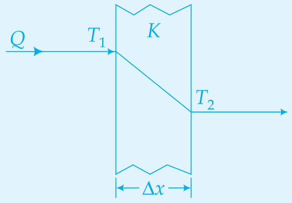
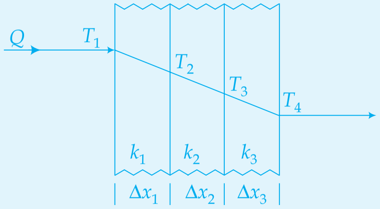
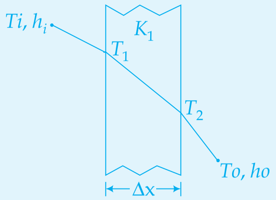
Heat and Mass Transfer–2

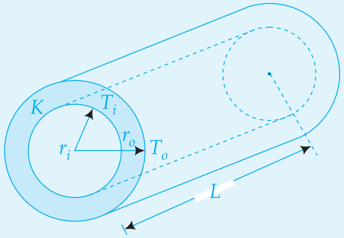
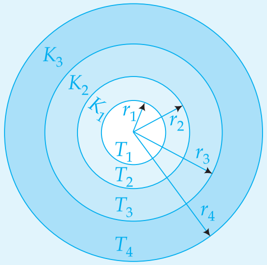
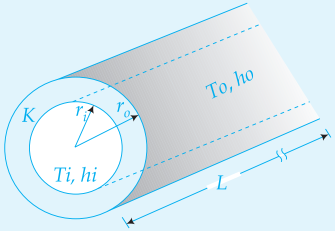
2.1.1 Steady State Conduction - One Dimension

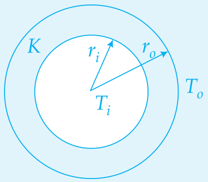
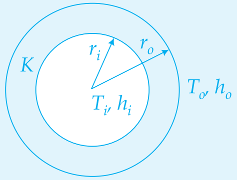
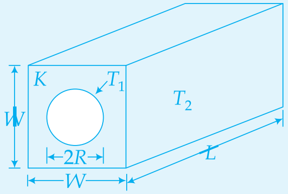
Sl. No.	*Description*	*Correlation*	*Eq. No.*
1.	General equation - one dimension Cartesian coordinates without heat generation	$\frac{\partial^2 T}{\partial x^2} = 0$	2.4a
	With heat generation	$\frac{\partial^2 T}{\partial x^2} + \frac{\dot{q}}{K} = 0$	2.4b
2.	Cylindrical coordinates no heat generation with heat generation	$\frac{\partial^2 T}{\partial r^2} + \frac{1}{r}\frac{\partial T}{\partial r} = 0$	2.5a
		$\frac{\partial^2 T}{\partial r^2} + \frac{1}{r}\frac{\partial T}{\partial r} + \frac{\dot{q}}{K} = 0$	2.5b

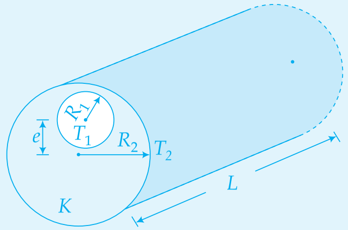
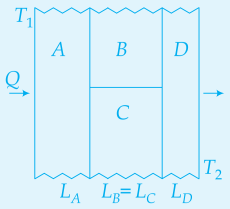
2.1.2 Conduction without Heat Generation

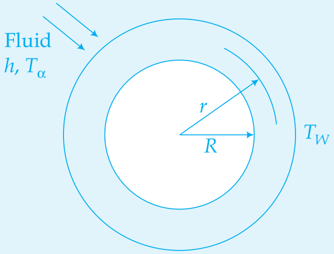
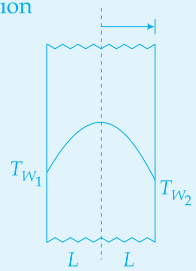
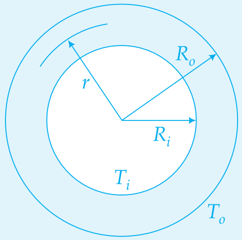
Sl. No.	*Description*	*Correlation*	*Eq. No.*	*Notations*
1.	Heat flow	$Q = \frac{\Delta T}{R}$	2.6	ΔT = Overall temperature difference, °C (or) K R = Overall thermal resistance, K/W (or) °C/W Q = Heat flow (or) Heat transfer, W A = Area of heat flow, m^2
2.	Plane wall 	$R = \frac{\Delta x}{KA}$	2.7	

3.	Composite wall Composite wall  	$R = \dfrac{\Delta x_1}{k_1 A} + \dfrac{\Delta x_2}{k_2 A} + \dfrac{\Delta x_3}{k_3 A}$	2.8	h_i = Inside heat transfer coefficient, W/m^{2}K h_o = Outside heat transfer coefficient, W/m^{2}K U = Overall heat transfer coefficient, W/m^{2}K k_o = Thermal conductivity at 0°C, W/mK β = Co-efficient of thermal expansion
4.	Plane wall with convection ends  	$R = \dfrac{1}{h_i A} + \dfrac{\Delta x}{kA} + \dfrac{1}{h_0 A}$ $Q = UA(\Delta T)$ where, $U = \dfrac{1}{A.R}$	2.9a 2.9b	
5.	Plane wall with variable thermal conductivity	$R = \dfrac{\Delta x}{k_m A}$ where, $k_m = K_0 \left[1 + \beta \dfrac{(T_1 + T_2)}{2}\right]$ Replace K by K_m for linear variation of thermal conductivity	2.10	

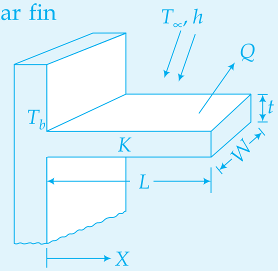
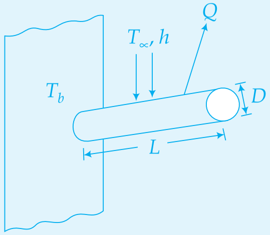
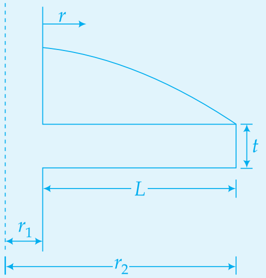
6.	Radial systems – cylinder  	$R = \dfrac{\ln \frac{r_o}{r_i}}{2\pi KL}$	2.11	r = Radius, m L = Length of the cylinder, m
7.	Multilayer cylinder  Length of the cylinder - L	$R = \dfrac{\ln \frac{r_2}{r_1}}{2\pi K_1 L} + \dfrac{\ln \frac{r_3}{r_2}}{2\pi K_2 L} + \dfrac{\ln \frac{r_4}{r_3}}{2\pi K_3 L}$	2.12	
8.	Cylinder with convective boundary conditions Heat flow  	$R = \dfrac{1}{h_i A_i} + \dfrac{\ln \frac{r_o}{r_i}}{2\pi KL} + \dfrac{1}{h_o A_o}$ $Q = U_i A_i \, \Delta T = U_o A_o \, \Delta T$ where, $U_i = \dfrac{1}{A_i R}$ $U_o = \dfrac{1}{A_o R}$	2.13a 2.13b	A_i = Inside area of the cylinder, $m^2 = 2\pi r_i L$ A_o = Outside area of the cylinder, m^2 $= 2\pi r_o L$

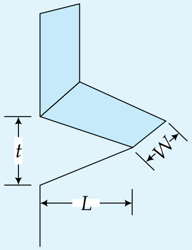
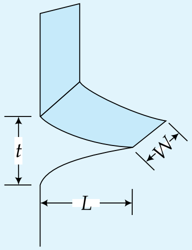
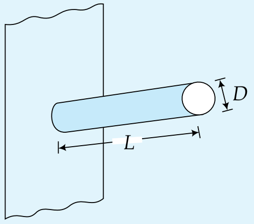
9.	Spherical systems – sphere 	$R = \frac{1}{4\pi K}\left[\frac{1}{r_i} - \frac{1}{r_o}\right]$	2.14	A_i = Inside area of the sphere, m^2 A_o = Outside area of the sphere, m^2
10.	Sphere with convective boundary conditions 	$R = \frac{1}{h_i A_i} + \frac{1}{4\pi K}\left[\frac{1}{r_i} - \frac{1}{r_o}\right] + \frac{1}{h_o A_o}$ where, $A_i = 4\pi r_i^2$ $A_o = 4\pi r_o^2$	2.15	
11.	Circular hole centered in a square solid of length L 	$R = \frac{1}{2\pi KL} \ln \frac{0.54\,W}{R}$ for $L >> W$	2.16	

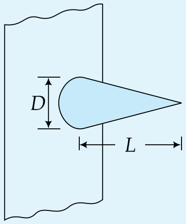
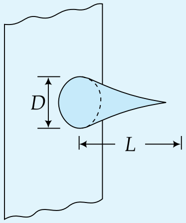
12.	Eccentric circular hole (Radius, R_1) in a cylindrical solid (Radius, R_2) of length L 	$R = \frac{1}{2\pi KL} \cosh^{-1} [(R_1^2 + R_2^2 + e^2)/(eR_1R_2)]$ 2.17	K_A, K_B, K_C, K_D = Thermal conductivity of A, B, C, D L = Thickness A_A, A_B, A_C, A_D = Area perpendicular to heat flow of A, B, C, D $A_A = A_B + A_C = A_D$
13.	Series - Parallel composite wall 	$R = R_1 + R_2 + R_3$ 2.18 $R_1 = \frac{LA}{K_A . A_A}$ $R_2 = \frac{R_B R_C}{R_B + R_C}$ $R_B = \frac{L_B}{K_B . A_B}$, $R_C = \frac{L_C}{K_C A_C}$ $R_3 = \frac{L_D}{K_D A_D}$	

3.	Sphere with heat sources  	$\frac{T_r - T_w}{T_o - T_w} = 1 - \left(\frac{r}{R}\right)^2$ $Q = \dot{q}\,\frac{4}{3}\pi R^3 = \text{hA}\,[T_w - T_\infty]$ $T_w = T_\infty + \frac{\dot{q}R}{3h}$ $T_o = T_w + \frac{\dot{q}R^2}{6K}$	2.21a 2.21b 2.21c 2.21d	
4.	Plane wall with asymmetric boundary condition  	$T_x = \frac{\dot{q}L^2}{2K}\left[1 - \frac{x^2}{L^2}\right] + \frac{(T_{w2} - T_{w1})}{2}\cdot\frac{x}{L}$ $+ \frac{(T_{w1} + T_{w2})}{2}$	2.22	
5.	Hollow cylinder with asymmetric boundary condition  	$T_r = T_o + \frac{\dot{q}}{4K}\,[R_o^2 - r^2] +$ $\left[(T_i - T_o) + \frac{\dot{q}[R_i^2 - R_o^2]}{4K}\ln\frac{r}{R_o}\right]$	2.23	
6.	Hollow cylinder with inner surface adiabatic	$T_r = T_o + \frac{\dot{q}}{4K}\,[R_o^2 - r^2] + \frac{\dot{q}}{2K}\,R_i^2 \ln\frac{r}{R_o}$	2.24	
7.	Hollow cylinder with outside surface adiabatic	$T_r = T_i + \frac{\dot{q}}{4K}\,[R_i^2 - r^2] + \frac{\dot{q}}{2K}\,R_o^2 \ln\left(\frac{r}{R_i}\right)$	2.25	

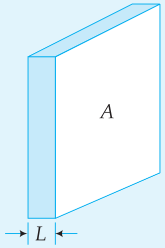
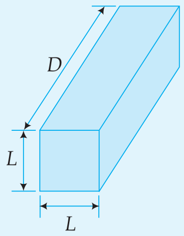
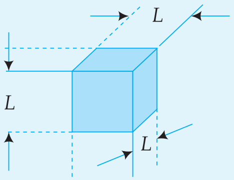
2.1.4 Fins (or) Extended Surfaces

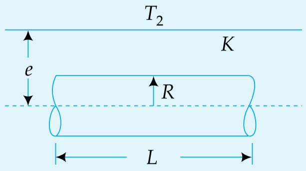
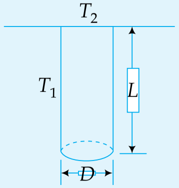
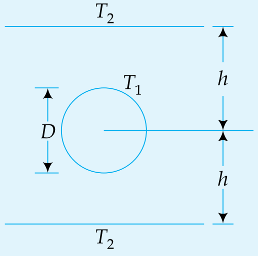
Sl. No.	Description	Correlation	Eq. No.	Notations
1.	Rectangular fin 	$P = 2W + 2t$ $A = W.t$	2.26a 2.26b	T_b = Base temperature of the fin T_∞ = Temperature of the fluid L = Length of the fin, m W = Width of the fin, m t = Thickness of the fin, m K = Thermal conductivity of the fin, W/mK h = Convective heat transfer coefficient, W/m^{2}K θ = Excess temperature = $T - T_\infty$ $\theta_b = T_b - T_\infty$ $\theta_L = T_{x=L} - T_\infty$ $\theta_o = T - T_o$
2.	Pin fin 	$P = \pi D$ $A = \frac{\pi}{k} D^2$ $m = \sqrt{\frac{hP}{KA}}$ $M = \sqrt{hPKA}\ \theta_o$	2.27a 2.27b 2.27c 2.27d	
3.	Circumferential fins 	$\frac{\theta}{\theta_b} = \frac{I_o(mr)\,K_1(mr_2) + K_0(mr)\,I_1(mr_2)}{I_0(mr_1)\,K_1(mr_2) + K_0(mr_1)\,I_1(mr_2)}$ $Q = 2\pi K t \theta_b\,(mr_1)\left[\frac{K_1(mr_1)\,I_1(mr_2) - I_1(mr_1)\,K_1(mr_2)}{I_0(mr_1)\,K_1(mr_2) + K_0(mr_1)\,I_1(mr_2)}\right]$ $\eta_f = \frac{2r_1/m}{(r_2^2 - r_1^2)}\left[\frac{K_1(mr_1)\,I_1(mr_2) - I_1(mr_1)\,K_1(mr_2)}{I_0(mr_1)\,K_1(mr_2) + K_0(mr_1)\,I_1(mr_2)}\right]$ where, I_0 & K_0 are modified zero order Bessel functions of the first and second kind I_1 & I_2 are modified first order Bessel functions of the first and second kind (refer Table 2.21)	2.28a 2.28b 2.28c	
4.	Circumferential, Rectangular, Triangular fins	$Q = \eta_f\ A_f.h[T_b - T_\infty]$	2.29	η_f = Fin efficiency A_f = Surface area of the fin, m^2

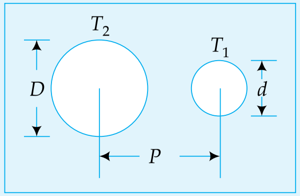
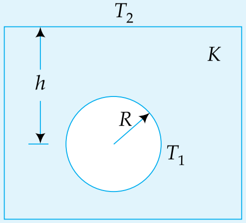
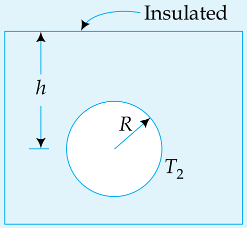
2.	Triangular straight fin  	$m = \sqrt{\dfrac{2h}{Kt}}$ $A_f = 2W\left[L^2 + \left(\dfrac{t}{2}\right)^2\right]^{1/2}$	$\dfrac{1}{mL}\dfrac{I_1(2mL)}{I_0(2mL)}$
3.	Parabolic straight fin  	$m = \sqrt{\dfrac{2h}{Kt}}$ $A_f = W\left[C_1 L + \dfrac{L^2}{t}\ln\left(\dfrac{t}{L} + C_1\right)\right]$ $C_1 = \left[1 + \left(\dfrac{t}{L}\right)^2\right]^{1/2}$	$\dfrac{2}{\left[4(mL)^2 + 1\right]^{1/2} + 1}$
4.	Pin fin  	$m = \sqrt{\dfrac{4h}{KD}}$ $A_f = \pi D L_C$ $L_C = L + \dfrac{D}{4}$	$\dfrac{\tanh mL_C}{mL_C}$

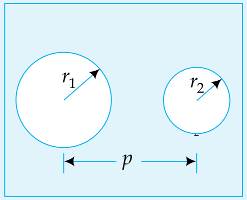
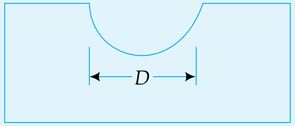
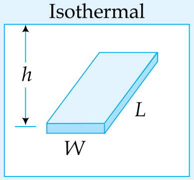
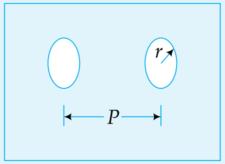
5.	Triangular pin fin 	$m = \sqrt{\frac{4h}{KD}}$ $A_f = \frac{\pi D}{2}\left[L^2 + \left(\frac{D}{2}\right)^2\right]^{\frac{1}{2}}$	$\frac{2}{mL}\frac{I_2(2mL)}{I_1(2mL)}$
6.	Parabolic pin fin 	$m = \sqrt{\frac{4h}{KD}}$ $A_f = \frac{\pi L^3}{8D}\left[C_3 C_4 - \frac{L}{2D}\ln\left(\frac{2DC_4}{L} + C_3\right)\right]$ $C_3 = 1 + 2\left(\frac{D}{L}\right)^2$ $C_4 = \left[1 + \left(\frac{D}{L}\right)\right]^{\frac{1}{2}}$	$\frac{2}{\left[\frac{4}{9}(mL)^2 + 1\right]^{\frac{1}{2}} + 1}$

2.1.5 Multidirectional Steady State Conduction

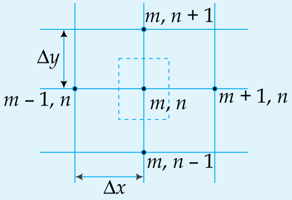
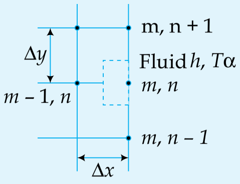
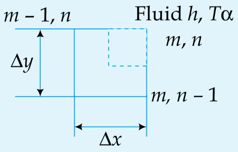
Sl. No.	*Description*	*Correlation*	*Eq. No.*	*Notations*
1.	Heat flow Conduction through a plane wall 	$Q = S.K.\Delta T$ $S = \frac{A}{L}$	2.30	Q = Heat transfer, W K = Thermal conductivity of the material, W/mK ΔT = Overall temperature difference S = Shape factor, m
2.	Conduction through the edge of adjoining walls 	$S = 0.54D$ $D > \frac{L}{5}$	2.31	
3.	Conduction through corner of three walls with a temperature difference ΔT across the walls 	$S = 0.15L$	2.32	

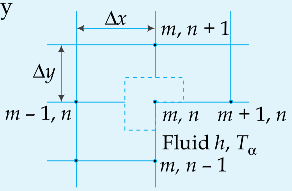
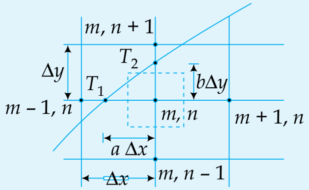
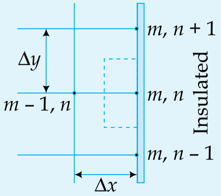
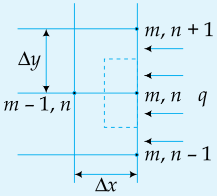
4.	Isothermal cylinder of length L, at T_1 placed horizontally in a semi-infinite medium having a surface temperature at T_2 	$S = \dfrac{2\pi L}{\cosh^{-1}\left(\dfrac{h}{R}\right)}$ for $L >> R$	2.33	
5.	Isothermal cylinder of length L, at T_1 placed vertically in a semi-infinite medium having a surface at T_2 	$S = \dfrac{2\pi L}{\ln\left(\dfrac{4L}{D}\right)}$ for $L >> D$	2.34	
6.	A horizontal circular cylinder buried midway between two faces of a slab 	$S = \dfrac{2\pi L}{\ln\left(\dfrac{8h}{\pi D}\right)}$ for $L >> D, h > \dfrac{D}{2}$	2.35	L = Length of the cylinder

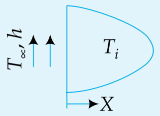
7.	Conduction between two cylinders of diameters D and d, of length L 	$S = \dfrac{2\pi L}{\cosh^{-1}\left[\dfrac{4P^2 - D^2 - d^2}{2Dd}\right]}$ for $L >> D, d, P$	2.36	
8.	An isothermal sphere at T_1 placed in a semi-infinite medium having a surface temperature, T_2 	$S = \dfrac{4\pi R}{1 - \left(\dfrac{R}{2h}\right)}$ for $h > \dfrac{D}{2}$	2.37	
9.	An isothermal sphere at T_1 placed near the insulated boundary of a semi-infinite medium at T_2 	$S = \dfrac{4\pi R}{1 + \left(\dfrac{R}{2h}\right)}$ for $h > \dfrac{D}{2}$	2.38	

10.	Two isothermal spheres buried in infinite medium  	$S = \dfrac{4\pi}{\dfrac{r_2}{r_1}\left[1 - \dfrac{\left(\dfrac{r_1}{p}\right)^4}{1 - \left(\dfrac{r_2}{p}\right)^2}\right] - \dfrac{2r_2}{p}}$	2.39	
11.	Hemisphere buried in semi-infinite medium  	$S = \pi D$	2.40	
12.	Thin rectangular plate of length L, buried in semi-infinite medium having isothermal surface  	$S = \dfrac{2\pi W}{\ln\left(\dfrac{4W}{L}\right)}$ for $h >> W,\ W > L$	2.41a	
		$S = \dfrac{\pi W}{\ln\left(\dfrac{4W}{L}\right)}$ for $h = 0,\ W > L$	2.41b	
		$S = \dfrac{2\pi W}{\ln\left(\dfrac{2\pi h}{L}\right)}$ for $W >> L,\ h > 2W$	2.41c	
13.	Parallel disks buried in infinite medium  	$S = \dfrac{4\pi}{2\left[\dfrac{\pi}{2} - \tan^{-1}\left(\dfrac{r}{p}\right)\right]}$	2.42	

2.1.6 Numerical Analysis: Nodal Formulas for Finite difference Calculations ($\Delta x = \Delta y$)

Sl. No.	Description	Correlation	Eq. No.	Notations
1.	Steady state energy balance on an interior nodal point  	$T_{m-1,n} + T_{m+1,n} + T_{m,n+1} + T_{m,n-1} - 4T_{m,n} = 0$	2.46	T = Temperature m = Locations indicating the x increment n = Locations indicating the y increment h = Heat transfer coefficient, W/m^2°C K = Thermal conductivity, W/m°C T_∞ = Adjoining fluid temperature
2.	Surface node with convection boundary  	$2T_{m-1,n} + T_{m,n-1} + T_{m,n+1} + \frac{2h.\Delta x}{K}\ T_\infty$ $- 2\left[\frac{h.\Delta x}{K} + 2\right] T_{m,n} = 0$	2.47	
3.	Exterior corner with convection boundary  	$T_{m,n-1} + T_{m-1,n} + 2.\frac{h\Delta x}{K} T_\infty - 2\left[1 + \frac{h.\Delta x}{K}\right] T_{m,n} = 0$	2.48	

4.	Interior corner with convection boundary  	$2[T_{m-1,n} + T_{m,n+1}] + T_{m+1,n} + T_{m,n-1} + 2\frac{h.\Delta x}{K}T_\infty$ $- 2\left[3 + \frac{h.\Delta x}{K}\right] T_{m,n} = 0$ 2.49	
5.	Node near curved boundary with specified temperature  	$\frac{2}{1+a}T_{m+1,n} + \frac{2}{1+b}T_{m,n-1} + \frac{2T_1}{a(1+a)} + \frac{2T_2}{b(1+b)}$ $- 2\left[\frac{1}{a} + \frac{1}{b}\right]T_{m,n} = 0$ 2.50	
6.	Node at a plane surface with insulated boundary  	$T_{m,n+1} + T_{m,n-1} + 2T_{m-1,n} - 4T_{m,n} = 0$ 2.51	
7.	Node at a plane surface with uniform heat flux  	$(2T_{m-1,n} + T_{m,n+1} + T_{m,n-1}) + \frac{2q.\Delta x}{K} - 4T_{m,n} = 0$ 2.52	

5.	Transient heat conduction with surface convection boundary conditions  $T_{(x,o)} = T_i$ $-K\frac{\partial T}{\partial x}\Big\vert_{x=0} = h[T_\infty - T_{(o,t)}]$	$\frac{T_{(x,t)} - T_i}{T_\infty - T_i} = erf\left[\frac{x}{2\sqrt{\alpha t}}\right] - \left[\exp\left(\frac{hx}{K} + \frac{h^2\alpha t}{K^2}\right)\right]$ $\left[erf\,\frac{x}{2\sqrt{\alpha t}} + \frac{h\sqrt{\alpha t}}{K}\right]$	2.60	
6.	Chart solutions: convection boundary conditions	$\frac{T(x,t) - T_\infty}{T_i - T_\infty} = f\left[\frac{x}{L}, \frac{hL}{K}, \frac{\alpha t}{L^2}\right]$	2.61	
7.	Heisler charts	$\frac{T_o - T_\infty}{T_i - T_\infty}$ Vs F_o for various values of $1/B_i$ $\frac{T(x,t)\ T_\infty}{T_o - T_\infty}$ Vs $\frac{1}{B_i}$ for various values of $\frac{x}{L}$ $\frac{T(x,t)\ T_\infty}{T_i - T_\infty} = \frac{T_o - T_\infty}{T_i - T_\infty} \times \frac{T(x,t)\ T_\infty}{T_o - T_\infty}$ (refer Figure 2.4 to 2.9)	2.62	T_o = Temperature at mid plane $\frac{x}{L} = o$
8.	Grober charts	$\frac{Q}{Q_i}$ Vs $\frac{h^2\alpha t}{K^2}$ for various values of B_i (refer Figure 2.10 to 2.12) $Q_i = \rho c L[T_i - T_\infty]$	2.63	T_o = Surface temperature i.e., at $x = o$ at any time 't'
9.	Systems with periodic variation	$\theta_o = T_o - T_m = \theta_{o,\max} \cos \omega t$ $\theta_{(x,t)} = \theta_{o,\max} \exp\left[-\sqrt{\omega/2\alpha}\,.x\right] \cos\left[\omega t - x\sqrt{\omega/2\alpha}\right]$ where, $\theta_{o\ \max} = T_{o,\max} - T_m$ $Q = \frac{2}{\sqrt{\omega\alpha}} KA\ \theta_{o,\max}$	2.64 2.65 2.66	$\omega = 2\pi f = \frac{2\pi}{t_o}$ f = Frequency of temperature wave i.e., number of complete cycles per unit time t_o = Period of temperature oscillations α = Thermal diffusivity, m^2/sec K = Thermal conductivity, W/mk

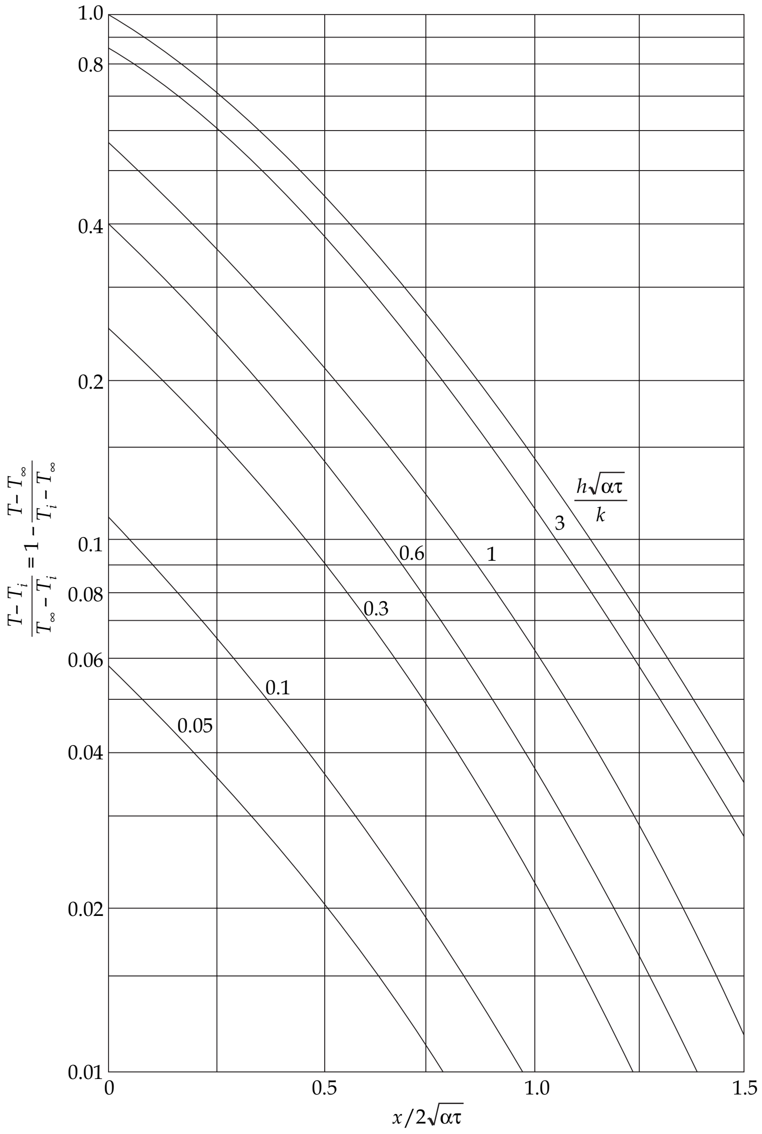


Fig. 2.3 Temperature distribution in the semi-infinite solid with convection boundary condition

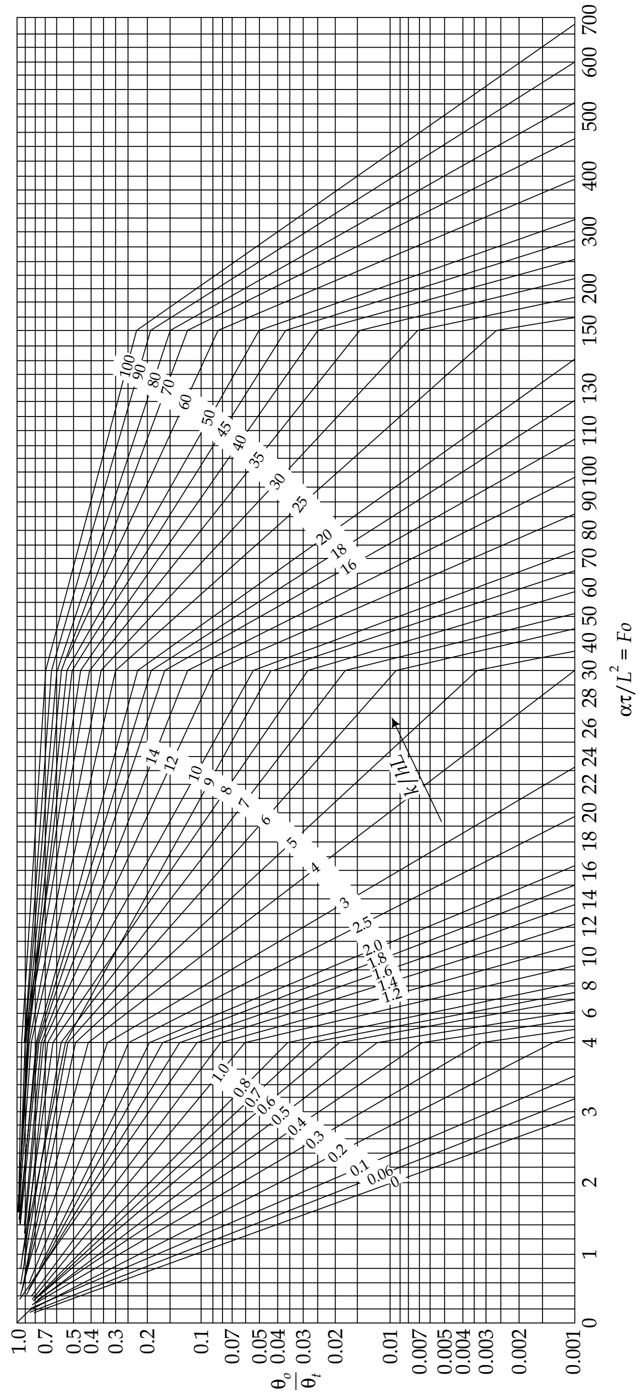


Fig. 2.4 Mid plane temperature for an infinite plate of thickness 2L

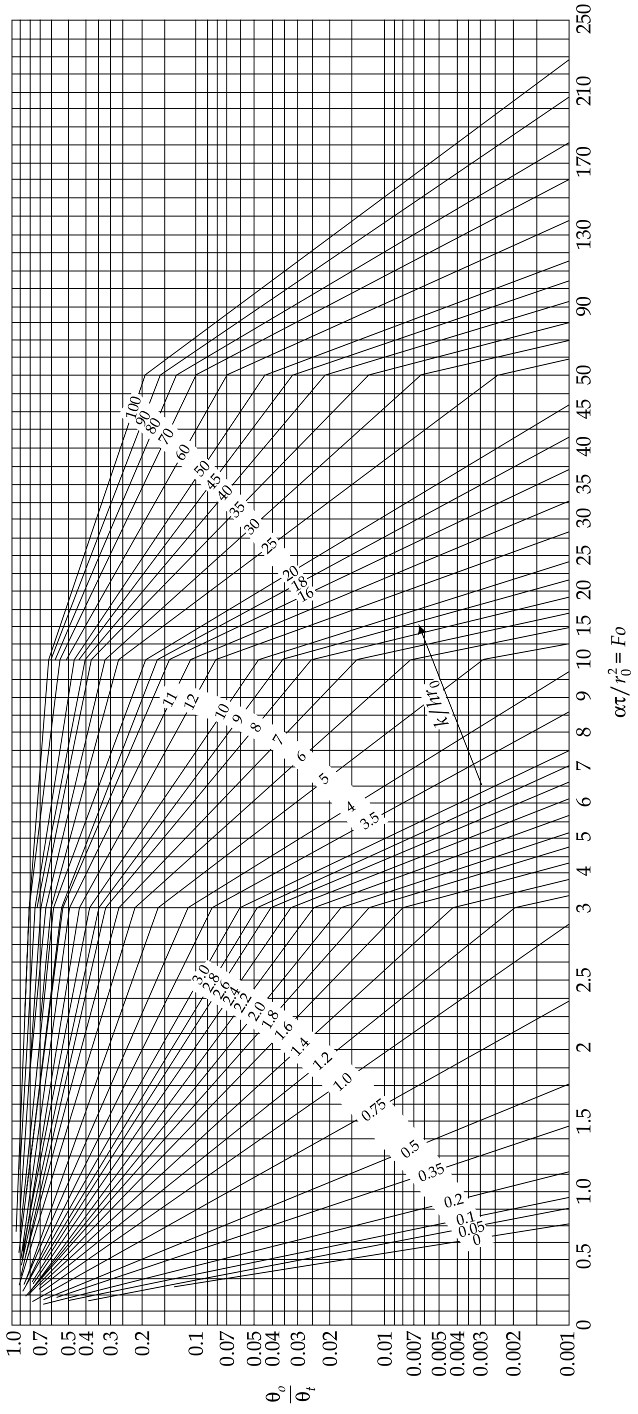


Fig. 2.6 Center temperature for a sphere of radius r_0

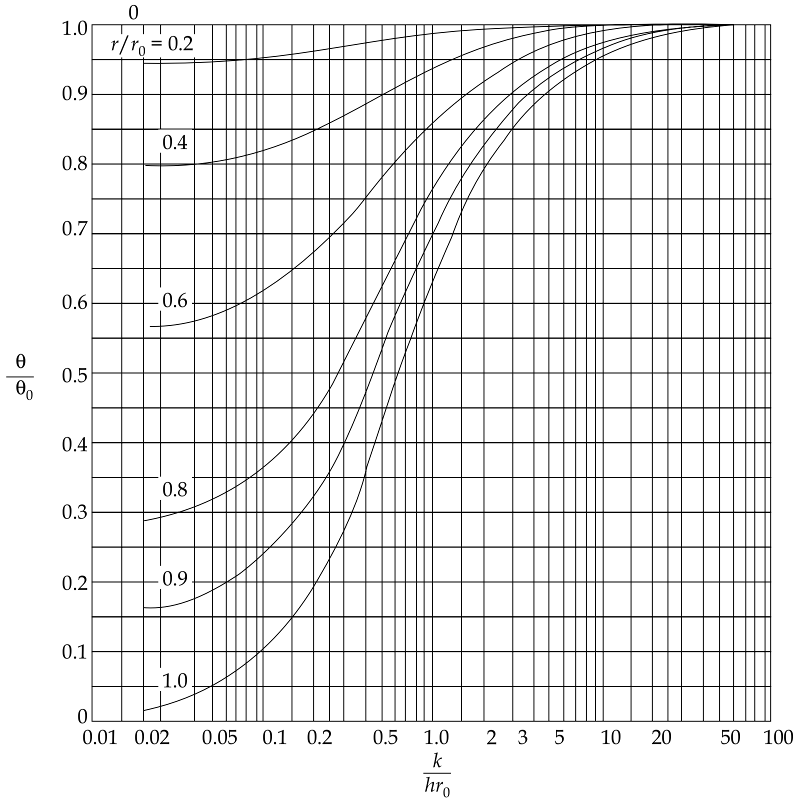


Fig. 2.8 Temperature as a function of axis temperature in an infinite cylinder of radius r_0

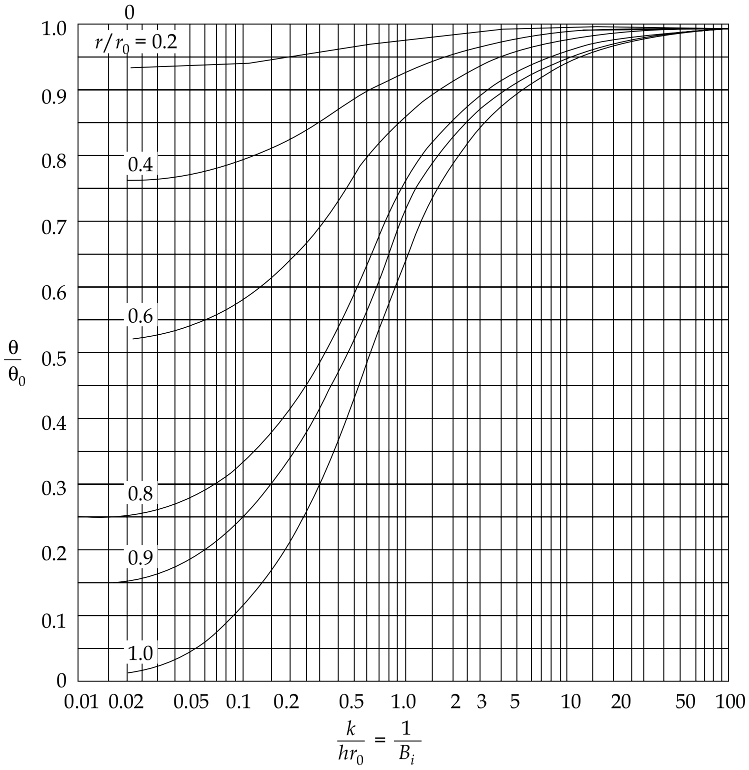


Fig. 2.9 Temperature as a function of center temperature for a sphere of radius r_0

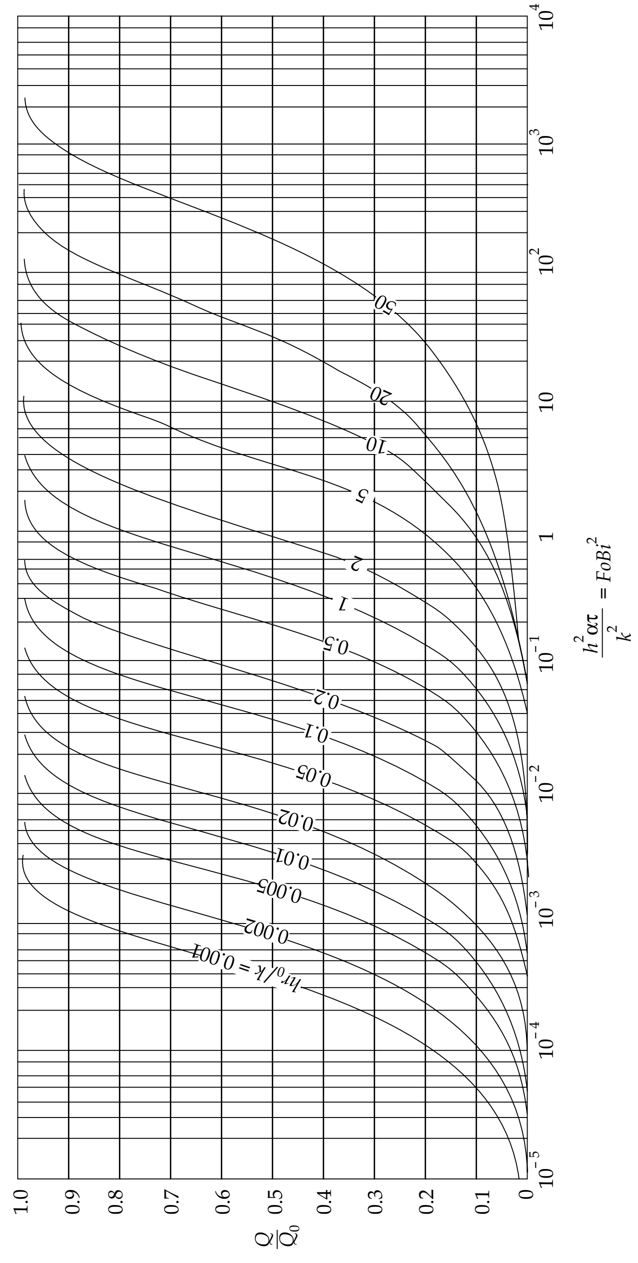


Fig. 2.11 Dimensionless heat loss Q/Q_0 for an infinite cylinder of radius r_0 with time

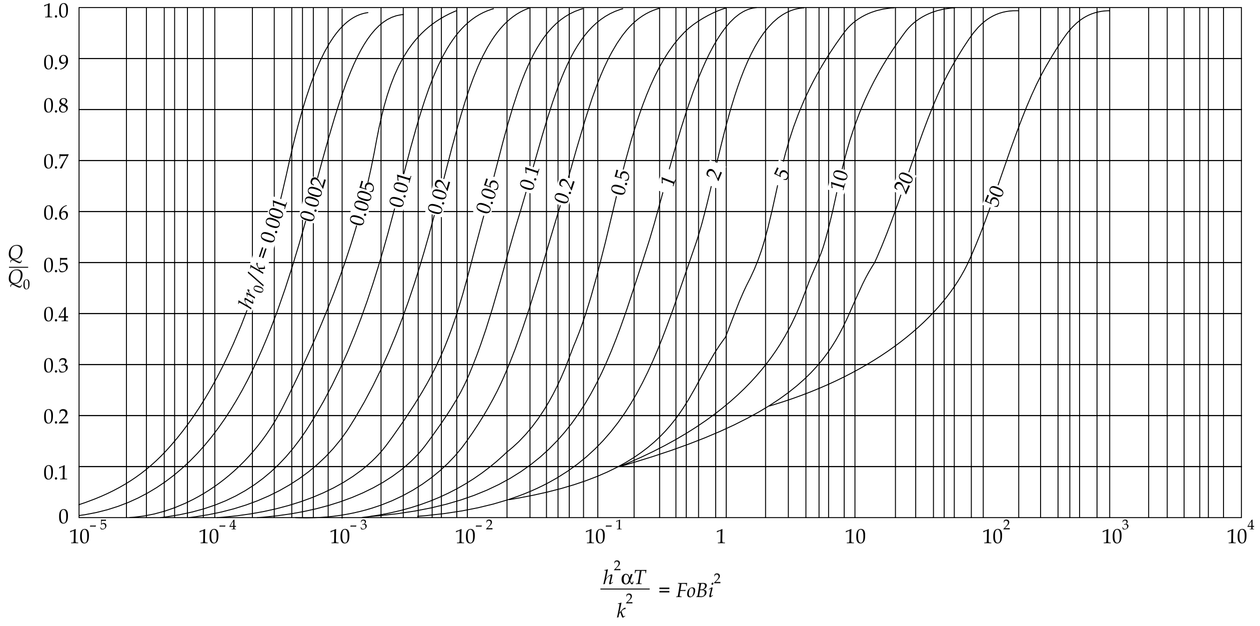


Fig. 2.12 Dimensionless heat loss Q/Q_0 for a sphere of radius r_0 with time

2.2 CONVECTION HEAT TRANSFER

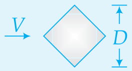
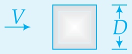
2.2.1 Dimensionless Groups

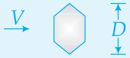
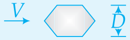
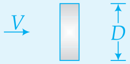
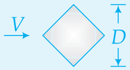
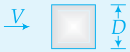
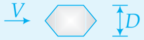
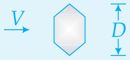
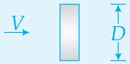
Sl. No.	*Group Name*	*Group*	*Interpretation*	*Notations*
1.	Coefficient of friction (C_f)	$\dfrac{\tau_s}{\dfrac{\rho V^2}{2}}$	Dimensionless surface shear stress	τ_s = Shear stress ρ = Density, Kg/m^3 V = Velocity, m/sec ΔP = Pressure drop L = Length, m d = Diameter, m U_m = Mean flow velocity, m/sec g = Gravitational force, m/s^2 β = coefficient of expansion, K^{-1} T_s = Surface temperature T_∞ = Fluid temperature v = Kinematic viscosity, m^2/sec $\nu = \mu/\rho$ μ = Dynamic viscosity, Kg/m sec h = Convective heat transfer coefficient, W/m^2°C K = Thermal conductivity, W/m°C α = Thermal diffusivity, m^2/sec C_p = Specific heat, kJ/kgK
2.	Friction factor (f)	$\dfrac{\Delta P}{\left(\dfrac{L}{d}\right)\left(\dfrac{\rho u_m^2}{2}\right)}$	Dimensionless pressure drop for internal flow	
3.	Grashof number (Gr)	$\dfrac{g\beta(T_s - T_\infty)L^3}{v^2}$	Ratio of buoyancy to viscous forces	
4.	Nusselt number (Nu)	$\dfrac{hL}{k}$	Dimensionless temperature gradient at the surface	
5.	Peclet number (Pe)	$\dfrac{VL}{\alpha} = \text{Re}_L\,\text{Pr}$	Dimensionless Independent heat transfer parameter	
6.	Prandtl number (Pr)	$\dfrac{\mu C_p}{k} = \dfrac{v}{\alpha}$	Ratio of the momentum and thermal diffusivities	
7.	Rayleigh number (Ra)	$\text{Gr}.\text{Pr}$		
8.	Reynolds number (Re)	$\dfrac{\rho VL}{\mu} = \dfrac{VL}{\gamma}$	Ratio of Inertia and viscous forces	
9.	Stanton number (St)	$\dfrac{h}{\rho VC_p} = \dfrac{Nu_L}{\text{Re}_L.\text{Pr}}$	Ratio of heat transfer coefficient to the heat flow per unit temperature rise	
10.	Graetz number (Gz)	$\text{Re}_L.\text{Pr}.\left(\dfrac{d}{L}\right)$		

2.2.2 Forced Convection - External Flow

External Flow: Properties are to be evaluated at $T_f = [T_w + T_\infty]/2$ (unless otherwise stated)

Sl. No.	Flow Condition	Restrictions	Correlation	Eq. No.	Notations
1.	**Flow Over Flat Plate:**				x = Distance from leading edge Re_x = Reynolds number at a distance 'x' T_f = Film temperature T_w = Plate surface temperature T_∞ = Free stream fluid temperature Re_L = Reynolds number at a distance 'L' L = Length of the plate C_{fx} = Friction coefficient at a distance 'x' $\overline{C}_{fx}$ = Average friction coefficient at a distance 'x' $\overline{C}_{fL}$ = Average friction coefficient at a distance 'L' Nu_x = Local Nusselt number at a distance of 'x' $\overline{Nu}_x$ =Average Nusselt number at a distance of 'x' St_x = Stanton number at a distance 'x' Subscripts = x, L, D, ... indicates the characteristic length
a.	Laminar flow	$Re_x < 5 \times 10^5$			
b.	Boundary layer thickness		$\delta = 5x\ Re_x^{-1/2}$	2.71	
c.	Local friction coefficient		$C_{fx} = 0.664\ Re_x^{-1/2}$	2.72	
d.	Average friction coefficient		$\overline{C}_{fx} = 1.328\ Re_x^{-1/2}$	2.73	
e.	Thermal boundary layer thickness		$\delta_t = \delta\ Pr^{-1/3}$	2.74	
f.	Turbulent flow	$5 \times 10^5 < Re_x < 10^9$			
g.	Boundary layer thickness		$\delta = 0.381\ Re_x^{-1/5}$	2.75	
h.	Local friction coefficient	$5 \times 10^5 < Re_x < 10^7$ $10^7 < Re_x < 10^9$	$C_{fx} = 0.0592\ Re_x^{-1/5}$ $C_{fx} = 0.37\ (\log Re_x)^{-2.594}$	2.76a 2.76b	
i.	Average friction coefficient	$Re_L < 10^8$	$\overline{C}_{fL} = 0.074\ Re_L^{-1/5} - 1742\ Re_L^{-1}$	2.77	
j.	Thermal boundary layer thickness		$\delta_t \simeq \delta$	2.78	
2.	Flow over flat plate for constant wall temperature, Laminar flow (T_w = constant)	$Re_x < 5 \times 10^5$ $0.5 \le Pr \le 50$ $Re_x < 5 \times 10^5$ $Re_x.Pr > 100$	$Nu_x = 0.332\ Re_x^{1/2}\ Pr^{1/3}$ $\overline{Nu}_x = 0.664\ Re_x^{1/2}\ Pr^{1/3}$ $Nu_x = \dfrac{0.3387\ Re_x^{1/2}\ Pr^{1/3}}{\left[1+\left(\dfrac{0.0468}{Pr}\right)^{2/3}\right]^{1/4}}$	2.79 2.80 2.81	
3.	For liquid metals	$Re_x < 5 \times 10^5$ $Pr << 1$	$Nu_x = 0.564\ (Re_x.Pr)^{1/3}$	2.82	
4.	For constant surface heat flux (q_w = constant)	$Re_x < 5 \times 10^5$ $0.6 < Pr < 50$	$Nu_x = 0.453\ Re_x^{1/2}\ Pr^{1/3}$	2.83	
		$Re_x < 5 \times 10^5$	$Nu_x = \dfrac{0.4637\ Re_x^{1/2}\ Pr^{1/3}}{\left[1+\left(\dfrac{0.0207}{Pr}\right)^{2/3}\right]^{1/4}}$	2.84	

			$10^3 - 2 \times 10^5$ $2 \times 10^5 - 10^6$ If $Pr \leq 10$, $n = 0.37$ $Pr > 10$, $n = 0.36$	0.26 0.076	0.6 0.7
12.	Cross flow of liquids across the cylinders	$0.1 < Re_D < 10^5$	$Nu_D = [0.35 + 0.56\, Re_D^{0.52}]\, Pr^{0.3}$		2.97
13.	Cross flow of gases and liquids	$1 < Re_D < 10^3$	$Nu_D = (0.43 + 0.50\, Re_D^{0.5})\, Pr^{0.38} \left[\frac{Pr_f}{Pr_w}\right]^{0.25}$		2.98
		$10^3 < Re_D < 10^5$ Pr_f at T_f Pr_w at T_w	$Nu_D = 0.25\, Re_D^{0.6}\, Pr^{0.38} \left[\frac{Pr_f}{Pr_w}\right]^{0.25}$		2.99
14.	Flow of air, water and liquid sodium	$10^2 < Re_D < 10^7$ $Pe_d > 0.2$	$Nu_D = 0.3 + \frac{0.62\, Re_D^{1/2}\, Pr^{1/3}}{\left[1 + \left(\frac{0.4}{Pr}\right)^{2/3}\right]^{1/4}} \cdot \left[1 + \left(\frac{Re_D}{282{,}000}\right)^{5/8}\right]^{4/5}$		2.100
		$40 < Re_D < 10^5$ $0.65 < Pr < 300$ $0.25 < \frac{\mu_\alpha}{\mu_w} < 5.2$ μ_α at T_∞ μ_W at T_w	$Nu_D = [0.4\, Re_D^{0.5} + 0.06\, Re_D^{2/3}] \times Pr^{0.4} \left[\frac{\mu_\alpha}{\mu_w}\right]^{0.25}$		2.101
15.	Flow over non-circular cylinders		$Nu_D = C\, Re_D^m\, Pr^{1/3}$		2.102
		Geometry	Re_D	C	m
		Square 	$5 \times 10^3 - 10^5$	0.246	0.588
			$5 \times 10^3 - 10^5$	0.102	0.675

		Hexagon 	$5 \times 10^3 - 1.95 \times 10^4$ $1.95 \times 10^4 - 10^5$	0.160 0.0385	0.638 0.782	
			$5 \times 10^3 - 10^5$	0.153	0.638	
		Vertical Plate 	$4 \times 10^3 - 1.5 \times 10^4$	0.228	0.731	
16.	Flow of gases across a single, non-circular long cylinder of various geometries		$Nu_D = C\, Re_D^n$		2.103	
		Geometry	Re_D	n	C	
			2500 - 7500 5000 - 100000	0.624 0.588	0.261 0.222	
			2500 - 8000 5000 - 100000	0.699 0.675	0.160 0.092	
			5000 - 100000	0.638	0.138	
			5000 - 19500 19500 - 100000	0.638 0.782	0.144 0.035	
			4000 - 15000	0.731	0.205	
			3000 - 15000	0.804	0.085	
			2500 - 15000	0.612	0.224	

22.	Flow across the tube bank	$N_L < 10$	$Nu_D = C_2\, Nu_D$ $(N_L \geq 10)$	2.112	C_2 = Correction factor

N_L	1	2	3	4	5	6	7	8	9
Aligned	0.64	0.80	0.87	0.90	0.92	0.94	0.96	0.98	0.99
Staggered	0.68	0.75	0.83	0.89	0.92	0.95	0.97	0.98	0.99

23.	Flow across the tube bank	$Nu_L \geq 20$ $0.7 < \text{Pr} < 500$ $1000 < \text{Re}_D < 2 \times 10^6$ Pr_w at T_w	$Nu_D = C\, \text{Re}_D^m\, \text{Pr}^{0.36}\, [\text{Pr}/\text{Pr}_w]^{1/4}$	2.113	

Configuration	Re_D	C	m
Aligned	$10 - 10^2$	0.80	0.40
Staggered	$10 - 10^2$	0.90	0.40
Aligned $(S_T/S_L > 0.7)$	$10^3 - 2 \times 10^5$	0.27	0.63
Staggered $(S_T/S_L < 2)$	$10^3 - 2 \times 10^5$	$0.35\ (S_T/S_L)^{1/5}$	0.60
Staggered $(S_T/S_L > 2)$	$10^3 - 2 \times 10^5$	0.40	0.60
Aligned	$2 \times 10^5 - 2 \times 10^6$	0.021	0.84
Staggered	$2 \times 10^5 - 2 \times 10^6$	0.022	0.84

24.	Flow through a packed bed and a fluidized bed	$90 \leq \text{Re}_d \leq 4000$	$\text{St}(\text{Pr})^{2/3} = \dfrac{2.06}{\varepsilon} (\text{Re}_d)^{-0.575}$	2.114	d = Effective diameter of a particle ε = Bed porosity or void fraction = 0.3 to 0.5
25.	Long flate plate, width 'D' perpendicular to flow in a gas	$1 < \text{Re}_D < 4 \times 10^5$	$Nu_D = 0.20\, \text{Re}_D^{2/3}$	2.115	
26.	Half-round cylinder with flat rear surface in a gas	$1 < \text{Re}_D < 4 \times 10^5$	$Nu_D = 0.16\, \text{Re}_D^{2/3}$	2.116	
27.	Square plate, dimension L, perpendicular to flow of gas or a liquid	$2 \times 10^4 < \text{Re}_L < 10^5$	$St_L\, \text{Pr}^{2/3} = 0.930\, \text{Re}_L^{-1/2}$	2.117	
28.	Heat transfer in High speed flow-flow in aircraft and missiles	$\text{Re}_x < 10^5$ (Laminar)	$St_x = 0.332\, (\text{Re}_x)^{-1/2}\, (\text{Pr})^{-2/3}$	2.118	T_{as} = Adiabatic surface temperature
		$10^5 < \text{Re}_x < 10_7$ (Turbulent)	$St_x = 0.0288\, (\text{Re}_x)^{-1/5}\, (\text{Pr})^{-2/3}$	2.119	
		$10^7 < \text{Re}_x < 10^9$ (Turbulent)	$St_x = [2.46/\text{In Re}_x)^{2.58}](\text{Pr})^{-2/3}$ Thermo Physical Properties are evaluated at $T = T_\infty + 0.5\, (T_w - T_\infty) + 0.22\, (T_{as} - T_\infty)$	2.120	

2.2.3 Forced Convection - Internal Flow

Internal Flow: Properties are evaluated at bulk mean temperature $T_b = (T_i + T_o)/2$

Sl. No.	Flow Condition	Restrictions	Correlation	Eq. No.	Notations
1.	Tube Flow: Laminar flow Friction factor	$\mathrm{Re}_D < 2300$	$f = 64/\mathrm{Re}_D$	2.121	D = Diameter of the tube L = Length of the tube T_i = Inlet flow temperature T_o = Outlet flow temperature T_w = Surface temperature of the tube T_b = Bulk mean temperature
2.	Laminar flow, fully developed with uniform heat flux (q = constant)		$Nu_D = 4.36$	2.122	
3.	Laminar flow, fully developed with uniform surface temperature (T_w = constant)		$Nu_D = 3.66$	2.123	
4.	Laminar flow in the entrance region of a circular tube with constant surface temperature		$Nu_D = 3.66 + \dfrac{0.0668\left(\dfrac{D}{L}\right)\mathrm{Re}_D.\mathrm{Pr}}{1 + 0.04\left[\left(\dfrac{D}{L}\right)\mathrm{Re}_D.\mathrm{Pr}\right]^{\frac{2}{3}}}$	2.124	
5.	Laminar flow in a circular tube at constant surface temperature	$0.48 < \mathrm{Pr} < 16{,}700$ $0.004 < \left(\dfrac{\mu}{\mu_w}\right) < 9.75$ μ_s at T_w	$Nu_D = 1.86\left[\dfrac{\mathrm{Re}.\mathrm{Pr}}{L/D}\right]^{\frac{1}{3}}\left[\dfrac{\mu}{\mu_w}\right]^{0.14}$	2.125	
6.	Turbulent flow Fully developed turbulent flow	$\mathrm{Re}_D > 2300$ $0.6 < \mathrm{Pr} < 100$	$Nu_D = 0.023\,\mathrm{Re}_D^{0.8}\,\mathrm{Pr}^n$ $n = 0.4$ for heating $n = 0.3$ for cooling	2.126	
		$0.7 \le \mathrm{Pr} \le 16{,}700$ $\mathrm{Re}_D \ge 10{,}000$ μ_W at T_W	$Nu_D = 0.027\,\mathrm{Re}_D^{4/5}\,\mathrm{Pr}^{1/3}\left(\dfrac{\mu}{\mu_w}\right)^{0.14}$	2.127	
		$0.5 < \mathrm{Pr} < 2000$ $3000 < \mathrm{Re}_D < 5 \times 10^6$	$Nu_D = \dfrac{\left(\dfrac{f}{\theta}\right)(\mathrm{Re}_D - 1000)\,\mathrm{Pr}}{1 + 12.7\left(\dfrac{f}{\theta}\right)^{1/2}(\mathrm{Pr}^{2/3} - 1)}$	2.128	

14.	Flow through the concentric tube annulus – fully developed turbulent flow		$Nu_{Dh} = 0.023\ \mathrm{Re}_{Dh}^{4/5}\ \mathrm{Pr}^n$ $n = 0.4$ for heating $n = 0.3$ for cooling $D_h = D_o - D_i$	2.136	
15.	Flow through the non-circular tubes		$Nu_{Dh} = 0.023\ \mathrm{Re}_{Dh}^{4/5}\ \mathrm{Pr}^4$ $n = 0.4$ for heating $n = 0.3$ for cooling $D_h = \frac{4\,A}{P}$	2.137	A = Cross-sectional area of flow P = Wetted perimeter

2.2.4 Natural (or) Free Convection

Properties are evaluated at film temperature $T_f = ½[T_w + T_\infty]$ [Unless otherwise stated]

Sl. No.	*Flow Condition*	*Restrictions*	*Correlation*	*Eq. No.*	*Notations*
1.	Free convection from vertical flat plates and cylinders with uniform wall temperature.		$Nu_L = C\ [\mathrm{Gr}_L\ \mathrm{Pr}]^m$	2.138	L = Height of the plate or cylinder T_w = Temperature of the surface of the wall or cylinder T_∞ = Temperature of the fluid
		$\mathrm{Gr}_L.\mathrm{Pr}$	C	m	
		10^4–10^9 (Laminar flow)	0.59	$\frac{1}{4}$	
		10^9–10^{13} (Turbulent flow)	0.021	$\frac{2}{5}$	
		10^9–10^{13}	0.10	$\frac{1}{3}$	
2.	Free convection from an Isothermal vertical plate or cylinder	$10^{-1} < \mathrm{Ra}_L < 10^{12}$	$\mathrm{Nu}_L = \left\{0.825 + \frac{0.387\ Ra_L^{1/6}}{\left[1 + \left(\frac{0.492}{\mathrm{Pr}}\right)^{9/16}\right]^{8/27}}\right\}^2$	2.139	

3.	Free convection on a vertical wall of height L subjected to a uniform heat flux 'q'	$Ra_L < 10^9$	$Nu_L = 0.68 + \dfrac{0.670\, Ra_L^{1/4}}{\left[1+\left(\dfrac{0.492}{\text{Pr}}\right)^{9/16}\right]^{4/9}}$	2.140	K = Thermal conductivity ν = Kinamatic viscosity β = Coefficient of thermal expansion g = Acceleration due to gravity = 9.81 m/sec^2
		$2 \times 10^3 < Ra_L < 10^{16}$	$Nu_L = 0.17\{\text{Gr}_L.\text{P}_r\}^{1/4}$	2.141	
4.	Free convection on a vertical plate with uniform heat flux 'q'	$10^5 < \text{Gr}_L^* \text{Pr} < 10^{11}$ (Laminar)	$Nu_L = 0.75\ (\text{Gr}_L^* \text{Pr})^{1/5}$	2.142	
		$2 \times 10^{13} < \text{Gr}_L^* \text{Pr} < 10^{16}$ (Turbulent)	$Nu_L = 0.645\ (\text{Gr}_L^* \text{Pr})^{0.22}$ Where, Gr_L^* modified Grashof number $\text{Gr}_L^* = \dfrac{g\beta qL^4}{Kg^2}$	2.143	
5.	For liquid metals	$\text{Pr} < 0.03$	$Nu_L = 0.68\,(\text{Gr}_L\ \text{Pr}^2)^{1/4}$	2.144	
6.	For Irregular solids	$10^4 < \text{Gr}_l\ \text{Pr} < 10^9$	$Nu_l = 0.52\,(\text{Gr}_l\ \text{Pr})^{1/4}$	2.145	l = Characteristic length = distance fluid particle travels in boundary layer A = Surface area of the plate P = Perimeter
7.	Free convection on a vertical cylinder	$10^4 < \text{Gr}_D\ \text{Pr} < 10^6$	$Nu_D = 0.775\,(\text{Gr}_D.\text{Pr})^{0.21}$	2.146	
8.	Horizontal plates with uniform wall temperature hot surface facing up (or) Cold surface facing down.	$10^4 \le \text{Gr}_L\ \text{Pr} \le 10^7$ $10^7 \le \text{Gr}_L\ \text{Pr} \le 10^{11}$ T_W = Constant	$Nu_L = 0.54\,(\text{Gr}_L\ \text{Pr})^{1/4}$ $Nu_L = 0.15\,(\text{Gr}_L\ \text{Pr})^{1/3}$ Characteristic length $L = \dfrac{A}{P}$	2.147a 2.147b	
9.	Hot surface facing down (or) Cold surface facing up	$10^5 \le \text{Gr}_L\ \text{Pr} \le 10^{10}$ T_W = Constant	$Nu_L = 0.27\,(\text{Gr}_L\ \text{Pr})^{1/4}$ Characteristic length $L = \dfrac{A}{P}$	2.148	
10.	Free convection on a horizontal plate subjected to uniform surface heat flux 'q' heated surface facing upward	$\text{Gr}_L\ \text{Pr} < 2 \times 10^8$	$Nu_L = 0.13\,(\text{Gr}_L\ \text{Pr})^{1/3}$	2.149a	
		$10^8 \le \text{Gr}_L\ \text{Pr} < 10^{11}$	$Nu_L = 0.16\,(\text{Gr}_L\ \text{Pr})^{1/3}$	2.149b	
11.	Heated surface facing downward	$10^6 \le \text{Gr}_L\ \text{Pr} < 10^{11}$	$Nu_L = 0.58\,(\text{Gr}_L\ \text{Pr})^{1/5}$ Properties are to be evaluated at $T_f = T_w - 0.25\ (T_w - T_\infty)$ and β at $(T_w + T_\infty)/2$	2.150	

18.	Free convection heat transfer from spheres to air	$1 < Gr_D.Pr < 10^5$	$Nu_D = 2 + 0.43(Gr_D.P_r)^{1/4}$	2.158	Ra = Gr.Pr. Ra = Rayleigh number Ra_W = Rayleigh number with characteristic length W L = Length of the rectangular cavity W = Width of the enclosure (Characteristic length)
19.	Spheres with water	$3 \times 10^5 < Gr_D.Pr < 8 \times 10^8$	$Nu_D = 2 + 0.5(Gr_D.Pr)^{1/4}$	2.159	
20.	Free convection in rectangular cavities	$10^4 < Ra_W < 10^7$ $1 < Pr < 2 \times 10^4$ $10 < \frac{L}{W} < 40$	$Nu_W = 0.42(Ra_W)^{0.25}(Pr)^{0.012}\left(\frac{L}{W}\right)^{-0.3}$	2.160a	
		$10^6 < Ra_W < 10^9$ $1 < Pr < 20$ $1 < \frac{L}{W} < 40$	$Nu_W = 0.046(Ra_W)^{1/3}$	2.160b	
21.	Free convection in concentric cylinders enclosure	$10^2 < Ra_c < 10^7$	$q = \frac{2\pi K_{eff}[T_i - T_o]}{\ln\left(\frac{d_o}{d_i}\right)}$	2.161	d_i = Outer diameter of the Inner tube d_o = Inner diameter of the outer tube $L = d_o - d_i$ = The characteristic length of the annular enclosure k_{eff} = Effective thermal conductivity q = Heat flux (or) rate of heat flow T_i & T_o are the temperatures of the Inner and the outer cylinder walls
			$\frac{k_{eff}}{k} = 0.386\left[\frac{Pr}{0.861 + Pr}\right]^{0.25}[Ra_c^*]$		
			$Ra_c = \frac{\left[\ln\left(\frac{d_o}{d_i}\right)\right]^4}{L^3[d_i^{-0.6} + d_0^{-0.6}]^5} Ra_L$		
			$Ra_L = \frac{g\beta[T_i - T_o]L^3}{\gamma^2}.Pr$		
			$L = \frac{1}{2}(d_o - d_i)$		

22.	Free convection heat transfer between concentric spheres		$q = K_{eff}\,\pi\left[\frac{d_i d_o}{L}\right][T_i - T_o]$	2.162	
			$\frac{K_{eff}}{K} = 0.74\left[\frac{\text{Pr}}{0.861+\text{Pr}}\right]^{1/4}\ [Ra_C^*]^{1/4}$		
			$Ra_C^* = \left[\frac{L}{(d_o d_i)^4}\ \frac{Ra_L}{[d_i^{-7/5}+d_o^{-7/5}]^5}\right]$		
			$Ra_L = \frac{g\beta[T_i - T_o]L^3}{\gamma^2}.\text{Pr}$		
			$L = \frac{1}{2}(d_o - d_i)$		
23.	Combined free and forced convection		$Nu^3 = [Nu_{\text{forced}}]^3 \pm [Nu_{\text{free}}]^3$	2.163	
24.	Natural convection between long rotating cylinder and a surrounding fluid	$\text{Re}_w > 800$	$Nu_D = 0.11(0.5\ \text{Re}_w^2 + Gr_D.\text{Pr})^{0.35}$	2.164	ω = Angular velocity, (or) rotating speed, rad/sec $\text{Re}_\omega = \frac{\omega\pi D^2}{\gamma}$ D = Diameter of the cylinder/disc/sphere
25.	Natural convection between rotating disk and a surrounding fluid	$\text{Re}_w < 5 \times 10^5$	$Nu_D = 0.35(\text{Re}_w)^{1/2}$	2.165	
26.	Natural convection between rotating sphere and a surrounding fluid	$\text{Re}_w < 5 \times 10^4$ $\text{Pr} > 0.7$	$Nu_D = 0.43\ \text{Re}_w^{0.5}\ \text{Pr}^{0.4}$	2.166a	
		$5 \times 10^4 < \text{Re}_w < 7 \times 10^5$	$Nu_D = 0.066\ \text{Re}_w^{0.67}\ \text{Pr}^{0.4}$	2.166b	

2.	Critical heat flux for nucleate pool boiling	$q_{\max} = 0.149\, h_{fg}\, \rho_w \left[\dfrac{\sigma . g(\rho_l - \rho_w)}{\rho_w^2}\right]^{1/4}$ 2.168	k_l = Thermal conductivity of saturated liquid, W/m°C $(\Delta T)_e$ = Excess Temperature = $T_w - T_{Sat}$ T_w, T_{Sat} = Temperature of wall and Saturation Temperature, respectively k_v = Thermal conductivity for Saturated vapour, W/m°C C_{pw} = Specific heat of Saturated vapour, J/Kg°C μ_W = Vapour viscosity, Kg/m.s d = Tube diameter h_b = Average heat transfer coefficient in the absence of radiation, W/m^2°C h = Total heat transfer coefficient, W/m^2°C h_r = Radiation heat transfer coefficient, W/m^2°C ε = Emissivity of the surface σ_s = Stefan Boltzmann constant = 5.67×10^{-8} W/m^{2}K^4 q = Heat flux, KW/m^2 h_p = Heat transfer coefficient at some pressure 'p' P = System Pressure P_1 = Standard atmospheric pressure
3.	Minimum heat flux from a large horizontal plate	$q_{\min} = C.\rho_w\, h_{fg}\left[\dfrac{g\sigma(\rho_l - \rho_w)}{(\rho_l + \rho_w)^2}\right]^{1/4}$ 2.169 where, c is constant equals to 0.09	
4.	Stable film boiling (or) film pool boiling in the absence of radiation	$h_b = 0.62\left[\dfrac{K_v^3\,\rho_w(\rho_l - \rho_w)\,g\,(h_{fg} + 0.4\,Cp_w\,\Delta T_e)}{\mu_w\, d\, \Delta T_e}\right]^{1/4}$ 2.170	
5.	Considering radiative heat transfer	$h = h_b\left[\dfrac{h_b}{h}\right]^{0.33} + h_r$ 2.171 $h_r = \dfrac{\sigma_s\,\varepsilon[T_w^4 - T_{Sat}^4]}{(T_w - T_{sat})}$ 2.172	
6.	Simplified relations for boiling heat transfer with water at atmospheric pressure	Surface — q, KW/m^2 — h, W/m^2°C 2.173 Horizontal — $q < 16$ — $1042\ (\Delta T_e)^{1/3}$ $16 < q < 240$ — $5.56\ (\Delta T_e)^3$ Vertical — $q < 3$ — $537\ (\Delta T_e)^{1/7}$ $3 < q < 63$ — $7.96\ (\Delta T_e)^3$	
7.	Boiling heat transfer with water at different pressures	$h_p = h\left[\dfrac{P}{P_1}\right]^{0.4}$ 2.174	

2.2.6 Condensation

Sl. No.	*Description*	*Correlation*	*Eq. No.*	*Notations*
1.	Laminar film wise condensation on a vertical plate	$h_m = 1.13 \left[\frac{g\rho_l(\rho_l-\rho_w)\,h_{fg}\,K_l^3}{\mu_l[T_v-T_w]\,L}\right]^{1/4}$ for Re < 1800 Physical Properties are evaluated at the film temperature $T_f = \frac{1}{2}[T_w + T_v]$	2.175	h_{fg} = Latent heat of condensation J/Kg L = Length of vertical plate T_v, T_w = Vapour and wall temperature, respectively $\dot{m}$ = Mass flow rate of condensate, Kg/sec P = Wetted Perimeter A_t = Condensing surface area, m^2 h_m = Average condensation heat transfer coefficient W/m^2°C N = Number of tubes L = Length of the tube $h_{m,\text{ vert}} = h_m$ for vertical tube $h_{m,\text{ horz}} = h_m$ for horizontal tube
2.	Film condensation on a vertical plate for turbulent flow	$h_m = 0.0077\,(\text{Re})^{0.4}\left[\frac{K_l^3\,\rho_l^2\,g}{\mu_l^2}\right]^{1/3}$ for Re > 1800 Reynolds number Re $= \frac{4\,\dot{m}}{\mu_l . P}$ P = Wetted perimeter for a vertical plate of width 'w' = πD for a vertical tube of outside diameter D = $2L$ for horizontal tubes each of length L arranged in vertical tiers $\dot{m} = \frac{A_t\,h_m\,[T_v - T_w]}{h_{fg}}$	2.176	
3.	Film condensation on Inclined plates	replace g by g Cos θ in above equations		
4.	Film condensation on horizontal tube and on horizontal tube banks	$h_m = 0.725\left[\frac{g\,\rho_l\,(\rho_l-\rho_w)\,h_{fg}\,K_l^3}{\mu_l[T_v - T_w]\,Nd}\right]^{1/4}$	2.177	
5.	Comparison for film wise condensation on a vertical tube of length 'L' and a horizontal tube of diameter 'd'	$\frac{h_{m,\text{vert}}}{h_{m,\text{horz}}} = 1.3\left[\frac{d}{L}\right]^{1/4}$	2.178	

10.	If $C_h < C_c$	$\varepsilon = \dfrac{T_{hi} - T_{ho}}{T_{hi} - T_{ci}}$ 2.189	C_h, C_c = Heat capacity of hot and cold fluid, W/k N = Number of Transfer Units (NTU) f = Friction factor V_t = Mass velocity of the tube fluid, Kg/m^{2}s L = Length of the tube n = Number of tube passes g = Gravitational acceleration, 9.8 m/s^2 ρ_t = Density of tube fluid, Kg/m^3 d_i = Inside diameter of a tube ϕ = Viscosity correction factor V_s = Shell side mass velocity, Kg/m^2 s N = Number of shell passes ρ_s = Density of shell fluid, Kg/m^3 D_h = Hydraulic diameter of the shell D_i = Inside diameter of the shell d_o = Outside diameter of the tube N_t = Number of tubes in the shell
11.	If $C_c < C_h$	$\varepsilon = \dfrac{T_{co} - T_{ci}}{T_{hi} - T_{ci}}$ 2.190	
12.	Correction factor	$F = \dfrac{\dfrac{\sqrt{R^2+1}}{R-1} \ln\left[\dfrac{1-P}{1-RP}\right]}{\ln\left[\dfrac{(2/P)-1-R+\sqrt{R^2+1}}{(2/P)-1-R-\sqrt{R^2+1}}\right]}$ 2.191	
		Where, $P = \left[\dfrac{T_{co} - T_{ci}}{T_{hi} - T_{ci}}\right]$	
		$R = \left[\dfrac{T_{hi} - T_{ho}}{T_{co} - T_{ci}}\right]$	
13.	Tube-side pressure drop	$\Delta P_t = \dfrac{f\, V_t^2 . L . n}{2 g \rho_t\, di\, \phi_t}$ 2.192 Where, $\phi_t = (\mu/\mu_w)^m$, $m = 0.14$ Re > 2100 $= 0.25$ Re < 2100	
14.	Shell-side pressure drop for an unbaffled shell	$\Delta P_s = \dfrac{f\, V_s^2 . L . N}{2 g \rho_s\, D_h\, \phi_s}$ 2.193	
		Where, $\phi_s = \left[\dfrac{\mu}{\mu_w}\right]^{0.14}$	
		$D_h = \dfrac{4[(\pi D_i^2/4) - (\pi d_o^2 N_t)]}{\pi d_o N_t + \pi D_i}$	
15.	Shell-side pressure drop for a shell with segmental baffles	$\Delta P_s = \dfrac{f\, V_s^2\, D_i\, (N_b + 1)}{2 g \rho_s\, D_h\, \phi_s}$ 2.194	
		N_b = Number of bottles	

Table 2.4 Effectiveness and NTU relations for Heat Exchangers

Sl. No.	*Flow Arrangement*	*Effectiveness Relation (ε)*	*NTU Relation (N)*
1.	*Concentric tube* Parallel flow	$\varepsilon = \frac{1 - \exp[-N(1+C)]}{1+C}$	$N = \frac{-\ln[1-\varepsilon(1+C)]}{1+C}$
2.	Counter flow	$\varepsilon = \frac{1 - \exp[-N(1-C)]}{1 - C\exp[-N(1-C)]} \quad (C < 1)$	$N = \frac{1}{C-1} \ln\left(\frac{\varepsilon - 1}{\varepsilon C - 1}\right) \quad (C < 1)$
		$\varepsilon = \frac{N}{1+N} \quad (C = 1)$	$N = \frac{\varepsilon}{1-\varepsilon} \quad (C = 1)$
3.	*Cross flow* – Both fluids unmixed	$\varepsilon = 1 - \exp\left[\frac{\exp(-NCn) - 1}{Cn}\right]$ where, $C \times n = N^{-0.22}$,	
4.	*Cross flow* – Both fluids mixed	$\varepsilon = \left[\frac{1}{1-\exp(-N)} + \frac{C}{1-\exp(-NC)} - \frac{1}{N}\right]^{-1}$	
5.	C_{max} mixed, C_{min} unmixed	$\varepsilon = (1/C)\{1 - \exp[-C(1 - e^{-N})]\}$	$N = -\ln\left[1 + \frac{1}{C}\ln(1 - C\varepsilon)\right]$
6.	C_{max} unmixed, C_{min} mixed	$\varepsilon = 1 - \exp\{-(1/C)[1 - \exp(-NC)]\}$	$N = \frac{-1}{C} \ln[1 + C\ln(1-\varepsilon)]$
7.	*Shell and Tube* One shell pass, 2, 4, 6 ... tube passes	$\varepsilon = 2\left\{1 + c + (1 + c^2)^{1/2} \times \frac{1 + \exp[-N(1+C^2)^{1/2}}{1 - \exp[-N(1+C^2)^{1/2}}\right\}^{-1}$	$N = -(1 + C^2)^{-1/2} \ln\left(\frac{E-1}{E+1}\right)$
			$E = \frac{2/\varepsilon - (1+C)}{(1+C^2)^{1/2}}$

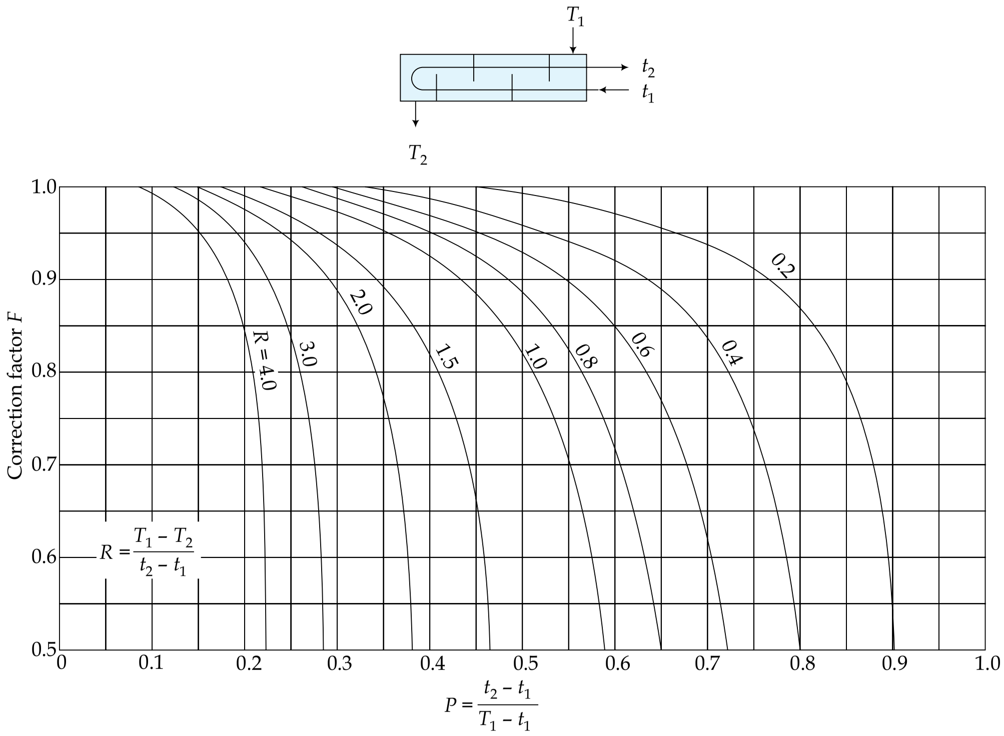


Fig. 2.13 Correction factor plot for exchanger with one shell pass and two, four, or any multiple of tube passes

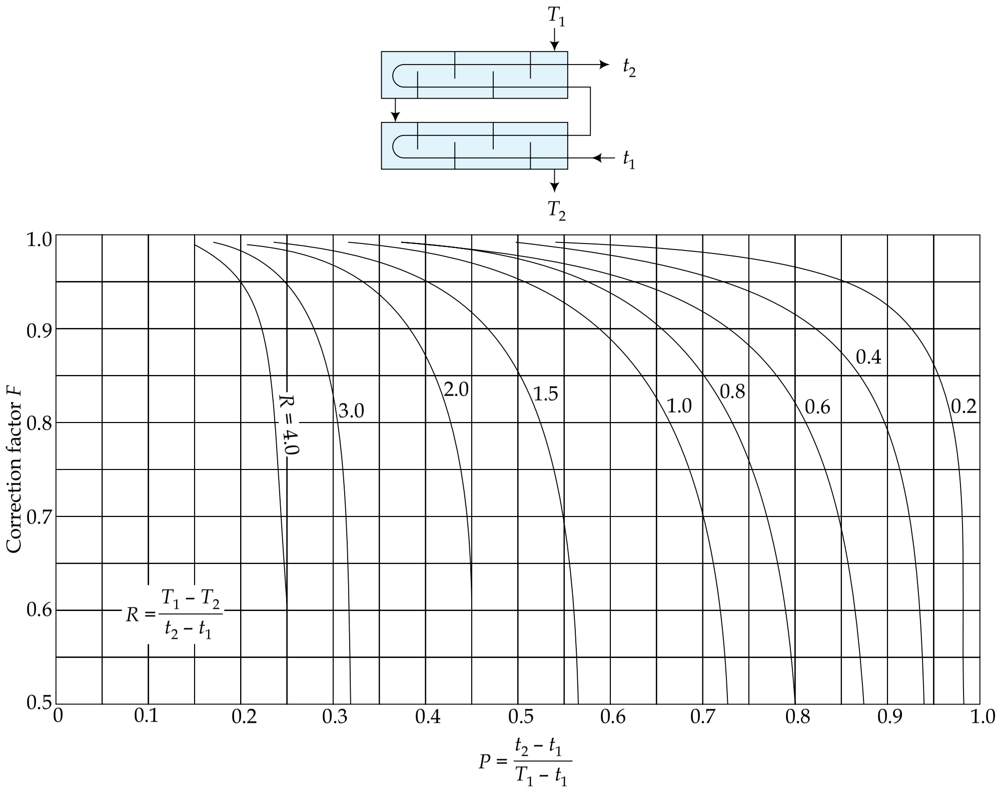


Fig. 2.14 Correction factor plot for exchanger with two shell pass and four, eight, or any multiple tube passes

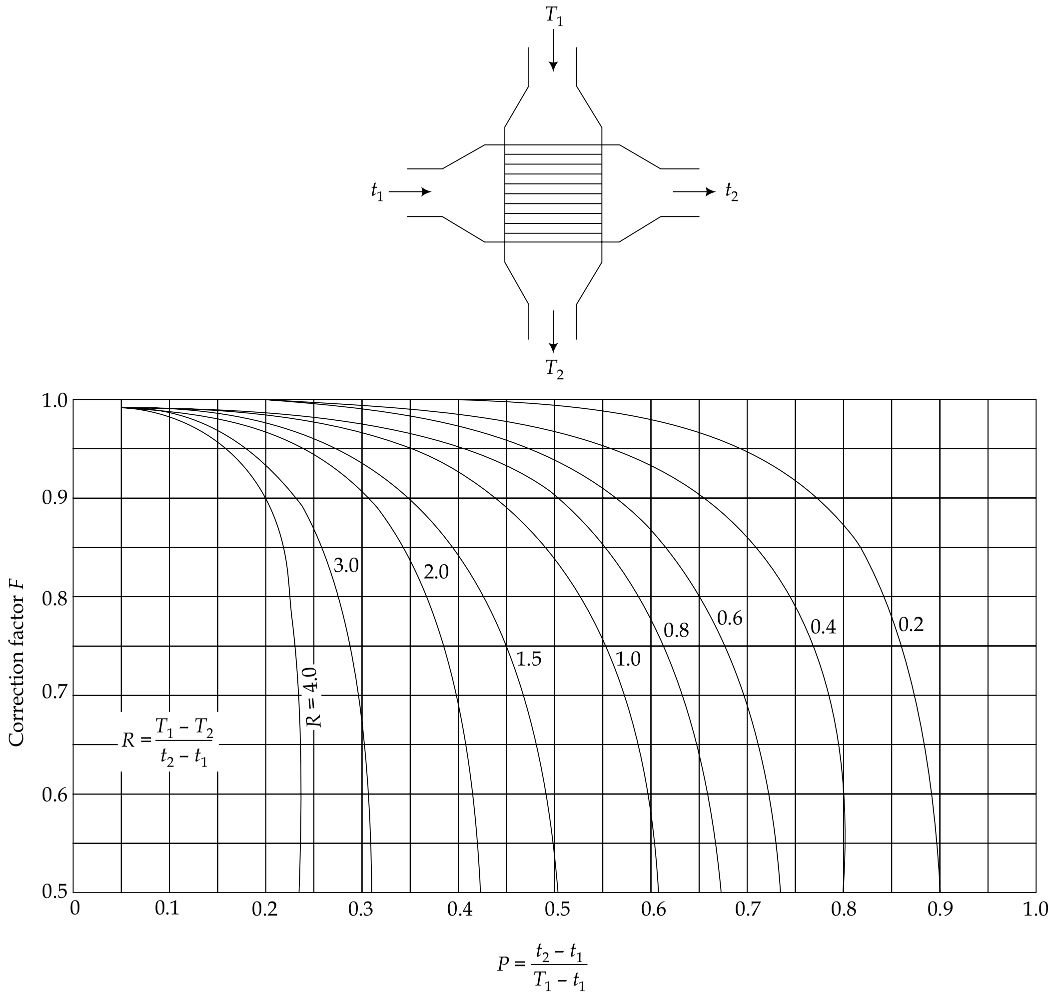


Fig. 2.16 Correction factor plot for single pass cross flow heat exchangers, one fluid mixed and the other unmixed

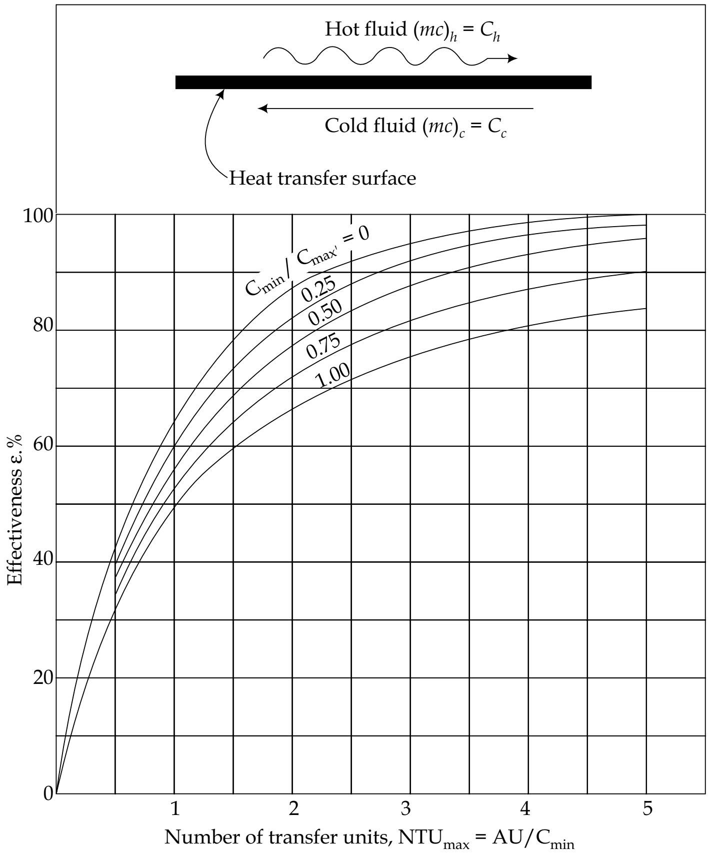


Fig. 2.18 Effectiveness for counter flow exchanger

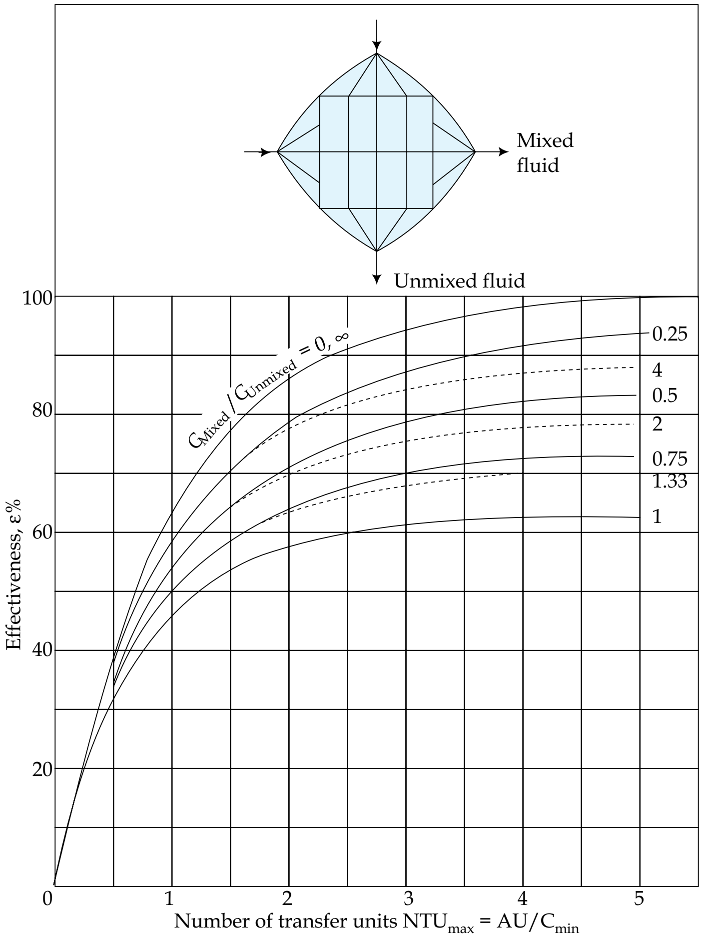


Fig. 2.19 Effectiveness for cross flow exchanger with one fluid mixed

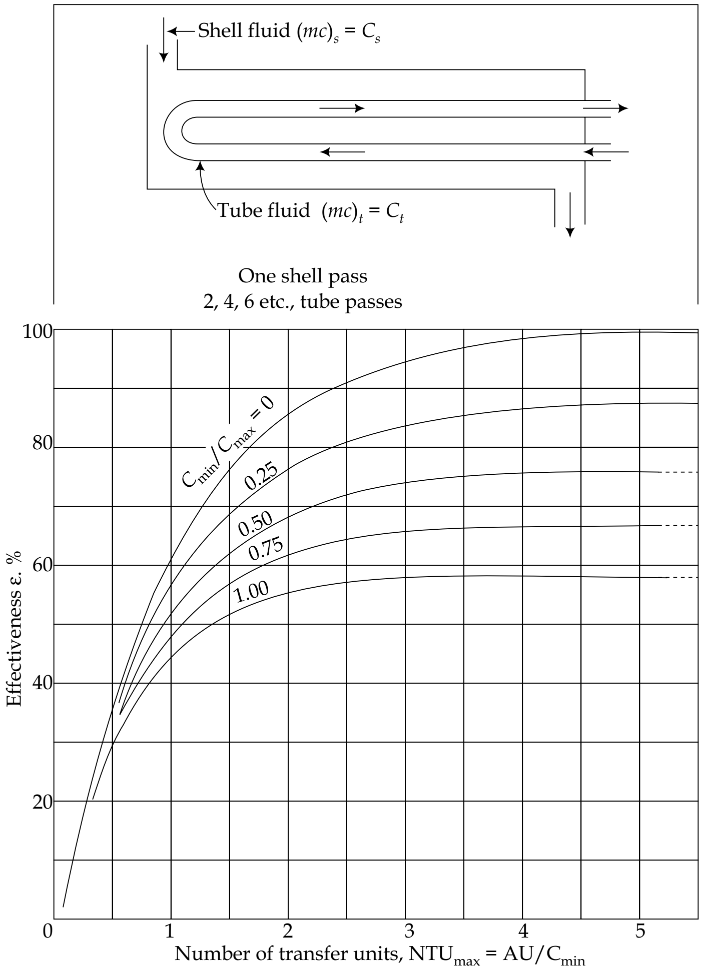


Fig. 2.21 Effectiveness for 1-2 parallel counter flow exchanger performance

2.3 RADIATION HEAT TRANSFER

Sl. No.	Description	Correlation	Eq. No.	Notations
1.	Wave length	$\lambda = C/\gamma$	2.195	λ = Wavelength, μm c = Speed of light = C_o/n $C_o = 2.998 \times 10^8$ m/s n = 1 for gases n = 1.5 for Glass E = Energy radiated h = Plank coefficient = 6.625×10^{-34} J-S γ = Frequency of Quantum K = Boltzmann's constant = 1.38066×10^{-23} J/molecule.K T = Absolute temperature $C_1 = 3.743 \times 10^8$ W.μm^4/m^2 $C_2 = 1.4387 \times 10^4$ μmK C_3 = 2897.6 μmK σ = Stefen-Boltzmann's constant = 5.67×10^{-8} W/m^{2}K^4 λ_{max} = Wavelength at which emissive power is maximum α = Absorptivity τ = Transmissivity ρ = Reflectivity E = Emissive power of a surface E_b = Emissive power of a black surface ε = Emissivity
2.	Quantum theory	$E = h\gamma$	2.196	
3.	Energy density of radiation per unit volume and per unit wavelength	$U_\lambda = \dfrac{8\pi hc\lambda^{-5}}{e^{hc/\lambda KT} - 1}$	2.197	
4.	Plank's Equation - manochromatic emissive power of a black body	$E_{b\lambda} = \dfrac{C_1\lambda^{-5}}{\exp(C_2/\lambda T) - 1}$	2.198	
5.	Wien's displacement law	$\lambda_{max}.T = C_3$	2.199	
6.	Stefan - Boltzmann law - Emissive power of a black body	$E_b = \sigma\, T^4$	2.200	
7.	Radiation emitted by a black body per unit area over wavelength band from $\lambda = 0$ to λ	$E_{b,\,0\text{-}\lambda}(T) = \int_0^\lambda E_{b\lambda}\,(T)\; d\lambda$	2.201	
8.	Radiant energy emitted by the black body between wavelengths λ_1 and λ_2	$E_{b,\lambda_1-\lambda_2} = E_{b,0-\lambda_2} - E_{b,0-\lambda_1}$	2.202	
9.	Radiant property	$\alpha + \tau + \rho = 1$	2.203	
10.	Emissivity of real surface	$\varepsilon = (E/E_b)$	2.204	
11.	Radiant energy emitted by real surface per unit area at temperature T,	$E = \varepsilon.\sigma\, T^4$	2.205	
12.	Kirchoff's Law	$\varepsilon = \alpha$	2.206	
13.	Relation between Irradiation (G) and Radiosity (J)	$J = \rho G + \varepsilon.E_b$	2.207	
14.	Net energy leaving a surface	$Q = [J - G]A = \dfrac{E_b - J}{(1-\varepsilon)/\varepsilon A}$	2.208	
15.	Total radiation which leaves surface 1 that reaches surface 2	$Q_{12} = \dfrac{J_1 - J_2}{1/A_1F_{12}}$	2.209	

16.	Radiation-balance equation for constant surface temperature of i_{th} surface	$J_i\,[1 - F_{ii}(1 - \varepsilon_i)] - (1 - \varepsilon_i) \sum_{j \neq i} F_{ij}\, J_j = \varepsilon_i\, E_{bi}$	2.210	A = Heat transfer area, m^2 J_1, J_2 = Radiosity of surface 1 & 2 respectively A_1, A_2 = Areas of surface 1 & 2 respectively J_i = Radiosity of 'i'th surface ε_i = Emissivity of 'i'th surface F_{ij} = View factor from surface 'i' to surface 'j' E_{bi} = J_i for insulated surface $F_{A_1 - A_2}$ (or) $F_{1\text{-}2}$ = View factor from (or) a surface of area A_1 to another surface of area A_2 r = Distance between the two surfaces f_{12} = Interchange factor from surface 1 to surface 2 T_1, T_2 = Temperature of body 1 & 2, respectively Q_{net} = Net heat interchange between the bodies, W
17.	Radiation-balance equation for surface in radiant balance i.e., Q/A	$J_i\,(1 - F_{ii}) - \sum_{j \neq i} F_{ij}\, J_j = 0$	2.211	
18.	Radiation-balance equation for surface with specified heat flux	$J_i\,(1 - F_{ii}) - \sum_{j \neq i} F_{ij}\, J_j = \dfrac{Q_i}{A_i}$	2.212	
19.	Shape factor (or) view factor between two finite surfaces	$F_{A_1 - A_2} = \dfrac{1}{A_1} \int_{A_1}\int_{A_2} \dfrac{\cos\theta_1 \cos\theta_2}{\pi r^2}\, dA_1\, dA_2$	2.213a	
		$F_{A_2 - A_1} = \dfrac{1}{A_2} \int_{A_1}\int_{A_2} \dfrac{\cos\theta_1 \cos\theta_2}{\pi r^2}\, dA_1\, dA_2$	2.213b	
		$A_1 F_{A_1 - A_2} = A_2 F_{A_2 - A_1}$	2.213c	
20.	Radiant heat exchange between two bodies or surfaces	$Q_{\text{nef}} = f_{12}\, F_{12}\, \sigma A_1\, [T_1^{\,4} - T_2^{\,4}]$ $= f_{12}\, F_{21}\, \sigma A_2\, [T_1^{\,4} - T_2^{\,4}]$	2.214 2.215	
21.	*Radiation Shields* For Parallel Plate system containing N shields between two surfaces with emissivities of all surfaces equal	$Q_N = \dfrac{A\sigma\,[T_1^4 - T_2^4]}{(N+1)\,(2/\varepsilon - 1)}$	2.216	
22.	Ratio of heat transfer rates for parallel plate systems with N shields and with no shield	$\dfrac{Q_N}{Q_O} = \dfrac{1}{N+1}$ $Q_O = \dfrac{A\sigma\,[T_1^4 - T_2^4]}{(2/\varepsilon - 1)}$	2.217	

Table 2.4a View factor and Interchange factor for different configurations

Sl. No.	*Configuration*	*View factor* (F_{12})	*Inter change factor* (f_{12})	*Notations*
1.	Infinite Parallel Plates	1	$\left(\frac{1}{\varepsilon_1}+\frac{1}{\varepsilon_2}-1\right)$	ε_1 & ε_2 = emissivity of body 1 and 2, respectively
2.	Body 1 completely enclosed by body 2, body 1 is very small	1	ε_1	
3.	Body 1 completely enclosed by body 2, body 1 is very large	1	$\frac{1}{\frac{1}{\varepsilon_1}+\frac{A_1}{A_2}\left(\frac{1}{\varepsilon_2}-1\right)}$	
4.	Concentric spheres or Infinitely long concentric cylinders	1	$\frac{1}{\frac{1}{\varepsilon_1}+\frac{A_1}{A_2}\left(\frac{1}{\varepsilon_2}-1\right)}$	
5.	Two rectangles with common side at right angles to each other	1	$\varepsilon_1\,\varepsilon_2$	
6.	Radiant exchange between two small gray bodies	F_{12}	$\varepsilon_1\,\varepsilon_2$	
7.	Radiant exchange between two black surfaces	F_{12}	1	

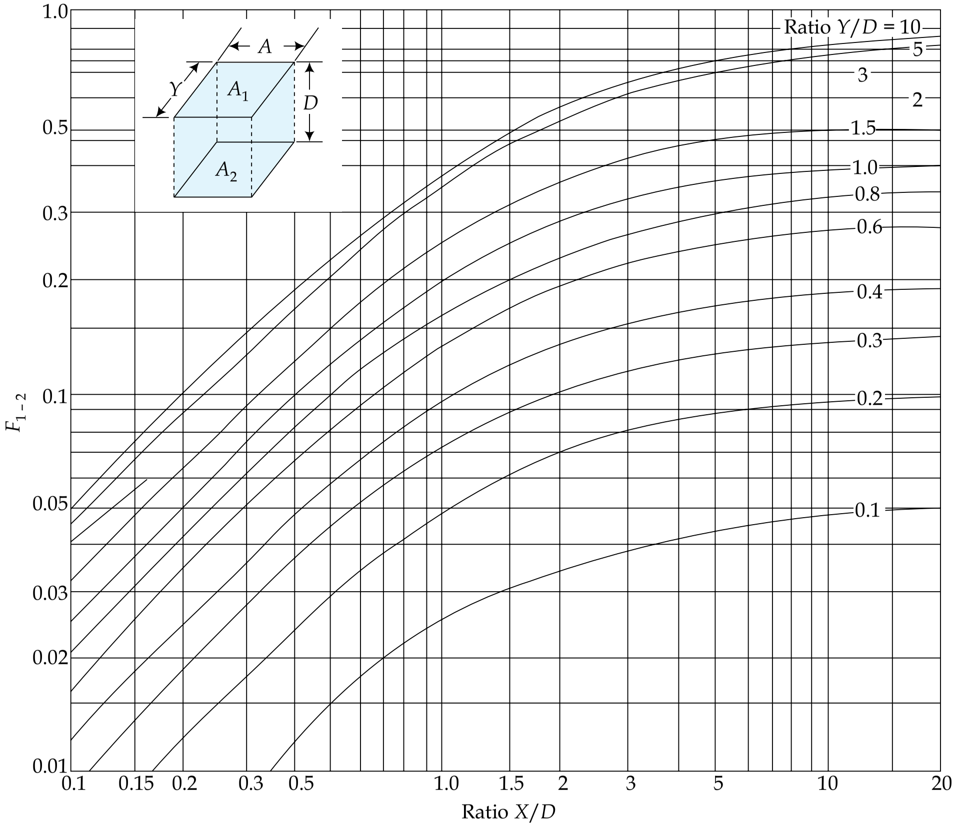
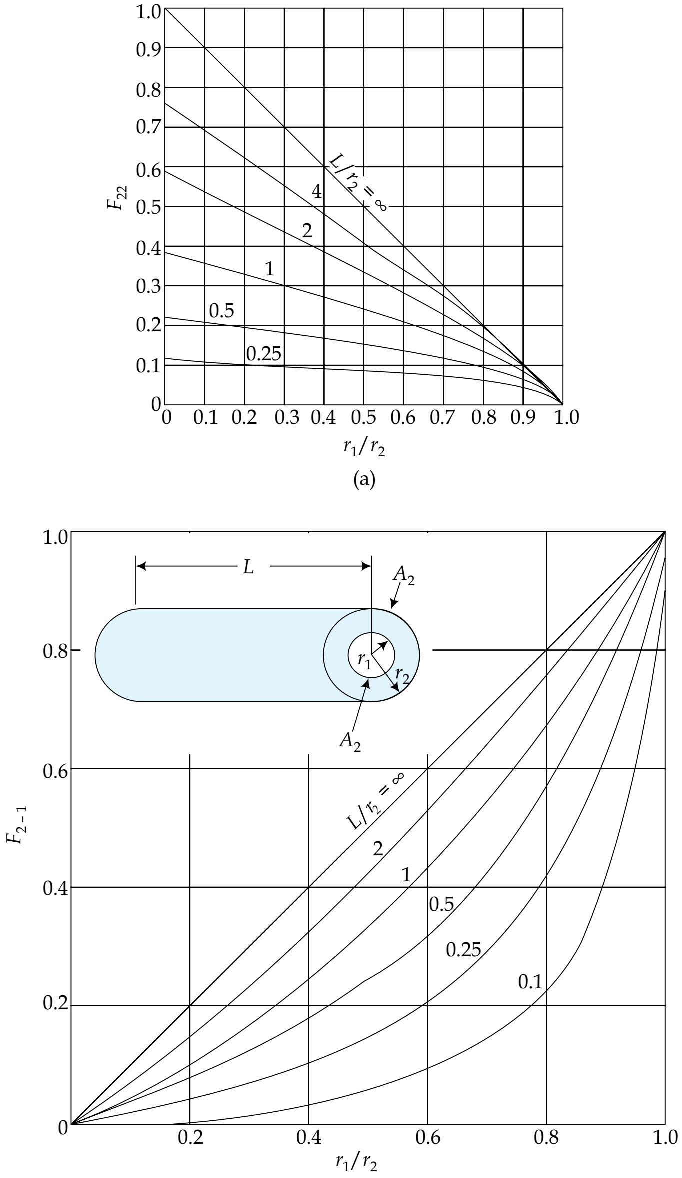


Fig. 2.24 Radiation shape factor for radiation between parallel rectangles



(b)

Fig. 2.27 Radiation shape factor for two concentric cylinders of finite length (a) Outer cylinder to itself (b) Outer cylinder to inner cylinders

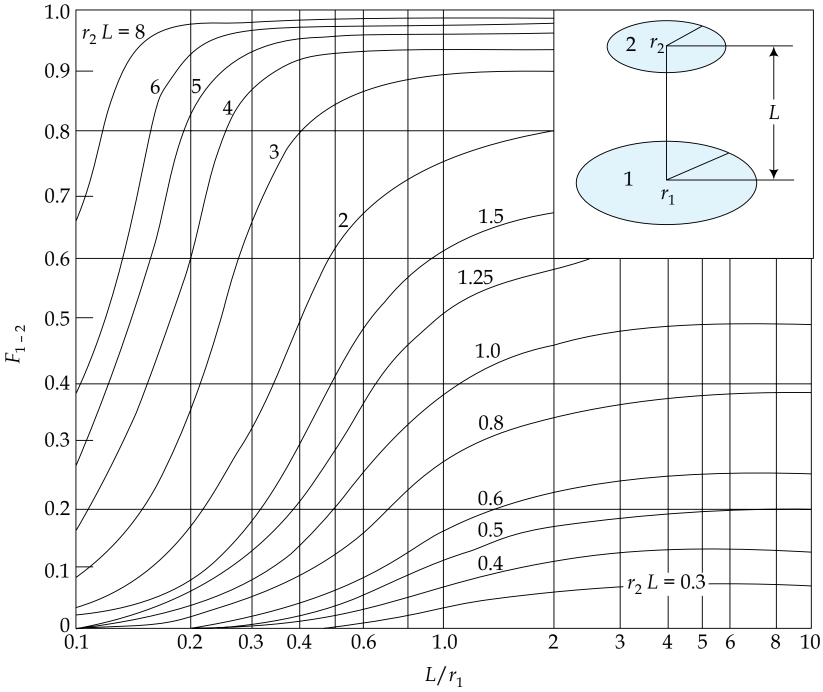


Fig. 2.28 Radiation shape factor for radiation between two parallel concentric disks

9.	Steady state diffusion across a layer of thickness Δx	$\dot{m}_A = \frac{-DA[C_{A_2} - C_{A_1}]}{\Delta x}$ $= h_D.A\,(C_{A2} - C_{A1})$	2.227	D_{mix} = Diffusion coefficient when component A diffuses into a mixture P_{mix2} & P_{mix1} = Partial Pressure of components other than diffusing component $\dot{m}_w$ = Mass flux of water M_w = Molecular weight of water P_{w1}, P_{w2} = Partial Pressure of water $(\Delta P)_{LM}$ = Log mean Partial pressures P_{a1}, P_{a2} = Partial Pressure of air h_D = Mass transfer coefficient B_i = Biot number F_o = Fourier number Sh_x = Sher wood number $= \frac{h_D.x}{D}$ Sc = Schmidt number $= \frac{\gamma}{D} = \frac{\mu}{\rho D}$ u_α = Free stream velocity D = Diffusion coefficient h = Heat transfer coefficient L_e = Lewis number $= \frac{Sc}{\text{Pr}} = \frac{\alpha}{D}$ α = Thermal diffusivity
10.	Steady state diffusion of component A into a stagnant mixture of component B, C, etc	$\frac{\dot{m}_A}{A} = D_{\text{mix}}.\frac{P\,M_A}{RT[x_2 - x_1]} \ln \frac{P_{\text{mix}\,2}}{P_{\text{mix}\,1}}$	2.228	
11.	Diffusion of water vapours through air	$\dot{m}_W = \frac{DA}{RT}\frac{M_w.P}{(x_2 - x_1)}\frac{[P_{W_1} - P_{W_2}]}{(\Delta P)_{LM}}$ $(\Delta P)_{LM} = \frac{P_{a_2} - P_{a_1}}{\ln \frac{P_{a_2}}{P_{a_1}}}$	2.229	
12.	Transient diffusion in an Infinite plate – The diffusion of 'A' of an Infinite plate of thickness $2L$ of 'B' having an initial concentration of A as $\dot{m}_{Ao}$, suddenly exposed to fluid mixture with concentration $\dot{m}_{A\alpha}$.	$\frac{\dot{m}_A - \dot{m}_{A\alpha}}{\dot{m}_{Ao} - \dot{m}_{A\alpha}} = e^{Bi,m\,Fo,m}$	2.230	
		$Bi,m = \frac{h_D\,L}{\rho\,D}$		
		$Fo,m = \frac{\varepsilon.D}{L^2}$		
13.	The diffusion of component 'A' in a semi-infinite plate of material 'B', having an initial concentration of A as $\dot{m}_{Ao}$, the slab is suddenly exposed to surface concentration $\dot{m}_{As}$	$\frac{\dot{m}_A - \dot{m}_{As}}{\dot{m}_{Ao} - \dot{m}_{As}} = \text{erf}\left[\frac{x}{z\sqrt{Dt}}\right]$	2.231	
14.	Flow over a Flat plate Laminar flow $(\text{Re}_x < 5 \times 10^5)$	$Sh_x = 0.332\ \text{Re}_x^{1/2}\ Sc^{1/3}$	2.232	
15.	Turbulent flow $(\text{Re}_x > 5 \times 10^5)$	$\overline{Sh}_x = 0.664\ \text{Re}_x^{1/2}\ Sc^{1/3}$	2.233	
16.	For mixed boundary layer condition	$Sh_L = (0.037\ \text{Re}_L^{4/5} - 870)\ Sc^{1/3}$	2.234	
17.	Flow over smooth flat plates: Laminar flow	$\frac{h_D}{u_\alpha}\ Sc^{2/3} = 0.332\ \text{Re}_x^{-1/2}$	2.235	

18.	Turbulent flow	$\frac{h_D}{u_\alpha} Sc^{2/3} = 0.0296 \text{ Re}_x^{-1/5}$	2.236	C & n are constants taken from the following table Re C n 0.4-4 0.989 0.330 4-40 0.911 0.385 40-4000 0.683 0.466 4,000-40,000 0.193 0.618 40,000-4,00,000 0.027 0.805
19.	Flow over cylinders and spheres	$Sh_D = C\,(\text{Re}_D)^h\ Sc^{1/3}$	2.237	
20.	Flow through the pipe Laminar flow for uniform wall mass concentration ($\text{Re}_D < 2000$)	$Sh = 3.66$	2.238	
21.	Laminar flow for uniform wall mass flux ($\text{Re}_D < 2000$)	$Sh = 4.36$	2.239	
22.	Turbulent flow ($\text{Re}_D > 2000$)	$Sh = 0.023 \text{ Re}^{0.83}\ Sc^{1/3}$	2.240	
23.	Simultaneous heat and mass transfer	$\frac{h}{h_D} = \rho Cp\ Le^{2/3}$	2.241	

Cr-Ni (chrome-nickel):														
15% Cr, 10% Ni	7,865	0.46	19	0.527										
18% Cr, 8% Ni (V2A)	7,817	0.46	16.3	0.444		16.3	17	17	19	19	22	27	31	
20% Cr, 15% Ni	7,833	0.46	15.1	0.415										
25% Cr, 20% Ni	7,865	0.46	12.8	0.361										
Tungsten steel W = 0%	7,897	0.452	73	2.026										
1%	7,913	0.448	66	1.858										
5%	8,073	0.435	54	1.525										
10%	8,314	0.419	48	1.391										
Copper: Pure	8,954	0.3831	386	11.23	407	386	379	374	369	363	353			
Aluminum bronze 95% Cu, 5% Al	8,666	0.41	83	2.33										
Bronze 75% Cu, 25% Sn	8,666	0.343	26	0.859										
Red brass 85% Cu, 9% Sn, 6% Zn	8,714	0.385	61	1.804		59	71							
Brass 70% Cu, 30% Zn	8,522	0.385	111	3.412	88		128		144	147	147			
German silver 62% Cu, 15% Ni, 22% Zn	8,618	0.394	24.9	0.733	19.2		31	40	45	48				
Constantan 60% Cu, 40% Ni	8,922	0.41	22.7	0.612	21		22.2	26						
Magnesium: Pure	1,746	1.013	171	9.708	178	171	168	163	157					
Mg-Al (electrolytic) 6-8% Al, 1-2% Zn	1,810	1	66	3.605		52	62	74	83					
Molybdenum	10,220	0.251	123	4.79	138	125	118	114	111	109	106	102	99	92
Nickel: Pure (99.9%)	8,906	0.4459	90	2.266	104	93	83	73	64	59				
Ni-Cr 90% Ni, 10% Cr	8.666	0.444	17	0.444		17.1	18.9	20.9	22.8	24.6				
80% Ni, 20% Cr	8,314	0.444	12.6	0.343		12.3	13.8	15.6	17.1	18	22.5			
Silver: Purest	10,524	0.234	419	17.00	419	417	415	412						
Pure (99.9%)	10,525	0.234	407	16.56	419	410	415	374	362	360				
Tin, pure	7,304	0.2265	64	3.884	74	65.9	59	57						
Tungsten	19,350	0.1344	163	6.271		166	151	142	133	126	112	76		
Zine, pure	7,144	0.3843	112.2	4.106	114	112	109	106	100	93				

**Constructed based on the data compiled in Refs. [15-26]

Table 2.6 Properties of Non-metals**

Substance	*Temperature* °C	*K* *W/m °C*	ρ *kg/m*^{3}	C_p *kJ/kg. °C*	$\alpha \times 10^7$ m^2/s
Structural and heat-resistant materials					
Asphalt	20-55	0.74-0.76			
Brick: Building brick, common	20	0.69	1600	0.84	5.2
Face		1.32	2000		
Carborundum brick	600		18.5		
	1400		11.1		
Chrome brick	200	2.32	3000	0.84	9.2
	550	2.47			9.8
	900	1.99			7.9
Diatomaceous earth, molded and fired	200	0.24			
	870	0.31			
Fireclay brick, burnt 2426°F	500	1.04	2000	0.96	5.4
	800	1.07			
	1100	1.09			
Burnt 2642°F	500	1.28	2300	0.96	5.8
	800	1.37			
	1100	1.40			
Missouri	200	1.00	2600	0.96	4.0
	600	1.47			
	1400	1.77			
Magnesite	200	3.81		1.13	
	650	2.77			
	1200	1.90			
Cement portland		0.29	1500		
Mortar	23	1.16			
Concrete, cinder	23	0.76			
Stone, 1-2-4 mix	20	1.37	1900-2300	0.88	8.2-6.8
Glass, window	20	0.78 (avg)	2700	0.84	3.4
Corosilicate	30-75	1.09	2200		
Plaster, gypsum	20	0.48	1440	0.84	4.0
Metal lath	20	0.47			
Wood lath	20	0.28			
Stone: Granite		1.73-3.98	2640	0.82	8-18
Limestone	100-300	1.26-1.33	2500	0.90	5.6-5.9
Marble		2.07-2.94	2500-2700	0.80	10-13.6
Sandstone	40	1.83	2160-2300	0.71	11.2-11.9

Wood (across the grain):					
balsa, 8.8 lb/ft^3	30	0.055	140		
Cypress	30	0.097	460		
Fir	23	0.11	420	2.72	0.96
Maple or oak	30	0.166	540	2.4	1.28
Yellow pine	23	0.147	640	2.8	0.82
White pine	30	0.112	430		
		Insulating material			
Asbestos: Loosely packed	–45	0.149			
	0	0.154	470-570	0.816	3.3-4
	100	0.161			
Asbestos-cement	20	0.74			
Boards					
Sheets Felt,	51	0.166			
40 laminations/in	38	0.057			
	150	0.069			
	260	0.083			
20 laminations/in	38	0.078			
	150	0.095			
	260	0.112			
corrugated, 4 plies/in	38	0.087			
	93	0.100			
	150	0.119			
Asbestos cement	-	2.08			
Balsam wool, 2.2 lb/ft^3	32	0.04	35		
Cardboard, corrugated	-	0.064			
Celotex	32	0.048			
Corkboard, 10 lb/ft^3	30	0.043	160		
Cork, regranulated	32	0.045	45-120	1.88	2-5.3
Ground	32	0.043	150		
Diatomaceous earth (sio-o-cel)	0	0.061	320		
Felt, hair	30	0.036	130-200		
Wool	30	0.052	330		
Fiber, insulating board	20	0.048	240		
Glass wool, 1.5 lb/ft^3	23	0.038	24	0.7	22.6
Insulex, dry	32	0.064			
		0.144			
Kapok	30	0.035			
Magnesia, 85%	38	0.067	270		
	93	0.071			
	150	0.074			
	204	0.080			

0	1,438.46	1.3636	0.257	0.211	1.081	2.38	1.94×10^{-3}
10	1,412.51	1.3645	0.232	0.204	1.066	2.18	
20	1,386.40	1.3653	0.210	0.199	1.050	2.00	
30	1,359.33	1.3662	0.190	0.192	1.035	1.83	
40	1,329.22	1.3674	0.173	0.185	1.019	1.70	
50	1,299.10	1.3683	0.162	0.177	0.999	1.61	
Dichlorodifluoromethane (Freon), CCl_2F_2							
–50	1,546.75	0.8750	0.310×10^{-6}	0.067	0.501×10^{-7}	6.2	2.63×10^{-3}
–40	1,518.71	0.8847	0.279	0.069	0.514	5.4	
–30	1,489.56	0.8956	0.253	0.069	0.526	4.8	
–20	1,460.57	0.9073	0.235	0.071	0.539	4.4	
–10	1,429.49	0.9203	0.221	0.073	0.550	4.0	
0	1,397.45	0.9345	0.214×10^{-6}	0.073	0.557×10^{-6}	3.8	
10	1,364.30	0.9496	0.203	0.073	0.560	3.6	
20	1,330.18	0.9659	0.198	0.073	0.560	3.5	
30	1,295.10	0.9835	0.194	0.071	0.560	3.5	
40	1,257.13	1.0019	0.191	0.069	0.555	3.5	
50	1,215.96	1.0216	0.190	0.067	0.545	3.5	
Glycerin, $C_3H_5(OH)_3$							
0	1,276.03	2.261	0.00831	0.282	0.983×10^{-7}	4.7×10^{3}	0.50×10^{-3}
10	1,270.11	2.319	0.00300	0.284	0.965	1.0	
20	1,264.02	2.386	0.00118	0.286	0.947	2.5	
30	1,258.09	2.445	0.00050	0.286	0.929	5.38	
40	1,252.01	2.512	0.00022	0.286	0.914	2.45	
50	1,244.96	2.583	0.00015	0.287	0.893	1.63	
Ethylene glycol, $C_2H_4(OH)_2$							
0	1,130.75	2.294	57.53×10^{-6}	0.242	0.934×10^{-7}	615	0.65×10^{-3}
20	1,116.65	2.382	19.18	0.249	0.939	204	
40	1,101.43	2.474	8.69	0.256	0.939	93	
60	1,087.66	2.562	4.75	0.260	0.932	51	
80	1,077.56	2.650	2.98	0.261	0.921	32.4	
100	1,058.50	2.742	2.03	0.263	0.908	22.4	
Engine oil (unused)							
0	899.12	1.796	0.00428	0.147	0.911×10^{-7}	47,100	0.70×10^{-3}
20	888.23	1.880	0.00090	0.145	0.872	10,400	
40	876.05	1.964	0.00024	0.144	0.834	2,870	
60	864.04	2.047	0.834×10^{-4}	0.140	0.800	1,050	
80	852.02	2.131	0.375	0.138	0.769	490	
100	840.01	2.219	0.203	0.137	0.738	276	

120	828.96	2.307	0.124	0.135	0.710	175	
140	816.94	2.395	0.080	0.133	0.686	116	
160	805.89	2.483	0.056	0.132	0.663	84	
Mercury, Hg							
0	13,628.22	0.1403	0.124×10^{-6}	8.20	42.99×10^{7}	0.0288	
20	13,579.04	0.1394	0.114	8.69	46.06	0.0249	1.82×10^{-4}
50	13,505.84	0.1386	0.104	9.40	50.22	0.0207	
100	13,384.58	0.1373	0.0928	10.51	57.16	0.0162	
150	13,264.28	0.1365	0.0853	11.49	63.54	0.0134	
200	13,144.94	0.1570	0.0802	12.34	69.08	0.0116	
250	13,025.60	0.1357	0.0765	13.07	74.06	0.0103	
315.5	12,847	0.134	0.0673	14.02	81.5	0.0083	
Eutectic calcium chloride solution, 29.9% $CaCl_2$							
–50	1,319.76	2.608	36.35×10^{-6}	0.402	1.166	312	
–40	1,314.96	2.6356	24.97	0.415	1.200	208	
–30	1,310.15	2.6611	17.18	0.429	1.234	139	
–20	1,305.51	2.688	11.04	0.445	1.267	87.1	
–10	1,300.70	2.713	6.96	0.459	1.300	53.6	
0	1,296.06	2.738	4.39	0.472	1.332	33.0	
10	1,291.41	2.763	3.35	0.485	1.363	24.6	
20	1,286.61	2.788	2.72	0.498	1.394	19.6	
30	1,281.96	2.814	2.27	0.511	1.419	16.0	
40	1,277.16	2.839	1.92	0.523	1.445	13.3	
50	1,272.51	2.868	1.65	0.535	1.468	11.3	
Methyl chloride, CH_3Cl							
–50	1,052.58	1.4759	0.320×10^{-6}	0.215	1.388	2.31	
–40	1,033.35	1.4826	0.318	0.209	1.368	2.32	
–30	1,016.53	1.4922	0.314	0.202	1.337	2.35	
–20	999.39	1.5043	0.309	0.196	1.301	2.38	
–10	981.45	1.5194	0.306	0.187	1.257	2.43	
0	962.39	1.5378	0.302	0.178	1.213	2.49	
10	942.36	1.5600	0.297	0.171	1.166	2.55	
20	923.31	1.5860	0.293	0.163	1.112	2.63	
30	903.12	1.6161	0.288	0.154	1.058	2.72	
40	883.10	1.6504	0.281	0.144	0.996	2.83	
50	861.15	1.6890	0.274	0.133	0.921	2.97	

[T] Constructed based on the data compiled in Refs. [23,24]

Table 2.8 Properties of Water (Saturated Liquid)**

°C	c_p kJ/kg. °C	ρ, kg/m^2	μ, kg/ms	k, W/m °C	Pr	$Gr_x Pr$
0	4.225	999.8	1.79×10^{-3}	0.566	13.25	
4.44	4.208	999.8	1.55	0.575	11.35	1.91×10^9
10	4.195	999.2	1.31	0.585	9.40	6.34×10^9
15.56	4.186	998.6	1.12	0.595	7.88	1.08×10^{10}
21.11	4.179	997.4	9.8×10^{-4}	0.604	6.78	1.46×10^{10}
26.67	4.179	995.8	8.6	0.614	5.85	1.91×10^{10}
32.22	4.174	994.9	7.65	0.623	5.12	2.48×10^{10}
37.78	4.174	993.0	6.82	0.630	4.53	3.3×10^{10}
43.33	4.174	990.6	6.16	0.637	4.04	4.19×10^{10}
48.89	4.174	988.8	5.62	0.644	3.64	4.89×10^{10}
54.44	4.179	985.7	5.13	0.649	3.30	5.66×10^{10}
60	4.179	983.3	4.71	0.654	3.01	6.48×10^{10}
65.55	4.183	980.3	4.3	0.659	2.73	7.62×10^{10}
71.1	4.186	977.3	4.01	0.665	2.53	8.84×10^{10}
76.67	4.191	973.7	3.72	0.668	2.33	9.85×10^{10}
82.22	4.195	970.2	3.47	0.673	2.16	1.09×10^{11}
87.78	4.199	966.7	3.27	0.675	2.03	
93.33	4.204	963.2	3.06	0.678	1.90	
104.4	4.216	955.1	2.67	0.684	1.66	
115.6	4.229	946.7	2.44	0.685	1.51	
126.7	4.250	937.2	2.19	0.685	1.36	
137.8	4.271	928.1	1.98	0.685	1.24	
148.9	4.296	918.0	1.86	0.684	1.17	
176.7	4.371	890.4	1.57	0.677	1.02	
204.4	4.467	859.4	1.36	0.665	1.00	
232.2	4.585	825.7	1.20	0.646	0.85	
260	4.731	785.2	1.07	0.616	0.83	
287.7	5.024	735.5	9.51×10^{-5}			
315.6	5.703	678.7	8.68			

Table 2.10 Properties of Gases at Atmospheric Pressure**

T, K	*ρ, kg/m*^{3}	c_p, *kJ/kg. °C*	*μ, kg/m s*	*V, m*^{2}*/s*	*k, W/m.°C*	*α, m*^{2}*/s*	*Pr*
Helium							
144	0.3379	5.200	125.5×10^{-7}	37.11×10^{-6}	0.0928	0.5275×10^{-4}	0.70
200	0.2435	5.200	156.6	64.38	0.1177	0.9288	0.694
255	0.1906	5.200	181.7	95.50	0.1357	1.3675	0.70
366	0.13280	5.200	230.5	173.6	0.1691	2.449	0.71
477	0.10204	5.200	275.0	269.3	0.197	3.716	0.72
589	0.08282	5.200	311.3	375.8	0.225	5.215	0.72
700	0.07032	5.200	347.5	494.2	0.251	6.661	0.72
800	0.06023	5.200	381.7	634.1	0.275	8.774	0.72
Hydrogen							
150	0.16371	12.602	5.595×10^{-7}	34.18×10^{-6}	0.0981	0.475×10^{-4}	0.718
200	0.12270	13.540	6.813	55.53	0.1282	0.772	0.719
250	0.09819	14.059	7.919	80.64	0.1561	1.130	0.713
300	0.08185	14.314	8.963	109.5	0.182	1.554	0.706
350	0.07016	14.436	9.954	141.9	0.206	2.031	0.697
400	0.06135	14.491	10.864	177.1	0.228	2.568	0.690
450	0.05462	14.499	11.779	215.6	0.251	3.164	0.682
500	0.04918	14.507	12.636	257.0	0.272	3.817	0.675
550	0.04469	14.532	13.475	301.6	0.292	4.516	0.668
600	0.04085	14.537	14.285	349.7	0.315	5.306	0.664
700	0.03492	14.574	15.89	455.1	0.351	6.903	0.659
800	0.03060	14.675	17.40	569	0.384	8.563	0.664
900	0.02723	14.821	18.78	690	0.412	10.217	0.676
Oxygen							
150	2.6190	0.9178	11.490×10^{-6}	4.387×10^{-6}	0.01367	0.05688×10^{-4}	0.773
200	1.9559	0.9131	14.850	7.593	0.01824	0.10214	0.745
250	1.5618	0.9157	17.87	11.45	0.02259	0.15794	0.725
300	1.3007	0.9203	20.63	15.86	0.02676	0.22353	0.709
350	1.1133	0.9291	23.16	20.80	0.03070	0.2968	0.702
400	0.9755	0.9420	25.54	26.18	0.03461	0.3768	0.695
450	0.8682	0.9567	27.77	31.99	0.03828	0.4609	0.694
500	0.7801	0.9722	29.91	38.34	0.04173	0.5502	0.697
550	0.7096	0.9881	31.97	45.05	0.04517	0.641	0.700
Nitrogen							
200	1.7108	1.0429	12.947×10^{-6}	7.568×10^{-6}	0.01824	0.10224×10^{-4}	0.747
300	1.1421	1.0408	17.84	15.63	0.02620	0.22044	0.713

400	0.8538	1.0459	21.98	25.74	0.03335	0.3734	0.691
500	0.6824	1.0555	25.70	37.66	0.03984	0.5530	0.684
600	0.5687	1.0756	29.11	51.19	0.04580	0.7486	0.686
700	0.4934	1.0969	32.13	65.13	0.05123	0.9466	0.691
800	0.4277	1.1225	34.84	81.46	0.05609	1.1685	0.700
900	0.3796	1.1464	37.49	91.06	0.06070	1.3946	0.711
1000	0.3412	1.1677	40.00	117.2	0.06475	1.6250	0.724
1100	0.3108	1.1857	42.28	136.0	0.06850	1.8591	0.736
1200	0.2851	1.2037	44.50	156.1	0.07184	2.0932	0.748
Carbon dioxide							
220	2.4733	0.783	11.105×10^{-6}	4.490×10^{-6}	0.010805	0.05920×10^{-4}	0.818
250	12.1657	0.804	12.590	5.813	0.012884	0.07401	0.793
300	1.7973	0.871	14.958	8.321	0.016572	0.10588	0.770
350	1.5362	0.900	17.205	11.19	0.02047	0.14808	0.755
400	1.3424	0.942	19.32	14.39	0.02461	0.19463	0.738
450	1.1918	0.980	21.34	17.90	0.02897	0.24813	0.721
500	1.0732	1.013	23.26	21.67	0.03352	0.3084	0.702
550	0.9739	1.047	25.08	25.74	0.03821	0.3750	0.685
600	0.8938	1.076	26.83	30.02	0.04311	0.4483	0.668
Ammonia, NH_3							
273	0.7929	2.177	9.353×10^{-6}	1.18×10^{-5}	0.0220	0.1308×10^{-4}	0.90
323	0.6487	2.177	11.035	1.70	0.0270	0.1920	0.88
373	0.5590	2.236	12.886	2.30	0.0327	0.2619	0.87
423	0.4934	2.315	14.672	2.97	0.0391	0.3432	0.87
473	0.4405	2.395	16.49	3.74	0.0467	0.4421	0.84
Water vapour							
380	0.5863	2.060	12.71×10^{-6}	2.16×10^{-5}	0.0246	0.2036×10^{-4}	1.060
400	0.5542	2.014	13.44	2.42	0.0261	0.2338	1.040
450	0.4902	1.980	15.25	3.11	0.0299	0.307	1.010
500	0.4405	1.985	17.04	3.86	0.0339	0.387	0.996
550	0.4005	1.997	18.84	4.70	0.0379	0.475	0.991
600	0.3652	2.026	20.67	5.66	0.0422	0.573	0.986
650	0.3380	2.056	22.47	6.64	0.0464	0.666	0.995
700	0.3140	2.085	24.26	7.72	0.0505	0.772	1.000
750	0.2931	2.119	26.04	8.88	0.0549	0.883	1.005
800	0.2739	2.152	27.86	10.20	0.0592	1.001	1.010
850	0.2579	2.186	29.69	11.52	0.0637	1.130	1.019

Carbon monoxide[T]							
220	1.55363	1.0429	13.832×10^{-6}	8.903×10^{-6}	0.01906	0.1176×10^{-4}	0.758
250	1.3649	1.0425	15.40	11.28	0.02144	0.15063	0.750
300	1.13876	1.0421	17.843	15.67	0.02525	0.21280	0.737
350	0.97425	1.0434	20.09	20.62	0.02883	0.2836	0.728
400	0.85363	1.0484	22.19	25.99	0.03226	0.3605	0.722
450	0.75848	1.0551	24.18	31.88	0.0436	0.4439	0.718
500	0.68223	1.0635	26.06	38.19	0.03863	0.5324	0.718
550	0.62024	1.0756	27.89	44.97	0.04162	0.6240	0.721
600	0.56850	1.0877	29.60	52.06	0.04446	0.7190	0.724
Fuel Gases[T]							
273	1.295	1.043	15.78×10^{-6}	12.20×10^{-6}	22.79×10^{-3}	0.1688×10^{-4}	0.72
373	0.950	1.068	20.38	21.54	31.28	0.30833	0.69
473	0.748	1.097	24.49	32.80	40.12	0.48888	0.67
573	0.617	1.122	28.22	45.81	48.38	0.70000	0.65
673	0.525	1.151	31.68	60.38	56.99	0.94166	0.64
773	0.457	1.185	34.84	76.30	65.59	1.21111	0.63
873	0.405	1.214	37.85	93.61	74.19	1.51666	0.62
973	0.363	1.239	40.68	112.1	82.69	1.83888	0.61
1073	0.329	1.264	43.37	131.8	91.53	2.19722	0.60
1173	0.301	1.290	45.9	152.5	100.13	2.58055	0.59
1273	0.275	1.306	48.35	174.3	108.97	3.03333	0.58
1373	0.257	1.323	50.69	197.1	117.46	3.45555	0.57
1473	0.240	1.340	52.98	221.00	126.77	3.9525	0.56
Sulphur dioxide[T]							
273	2.926	0.607	1.23×10^{-6}	4.14	8.37×10^{-3}	0.0472×10^{-4}	0.874
373	2.140	0.662	1.64	7.51	12.33	0.0872	0.863
473	1.690	0.712	2.04	11.80	16.63	0.1244	0.856
573	1.395	0.754	2.43	17.10	21.28	0.2014	0.848
673	1.185	0.783	2.81	23.30	25.82	0.2777	0.834
753	1.033	0.808	3.19	30.40	30.70	0.3666	0.822
853	0.916	0.825	3.57	38.30	35.80	0.4722	0.806
953	0.892	0.837	3.94	46.80	41.05	0.5972	0.788
1073	0.743	0.850	4.30	56.50	46.29	0.7333	0.774
1173	0.681	0.858	4.66	66.80	51.87	0.8888	0.755
1273	0.626	0.867	5.02	78.30	57.57	1.0611	0.740

[T] Constructed based on the data compiled in Refs. [18, 23]

Table 2.12 Physical properties of liquid metals**

Metal	*Melting point, °C*	*Boiling point, °C*	*T, °C*	*ρ, kg/m^3*	*C_p, kJ/(kg.°C)*	*$\mu \times 10^4$ kg/(m.s)*	*$v \times 10^6$, m^2/s*	*k, W/(m.°C)*	*$\alpha \times 10^6$, m^2/s*	*Pr*
Bismuth	271	1477	315	10,011	0.144	16.2	0.160	16.4	11.25	0.0142
			538	9,739	0.155	11.0	0.113	15.6	10.34	0.0110
			760	9,467	0.165	7.9	0.083	15.6	9.98	0.0083
Lead	327	1737	371	10,540	0.159	2.40	0.023	16.1	9.61	0.024
			704	10,140	0.155	1.37	0.014	14.9	9.48	0.0143
Lithium	179	1317	204.4	509.2	4.365	5.416	1.1098	46.37	20.96	0.051
			315.6	498.8	4.270	4.465	0.8982	43.08	20.32	0.0443
			426.7	489.1	4.211	3.927	0.8053	38.24	18.65	0.0432
			537.8	476.3	4.171	3.473	0.7304	30.45	15.40	0.0476
Mercury	–38.9	357	–17.8	13,707.1	0.1415	18.334	0.1342	9.76	5.038	0.0266
			100	13,384.5	0.1373	12.420	0.0928	10.51	5.716	0.0162
			200	13,144.9	0.1570	10.541	0.0802	12.34	6.908	0.0116
Sodium	97.8	883	93.3	931.6	1.384	7.131	0.7689	84.96	56.29	0.0116
			204.4	907.5	1.339	4.521	0.5010	80.81	66.80	0.0075
			315.6	878.5	1.304	3.294	0.3766	75.78	66.47	0.00567
			426.7	852.8	1.277	2.522	0.2968	69.39	64.05	0.00464
			537.8	823.8	1.264	2.315	0.2821	64.37	62.09	0.00455
			648.9	790.0	1.261	1.964	0.2496	60.56	61.10	0.00408
			760.0	767.5	1.270	1.716	0.2245	56.58	58.34	0.00385
Potassium	63.9	760	426.7	741.7	0.766	2.108	0.2839	39.45	69.74	0.0041
			537.8	714.4	0.762	1.711	0.2400	36.51	67.39	0.0036
			648.9	690.3	0.766	1.463	0.2116	33.74	64.10	0.0033
			760.0	667.7	0.783	1.331	0.1987	31.15	59.86	0.0033
NaK (56% Na, 44% K)	–11.1	784	93.3	889.8	1.130	5.622	0.6347	25.78	27.76	0.0246
			204.4	865.6	1.089	3.803	0.4414	26.47	28.23	0.0155
			315.6	838.3	1.068	2.935	0.3515	27.17	30.50	0.0115
			426.7	814.2	1.051	2.150	0.2652	27.68	32.52	0.0081
			537.8	788.4	1.047	2.026	0.2581	27.68	33.71	0.0076
			648.9	759.5	1.051	1.695	0.2240	27.68	34.86	0.0064

**Data collected from Ref. [23]

Table 2.13 Normal Fouling Factors**

Type of fluid	*Fouling factor, m^2°C/W*
Sea water below 50°C	0.0001
Above 50°C	0.0022
Treated boiler feed water above 50°C	0.0002
River water below 50°C	0.0002 – 0.001
Fuel oil	0.0009
Refrigerating liquid	0.0002
Industrial air	0.0004
Steam, non-oil bearing	0.00009
Steam, oil bearing	0.0003 – 0.0004
Alcohol vapours	0.00009
Quenching oil	0.0007
Organic vapours	0.00009
Organic liquids	0.00018
Brine (Cooling)	0.00018
Exhaust steam	0.00018
Liquid gasoline and liquefied petroleum gases	0.0002 – 0.0004
Vegetable oil	0.0005
Caustic solution	0.0004
Methanol, ethanol and ethylene glycol solutions	0.0004
Natural gas	0.0002 – 0.0004
Compressed air	0.0002
Solvent vapours	0.0004 – 0.0005

**Constructed based on data compiled in Refs. [15 – 24]

Table 2.14 Magnitude of the Overall heat transfer coefficients**

Sl. No	*Fluid Combination*	*U, W/m^2 K*
1.	Water to Water	850 – 1700
2.	Water to Oil	110 – 350
3.	Steam condenser (Water in tubes)	1000 – 6000
4.	Ammonia condenser (Water in tubes)	800 – 1400
5.	Alcohol condenser (Water in tubes)	250 – 700
6.	Finned tube heat exchanger (Water in tubes, air in cross flow)	25 – 50
7.	Finned tube heat exchanger (Steam in tubes, air in cross flow)	28 – 280
8.	Gas to Gas	10 – 40
9.	Gas to Water	10 – 250
10.	Light organics to Water	370 – 730
11.	Heavy organics to Water	25 – 370
12.	Steam to Water	1000 – 3500

13.	Steam to ammonia	1000 – 3500
14.	Steam to gases	25 – 250
15.	Steam to light organics	500 – 1000
16.	Steam to heavy organics	30 – 300
17.	Steam to fuel oil	56 – 340
18.	Feed water heater	1100 – 8500
19.	Freon–12 condenser with water coolent	280 - 850

Constructed based on data compiled in Refs. [15 - 24]

Table 2.15 Surface Tension and other physical properties[**] for Boiling and Condensation Heat Transfer

Fluid	T_{Sat}, *K*	*P* (10^5 *N/m*^{2})	ρ_l (*kg/m*^{3})	ρ_v (*kg/m*^{3})	h_{fg} (*kJ/kg*)	σ (*N/m*)
Ammonia	223	0.409	702	0.38	1417	0.038
	300	10.66	600	8.39	1158	0.020
Ethanol	351	1.013	757	1.44	846	0.018
Helium	4.2	1.013	125	16.9	20.42	0.0001
Hydrogen	20.3	1.013	70.8	—	442	0.002
Lithium	600	4.2×10^{-9}	503	–	22340	0.375
	800	9.6×10^{-9}	483	10^{-6}	21988	0.348
Mercury	630	1.013	12740	3.9	301	0.417
Nitrogen	77.3	1.013	809	4.61	198.4	0.0089
Oxygen	90.2	1.013	1134	—	213.1	0.013
Potassium	400	1.84×10^{-7}	814	2.2×10^{-7}	2196	0.110
	800	0.0612	720	0.037	2042	0.083
Refrigerant-12	243	1.004	1488	6.27	165.3	0.016
Refrigerant-22	200	0.166	1497	0.87	252.8	0.024
	250	2.174	1360	9.64	221.9	0.016
	300	10.96	1187	46.55	180.1	0.007
Sodium	500	7.64×10^{-7}	898	4.3×10^{-7}	4438	0.175
	1000	0.1955	776	0.059	4022	0.130
Water	323	0.1235	998	0.08	2383	0.068
	373	1.0133	958	0.6	2257	0.059
	423	4.758	917	2.55	2114	0.048
	473	15.54	865	7.85	1941	0.037
	523	39.73	799	19.95	1716	0.026
	573	85.81	712	46.15	1405	0.014

[**] Data collected from Ref. [15]

Nickel		
Electrolytic	37-260	0.04-0.06
Pure, polished	260	0.07
Oxidized at 600°C	260-540	0.37-0.48
Platinum		
Plate, polished	260-540	0.06-0.10
Filament	26-1225	0.04-0.19
Silver		
Polished	37-625	0.02-0.03
Stainless steel		
Polished	23	0.17
Cleaned	23	0.21-0.39
Tin		
Polished	37	0.05
Tungsten		
Filament	3300	0.39
Zinc		
Polished	225-325	0.05-0.06
Oxidized at 400°C	400	0.11
Galvanized	23-27	0.23-0.28
Non-metals		
Alumina (85-99.5% Al_2O_3), effect of mean grain size		
10 μm	1000-1560	0.30-0.18
50 μm	1000-1560	0.39-0.28
100 μm	1000-1560	0.50-0.40
Asbestos		
Paper	37	0.93
Board	37	0.96
Brick		
Magnesite, refractory	1000	0.38
Red, rough	21	0.93
Gray, glazed	1100	0.75
Silica	540	0.80
Carbon		
Filament	1050-1400	0.526
Candle soot	95-270	0.952
Lampblack	20	0.93-0.967
Ceramic		
Earthenware, glazed	20	0.90
Earthenware, matte	20	0.93
Porcelain	22	0.92
Refractory, black	93	0.94
Clay, fired	70	0.91
Concrete, rough	37	0.94
Glass		
Smooth	22	0.94
Pyrex, lead, and soda	260-530	0.95-0.85
Ice		
Smooth	0	0.97
Rough crystals	0	0.985
Marble, light gray, polished	22	0.93
Mica	37	0.75
Paints		
Aluminum 10%, Lacquer 22%	100	0.52
Aluminum 26%, Lacquer 27%	100	0.30
Other aluminum Paints	100	0.27
Lacquer, white	100	0.925
Lacquer, black matte	80	0.97
Oil paints, all colors	100	0.92-0.96
Oil paints	20	0.89-0.97
Paper		
Ordinary	20-95	0.80-0.92
Tar	20	0.93
Porcelain, glazed	22	0.92
Quartz		
Glass, 1.98 mm thick	280	0.90
Glass, 1.98 mm thick	840	0.41
Glass, 6.88 mm thick	280	0.93
Glass, 6.88 mm thick	840	0.47
Rubber		
Hard	23	0.94
Soft, gray	23	0.86
Soil	37	0.93-0.96
Water, deep	0.-100	0.96
Wood	20	0.80-0.90

Constructed based on the data compiled in Refs. [16, 23]

Table 2.19 Solar absorptivity of surfaces (receiving surface at room temperature)**

Surface	α	*Surface*	α
Metals		Non metals	
Aluminum		Asphalt	
Polished	0.10	Pavement	0.85
Anodized	0.14	Pavement free from dust	0.93
Foil	0.15	Brick	
Brass		White glazed	0.26
Polished	0.3-0.5	Red	0.70-0.77
Dull	0.4-0.65	Concrete	
Chromium, electroplated	0.41	Uncolored	0.65
Copper		Brown	0.85
Highly polished	0.18	Black	0.91
Clean	0.25	Earth, plowed field	0.75
Tarnished by exposure	0.64	Granite	0.45
Gold	0.21	Grass	0.75-0.8
Iron		Gravel	0.29
Matte, oxidized	0.96	Leaves, green	0.71-0.79
Lead roofing, old	0.77	Magnesium oxide (MgO)	0.15
Nickel		Marble	
Highly polished	0.15	White	0.44
Polished	0.36	Ground, unpolished	0.47
Oxidized	0.79	Paints	
Platinum, bright	0.31	Oil, white lead	0.24-0.26
Silver		Oil, light cream	0.30
Highly polished	0.07	Oil, light green	0.50
Polished	0.13	Aluminum	0.55
Stainless steel, type 301		Oil, light gray	0.75
Polished	0.37	Oil, black on galvanized iron	0.90
Clean	0.52	Paper	
Zinc		White	0.28
Highly polished	0.34	Sand	0.76
Polished	0.55	Sawdust	0.75
		Slate	
		Silver gray	0.79
		Blue gray	0.85
		Dark gray	0.90
		Snow, clean	0.2-0.35
		Soot, coal	0.95
		Zinc oxide	0.15

**Data collected from Refs. [23]

Table 2.20 Hyperbolic Functions

x	sinh x	cosh x	tanh x	x	sinh x	cosh x	tanh x
0	0	1	0	2	3.6269	3.7622	0.96403
0.1	0.1002	1.005	0.09967	2.1	4.0219	4.1443	0.97045
0.2	0.2013	1.0201	0.19738	2.2	4.4571	4.5679	0.97574
0.3	0.3045	1.0453	0.29131	2.3	4.937	5.0372	0.9801
0.4	0.4108	1.0811	0.37995	2.4	5.4662	5.5569	0.98367
0.5	0.5211	1.1276	0.46212	2.5	6.0502	6.1323	0.98661
0.6	0.6367	1.1855	0.53705	2.6	6.6947	6.769	0.98903
0.7	0.7586	1.2552	0.60437	2.7	7.4063	7.4735	0.99101
0.8	0.8881	1.3374	0.66404	2.8	8.1919	8.2527	0.99263
0.9	1.0265	1.4331	0.7163	2.9	9.0596	9.1146	0.99396
1	1.1752	1.5431	0.76159	3	10.018	10.068	0.99505
1.1	1.3356	1.6685	0.8005	3.5	16.543	16.573	0.99818
1.2	1.5095	1.8107	0.83365	4	27.29	27.308	0.99933
1.3	1.6984	1.9709	0.86172	4.5	45.003	45.014	0.99975
1.4	1.9043	2.1509	0.88535	5	74.203	74.21	0.99991
1.5	2.1293	2.3524	0.90515	6	201.71	201.72	0.99999
1.6	2.3756	2.5775	0.92167	7	548.32	548.32	1
1.7	2.6456	2.8283	0.93541	8	1490.5	1490.5	1
1.8	2.9422	3.1075	0.94681	9	4051.5	4051.5	1
1.9	3.2682	3.4177	0.95624	10	1101.3	1101.3	1

The hyperbolic functions are defined as
Sinh $x = \frac{1}{2}(e^{x} - e^{-x})$; Cosh $x = \frac{1}{2}(e^{x} + e^{-x})$; Tanh x = Sinh x/Cosh x

Table 2.21 Bessel functions of the first kind and second kind

	$I_0(y)$ Zero order Bessel function of first kind										
	y	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
	0	1	1.0025	1.01	1.0226	1.0404	1.0635	1.092	1.1263	1.1665	1.213
	1	1.2661	1.3262	1.3937	1.4693	1.5534	1.6467	1.75	1.864	1.9896	2.1277
	2	2.2796	2.4463	2.6291	2.8296	3.0493	3.2898	3.5533	3.8417	4.1573	4.5027
	3	4.8808	5.2945	5.7472	6.2426	6.7848	7.3782	8.0277	8.7386	9.5169	10.369
10 ×	4	1.1302	1.2324	1.3442	1.4668	1.601	1.7481	1.9093	2.0858	2.2794	2.4915
10 ×	5	2.724	2.9789	3.2584	3.5648	3.9009	4.2695	4.6738	5.1173	5.6038	6.1377
10 ×	6	6.7234	7.3663	8.0718	8.8462	9.6962	10.629	11.654	12.779	14.014	15.37
10^2 ×	7	1.6859	1.8495	2.0292	2.2266	2.4434	2.6816	2.9433	3.2309	3.5468	3.8941
10^3 ×	8	4.2756	4.695	5.1559	5.6626	6.2194	6.8316	7.5046	8.2445	9.058	9.9524
10^4 ×	9	1.0936	1.2019	1.3207	1.4514	1.5953	1.7535	1.9275	2.1189	2.3294	2.5611

$$I_0(y) \approx \frac{0.3989\,e^{y}}{y^{\frac{1}{2}}}\left\{1+\frac{1}{8y}+\frac{9}{128y^2}+\frac{75}{1024y^3}\right\}$$

	$K_0(y)$ Zero order Bessel function of second kind										
	y	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
	0	∞	2.4271	1.7527	1.3725	1.1145	0.9244	0.7775	0.6605	0.5653	0.4867
	1	0.421	0.3656	0.3185	0.2782	0.2437	0.2138	0.188	0.1655	0.1459	0.1288
10^{-1} ×	2	1.1389	1.0078	0.8926	0.7914	0.7022	0.6235	0.554	0.4926	0.4382	0.3901
10^{-1} ×	3	0.3474	0.3095	0.2759	0.2461	0.2196	0.196	0.175	0.1563	0.1397	0.1248
10^{-2} ×	4	1.116	0.998	0.8927	0.7988	0.7149	0.64	0.573	0.5132	0.4597	0.4119
10^{-2} ×	5	0.3691	0.3308	0.2966	0.2659	0.2385	0.2139	0.1918	0.1721	0.1544	0.1386
10^{-3} ×	6	1.244	1.1167	1.0025	0.9001	0.8083	0.7259	0.652	0.5857	0.5262	0.4728
10^{-3} ×	7	0.4248	0.3817	0.3431	0.3084	0.2772	0.2492	0.224	0.2014	0.1811	0.1629
10^{-4} ×	8	1.4647	1.3173	1.1849	1.0658	0.9588	0.8626	0.7761	0.6983	0.6283	0.5654
10^{-4} ×	9	0.5088	0.4579	0.4121	0.371	0.3339	0.3006	0.2706	0.2436	0.2193	0.1977

$$K_0(y) \approx \frac{1.2533\,e^{-y}}{y^{\frac{1}{2}}}\left\{1-\frac{1}{8y}+\frac{9}{128y^2}-\frac{75}{1024y^3}\right\}$$

Table 2.22 Gaussian Error Function

$x/2\sqrt{\alpha\tau}$	$erf(x/2\sqrt{\alpha\tau})$	$x/2\sqrt{\alpha\tau}$	$erf(x/2\sqrt{\alpha\tau})$	$x/2\sqrt{\alpha\tau}$	$erf(x/2\sqrt{\alpha\tau})$
0.00	0.00000	0.76	0.71754	1.52	0.96841
0.02	0.02256	0.78	0.73001	1.54	0.97059
0.04	0.04511	0.80	0.74210	1.56	0.97263
0.06	0.06762	0.82	0.75381	1.58	0.97455
0.08	0.09008	0.84	0.76514	1.60	0.97636
0.10	0.11246	0.86	0.77610	1.62	0.97804
0.12	0.13476	0.88	0.78669	1.64	0.97962
0.14	0.15695	0.90	0.79691	1.66	0.98110
0.16	0.17901	0.92	0.80677	1.68	0.98249
0.18	0.20094	0.94	0.81627	1.70	0.98379
0.20	0.22270	0.96	0.82542	1.72	0.98500
0.22	0.24430	0.98	0.83423	1.74	0.98613
0.24	0.26570	1.00	0.84270	1.76	0.98719
0.26	0.28690	1.02	0.85084	1.78	0.98817
0.28	0.30788	1.04	0.85865	1.80	0.98909
0.30	0.32863	1.06	0.86614	1.82	0.98994
0.32	0.34913	1.08	0.87333	1.84	0.99074
0.34	0.36936	1.10	0.88020	1.86	0.99147
0.36	0.38933	1.12	0.88079	1.88	0.99216
0.38	0.40901	1.14	0.89308	1.90	0.99279
0.40	0.42839	1.16	0.89910	1.92	0.99338
0.42	0.44749	1.18	0.90484	1.94	0.99392
0.44	0.46622	1.20	0.91031	1.96	0.99443
0.46	0.48466	1.22	0.91553	1.98	0.99489
0.48	0.50275	1.24	0.92050	2.00	0.995322
0.50	0.52050	1.26	0.92524	2.10	0.997020
0.52	0.53790	1.28	0.92973	2.20	0.998137
0.54	0.55494	1.30	0.93401	2.30	0.998857
0.56	057162	1.32	0.93806	2.40	0.999311
0.58	0.58792	1.34	0.94191	2.50	0.999593
0.60	0.60386	1.36	0.94556	2.60	0.999764
0.62	0.61941	1.38	0.94902	2.70	0.999866
0.64	0.63459	1.40	0.95228	2.80	0.999925
0.66	0.64938	1.42	0.95538	2.90	0.999959
0.68	0.66278	1.44	0.95830	3.00	0.999978
0.70	0.67780	1.46	0.96105	3.20	0.999994
0.72	0.69143	1.48	0.96365	3.40	0.999998
0.74	0.70468	1.50	0.96610	3.60	1.000000

The Gaussian error function is defined as

$$erf\,(x) = \frac{2}{\sqrt{\Pi}}\int_0^r e^{-v^2}dv$$

$$erf\,(\infty) = 1$$