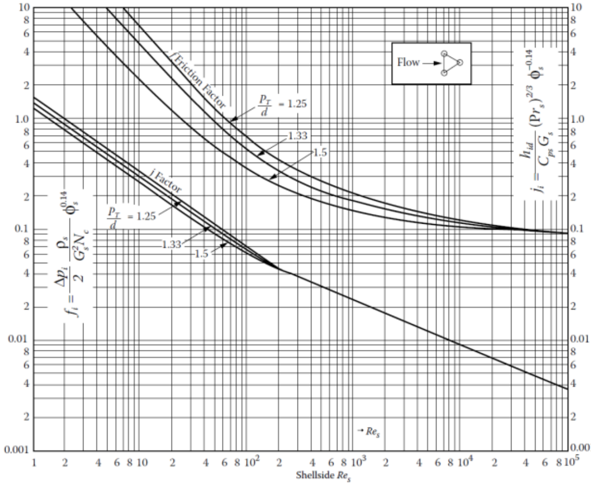


Fig. 9a Ideal tube bank $j_i$ and $f_i$ factors for 30° layout

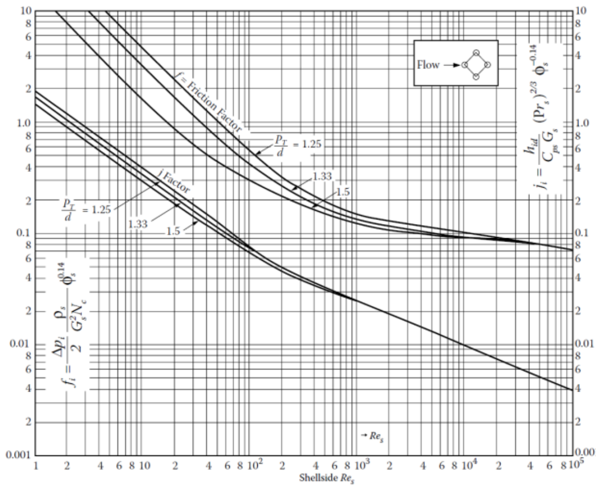


Fig. 9b Ideal tube bank $j_i$ and $f_i$ factors for 45° layout

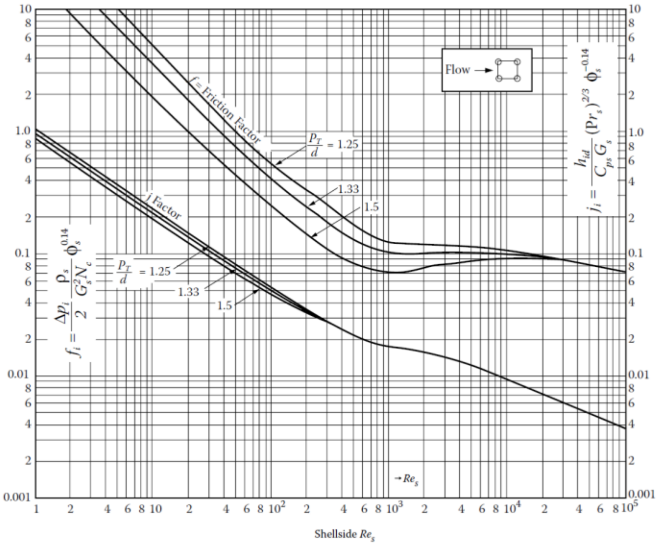


Fig. 9c Ideal tube bank $j_i$ and $f_i$ factors for 90° layout

**Item # 105** Pressure drop

For $R_{es} \geq 100$

$$\Delta P_w = N_b \left[ (2 + 0.6 N_{tcw}) \frac{(\dot{G}_w)^2}{2\rho_s} \right] R_l \tag{27}$$

$$\dot{G}_w = \frac{\dot{m}_s}{\sqrt{S_m S_w}} \tag{28}$$

For $R_{es} < 100$

$$\Delta P_w = N_b \left\{ \frac{26\, \dot{G}_w\, \mu_s}{\rho_s} \left[ \left( \frac{N_{tcw}}{L_{tp} - d_o} \right) + \frac{L_{bc}}{D_w^2} + \left[ \frac{\dot{G}_w^2}{2\rho_s} \right] \bigg] \bigg] \right\} R_l \tag{29}$$

$$D_w = \frac{4 S_w}{\pi d_o N_{tw} + \pi D_s (\theta_{ds}/360)} \tag{30}$$

$$N_{tw} = N_{tt} F_w \tag{31}$$

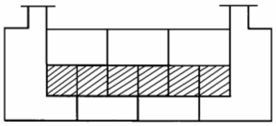
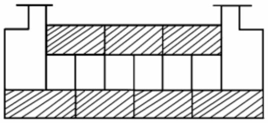
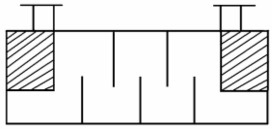
**Item # 106**

$$\Delta P_e = 2\, \Delta P_{bi} (1 + N_{tcw}/N_{tcc}) R_b R_s \tag{32}$$

Number 2 in the right hand side of the above equation is according to Shah, Fundamentals of Heat Exchanger Design, 2003, John Wiley.

**Item # 107**

$$\Delta P_s = \Delta P_c + \Delta P_w + \Delta P_e \tag{33}$$

| | | |
|---|---|---|
|  |  |  |
| Pressure drop in cross flow between baffle tips $\Delta P_c$ | Pressure drop in window $\Delta P_w$ | Pressure drop at the two ends $\Delta P_e$ |
| Fig. R10 Shell side pressure drop | | |