HEAT TRANSFER DATA SHEETS

Nusselt number = $Nu = \dfrac{hL}{k}$

Sherwood number = $Sh = \dfrac{h_m L}{D}$

Grashof number = $Gr = \dfrac{g\,\beta\,\Delta T\,\rho^2\,L^3}{\mu^2} = \dfrac{g\,\beta\,\Delta T\,L^3}{\nu^2}$

Prandtl number = $Pr = \dfrac{C\mu}{k} = \dfrac{\nu}{\alpha}$

Schmidt number = $Sc = \dfrac{\nu}{D}$

Rayleigh number = Ra = Gr × Pr

$\beta = \dfrac{1}{T}$ for ideal gas

$$\frac{1}{UA} = \left(\frac{1}{h_i A_i} + \frac{F_{f,i}}{A_i} + \frac{\ell n\left(r_2 / r_1 \right)}{2\pi k L} + \frac{F_{f,o}}{A_o} + \frac{1}{h_o A_o} \right)$$

$$\Delta T_{lm} = \frac{\Delta T_2 - \Delta T_1}{\ell n\,(\Delta T_2 / \Delta T_1)}$$

$$NTU = \frac{UA}{C_{min}}$$

$$\varepsilon = \frac{C_h (T_{hi} - T_{ho})}{C_{min} (T_{hi} - T_{ci})} = \frac{C_c (T_{co} - T_{ci})}{C_{min} (T_{hi} - T_{ci})}$$

CONVECTION HEAT TRANSFER CORRELATIONS

1. External Flows

Local Nu for laminar flow on a flat plate with constant surface temperature. $0.6 \le Pr \le 50$.

$$Nu_x = 0.332\, Pr^{1/3} Re_x^{\,1/2}$$

Average Nu for laminar flow over flat plate with constant surface temperature. $0.6 \le Pr \le 50$.

$$\overline{Nu_x} = 0.664\, Pr^{1/3} Re_x^{\,1/2}$$

Local Nu for laminar flow on a flat plate with constant heat flux. $0.6 \le Pr \le 50$.

$$Nu_x = 0.453\, Pr^{1/3} Re_x^{\,1/2}$$

Local Nu for turbulent flow over a flat plate with constant surface temperature.
$5\times10^5 \le Re_x \le 10^8$; $0.6 \le Pr \le 60$

$$Nu_x = 0.0296\, Re_x^{0.8} Pr^{1/3}$$

Average Nu for turbulent flow over a flat plate with constant surface temperature.
$5\times10^5 \le Re_x \le 10^8$; $0.6 \le Pr \le 60$

$$\overline{\mathrm{Nu}_L} = 0.037\, Re_L^{0.8} Pr^{1/3}$$

Average Nu for mixed flow conditions over flat plate, i.e. starting laminar and becoming turbulent.
$Re_{x,crit} = 5\times10^5$; $Re_L < 10^8$; $0.6 < Pr < 60$.

$$\overline{Nu_L} = Pr^{1/3}\left(0.037\, Re_L^{0.8} - 870\right)$$

Average Nu for cylinder in cross flow. $Pr \ge 0.7$

$$\overline{Nu_D} = C\, Re_D^m\, Pr^{1/3}$$

Re_D	C	m
0.4 - 4	0.989	0.330
4 - 40	0.911	0.385
40 - 4000	0.683	0.466
4000 - 40,000	0.193	0.618
40,000 - 400,000	0.027	0.805

2. Internal flow in Circular Channels

Laminar fully developed flow with constant heat flux. $Pr \geq 0.6$

$$Nu_D = 4.36$$

Laminar fully developed flow with constant surface temperature. $Pr \geq 0.6$

$$Nu_D = 3.66$$

Laminar, combined entry length with constant surface temperature

$$Nu_D = 1.86\left(\frac{Re_D\ Pr}{L/D}\right)^{1/3}$$

Fully developed turbulent flow. $0.6 \leq Pr \leq 160$; $Re_D \geq 2500$; $L/D \geq 10$; $n = 0.4$ for heated tube and 0.3 for cooled tube.

$$Nu_D = 0.023\, Re_D^{4/5}\ Pr^n$$

Not fully developed turbulent flow (entrance region). $10 \leq L/D \leq 400$ (Properties at mean bulk temperature).

$$Nu_D = 0.036\, Re^{0.8}\ Pr^{1/3}(D/L)^{0.055}$$

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3. Free Convection

Flat vertical plate with constant surface temperature, all values of Ra_L

$$\overline{Nu_L} = \left[0.825 + \frac{0.387\ Ra_L^{1/6}}{\left[1+(0.492/Pr)^{9/16}\right]^{8/27}}\right]^2$$

Horizontal plate hot surface up or cold surface down. Characteristic length = surface area ÷ perimeter. $10^4 \leq Ra_L \leq 10^7$; and $10^7 \leq Ra_L \leq 10^{11}$ respectively.

$$\overline{Nu_L} = 0.54\ Ra_L^{1/4}$$

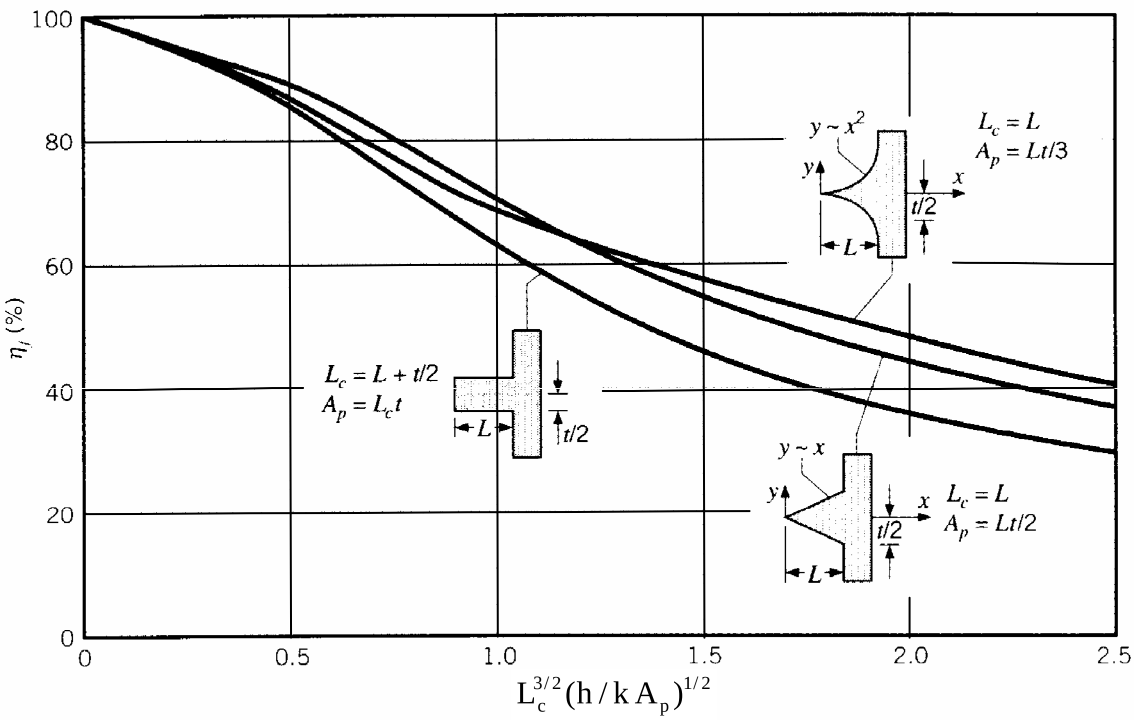
$$\overline{\mathrm{Nu}_\mathrm{L}} = 0.15\ Ra_L^{1/3}$$

Flat plate cold surface up or hot surface down. $10^5 \leq Ra_L \leq 10^{10}$. Characteristic length = surface area ÷ perimeter.

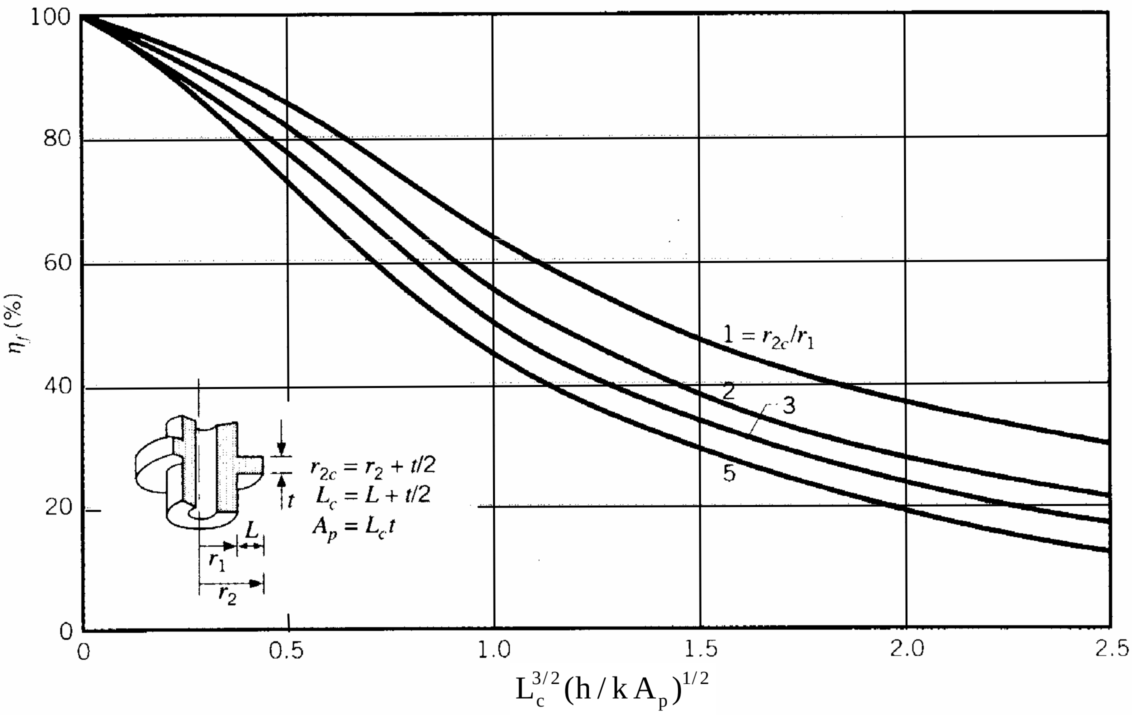
$$\overline{Nu_L} = 0.27\ Ra_L^{1/4}$$

Horizontal cylinder. $Ra_D \leq 10^{12}$

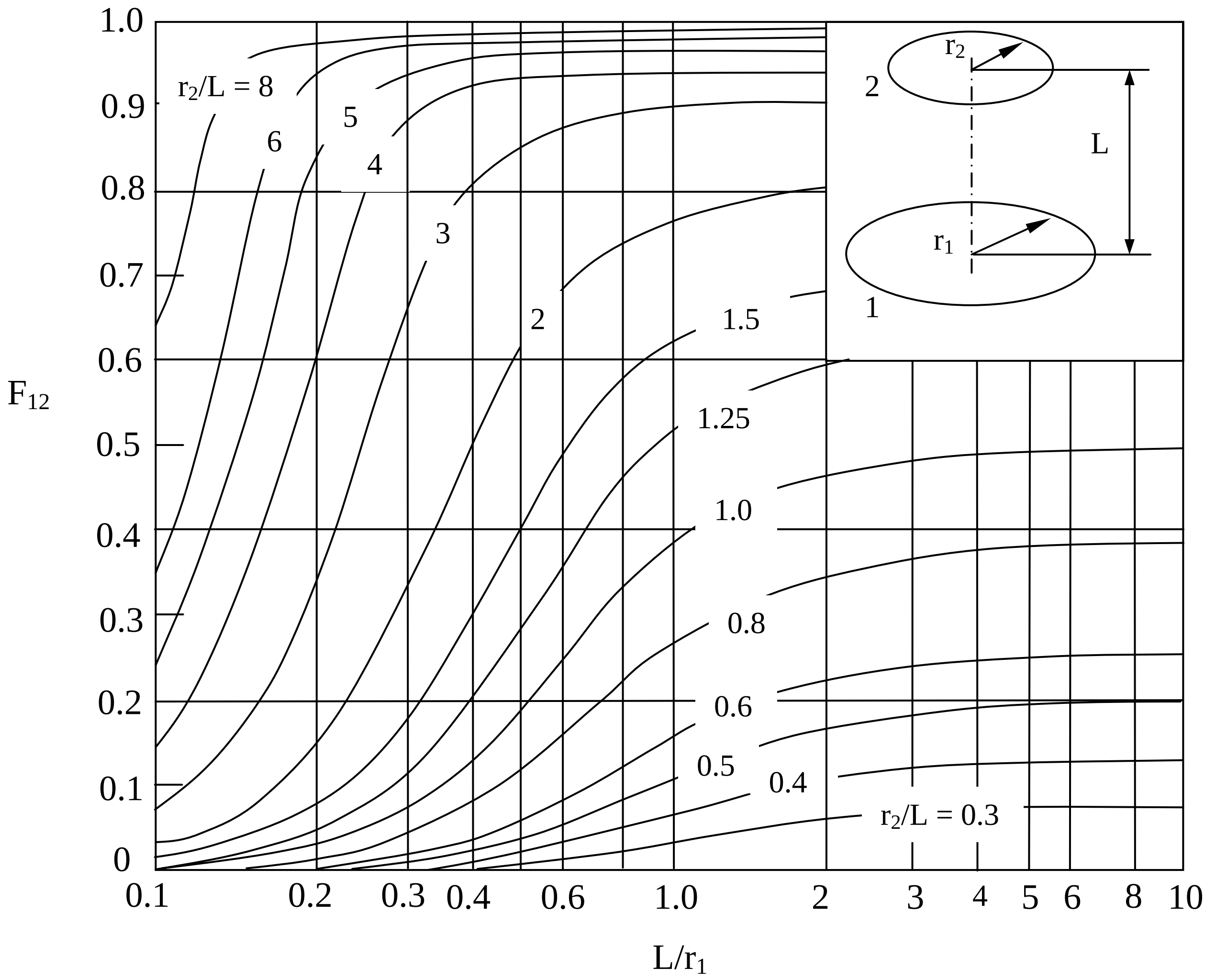
$$\overline{Nu_D} = \left[0.6 + \frac{0.387\ Ra_D^{1/6}}{\left[1 + (0.559/Pr)^{9/16}\right]^{8/27}}\right]^2$$



Efficiency of straight fins (rectangular, triangular and parabolic profile)



Efficiency of annular fins of rectangular profile



View Factor for two coaxial parallel discs

Saturated Water and Steam

t [°C]	p_s [bar]	v_f 10^{-2}[m^3/kg]	c_{pf} [kJ/kg K]	c_{pg}	μ_f 10^{-6}[kg/m s]	μ_g	k_f 10^{-6}[kW/m K]	k_g	$(Pr)_f$	$(Pr)_g$
0.01	0.006112	0.10002	4.210	1.86	1752	8.49	569	16.3	12.96	0.97
5	0.008719	0.10001	4.204	1.86	1501	8.66	578	16.7	10.92	0.96
10	0.01227	0.10003	4.193	1.86	1300	8.83	587	17.1	9.29	0.96
15	0.01704	0.10010	4.186	1.87	1136	9.00	595	17.5	7.99	0.96
20	0.02337	0.10018	4.183	1.87	1002	9.18	603	17.9	6.95	0.96
25	0.03166	0.10030	4.181	1.88	890	9.35	611	18.3	6.09	0.96
30	0.04242	0.10044	4.179	1.88	797	9.52	618	18.7	5.39	0.96
35	0.05622	0.10060	4.178	1.88	718	9.70	625	19.1	4.80	0.96
40	0.07375	0.10079	4.179	1.89	651	9.87	632	19.5	4.30	0.96
45	0.09582	0.10099	4.181	1.89	594	10.0	638	19.9	3.89	0.95
50	0.1233	0.1012	4.182	1.90	544	10.2	643	20.4	3.54	0.95
55	0.1574	0.1015	4.183	1.90	501	10.4	648	20.8	3.23	0.95
60	0.1992	0.1017	4.185	1.91	463	10.6	653	21.2	2.97	0.95
65	0.2501	0.1020	4.188	1.92	430	10.7	658	21.6	2.74	0.95
70	0.3116	0.1023	4.191	1.93	400	10.9	662	22.0	2.53	0.96
75	0.3855	0.1026	4.194	1.94	374	11.1	666	22.5	2.36	0.96
80	0.4736	0.1029	4.198	1.95	351	11.3	670	22.9	2.20	0.96
85	0.5780	0.1032	4.203	1.96	330	11.4	673	23.3	2.06	0.96
90	0.7011	0.1036	4.208	1.97	311	11.6	676	23.8	1.94	0.96
95	0.8453	0.1040	4.213	1.99	294	11.8	678	24.3	1.83	0.97
100	1.01325	0.1044	4.219	2.01	279	12.0	681	24.8	1.73	0.97
105	1.208	0.1048	4.226	2.03	265	12.2	683	25.3	1.64	0.98
110	1.433	0.1052	4.233	2.05	252	12.4	684	25.8	1.56	0.99
115	1.691	0.1056	4.240	2.07	241	12.6	686	26.3	1.49	0.99
120	1.985	0.1060	4.248	2.09	230	12.8	687	26.8	1.42	1.00
125	2.321	0.1065	4.26	2.12	220	13.0	687	27.3	1.36	1.01
130	2.701	0.1070	4.27	2.15	211	13.2	688	27.8	1.31	1.02
135	3.131	0.1075	4.28	2.18	203	13.4	688	28.3	1.26	1.03
140	3.614	0.1080	4.29	2.21	195	13.5	688	28.8	1.22	1.04
145	4.155	0.1085	4.30	2.25	188	13.7	687	29.4	1.18	1.05
150	4.760	0.1091	4.32	2.29	181	13.9	687	30.0	1.14	1.07
160	6.181	0.1102	4.35	2.38	169	14.2	684	31.3	1.07	1.09
170	7.920	0.1114	4.38	2.49	159	14.6	681	32.6	1.02	1.12
180	10.03	0.1128	4.42	2.62	149	15.0	676	34.1	0.97	1.15
190	12.55	0.1142	4.46	2.76	141	15.3	671	35.7	0.94	1.18
200	15.55	0.1157	4.51	2.91	134	15.7	665	37.5	0.91	1.22
210	19.08	0.1173	4.56	3.07	127	16.0	657	39.4	0.88	1.25
220	23.20	0.1190	4.63	3.25	121	16.3	648	41.5	0.86	1.28
230	27.98	0.1209	4.70	3.45	116	16.7	639	43.9	0.85	1.31
240	33.48	0.1229	4.78	3.68	111	17.1	628	46.5	0.84	1.35
250	39.78	0.1251	4.87	3.94	107	17.5	616	49.5	0.85	1.39
260	46.94	0.1276	4.98	4.22	103	17.9	603	52.8	0.85	1.43
270	55.05	0.1302	5.10	4.55	99	18.3	589	56.6	0.86	1.47
280	64.19	0.1332	5.24	4.98	96	18.8	574	61.0	0.88	1.53
290	74.45	0.1366	5.42	5.46	93	19.3	558	66.0	0.90	1.60
300	85.92	0.1404	5.65	6.18	90	19.8	541	72.0	0.94	1.70
320	112.9	0.1499								
340	146.1	0.1639								
360	186.7	0.1894								
370	210.5	0.2225								
374.15	221.2	0.317								

The values for saturated water can be used with good accuracy above saturation pressure. The values for saturated steam can be used with only moderate accuracy below saturation pressure at temperatures greater than 200 °C.

Saturated Water and Steam

t [°C]	p_s [bar]	v_g [m³/kg]	h_f [kJ/kg]	h_{fg} [kJ/kg]	h_g [kJ/kg]	s_f [kJ/kg K]	s_{fg} [kJ/kg K]	s_g [kJ/kg K]
0.01	0.006112	206.1	0*	2500.8	2500.8	0†	9.155	9.155
1	0.006566	192.6	4.2	2498.3	2502.5	0.015	9.113	9.128
2	0.007054	179.9	8.4	2495.9	2504.3	0.031	9.071	9.102
3	0.007575	168.2	12.6	2493.6	2506.2	0.046	9.030	9.076
4	0.008129	157.3	16.8	2491.3	2508.1	0.061	8.989	9.050
5	0.008719	147.1	21.0	2488.9	2509.9	0.076	8.948	9.024
6	0.009346	137.8	25.2	2486.6	2511.8	0.091	8.908	8.999
7	0.01001	129.1	29.4	2484.3	2513.7	0.106	8.868	8.974
8	0.01072	121.0	33.6	2481.9	2515.5	0.121	8.828	8.949
9	0.01147	113.4	37.8	2479.6	2517.4	0.136	8.788	8.924
10	0.01227	106.4	42.0	2477.2	2519.2	0.151	8.749	8.900
11	0.01312	99.90	46.2	2474.9	2521.1	0.166	8.710	8.876
12	0.01401	93.83	50.4	2472.5	2522.9	0.180	8.671	8.851
13	0.01497	88.17	54.6	2470.2	2524.8	0.195	8.633	8.828
14	0.01597	82.89	58.8	2467.8	2526.6	0.210	8.594	8.804
15	0.01704	77.97	62.9	2465.5	2528.4	0.224	8.556	8.780
16	0.01817	73.38	67.1	2463.1	2530.2	0.239	8.518	8.757
17	0.01936	69.09	71.3	2460.8	2532.1	0.253	8.481	8.734
18	0.02063	65.08	75.5	2458.4	2533.9	0.268	8.444	8.712
19	0.02196	61.34	79.7	2456.0	2535.7	0.282	8.407	8.689
20	0.02337	57.84	83.9	2453.7	2537.6	0.296	8.370	8.666
21	0.02486	54.56	88.0	2451.4	2539.4	0.310	8.334	8.644
22	0.02642	51.49	92.2	2449.0	2541.2	0.325	8.297	8.622
23	0.02808	48.62	96.4	2446.6	2543.0	0.339	8.261	8.600
24	0.02982	45.92	100.6	2444.2	2544.8	0.353	8.226	8.579
25	0.03166	43.40	104.8	2441.8	2546.6	0.367	8.190	8.557
26	0.03360	41.03	108.9	2439.5	2548.4	0.381	8.155	8.536
27	0.03564	38.81	113.1	2437.2	2550.3	0.395	8.120	8.515
28	0.03778	36.73	117.3	2434.8	2552.1	0.409	8.085	8.494
29	0.04004	34.77	121.5	2432.4	2553.9	0.423	8.050	8.473
30	0.04242	32.93	125.7	2430.0	2555.7	0.436	8.016	8.452
32	0.04754	29.57	134.0	2425.3	2559.3	0.464	7.948	8.412
34	0.05318	26.60	142.4	2420.5	2562.9	0.491	7.881	8.372
36	0.05940	23.97	150.7	2415.8	2566.5	0.518	7.814	8.332
38	0.06624	21.63	159.1	2411.0	2570.1	0.545	7.749	8.294
40	0.07375	19.55	167.5	2406.2	2573.7	0.572	7.684	8.256
42	0.08198	17.69	175.8	2401.4	2577.2	0.599	7.620	8.219
44	0.09100	16.03	184.2	2396.6	2580.8	0.625	7.557	8.182
46	0.1009	14.56	192.5	2391.8	2584.3	0.651	7.494	8.145
48	0.1116	13.23	200.9	2387.0	2587.9	0.678	7.433	8.111
50	0.1233	12.04	209.3	2382.1	2591.4	0.704	7.371	8.075
55	0.1574	9.578	230.2	2370.1	2600.3	0.768	7.223	7.991
60	0.1992	7.678	251.1	2357.9	2609.0	0.831	7.078	7.909
65	0.2501	6.201	272.0	2345.7	2617.7	0.893	6.937	7.830
70	0.3116	5.045	293.0	2333.3	2626.3	0.955	6.800	7.755
75	0.3855	4.133	313.9	2320.8	2634.7	1.015	6.666	7.681
80	0.4736	3.408	334.9	2308.3	2643.2	1.075	6.536	7.611
85	0.5780	2.828	355.9	2295.6	2651.5	1.134	6.410	7.544
90	0.7011	2.361	376.9	2282.8	2659.7	1.192	6.286	7.478
95	0.8453	1.982	398.0	2269.8	2667.8	1.250	6.166	7.416
100	1.01325	1.673	419.1	2256.7	2675.8	1.307	6.048	7.355

† u and s are chosen to be zero for saturated liquid at the triple point.

Note: values of v_f can be found on p. 10.

Dry Air at Low Pressure

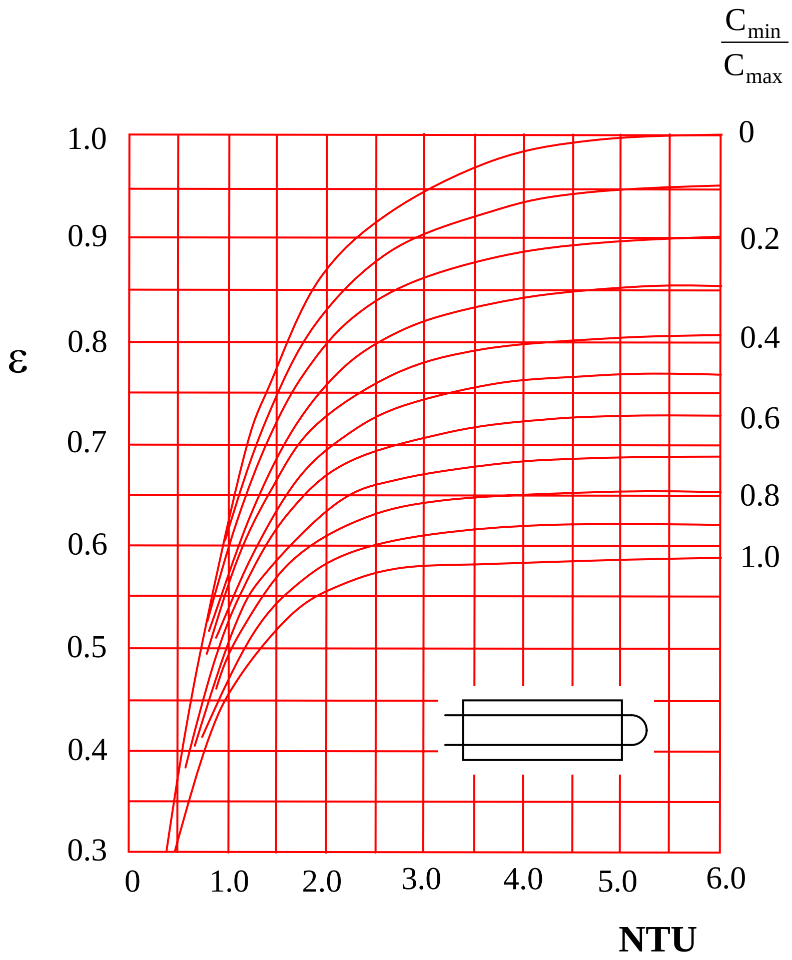
T [K]	c_p [kJ/kg K]	c_v [kJ/kg K]	γ	μ 10^{-5}[kg/m s]	k 10^{-5}[kW/m K]	Pr	at 1 atm ρ [kg/m³]	at 1 atm ν 10^{-5}[m²/s]
175	1.0023	0.7152	1.401	1.182	1.593	0.744	2.017	0.586
200	1.0025	0.7154	1.401	1.329	1.809	0.736	1.765	0.753
225	1.0027	0.7156	1.401	1.467	2.020	0.728	1.569	0.935
250	1.0031	0.7160	1.401	1.599	2.227	0.720	1.412	1.132
275	1.0038	0.7167	1.401	1.725	2.428	0.713	1.284	1.343
300	1.0049	0.7178	1.400	1.846	2.624	0.707	1.177	1.568
325	1.0063	0.7192	1.400	1.962	2.816	0.701	1.086	1.807
350	1.0082	0.7211	1.398	2.075	3.003	0.697	1.009	2.056
375	1.0106	0.7235	1.397	2.181	3.186	0.692	0.9413	2.317
400	1.0135	0.7264	1.395	2.286	3.365	0.688	0.8824	2.591
450	1.0206	0.7335	1.391	2.485	3.710	0.684	0.7844	3.168
500	1.0295	0.7424	1.387	2.670	4.041	0.680	0.7060	3.782
550	1.0398	0.7527	1.381	2.849	4.357	0.680	0.6418	4.439
600	1.0511	0.7640	1.376	3.017	4.661	0.680	0.5883	5.128
650	1.0629	0.7758	1.370	3.178	4.954	0.682	0.5430	5.853
700	1.0750	0.7879	1.364	3.332	5.236	0.684	0.5043	6.607
750	1.0870	0.7999	1.359	3.482	5.509	0.687	0.4706	7.399
800	1.0987	0.8116	1.354	3.624	5.774	0.690	0.4412	8.214
850	1.1101	0.8230	1.349	3.763	6.030	0.693	0.4153	9.061
900	1.1209	0.8338	1.344	3.897	6.276	0.696	0.3922	9.936
950	1.1313	0.8442	1.340	4.026	6.520	0.699	0.3716	10.83
1000	1.1411	0.8540	1.336	4.153	6.754	0.702	0.3530	11.76
1050	1.1502	0.8631	1.333	4.276	6.985	0.704	0.3362	12.72
1100	1.1589	0.8718	1.329	4.396	7.209	0.707	0.3209	13.70
1150	1.1670	0.8799	1.326	4.511	7.427	0.709	0.3069	14.70
1200	1.1746	0.8875	1.323	4.626	7.640	0.711	0.2941	15.73
1250	1.1817	0.8946	1.321	4.736	7.849	0.713	0.2824	16.77
1300	1.1884	0.9013	1.319	4.846	8.054	0.715	0.2715	17.85
1350	1.1946	0.9075	1.316	4.952	8.253	0.717	0.2615	18.94
1400	1.2005	0.9134	1.314	5.057	8.450	0.719	0.2521	20.06
1500	1.2112	0.9241	1.311	5.264	8.831	0.722	0.2353	22.36
1600	1.2207	0.9336	1.308	5.457	9.199	0.724	0.2206	24.74
1700	1.2293	0.9422	1.305	5.646	9.554	0.726	0.2076	27.20
1800	1.2370	0.9499	1.302	5.829	9.899	0.728	0.1961	29.72
1900	1.2440	0.9569	1.300	6.008	10.233	0.730	0.1858	32.34
2000	1.2505	0.9634	1.298	—	—	—	0.1765	—
2100	1.2564	0.9693	1.296	—	—	—	0.1681	—
2200	1.2619	0.9748	1.295	—	—	—	0.1604	—
2300	1.2669	0.9798	1.293	—	—	—	0.1535	—
2400	1.2717	0.9846	1.292	—	—	—	0.1471	—
2500	1.2762	0.9891	1.290	—	—	—	0.1412	—
2600	1.2803	0.9932	1.289	—	—	—	0.1358	—
2700	1.2843	0.9972	1.288	—	—	—	0.1307	—
2800	1.2881	1.0010	1.287	—	—	—	0.1261	—
2900	1.2916	1.0045	1.286	—	—	—	0.1217	—
3000	1.2949	1.0078	1.285	—	—	—	0.1177	—

The values for air can also be used with reasonable accuracy for CO, N_2 and O_2.

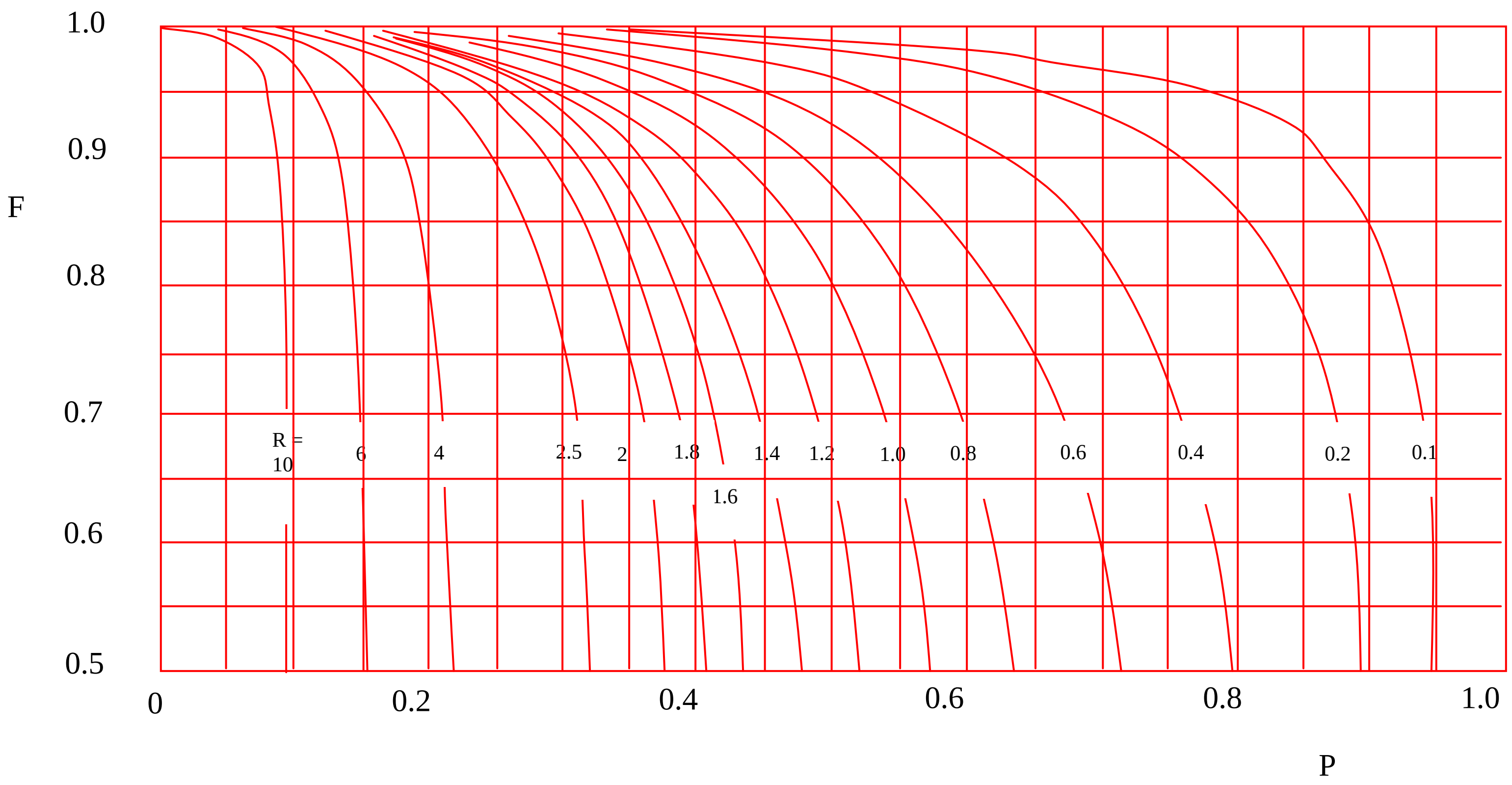
The values of the thermodynamic properties c_v and c_p on pp. 16 and 17 are those at zero pressure. The values for the gases are quite accurate over a wide range of pressure, but those for the vapours increase appreciably with pressure.

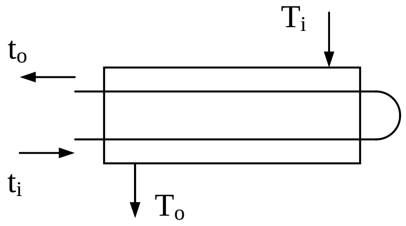
The transport properties μ and k for air are accurate over a wide range of pressure, except at such low pressures that the mean free path of the molecules is comparable to the distance between the solid surfaces containing the gas.

At high temperatures (>1500 K for air) dissociation becomes appreciable and pressure is a significant variable for both gases and vapours: the values on pp. 16 and 17 apply only to undissociated states.



Effectiveness of a shell-and-tube heat exchanger with one shell and any multiple of two tube passes (2, 4, etc)





$$P = \frac{t_o - t_i}{T_i - t_i}$$

$$R = \frac{T_i - T_o}{t_o - t_i}$$

Correction factor for a shell-and-tube heat exchanger with one shell and any multiple of two tube passes (two, four, etc tube passes)

Generalised Solution Methodologies

If a surface is open then any radiation that passes through it is unlikely to return. Therefore an open surface acts as a black body with ε =1.

If a surface is adiabatic then the resistance (1- ε) / εA becomes irrelevant and $E_{bi} = J_i$

If one surface cannot see another then the view factor F will be zero and the resistance will be infinite. This indicates there will be no heat transfer between those surfaces by radiation.

For general problems involving more than 3 bodies a large number of simultaneous linear equations may need to be solved and this can be done by Gauss-Siedel method. The general set of equations are given by:

$$[M][J]=[S]$$

where [M] is a n x n matrix for n bodies where the components are given by:

$$M_{ij=i} = \frac{1-(1-\varepsilon_i)F_{i-i}}{\varepsilon_i} \quad \& \quad M_{ij\neq i} = \frac{-(1-\varepsilon_i)F_{i-j}}{\varepsilon_i}$$

[J] and [S] are 1 x n matrices which are given by: $[J]=\begin{bmatrix} J_1 \\ J_2 \\ .. \\ .. \\ J_n \end{bmatrix}$ & $[S]=\begin{bmatrix} \sigma.T_1^{\,4} \\ \sigma.T_2^{\,4} \\ .. \\ .. \\ \sigma.T_n^{\,4} \end{bmatrix}$

For some problem it is easier to write [S] matrix as:

$$[S] = \begin{bmatrix} \sigma.T_1^4 \\ \sigma.T_2^4 \\ .. \\ \sigma.T_k^4 \\ q_{k+1} \\ \ldots \\ \ldots. \\ q_n \end{bmatrix}$$

For this case [M] matrix takes the following form:

$$M_{ij=i} = \frac{1-(1-\varepsilon_i)F_{i-i}}{\varepsilon_i} \quad \& \quad M_{ij\neq i} = \frac{-(1-\varepsilon_i)F_{i-j}}{\varepsilon_i}$$ for i = 1,2,…..k

$$M_{ij=i} = 1-F_{i-i} \quad \& \quad M_{ij\neq i} = -F_{i-j}$$ for i = k+1,k+2,…..n

The radiosity matrix [J] remains unchanged and one needs to solve [M] [J] = [S]