B

Physical and Chemical Property Data

Table B.1 Atomic weights and numbers

Based on the atomic mass of ^{12}C. Values for atomic weights apply to elements as they exist in nature.

Name	Symbol	Relative atomic mass	Atomic number
Actinium	Ac	–	89
Aluminium	Al	26.9815	13
Americium	Am	–	95
Antimony	Sb	121.75	51
Argon	Ar	39.948	18
Arsenic	As	74.9216	33
Astatine	At	–	85
Barium	Ba	137.34	56
Berkelium	Bk	–	97
Beryllium	Be	9.0122	4
Bismuth	Bi	208.98	83
Boron	B	10.811	5
Bromine	Br	79.904	35
Cadmium	Cd	112.40	48
Caesium	Cs	132.905	55
Calcium	Ca	40.08	20
Californium	Cf	–	98
Carbon	C	12.011	6
Cerium	Ce	140.12	58
Chlorine	Cl	35.453	17
Chromium	Cr	51.996	24
Cobalt	Co	58.9332	27
Copper	Cu	63.546	29
Curium	Cm	–	96
Dysprosium	Dy	162.50	66
Einsteinium	Es	–	99
Erbium	Er	167.26	68
Europium	Eu	151.96	63
Fermium	Fm	–	100
Fluorine	F	18.9984	9
Francium	Fr	–	87
Gadolinium	Gd	157.25	64
Gallium	Ga	69.72	31
Germanium	Ge	72.59	32
Gold	Au	196.967	79
Hafnium	Hf	178.49	72
Helium	He	4.0026	2
Holmium	Ho	164.930	67
Hydrogen	H	1.00797	1
Indium	In	114.82	49
Iodine	I	126.9044	53
Iridium	Ir	192.2	77
Iron	Fe	55.847	26
Krypton	Kr	83.80	36
Lanthanum	La	138.91	57

Name	Symbol	Relative atomic mass	Atomic number
Lawrencium	Lr	–	103
Lead	Pb	207.19	82
Lithium	Li	6.939	3
Lutetium	Lu	174.97	71
Magnesium	Mg	24.312	12
Manganese	Mn	54.938	25
Mendelevium	Md	–	101
Mercury	Hg	200.59	80
Molybdenum	Mo	95.94	42
Neodymium	Nd	144.24	60
Neon	Ne	20.183	10
Neptunium	Np	–	93
Nickel	Ni	58.71	28
Niobium	Nb	92.906	41
Nitrogen	N	14.0067	7
Nobelium	No	–	102
Osmium	Os	190.2	76
Oxygen	O	15.9994	8
Palladium	Pd	106.4	46
Phosphorus	P	30.9738	15
Platinum	Pt	195.09	78
Plutonium	Pu	–	94
Polonium	Po	–	84
Potassium	K	39.102	19
Praseodymium	Pr	140.907	59
Promethium	Pm	–	61
Protactinium	Pa	–	91
Radium	Ra	–	88
Radon	Rn	–	86
Rhenium	Re	186.2	75
Rhodium	Rh	102.905	45
Rubidium	Rb	85.47	37
Ruthenium	Ru	101.07	44
Samarium	Sm	150.35	62
Scandium	Sc	44.956	21
Selenium	Se	78.96	34
Silicon	Si	28.086	14
Silver	Ag	107.868	47
Sodium	Na	22.9898	11
Strontium	Sr	87.62	38
Sulphur	S	32.064	16
Tantalum	Ta	180.948	73
Technetium	Tc	–	43
Tellurium	Te	127.60	52
Terbium	Tb	158.924	65
Thallium	Tl	204.37	81
Thorium	Th	232.038	90
Thulium	Tm	168.934	69
Tin	Sn	118.69	50
Titanium	Ti	47.90	22
Tungsten	W	183.85	74
Uranium	U	238.03	92
Vanadium	V	50.942	23
Wolfram (Tungsten)	W	183.85	74
Xenon	Xe	131.30	54
Ytterbium	Yb	173.04	70
Yttrium	Y	88.905	39
Zinc	Zn	65.37	30
Zirconium	Zr	91.22	40

Table B.2 Degree of reduction of biological materials

(Adapted from J.A. Roels, 1983, *Energetics and Kinetics in Biotechnology*, Elsevier Biomedical Press, Amsterdam)

Compound	Formula	Degree of reduction γ relative to NH_3	Degree of reduction γ relative to N_2
Acetaldehyde	C_2H_4O	5.00	5.00
Acetic acid	$C_2H_4O_2$	4.00	4.00
Acetone	C_3H_6O	5.33	5.33
Adenine	$C_5H_5N_5$	2.00	5.00
Alanine	$C_3H_7O_2N$	4.00	5.00
Ammonia	NH_3	0	3.00
Arginine	$C_6H_{14}O_2N_4$	3.67	5.67
Asparagine	$C_4H_8O_3N_2$	3.00	4.50
Aspartic acid	$C_4H_7O_4N$	3.00	3.75
n-Butanol	$C_4H_{10}O$	6.00	6.00
Butyraldehyde	C_4H_8O	5.50	5.50
Butyric acid	$C_4H_8O_2$	5.00	5.00
Carbon monoxide	CO	2.00	2.00
Citric acid	$C_6H_8O_7$	3.00	3.00
Cytosine	$C_4H_5ON_3$	2.50	4.75
Ethane	C_2H_6	7.00	7.00
Ethanol	C_2H_6O	6.00	6.00
Ethene	C_2H_4	6.00	6.00
Ethylene glycol	$C_2H_6O_2$	5.00	5.00
Ethyne	C_2H_2	5.00	5.00
Formaldehyde	CH_2O	4.00	4.00
Formic acid	CH_2O_2	2.00	2.00
Fumaric acid	$C_4H_4O_4$	3.00	3.00
Glucitol	$C_6H_{14}O_6$	4.33	4.33
Gluconic acid	$C_6H_{12}O_7$	3.67	3.67
Glucose	$C_6H_{12}O_6$	4.00	4.00
Glutamic acid	$C_5H_9O_4N$	3.60	4.20
Glutamine	$C_5H_{10}O_3N_2$	3.60	4.80
Glycerol	$C_3H_8O_3$	4.67	4.67
Glycine	$C_2H_5O_2N$	3.00	4.50
Graphite	C	4.00	4.00
Guanine	$C_5H_5ON_5$	1.60	4.60
Histidine	$C_6H_9O_2N_3$	3.33	4.83
Hydrogen	H_2	2.00	2.00
Isoleucine	$C_6H_{13}O_2N$	5.00	5.50
Lactic acid	$C_3H_6O_3$	4.00	4.00
Leucine	$C_6H_{13}O_2N$	5.00	5.50
Lysine	$C_6H_{14}O_2N_2$	4.67	5.67
Malic acid	$C_4H_6O_5$	3.00	3.00
Methane	CH_4	8.00	8.00
Methanol	CH_4O	6.00	6.00
Oxalic acid	$C_2H_2O_4$	1.00	1.00
Palmitic acid	$C_{16}H_{32}O_2$	5.75	5.75
Pentane	C_5H_{12}	6.40	6.40
Phenylalanine	$C_9H_{11}O_2N$	4.44	4.78
Proline	$C_5H_9O_2N$	4.40	5.00
Propane	C_3H_8	6.67	6.67
iso-Propanol	C_3H_8O	6.00	6.00
Propionic acid	$C_3H_6O_2$	4.67	4.67
Pyruvic acid	$C_3H_4O_3$	3.33	3.33
Serine	$C_3H_7O_3N$	3.33	4.33
Succinic acid	$C_4H_6O_4$	3.50	3.50

Compound	Formula	Degree of reduction γ relative to NH_3	Degree of reduction γ relative to N_2
Threonine	$C_4H_9O_3N$	4.00	4.75
Thymine	$C_5H_6O_2N_2$	3.20	4.40
Tryptophan	$C_{11}H_{12}O_2N_2$	4.18	4.73
Tyrosine	$C_9H_{11}O_3N$	4.22	4.56
Uracil	$C_4H_4O_2N_2$	2.50	4.00
Valeric acid	$C_5H_{10}O_2$	5.20	5.20
Valine	$C_5H_{11}O_2N$	4.80	5.40
Biomass	$CH_{1.8}O_{0.5}N_{0.2}$	4.20	4.80

Table B.3 Heat capacities

(Adapted from R.M. Felder and R.W. Rousseau, 1978, *Elementary Principles of Chemical Processes*, John Wiley and Sons, New York)

C_p (J gmol^{-1} °C^{-1}) = $a + bT + cT^2 + dT^3$

Example. For acetone gas between 0°C and 1200°C:

C_p (J gmol^{-1} °C^{-1}) = $71.96 + (20.10 \times 10^{-2})\ T - (12.78 \times 10^{-5})\ T^2 + (34.76 \times 10^{-9})\ T^3$, where T is in °C.

Note that some equations require T in K, as indicated.

State: g = gas; l = liquid; c = crystal.

Compound	State	Temperature unit	a	$b.10^2$	$c.10^5$	$d.10^9$	Temperature range (units of T)
Acetone	g	°C	71.96	20.10	−12.78	34.76	0–1200
Air	g	°C	28.94	0.4147	0.3191	−1.965	0–1500
	g	K	28.09	0.1965	0.4799	−1.965	273–1800
Ammonia	g	°C	35.15	2.954	0.4421	−6.686	0–1200
Calcium hydroxide	c	K	89.5				276–373
Carbon dioxide	g	°C	36.11	4.233	−2.887	7.464	0–1500
Ethanol	l	°C	103.1				0
	l	°C	158.8				100
	g	°C	61.34	15.72	−8.749	19.83	0–1200
Formaldehyde	g	°C	34.28	4.268	0.000	−8.694	0–1200
Hydrogen	g	°C	28.84	0.00765	0.3288	−0.8698	0–1500
Hydrogen chloride	g	°C	29.13	−0.1341	0.9715	−4.335	0–1200
Hydrogen sulphide	g	°C	33.51	1.547	0.3012	−3.292	0–1500
Methane	g	°C	34.31	5.469	0.3661	−11.00	0–1200
	g	K	19.87	5.021	1.268	−11.00	273–1500
Methanol	l	°C	75.86				0
	l	°C	82.59				40
	g	°C	42.93	8.301	−1.87	−8.03	0–700
Nitric acid	l	°C	110.0				25
Nitrogen	g	°C	29.00	0.2199	0.5723	−2.871	0–1500
Oxygen	g	°C	29.10	1.158	−0.6076	1.311	0–1500
Sulphur							
(rhombic)	c	K	15.2	2.68			273–368
(monoclinic)	c	K	18.3	1.84			368–392
Sulphuric acid	l	°C	139.1	15.59			10–45
Sulphur dioxide	g	°C	38.91	3.904	−3.104	8.606	0–1500
Water	l	°C	75.4				0–100
	g	°C	33.46	0.6880	0.7604	-3.593	0–1500

Table B.4 Mean heat capacities of gases

(Adapted from D.M. Himmelblau, 1974, *Basic Principles and Calculations in Chemical Engineering*, 3rd edn, Prentice-Hall, New Jersey)

Reference state: $T_{ref} = 0°C$; $P_{ref} = 1$ atm.

T(°C)	C_{pm} (J gmol^{-1} °C^{-1})					
	Air	O_2	N_2	H_2	CO_2	H_2O
0	29.06	29.24	29.12	28.61	35.96	33.48
18	29.07	29.28	29.12	28.69	36.43	33.51
25	29.07	29.30	29.12	28.72	36.47	33.52
100	29.14	29.53	29.14	28.98	38.17	33.73
200	29.29	29.93	29.23	29.10	40.12	34.10
300	29.51	30.44	29.38	29.15	41.85	34.54
400	29.78	30.88	29.60	29.22	43.35	35.05
500	30.08	31.33	29.87	29.28	44.69	35.59

Table B.5 Specific heats of organic liquids

(From R.H. Perry, D.W. Green and J.O. Maloney, Eds, 1984, *Chemical Engineers' Handbook*, 6th edn, McGraw-Hill, New York)

Compound	Formula	Temperature (°C)	C_p (cal g^{-1} °C^{-1})
Acetic acid	$C_2H_4O_2$	26 to 95	0.522
Acetone	C_3H_6O	3 to 22.6	0.514
		0	0.506
		24.2 to 49.4	0.538
Acetonitrile	C_2H_3N	21 to 76	0.541
Benzaldehyde	C_7H_6O	22 to 172	0.428
Butyl alcohol (*n*-)	$C_4H_{10}O$	2.3	0.526
		19.2	0.563
		21 to 115	0.687
		30	0.582
Butyric acid (*n*-)	$C_4H_8O_2$	0	0.444
		40	0.501
		20 to 100	0.515
Carbon tetrachloride	CCl_4	0	0.198
		20	0.201
		30	0.200
Chloroform	$CHCl_3$	0	0.232
		15	0.226
		30	0.234
Cresol			
(*o*-)	C_7H_8O	0 to 20	0.497
(*m*-)		21 to 197	0.551
		0 to 20	0.477
Dichloroacetic acid	$C_2H_2Cl_2O_2$	21 to 106	0.349
		21 to 196	0.348
Diethylamine	$C_4H_{11}N$	22.5	0.516
Diethyl malonate	$C_7H_{12}O_4$	20	0.431
Diethyl oxalate	$C_6H_{10}O_4$	20	0.431
Diethyl succinate	$C_8H_{14}O_4$	20	0.450
Dipropyl malonate	$C_9H_{16}O_4$	20	0.431
Dipropyl oxalate (*n*-)	$C_8H_{14}O_4$	20	0.431
Dipropyl succinate	$C_{10}H_{18}O_4$	20	0.450

Compound	Formula	Temperature (°C)	C_p (cal g^{-1} $°C^{-1}$)
Ethanol	C_2H_6O	0 to 98	0.680
Ether	$C_4H_{10}O$	−5	0.525
		0	0.521
		30	0.545
		80	0.687
		120	0.800
		140	0.819
		180	1.037
Ethyl acetate	$C_4H_8O_2$	20	0.457
		20	0.476
Ethylene glycol	$C_2H_6O_2$	−11.1	0.535
		0	0.542
		2.5	0.550
		5.1	0.554
		14.9	0.569
		19.9	0.573
Formic acid	CH_2O_2	0	0.436
		15.5	0.509
		20 to 100	0.524
Furfural	$C_5H_4O_2$	0	0.367
		20 to 100	0.416
Glycerol	$C_3H_8O_3$	15 to 50	0.576
Hexadecane (*n*-)	$C_{16}H_{34}$	0 to 50	0.496
Isobutyl acetate	$C_6H_{12}O_2$	20	0.459
Isobutyl alcohol	$C_4H_{10}O$	21 to 109	0.716
		30	0.603
Isobutyl succinate	$C_{12}H_{22}O_4$	0	0.442
Isobutyric acid	$C_4H_8O_2$	20	0.450
Lauric acid	$C_{12}H_{24}O_2$	40 to 100	0.572
		57	0.515
Methanol	CH_4O	5 to 10	0.590
		15 to 20	0.601
Methyl butyl ketone	$C_6H_{12}O$	21 to 127	0.553
Methyl ethyl ketone	C_4H_8O	20 to 78	0.549
Methyl formate	$C_2H_4O_2$	13 to 29	0.516
Methyl propionate	$C_4H_8O_2$	20	0.459
Palmitic acid	$C_{16}H_{32}O_2$	65 to 104	0.653
Propionic acid	$C_3H_6O_2$	0	0.444
		20 to 137	0.560
Propyl acetate (*n*-)	$C_5H_{10}O_2$	20	0.459
Propyl butyrate	$C_7H_{14}O_2$	20	0.459
Propyl formate (*n*-)	$C_4H_8O_2$	20	0.459
Pyridine	C_5H_5N	20	0.405
		21 to 108	0.431
		0 to 20	0.395
Quinoline	C_9H_7N	0 to 20	0.352
Salicylaldehyde	$C_7H_6O_2$	18	0.382
Stearic acid	$C_{18}H_{36}O_2$	75 to 137	0.550

Table B.6 Specific heats of organic solids

(From R.H. Perry, D.W. Green and J.O. Maloney, Eds, 1984, *Chemical Engineers' Handbook*, 6th edn, McGraw-Hill, New York)

Compound	Formula	Temperature (°C) T	C_p (cal g^{-1} °C^{-1})
Acetic acid	$C_2H_4O_2$	−200 to 25	$0.330 + 0.00080T$
Acetone	C_3H_6O	−210 to −80	$0.540 + 0.0156T$
Aniline	C_6H_7N		0.741
Capric acid	$C_{10}H_{20}O_2$	8	0.695
Chloroacetic acid	$C_2H_3ClO_2$	60	0.363
Crotonic acid	$C_4H_6O_2$	38 to 70	$0.520 + 0.00020T$
Dextrin	$(C_6H_{10}O_5)_x$	0 to 90	$0.291 + 0.00096T$
Diphenylamine	$C_{12}H_{11}N$	26	0.337
Erythritol	$C_4H_{10}O_4$	60	0.351
Ethylene glycol	$C_2H_6O_2$	−190 to −40	$0.366 + 0.00110T$
Formic acid	CH_2O_2	−22	0.387
		0	0.430
Glucose	$C_6H_{12}O_6$	0	0.277
		20	0.300
Glutaric acid	$C_5H_8O_4$	20	0.299
Glycerol	$C_3H_8O_3$	0	0.330
Hexadecane	$C_{16}H_{34}$		0.495
Lactose	$C_{12}H_{22}O_{11}$	20	0.287
	$C_{12}H_{22}O_{11}.H_2O$	20	0.299
Lauric acid	$C_{12}H_{24}O_2$	−30 to 40	$0.430 + 0.000027T$
Levoglucosane	$C_6H_{10}O_5$	40	0.607
Levulose	$C_6H_{12}O_6$	20	0.275
Malonic acid	$C_3H_4O_4$	20	0.275
Maltose	$C_{12}H_{22}O_{11}$	20	0.320
Mannitol	$C_6H_{14}O_6$	0 to 100	$0.313 + 0.00025T$
Oxalic acid	$C_2H_2O_4$	−200 to 50	$0.259 + 0.00076T$
	$C_2H_2O_4.2H_2O$	0	0.338
		50	0.385
		100	0.416
Palmitic acid	$C_{16}H_{32}O_2$	0	0.382
		20	0.430
Phenol	C_6H_6O	14 to 26	0.561
Succinic acid	$C_4H_6O_4$	0 to 160	$0.248 + 0.00153T$
Sucrose	$C_{12}H_{22}O_{11}$	20	0.299
Sugar (cane)	$C_{12}H_{22}O_{11}$	22 to 51	0.301
Tartaric acid	$C_4H_6O_6$	36	0.287
	$C_4H_6O_6.H_2O$	0	0.308
		50	0.366
Urea	CH_4N_2O	20	0.320

Table B.7 Normal melting points and boiling points, and standard heats of phase change

(From R.M. Felder and R.W. Rousseau, 1978, *Elementary Principles of Chemical Processes*, John Wiley, New York).

All thermodynamic data are at 1 atm.

Compound	Molecular weight	Melting temperature (°C)	Δh_f at melting point (kJ gmol^{-1})	Normal boiling point (°C)	Δh_v at boiling point (kJ gmol^{-1})
Acetaldehyde	44.05	−123.7		20.2	25.1
Acetic acid	60.05	16.6	12.09	118.2	24.39
Acetone	58.08	−95.0	5.69	56.0	30.2
Ammonia	17.03	−77.8	5.653	−33.43	23.351
Benzaldehyde	106.12	−26.0		179.0	38.40
Carbon dioxide	44.01	−56.6	8.33	(sublimates at −78°C)	
Chloroform	119.39	−63.7		61.0	
Ethanol	46.07	−114.6	5.021	78.5	38.58
Formaldehyde	30.03	−92		−19.3	24.48
Formic acid	46.03	8.30	12.68	100.5	22.25
Glycerol	92.09	18.20	18.30	290.0	
Hydrogen	2.016	−259.19	0.12	−252.76	0.904
Hydrogen chloride	36.47	−114.2	1.99	−85.0	16.1
Hydrogen sulphide	34.08	−85.5	2.38	−60.3	18.67
Methane	16.04	−182.5	0.94	−161.5	8.179
Methanol	32.04	−97.9	3.167	64.7	35.27
Nitric acid	63.02	−41.6	10.47	86	30.30
Nitrogen	28.02	−210.0	0.720	−195.8	5.577
Oxalic acid	90.04			(decomposes at 186°C)	
Oxygen	32.00	−218.75	0.444	−182.97	6.82
Phenol	94.11	42.5	11.43	181.4	
Phosphoric acid	98.00	42.3	10.54		
Sodium chloride	58.45	808	28.5	1465	170.7
Sodium hydroxide	40.00	319	8.34	1390	
Sulphur					
(rhombic)	256.53	113	10.04	444.6	83.7
(monoclinic)	256.53	119	14.17	444.6	83.7
Sulphur dioxide	64.07	−75.48	7.402	−10.02	24.91
Sulphuric acid	98.08	10.35	9.87	(decomposes at 340°C)	
Water	18.016	0.00	6.0095	100.00	40.656

Table B.8 Heats of combustion

(From *Handbook of Chemistry and Physics*, 1992, 73rd edn, CRC Press, Boca Raton; *Handbook of Chemistry and Physics*, 1976, 57th edn, CRC Press, Boca Raton; and R.M. Felder and R.W. Rousseau, 1978, *Elementary Principles of Chemical Processes*, John Wiley, New York)

Reference conditions: 1 atm and 25°C or 20°C; values marked with an asterisk refer to 20°C.
Products of combustion are taken to be CO_2 (gas), H_2O (liquid) and N_2 (gas); therefore, $\Delta h_c^\circ = 0$ for CO_2 (g), H_2O (l) and N_2 (g).
State: g = gas; l = liquid; c = crystal; s = solid.

Compound	Formula	Molecular weight	State	Heat of combustion Δh_c° (kJ gmol^{-1})
Acetaldehyde	C_2H_4O	44.053	l	−1166.9
			g	−1192.5
Acetic acid	$C_2H_4O_2$	60.053	l	−874.2
			g	−925.9
Acetone	C_3H_6O	58.080	l	−1789.9
			g	−1820.7

Compound	Formula	Molecular weight	State	Heat of combustion Δh_c° (kJ gmol^{-1})
Acetylene	C_2H_2	26.038	g	−1301.1
Adenine	$C_5H_5N_5$	135.128	c	−2778.1
			g	−2886.9
Alanine (D-)	$C_3H_7O_2N$	89.094	c	−1619.7
Alanine (L-)	$C_3H_7O_2N$	89.094	c	−1576.9
			g	−1715.0
Ammonia	NH_3	17.03	g	−382.6
Ammonium ion	NH_4^+			−383
Arginine (D-)	$C_6H_{14}O_2N_4$	174.203	c	−3738.4
Asparagine (L-)	$C_4H_8O_3N_2$	132.119	c	−1928.0
Aspartic acid (L-)	$C_4H_7O_4N$	133.104	c	−1601.1
Benzaldehyde	C_7H_6O	106.124	l	−3525.1
			g	−3575.4
Butanoic acid	$C_4H_8O_2$	88.106	l	−2183.6
			g	−2241.6
1-Butanol	$C_4H_{10}O$	74.123	l	−2675.9
			g	−2728.2
2-Butanol	$C_4H_{10}O$	74.123	l	−2660.6
			g	−2710.3
Butyric acid	$C_4H_8O_2$	88.106	l	−2183.6
			g	−2241.6
Caffeine	$C_8H_{10}O_2N_4$		s	−4246.5*
Carbon	C	12.011	c	−393.5
Carbon monoxide	CO	28.010	g	−283.0
Citric acid	$C_6H_8O_7$		s	−1962.0
Codeine	$C_{18}H_{21}O_3N.H_2O$		s	−9745.7*
Cytosine	$C_4H_5ON_3$	111.103	c	−2067.3
Ethane	C_2H_6	30.070	g	−1560.7
Ethanol	C_2H_6O	46.069	l	−1366.8
			g	−1409.4
Ethylene	C_2H_4	28.054	g	−1411.2
Ethylene glycol	$C_2H_6O_2$	62.068	l	−1189.2
			g	−1257.0
Formaldehyde	CH_2O	30.026	g	−570.7
Formic acid	CH_2O_2	46.026	l	−254.6
			g	−300.7
Fructose (D-)	$C_6H_{12}O_6$		s	−2813.7
Fumaric acid	$C_4H_4O_4$	116.073	c	−1334.0
Galactose (D-)	$C_6H_{12}O_6$		s	−2805.7
Glucose (D-)	$C_6H_{12}O_6$		s	−2805.0
Glutamic acid (L-)	$C_5H_9O_4N$	147.131	c	−2244.1
Glutamine (L-)	$C_5H_{10}O_3N_2$	146.146	c	−2570.3
Glutaric acid	$C_5H_8O_4$	132.116	c	−2150.9
Glycerol	$C_3H_8O_3$	92.095	l	−1655.4
			g	−1741.2
Glycine	$C_2H_5O_2N$	75.067	c	−973.1
Glycogen	$(C_6H_{10}O_5)_x$ per kg		s	−17530.1*
Guanine	$C_5H_5ON_5$	151.128	c	−2498.2
Hexadecane	$C_{16}H_{34}$	226.446	l	−10699.2
			g	−10780.5
Hexadecanoic acid	$C_{16}H_{32}O_2$	256.429	c	−9977.9
			l	−10031.3
			g	−10132.3
Histidine (L-)	$C_6H_9O_2N_3$	155.157	c	−3180.6
Hydrogen	H_2	2.016	g	−285.8
Hydrogen sulphide	H_2S	34.08		−562.6
Inositol	$C_6H_{12}O_6$		s	−2772.2*
Isoleucine (L-)	$C_6H_{13}O_2N$	131.175	c	−3581.1
Isoquinoline	C_9H_7N	129.161	l	−4686.5

Compound	Formula	Molecular weight	State	Heat of combustion Δh_c° (kJ gmol^{-1})
Lactic acid (D,L-)	$C_3H_6O_3$		l	−1368.3
Lactose	$C_{12}H_{22}O_{11}$		s	−5652.5
Leucine (D-)	$C_6H_{13}O_2N$	131.175	c	−3581.7
Leucine (L-)	$C_6H_{13}O_2N$	131.175	c	−3581.6
Lysine	$C_6H_{14}O_2N_2$	146.189	c	−3683.2
Malic acid (L-)	$C_4H_6O_5$		s	−1328.8
Malonic acid	$C_3H_4O_4$		s	−861.8
Maltose	$C_{12}H_{22}O_{11}$		s	−5649.5
Mannitol (D-)	$C_6H_{14}O_6$		s	−3046.5*
Methane	CH_4	16.043	g	−890.8
Methanol	CH_4O	32.042	l	−726.1
			g	−763.7
Morphine	$C_{17}H_{19}O_3N.H_2O$		s	−8986.6*
Nicotine	$C_{10}H_{14}N_2$		l	−5977.8*
Oleic acid	$C_{18}H_{34}O_2$		l	−11126.5
Oxalic acid	$C_2H_2O_4$	90.036	c	−251.1
Papaverine	$C_{20}H_{21}O_4N$		s	−10375.8*
Pentane	C_5H_{12}	72.150	l	−3509.0
			g	−3535.6
Phenylalanine (L-)	$C_9H_{11}O_2N$	165.192	c	−4646.8
Phthalic acid	$C_8H_6O_4$	166.133	c	−3223.6
Proline (L-)	$C_5H_9O_2N$	115.132	c	−2741.6
Propane	C_3H_8	44.097	g	−2219.2
1-Propanol	C_3H_8O	60.096	l	−2021.3
			g	−2068.8
2-Propanol	C_3H_8O	60.096	l	−2005.8
			g	−2051.1
Propionic acid	$C_3H_6O_2$	74.079	l	−1527.3
			g	−1584.5
1,2-Propylene glycol	$C_3H_8O_2$	76.095	l	−1838.2
			g	−1902.6
1,3-Propylene glycol	$C_3H_8O_2$	76.095	l	−1859.0
			g	−1931.8
Pyridine	C_5H_5N	79.101	l	−2782.3
			g	−2822.5
Pyrimidine	$C_4H_4N_2$	80.089	l	−2291.6
			g	−2341.6
Salicylic acid	$C_7H_6O_3$	138.123	c	−3022.2
			g	−3117.3
Serine (L-)	$C_3H_7O_3N$	105.094	c	−1448.2
Starch	$(C_6H_{10}O_5)_x$ per kg		s	−17496.6*
Succinic acid	$C_4H_6O_4$	118.089	c	−1491.0
Sucrose	$C_{12}H_{22}O_{11}$		s	−5644.9
Thebaine	$C_{19}H_{21}O_3N$		s	−10221.7*
Threonine (L-)	$C_4H_9O_3N$	119.120	c	−2053.1
Thymine	$C_5H_6O_2N_2$	126.115	c	−2362.2
Tryptophan (L-)	$C_{11}H_{12}O_2N_2$	204.229	c	−5628.3
Tyrosine (L-)	$C_9H_{11}O_3N$	181.191	c	−4428.6
Uracil	$C_4H_4O_2N_2$	112.088	c	−1716.3
			g	−1842.8
Urea	CH_4ON_2	60.056	c	−631.6
			g	−719.4
Valine (L-)	$C_5H_{11}O_2N$	117.148	c	−2921.7
			g	−3084.5
Xanthine	$C_5H_4O_2N_4$	152.113	c	−2159.6
Xylose	$C_5H_{10}O_5$		s	−2340.5
Biomass	$CH_{1.8}O_{0.5}N_{0.2}$	25.9	s	−552

C

Steam Tables

(From R.W. Haywood, *Thermodynamic Tables in SI (Metric) Units*, 1972, 2nd edn, Cambridge University Press, Cambridge)

Table C.1 Enthalpy of saturated water and steam (Temperatures from 0.01°C to 100°C)

Reference state: Triple point of water: 0.01°C, 0.6112 kPa.

		Specific enthalpy (kJ kg^{-1})		
Temperature (°C)	Pressure (kPa)	Saturated liquid	Evaporation (Δh_v)	Saturated vapour
0.01 (Triple point)	0.611	+0.0	2501.6	2501.6
2	0.705	8.4	2496.8	2505.2
4	0.813	16.8	2492.1	2508.9
6	0.935	25.2	2487.4	2512.6
8	1.072	33.6	2482.6	2516.2
10	1.227	42.0	2477.9	2519.9
12	1.401	50.4	2473.2	2523.6
14	1.597	58.8	2468.5	2527.2
16	1.817	67.1	2463.8	2530.9
18	2.062	75.5	2459.0	2534.5
20	2.34	83.9	2454.3	2538.2
22	2.64	83.9	2454.3	2538.2
24	2.98	100.6	2444.9	2545.5
25	3.17	104.8	2442.5	2547.3
26	3.36	108.9	2440.2	2549.1
28	3.78	117.3	2435.4	2552.7
30	4.24	125.7	2430.7	2556.4
32	4.75	134.0	2425.9	2560.0
34	5.32	142.4	2421.2	2563.6
36	5.94	150.7	2416.4	2567.2
38	6.62	159.1	2411.7	2570.8
40	7.38	167.5	2406.9	2574.4
42	8.20	175.8	2402.1	2577.9
44	9.10	184.2	2397.3	2581.5
46	10.09	192.5	2392.5	2585.1
48	11.16	200.9	2387.7	2588.6
50	12.34	209.3	2382.9	2592.2
52	13.61	217.6	2378.1	2595.7
54	15.00	226.0	2373.2	2599.2
56	16.51	234.4	2368.4	2602.7
58	18.15	242.7	2363.5	2606.2
60	19.92	251.1	2358.6	2609.7
62	21.84	259.5	2353.7	2613.2
64	23.91	267.8	2348.8	2616.6
66	26.15	276.2	2343.9	2620.1
68	28.56	284.6	2338.9	2623.5
70	31.16	293.0	2334.0	2626.9

Temperature (°C)	Pressure (kPa)	Specific enthalpy (kJ kg^{-1}) Saturated liquid	Evaporation (Δh_v)	Saturated vapour
72	33.96	301.4	2329.0	2630.3
74	36.96	309.7	2324.0	2633.7
76	40.19	318.1	2318.9	2637.1
78	43.65	326.5	2313.9	2640.4
80	47.36	334.9	2308.8	2643.8
82	51.33	343.3	2303.8	2647.1
84	55.57	351.7	2298.6	2650.4
86	60.11	360.1	2293.5	2653.6
88	64.95	368.5	2288.4	2656.9
90	70.11	376.9	2283.2	2660.1
92	75.61	385.4	2278.0	2663.4
94	81.46	393.8	2272.8	2666.6
96	87.69	402.2	2267.5	2669.7
98	94.30	410.6	2262.2	2672.9
100 (Boiling point)	101.325	419.1	2256.9	2676.0

Table C.2 Enthalpy of saturated water and steam

(Pressures from 0.6112 kPa to 22 120 kPa)

Reference state: Triple point of water: 0.01°C, 0.6112 kPa.

Pressure (kPa)	Temperature (°C)	Specific enthalpy (kJ kg^{-1}) Saturated liquid	Evaporation (Δh_v)	Saturated vapour
0.6112 (Triple point)	0.01	+0.0	2501.6	2501.6
0.8	3.8	15.8	2492.6	2508.5
1.0	7.0	29.3	2485.0	2514.4
1.4	12.0	50.3	2473.2	2523.5
1.8	15.9	66.5	2464.1	2530.6
2.0	17.5	73.5	2460.2	2533.6
2.4	20.4	85.7	2453.3	2539.0
2.8	23.0	96.2	2447.3	2543.6
3.0	24.1	101.0	2444.6	2545.6
3.5	26.7	111.8	2438.5	2550.4
4.0	29.0	121.4	2433.1	2554.5
4.5	31.0	130.0	2428.2	2558.2
5.0	32.9	137.8	2423.8	2561.6
6	36.2	151.5	2416.0	2567.5
7	39.0	163.4	2409.2	2572.6
8	41.5	173.9	2403.2	2577.1
9	43.8	183.3	2397.9	2581.1
10	45.8	191.8	2392.9	2584.8
12	49.4	206.9	2384.3	2591.2
14	52.6	220.0	2376.7	2596.7
16	55.3	231.6	2370.0	2601.6
18	57.8	242.0	2363.9	2605.9
20	60.1	251.5	2358.4	2609.9

Pressure (kPa)	Temperature (°C)	Specific enthalpy (kJ kg^{-1}) Saturated liquid	Evaporation (Δh_v)	Saturated vapour
24	64.1	268.2	2348.6	2616.8
28	67.5	282.7	2340.0	2622.7
30	69.1	289.3	2336.1	2625.4
35	72.7	304.3	2327.2	2631.5
40	75.9	317.7	2319.2	2636.9
45	78.7	329.6	2312.0	2641.7
50	81.3	340.6	2305.4	2646.0
55	83.7	350.6	2299.3	2649.9
60	86.0	359.9	2293.6	2653.6
65	88.0	368.6	2288.3	2656.9
70	90.0	376.8	2283.3	2660.1
80	93.5	391.7	2274.1	2665.8
90	96.7	405.2	2265.6	2670.9
100	99.6	417.5	2257.9	2675.4
101.325 (Boiling point)	100.0	419.1	2256.9	2676.0
120	104.8	439.4	2244.1	2683.4
140	109.3	458.4	2231.9	2690.3
160	113.3	475.4	2220.9	2696.2
180	116.9	490.7	2210.8	2701.5
200	120.2	504.7	2201.6	2706.3
220	123.3	517.6	2193.0	2710.6
240	126.1	529.6	2184.9	2714.5
260	128.7	540.9	2177.3	2718.2
280	131.2	551.4	2170.1	2721.5
300	133.5	561.4	2163.2	2724.7
320	135.8	570.9	2156.7	2727.6
340	137.9	579.9	2150.4	2730.3
360	139.9	588.5	2144.4	2732.9
380	141.8	596.8	2138.6	2735.3
400	143.6	604.7	2133.0	2737.6
420	145.4	612.3	2127.5	2739.8
440	147.1	619.6	2122.3	2741.9
460	148.7	626.7	2117.2	2743.9
480	150.3	633.5	2112.2	2745.7
500	151.8	640.1	2107.4	2747.5
550	155.5	655.8	2095.9	2751.7
600	158.8	670.4	2085.0	2755.5
650	162.0	684.1	2074.7	2758.9
700	165.0	697.1	2064.9	2762.0
750	167.8	709.3	2055.5	2764.8
800	170.4	720.9	2046.5	2767.5
850	172.9	732.0	2037.9	2769.9
900	175.4	742.6	2029.5	2772.1
950	177.7	752.8	2021.4	2774.2
1000	179.9	762.6	2013.6	2776.2
1100	184.1	781.1	1998.5	2779.7
1200	188.0	798.4	1984.3	2782.7
1300	191.6	814.7	1970.7	2785.4
1400	195.0	830.1	1957.7	2787.8
1500	198.3	844.7	1945.2	2789.9
1600	201.4	858.6	1933.2	2791.7
1700	204.3	871.8	1921.5	2793.4
1800	207.1	884.6	1910.3	2794.8

Pressure (kPa)	Temperature (°C)	Specific enthalpy (kJ kg^{-1})		
		Saturated liquid	Evaporation (Δh_v)	Saturated vapour
1900	209.8	896.8	1899.3	2796.1
2000	212.4	908.6	1888.6	2797.2
2200	217.2	931.0	1868.1	2799.1
2400	221.8	951.9	1848.5	2800.4
2600	226.0	971.7	1829.6	2801.4
2800	230.0	990.5	1811.5	2802.0
3000	233.8	1008.4	1793.9	2802.3
3200	237.4	1025.4	1776.9	2802.3
3400	240.9	1041.8	1760.3	2802.1
3600	244.2	1057.6	1744.2	2801.7
3800	247.3	1072.7	1728.4	2801.1
4000	250.3	1087.4	1712.9	2800.3
4200	253.2	1101.6	1697.8	2799.4
4400	256.0	1115.4	1682.9	2798.3
4600	258.8	1128.8	1668.3	2797.1
4800	261.4	1141.8	1653.9	2795.7
5000	263.9	1154.5	1639.7	2794.2
5200	266.4	1166.8	1625.7	2792.6
5400	268.8	1178.9	1611.9	2790.8
5600	271.1	1190.8	1598.2	2789.0
5800	273.3	1202.3	1584.7	2787.0
6000	275.6	1213.7	1571.3	2785.0
6200	277.7	1224.8	1558.0	2782.9
6400	279.8	1235.7	1544.9	2780.6
6600	281.8	1246.5	1531.9	2778.3
6800	283.8	1257.0	1518.9	2775.9
7000	285.8	1267.4	1506.0	2773.5
7200	287.7	1277.6	1493.3	2770.9
7400	289.6	1287.7	1480.5	2768.3
7600	291.4	1297.6	1467.9	2765.5
7800	293.2	1307.4	1455.3	2762.8
8000	295.0	1317.1	1442.8	2759.9
8400	298.4	1336.1	1417.9	2754.0
8800	301.7	1354.6	1393.2	2747.8
9000	303.3	1363.7	1380.9	2744.6
10000	311.0	1408.0	1319.7	2727.7
11000	318.0	1450.6	1258.7	2709.3
12000	324.6	1491.8	1197.4	2689.2
13000	330.8	1532.0	1135.0	2667.0
14000	336.6	1571.6	1070.7	2642.4
15000	342.1	1611.0	1004.0	2615.0
16000	347.3	1650.5	934.3	2584.9
17000	352.3	1691.7	859.9	2551.6
18000	357.0	1734.8	779.1	2513.9
19000	361.4	1778.7	692.0	2470.6
20000	365.7	1826.5	591.9	2418.4
21000	369.8	1886.3	461.3	2347.6
22000	373.7	2011	185	2196
22120 (Critical point)	374.15	2108	0	2108

Table C.3 Enthalpy of superheated steam

Reference state: Triple point of water: 0.01°C, 0.6112 kPa.

Pressure (kPa)	10	50	100	500	1000	2000	4000	6000	8000	10000	15000	20000	22120*	30000	50000
Saturation temperature (°C)	45.8	81.3	99.6	151.8	179.9	212.4	250.3	275.6	295.0	311.0	342.1	365.7	374.15	–	–
State	Specific enthalpy at saturation (kJ kg^{-1})														
Water	191.8	340.6	417.5	640.1	762.6	908.6	1087.4	1213.7	1317.1	1408.0	1611.0	1826.5	2108	–	–
Steam	2584.8	2646.0	2675.4	2747.5	2776.2	2797.2	2800.3	2785.0	2759.9	2727.7	2615.0	2418.4	2108	–	–
Temperature (°C)	Specific enthalpy (kJ kg^{-1})														
0	0.0	0.0	0.1	0.5	1.0	2.0	4.0	6.1	8.1	10.1	15.1	20.1	22.2	30.0	49.3
25	104.8	104.8	104.9	105.2	105.7	106.6	108.5	110.3	112.1	114.0	118.6	123.1	125.1	132.2	150.2
50	2593	209.3	209.3	209.7	210.1	211.0	212.7	214.4	216.1	217.8	222.1	226.4	228.2	235.0	251.9
75	2640	313.9	314.0	314.3	314.7	315.5	317.1	318.7	320.3	322.0	326.0	330.0	331.7	338.1	354.2
100	2688	2683	2676	419.4	419.7	420.5	422.0	423.5	425.0	426.5	430.3	434.0	435.7	441.6	456.8
125	2735	2731	2726	525.2	525.5	526.2	527.6	529.0	530.4	531.8	535.3	538.8	540.2	545.8	560.1
150	2783	2780	2776	632.2	632.5	633.1	634.3	635.6	636.8	638.1	641.3	644.5	645.8	650.9	664.1
175	2831	2829	2826	2800	741.1	741.7	742.7	743.8	744.9	746.0	748.7	751.5	752.7	757.2	769.1
200	2880	2878	2875	2855	2827	852.6	853.4	854.2	855.1	855.9	858.1	860.4	861.4	865.2	875.4
225	2928	2927	2925	2909	2886	2834	967.2	967.7	968.2	968.8	970.3	971.8	972.5	975.3	983.4
250	2977	2976	2975	2961	2943	2902	1085.8	1085.8	1085.8	1085.8	1086.2	1086.7	1087.0	1088.4	1093.6
275	3027	3026	3024	3013	2998	2965	2886	1210.8	1210.0	1209.2	1207.7	1206.6	1206.3	1205.6	1206.7
300	3077	3076	3074	3065	3052	3025	2962	2885	2787	1343.4	1338.3	1334.3	1332.8	1328.7	1323.7
325	3127	3126	3125	3116	3106	3083	3031	2970	2899	2811	1486.0	1475.5	1471.8	1461.1	1446.0
350	3177	3177	3176	3168	3159	3139	3095	3046	2990	2926	2695	1647.1	1636.5	1609.9	1576.3
375	3228	3228	3227	3220	3211	3194	3156	3115	3069	3019	2862	2604	2319	1791	1716
400	3280	3279	3278	3272	3264	3249	3216	3180	3142	3100	2979	2820	2733	2162	1878
425	3331	3331	3330	3325	3317	3303	3274	3243	3209	3174	3075	2957	2899	2619	2068
450	3384	3383	3382	3377	3371	3358	3331	3303	3274	3244	3160	3064	3020	2826	2293
475	3436	3436	3435	3430	3424	3412	3388	3363	3337	3310	3237	3157	3120	2969	2522
500	3489	3489	3488	3484	3478	3467	3445	3422	3399	3375	3311	3241	3210	3085	2723
600	3706	3705	3705	3702	3697	3689	3673	3656	3640	3623	3580	3536	3516	3443	3248
700	3929	3929	3928	3926	3923	3916	3904	3892	3879	3867	3835	3804	3790	3740	3610
800	4159	4159	4158	4156	4154	4149	4140	4131	4121	4112	4089	4065	4055	4018	3925

* Critical isobar.