Heat Transfer Design Guidelines

(Reference: R.K.Sinnot, Coulson & Richardson's Chemical Engineering, Volume 6, Edition 3, Butterworth-Heinemann, 1999)

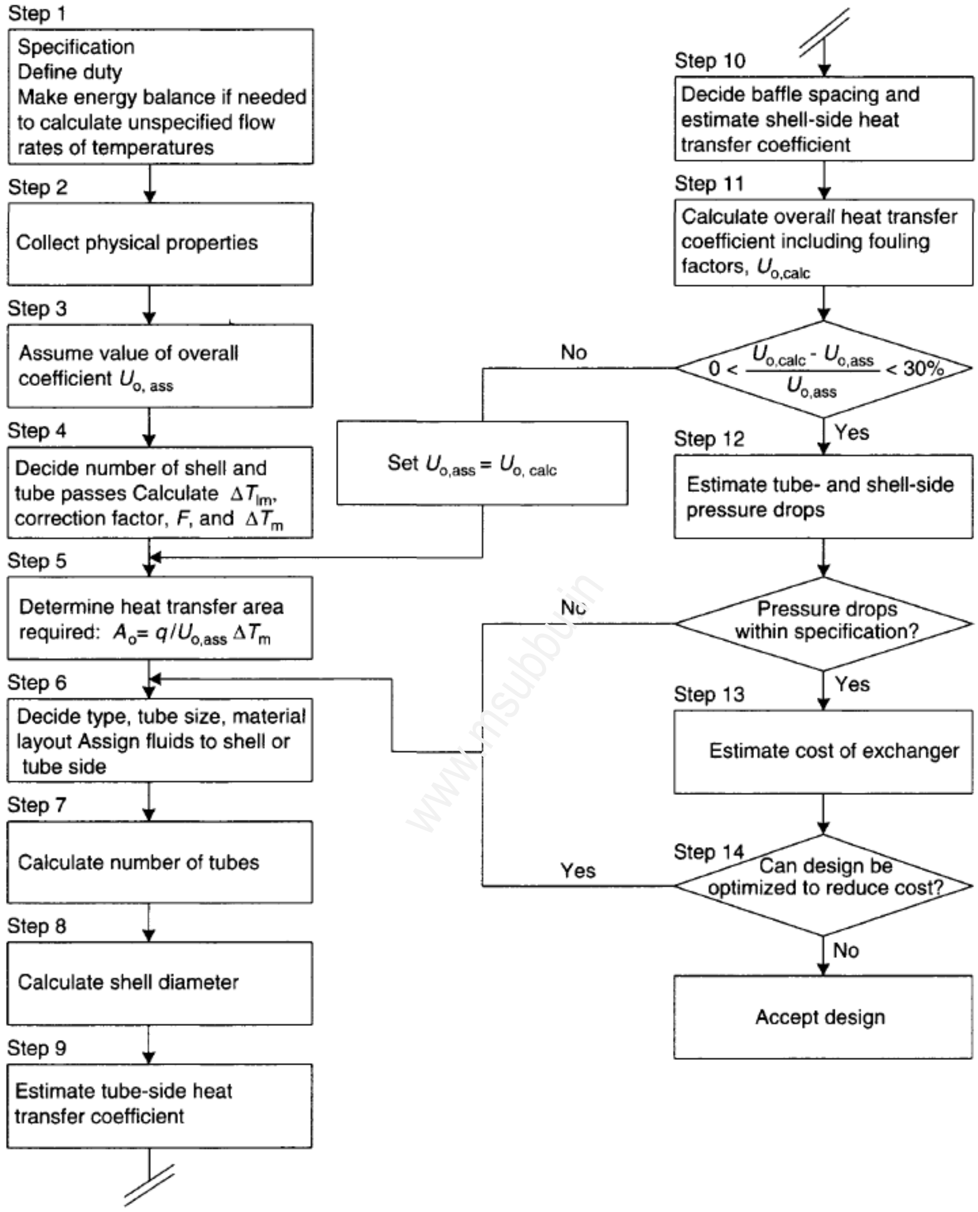

Figure A. Design procedure for shell-and-tube heat exchangers

Heat Transfer rate:

$$Q = UA\Delta T_m$$

where Q = heat transferred per unit time, W,
U = the overall heat transfer coefficient, W/m^2°C,
A = heat-transfer area, m^2,
ΔT_m = the mean temperature difference, the temperature driving force, °C.

$$\frac{1}{U_o} = \frac{1}{h_o} + \frac{1}{h_{od}} + \frac{d_o \ln\left(\frac{d_o}{d_i}\right)}{2k_w} + \frac{d_o}{d_i} \times \frac{1}{h_{id}} + \frac{d_o}{d_i} \times \frac{1}{h_i}$$

where U_o = the overall coefficient based on the outside area of the tube, W/m^2°C,
h_o = outside fluid film coefficient, W/m^2°C,
h_i = inside fluid film coefficient, W/m^2°C,
h_{od} = outside dirt coefficient (fouling factor), W/m^2°C,
h_{id} = inside dirt coefficient, W/m^2°C,
k_w = thermal conductivity of the tube wall material, W/m°C,
d_i = tube inside diameter, m,
d_o = tube outside diameter, m.

Temperature Difference:

$$\Delta T_{lm} = \frac{(T_1 - t_2) - (T_2 - t_1)}{\ln \frac{(T_1 - t_2)}{(T_2 - t_1)}}$$

where ΔT_{lm} = log mean temperature difference,
T_1 = inlet shell-side fluid temperature,
T_2 = outlet shell-side fluid temperature,
t_1 = inlet tube-side temperature,
t_2 = outlet tube-side temperature.

$$\Delta T_m = F_t \Delta T_{lm}$$

F_t is a function of R and S

$$R = \frac{(T_1 - T_2)}{(t_2 - t_1)}$$

$$S = \frac{(t_2 - t_1)}{(T_1 - t_1)}$$

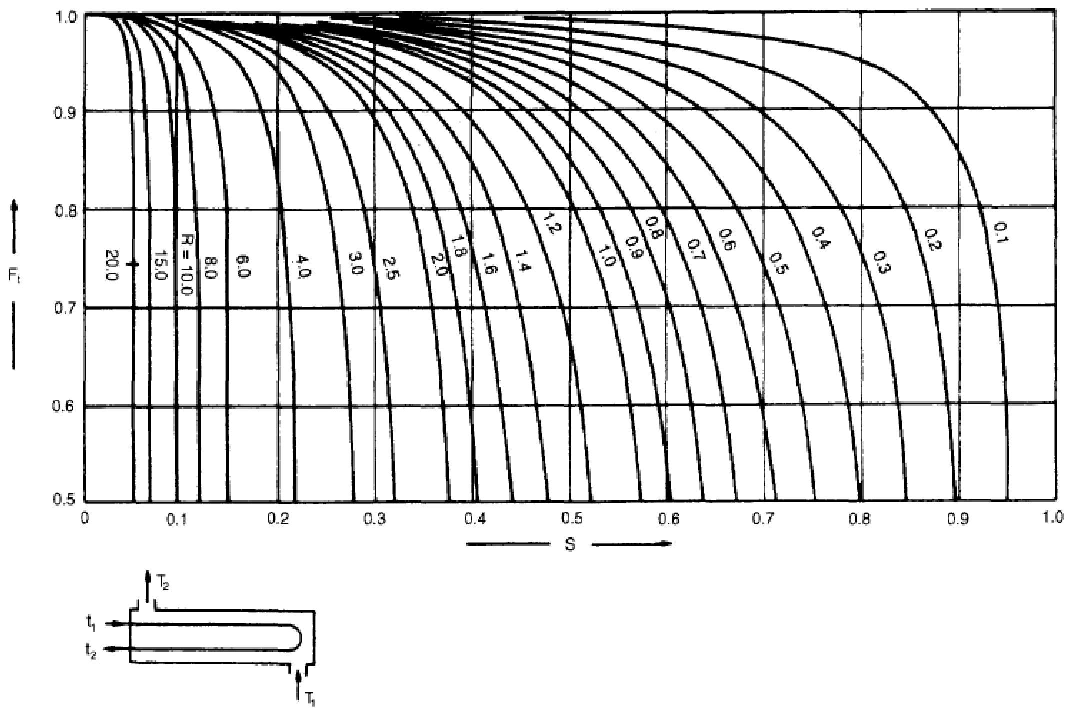

Figure 12.19. Temperature correction factor: one shell pass; two or more even tube 'passes

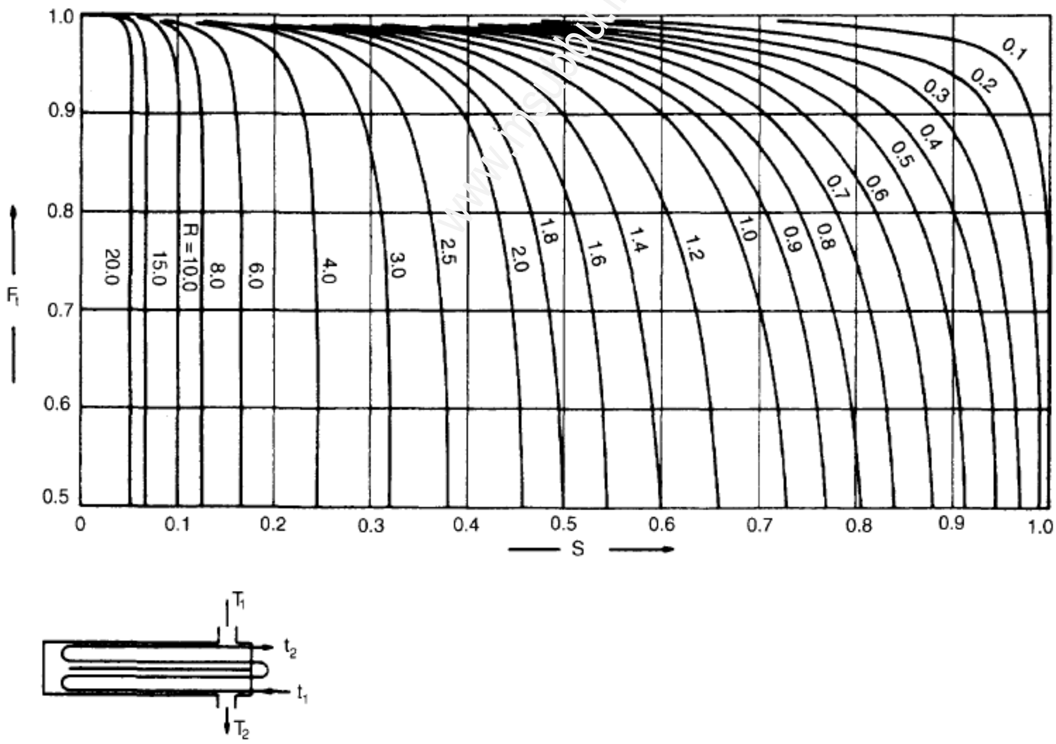

Figure 12.20. Temperature correction factor: two shell passes; four or multiples of four tube passes

Table 12.1. Typical overall coefficients

Shell and tube exchangers

Hot fluid	Cold fluid	U (W/m^2°C)
Heat exchangers		
Water	Water	800–1500
Organic solvents	Organic solvents	100–300
Light oils	Light oils	100–400
Heavy oils	Heavy oils	50–300
Gases	Gases	10–50
Coolers		
Organic solvents	Water	250–750
Light oils	Water	350–900
Heavy oils	Water	60–300
Gases	Water	20–300
Organic solvents	Brine	150–500
Water	Brine	600–1200
Gases	Brine	15–250
Heaters		
Steam	Water	1500–4000
Steam	Organic solvents	500–1000
Steam	Light oils	300–900
Steam	Heavy oils	60–450
Steam	Gases	30–300
Dowtherm	Heavy oils	50–300
Dowtherm	Gases	20–200
Flue gases	Steam	30–100
Flue	Hydrocarbon vapours	30–100
Condensers		
Aqueous vapours	Water	1000–1500
Organic vapours	Water	700–1000
Organics (some non-condensables)	Water	500–700
Vacuum condensers	Water	200–500
Vaporisers		
Steam	Aqueous solutions	1000–1500
Steam	Light organics	900–1200
Steam	Heavy organics	600–900

Table 12.2. Fouling factors (coefficients), typical values

Fluid	Coefficient (W/m^2 °C)	Factor (resistance) (m^2°C/W)
River water	3000–12,000	0.0003–0.0001
Sea water	1000–3000	0.001–0.0003
Cooling water (towers)	3000–6000	0.0003–0.00017
Towns water (soft)	3000–5000	0.0003–0.0002
Towns water (hard)	1000–2000	0.001–0.0005
Steam condensate	1500–5000	0.00067–0.0002
Steam (oil free)	4000–10,000	0.0025–0.0001
Steam (oil traces)	2000–5000	0.0005–0.0002
Refrigerated brine	3000–5000	0.0003–0.0002
Air and industrial gases	5000–10,000	0.0002–0.0001
Flue gases	2000–5000	0.0005–0.0002
Organic vapours	5000	0.0002
Organic liquids	5000	0.0002
Light hydrocarbons	5000	0.0002
Heavy hydrocarbons	2000	0.0005
Boiling organics	2500	0.0004
Condensing organics	5000	0.0002
Heat transfer fluids	5000	0.0002
Aqueous salt solutions	3000–5000	0.0003–0.0002

Table 12.6. Conductivity of metals

Metal	Temperature (°C)	k_w(W/m°C)
Aluminium	0	202
	100	206
Brass	0	97
(70 Cu, 30 Zn)	100	104
	400	116
Copper	0	388
	100	378
Nickel	0	62
	212	59
Cupro-nickel (10 per cent Ni)	0–100	45
Monel	0–100	30
Stainless steel (18/8)	0–100	16
Steel	0	45
	100	45
	600	36
Titanium	0–100	16

Tube side Calculations

Tube side heat transfer coefficient:

$$Nu = C Re^{0.8} Pr^{0.33} \left(\frac{\mu}{\mu_w}\right)^{0.14}$$

where $C = 0.021$ for gases,
$= 0.023$ for non-viscous liquids,
$= 0.027$ for viscous liquids.

where Nu = Nusselt number = $(h_i d_e / k_f)$,
Re = Reynolds number = $(\rho u_t d_e / \mu) = (G_t d_e / \mu)$,
Pr = Prandtl number = $(C_p \mu / k_f)$
and: h_i = inside coefficient, W/m^2°C,
d_e = equivalent (or hydraulic mean) diameter, m

$$d_e = \frac{4 \times \text{cross-sectional area for flow}}{\text{wetted perimeter}} = d_i \text{ for tubes,}$$

u_t = fluid velocity, m/s,
k_f = fluid thermal conductivity, W/m°C,
G_t = mass velocity, mass flow per unit area, kg/m^{2}s,
μ = fluid viscosity at the bulk fluid temperature, Ns/m^2,

μ_w = fluid viscosity at the wall,
C_p = fluid specific heat, heat capacity, J/kg°C.

Heat transfer coefficient estimation from chart:

$$\frac{h_i d_i}{k_f} = j_h Re Pr^{0.33} \left(\frac{\mu}{\mu_w}\right)^{0.14}$$

Tube side pressure drop:

$$\Delta P_t = N_p \left[8 j_f \left(\frac{L}{d_i}\right) \left(\frac{\mu}{\mu_w}\right)^{-m} + 2.5 \right] \frac{\rho u_t^2}{2}$$

where ΔP_t = tube-side pressure drop, N/m^2 (Pa),
N_p = number of tube-side passes,
u_t = tube-side velocity, m/s,
L = length of one tube.

Shell Side Calculations

Cross flow area for shell:

$$A_s = \frac{(p_t - d_o)D_s l_B}{p_t}$$

where p_t = tube pitch,
d_o = tube outside diameter,
D_s = shell inside diameter, m,
l_B = baffle spacing, m.

Calculate the shell-side mass velocity G_s and the linear velocity u_s:

$$G_s = \frac{W_s}{A_s}$$

$$u_s = \frac{G_s}{\rho}$$

where W_s = fluid flow-rate on the shell-side, kg/s,
ρ = shell-side fluid density, kg/m^3.

Shell side equivalent diameter:

Square pitch:

$$d_e = \frac{4\left(\frac{p_t^2 - \pi d_o^2}{4}\right)}{\pi d_o} = \frac{1.27}{d_o}(p_t^2 - 0.785 d_o^2)$$

Triangular pitch:

$$d_e = \frac{4\left(\frac{p_t}{2} \times 0.87 p_t - \frac{1}{2}\pi \frac{d_o^2}{4}\right)}{\frac{\pi d_o}{2}} = \frac{1.10}{d_o}(p_t^2 - 0.917 d_o^2)$$

Reynolds number:

$$Re = \frac{G_s d_e}{\mu} = \frac{u_s d_e \rho}{\mu}$$

Shell side Heat Transfer coefficient:

$$Nu = \frac{h_s d_e}{k_f} = j_h Re Pr^{1/3} \left(\frac{\mu}{\mu_w}\right)^{0.14}$$

Shell side pressure drop:

$$\Delta P_s = 8 j_f \left(\frac{D_s}{d_e}\right)\left(\frac{L}{l_B}\right)\frac{\rho u_s^2}{2}\left(\frac{\mu}{\mu_w}\right)^{-0.14}$$

where L = tube length,
l_B = baffle spacing.

Shell and Tube side fluid velocities

Liquids

Tube-side, process fluids: 1 to 2 m/s, maximum 4 m/s if required to reduce fouling; water: 1.5 to 2.5 m/s.

Shell-side: 0.3 to 1 m/s.

Vapours

For vapours, the velocity used will depend on the operating pressure and fluid density; the lower values in the ranges given below will apply to high molecular weight materials.

Vacuum	50 to 70 m/s
Atmospheric pressure	10 to 30 m/s
High pressure	5 to 10 m/s

Allowable Pressure Drops

Liquids

Viscosity	<1 mN s/m^2	35 kN/m^2
	1 to 10 mN s/m^2	50–70 kN/m^2

Gas and vapours

High vacuum	0.4–0.8 kN/m^2
Medium vacuum	0.1 × absolute pressure
1 to 2 bar	0.5 × system gauge pressure
Above 10 bar	0.1 × system gauge pressure

Shell Diameter to Accommodate the Tubes

Relation between Tube count and Tube bundle diameter:

$$N_t = K_1 \left(\frac{D_b}{d_o}\right)^{n_1}, \qquad (12.3a)$$

$$D_b = d_o \left(\frac{N_t}{K_1}\right)^{1/n_1}, \qquad (12.3b)$$

where N_t = number of tubes,
D_b = bundle diameter, mm,
d_o = tube outside diameter, mm.

Table 12.4. Constants for use in equation 12.3

Triangular pitch, $p_t = 1.25d_o$					
No. passes	1	2	4	6	8
K_1	0.319	0.249	0.175	0.0743	0.0365
n_1	2.142	2.207	2.285	2.499	2.675
Square pitch, $p_t = 1.25d_o$					
No. passes	1	2	4	6	8
K_1	0.215	0.156	0.158	0.0402	0.0331
n_1	2.207	2.291	2.263	2.617	2.643

Standard Tube dimensions:

Table 12.3. Standard dimensions for steel tubes

Outside diameter (mm)	Wall thickness (mm)				
16	1.2	1.6	2.0	—	—
20	—	1.6	2.0	2.6	—
25	—	1.6	2.0	2.6	3.2
30	—	1.6	2.0	2.6	3.2
38	—	—	2.0	2.6	3.2
50	—	—	2.0	2.6	3.2

The preferred lengths of tubes for heat exchangers are: 6 ft. (1.83 m), 8 ft (2.44 m), 12 ft (3.66 m), 16 ft (4.88 m) 20 ft (6.10 m), 24 ft (7.32 m). For a given surface area, the use of longer tubes will reduce the shell diameter; which will generally result in a lower cost exchanger, particularly for high shell pressures. The optimum tube length to shell diameter will usually fall within the range of 5 to 10.

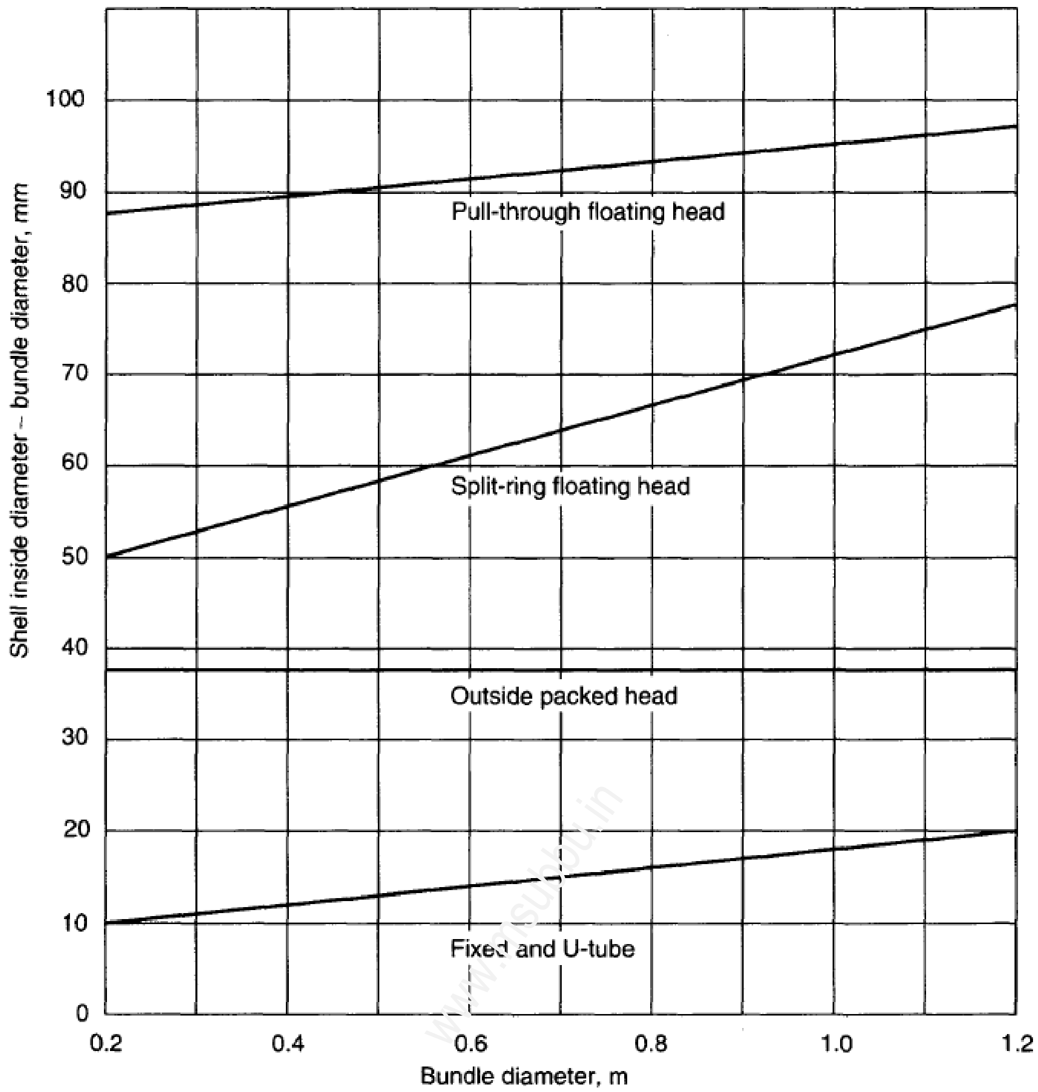

Figure 12.10. Shell-bundle clearance

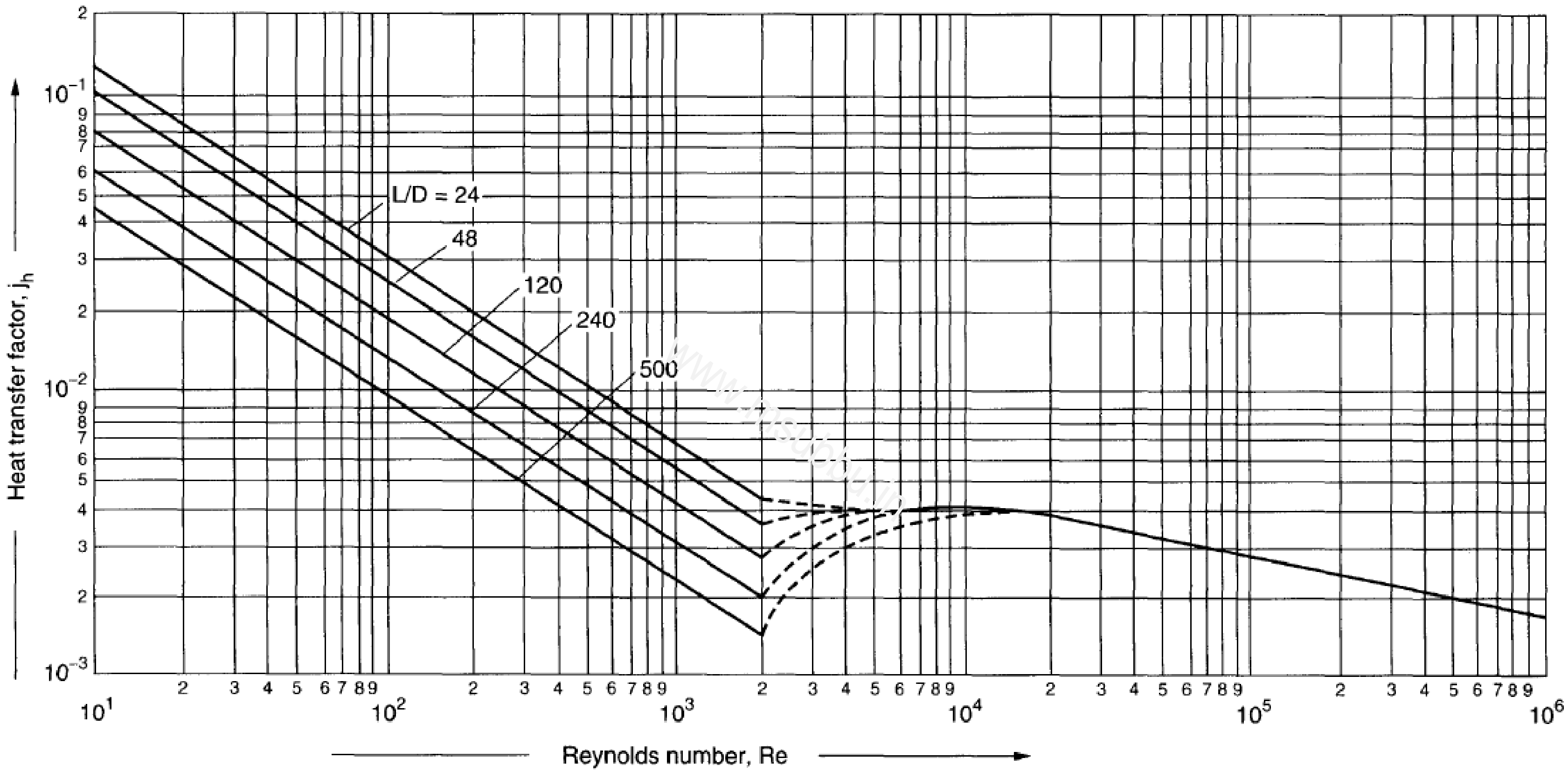

Figure 12.23. Tube-side heat-transfer factor

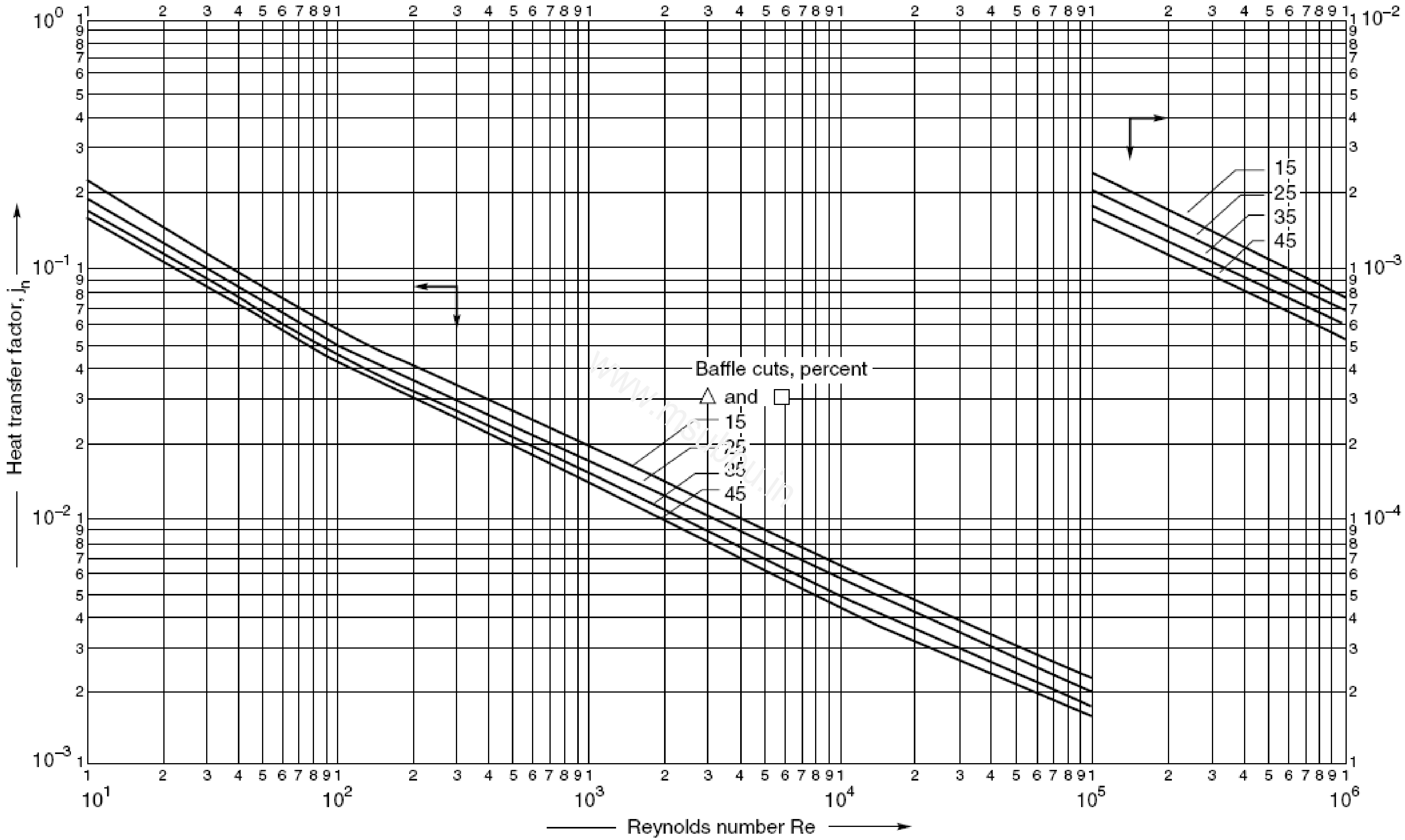

Figure 12.29. Shell-side heat-transfer factors, segmental baffles

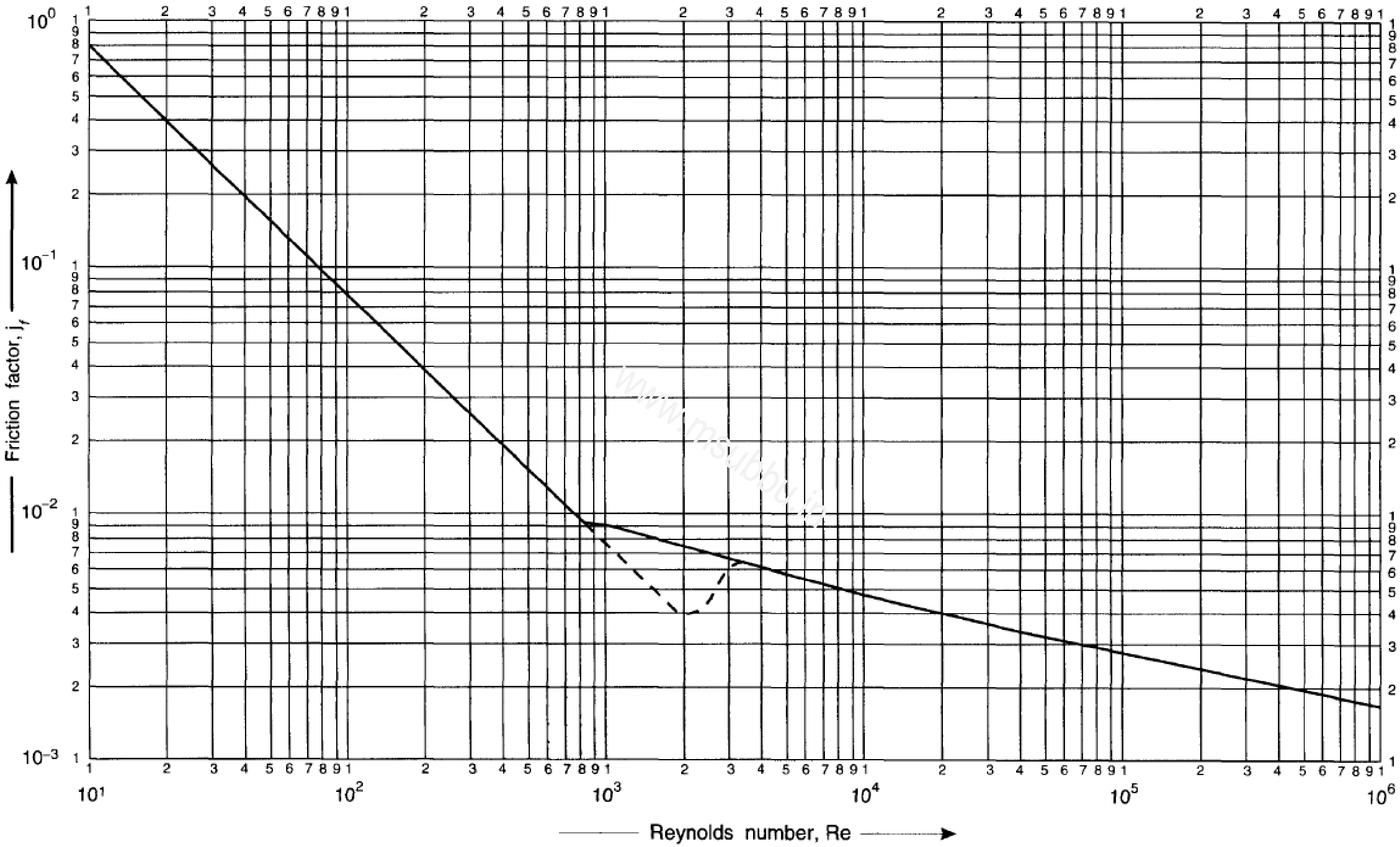

Figure 12.24. Tube-side friction factors

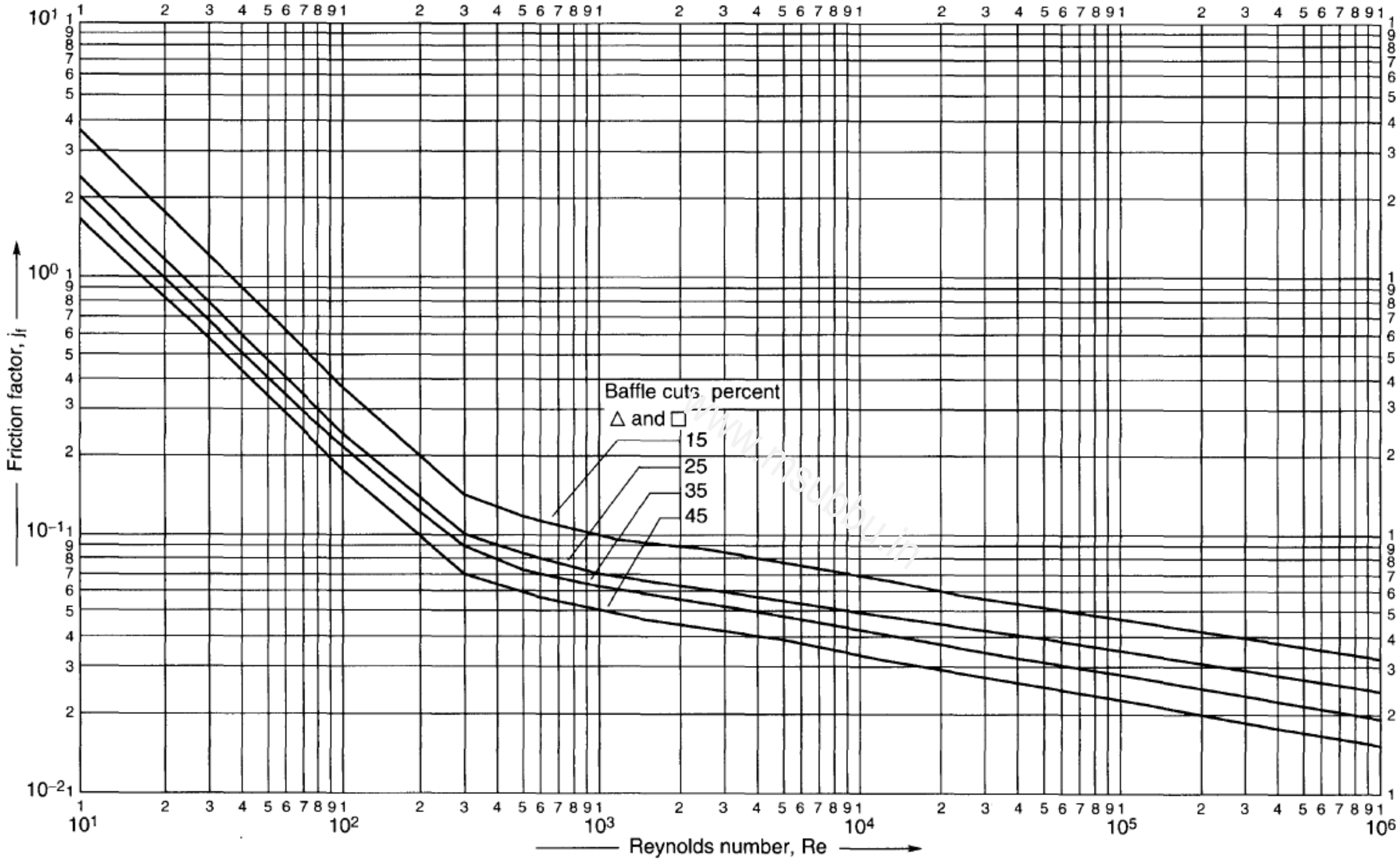

Figure 12.30. Shell-side friction factors, segmental baffles