

TABLE A.2 Continued

Composition	Melting Point (K)	Properties at Various Temperatures (K)													
		Properties at 300 K				k (W/m · K)/ c_p (J/kg · K)									
		ρ (kg/m ³)	c_p (J/kg · K)	k (W/m · K)	$\alpha \cdot 10^6$ (m ² /s)	100	200	400	600	800	1000	1200	1500	2000	2500
Silicon carbide	3100	3160	675	490	230			—	—	—	87	58	30		
								880	1050	1135	1195	1243	1310		
Silicon dioxide, crystalline (quartz)	1883	2650													
				10.4		39	16.4	7.6	5.0	4.2					
				6.21		20.8	9.5	4.70	3.4	3.1					
			745			—	—	885	1075	1250					
Silicon dioxide, polycrystalline (fused silica)	1883	2220	745	1.38	0.834	0.69	1.14	1.51	1.75	2.17	2.87	4.00			
						—	—	905	1040	1105	1155	1195			
Silicon nitride	2173	2400	691	16.0	9.65	—	—	13.9	11.3	9.88	8.76	8.00	7.16	6.20	
						—	578	778	937	1063	1155	1226	1306	1377	
Sulfur	392	2070	708	0.206	0.141	0.165	0.185								
						403	606								
Thorium dioxide	3573	9110	235	13	6.1			10.2	6.6	4.7	3.68	3.12	2.73	2.5	
								255	274	285	295	303	315	330	
Titanium dioxide, polycrystalline	2133	4157	710	8.4	2.8			7.01	5.02	3.94	3.46	3.28			
								805	880	910	930	945			

TABLE A.5 Thermophysical Properties of Saturated Fluids^a

Saturated Liquids

T (K)	ρ (kg/m ³)	c_p (kJ/kg · K)	$\mu \cdot 10^2$ (N · s/m ²)	$\nu \cdot 10^6$ (m ² /s)	$k \cdot 10^3$ (W/m · K)	$\alpha \cdot 10^7$ (m ² /s)	Pr	$\beta \cdot 10^3$ (K ⁻¹)
Engine Oil (Unused)								
273	899.1	1.796	385	4280	147	0.910	47,000	0.70
280	895.3	1.827	217	2430	144	0.880	27,500	0.70
290	890.0	1.868	99.9	1120	145	0.872	12,900	0.70
300	884.1	1.909	48.6	550	145	0.859	6400	0.70
310	877.9	1.951	25.3	288	145	0.847	3400	0.70
320	871.8	1.993	14.1	161	143	0.823	1965	0.70
330	865.8	2.035	8.36	96.6	141	0.800	1205	0.70
340	859.9	2.076	5.31	61.7	139	0.779	793	0.70

TABLE A.5 Continued

Saturated Liquids (Continued)

T (K)	ρ (kg/m ³)	c_p (kJ/kg · K)	$\mu \cdot 10^2$ (N · s/m ²)	$\nu \cdot 10^6$ (m ² /s)	$k \cdot 10^3$ (W/m · K)	$\alpha \cdot 10^7$ (m ² /s)	Pr	$\beta \cdot 10^3$ (K ⁻¹)
Refrigerant-134a (C ₂ H ₂ F ₄)								
230	1426.8	1.249	0.04912	0.3443	112.1	0.629	5.5	2.02
240	1397.7	1.267	0.04202	0.3006	107.3	0.606	5.0	2.11
250	1367.9	1.287	0.03633	0.2656	102.5	0.583	4.6	2.23
260	1337.1	1.308	0.03166	0.2368	97.9	0.560	4.2	2.36
270	1305.1	1.333	0.02775	0.2127	93.4	0.537	4.0	2.53
280	1271.8	1.361	0.02443	0.1921	89.0	0.514	3.7	2.73
290	1236.8	1.393	0.02156	0.1744	84.6	0.491	3.5	2.98
300	1199.7	1.432	0.01905	0.1588	80.3	0.468	3.4	3.30
310	1159.9	1.481	0.01680	0.1449	76.1	0.443	3.3	3.73
320	1116.8	1.543	0.01478	0.1323	71.8	0.417	3.2	4.33
330	1069.1	1.627	0.01292	0.1209	67.5	0.388	3.1	5.19

TABLE A.4 Thermophysical Properties
of Gases at Atmospheric Pressure^a

<i>T</i> (K)	<i>ρ</i> (kg/m ³)	<i>c_p</i> (kJ/kg · K)	<i>μ</i> · 10 ⁷ (N · s/m ²)	<i>ν</i> · 10 ⁶ (m ² /s)	<i>k</i> · 10 ³ (W/m · K)	<i>α</i> · 10 ⁶ (m ² /s)	<i>Pr</i>
Air, <i>M</i> = 28.97 kg/kmol							
100	3.5562	1.032	71.1	2.00	9.34	2.54	0.786
150	2.3364	1.012	103.4	4.426	13.8	5.84	0.758
200	1.7458	1.007	132.5	7.590	18.1	10.3	0.737
250	1.3947	1.006	159.6	11.44	22.3	15.9	0.720
350	0.9950	1.009	208.2	20.92	30.0	29.9	0.700

$$\frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(k\frac{\partial T}{\partial y}\right) + \frac{\partial}{\partial z}\left(k\frac{\partial T}{\partial z}\right) + q = \rho c_p \frac{\partial T}{\partial t}$$

$$\frac{1}{r}\frac{\partial}{\partial r}\left(kr\frac{\partial T}{\partial r}\right) + \frac{1}{r^2}\frac{\partial}{\partial \phi}\left(k\frac{\partial T}{\partial \phi}\right) + \frac{\partial}{\partial z}\left(k\frac{\partial T}{\partial z}\right) + q = \rho c_p \frac{\partial T}{\partial t}$$

$$\begin{aligned} &\frac{1}{r^2}\frac{\partial}{\partial r}\left(kr^2\frac{\partial T}{\partial r}\right) + \frac{1}{r^2\sin^2\theta}\frac{\partial}{\partial \phi}\left(k\frac{\partial T}{\partial \phi}\right) \\ &+ \frac{1}{r^2\sin\theta}\frac{\partial}{\partial \theta}\left(k\sin\theta\frac{\partial T}{\partial \theta}\right) + q = \rho c_p \frac{\partial T}{\partial t} \end{aligned}$$

$$R_{t,\text{conv}} = \frac{1}{hA}$$

$$\alpha = k/\rho c_p$$

⌞

$$\eta_f \equiv \frac{q_f}{q_{\max}} = \frac{q_f}{hA_f\theta_b}$$

$$\frac{\rho Vc}{hA_s} \ln \frac{\theta_i}{\theta} = t$$

$$\frac{\theta}{\theta_i} = \frac{T - T_{\infty}}{T_i - T_{\infty}} = \exp \left[- \left(\frac{hA_s}{\rho Vc} \right) t \right]$$

$$\frac{hL}{k} \equiv Bi$$

$$Fo \equiv \frac{\alpha t}{L_c^2}$$

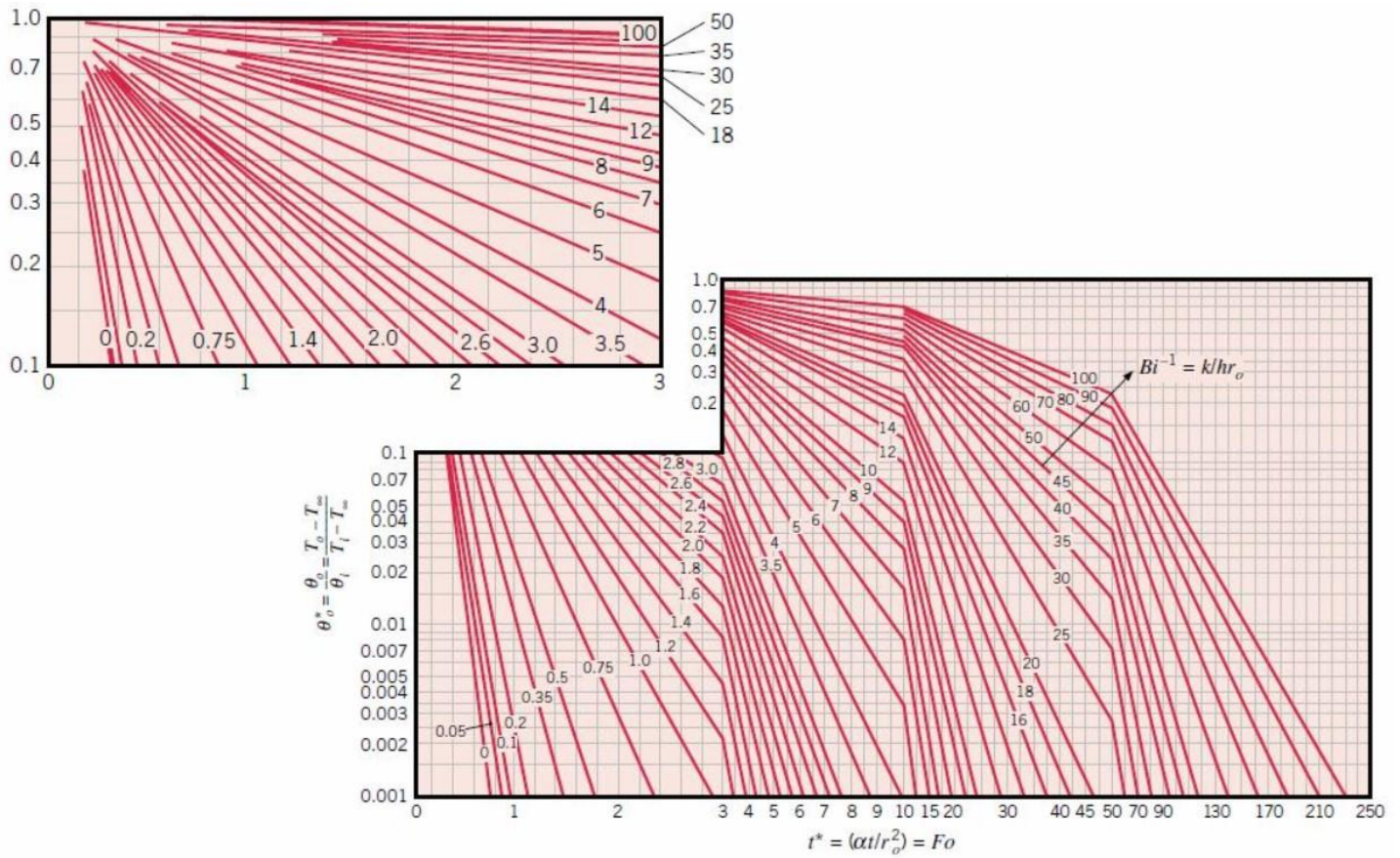
TABLE 3.1 Thermal contact resistance for (a) metallic interfaces under vacuum conditions and (b) aluminum interface (10- μm surface roughness, 10^5 N/m^2) with different interfacial fluids [1]

Thermal Resistance, $R''_{t,c} \times 10^4 (\text{m}^2 \cdot \text{K/W})$

(a) Vacuum Interface			(b) Interfacial Fluid	
Contact pressure	100 kN/m ²	10,000 kN/m ²	Air	2.75
Stainless steel	6–25	0.7–4.0	Helium	1.05
Copper	1–10	0.1–0.5	Hydrogen	0.720
Magnesium	1.5–3.5	0.2–0.4	Silicone oil	0.525
Aluminum	1.5–5.0	0.2–0.4	Glycerine	0.265

TABLE 3.3

	Plane Wall	Cylindrical Wall ^a	Spherical Wall ^a
Thermal resistance ($R_{t,\text{cond}}$)	$\frac{L}{kA}$	$\frac{\ln(r_2/r_1)}{2\pi Lk}$	$\frac{(1/r_1) - (1/r_2)}{4\pi k}$



Center temperature as a function of time in a sphere of radius r_o [1].

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0$$

$$u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} = -\frac{1}{\rho} \frac{dp_\infty}{dx} + \nu \frac{\partial^2 u}{\partial y^2}$$

$$u \frac{\partial T}{\partial x} + v \frac{\partial T}{\partial y} = \alpha \frac{\partial^2 T}{\partial y^2} + \frac{\nu}{c_p} \left(\frac{\partial u}{\partial y} \right)^2$$

$$h = \frac{-k_f \partial T / \partial y|_{y=0}}{T_s - T_\infty}$$

$$\bar{h} = \frac{1}{A_s} \int_{A_s} h dA_s$$

$$Re_{x,c} \equiv \frac{\rho u_\infty x_c}{\mu} = 5 \times 10^5$$

$$Re_L = \frac{VL}{\nu}$$

$$\overline{Nu} = \frac{\bar{h}L}{k_f}$$

$$Nu \equiv \frac{hL}{k_f}$$

$$\overline{Nu}_D \equiv \frac{\bar{h}D}{k}$$

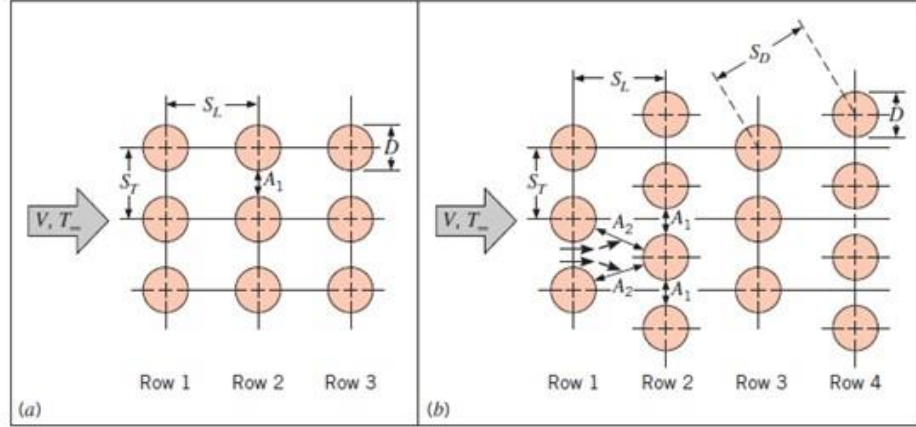


FIGURE 7.12 Tube arrangements in a bank. (a) Aligned. (b) Staggered.

The Reynolds number $Re_{D,\max}$ for the foregoing correlation is based on the *maximum fluid velocity* occurring within the tube bank, $Re_{D,\max} \equiv \rho V_{\max} D / \mu$. For the aligned arrangement, $V_{\max}$ occurs at the transverse plane A_1 of Figure 7.12a, and from the mass conservation requirement for an incompressible fluid

$$V_{\max} = \frac{S_T}{S_T - D} V \quad (7.60)$$

For the staggered configuration, the maximum velocity may occur at either the transverse plane A_1 or the diagonal plane A_2 of Figure 7.12b. It will occur at A_2 if the rows are spaced such that

$$2(S_D - D) < (S_T - D)$$

The factor of 2 results from the bifurcation experienced by the fluid moving from the A_1 to the A_2 planes. Hence $V_{\max}$ occurs at A_2 if

$$S_D = \left[S_L^2 + \left(\frac{S_T}{2} \right)^2 \right]^{1/2} < \frac{S_T + D}{2}$$

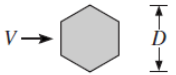
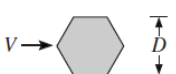
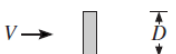
in which case it is given by

$$V_{\max} = \frac{S_T}{2(S_D - D)} V \quad (7.61)$$

TABLE 7.4 Constants of Equation 7.53 for the circular cylinder in cross flow [17]

Re_D	C	m
1–40	0.75	0.4
40–1000	0.51	0.5
10^3 – 2×10^5	0.26	0.6
2×10^5 – 10^6	0.076	0.7

TABLE 7.3 Constants of Equation 7.52 for noncircular cylinders in cross flow of a gas [13, 14]^a

Geometry	Re_D	C	m
Square 	6000–60,000	0.304	0.59
	5000–60,000	0.158	0.66
Hexagon 	5200–20,400	0.164	0.638
	20,400–105,000	0.039	0.78
Thin plate perpendicular to flow 	Front 10,000–50,000 Back 7000–80,000	0.667 0.191	0.500 0.667

^aThese tabular values are based on the recommendations of Sparrow et al. [14] for air, with extension to other fluids through the $Pr^{1/3}$ dependence of Equation 7.52. A Prandtl number of $Pr = 0.7$ was assumed for the experimental results for air that are described in [14].

TABLE 7.5 Constants of Equation 7.58 for the tube bank in cross flow [16]

Conguration	$Re_{D,max}$	C_1	m
Aligned	10 – 10^2	0.80	0.40
Staggered	10 – 10^2	0.90	0.40
Aligned	10^2 – 10^3	Approximate as a single (isolated) cylinder	
Staggered	10^2 – 10^3		
Aligned ($S_T/S_L > 0.7$) ^a	10^3 – 2×10^5	0.27	0.63
Staggered ($S_T/S_L < 2$)	10^3 – 2×10^5	$0.35(S_T/S_L)^{1/5}$	0.60
Staggered ($S_T/S_L > 2$)	10^3 – 2×10^5	0.40	0.60
Aligned	2×10^5 – 2×10^6	0.021	0.84
Staggered	2×10^5 – 2×10^6	0.022	0.84

^aFor $S_T/S_L < 0.7$, heat transfer is inefficient and aligned tubes should not be used.

$$\Delta T_{\text{lm}} = \frac{(T_s - T_i) - (T_s - T_o)}{\ln\left(\frac{T_s - T_i}{T_s - T_o}\right)}$$

$$\frac{T_s - T_o}{T_s - T_i} = \exp\left(-\frac{\pi DN \bar{h}}{\rho V N_T S_T c_p}\right)$$

where N is the total number of tubes in the bank and N_T is the number of tubes in each row.

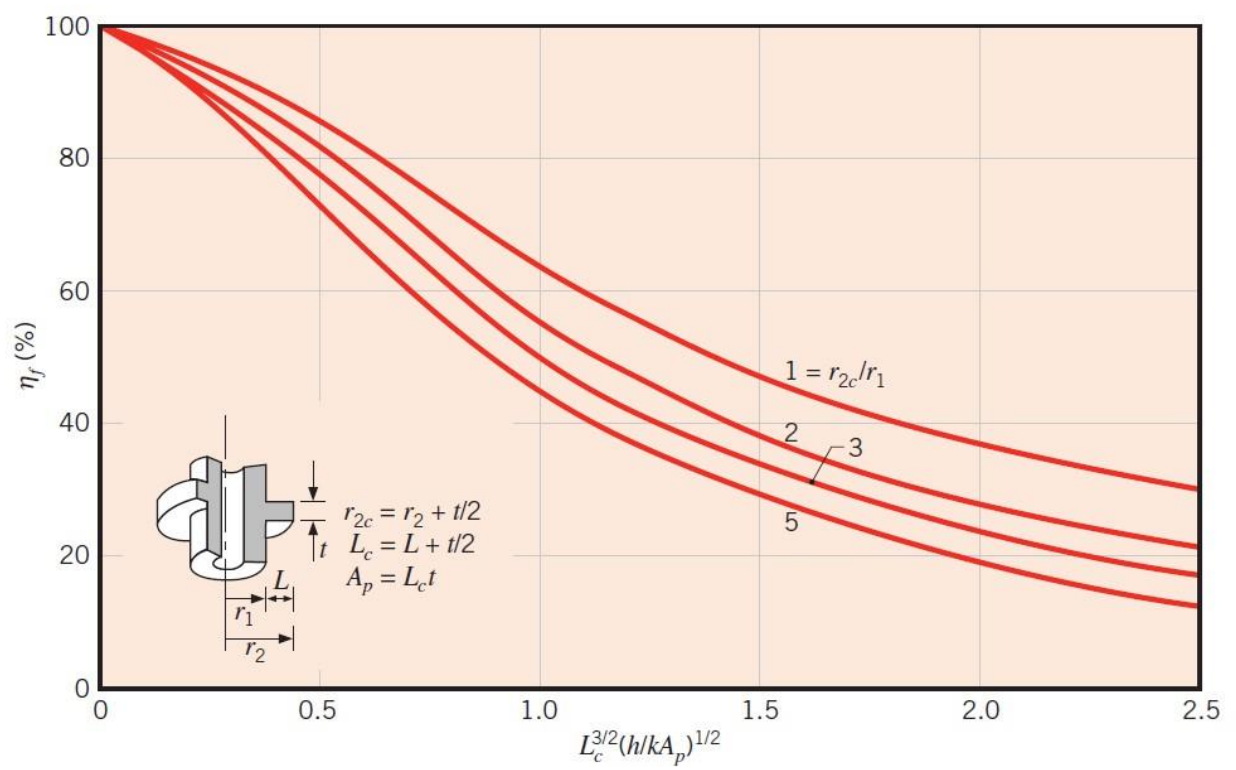
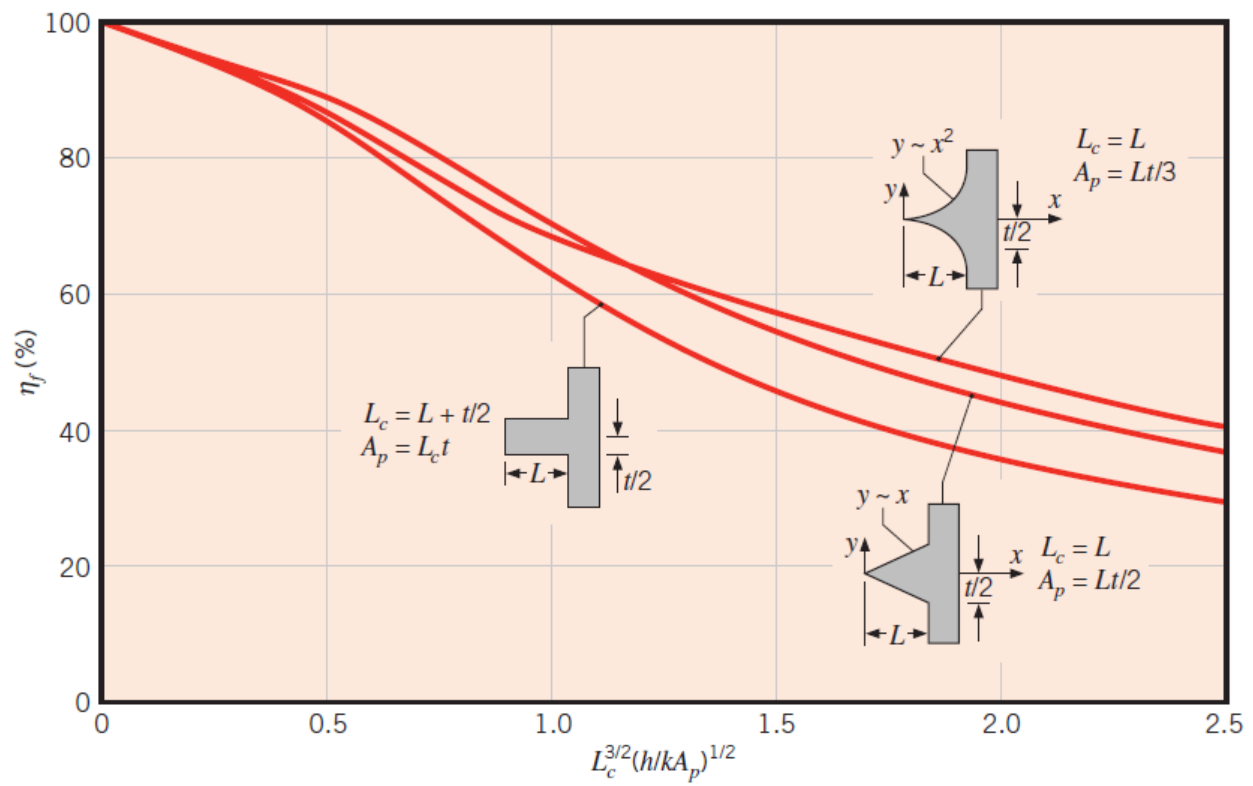
$$T_m(x) = T_{m,i} + \frac{q_s'' P}{mc_p} x \quad q_s'' = \text{constant}$$

$$\frac{\Delta T_o}{\Delta T_i} = \frac{T_s - T_{m,o}}{T_s - T_{m,i}} = \exp\left(-\frac{PL}{mc_p} \bar{h}\right) \quad T_s = \text{constant}$$

$$q_{\text{conv}} = \bar{h} A_s \Delta T_{\text{lm}} \quad T_s = \text{constant}$$

$$\left[\bar{Nu}_D = C_1 Re_{D,\text{max}}^m Pr^{0.36} \left(\frac{Pr}{Pr_s}\right)^{1/4} \right] \quad (7.58)$$

$$\left[\begin{array}{l} N_L \geq 20 \\ 0.7 \leq Pr \leq 500 \\ 10 \leq Re_{D,\text{max}} \leq 2 \times 10^6 \end{array} \right]$$



$$\left(\frac{x_{fd,h}}{D}\right)_{\text{lam}} \approx 0.05 Re_D$$

$$10 \lesssim \left(\frac{x_{fd,h}}{D}\right)_{\text{turb}}$$

$$\left(\frac{x_{fd,t}}{D}\right)_{\text{lam}} \approx 0.05 Re_D Pr$$

$$Re_D \equiv \frac{\rho u_m D}{\mu} = \frac{u_m D}{\nu}$$

$$Re_{D,c} \approx 2300$$

$$I_{\lambda,b}(\lambda, T) = \frac{2hc_o^2}{\lambda^5 [\exp(hc_o/\lambda k_B T) - 1]} \quad (12.29)$$

where $h = 6.626 \times 10^{-34} \text{ J}\cdot\text{s}$ and $k_B = 1.381 \times 10^{-23} \text{ J/K}$ are the universal Planck and Boltzmann constants, respectively, $c_o = 2.998 \times 10^8 \text{ m/s}$ is the speed of light in vacuum, and T is the *absolute* temperature of the blackbody (K).

$$E_{\lambda,b}(\lambda, T) = \pi I_{\lambda,b}(\lambda, T) = \frac{C_1}{\lambda^5 [\exp(C_2/\lambda T) - 1]} \quad (12.30)$$

where the first and second radiation constants are $C_1 = 2\pi hc_o^2 = 3.742 \times 10^8 \text{ W}\cdot\mu\text{m}^4/\text{m}^2$ and $C_2 = (hc_o/k_B) = 1.439 \times 10^4 \mu\text{m}\cdot\text{K}$.

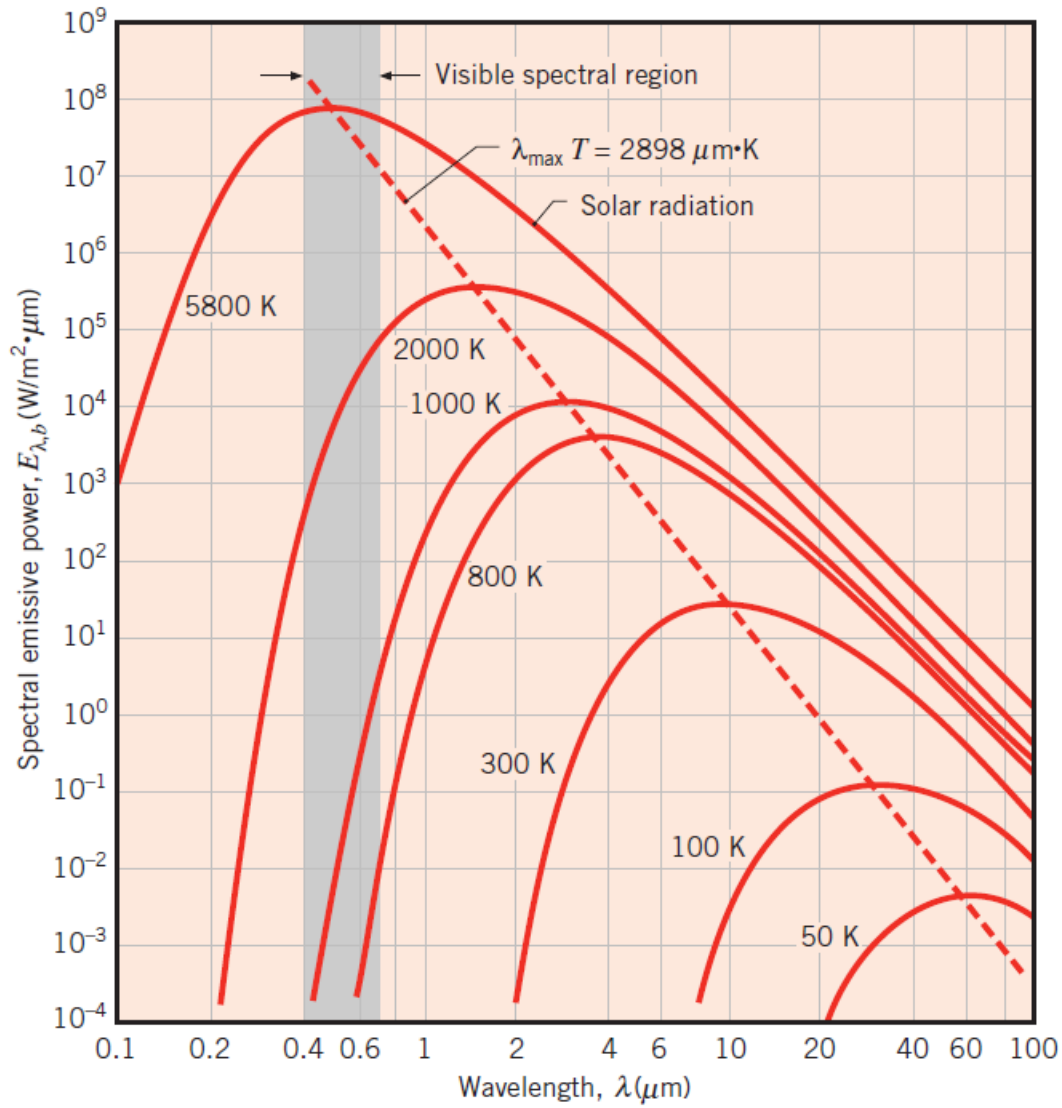


FIGURE 12.12 Spectral blackbody emissive power.

$$E_b = \sigma T^4 \quad (12.32)$$

$$F_{(0 \rightarrow \lambda)} \equiv \frac{\int_0^\lambda E_{\lambda,b} d\lambda}{\int_0^\infty E_{\lambda,b} d\lambda} = \frac{\int_0^\lambda E_{\lambda,b} d\lambda}{\sigma T^4} = \int_0^{\lambda T} \frac{E_{\lambda,b}}{\sigma T^5} d(\lambda T) = f(\lambda T) \quad (12.34)$$

TABLE 12.2 Blackbody Radiation Functions

λT ($\mu\text{m} \cdot \text{K}$)	$F_{(0 \rightarrow \lambda)}$	$I_{\lambda,b}(\lambda, T)/\sigma T^5$ ($\mu\text{m} \cdot \text{K} \cdot \text{sr})^{-1}$	$\frac{I_{\lambda,b}(\lambda, T)}{I_{\lambda,b}(\lambda_{\text{max}}, T)}$
200	0.000000	0.375034×10^{-27}	0.000000
400	0.000000	0.490335×10^{-13}	0.000000
600	0.000000	0.104046×10^{-8}	0.000014
800	0.000016	0.991126×10^{-7}	0.001372
1,000	0.000321	0.118505×10^{-5}	0.016406
1,200	0.002134	0.523927×10^{-5}	0.072534
1,400	0.007790	0.134411×10^{-4}	0.186082
1,600	0.019718	0.249130	0.344904
1,800	0.039341	0.375568	0.519949
2,000	0.066728	0.493432	0.683123
2,200	0.100888	0.589649×10^{-4}	0.816329
2,400	0.140256	0.658866	0.912155
2,600	0.183120	0.701292	0.970891
2,800	0.227897	0.720239	0.997123
2,898	0.250108	0.722318×10^{-4}	1.000000

TABLE 12.2 Continued

λT ($\mu\text{m} \cdot \text{K}$)	$F_{(0 \rightarrow \lambda)}$	$I_{\lambda,b}(\lambda, T)/\sigma T^5$ ($\mu\text{m} \cdot \text{K} \cdot \text{sr}$) $^{-1}$	$\frac{I_{\lambda,b}(\lambda, T)}{I_{\lambda,b}(\lambda_{\text{max}}, T)}$
3,000	0.273232	0.720254×10^{-4}	0.997143
3,200	0.318102	0.705974	0.977373
3,400	0.361735	0.681544	0.943551
3,600	0.403607	0.650396	0.900429
3,800	0.443382	0.615225×10^{-4}	0.851737
4,000	0.480877	0.578064	0.800291
4,200	0.516014	0.540394	0.748139
4,400	0.548796	0.503253	0.696720
4,600	0.579280	0.467343	0.647004
4,800	0.607559	0.433109	0.599610
5,000	0.633747	0.400813	0.554898
5,200	0.658970	0.370580×10^{-4}	0.513043
5,400	0.680360	0.342445	0.474092
5,600	0.701046	0.316376	0.438002
5,800	0.720158	0.292301	0.404671
6,000	0.737818	0.270121	0.373965
6,200	0.754140	0.249723×10^{-4}	0.345724
6,400	0.769234	0.230985	0.319783
6,600	0.783199	0.213786	0.295973
6,800	0.796129	0.198008	0.274128
7,000	0.808109	0.183534	0.254090
7,200	0.819217	0.170256×10^{-4}	0.235708
7,400	0.829527	0.158073	0.218842
7,600	0.839102	0.146891	0.203360
7,800	0.848005	0.136621	0.189143
8,000	0.856288	0.127185	0.176079
8,500	0.874608	0.106772×10^{-4}	0.147819
9,000	0.890029	0.901463×10^{-5}	0.124801
9,500	0.903085	0.765338	0.105956
10,000	0.914199	0.653279×10^{-5}	0.090442
10,500	0.923710	0.560522	0.077600
11,000	0.931890	0.483321	0.066913
11,500	0.939959	0.418725	0.057970
12,000	0.945098	0.364394×10^{-5}	0.050448
13,000	0.955139	0.279457	0.038689
14,000	0.962898	0.217641	0.030131
15,000	0.969981	0.171866×10^{-5}	0.023794
16,000	0.973814	0.137429	0.019026
18,000	0.980860	0.908240×10^{-6}	0.012574
20,000	0.985602	0.623310	0.008629
25,000	0.992215	0.276474	0.003828
30,000	0.995340	0.140469×10^{-6}	0.001945
40,000	0.997967	0.473891×10^{-7}	0.000656
50,000	0.998953	0.201605	0.000279
75,000	0.999713	0.418597×10^{-8}	0.000058
100,000	0.999905	0.135752	0.000019

$$\varepsilon(T) \equiv \frac{E(T)}{E_b(T)} \quad (12.36)$$

$$E(T) = \varepsilon(T)E_b(T) = \varepsilon(T)\sigma T^4 \quad (12.37)$$

$$\varepsilon_\lambda(\lambda, T) \equiv \frac{E_\lambda(\lambda, T)}{E_{\lambda,b}(\lambda, T)} \quad (12.40)$$

TABLE 7.7 Summary of convection heat transfer correlations for external flow^{a,b}

Correlation		Geometry	Conditions ^c
$\delta = 5x Re_x^{-1/2}$	(7.19)	Flat plate	Laminar, T_f
$C_{f,x} = 0.664 Re_x^{-1/2}$	(7.20)	Flat plate	Laminar, local, T_f
$Nu_x = 0.332 Re_x^{1/2} Pr^{1/3}$	(7.23)	Flat plate	Laminar, local, T_f , $Pr \gtrsim 0.6$
$\delta_t = \delta Pr^{-1/3}$	(7.24)	Flat plate	Laminar, T_f
$\bar{C}_{f,x} = 1.328 Re_x^{-1/2}$	(7.29)	Flat plate	Laminar, average, T_f
$\bar{Nu}_x = 0.664 Re_x^{1/2} Pr^{1/3}$	(7.30)	Flat plate	Laminar, average, T_f , $Pr \gtrsim 0.6$
$Nu_x = 0.564 Pe_x^{1/2}$	(7.32)	Flat plate	Laminar, local, T_f , $Pr \lesssim 0.05$, $Pe_x \gtrsim 100$
$C_{f,x} = 0.0592 Re_x^{-1/5}$	(7.34)	Flat plate	Turbulent, local, T_f , $Re_x \lesssim 10^8$
$\delta = 0.37x Re_x^{-1/5}$	(7.35)	Flat plate	Turbulent, T_f , $Re_x \lesssim 10^8$

TABLE 7.7 (Continued)

Correlation		Geometry	Conditions ^c
$Nu_x = 0.0296 Re_x^{4/5} Pr^{1/3}$	(7.36)	Flat plate	Turbulent, local, T_f , $Re_x \lesssim 10^8$, $0.6 \lesssim Pr \lesssim 60$
$\overline{C}_{f,L} = 0.074 Re_L^{-1/5} - 1742 Re_L^{-1}$	(7.40)	Flat plate	Mixed, average, T_f , $Re_{x,c} = 5 \times 10^5$, $Re_L \lesssim 10^8$
$\overline{Nu}_L = (0.037 Re_L^{4/5} - 871) Pr^{1/3}$	(7.38)	Flat plate	Mixed, average, T_f , $Re_{x,c} = 5 \times 10^5$, $Re_L \lesssim 10^8$, $0.6 \lesssim Pr \lesssim 60$
$\overline{Nu}_D = C Re_D^n Pr^{1/3}$ (Table 7.2)	(7.52)	Cylinder	Average, T_f , $0.4 \lesssim Re_D \lesssim 4 \times 10^5$, $Pr \gtrsim 0.7$
$\overline{Nu}_D = C Re_D^n Pr^n (Pr/Pr_s)^{1/4}$ (Table 7.4)	(7.53)	Cylinder	Average, T_∞ , $1 \lesssim Re_D \lesssim 10^6$, $0.7 \lesssim Pr \lesssim 500$
$\overline{Nu}_D = 0.3 + [0.62 Re_D^{1/2} Pr^{1/3} \times [1 + (0.4/Pr)^{2/3}]^{-1/4}] \times [1 + (Re_D/282,000)^{5/8}]^{4/5}$	(7.54)	Cylinder	Average, T_f , $Re_D Pr \gtrsim 0.2$
$\overline{Nu}_D = 2 + (0.4 Re_D^{1/2} + 0.06 Re_D^{2/3}) Pr^{0.4} \times (\mu/\mu_s)^{1/4}$	(7.56)	Sphere	Average, T_∞ , $3.5 \lesssim Re_D \lesssim 7.6 \times 10^4$, $0.71 \lesssim Pr \lesssim 380$, $1.0 \lesssim (\mu/\mu_s) \lesssim 3.2$
$\overline{Nu}_D = 2 + 0.6 Re_D^{1/2} Pr^{1/3}$	(7.57)	Falling drop	Average, T_∞
$\overline{Nu}_D = C_1 C_2 Re_{D,max}^n Pr^{0.36} (Pr/Pr_s)^{1/2}$ (Tables 7.5, 7.6)	(7.58), (7.59)	Tube bank ^d	Average, $\overline{T}$, $10 \lesssim Re_D \lesssim 2 \times 10^6$, $0.7 \lesssim Pr \lesssim 500$
Single round nozzle	(7.71)	Impinging jet	Average, T_f , $2000 \lesssim Re \lesssim 4 \times 10^5$, $2 \lesssim (H/D) \lesssim 12$, $2.5 \lesssim (r/D) \lesssim 7.5$
Single slot nozzle	(7.75)	Impinging jet	Average, T_f , $3000 \lesssim Re \lesssim 9 \times 10^4$, $2 \lesssim (H/W) \lesssim 10$, $4 \lesssim (x/W) \lesssim 20$
Array of round nozzles	(7.73)	Impinging jet	Average, T_f , $2000 \lesssim Re \lesssim 10^5$, $2 \lesssim (H/D) \lesssim 12$, $0.004 \lesssim A_r \lesssim 0.04$
Array of slot nozzles	(7.77)	Impinging jet	Average, T_f , $1500 \lesssim Re \lesssim 4 \times 10^4$, $2 \lesssim (H/W) \lesssim 80$, $0.008 \lesssim A_r \lesssim 2.5 A_{r,o}$
$\varepsilon \tilde{j}_H = \varepsilon \tilde{j}_m = 2.06 Re_D^{-0.375}$	(7.81)	Packed bed of spheres ^d	Average, $\overline{T}$, $90 \lesssim Re_D \lesssim 4000$, Pr (or Sc) ≈ 0.7

^aCorrelations in this table pertain to isothermal surfaces; for special cases involving an unheated starting length or a uniform surface heat flux, see Section 7.2.4 or 7.2.5.

^bWhen the heat and mass transfer analogy is applicable, the corresponding mass transfer correlations may be obtained by replacing Nu and Pr by Sh and Sc , respectively.

^cThe temperature listed under "Conditions" is the temperature at which properties should be evaluated.

^dFor tube banks and packed beds, properties are evaluated at the average fluid temperature, $\overline{T} = (T_i + T_o)/2$.

TABLE 8.4 Summary of convection correlations for flow in a circular tube^{a,b,e}

Correlation		Conditions
$f = 64/Re_D$	(8.19)	Laminar, fully developed
$Nu_D = 4.36$	(8.53)	Laminar, fully developed, uniform q''_s
$Nu_D = 3.66$	(8.55)	Laminar, fully developed, uniform T_s
$\overline{Nu}_D = 3.66 + \frac{0.0668 Gz_D}{1 + 0.04 Gz_D^{2/3}}$	(8.57)	Laminar, thermal entry (or combined entry with $Pr \geq 5$), uniform T_s , $Gz_D = (D/x) Re_D Pr$
$\overline{Nu}_D = \frac{\frac{3.66}{\tanh[2.264 Gz_D^{-1/3} + 1.7 Gz_D^{-2/3}]} + 0.0499 Gz_D \tanh(Gz_D^{-1})}{\tanh(2.432 Pr^{1/6} Gz_D^{-1/6})}$	(8.58)	Laminar, combined entry, $Pr \geq 0.1$, uniform T_s , $Gz_D = (D/x) Re_D Pr$
$\frac{1}{\sqrt{f}} = -2.0 \log \left[\frac{e/D}{3.7} + \frac{2.51}{Re_D \sqrt{f}} \right]$	(8.20) ^c	Turbulent, fully developed
$f = (0.790 \ln Re_D - 1.64)^{-2}$	(8.21) ^c	Turbulent, fully developed, smooth walls, $3000 \leq Re_D \leq 5 \times 10^6$
$Nu_D = 0.023 Re_D^{4/5} Pr^n$	(8.60) ^d	Turbulent, fully developed, $0.6 \leq Pr \leq 160$, $Re_D \geq 10,000$, $(L/D) \geq 10$, $n = 0.4$ for $T_s > T_m$ and $n = 0.3$ for $T_s < T_m$
$Nu_D = 0.027 Re_D^{4/5} Pr^{1/3} \left(\frac{\mu}{\mu_s} \right)^{0.14}$	(8.61) ^d	Turbulent, fully developed, $0.7 \leq Pr \leq 16,700$, $Re_D \geq 10,000$, $L/D \geq 10$
$Nu_D = \frac{(f/8)(Re_D - 1000) Pr}{1 + 12.7(f/8)^{1/2}(Pr^{2/3} - 1)}$	(8.62) ^d	Turbulent, fully developed, $0.5 \leq Pr \leq 2000$, $3000 \leq Re_D \leq 5 \times 10^6$, $(L/D) \geq 10$
$Nu_D = 4.82 + 0.0185(Re_D Pr)^{0.827}$	(8.64)	Liquid metals, turbulent, fully developed, uniform q''_s , $3.6 \times 10^3 \leq Re_D \leq 9.05 \times 10^5$, $3 \times 10^{-3} \leq Pr \leq 5 \times 10^{-2}$, $10^3 \leq Re_D Pr \leq 10^4$
$Nu_D = 5.0 + 0.025(Re_D Pr)^{0.8}$	(8.65)	Liquid metals, turbulent, fully developed, uniform T_s , $Re_D Pr \geq 100$

^aThe mass transfer correlations may be obtained by replacing Nu_D and Pr by Sh_D and Sc , respectively.

^bProperties in Equations 8.53, 8.55, 8.60, 8.61, 8.62, 8.64, and 8.65 are based on T_m ; properties in Equations 8.19, 8.20, and 8.21 are based on $T_f = (T_s + T_m)/2$; properties in Equations 8.57 and 8.58 are based on $\bar{T}_m = (T_{m,i} + T_{m,o})/2$.

^cEquation 8.20 pertains to smooth or rough tubes. Equation 8.21 pertains to smooth tubes.

^dAs a first approximation, Equations 8.60, 8.61, or 8.62 may be used to evaluate the average Nusselt number $\overline{Nu}_D$ over the entire tube length, if $(L/D) \geq 10$. The properties should then be evaluated at the average of the mean temperature, $\bar{T}_m = (T_{m,i} + T_{m,o})/2$.

^eFor tubes of noncircular cross section, $Re_D = D_h u_m / \nu$, $D_h = 4A_c/P$, and $u_m = m/\rho A_c$. Results for fully developed laminar flow are provided in Table 8.1. For turbulent flow, Equation 8.60 may be used as a first approximation.

