Appendices

A.1 Derivation of Fourier Series Mathematical Equation

The heat exchanger core frontal face is a rectangular domain having edges $2a$, $2b$ in x-y plane as shown in Figure 4.10b and will be a square domain when $a = b$. The sides of the rectangle are along the straight lines $x = a$, $x = -a$, $y = b$ and $y = -b$.

The Navier-Stokes equations are,

$$\rho\left(\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} + w\frac{\partial u}{\partial z}\right) = -\frac{\partial p}{\partial x} + \mu\left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} + \frac{\partial^2 u}{\partial z^2}\right) \tag{A-1}$$

$$= -\frac{\partial p}{\partial x} + \mu\left(\nabla^2 u\right) \tag{A-2}$$

$$\rho\left(\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} + w\frac{\partial v}{\partial z}\right) = -\frac{\partial p}{\partial y} + \mu\left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} + \frac{\partial^2 v}{\partial z^2}\right) \tag{A-3}$$

$$= -\frac{\partial p}{\partial y} + \mu\left(\nabla^2 v\right) \tag{A-4}$$

$$\rho\left(\frac{\partial w}{\partial t} + u\frac{\partial w}{\partial x} + v\frac{\partial w}{\partial y} + w\frac{\partial w}{\partial z}\right) = -\frac{\partial p}{\partial z} + \mu\left(\frac{\partial^2 w}{\partial x^2} + \frac{\partial^2 w}{\partial y^2} + \frac{\partial^2 w}{\partial z^2}\right) \tag{A-5}$$

$$= -\frac{\partial p}{\partial z} + \mu\left(\nabla^2 w\right) \tag{A-6}$$

Consider that the cold fluid flows in the z-direction, which is parallel to the wall of the rectangular duct. There is no cross flow for the cold fluid. Hence

$$u \equiv 0,\ v \equiv 0,\ w = w(x,y) \tag{A-7}$$

$$\text{and } \frac{\partial w}{\partial z} = 0 \tag{A-8}$$

Inertial terms drop out from the full Navier–Stokes equations. There is a constant pressure gradient in the z-direction and $-\dfrac{\partial p}{\partial z}$ = constant.

Actually the flow of the hot fluid is in the y-direction and is perpendicular to the flow of the cold fluid.

Compact Heat Exchangers – Analysis, Design and Optimization using FEM and CFD Approach, First Edition. C. Ranganayakulu and K.N. Seetharamu.

The cold fluid flows under the influence of a constant pressure gradient in the z-direction and its equation is

$$\frac{\partial^2 W_C}{\partial x^2}+\frac{\partial^2 W_C}{\partial y^2}=\frac{1}{\mu}\frac{\partial P_C}{\partial z}=\text{a constant} \tag{A-9}$$

The same equation can be used for other fluid provided the x, y, z coordinates are changed accordingly. Similarly, the hot fluid flows under the influence of a constant pressure gradient in the x-direction and its equation is

$$\frac{\partial^2 W_h}{\partial y^2}+\frac{\partial^2 W_h}{\partial z^2}=\frac{1}{\mu}\frac{\partial P_h}{\partial x}=\text{a constant} \tag{A-10}$$

Only one equation can be shown by removing the suffix c or h in the above Equations A-1,2 to avoid repetitions of the equations. Then the equation for the fluid (cold or hot) at the exchanger inlet duct can be represented as

$$\frac{\partial^2 W}{\partial x^2}+\frac{\partial^2 W}{\partial y^2}=\frac{1}{\mu}\frac{\partial P}{\partial z}=D=\text{a constant} \tag{A-11}$$

On boundary,

$$\text{at } x=\pm a,\quad W(\pm a, y)=0 \tag{A-12}$$

$$\text{at } y=\pm b,\quad W(x,\pm b)=0 \tag{A-13}$$

The term $\frac{1}{\mu}\frac{\partial P}{\partial z}$ is a constant that can be regarded as known since the choice of the pressure gradient is in one's control here. As such there is only one unknown, viz., $W = W(x,y)$ controlled by Equations A-1–3 above. The solution based on Fourier series expansion [1,2] is as follows:

Then

$$D=\sum_{m,n=0}^{\infty} D_{m,n}\cos\frac{(2m+1)\pi x}{2a}\cos\frac{(2n+1)\pi y}{2b} \tag{A-14}$$

$$(-\mathrm{a}<\mathrm{x}<\mathrm{a},\ -\mathrm{b}<\mathrm{y}<\mathrm{b})$$

$$\int_{-a}^{a}\cos\frac{(2p+1)\pi x}{2a}\cos\frac{(2q+1)\pi x}{2a}dx=\begin{cases}0 & if\ \ p\neq q\\ a & if\ \ p=q\end{cases} \tag{A-15}$$

$$\text{Equation A}-14\Rightarrow \int_{-a}^{a} D\ \cos\frac{(2p+1)\pi x}{2a}dx=\sum_{n=0}^{\infty}(D_{pn})(a)\ \cos\frac{(2n+1)\pi y}{2b} \tag{A-16}$$

$$LHS=D\frac{2a}{(2p+1)\pi}\left[\sin\frac{(2p+1)\pi x}{2a}\right]_{-a}^{+a}=D\frac{4a}{(2p+1)\pi}\sin\frac{(2p+1)\pi}{2} \tag{A-17}$$

$$\text{Equation A}-16 \Rightarrow \frac{4aD}{(2p+1)\pi}\ \sin\frac{(2p+1)\pi}{2}\int_{-b}^{b}\cos\frac{(2q+1)\pi y}{2b}\ dy = D_{pq}\ ab \tag{A-18}$$

$$LHS = \frac{4a\ D}{(2p+1)\pi}\sin\frac{(2p+1)\pi}{2}\ \frac{2b}{(2q+1)\pi}\ (2)\ \sin\frac{(2q+1)\pi}{2} \tag{A-19}$$

$$D_{pq} = \frac{16\ D}{(2p+1)\ (2q+1)\pi^2}\ \sin\frac{(2p+1)\pi}{2}\ \sin\frac{(2q+1)\pi}{2} \tag{A-20}$$

$$= \frac{16\ D}{(2p+1)\ (2q+1)\pi^2}\ (-1)^p\ (-1)^q = \frac{16\ D\ (-1)^{p+q}}{(2p+1)\ (2q+1)\prod^2} \tag{A-21}$$

In the Equation A-14, the Fourier coefficients are

$$D_{mn} = \frac{16\ D\ (-1)^{m+n}}{(2m+1)\ (2n+1)\ \pi^2} \tag{A-22}$$

$(m,n = 0, 1, 2, \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots)$

$$\frac{\partial^2 W}{\partial x^2} + \frac{\partial^2 W}{\partial y^2} = \sum_{m,n=0}^{\infty} A_{m,n}\ \cos\frac{(2m+1)\pi x}{2a}\ \cos\frac{(2n+1)\pi y}{2b} \tag{A-23}$$

$$W = \sum_{p,q} E_{pq}\ \cos\frac{(2p+1)\pi x}{2a}\ \cos\frac{(2q+1)\pi y}{2b} \tag{A-24}$$

$$\frac{\partial^2 W}{\partial x^2} = \sum_{p,q} E_{pq}\ \left\{-\left[\frac{(2p+1)\pi}{2a}\right]^2\right\}\ \cos\frac{(2p+1)\pi x}{2a}\ \cos\frac{(2q+1)\pi y}{2b} \tag{A-25}$$

$$\frac{\partial^2 W}{\partial y^2} = \sum_{p,q} E_{pq}\ \left\{-\left[\frac{(2q+1)\pi}{2b}\right]^2\right\}\ \cos\frac{(2p+1)\pi x}{2a}\ \cos\frac{(2q+1)\pi y}{2b} \tag{A-26}$$

$$\nabla^2\ W = \frac{\partial^2 W}{\partial x^2} + \frac{\partial^2 W}{\partial y^2} \tag{A-27}$$

$$= -\sum_{p,q} E_{pq}\ \left[\frac{(2p+1)^2\pi^2}{4a^2} + \frac{(2q+1)^2\pi^2}{4b^2}\right]\ \cos\frac{(2p+1)\pi x}{2a}\ \cos\frac{(2q+1)\pi y}{2b} \tag{A-28}$$

$$= -E_{pq}\left\{\frac{(2p+1)^2}{a^2} + \frac{(2q+1)^2}{b^2}\right\}\ \left(\frac{\pi^2}{4}\right) \equiv D_{pq} \tag{A-29}$$

Comparison of Equation A-11 along with Equation A-14 and Equation A-29 leads to

$$E_{mn} = -\frac{4}{\pi^2}\ \left[\frac{(2m+1)^2}{a^2} + \frac{(2n+1)^2}{b^2}\right]^{-1}\ D_{mn} \tag{A-30}$$

$$= \frac{-64D\ (-1)^{m+n}}{(2m+1)\ (2n+1)\pi^4}\ \frac{1}{\left[\frac{(2m+1)^2}{a^2} + \frac{(2n+1)^2}{b^2}\right]} \tag{A-31}$$

the solution to represent the fluid velocity (*W*) is

$$W(x,y) = \frac{64D}{\pi^4} \sum_{m,n=0}^{\infty} \left\{ \frac{(-1)^{m+n+1}}{\left[\frac{(2m+1)^2}{a^2} + \frac{(2n+1)^2}{b^2}\right]} \frac{\cos\frac{(2m+1)\pi x}{2a} \cos\frac{(2n+1)\pi y}{2b}}{(2m+1)(2n+1)} \right\} \tag{A-32}$$

Verification:

The correctness of the solution A-32 can be verified by partial differentiation with respect to x twice and partial differentiation with respect to y twice and adding the two results.

Over the rectangle $-a < x < a$ and $-b < y < b$, we have the expansion

$$1 = \frac{16}{\pi^2} \sum_{m,n=0}^{\infty} \frac{(-1)^{m+n}}{(2m+1)\ (2n+1)} \cos\frac{(2m+1)\pi x}{2a} \cos\frac{(2n+1)\pi y}{2b} \tag{A-33}$$

The function 1, over the rectangle in Figure 4.10b, satisfies the usual Dirichlet's conditions for the Fourier expansion. This expansion is directly verifiable.

Double Fourier expansion of function 1 in terms of the class of functions $\cos\frac{(2m+1)\pi x}{2a} \quad \cos\frac{(2n+1)\pi y}{2b}$ (which is a "complete" set of orthogonal functions) over the rectangular domain $(-a < x < a, \quad -b < y < b.)$ is certainly possible and the expansion in Equation A-33 is valid over the above rectangular domain.

The functions

$$\cos\frac{\prod x}{2a},\ \cos\frac{3\pi x}{2a},\ \cos\frac{5\pi x}{2a},\ \ldots\ldots\ldots\ldots,\left\{\cos\frac{(2m+1)\pi x}{2a}\ ;\ m=0,\ 1,\ 2\cdots\right\} \tag{A-34}$$

Constitute a complete set of functions over the interval $-a < x < a$.

Similarly, the functions

$$\cos\frac{\pi y}{2b},\ \cos\frac{3\pi y}{2b},\ \cos\frac{5\pi y}{2b},\ \ldots\ldots\ldots\ldots,\left\{\cos\frac{(2n+1)\pi y}{2b}\ ;\ n=0,\ 1,\ 2\cdots\right\} \tag{A-35}$$

forms a complete set over the interval $-b < x < b$

By a direct multiplication of the above two complete sets of functions

$$\cos\frac{(2n+1)\pi x}{2a} \quad \cos\frac{(2m+1)\pi y}{2b} \quad ;\ (m,n=0,\ 1,\ 2,\cdots)$$

constitute a complete set of functions.

$$\cos\frac{(2m+1)\pi x}{2a} \quad \cos\frac{(2n+1)\pi y}{2b}, (m,n=0,1,2,\ldots), \tag{A-36}$$

over the domain $(-a < x < a) \times (-b < y < b)$, i.e. over the rectangular domain referred to earlier.

$$D_{m,n} = \frac{16}{\pi^2} \sum_{m,n=0}^{\infty} \left\{ \frac{(-1)^{m+n}}{(2m+1)\ (2n+1)} \right\} D \tag{A-37}$$

The above observations confirm that the function $W(x,y)$ defined in, for example, A-32 does satisfy the equation

$$\frac{\partial^2 W}{\partial x^2} + \frac{\partial^2 W}{\partial y^2} = D$$

Non-slip boundary conditions:
The non-slip boundary condition requires that

$$W = 0 \quad on \quad x = \pm a \text{ for all } y \text{ in the range } -b < y < b \tag{A-38}$$

$$\text{and } W = 0 \quad on \quad y = \pm b \text{ for all } x \text{ in the range } -a < x < a \tag{A-39}$$

and these can be directly checked by noting that

$$\cos(2m+1)\frac{\pi}{2} = 0, \text{ for all integer values of } m \text{ and} \tag{A-40}$$

$$\cos(2n+1)\frac{\pi}{2} = 0, \text{ for all integer values of } n. \tag{A-41}$$

A.2 Molar, Gas and Critical Properties

	Properties of various ideal gases at 25° C, 100 kPa∗ *(SI units)*						
Gas	**Chemical formula**	**Molecular mass**	***R*** **kJ/kg · K**	***ρ*** **kg/m³**	***Cp**** **kJ/kg · K**	***Cp**** **kJ/kg · K**	***k***
Steam	H_2O	18.015	0.4615	0.0231	1.872	1.41	1.327
Acetylene	C_2H_2	26.038	0.3193	1.05	1.699	1.38	1.231
Air	–	28.97	0.287	1.169	1.004	0.717	1.4
Ammonia	NH_3	17.031	0.4882	0.694	2.13	1.642	1.297
Argon	Ar	39.948	0.2081	1.613	0.52	0.312	1.667
Butane	C_4H_{10}	58.124	0.143	2.407	1.716	1.573	1.091
Carbon monoxide	CO	28.01	0.2968	1.13	1.041	0.744	1.399
Carbon dioxide	CO_2	44.01	0.1889	1.775	0.842	0.653	1.289
Ethane	C_2H_4	30.07	0.2765	1.222	1.766	1.49	1.186
Ethanol	C_2H_5OH	46.069	0.1805	1.883	1.427	1.246	1.145
Ethylene	C_2H_4	28.054	0.2964	1.138	1.548	1.252	1.237
Helium	He	4.003	2.0771	0.1615	5.193	3.116	1.667
Hydrogen	H_2	2.016	4.1243	0.0813	14.209	1.008	1.409

(*Continued*)

Gas	Chemical formula	Molecular mass	R kJ/kg · K	ρ kg/m^3	C_p* kJ/kg · K	C_p* kJ/kg · K	k
	Properties of various ideal gases at 25 ° C, 100 kPa∗ (SI units)						
Methane	CH_4	16.043	0.5183	0.648	2.254	1.736	1.299
Methanol	CH_2OH	32.042	0.2595	1.31	1.405	1.146	1.227
Neon	Ne	20.183	0.412	0.814	1.03	0.618	1.667
Nitric oxide	NO	30.006	0.2771	1.21	0.993	0.716	1.387
Nitrogen	N_2	28.013	0.2968	1.13	1.042	0.745	1.4
Nitrous oxide	N_2O	44.013	0.1889	1.775	0.879	0.69	1.274
n-octane	C_8H_{18}	114.23	0.07279	0.092	1.711	1.638	1.044
Oxygen	O_2	31.999	0.2598	1.292	0.922	0.662	1.393
Propane	C_3H_2	44.094	0.1886	1.808	1.679	1.49	1.126
R-12	CCI_2F_2	120.914	0.06876	4.98	0.616	0.547	1.126
R-22	$CHCLF_2$	86.469	0.09616	3.54	0.658	0.562	1.171
R-134a	CF_3CH_2F	102.03	0.08149	4.2	0.852	0.771	1.106
Sulfur dioxide	SO_2	64.059	0.1298	2.618	0.624	0.494	1.263
Sulfur trioxide	SO_3	80.053	0.10386	3.272	0.635	0.531	1.196

A.3 Thermo-Physical Properties of Gases at Atmospheric Pressure

T (K)	ρ (kg/m^3)	c_p (kJ/kg·K)	$\mu.10^7$ (N.s/m^2)	$v.10^6$ (m^2/s)	$k.10^3$ (W/m.K)	$\alpha.10^6$ (m^2/s)	Pr
Air							
100	3.5562	1.032	71.1	2	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	7.59	18.1	10.3	0.737
250	1.3947	1.006	159.6	11.44	22.3	15.9	0.72
300	1.1614	1.007	184.6	15.89	26.3	22.5	0.707

T (K)	ρ (kg/m^3)	c_p (kJ/kg·K)	$\mu.10^7$ (N.s/m^2)	$v.10^6$ (m^2/s)	$k.10^3$ (W/m.K)	$\alpha.10^6$ (m^2/s)	Pr
350	0.995	1.009	208.2	20.92	30	29.9	0.7
400	0.8711	1.014	230.1	26.41	33.8	38.3	0.69
450	0.774	1.021	250.7	32.39	37.3	47.2	0.686
500	0.6964	1.03	270.1	38.79	40.7	56.7	0.684
550	0.6329	1.04	288.4	45.57	43.9	66.7	0.683
600	0.5804	1.051	305.8	52.69	46.9	76.9	0.685
650	0.5356	1.063	322.5	60.21	49.7	87.3	0.69
700	0.4975	1.075	338.8	68.1	52.4	98	0.695
750	0.4643	1.087	354.6	76.37	54.9	109	0.702
800	0.4354	1.099	369.8	84.93	57.3	120	0.709
850	0.4097	1.11	384.3	93.8	59.6	131	0.716
900	0.3868	1.121	398.1	102.9	62	143	0.72
950	0.3666	1.131	411.3	112.2	64.3	155	0.723
1000	0.3482	1.141	424.4	121.9	66.7	168	0.726
1100	0.3166	1.159	449	141.8	71.5	195	0.728
1200	0.2902	1.175	473	162.9	76.3	224	0.728
1300	0.2679	1.189	496	185.1	82	238	0.719
1400	0.2488	1.207	530	213	91	303	0.703
1500	0.2322	1.23	557	240	100	350	0.685
1600	0.2177	1.248	584	268	106	390	0.688
1700	0.2049	1.267	611	298	113	435	0.685
1800	0.1935	1.286	637	329	120	482	0.683
1900	0.1833	1.307	663	362	128	534	0.677
2000	0.1741	1.337	689	396	137	589	0.672
2100	0.1658	1.372	715	431	147	646	0.667
2200	0.1582	1.417	740	468	160	714	0.655
2300	0.1513	1.478	766	506	175	783	0.647
2400	0.1448	1.558	792	547	196	869	0.63
2500	0.1389	1.665	818	589	222	960	0.613
3000	0.1135	2.726	955	841	486	1570	0.536

(*Continued*)

T (K)	ρ (kg/m^3)	c_p (kJ/kg·K)	$\mu.10^7$ ($N.s/m^2$)	$v.10^6$ (m^2/s)	$k.10^3$ (W/m.K)	$\alpha.10^6$ (m^2/s)	Pr
Ammonia (NH_3)							
300	0.6894	2.158	101.5	14.7	24.7	16.6	0.887
320	0.6448	2.17	109	16.9	27.2	19.4	0.87
340	0.6059	2.192	116.5	19.2	29.3	22.1	0.872
360	0.5716	2.221	124	21.7	31.6	24.9	0.872
380	0.541	2.254	131	24.2	34	27.9	0.869
400	0.5136	2.287	138	26.9	37	31.5	0.853
420	0.4888	2.322	145	29.7	40.4	35.6	0.833
440	0.4664	2.357	152.5	32.7	43.5	39.6	0.826
460	0.446	2.393	159	35.7	46.3	43.4	0.822
480	0.4273	2.43	166.5	39	49.2	47.4	0.822
500	0.4101	2.467	173	42.2	52.5	51.9	0.813
20	0.3942	2.504	180	45.7	54.5	55.2	0.827
540	0.3795	2.54	186.5	49.1	57.5	59.7	0.824
560	0.3708	2.577	193	52	60.6	63.4	0.827
580	0.3533	2.613	199.5	56.5	63.8	69.1	0.817
Carbon dioxide (CO_2)							
280	1.9022	0.83	140	7.36	15.2	9.63	0.765
300	1.773	0.851	149	8.4	16.55	11	0.766
320	1.6609	0.872	156	9.39	18.05	12.5	0.754
340	1.5618	0.891	165	10.6	19.7	14.2	0.746
360	1.4743	0.908	173	11.7	21.2	15.8	0.741
380	1.3961	0.926	181	13	22.75	17.6	0.737
400	1.3257	0.942	190	14.3	24.3	19.5	0.737
450	1.1782	0.981	210	17.8	28.3	24.5	0.728
500	1.0594	1.02	231	21.8	32.5	30.1	0.725
550	0.9625	1.05	251	26.1	36.6	36.2	0.721
600	0.8826	1.08	270	30.6	40.7	42.7	0.717
650	0.8143	1.1	288	35.4	44.5	49.7	0.712
700	0.7564	1.13	305	40.3	48.1	56.3	0.717
750	0.7057	1.15	321	45.5	51.7	63.7	0.714
800	0.6614	1.17	337	51	55.1	71.2	0.716

T (K)	ρ (kg/m³)	c_p (kJ/kg·K)	μ.10⁷ (N.s/m²)	v.10⁶ (m²/s)	k.10³ (W/m.K)	α.10⁶ (m²/s)	Pr
Carbon monoxide (CO)							
200	1.6888	1.045	127	7.52	17	9.63	0.781
220	1.5341	1.044	137	8.93	19	11.9	0.753
240	1.4055	1.043	147	10.5	20.6	14.1	0.744
260	1.2967	1.043	157	12.1	22.1	16.3	0.741
280	1.2038	1.042	166	13.8	23.6	18.8	0.733
300	1.1233	1.043	175	15.6	25	21.3	0.73
320	1.0529	1.043	184	17.5	26.3	23.9	0.73
340	0.9909	1.044	193	19.5	27.8	26.9	0.725
360	0.9357	1.045	202	21.6	29.1	29.8	0.725
380	0.8864	1.047	210	23.7	30.5	32.9	0.729
400	0.8421	1.049	218	25.9	31.8	36	0.719
450	0.7483	1.055	237	31.7	35	44.3	0.714
500	0.67352	1.065	254	37.7	38.1	53.1	0.71
550	0.61226	1.076	271	44.3	41.1	62.4	0.71
600	0.56126	1.088	286	51	44	72.1	0.707
650	0.51806	1.101	301	58.1	47	82.4	0.705
700	0.48102	1.114	315	65.5	50	93.3	0.702
750	0.44899	1.127	329	73.3	52.8	104	0.702
800	0.42095	1.14	343	81.5	55.5	116	0.705
Helium (He)							
100	0.4871	5.193	96.3	19.8	73	28.9	0.686
120	0.406	5.193	107	26.4	81.9	38.8	0.679
140	0.3481	5.193	118	33.9	90.7	50.2	0.676
160	–	5.193	129	–	99.2	–	–
180	0.2708	5.193	139	51.3	107.2	76.2	0.673
200	–	5.193	150	–	115.1	–	–
220	0.2216	5.193	160	72.2	123.1	107	0.675
240	–	5.193	170	–	130	–	–
260	0.1875	5.193	180	96	137	141	0.682
280	–	5.193	190	–	145	–	–

(*Continued*)

T (K)	ρ (kg/m³)	c_p (kJ/kg·K)	$\mu.10^7$ (N.s/m²)	$v.10^6$ (m²/s)	$k.10^3$ (W/m.K)	$\alpha.10^6$ (m²/s)	Pr
300	0.1625	5.193	199	122	152	180	0.68
350	–	5.193	221	–	170	–	–
400	0.1219	5.193	243	199	187	295	0.675
450	–	5.193	263	–	204	–	–
500	0.09754	5.193	283	290	220	434	0.668
550	–	5.193	–	–	–	–	–
600	–	5.193	320	–	252	–	–
650	–	5.193	332	–	264	–	–
700	0.06969	5.193	350	502	278	768	0.654
750	–	5.193	364	–	291	–	–
800	–	5.193	382	–	304	–	–
900	–	5.193	414	–	330	–	–
1000	0.04879	5.193	446	914	354	1400	0.654
Hydrogen (H_2)							
100	0.24255	11.23	42.1	17.4	67	24.6	0.707
150	0.16156	12.6	56	34.7	101	49.6	0.699
200	0.12115	13.54	68.1	56.2	131	79.9	0.704
250	0.09693	14.06	78.9	81.4	157	115	0.707
300	0.08078	14.31	89.6	111	183	158	0.701
350	0.06924	14.43	98.8	143	204	204	0.7
400	0.06059	14.48	108.2	179	226	258	0.695
450	0.05386	14.5	117.2	218	247	316	0.689
500	0.04848	14.52	126.4	261	266	378	0.691
550	0.04407	14.53	134.3	305	285	445	0.685
600	0.0404	14.55	142.4	352	305	519	0.678
700	0.03463	14.61	157.8	456	342	676	0.675
800	0.0303	14.7	172.4	569	378	849	0.67
900	0.02694	14.83	186.5	692	412	1030	0.671
1000	0.02424	14.99	201.3	830	448	1230	0.673
1100	0.02204	15.17	213	966	488	1460	0.662
1200	0.0202	15.37	226.2	1120	528	1700	0.659
1300	0.01865	15.59	238.5	1279	568	1955	0.655

T (K)	ρ (kg/m³)	c_p (kJ/kg·K)	$\mu.10^7$ (N.s/m²)	$v.10^6$ (m²/s)	$k.10^3$ (W/m.K)	$\alpha.10^6$ (m²/s)	Pr
1400	0.01732	15.81	250.7	1447	610	2230	0.65
1500	0.01616	16.02	262.7	1626	655	2530	0.643
1600	0.0152	16.28	273.7	1801	697	2815	0.639
1700	0.0143	16.58	284.9	1992	742	3130	0.637
1800	0.0135	16.96	296.1	2193	786	3435	0.639
1900	0.0128	17.49	307.2	2400	835	3730	0.643
2000	0.0121	18.25	318.2	2630	878	3975	0.661
Nitrogen (N_2)							
100	3.4388	1.07	68.8	2	9.58	2.6	0.768
150	2.2594	1.05	100.6	4.45	13.9	5.86	0.759
200	1.6883	1.043	129.2	7.65	18.3	10.4	0.736
250	1.3488	1.042	154.9	11.48	22.2	15.8	0.727
300	1.1233	1.041	178.2	15.86	25.9	22.1	0.716
350	0.9625	1.042	200	20.78	29.3	29.2	0.711
400	0.8425	1.045	220.4	26.16	32.7	37.1	0.704
450	0.7485	1.05	239.6	32.01	35.8	45.6	0.703
500	0.6739	1.056	257.7	38.24	38.9	54.7	0.7
550	0.6124	1.065	274.7	44.86	41.7	63.9	0.702
600	0.5615	1.075	290.8	51.79	44.6	73.9	0.701
700	0.4812	1.098	321	66.71	49.9	94.4	0.706
800	0.4211	1.22	349.1	82.9	54.8	116	0.715
900	0.3743	1.146	375.3	100.3	59.7	139	0.721
1000	0.3368	1.167	399.9	118.7	64.7	165	0.721
1100	0.3062	1.187	423.2	138.2	70	193	0.718
1200	0.2807	1.204	445.3	158.6	75.8	224	0.707
1300	0.2591	1.219	466.2	179.9	81	256	0.701
Oxygen (O_2)							
100	3.945	0.962	76.4	1.94	9.25	2.44	0.796
150	2.585	0.921	114.8	4.44	13.8	5.8	0.766
200	1.93	0.915	147.5	7.64	18.3	10.4	0.737
250	1.542	0.915	178.6	11.58	22.6	16	0.723

(*Continued*)

T (K)	ρ (kg/m^3)	c_p (kJ/kg·K)	$\mu.10^7$ (N.s/m^2)	$v.10^6$ (m^2/s)	$k.10^3$ (W/m.K)	$\alpha.10^6$ (m^2/s)	Pr
300	1.284	0.92	207.2	16.14	26.8	22.7	0.711
350	1.1	0.929	233.5	21.23	29.6	29	0.733
400	0.962	0.942	258.2	26.84	33	36.4	0.737
450	0.8554	0.956	281.4	32.9	36.3	44.4	0.741
500	0.7698	0.972	303.3	39.4	41.2	55.1	0.716
550	0.6998	0.988	324	46.3	44.1	63.8	0.726
600	0.6414	1.003	343.7	53.59	47.3	73.5	0.729
700	0.5498	1.031	380.8	69.26	52.8	93.1	0.744
800	0.481	1.054	415.2	86.32	58.9	116	0.743
900	0.4275	1.074	447.2	104.6	64.9	141	0.74
1000	0.3848	1.09	477	124	71	169	0.733
1100	0.3498	1.103	505.5	144.5	75.8	196	0.736
1200	0.3206	1.115	532.5	166.1	81.9	229	0.725
1300	0.296	1.125	588.4	188.6	87.1	262	0.721
Water vapour (steam)							
380	0.5863	2.06	127.1	21.68	24.6	20.4	1.06
400	0.5542	2.014	134.4	24.25	26.1	23.4	1.04
450	0.4902	1.98	152.5	31.11	29.9	30.8	1.01
500	0.4405	1.985	170.4	38.68	33.9	38.8	0.998
550	0.4005	1.997	188.4	47.04	37.9	47.4	0.993
600	0.3652	2.026	206.7	56.6	42.2	57	0.993
650	0.338	2.056	224.7	66.48	46.4	66.8	0.996
700	0.314	2.085	242.6	77.26	50.5	77.1	1
750	0.2931	2.119	260.4	88.84	54.9	88.4	1
800	0.2739	2.152	278.6	101.7	59.2	100	1.01
850	0.2579	2.186	296.9	115.1	63.7	113	1.02

A.4 Properties of Solid Materials

		Properties at 300 K				Properties at various temperatures (K) k (W/m.K)/ C_p (J/kg.K)									
Composition	Melting point (K)	ρ (kg/m^3)	C_p (J/kg · K)	k (W/m · K)	$\alpha . \_10^{-6}$ (m^2/s)	100	200	400	600	800	1000	1200	1500	2000	2500
Aluminium															
Pure	933	2702	903	237	97.1	302	237	240	231	218					
						482	798	949	1033	1146					
Alloy 2024-T6	775	2770	875	177	73	65	163	186	186						
(4.5% Cu, 1.5% Mg,						473	787	925	1042						
0.6% Mn)															
Alloy 195, Cast		2790	883	168	68.2			174	185						
(4.5% Cu)															
Beryllium	1550	1850	1825	200	59.2	990	301	161	126	106	90.8	78.7			
						203	1114	2191	2604	2823	3018	3227	3519		
Bismuth	545	9780	122	7.86	6.59	16.5	9.69	7.04							
						112	120	127							
Boron	2573	2500	1107	27	9.76	190	55.5	16.8	10.6	9.6	9.85				
						128	600	1463	1892	2160	2338				
Cadmium	594	8650	231	96.8	48.4	203	99.3	94.7							
						198	222	242							
Chromium	2118	7160	449	93.7	29.1	159	111	90.9	80.7	71.3	65.4	61.9	57.2	49.4	
						192	384	484	542	581	616	682	779	937	

(*Continued*)

Composition	Melting point (K)	Properties at 300 K				Properties at various temperatures (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
Cobalt	1769	8862	421	99.2	26.6	167	122	85.4	67.4	58.2	52.1	49.3	42.5		
						236	379	450	503	550	628	733	674		
Copper															
Pure	1358	8933	385	401	117	482	413	393	379	366	352	339			
						252	356	397	417	433	451	480			
Commercial bronze	1293	8800	420	52	14		42	52	59						
(90% Cu, 10% Al)							785	460	545						
Phosphor gear bronze	1104	8780	355	54	17		41	65	74						
(89% Cu, 11% Sn)															
Cartridge brass	1188	8530	380	110	33.9	75	95	137	149						
(70% Cu, 30% Zn)							360	395	425						
Constantan	1493	8920	384	23	6.71	17	19								
(55% Cu, 45% Ni)						237	362								
Germanium	1211	5360	322	59.9	34.7	232	96.8	43.2	27.3	19.8	17.4	17.4			
						190	290	337	348	357	375	395			
Gold	1336	19300	129	317	127	327	323	311	298	284	270	255			
						109	124	131	135	140	145	155			
Iridium	2720	22500	130	147	50.3	172	153	144	138	132	126	120	111		
						90	122	133	138	144	153	161	172		

Iron													
Pure	1810	7870	447	80.2	23.1	134	94	69.5	54.7	43.3	32.8	28.3	32.1
						216	384	490	574	680	975	609	654
Armco													
(99.75% pure)		7870	447	72.7	20.7	95.6	80.6	65.7	53.1	42.2	32.3	28.7	31.4
						215	384	490	574	680	975	609	654
Carbon steels													
Plain carbon		7854	434	60.5	17.7			56.7	48	39.2	30		
(Mn ≤ 1%, Si ≤ 0.1%)								487	559	685	1169		
AISI 1010		7832	434	63.9	18.8			58.7	48.8	39.2	31.3		
								487	559	685	1168		
Carbon–silicon		7817	446	51.9	14.9			49.8	44	37.4	29.3		
(Mn ≤ 1%, 0.1% < Si ≤0.6%)								501	582	699	971		
Carbon–manganese–silicon		8131	434	41	11.6			42.2	39.7	35	27.6		
(1% < Mn ≤ 1.65%, 0.1% < Si ≤ 0.6%)								487	559	685	1090		
Chromium (low) steels													
Cr– Mo–Si		7822	444	37.7	10.9			38.2	36.7	33.3	26.9		
(0.18%,0.65% Cr, 0.23% Mo, 0.6% Si)								492	575	688	969		

(*Continued*)

Composition	Melting point (K)	Properties at 300 K ρ (kg/m^3)	C_p (J/kg · K)	k (W/m · K)	$\alpha \cdot 10^{-6}$ (m^2/s)	Properties at various temperatures (K) k (W/m.K)/ C_p (J/kg.K) 100	200	400	600	800	1000	1200	1500	2000	2500
1 Cr– Mo		7858	442	42.3	12.2			42	39.1	34.5	27.4				
(0.16% C, 1% Cr,								492	575	688	969				
0.54% Mo, 0.39% Si)															
1 Cr–V		7836	443	48.9	14.1			46.8	42.1	36.3	28.2				
(0.2% C, 1.02% Cr,								492	575	688	969				
0.15% V)															
Stainless steels															
AISI 302		8055	480	15.1	3.91			17.3	20	22.8	25.4				
								512	559	585	606				
AISI 304	1670	7900	477	14.9	3.95	9.2	12.6	16.6	19.8	22.6	25.4	28	31.7		
						272	402	515	557	582	611	640	682		
AISI 316		8238	468	13.4	3.48			15.2	18.3	21.3	24.2				
								504	550	576	602				
AISI 347		7978	480	14.2	3.71			15.8	18.9	21.9	24.7				
								513	559	585	606				
Lead	601	11340	129	35.3	24.1	39.7	36.7	34	31.4						
						118	125	132	142						
Magnesium	923	1740	1024	156	87.6	169	159	153	149	146					
						649	934	1074	1170	1267					
Molybdenum	2894	10240	251	138	53.7	179	143	134	126	118	112	105	98	90	86
						141	224	261	275	285	295	308	330	380	459

Nickel														
Pure	1728	8900	444	90.7	23	164	107	80.2	65.6	67.6	71.8	76.2	82.6	
						232	383	485	592	530	562	594	616	
Nichrome	1672	8400	420	12	3.4			14	16	21				
(80% Ni, 20% Cr)								480	525	545				
Inconel X-750	1665	8510	439	11.7	3.1	8.7	10.3	13.5	17	20.5	24	27.6	33	
(73% Ni, 15% Cr, 6.7% Fe)						–	372	473	510	546	626	–	–	
Niobium	2741	8570	265	53.7	23.6	55.2	52.6	55.2	58.2	61.3	64.4	67.5	72.1	79.1
						188	249	274	283	292	301	310	324	347
Palladium	1827	12020	244	71.8	24.5	76.5	71.6	73.6	79.7	86.9	94.2	102	110	
						168	227	251	261	271	281	291	307	
Platinum														
Pure	2045	21450	133	71.6	25.1	77.5	72.6	71.8	73.2	75.6	78.7	82.6	89.5	99.4
						100	125	136	141	146	152	157	165	179
Alloy 60Pt–40Rh	1800	16630	162	47	17.4			52	59	65	69	73	76	
(60% Pt, 40% Rh)								–	–	–	–	–	–	
Rhenium	3453	21100	136	47.9	16.7	58.9	51	46.1	44.2	44.1	44.6	45.7	47.8	51.9
						97	127	139	145	151	156	162	171	186
Rhodium	2236	12450	243	150	49.6	186	154	146	136	127	121	116	110	112
						147	220	253	274	293	311	327	349	376
Silicon	1685	2330	712	148	89.2	884	264	98.9	61.9	42.2	31.2	25.7	22.7	
						259	556	790	867	913	946	967	992	

(*Continued*)

Composition	Melting point (K)	Properties at 300 K ρ (kg/m^3)	C_p (J/kg · K)	k (W/m · K)	$\alpha \cdot 10^{-6}$ (m^2/s)	Properties at various temperatures (K) k (W/m.K)/ C_p (J/kg.K) 100	200	400	600	800	1000	1200	1500	2000	2500
Silver	1235	10500	235	429	174	444	430	425	412	396	379	361			
						187	225	239	250	262	277	292			
Tantalum	3269	16600	140	57.5	24.7	59.2	57.5	57.8	58.6	59.4	60.2	61	62.2	64.1	65.6
						110	133	144	146	149	152	155	160	172	189
Thorium	2023	11700	118	54	39.1	59.8	54.6	54.5	55.8	56.9	56.9	58.7			
						99	112	124	134	145	156	167			
Tin	505	7310	227	66.6	40.1	85.2	73.3	62.2							
						188	215	243							
Titanium	1953	4500	522	21.9	9.32	30.5	24.5	20.4	19.4	19.7	20.7	22	24.5		
						300	465	551	591	633	675	620	686		
Tungsten	3660	19300	132	174	68.3	208	186	159	137	125	118	113	107	100	
						87	122	137	142	145	148	152	157	167	
Uranium	1406	19070	116	27.6	12.5	21.7	25.1	29.6	34	38.8	43.9	49			
						94	108	125	146	176	180	161			
Vanadium	2192	6100	489	30.7	10.3	35.8	31.3	31.3	33.3	35.7	38.2	40.8	44.6	50.9	
						258	430	515	540	563	597	645	714	867	
Zinc	693	7140	389	116	41.8	117	118	111	103						
						297	367	402	436						
Zirconium	2125	6570	278	22.7	12.4	33.2	25.2	21.6	20.7	21.6	23.7	26	28.8	33	
						205	264	300	322	342	362	344	344	344	

A.5 Thermo-Physical Properties of Saturated Fluids

Saturated liquids								
T (K)	ρ (kg/m^3)	c_p (kJ/kg · K)	$\mu.10^{-2}$ (N · s/m^2)	$v.10^{-2}$ (m^2/s)	$k.10^{-3}$ (W/m · K)	$\alpha.10^{-7}$ (m^2/s)	Pr	$\beta.10^{-3}$
Engine oil (unused)								
273	899.1	1.796	385	4280	147	0.91	47,000	0.7
280	895.3	1.827	217	2430	144	0.88	27,500	0.7
290	890	1.868	99.9	1120	145	0.872	12,900	0.7
300	884.1	1.909	48.6	550	145	0.859	6400	0.7
310	877.9	1.951	25.3	288	145	0.847	3400	0.7
320	871.8	1.993	14.1	161	143	0.823	1965	0.7
330	865.8	2.035	8.36	96.6	141	0.8	1205	0.7
340	859.9	2.076	5.31	61.7	139	0.779	793	0.7
350	853.9	2.118	3.56	41.7	138	0.763	546	0.7
360	847.8	2.161	2.52	29.7	138	0.753	395	0.7
370	841.8	2.206	1.86	22	137	0.738	300	0.7
380	836	2.25	1.41	16.9	136	0.723	233	0.7
390	830.6	2.294	1.1	13.3	135	0.709	187	0.7
400	825.1	2.337	0.874	10.6	134	0.695	152	0.7
410	818.9	2.381	0.698	8.52	133	0.682	125	0.7
420	812.1	2.427	0.564	6.94	133	0.675	103	0.7
430	806.5	2.471	0.47	5.83	132	0.662	88	0.7
Ethylene glycol [$C_2H_4(OH)_2$]								
273	1130.8	2.294	6.51	57.6	242	0.933	617	0.65
280	1125.8	2.323	4.2	37.3	244	0.933	400	0.65
290	1118.8	2.368	2.47	22.1	248	0.936	236	0.65
300	1114.4	2.415	1.57	14.1	252	0.939	151	0.65
310	1103.7	2.46	1.07	9.65	255	0.939	103	0.65
320	1096.2	2.505	0.757	6.91	258	0.94	73.5	0.65
330	1089.5	2.549	0.561	5.15	260	0.936	55	0.65
340	1083.8	2.592	0.431	3.98	261	0.929	42.8	0.65
350	1079	2.637	0.342	3.17	261	0.917	34.6	0.65
360	1074	2.682	0.278	2.59	261	0.906	28.6	0.65
370	1066.7	2.728	0.228	2.14	262	0.9	23.7	0.65
373	1058.5	2.742	0.215	2.03	263	0.906	22.4	0.65
Glycerin [$C_3H_5(OH)_3$]								
273	1276	2.261	1060	8310	282	0.977	85,000	0.47
280	1271.9	2.298	534	4200	284	0.972	43,200	0.47

(*Continued*)

Saturated liquids								
T (K)	ρ (kg/m^3)	c_p (kJ/kg · K)	$\mu.10^{-2}$ (N · s/m^2)	$v.10^{-2}$ (m^2/s)	$k.10^{-3}$ (W/m · K)	$\alpha.10^{-7}$ (m^2/s)	Pr	$\beta.10^{-3}$
290	1265.8	2.367	185	1460	286	0.955	15,300	0.48
300	1259.9	2.427	79.9	634	286	0.935	6780	0.48
310	1253.9	2.49	35.2	281	286	0.916	3060	0.49
320	1247.2	2.564	21	168	287	0.897	1870	0.5
Refrigerant-134a ($C_2H_2F_4$)								
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	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	0.56	4.2	2.36
270	1305.1	1.333	0.02775	0.2127	93.4	0.537	4	2.53
280	1271.8	1.361	0.02443	0.1921	89	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	3.3
310	1159.9	1.481	0.0168	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
340	1015	1.751	0.01118	0.1102	63.1	0.355	3.1	6.57
350	951.3	1.961	0.00951	0.1	58.6	0.314	3.2	9.1
360	870.1	2.437	0.00781	0.0898	54.1	0.255	3.5	15.39
370	740.3	5.105	0.0058	0.0783	51.8	0.137	5.7	55.24
Refrigerant-22 ($CHClF_2$)								
230	1416	1.087	0.03558	0.2513	114.5	0.744	3.4	2.05
240	1386.6	1.1	0.03145	0.2268	109.8	0.72	3.2	2.16
250	1356.3	1.117	0.02796	0.2062	105.2	0.695	3	2.29
260	1324.9	1.137	0.02497	0.1884	100.7	0.668	2.8	2.45
270	1292.1	1.161	0.02235	0.173	96.2	0.641	2.7	2.63
280	1257.9	1.189	0.02005	0.1594	91.7	0.613	2.6	2.86
290	1221.7	1.223	0.01798	0.1472	87.2	0.583	2.5	3.15
300	1183.4	1.265	0.0161	0.1361	82.6	0.552	2.5	3.51
310	1142.2	1.319	0.01438	0.1259	78.1	0.518	2.4	4
320	1097.4	1.391	0.01278	0.1165	73.4	0.481	2.4	4.69
330	1047.5	1.495	0.01127	0.1075	68.6	0.438	2.5	5.75
340	990.1	1.665	0.0098	0.0989	63.6	0.386	2.6	7.56
350	920.1	1.997	0.00831	0.0904	58.3	0.317	2.8	11.35
360	823.4	3.001	0.00668	0.0811	53.1	0.215	3.8	23.88

Saturated liquids

T (K)	*ρ* (kg/m³)	c_p (kJ/kg · K)	$\mu.10^{-2}$ (N · s/m²)	$v.10^{-2}$ (m²/s)	$k.10^{-3}$ (W/m · K)	$\alpha.10^{-7}$ (m²/s)	*Pr*	$\beta.10^{-3}$
Mercury (Hg)								
273	13,595	0.1404	0.1688	0.124	8180	42.85	0.029	0.181
300	13,529	0.1393	0.1523	0.1125	8540	45.3	0.0248	0.181
350	13,407	0.1377	0.1309	0.0976	9180	49.75	0.0196	0.181
400	13,287	0.1365	0.1171	0.0882	9800	54.05	0.0163	0.181
450	13,167	0.1357	0.1075	0.0816	10,400	58.1	0.014	0.181
500	13,048	0.1353	0.1007	0.0771	10,950	61.9	0.0125	0.182
550	12,929	0.1352	0.0953	0.0737	11,450	65.55	0.0112	0.184
600	12,809	0.1355	0.0911	0.0711	11,950	68.8	0.0103	0.187

Saturated liquid – vapour, 1 atm

Fluid	*Tsat* (K)	h_{fg} (kJ/kg)	ρ_f (kg/m³)	ρ_g (kg/m³)	$\sigma \cdot 10^3$ (N/m)
Ethanol	351	846	757	1.44	17.7
Ethylene glycol	470	812	1111c	–	32.7
Glycerin	563	974	1260c	–	63.0c
Mercury	630	301	12,740	3.9	417
Refrigerant R-134a	247	217	1377	5.26	15.4
Refrigerant R-22	232	234	1409	4.7	18.1

A.6 Thermo-Physical Properties of Saturated Water

Temp,	Pressure,	Specific volume (m^3/kg)		Heat of vaporization, h_{fg}	Specific heat (kJ/kg · K)		Viscosity (N.s/m^2)		Thermal conductivity (W/m.K)		Prandtl number		Surface tension, $\sigma_f \cdot 10^{-3}$	Expansion coefficient, $\beta_f \cdot 10^{-6}$	Temp
T(K)	p (bars)[b]	$v_f \cdot 10^3$	v_g	(kJ/kg · K)	$c_{p,f}$	$c_{p,g}$	$\mu_f \cdot 10^{-6}$	$\mu_g \cdot 10^{-6}$	$k_f \cdot 10^3$	$k_g \cdot 10^3$	Pr_f	Pr_g	(N/m)	(K^{-1})	T(K)
273.15	0.00611	1	206.3	2502	4.217	1.854	1750	8.02	569	18.2	12.99	0.82	75.5	–68.05	273.15
275	0.00697	1	181.7	2497	4.211	1.855	1652	8.09	574	18.3	12.22	0.82	75.3	–32.74	275
280	0.0099	1	130.4	2485	4.198	1.858	1422	8.29	582	18.6	10.26	0.83	74.8	46.04	280
285	0.01387	1	99.4	2473	4.189	1.861	1225	8.49	590	18.9	8.81	0.83	74.3	114.1	285
290	0.01917	1.001	69.7	2461	4.184	1.864	1080	8.69	598	19.3	7.56	0.84	73.7	174	290
295	0.02617	1.002	51.94	2449	4.181	1.868	959	8.89	606	19.5	6.62	0.85	72.7	227.5	295
300	0.03531	1.003	39.13	2438	4.179	1.872	855	9.09	613	19.6	5.83	0.86	71.7	276.1	300
305	0.04712	1.005	29.74	2426	4.178	1.877	769	9.29	620	20.1	5.2	0.87	70.9	320.6	305
310	0.06221	1.007	22.93	2414	4.178	1.882	695	9.49	628	20.4	4.62	0.87	70	361.9	310
315	0.08132	1.009	17.82	2402	4.179	1.888	631	9.69	634	20.7	4.16	0.88	69.2	400.4	315
320	0.1053	1.011	13.98	2390	4.18	1.895	577	9.89	640	21	3.77	0.89	68.3	436.7	320
325	0.1351	1.013	11.06	2378	4.182	1.903	528	10.09	645	21.3	3.42	0.9	67.5	471.2	325
330	0.1719	1.016	8.82	2366	4.184	1.911	489	10.29	650	21.7	3.15	0.91	66.6	504	330
335	0.2167	1.018	7.09	2354	4.186	1.92	453	10.49	656	22	2.88	0.92	65.8	535.5	335
340	0.2713	1.021	5.74	2342	4.188	1.93	420	10.69	660	22.3	2.66	0.93	64.9	566	340
345	0.3372	1.024	4.683	2329	4.191	1.941	389	10.89	668	22.6	2.45	0.93	64.1	595.4	345
350	0.4163	1.027	3.846	2317	4.195	1.954	365	11.09	668	23	2.29	0.94	63.2	624.2	350
355	0.51	1.03	3.18	2304	4.199	1.968	343	11.29	671	23.3	2.14	0.95	62.3	652.3	355
360	0.6209	1.034	2.645	2291	4.203	1.983	324	11.49	674	23.7	2.02	0.96	61.4	697.9	360

365	0.7514	1.038	2.212	2278	4.209	1.999	306	11.69	677	24.1	1.91	0.97	60.5	707.1	365
370	0.904	1.041	1.861	2265	4.214	2.017	289	11.89	679	24.5	1.8	0.98	59.5	728.7	370
373.15	1.0133	1.044	1.679	2257	4.217	2.029	279	12.02	680	24.8	1.76	0.98	58.9	750.1	373.15
375	1.0815	1.045	1.574	2252	4.22	2.036	274	12.09	681	24.9	1.7	0.99	58.6	761	375
380	1.2869	1.049	1.337	2239	4.226	2.057	260	12.29	683	25.4	1.61	1	57.6	788	380
385	1.5233	1.053	1.142	2225	4.232	2.08	248	12.49	685	25.8	1.53	1	56.6	814	385
390	1.794	1.058	0.98	2212	4.239	2.104	237	12.69	686	26.3	1.47	1.01	55.6	841	390
400	2.455	1.067	0.731	2183	4.256	2.158	217	13.05	688	27.2	1.34	1.03	53.6	896	400
410	3.302	1.077	0.553	2153	4.278	2.221	200	13.42	688	28.2	1.24	1.05	51.5	952	410
420	4.37	1.088	0.425	2123	4.302	2.291	185	13.79	688	29.8	1.16	1.08	49.4	1010	420
430	5.699	1.099	0.331	2091	4.331	2.369	173	14.14	685	30.4	1.09	1.1	47.2		430
440	7.333	1.11	0.261	2059	4.36	2.46	162	14.5	682	31.7	1.04	1.12	45.1		440
450	9.319	1.123	0.208	2024	4.4	2.56	152	14.85	678	33.1	0.99	1.14	42.9		450
460	11.71	1.137	0.167	1989	4.44	2.68	143	15.19	673	34.6	0.95	1.17	40.7		460
470	14.55	1.152	0.136	1951	4.48	2.79	136	15.54	667	36.3	0.92	1.2	38.5		470
480	17.9	1.167	0.111	1912	4.53	2.94	129	15.88	660	38.1	0.89	1.23	36.2		480
490	21.83	1.184	0.0922	1870	4.59	3.1	124	16.23	651	40.1	0.87	1.25	33.9	–	490
500	26.4	1.203	0.0766	1825	4.66	3.27	118	16.59	642	42.3	0.86	1.28	31.6	–	500
510	31.66	1.222	0.0631	1779	4.74	3.47	113	16.95	631	44.7	0.85	1.31	29.3	–	510
520	37.7	1.244	0.0525	1730	4.84	3.7	108	17.33	621	47.5	0.84	1.35	26.9	–	520
530	44.58	1.268	0.0445	1679	4.95	3.96	104	17.72	608	50.6	0.85	1.39	24.5	–	530
540	52.38	1.294	0.0375	1622	5.08	4.27	101	18.1	594	54	0.86	1.43	22.1	–	540
550	61.19	1.323	0.0317	1564	5.24	4.64	97	18.6	580	58.3	0.87	1.47	19.7	–	550
560	71.08	1.355	0.0269	1499	5.43	5.09	94	19.1	563	63.7	0.9	1.52	17.3	–	560

(*Continued*)

Temp,	Pressure,	Specific volume (m^3/kg)		Heat of vaporization, h_{fg}	Specific heat (kJ/kg · K)		Viscosity (N.s/m^2)		Thermal conductivity (W/m.K)		Prandtl number		Surface tension, $\sigma_f \cdot 10^{-3}$	Expansion coefficient, $\beta_f \cdot 10^{-6}$	Temp
T(K)	p (bars)[b]	$v_f \cdot 10^3$	v_g	(kJ/kg · K)	$c_{p,f}$	$c_{p,g}$	$\mu_f \cdot 10^{-6}$	$\mu_g \cdot 10^{-6}$	$k_f \cdot 10^3$	$k_g \cdot 10^3$	Pr_f	Pr_g	(N/m)	(K^{-1})	T(K)
570	82.16	1.392	0.0228	1429	5.68	5.67	91	19.7	548	76.7	0.94	1.59	15	–	570
580	94.51	1.433	0.0193	1353	6	6.4	88	20.4	528	76.7	0.99	1.68	12.8	–	580
590	108.3	1.482	0.0163	1274	6.41	7.35	84	21.5	513	84.1	1.05	1.84	10.5	–	590
600	123.5	1.541	0.0137	1176	7	8.75	81	22.7	497	92.9	1.14	2.15	8.4	–	600
610	137.3	1.612	0.0115	1068	7.85	11.1	77	24.1	467	103	1.3	2.6	6.3	–	610
620	159.1	1.705	0.0094	941	9.35	15.4	72	25.9	444	114	1.52	3.46	4.5	–	620
625	169.1	1.778	0.0085	858	10.6	18.3	70	27	430	121	1.65	4.2	3.5	–	625
630	179.7	1.856	0.0075	781	12.6	22.1	67	28	412	130	2	4.8	2.6	–	630
635	190.9	1.935	0.0066	683	16.4	27.6	64	30	392	141	2.7	6	1.5	–	635
640	202.7	2.075	0.0057	560	26	42	59	32	367	155	4.2	9.6	0.8	–	640
645	215.2	2.351	0.0045	361	90	–	54	37	331	178	12	26	0.1	–	645
647.3c	221.2	3.17	0.0032	0	∞	∞	45	45	238	238	∞	∞	0	–	647.3c

A.7 Solar Radiative Properties of Selected Materials

Description/composition	α_s	ε	α_s/ε	τ_s
Aluminum				
Polished	0.09	0.03	3	
Anodized	0.14	0.84	0.17	
Quartz overcoated	0.11	0.37	0.3	
Foil	0.15	0.05	3	
Brick, red (Purdue)	0.63	0.93	0.68	
Concrete	0.6	0.88	0.68	
Galvanized sheet metal				
Clean, new	0.65	0.13	5	
Oxidized, weathered	0.8	0.28	2.9	
Glass, 3.2 mm thickness				
Float or tempered				0.79
Low iron oxide type				0.88
Metal, plated				
Black sulfide	0.92	0.1	9.2	
Black cobalt oxide	0.93	0.3	3.1	
Black nickel oxide	0.92	0.08	11	
Black chrome	0.87	0.09	9.7	
Mylar, 0.13 mm thickness				0.87
Paints				
Black (Parsons)	0.98	0.98	1	
White, acrylic	0.26	0.9	0.29	
White, zinc oxide	0.16	0.93	0.17	
Plexiglas, 3.2 mm thickness				0.9
Snow				
Fine particles, fresh	0.13	0.82	0.16	
Ice granules	0.33	0.89	0.37	
Tedlar, 0.10-mm thickness				0.92
Teflon, 0.13-mm thickness				0.92

A.8 Thermo-Physical Properties of Fluids

Engine oil

T (°C)	ρ (kg/m^3)	c_p (J/kg·K)	k (W/m·K)	$\mu \times 10^2$ (N.s/m^2)	Pr
0	899	1796	0.147	384.8	47100
20	888	1880	0.145	79.92	10400
40	876	1964	0.144	21.02	2870
60	864	2047	0.14	7.249	1050
80	852	2131	0.138	3.195	490
100	840	2219	0.137	1.705	276
120	828	2307	0.135	1.027	175
140	816	2395	0.133	0.653	116
160	805	2483	0.132	0.451	84

50% Ethylene glycol

T (°C)	ρ (kg/m^3)	c_p (J/kg·K)	k (W/mK)	$\mu \times 10^2$ (N.s/m^2)	Pr
0	1083	3180	0.379	1.029	86.3
20	1072	3310	0.319	0.459	47.6
40	1061	3420	0.404	0.238	20.1
60	1048	3520	0.417	0.139	11.8
80	1034	3590	0.429	0.099	8.3
100	1020	3650	0.442	0.08	6.6
120	1003	3680	0.454	0.066	5.4

Ethylene glycol

T (°C)	ρ (kg/m^3)	c_p (J/kg·K)	k (W/m·K)	$\mu \times 10^2$ (N.s/m^2)	Pr
0	1130	2294	0.242	6.501	615
20	1116	2382	0.249	2.14	204
40	1101	2474	0.256	0.957	93
60	1087	2562	0.26	0.516	51
80	1077	2650	0.261	0.321	32.4
100	1058	2742	0.263	0.215	22.4

Glycerin

T (°C)	ρ (kg/m^3)	c_p (J/kg·K)	k (W/m·K)	$\mu \times 10^2$ (N.s/m^2)	Pr
0	1276	2261	0.282	1060.4	84700
10	1270	2319	0.284	381	31000
20	1264	2386	0.286	149.2	12500
30	1258	2445	0.286	62.9	5380
40	1252	2512	0.286	27.5	2450
50	1244	2583	0.287	18.7	1630

Water

T (°C)	ρ (kg/m^3)	c_p (J/kg·K)	k (W/mK)	$\mu \times 10^2$ (N.s/m^2)	Pr
0	1002	4217	0.552	1792	13.6
20	1000	4181	0.597	1006	7.02
40	994	4178	0.628	654	4.34
60	985	4184	0.651	471	3.02
80	974	4196	0.668	355	2.22
100	960	4216	0.68	282	1.74
120	945	4250	0.685	233	1.45
140	928	4283	0.684	199	1.24
160	909	4342	0.67	173	1.1
180	889	4417	0.675	154	1
200	866	4505	0.665	139	0.94
220	842	4610	0.572	126	0.89
240	815	4756	0.635	117	0.87
260	785	4949	0.611	108	0.87
280	752	5208	0.58	102	0.91
300	714	5728	0.54	96	1.11

Note: Most of the property tables are taken from Internet sites:
www.efunda.com/materials/common_matl/common_matl.cfm
pubs.acs.org/doi/abs/10.1021/ja01611a113
https://en.Wikipedia.org/wiki
mathscinotes.com/wp-content/uploads/2016/01
onlinelibrary.wiley.com/doi/10.1002/9781118131473.app2

References

1 Sokolnikoff I.S, Sokolnikoff E.S., *Higher Mathematics for Engineers and Physicists*, McGraw Hill Book Co., 1949.

2 Spiegel M.R., *Advanced Calculus*, Schaum Publishing Co., 1963.

Index

Compact Heat Exchangers – Analysis, Design and Optimization using FEM and CFD Approach, First Edition. C. Ranganayakulu and K.N. Seetharamu.