4

Mechanical Engineering

Basic Mechanical Properties

Symbol	Definition	Remarks
E	Modulus of elasticity; Young's modulus; $E = \sigma/\varepsilon_e$	Hooke's law; T and ε_p effects small
G	Shear modulus of elasticity; $G = \dfrac{\tau}{\gamma_e} = E/2(1+v)$	T and ε_p effects small
v	Poisson's ratio; $v = \dfrac{\varepsilon_{lateral}}{\varepsilon_{longit.}}$	T and ε_p effects small
σ_{PL}	Proportional limit; at onset of noticeable yielding (or at onset of nonlinear elastic behavior)	Flow property; inaccurate; T and ε_p effects large
σ_y	0.2% offset yield strength (but yielding can occur at $\sigma < \sigma_y$ if $\sigma_{PL} < \sigma_y$)	Flow property; accurate; T and ε_p effects large
σ_f	True fracture strength; $\sigma_f = \dfrac{P_f}{A_f}$	Fracture property; T and ε_p effects medium
ε_f	True fracture ductility; $\varepsilon_f = \ln \dfrac{A_O}{A_f} = \ln \dfrac{100}{100 - \%RA}$	Max. ε_p; fracture property; T and ε_p effects medium
% RA	Percent reduction of area; $\%RA = \dfrac{A_O - A_f}{A_O} \times 100$	Fracture property; T and ε_p effects medium
n	Strain hardening exponent; $\sigma = K\varepsilon_p^n$	Flow property; T and ε_p effects small to large
Toughness	Area under σ vs. ε_p curve	True toughness or intrinsic toughness; T and ε_p effects large
σ_u	Ultimate strength; $\dfrac{P_{max}}{A_O}$	Fracture property; T and ε_p effects medium
M_r	Modulus of resilience; $M_r = \dfrac{\sigma_{PL}^2}{2E}$	Area under original elastic portion of $\sigma - \varepsilon$ curve

Notes: T is temperature; ε_p refers to prior plastic strain, especially cyclic plastic strain (fatigue) (these are qualitative indicators here; exceptions are possible)

$$\underset{\text{total}}{\varepsilon_t} = \underset{\text{elastic}}{\varepsilon_e} + \underset{\text{plastic}}{\varepsilon_p} = \frac{\sigma}{E} + \left(\frac{\sigma}{K}\right)^{1/n} = \frac{\sigma}{E} + \varepsilon_f\left(\frac{\sigma}{\sigma_f}\right)^{1/n}$$

From Sandor, B.I., Mechanics of solids, in *The CRC Handbook of Mechanical Engineering*, Kreith, F., Ed., CRC Press, Boca Raton, FL, 1998, p. 1-75.

Symbols and Definitions for Selected Properties

Property	Symbol	Definition	Property	Symbol	Definition
Pressure	p		Specific heat, constant volume	c_v	$(\partial u/\partial T)_v$
Temperature	T		Specific heat, constant pressure	c_p	$(\partial h/\partial T)_p$
Specific volume	v		Volume expansivity	β	$\frac{1}{v}(\partial v/\partial T)_p$
Specific internal energy	u		Isothermal compressivity	κ	$-\frac{1}{v}(\partial v/\partial p)_T$
Specific entropy	s		Isentropic compressibility	α	$-\frac{1}{v}(\partial v/\partial p)_s$
Specific enthalpy	h	$u + pv$	Isothermal bulk modulus	B	$-v(\partial p/\partial v)_T$
Specific Helmholtz function	ψ	$u - Ts$	Isentropic bulk modulus	B_s	$-v(\partial p/\partial v)_s$
Specific Gibbs function	g	$h - Ts$	Joule-Thomson coefficient	μ_J	$(\partial T/\partial p)_h$
Compressibility factor	Z	pv/RT	Joule coefficient	η	$(\partial T/\partial v)_u$
Specific heat ratio	k	c_p/c_v	Velocity of sound	c	$\sqrt{-v^2(\partial p/\partial v)_s}$

From Moran, M.J., Property relations and data, in *The CRC Handbook of Mechanical Engineering*, Kreith, F., CRC Press, Boca Raton, FL, 1998, p. **2**-25.

Heating Values in kJ/kg of Selected Hydrocarbons at 25°C

		Higher Value[a]		Lower Value[b]	
Hydrocarbon	Formula	Liquid Fuel	Gas. Fuel	Liquid Fuel	Gas. Fuel
Methane	CH_4	—	55,496	—	50,010
Ethane	C_2H_6	—	51,875	—	47,484
Propane	C_3H_8	49,973	50,343	45,982	46,352
n-Butane	C_4H_{10}	49,130	49,500	45,344	45,714
n-Octane	C_8H_{18}	47,893	48,256	44,425	44,788
n-Dodecane	$C_{12}H_{26}$	47,470	47,828	44,109	44,467
Methanol	CH_3OH	22,657	23,840	19,910	21,093
Ethanol	C_3H_5OH	29,676	30,596	26,811	27,731

[a] H_2O liquid in the products.
[b] H_2O vapor in the products.

From Moran, M. J., Combustion, in *The CRC Handbook of Mechanical Engineering*, Kreith, F., CRC Press, Boca Raton, FL, 1998, p. **2**-62.

Some Fuel Properties of Four Different Biomass Types

Property	Pine Shavings	Switchgrass	Rice Hull	Rice Straw
Ash %	1.43	10.10	18.34	15.90
Carbon	48.54	47.79	40.96	41.78
Hydrogen	5.85	5.76	4.30	4.63
Nitrogen	0.47	1.17	0.40	0.70
Sulfur	0.01	0.10	0.02	0.08
Oxygen	43.69	35.07	35.86	36.57
Btu/lb	8337	7741	6944	7004
GJ/t	19.38	17.99	16.14	16.28

From Reed, M.C., Wright, L.L., Overend, R.P., and Carlton, W., Biomass energy, in *The CRC Handbook of Mechanical Engineering,* Kreith, F., CRC Press, Boca Raton, FL, 1998, p. 7-26.

Physical Properties of Selected Ceramics

Material	Porcelain	Cordierite Refractory	Alumina, Alumina Silicate Refractories	Magnesium Silicate
Specific gravity	2.2–2.4	1.6–2.1	2.2–2.4	2.3–2.8
Coefficient of linear thermal expansion, ppm/°C, 20–700°	$5.0–6.5 \times 10^6$	$2.5–3.0 \times 10^6$	$5.0–7.0 \times 10^6$	11.5×10^6
Safe operating temperature, °C	~400	1,250	1,300–1,700	1,200
Thermal conductivity (cal/cm²/cm/sec/°C)	0.004–0.005	0.003–0.004	0.004–0.005	0.003–0.005
Tensile strength (psi)	1,500–2,500	1,000–3,500	700–3,000	2,500
Compressive strength (psi)	25,000–50,000	20,000–45,000	13,000–60,000	20,000–30,000
Flexural strength (psi)	3,500–6,000	1,500–7,000	1,500–6,000	7,000–9,000
Impact strength (ft-lb; $^1/_2$″ rod)	0.2–0.3	0.2–0.25	0.17–0.25	0.2–0.3
Modulus of elasticity (psi)	$7–10 \times 10^6$	$2–5 \times 10^6$	$2–5 \times 10^6$	$4–5 \times 10^6$
Thermal shock resistance	Moderate	Excellent	Excellent	Good
Dielectric strength, (V/mil; 0.25″ specimen)	40–100	40–100	40–100	80–100
Resistivity (Ω/cm², 22°C)	$10^2–10^4$	$10^2–10^4$	$10^2–10^4$	$10^2–10^5$
Power factor at 10^6 Hz	0.010–0.020	0.004–0.010	0.002–0.010	0.008–0.010
Dielectric constant	6.0–7.0	4.5–5.5	4.5–6.5	5.0–6.0

From Lehman, R.L., Strange, D.J., and Fischer, III, W.F., Ceramics and glass, in *The CRC Handbook of Mechanical Engineering,* Kreith, F., CRC Press, Boca Raton, FL, 1998, p. 12-85.

Steel Pipe Sizes

Nominal Pipe Size, in.	Outside Diameter, in.	Schedule Number or Weight	Wall Thickness, in.	Inside Diameter, in.	Surface Area: Outside, ft²/ft	Surface Area: Inside, ft²/ft	Areas and Weights Cross-sectional: Metal Area, in.²	Areas and Weights Cross-sectional: Flow Area, in.²	Weight: Pipe lb/ft
¾	1.05	40	0.113	0.824	0.275	0.216	0.333	0.533	1.131
		80	0.154	0.742	0.275	0.194	0.434	0.432	1.474
1	1.315	40	0.133	1.049	0.344	0.275	0.494	0.864	1.679
		80	0.179	0.957	0.344	0.250	0.639	0.719	2.172
1¼	1.660	40	0.140	1.38	0.434	0.361	0.668	1.496	2.273
		80	0.191	1.278	0.434	0.334	0.881	1.283	2.997
1½	1.900	40	0.145	1.61	0.497	0.421	0.799	2.036	2.718
		80	0.200	1.50	0.497	0.393	1.068	1.767	3.632
2	2.375	40	0.154	2.067	0.622	0.541	1.074	3.356	3.653
		80	0.218	1.939	0.622	0.508	1.477	2.953	5.022
2½	2.875	40	0.203	2.469	0.753	0.646	1.704	4.79	5.794
		80	0.276	2.323	0.753	0.608	2.254	4.24	7.662
3	3.5	40	0.216	3.068	0.916	0.803	2.228	7.30	7.58
		80	0.300	2.900	0.916	0.759	3.016	6.60	10.25
3½	4.0	40	0.226	3.548	1.047	0.929	2.680	9.89	9.11
		80	0.318	3.364	1.047	0.881	3.678	8.89	12.51
4	4.5	40	0.237	4.026	1.178	1.054	3.17	12.73	10.79
		80	0.337	3.826	1.178	1.002	4.41	11.50	14.99
5	5.563	10 S	0.134	5.295	1.456	1.386	2.29	22.02	7.77
		40	0.258	5.047	1.456	1.321	4.30	20.01	14.62
		80	0.375	4.813	1.456	1.260	6.11	18.19	20.78
6	6.625	10 S	0.134	6.357	1.734	1.664	2.73	31.7	9.29
		40	0.280	6.065	1.734	1.588	5.58	28.9	18.98
		80	0.432	5.761	1.734	1.508	8.40	26.1	28.58
8	8.625	10 S	0.148	8.329	2.258	2.180	3.94	54.5	13.40
		30	0.277	8.071	2.258	2.113	7.26	51.2	24.7
		80	0.500	7.625	2.258	1.996	12.76	45.7	43.4
10	10.75	10 S	0.165	10.420	2.81	2.73	5.49	85.3	18.7
		30	0.279	10.192	2.81	2.67	9.18	81.6	31.2
		Extra heavy	0.500	9.750	2.81	2.55	16.10	74.7	54.7
12	12.75	10 S	0.180	12.390	3.34	3.24	7.11	120.6	24.2
		30	0.330	12.09	3.34	3.17	12.88	114.8	43.8
		Extra heavy	0.500	11.75	3.34	3.08	19.24	108.4	65.4
14	14.0	10	0.250	13.5	3.67	3.53	10.80	143.1	36.7
		Standard	0.375	13.25	3.67	3.47	16.05	137.9	54.6
		extra heavy	0.500	13.00	3.67	3.40	21.21	132.7	72.1
16	16.0	10	0.250	15.50	4.19	4.06	12.37	188.7	42.1
		Standard	0.375	15.25	4.19	3.99	18.41	182.7	62.6
		extra heavy	0.500	15.00	4.19	3.93	24.35	176.7	82.8
18	18.0	10 S	0.188	17.624	4.71	4.61	10.52	243.9	35.8
		Standard	0.375	17.25	4.71	4.52	20.76	233.7	70.6
		extra heavy	0.500	17.00	4.71	4.45	27.49	227.0	93.5
20	20.0	10 S	0.218	19.564	5.24	5.12	13.55	300.6	46.1
		Standard	0.375	19.25	5.24	5.04	23.12	291	78.6
		extra heavy	0.500	19.00	5.24	4.97	30.6	283.5	104.1
22	22.0	10	0.250	21.50	5.76	5.63	17.1	363	58.1
		Standard	0.375	21.25	5.76	5.56	25.5	355	86.6
		extra heavy	0.500	21.00	5.76	5.50	33.8	346	114.8
24	24.0	10	0.250	23.50	6.28	6.15	18.7	434	63.4
		Standard	0.375	23.25	6.28	6.09	27.8	425	94.6
		extra heavy	0.500	23.00	6.28	6.02	36.9	415	125.5
26	26.0	Standard	0.375	25.25	6.81	6.61	30.2	501	102.6
		extra heavy	0.500	25.00	6.81	6.54	40.1	491	136.2
30	30.0	10	0.312	29.376	7.85	7.69	29.1	678	98.9
		Standard	0.375	29.250	7.85	7.66	34.9	672	118.7
		extra heavy	0.500	29.00	7.85	7.59	46.3	661	157.6
34	34.0	Standard	0.375	33.250	8.90	8.70	39.6	868	134.7
		extra heavy	0.500	33.00	8.90	8.64	52.6	855	178.9
36	36.0	Standard	0.375	35.25	9.42	9.23	42.0	976	142.7
		extra heavy	0.500	35.00	9.42	9.16	55.8	962	189.6
42	42.0	Standard	0.375	41.25	11.0	10.8	49.0	1336	166.7
		extra heavy	0.500	41.00	11.0	10.73	65.2	1320	221.6

From Kreith, F., Ed., *The CRC Handbook of Mechanical Engineering,* CRC Press, Boca Raton, FL, 1998, p. E-81. Originally from *Design Properties of Pipe,* Chemetron Corporation, 1958.

Commercial Copper Tubing*

The following table gives dimensional data and weights of copper tubing used for automotive, plumbing, refrigeration, and heat exchanger services. For additional data see the standards handbooks of the Copper Development Association, Inc., the ASTM standards, and the "SAE Handbook."

Dimensions in this table are actual specified measurements, subject to accepted tolerances. Trade size designations are usually by actual OD, except for water and drainage tube (plumbing), which measures 1/8-in. larger OD. A 1/2-in. plumbing tube, for example, measures 5/8-in. OD, and 2-in. plumbing tube measures 2 1/8-in. OD.

KEY TO GAGE SIZES

Standard-gage wall thicknesses are listed by numerical designation (14 to 21), BWG or Stubs gage. These gage sizes are standard for tubular heat exchangers. The letter *A* designates SAE tubing sizes for automotive service. Letter designations *K* and *L* are the common sizes for plumbing services, soft or hard temper.

OTHER MATERIALS

These same dimensional sizes are also common for much of the commercial tubing available in aluminum, mild steel, brass, bronze, and other alloys. Tube weights in this table are based on copper at 0.323 lb/in^3. For other materials the weights should be multiplied by the following approximate factors:

aluminum	0.30	monel	0.96
mild steel	0.87	stainless steel	0.89
brass	0.95		

Size, OD		*Wall Thickness*			*Flow Area*		*Metal*	*Surface Area*		
in.	*mm*	*in.*	*mm*	*gage*	*in.*^{2}	*mm*^{2}	*Area, in.*^{2}	*Inside, ft*^{2}*/ft*	*Outside, ft*^{2}*/ft*	*Weight, lb/ft*
1/8	3.2	.030	0.76	A	0.003	1.9	0.012	0.017	0.033	0.035
3/16	4.76	.030	0.76	A	0.013	8.4	0.017	0.034	0.049	0.058
1/4	6.4	.030	0.76	A	0.028	18.1	0.021	0.050	0.066	0.080
1/4	6.4	.049	1.24	18	0.018	11.6	0.031	0.038	0.066	0.120
5/16	7.94	.032	0.81	21A	0.048	31.0	0.028	0.065	0.082	0.109
3/8	9.53	.032	0.81	21A	0.076	49.0	0.033	0.081	0.098	0.134
3/8	9.53	.049	1.24	18	0.060	38.7	0.050	0.072	0.098	0.195
1/2	12.7	.032	0.81	21A	0.149	96.1	0.047	0.114	0.131	0.182
1/2	12.7	.035	0.89	20L	0.145	93.6	0.051	0.113	0.131	0.198
1/2	12.7	.049	1.24	18K	0.127	81.9	0.069	0.105	0.131	0.269
1/2	12.7	.065	1.65	16	0.108	69.7	0.089	0.97	0.131	0.344
5/8	15.9	.035	0.89	20A	0.242	156	0.065	0.145	0.164	0.251
5/8	15.9	.040	1.02	L	0.233	150	0.074	0.143	0.164	0.285
5/8	15.9	.049	1.24	18K	0.215	139	0.089	0.138	0.164	0.344
3/4	19.1	.035	0.89	20A	0.363	234	0.079	0.178	0.196	0.305
3/4	19.1	.042	1.07	L	0.348	224	0.103	0.174	0.196	0.362
3/4	19.1	.049	1.24	18K	0.334	215	0.108	0.171	0.196	0.418
3/4	19.1	.065	1.65	16	0.302	195	0.140	0.162	0.196	0.542
3/4	19.1	.083	2.11	14	0.268	173	0.174	0.151	0.196	0.674
7/8	22.2	.045	1.14	L	0.484	312	0.117	0.206	0.229	0.455
7/8	22.2	.065	1.65	16K	0.436	281	0.165	0.195	0.229	0.641
7/8	22.2	.083	2.11	14	0.395	255	0.206	0.186	0.229	0.800
1	25.4	.065	1.65	16	0.594	383	0.181	0.228	0.262	0.740
1	25.4	.083	2.11	14	0.546	352	0.239	0.218	0.262	0.927
1 1/8	28.6	.050	1.27	L	0.825	532	0.176	0.268	0.294	0.655

*Compiled and computed.

Commercial Copper Tubing* (continued)

Size, OD		*Wall Thickness*			*Flow Area*		*Metal Area,*	*Surface Area*		*Weight,*
in.	*mm*	*in.*	*mm*	*gage*	*in.*^{2}	*mm*^{2}	*in.*^{2}	*Inside,* *ft*^{2}/*ft*	*Outside,* *ft*^{2}/*ft*	*lb/ft*
1 1/8	28.6	.065	1.65	16K	0.778	502	0.216	0.261	0.294	0.839
1 1/4	31.8	.065	1.65	16	0.985	636	0.242	0.293	0.327	0.938
1 1/4	31.8	.083	2.11	14	0.923	596	0.304	0.284	0.327	1.18
1 3/8	34.9	.055	1.40	L	1.257	811	0.228	0.331	0.360	0.884
1 3/8	34.9	.065	1.65	16K	1.217	785	0.267	0.326	0.360	1.04
1 1/2	38.1	.065	1.65	16	1.474	951	0.294	0.359	0.393	1.14
1 1/2	38.1	.083	2.11	14	1.398	902	0.370	0.349	0.393	1.43
1 5/8	41.3	.060	1.52	L	1.779	1148	0.295	0.394	0.425	1.14
1 5/8	41.3	.072	1.83	K	1.722	1111	0.351	0.388	0.425	1.36
2	50.8	.083	2.11	14	2.642	1705	0.500	0.480	0.628	1.94
2	50.8	.109	2.76	12	2.494	1609	0.620	0.466	0.628	2.51
2 1/8	54.0	.070	1.78	L	3.095	1997	0.449	0.520	0.556	1.75
2 1/8	54.0	.083	2.11	14K	3.016	1946	0.529	0.513	0.556	2.06
2 5/8	66.7	.080	2.03	L	4.77	3078	0.645	0.645	0.687	2.48
2 5/8	66.7	.095	2.41	13K	4.66	3007	0.760	0.637	0.687	2.93
3 1/8	79.4	.090	2.29	L	6.81	4394	0.950	0.771	0.818	3.33
3 1/8	79.4	.109	2.77	12K	6.64	4284	1.034	0.761	0.818	4.00
3 5/8	92.1	.100	2.54	L	9.21	5942	1.154	0.897	0.949	4.29
3 5/8	92.1	.120	3.05	11K	9.00	5807	1.341	0.886	0.949	5.12
4 1/8	104.8	.110	2.79	L	11.92	7691	1.387	1.022	1.080	5.38
4 1/8	104.8	.134	3.40	10K	11.61	7491	1.682	1.009	1.080	6.51

From Kreith, F., Ed., *The CRC Handbook of Mechanical Engineering,* CRC Press, Boca Raton, FL, 1998, p. **E**-82 to **E**-83.

Summary of Definitions

Systems (Machining/Manufacturing)	Definitions
Machining System	One or more machine tools and tooling, and auxiliary equipment (e.g., material handling, control, communications) that operate in a coordinated manner to produce parts at the required volumes and quality.
Dedicated Machining System (DMS)	A machining system designed for production of a specific part, and uses transfer line technology with fixed tooling and automation.
Flexible Manufacturing System (FMS)	A machining system configuration with fixed hardware and fixed, but programmable, software to handle changes in work orders, production schedules, part programs, and tooling for several types of parts.
Reconfigurable Manufacturing System (RMS)	A machining system that can be created by incorporating basic process modules, both hardware and software, that can be rearranged or replaced quickly and reliably. Reconfiguration will allow adding, removing, or modifying specific process capabilities, controls, software, or machine structure to adjust production capacity in response to changing market demands or technologies. This type of system will provide customized flexibility for a particular part family, and will be open-ended, so that it can be improved, upgraded, and reconfigured, rather than replaced.

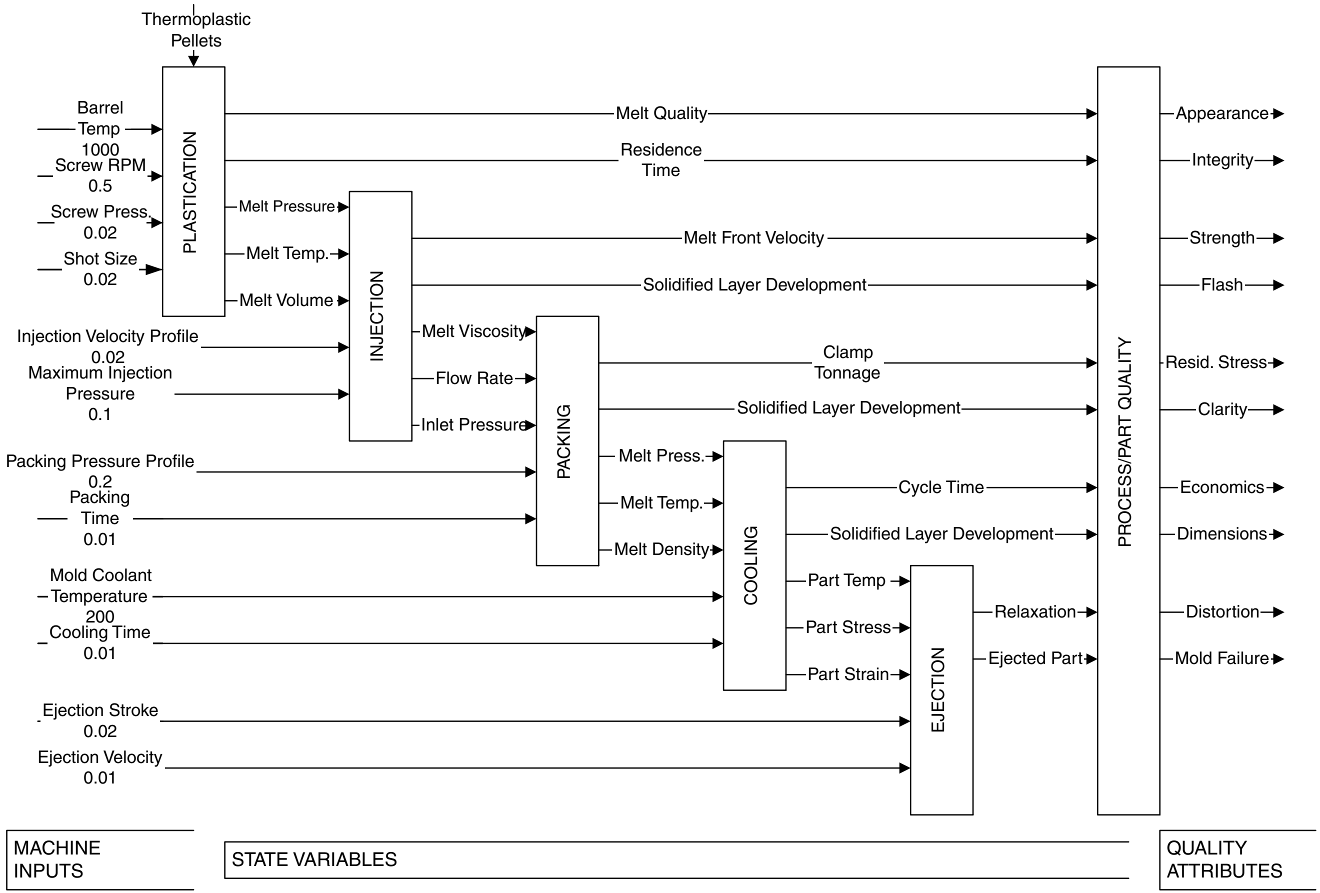
Note: A part family is defined as one or more part types with similar dimensions, geometric features, and tolerances, such that they can be produced on the same, or similar, production equipment.

From Mehrabi, M.G., Ulsoy, A.G., and Koren, Y., Manufacturing systems and their design principles, in *The Mechanical Systems Design Handbook*, Nwokah, O.D.I., and Hurmuzlu, Y., Eds., CRC Press, Boca Raton, FL, 2002, p. 4.

CAPP System Characteristics and Their Effects

Characteristic	Effects
Complete	• Provides a complete manufacturing solution for the part in question. • Meets all the end-user's requirements. • Facilitates the generation of multiple solutions.
Extendable	• New technologies can be merged into the system. • The system can be extended by the end-user or a third-party software developer.
Adaptable	• The system can be used by many different types of end-users.
User Inclusive	• Utilizes human expertise and computer efficiency in correct proportions. • Promotes synthesis and analysis in addition to automation and simulation.
User Friendly	• Easy to implement and maintain. • Easy to use.
Teachable	• Allows the expertise of the end-user to be incorporated into the system. • The system can act as an archiving tool for the end-user's expertise. • The system can be used to train new process planners.
Customizable	• The system (and its cost) can be tailored to the end-user's requirements.
Modular	• Facilitates extendability, adaptability, customizability, and cost effectiveness.
Robust	• Provides consistently "correct" (by the end-user's standard) solutions. • Reduces human error.
Efficient	• Solutions are generated in a more timely fashion than by conventional planning. • The work load for a process planner generating a solution is reduced.
Integratable	• Implementation is not computer hardware or software specific.
Cost Effective	• The system in a customized form suits the budget of a wide range of end-users.

From Yip-Hoi, D., Computer-aided process planning for machining, in *The Mechanical Systems Design Handbook*, Nwokah, O.D.I., and Hurmuzlu, Y., Eds., CRC Press, Boca Raton, FL, 2002, p. 24.

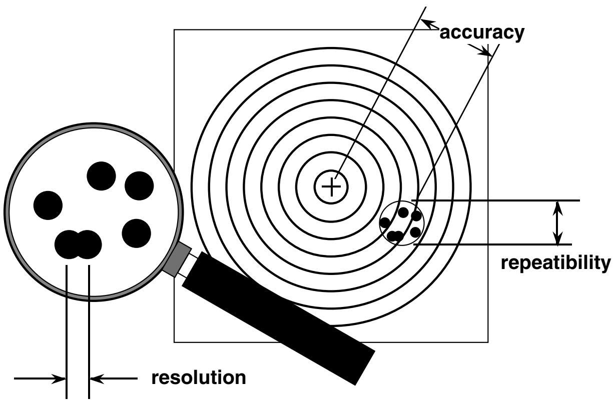


System's view of the injection molding process. (From Kazmer, D. and Danai, K., Control of polymer processing, in *The Mechanical Systems Design Handbook*, Nwokah, O.D.I., and Hurmuzlu, Y., Eds., CRC Press, Boca Raton, FL, 2002, p. 141.)

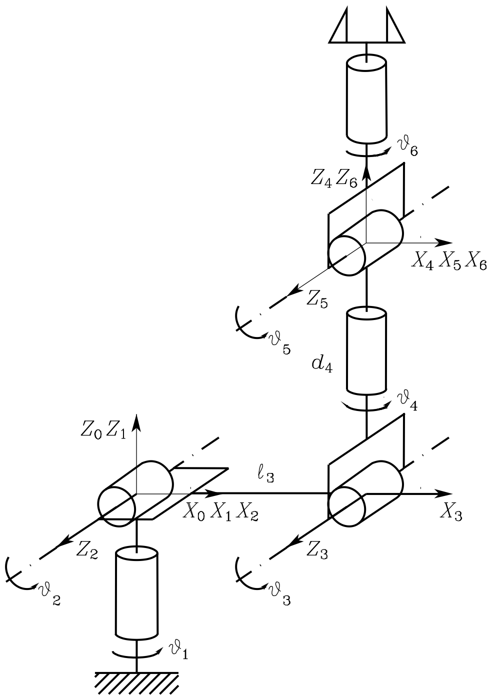
Magnitude of Process Variation by Machine Input

Control Quality	Low (Class 9)	High (Class 1)
Melt temperature (C)	5	1
Mold temperature (C)	8	2
Injection time (sec)	0.17	0.04
Pack pressure (Mpa)	0.5	0.1
Pack time (sec)	0.02	0.09
Cooling time (sec)	0.86	0.20

From Kazmer, D. and Danai, K., Control of polymer processing, in *The Mechanical Systems Design Handbook*, Nwokah, O.D.I., and Hurmuzlu, Y., Eds., CRC Press, Boca Raton, FL, 2002, p. 143.



Visualization of accuracy, repeatability, and resolution. (From Kurfess, T.R., Precision manufacturing, in *The Mechanical Systems Design Handbook*, Nwokah, O.D.I., and Hurmuzlu, Y., Eds., CRC Press, Boca Raton, FL, 2002, p. 153. Originally from Dorf, R. and Kusiak, A., *Handbook of Design, Manufacturing, and Automation*, John Wiley, New York, 1994. With permission.)

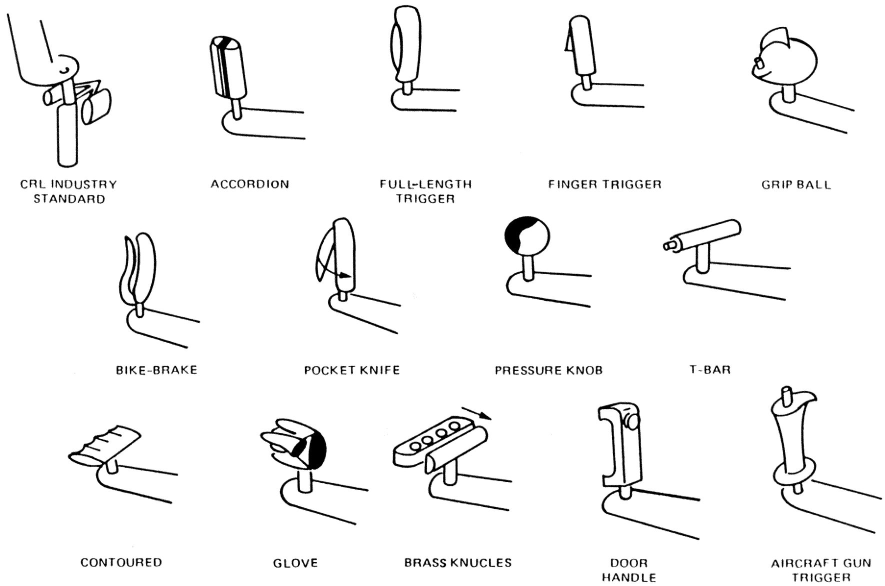


Anthropomorphic robot with frame assignment. (From Siciliano, B., Robot kinematics, in *The Mechanical Systems Design Handbook*, Nwokah, O.D.I., and Hurmuzlu, Y., Eds., CRC Press, Boca Raton, FL, 2002, p. 460.)

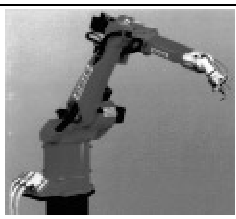
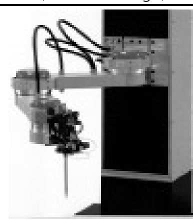
Denavit-Hartenberg Parameters of the Anthropomorphic Robot

i	α_i	ℓ_i	ϑ_i	d_i
1	0	0	q_1	0
2	$\pi/2$	0	q_2	0
3	0	ℓ_3	q_3	0
4	$-\pi/2$	0	q_4	d_4
5	$\pi/2$	0	q_5	0
6	$-\pi/2$	0	q_6	0

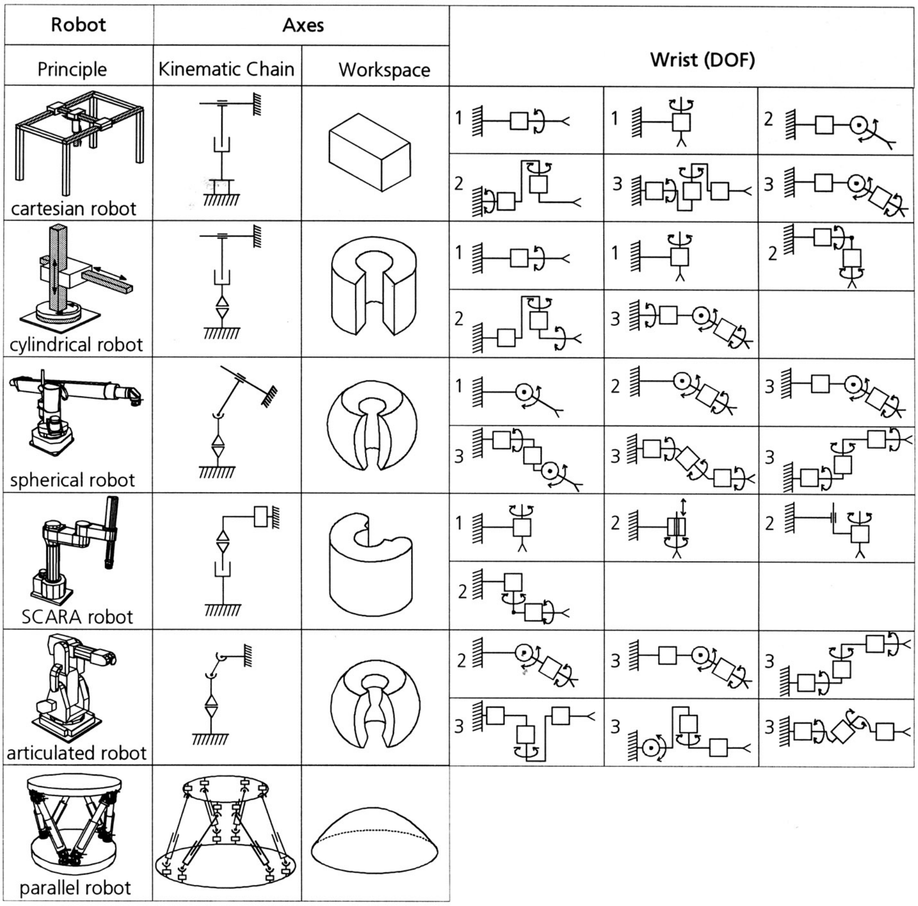
From Siciliano, B., Robot kinematics, in *The Mechanical Systems Design Handbook*, Nwokah, O.D.I., and Hurmuzlu, Y., Eds., CRC Press, Boca Raton, FL, 2002, p. 460.



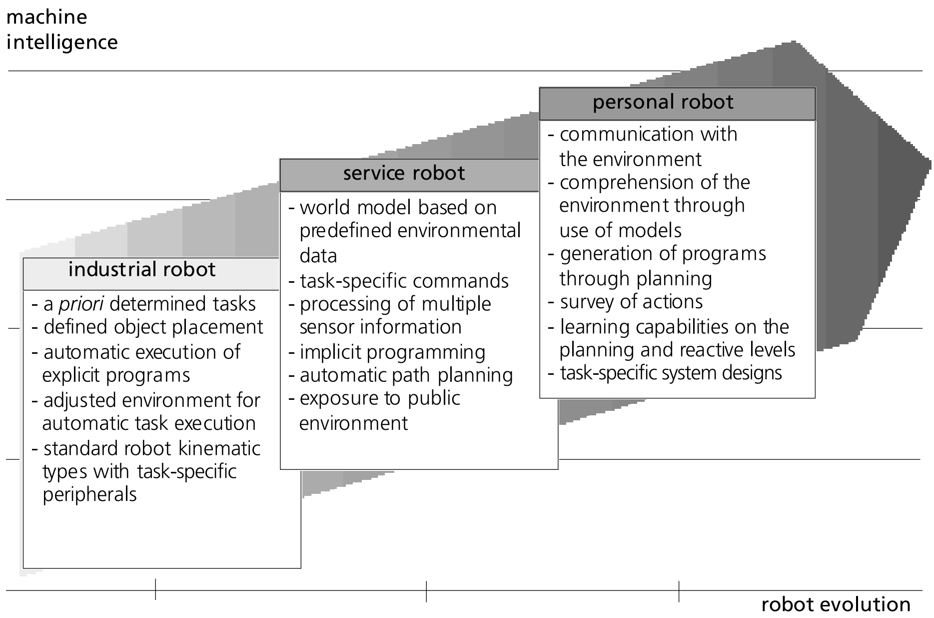
Basic grip and trigger concepts. (From Bejczy, A.K., Teleoperation and telerobotics, in *The Mechanical Systems Design Handbook*, Nwokah, O.D.I., and Hurmuzlu, Y., Eds., CRC Press, Boca Raton, FL, 2002, p. 687.)

Specialization of robots			
universal robot	application specific	specialist (modular design)	specialist (customized design)
			
Examples: Reis RV6	ABB Flex Palettizer	CMB Modular Robot	IPA Robot Refuelling
• design fits standard applications • product variants according to payload, dexterity, working envelope • use of customized components • high manufacturing quantities	• application-oriented designs • integrated process-control functions • preconfigured workcells available • medium manufacturing quantities	• task specific design • integration of standard modules (axis, control, sensors) • preferred applications: material handling • small manufacturing quantities	• task specific designs • primary applications: nonmanufacturing fields (service robots) • task based kinematic structure • small to large manufacturing quantities

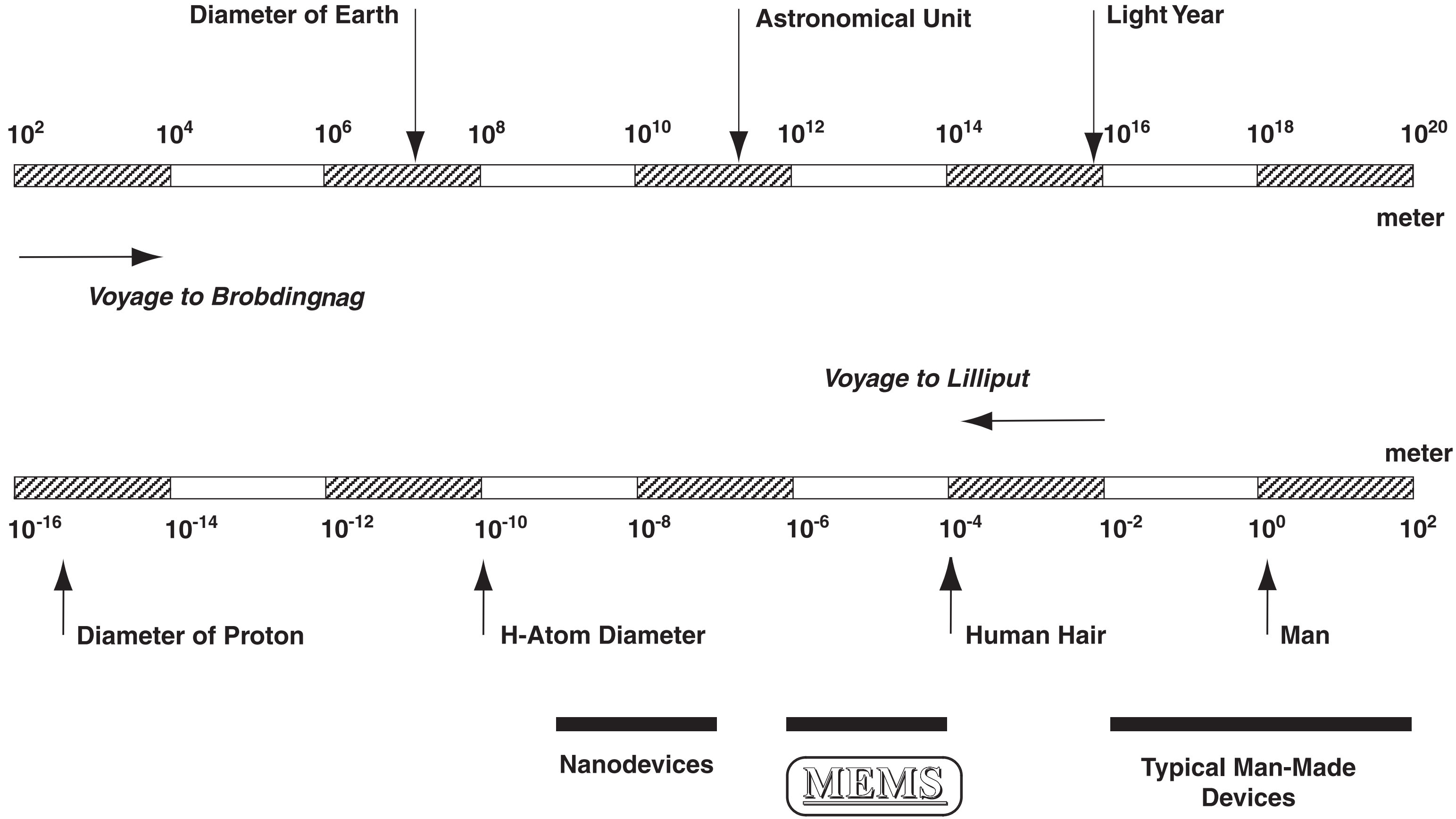
Examples of specialization of robot designs. (From Hagele, M. and Schraft, R.D., Present state and furture trends in mechanical systems design for robot application, in *The Mechanical Systems Design Handbook*, Nwokah, O.D.I., and Hurmuzlu, Y., Eds., CRC Press, Boca Raton, FL, 2002, p. 781. Originally courtesy of Reis Robotics, ABB Flexible Automation, and CMB Automation. From Warnecke, H.-J. et al., in *Handbook of Industrial Robotics,* 1999, p. 42. Reprinted with permission of John Wiley & Sons.)



Typical arm and wrist configurations of industrial robots. (From Hagele, M. and Schraft, R.D., Present state and furture trends in mechanical systems design for robot application, in *The Mechanical Systems Design Handbook*, Nwokah, O.D.I., and Hurmuzlu, Y., Eds., CRC Press, Boca Raton, FL, 2002, p. 784.)



From industrial robots to service robots — the evolution of machine intelligence. (From Hagele, M. and Schraft, R.D., Present state and furture trends in mechanical systems design for robot application, in *The Mechanical Systems Design Handbook*, Nwokah, O.D.I., and Hurmuzlu, Y., Eds., CRC Press, Boca Raton, FL, 2002, p. 795.)

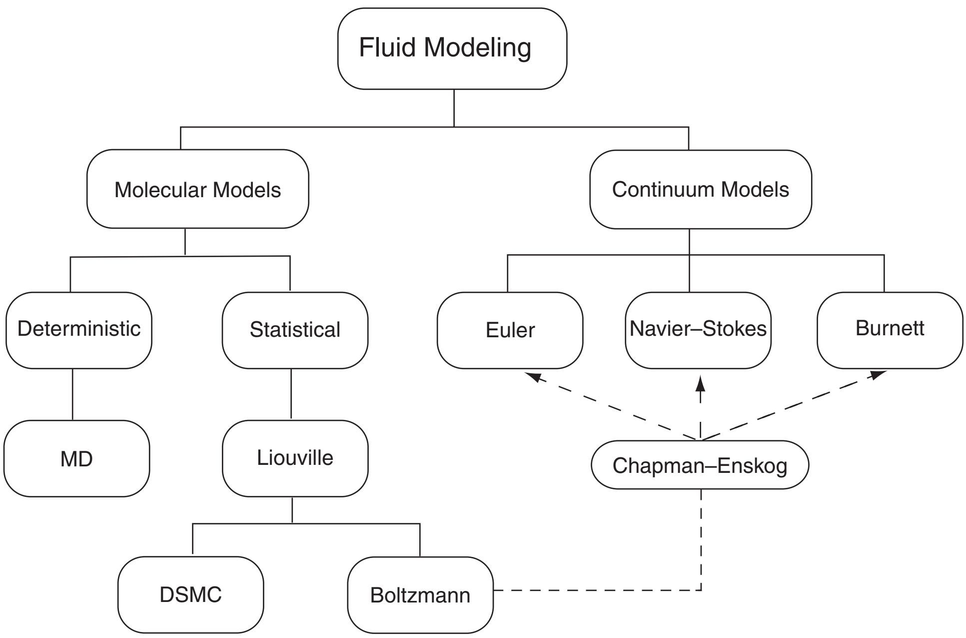


Scale of things, in meters. Lower scale continues in the upper bar from left to right. One meter is 10^6 µm, 10^9 nm, or 10^{10} Å. (From Gal-el-Hak, M., Introduction, in *The MEMS Handbook*, Gal-el-Hak, M., Ed., CRC Press, Boca Raton, FL, 2002, p. **1**-2.)

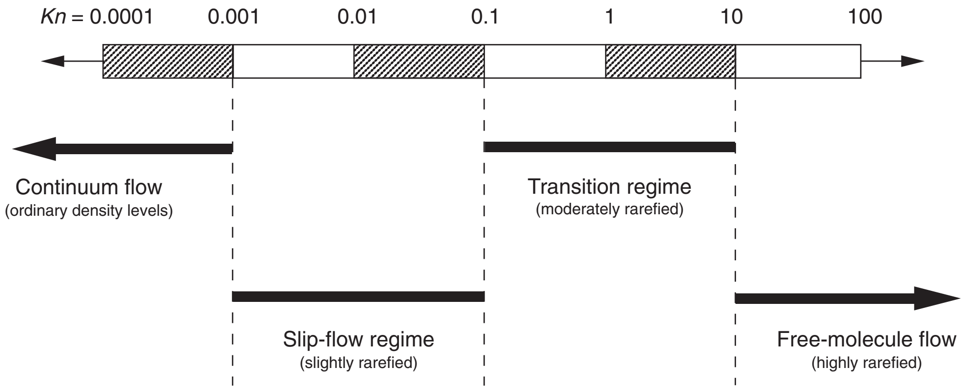
Metals

	Young's Modulus (GPa)	Yield Strength (GPa)	Ultimate Strength (GPa)	Method	Comments
Aluminum;	8–38	—	0.04–0.31	Tension	110–160 μm thick
modulus of bulk	40	—	0.15	Tension	1.0 μm thick
material = 69 GPa					
	69–85	—	—	Bending	Various lengths
Copper;	86–137	0.12–0.24	0.33–0.38	Tension	Plated; annealed
modulus of bulk	108–145	—	—	Indentation	Various locations
material = 117 GPa					
	98 ± 4	—	—	Tension	Laser speckle
Gold;	40–80	—	0.2–0.4	Tension	0.06–16 μm thick
modulus of bulk	57	0.26	—	Bending	~1 μm thick
material = 74 GPa					
	74	—	—	Indentation	~1 μm thick
	82	—	0.33–0.36	Tension	0.8 μm thick
	—	—	0.22–0.27	Bending	Composite beam
Titanium;					
modulus of bulk	96 ± 12	—	0.95 ± 0.15	Tension	0.5 μm thick
material = 110 GPa					
Ti–Al–Ti	—	0.07–0.12	0.14–0.19	Tension	Composite film

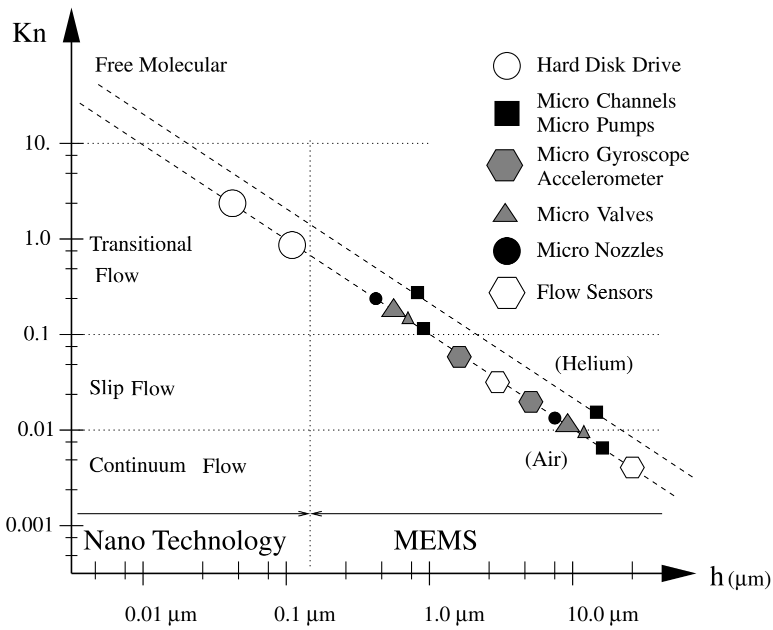
From Sharpe, Jr., W.N., Mechanical properties of MEMS materials, in *The MEMS Handbook*, Gal-el-Hak, M., Ed., CRC Press, Boca Raton, FL, 2002, p. **3**-19.



Molecular and continuum flow models. (From Gad-el-Hak, M., Flow physics, in *The MEMS Handbook*, Gal-el-Hak, M., Ed., CRC Press, Boca Raton, FL, 2002, p. **4**-3. Originally from Gad-el-Hak, M. (1999) *J. Fluids Eng.* **121**, pp. 5–33, ASME, New York. With permission.)



Knudsen number regimes. (From Gad-el-Hak, M., Flow physics, in *The MEMS Handbook*, Gal-el-Hak, M., Ed., CRC Press, Boca Raton, FL, 2002, p. **4**-6. Originally from Gad-el-Hak, M. (1999) *J. Fluids Eng.* **121**, pp. 5–33, ASME, New York. With permission.)



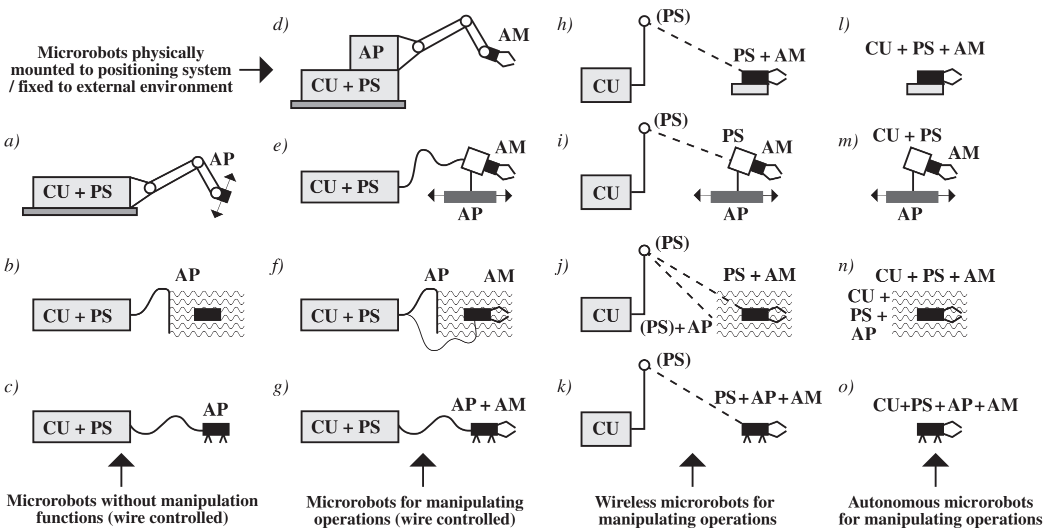
The operation range for typical MEMS and nanotechnology applications under standard conditions spans the entire Knudsen regime (continuum, slip, transition and free molecular flow regimes). (From Bestok, A., Molecular-based microfluidic simulation models, in *The MEMS Handbook*, Gal-el-Hak, M., Ed., CRC Press, Boca Raton, FL, 2002, p. **8**-3.)

Classification of Microrobots According to Size and Fabrication Technology

Robot Class	Size and Fabrication Technology
Miniature robots or minirobots:	Having a size on the order of a few cubic centimeters and fabricated by assembling conventional miniature components as well as some micromachines (such as MEMS-based microsensors)
MEMS-based microrobots (or microrobots[a])	Defined as a sort of "modified chip" fabricated by silicon MEMS-based technologies (such as batch-compatible bulk or surface micromachining or by micromolding and/or replication method) having features in the micrometer range
Nanorobots	Operating at a scale similar to the biological cell (on the order of a few hundred nanometers) and fabricated by nonstandard mechanical methods such as protein engineering

[a] To distinguish a MEMS-based microrobot with *micro*meter-sized components from the whole class of microrobots (including mini-, micro-, and nanorobots), several more or less confusing notations have been proposed. In this publication, the term *MEMS-based microrobot* is introduced and used. The term *MEMS-based microrobot* differs from the notation originally used by Dario et al., but the content is the same.

From Ebefors, T. and Stemme, G., Microrobotics, in *The MEMS Handbook*, Gal-el-Hak, M., Ed., CRC Press, Boca Raton, FL, 2002, p. **28**-4.

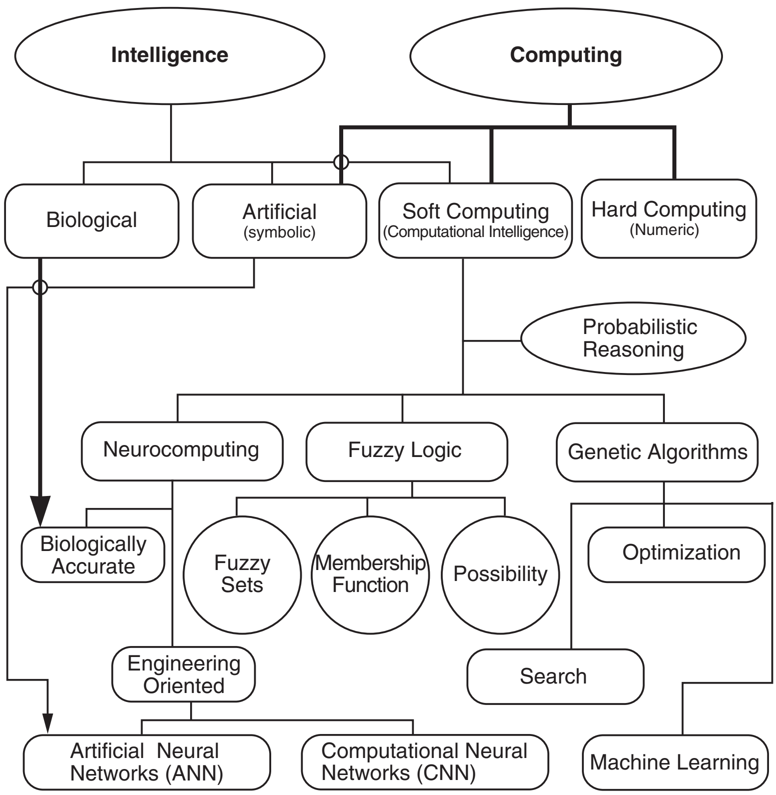


Classification of microrobots by functionality (modification of earlier presented classification schemes). CU indicates the control unit; PS, the power source or power supply; AP, the actuators for positioning; AM, the actuators for manipulation. (From Ebefors, T. and Stemme, G., Microrobotics, in *The MEMS Handbook*, Gal-el-Hak, M., Ed., CRC Press, Boca Raton, FL, 2002, p. **28**-5.)

Thermal Conductivity, Coefficient of Thermal Expansion, Cost Estimates, and Scaling Trends of Current and Potential Substrate Materials

Materials	Thermal Conductivity (W/cm-K)	Coefficient of Thermal Expansion (10^{-6}/K)	Cost of Substrate ($/in^2)	Scaling with Area Cost Trend
Alumina	0.25	6.7	0.09	6" limit
FR-4	Depends on copper	13.0	0.07	Constant to 36"
A1N	1.00–2.00	4.1	0.35	6" limit
Silicon	1.48	4.7	1.00	6–10" limit
Heat pipe in silicon	8.00 → 20.00 (?)	4.7	3.00	6–10" limit
A1	2.37	41.8	0.0009	Scales as area
Cu	3.98	28.7	0.0015	Scales as area
Diamond	10.00–20.00	1.0–1.5	1000.00	Scales as area^2
Kovar	0.13	5.0	0.027	Scales as area
Heat pipe in Kovar	>8.00	5.0	0.10	Scales as area
A1SiC	2.00 (at 70%)	7.0 (?)	1.00	Casting size limited

From Peterson, G.P., Micro heat pipes and micro heat spreaders, in *The MEMS Handbook*, Gal-el-Hak, M., Ed., CRC Press, Boca Raton, FL, 2002, p. **31**-17.



Tools for soft computing. (From Gal-el-Hak, M., Flow control, in *The MEMS Handbook*, Gal-el-Hak, M., Ed., CRC Press, Boca Raton, FL, 2002, p. **33**-36. Originally from Gad-el-Hak, M. (2000) *Flow Control: Passive, Active, and Reactive Flow Management*. Reprinted with permission of Cambridge University Press, New York.)

Saturated Steam, Water, and Ice — SI Units

Subscripts:

- *f* refers to a property of liquid in equilibrium with vapor
- *g* refers to a property of vapor in equilibrium with liquid
- *i* refers to a property of solid in equilibrium with vapor
- *fg* refers to a change by evaporation
- *ig* refers to a change by sublimation

Temperature C	Temperature K	Pressure, MN/m²	Specific Volume, m³/kg		Specific Internal Energy, kJ/kg		Specific enhalpy, kJ/kg			Specific Entropy, kJ/kg·K	
Solid—Vapor			v_i	v_g	u_i	u_g	h_i	h_{ig}	h_g	s_i	s_g
–40	233.15	0.000 012 9	0.000 084 1	83.54	–411.70	2 319.6	–411.70	2 838.9	2 427.2	–1.532	10.644
–30	243.15	0.000 038 1	0.001 085 8	29.43	–393.23	2 333.6	–393.23	2 839.0	2 445.8	–1.455	10.221
–20	253.15	0.000 103 5	0.001 087 4	11.286	–374.03	2 347.5	–374.03	2 838.4	2 464.3	–1.377	9.835
–10	263.15	0.000 260 2	0.001 089 1	4.667	–354.09	2 361.4	–354.09	2 837.0	2 482.9	–1.299	9.481
0	273.15	0.000 610 8	0.001 090 8	2.063	–333.43	2 375.3	–333.43	2 834.8	2 501.3	–1.221	9.157
0.01	273.16	0.000 611 3	0.001 090 8	2.061	–333.40	2 375.3	–333.40	2 834.8	2 501.4	–1.221	9.156
Liquid—Vapor			v_f	v_g	u_f	u_g	h_f	h_{fg}	h_g	s_f	s_g
0	273.15	0.000 610 9	0.001 000 2	206.278	–0.03	2 375.3	–0.02	2 501.4	2 501.3	–0.000 1	9.156 5
0.01	273.16	0.000 611 3	0.001 000 2	206.136	0	2 375.3	+0.01	2 501.3	2 501.4	0	9.156 2
5.00	278.15	0.000 872 1	0.001 000 1	147.120	+20.97	2 382.3	20.98	2 489.6	2 510.6	+0.076 1	9.025 7
6.98	280.13	0.001 000 0	0.001 000 2	129.208	29.30	2 385.0	29.30	2 484.9	2 514.2	0.105 9	8.975
10.00	283.15	0.001 227 6	0.001 000 4	106.379	42.00	2 389.2	42.01	2 477.7	2 519.8	0.151 0	8.900 8
13.03	286.18	0.001 500 0	0.001 000 7	87.980	54.71	2 393.3	54.71	2 470.6	2 525.3	0.195 7	8.827 9
15.00	288.15	0.001 705 1	0.001 000 9	77.926	62.99	2 396.1	62.99	2 465.9	2 528.9	0.224 5	8.781 4
17.50	290.65	0.002 000 0	0.001 001 3	67.004	73.48	2 399.5	73.48	2 460.0	2 533.5	0.260 7	8.723 7
20.00	293.15	0.002 339	0.001 001 8	57.791	83.95	2 402.9	83.96	2 454.1	2 538.1	0.296 6	8.667 2
24.08	297.23	0.003 000 0	0.001 002 7	45.665	101.04	2 408.5	101.05	2 444.5	2 545.5	0.354 5	8.577 6
25.00	298.15	0.003 169	0.001 002 9	43.360	104.88	2 409.8	104.89	2 442.3	2 547.2	0.367 4	8.558 0
28.96	302.11	0.004 000	0.001 004 0	34.800	121.45	2 415.2	121.46	2 432.9	2 554.4	0.422 6	8.474 6
30.00	303.15	0.004 246	0.001 004 3	32.894	125.78	2 416.6	125.79	2 430.5	2 556.3	0.436 9	8.453 3
32.88	306.03	0.005 000	0.001 005 3	28.192	137.81	2 420.5	137.82	2 423.7	2 561.5	0.476 4	8.395 1
35.00	308.15	0.005 628	0.001 006 0	25.216	146.67	2 423.4	146.68	2 418.6	2 565.3	0.505 3	8.353 1
36.16	309.31	0.006 000	0.001 006 4	23.739	151.53	2 425.0	151.53	2 415.9	2 567.4	0.521 0	8.330 4
39.00	312.15	0.007 000	0.001 007 4	20.530	163.39	2 428.8	163.40	2 409.1	2 572.5	0.559 2	8.275 8
40.00	313.15	0.007 384	0.001 007 8	19.523	167.56	2 430.1	167.57	2 406.7	2 574.3	0.572 5	8.257 0
41.51	314.66	0.008 000	0.001 008 4	18.103	173.87	2 432.2	173.88	2 403.1	2 577.0	0.592 6	8.228 7
43.76	316.91	0.009 000	0.001 009 4	16.203	183.27	2 435.2	183.29	2 397.7	2 581.0	0.622 4	8.187 2
45.00	318.15	0.009 593	0.001 009 9	15.258	188.44	2 436.8	188.45	2 394.8	2 583.2	0.638 7	8.164 8
45.81	318.96	0.010 000	0.001 010 2	14.674	191.82	2 437.9	191.83	2 392.8	2 584.7	0.649 3	8.150 2
50.00	323.15	0.012 349	0.001 012 1	12.032	209.32	2 443.5	209.33	2 382.7	2 592.1	0.703 8	8.076 3
53.97	327.12	0.015 000	0.001 014 1	10.022	225.92	2 448.7	225.94	2 373.1	2 599.1	0.754 9	8.008 5
55.00	328.15	0.015 758	0.001 014 6	9.568	230.21	2 450.1	230.23	2 370.7	2 600.9	0.767 9	7.991 3
60.00	333.15	0.019 940	0.001 017 2	7.671	251.11	2 456.6	251.13	2 358.5	2 609.6	0.831 2	7.909 6
60.06	333.21	0.020 000	0.001 017 2	7.649	251.38	2 456.7	251.40	2 358.3	2 609.7	0.832 0	7.908 5
65.00	338.15	0.025 030	0.001 019 9	6.197	272.02	2 463.1	272.06	2 346.2	2 618.3	0.893 5	7.831 0
69.10	342.25	0.030 000	0.001 022 3	5.22l9	289.20	2 468.4	289.23	2 336.1	2 625.3	0.943 9	7.768 6
70.00	343.15	0.031 190	0.001 022 8	5.042	292.95	2 469.6	292.98	2 333.8	2 626.8	0.954 9	7.755 3
75.00	348.15	0.038 580	0.001 025 9	4.131	313.90	2 475.9	313.93	2 221.4	2 635.3	1.015 5	7.682 4
75.87	349.02	0.040 000	0.001 026 5	3.993	317.53	2 477.0	317.58	2 319.2	2 636.8	1.025 9	7.670 0
80.00	353.15	0.047 390	0.001 029 1	3.407	334.86	2 482.2	334.91	2 308.8	2 643.7	1.075 3	7.612 2
81.33	354.48	0.050 000	0.001 030 0	3.240	340.44	2 483.9	340.49	2 305.4	2 645.9	1.091 0	7.593 9
85.00	358.15	0.057 830	0.001 032 5	2.828	355.84	2 488.4	355.90	2 296.0	2 651.9	1.134 3	7.544 5
85.94	359.09	0.060 000	0.001 033 1	2.732	359.79	2 489.6	359.86	2 293.6	2 653.5	1.145 3	7.532 0
89.95	363.10	0.070 000	0.001 036 0	2.365	376.63	2 494.5	376.70	2 283.3	2 660.0	1.191 9	7.479 7
90.00	363.15	0.070 140	0.001 036 0	2.361	376.85	2 494.5	376.92	2 283.2	2 660.1	1.192 5	7.479 1
93.50	366.65	0.080 000	0.001 038 6	2.087	391.58	2 498.8	391.66	2 274.1	2 665.8	1.232 9	7.434 6
95.00	368.15	0.084 550	0.001 039 7	1.981 9	397.88	2 500.6	397.96	2 270.2	2 668.1	1.250 0	7.415 9

Saturated Steam, Water, and Ice — SI Units (continued)

Liquid—Vapor			v_f	v_g	u_f	u_g	h_f	h_{fg}	h_g	s_f	s_g
96.71	369.86	0.090 000	0.001 041 0	1.869	405.06	2 502.6	405.15	2 265.7	2 670.9	1.269 5	7.394 9
99.63	372.78	0.100 000	0.001 043 2	1.694 0	417.36	2 506.1	417.46	2 258.0	2 675.5	1.302 6	7.359 4
100.00	373.15	0.101 350	0.001 043 5	1.672 9	418.94	2 506.5	419.04	2 257.0	2 676.1	1.306 9	7.354 9
110.00	383.15	0.143 270	0.001 051 6	1.210 2	461.14	2 518.1	461.30	2 230.2	2 691.5	1.418 5	7.238 7
111.37	384.52	0.150 000	0.001 052 8	1.159 3	466.94	2 519.7	467.11	2 226.5	2 693.6	1.433 6	7.223 3
120.00	393.15	0.198 530	0.001 060 3	0.891 9	503.50	2 529.3	503.71	2 202.6	2 706.3	1.527 6	7.129 6
120.23	393.38	0.200 000	0.001 060 5	0.885 7	504.49	2 529.5	504.70	2 201.9	2 706.7	1.530 1	7.127 1
130.00	403.15	0.270 000	0.001 069 7	0.668 5	546.02	2 539.9	546.31	2 174.2	2 720.5	1.634 4	7.026 9
133.55	406.70	0.300 000	0.001 073 2	0.605 8	561.15	2 543.6	561.47	1 163.8	2 725.3	1.671 8	6.991 9
140.00	413.15	0.361 300	0.001 079 7	0.508 9	588.74	2 550.0	589.13	2 144.7	2 733.9	1.739 1	6.929 9
143.63	416.78	0.400 000	0.001 083 6	0.462 5	604.31	2 553.6	604.74	2 133.8	2 738.6	1.776 6	6.895 9
150.00	423.15	0.475 800	0.001 090 5	0.392 8	631.68	2 559.5	632.20	2 114.3	2 746.5	1.841 8	6.837 9
151.86	425.01	0.500 000	0.001 092 6	0.374 9	639.68	2 561.2	640.23	2 108.5	2 748.7	1.860 7	6.821 3
160.00	433.15	0.617 800	0.001 102 0	0.307 1	674.87	2 568.4	675.55	2 082.6	2 758.1	1.942 7	6.750 2
170.00	443.15	0.791 700	0.001 114 3	0.242 8	718.33	2 576.5	719.21	2 049.5	2 768.7	2.041 9	6.666 3
179.91	453.06	1.000 000	0.001 127 3	0.194 44	761.68	2 583.6	762.81	2 015.3	2 778.1	2.138 7	6.586 5
180.00	453.15	1.002 100	0.001 127 4	0.194 05	762.09	2 583.7	763.22	2 015.0	2 778.2	2.139 6	6.585 7
190.00	463.15	1.254 400	0.001 141 4	0.156 54	806.19	2 590.0	807.62	1 978.8	2 786.4	2.235 9	6.507 9
198.32	471.47	1.500 000	0.001 153 9	0.131 77	843.16	2 594.5	844.89	1 947.3	2 792.2	2.315 0	6.444 8
200.00	473.15	1.553 800	0.001 156 5	0.127 36	850.65	2 595.3	852.45	1 940.7	2 793.2	2.330 9	6.432 3
210.00	483.15	1.906 200	0.001 172 6	0.104 41	895.53	2 599.5	897.76	1 900.7	2 798.5	2.424 8	6.358 5
212.42	485.57	2.000 000	0.001 176 7	0.099 63	906.44	2 600.3	908.79	1 890.7	2 799.5	2.447 4	6.340 9
220.00	493.15	2.318 000	0.001 190 0	0.086 19	940.87	2 602.4	943.62	1 858.5	2 802.1	2.517 8	6.286 1
223.99	497.14	2.500 000	0.001 197 3	0.079 98	959.11	2 603.1	962.11	1 841.0	2 803.1	2.554 7	6.257 5
230.00	503.15	2.795 000	0.001 208 8	0.071 58	986.74	2 603.9	990.12	1 813.8	2 804.0	2.609 9	6.214 6
233.90	507.05	3.000 000	0.001 216 5	0.066 68	1 004.78	2 604.1	1 008.42	1 795.7	2 804.2	2.645 7	6.186 9
240.00	513.15	3.344 000	0.001 229 1	0.059 76	1 033.21	2 604.0	1 037.32	1 766.5	2 803.8	2.701 5	6.143 7
242.60	515.75	3.500 000	0.001 234 7	0.057 07	1 045.43	2 603.7	1 049.75	1 753.7	2 803.4	2.725 3	6.125 3
250.00	523.15	3.973 000	0.001 251 2	0.050 13	1 080.39	2 602.4	1 085.36	1 716.2	2 801.5	2.792 7	6.073 0
250.40	523.55	4.000 000	0.001 252 2	0.049 78	1 082.31	2 602.3	1 087.31	1 714.1	2 801.4	2.796 4	6.070 1
260.00	533.15	4.688 000	0.001 275 5	0.042 21	1 128.39	2 599.0	1 134.37	1 662.5	2 796.9	2.883 8	6.001 9
263.99	537.14	5.000 000	0.001 285 9	0.039 44	1 147.81	2 597.1	1 154.23	1 640.1	2 794.3	2.920 2	5.973 4
270.00	543.15	5.499 000	0.001 302 3	0.035 64	1 177.36	2 593.7	1 184.51	1 605.2	2 789.7	2.975 1	5.930 1
275.64	548.79	6.000 000	0.001 318 7	0.032 44	1 205.44	2 589.7	1 213.35	1 571.0	2 784.3	3.026 7	5.889 2
280.00	553.15	6.412 000	0.001 332 1	0.030 17	1 227.46	2 586.1	1 235.99	1 543.6	2 779.6	3.066 8	5.857 1
285.88	559.03	7.000 000	0.001 351 3	0.027 37	1 257.55	2 580.5	1 267.00	1 505.1	2 772.1	3.121 1	5.813 3
290.00	563.15	7.436 000	0.001 365 6	0.025 57	1 278.92	2 576.0	1 289.07	1 477.1	2 766.2	3.159 4	5.782 1
295.06	568.21	8.000 000	0.001 384 2	0.023 52	1 305.57	2 569.8	1 316.64	1 441.3	2 758.0	3.206 8	5.743 2
300.00	573.15	8.581 000	0.001 403 6	0.021 67	1 332.0	2 563.0	1 344.0	1 404.9	2 749.0	3.253 4	5.704 5
303.40	576.55	9.000 000	0.001 417 8	0.020 48	1 350.51	2 557.8	1 363.26	1 378.9	2 742.1	3.285 8	5.677 2
310.00	583.15	9.856 000	0.001 447 4	0.018 350	1 387.1	2 546.4	1 401.3	1 326.0	2 727.3	3.349 3	5.623 0
311.06	584.21	10.000 000	0.001 452 4	0.018 026	1 393.04	2 544.4	1 407.56	1 317.1	2 724.7	3.359 3	5.614 1
320.00	593.15	11.274 000	0.001 498 8	0.015 488	1 444.6	2 525.5	1 461.5	1 238.6	2 700.1	3.448 0	5.536 2
324.75	597.90	12.000 000	0.001 526 7	0.014 263	1 473.0	2 513.7	1 491.3	1 193.6	2 684.9	3.496 2	5.492 4
330.00	603.15	12.845 000	0.001 560 7	0.012 996	1 505.3	2 498.9	1 525.3	1 140.6	2 665.9	3.550 7	5.441 7
336.75	609.90	14.000 000	0.001 610 7	0.011 485	1 548.6	2 476.8	1 571.1	1 066.5	2 637.6	3.623 2	5.371 7
340.00	613.15	14.586 000	0.001 637 9	0.001 079 7	1 570.3	2 464.6	1 594.2	1 027.9	2 622.0	3.659 4	5.335 7
347.44	620.59	16.000 000	0.001 710 7	0.009 306	1 622.7	2 431.7	1 650.1	930.6	2 580.6	3.746 1	5.245 5
350.00	623.15	16.513 000	0.001 740 3	0.008 813	1 641.9	2 418.4	1 670.6	893.4	2 563.9	3.777 7	5.211 2
357.06	630.21	18.000 000	0.001 839 7	0.007 489	1 698.9	2 374.3	1 732.0	777.1	2 509.1	3.871 5	5.104 4
360.00	633.15	18.651 000	0.001 892 5	0.006 945	1 725.2	2 351.5	1 760.5	720.5	2 481.0	3.914 7	5.052 6
365.81	638.96	20.000 000	0.002 036	0.005 834	1 785.6	2 293.0	1 826.3	583.4	2 409.7	4.013 9	4.926 9
370.00	643.15	21.030 000	0.002 213	0.004 925	1 844.0	2 228.5	1 890.5	441.6	2 332.1	4.110 6	4.797 1
373.80	646.95	22.000 000	0.002 742	0.003 568	1 961.9	2 087.1	2 022.2	143.4	2 165.6	4.311 0	4.532 7
374.136	647.286	22.090 000	0.003 155	0.003 155	2 029.6	2 029.6	2 099.3	0	2 099.3	4.429 8	4.429 8

From Bolz, R.E. and Tuve, G.L., Gases and vapors, in *CRC Handbook of Tables for Applied Engineering Science*, CRC Press, Boca Raton, FL, 1973, pp. 24–25. Originally condensed from Keenan, J.H., Keyes, F.G., Hill, P.G., and Moore, J.G., *Steam Tables: Thermodynamic Properties of Water Including Vapor, Liquid, and Solid Phases*, John Wiley & Sons, New York, 1969.

Viscosity and Thermal Conductivity of Steam and Water—SI Units

Symbols and Units

μ = dynamic viscosity. For N·s/m² (= kg/m·s) multiply tabulated values by 10^{-6}

ν = kinematic viscosity. For m²/s multiply tabulated values by 10^{-6}

k = thermal conductivity in MW/m·K

Temperature		Pressure								
		0.1 MN/m²			0.5 MN/m²			1.0 MN/m²		
C	*K*	μ	*ν*	*k*	μ	*ν*	*k*	μ	*ν*	*k*
0	273.15	1 750	1.75	569	1 750	1.75	569	1 750	1.75	570
50	323.15	544	0.551	643	544	0.551	644	544	0.550	644
100	373.15	12.11	20.54	24.8	279	0.291	681	279	0.291	681
150	423.15	14.15	27.39	28.7	181	0.198	687	181	0.198	687
200	473.15	16.18	35.14	33.2	16.02	6.81	33.8	15.85	0.327	35.1
250	523.15	18.22	48.83	38.2	18.14	8.61	38.6	18.06	0.420	39.3
300	573.15	20.25	53.44	43.4	20.23	10.57	43.8	20.22	0.522	44.4
350	623.15	22.3	64.02	49.0	—	—	49.4	—	—	49.9
400	673.15	24.3	75.40	54.9	24.4	15.06	55.3	24.4	7.48	55.7
450	723.15	26.4	88.0	61.1	26.4	17.5	61.4	26.5	0.88	61.8
500	773.15	28.4	101.3	67.4	28.4	20.2	67.7	28.5	0.101	68.2
550	823.15	30.4	115.4	73.9	30.5	23.1	74.3	30.5	0.115	74.7
600	873.15	32.5	130.9	80.6	32.5	26.1	80.9	32.6	0.131	81.4
650	923.15	34.5	146.9	87.4	34.5	29.3	87.7	34.6	0.147	88.2
700	973.15	36.5	163.9	94.3	36.6	32.8	94.6	36.6	0.164	95.0

Temperature		Pressure								
		5.0 MN/m²			10 MN/m²			20 MN/m²		
C	*K*	μ	*ν*	*k*	μ	*ν*	*k*	μ	*ν*	*k*
0	273.15	1 750	1.75	573	1 750	1.74	577	1 740	1.72	585
50	323.15	545	0.550	647	545	0.549	651	546	0.548	659
100	373.15	280	0.291	684	281	0.292	688	283	0.293	695
150	423.15	182	0.198	690	183	0.199	693	186	0.200	700
200	473.15	135	0.155	668	136	0.156	672	138	0.158	681
250	523.15	107	0.134	618	108	0.134	625	111	0.136	639
300	573.15	20.06	0.909	52.5	90.5	0.126	545	93	0.127	571
350	623.15	—	—	55.4	—	—	68.8	73.5	0.122	454
400	673.15	25.0	1.45	60.2	25.8	0.682	68.6	28.6	0.285	107
450	723.15	26.9	1.70	65.9	27.6	0.821	72.4	29.6	0.376	93
500	773.15	28.9	1.98	72.0	29.5	0.967	77.6	31.1	0.459	93
550	823.15	30.9	2.28	78.4	31.5	1.123	83.5	32.8	0.543	96
600	873.15	32.9	2.59	85.0	33.4	1.282	89.8	34.6	0.629	101
650	923.15	34.9	2.92	91.7	35.4	1.452	96	36.5	0.719	107
700	973.15	36.9	3.27	98.6	37.4	1.630	103	38.4	0.812	113

Temperature		Pressure								
		30 MN/m²			40 MN/m²			50 MN/m²		
C	*K*	μ	*ν*	*k*	μ	*ν*	*k*	μ	*ν*	*k*
0	273.15	1.740	1.71	592	1 730	1.70	599	1 720	1.68	606
50	323.15	547	0.547	666	548	0.545	672	549	0.544	678
100	373.15	285	0.293	701	287	0.294	707	289	0.295	713
150	423.15	188	0.201	706	190	0.203	713	192	0.204	720
200	473.15	140	0.159	689	143	0.161	697	145	0.162	704
250	523.15	113	0.137	652	116	0.139	662	118	0.140	671
300	573.15	95.5	0.127	592	98.1	0.128	609	101	0.130	622

Viscosity and Thermal Conductivity of Steam and Water—SI Units (continued)

350	623.15	78.5	0.122	496	82.5	0.122	529	85	0.123	522
400	673.15	45.8	0.128	264	62.8	0.120	390	28.6	0.120	436
450	723.15	33.1	0.223	138	41.1	0.152	220	29.6	0.130	301
500	773.15	33.4	0.290	116	36.9	0.208	153	31.1	0.164	206
550	823.15	34.6	0.352	112	36.9	0.258	134	32.8	0.205	163
600	873.15	36.1	0.413	114	37.9	0.307	130	34.6	0.245	149
650	923.15	37.7	0.475	118	39.2	0.355	132	36.5	0.286	147
700	973.15	39.5	0.540	124	40.8	0.406	135	38.4	0.327	148

From Bolz, R.E. and Tuve, G.L., Gases and vapors, in *CRC Handbook of Tables for Applied Engineering Science*, CRC Press, Boca Raton, FL, 1973, p 37. Originally adapted from Keenan, J.H., Keyes, F.G., Hill, P.G., and Moore, J.G., *Steam Tables: Thermodynamic Properties of Water Including Vapor, Liquid, and Solid Phases*, John Wiley & Sons, New York, 1969.

Properties of Gases

Gases and Vapors, Including Fuels and Refrigerants, English and Metric Units
The properties of pure gases are given at 25 deg C (77 deg F, 298 K) and atmospheric pressure (except as stated).

Common Name(s)	Acetylene (Ethyne)	Air [Mixture]	Ammonia, anhyd.	Argon
Chemical Formula	C_2H_2		NH_3	Ar
Refrigerant Number	—	729	717	740
Chemical and Physical Properties				
Molecular weight	26.04	28.966	17.02	39.948
Specific gravity, air = 1	0.90	1.00	0.59	1.38
Specific volume, ft^3/lb	14.9	13.5	23.0	9.80
Specific volume, m^3/kg	0.93	0.842	1.43	0.622
Density of liquid (at atm bp), lb/ft^3	43.0	54.6	42.6	87.0
Density of liquid (at atm bp), kg/m^3	693.	879.	686.	1 400.
Vapor pressure at 25 deg C, psia			145.4	
Vapor pressure at 25 deg C, MN/m^2			1.00	
Viscosity (abs), lbm/ft·sec	6.72×10^{-6}	12.1×10^{-6}	6.72×10^{-6}	13.4×10^{-6}
Viscosity (abs), centipoises[a]	0.01	0.018	0.010	0.02
Sound velocity in gas, m/sec	343	346	415	322
Thermal and Thermodynamic Properties				
Specific heat, c_p, Btu/b·deg F or cal/g·degC	0.40	0 240.3	0.52	0.125
Specific heat, c_p, J/kg·K	1 674.	1 005.	2 175.	523.
Specific heat ratio, c_p/c_{pv}	1.25	1.40	1.3	1.67
Gas constant R, ft-lb/lb·deg F	59.3	53.3	90.8	38.7
Gas constant R, J/kg·deg C	319	286.8	488.	208.
Thermal conductivity, Btu/hr·ft·deg F	0.014	0.0151	0.015	0.010 2
Thermal conductivity, W/m·deg C	0.024	0.026	0.026	0.017 2
Boiling point (sat 14.7 psia), deg F	–103	–320	–28.	–303.
Boiling point (sat 760 mm), deg C	–75	–195	–33.3	–186
Latent heat of evap (at bp), Btu/lb	264	88.2	589.3	70.
Latent heat of evap (at bp), J/kg	614 000	205 000	1 373 000	163 000
Freezing (melting) point, deg F (1 atm)	–116	–357.2	–107.9	–308.5
Freezing (melting) point, deg C (1 atm)	–82.2	–216.2	–77.7	–189.2
Latent heat of fusion, Btu/lb	23.	10.0	143.0	
Latent heat of fusion, J/kg	53 500	23 200	332 300	
Critical temperature, deg F	97.1	–220.5	271.4	–187.6
Critical temperature, deg C	36.2	–140.3	132.5	–122
Critical pressure, psia	907.	550.	1 650.	707.

Properties of Gases (continued)

Critical pressure, MN/m²	6.25	3.8	11.4	4.87
Critical volume, ft³/lb		0.050	0.068	0.029 9
Critical volume, m³/kg		0.003	0.004 24	0.001 86
Flammable (yes or no)	Yes	No	No	No
Heat of combustion, Btu/ft³	1 450	—	—	—
Heat of combustion, Btu/lb	21 600	—	—	—
Heat of combustion, kJ/kg	50 200	—	—	—

[a] For N·sec/m² divide by 1 000.

Common Name(s)	Butadiene	*n*-Butane	Isobutane (2-Methylpropane)	l-Butene (Butylene)
Chemical Formula	C_4H_6	C_4H_{10}	C_4H_{10}	C_4H_8
Refrigerant Number	—	600	600a	—
Chemical and Physical Properties				
Molecular weight	54.09	58.12	58.12	56.108
Specific gravity, air = 1	1.87	2.07	2.07	1.94
Specific volume, ft³/lb	7.1	6.5	6.5	6.7
Specific volume, m³/kg	0.44	0.405	0.418	0.42
Density of liquid (at atm bp), lb/ft³		37.5	37.2	
Density of liquid (at atm bp), kg/m³		604.	599.	
Vapor pressure at 25 deg C, psia		35.4	50.4	
Vapor pressure at 25 deg C, MN/m²		0.024 4	0.347	
Viscosity (abs), lbm/ft·sec		4.8×10^{-6}		
Viscosity (abs), centipoises[a]		0.007		
Sound velocity in gas, m/sec	226	216	216	222
Thermal and Thermodynamic Properties				
Specific heat, c_p, Btu/b·deg F or cal/g·degC	0.341	0.39	0.39	0.36
Specific heat, c_p, J/kg·K	1 427.	1 675.	1 630.	1 505.
Specific heat ratio, c_p/c_{pv}	1.12	1.096	1.10	1.112
Gas constant *R*, ft-lb/lb·deg F	28.55	26.56	26.56	27.52
Gas constant *R*, J/kg·deg C	154.	143.	143.	148.
Thermal conductivity, Btu/hr·ft·deg F		0.01	0.01	
Thermal conductivity, W/m·deg C		0.017	0.017	
Boiling point (sat 14.7 psia), deg F	24.1	31.2	10.8	20.6
Boiling point (sat 760 mm), deg C	–4.5	–0.4	–11.8	–6.3
Latent heat of evap (at bp), Btu/lb		165.6	157.5	167.9
Latent heat of evap (at bp), J/kg		386 000	366 000	391 000
Freezing (melting) point, deg F (1 atm)	–164	–217.	–229	–301 6
Freezing (melting) point, deg C (1 atm)	–109.	–138.	–145	–185.3
Latent heat of fusion, Btu/lb		19.2		16.4
Latent heat of fusion, J/kg		44 700		38 100
Critical temperature, deg F		306	273.	–291.
Critical temperature, deg C	171.	152.	134.	144.
Critical pressure, psia	652.	550.	537.	621.
Critical pressure, MN/m²		3.8	3.7	4.28
Critical volume, ft³/lb		0.070		0.068
Critical volume, m³/kg		0.004 3		0.004 2
Flammable (yes or no)	Yes	Yes	Yes	Yes
Heat of combustion, Btu/ft³	2 950	3 300	3 300	3 150
Heat of combustion, Btu/lb	20 900	21 400	21 400	21 000
Heat of combustion, kJ/kg	48 600	49 700	49 700	48 800

[a] For N·sec/m² divide by 1 000.

Properties of Gases (continued)

Common Name(s)	cis-2-Butene	trans-2-Butene	Isobutene	Carbon Dioxide CO_2
Chemical Formula	C_4H_8	C_4H_8	C_4H_8	CO_2
Refrigerant Number	—	—	—	744
Chemical and Physical Properties				
Molecular weight	56.108	56.108	56.108	44.01
Specific gravity, air = 1	1.94	1.94	1.94	1.52
Specific volume, ft^3/lb	6.7	6.7	6.7	8.8
Specific volume, m^3/kg	0.42	0.42	0.42	0.55
Density of liquid (at atm bp), lb/ft^3				—
Density of liquid (at atm bp), kg/m^3				—
Vapor pressure at 25 deg C, psia				931.
Vapor pressure at 25 deg C, MN/m^2				6.42
Viscosity (abs), lbm/ft·sec				9.4×10^{-6}
Viscosity (abs), centipoises[a]				0.014
Sound velocity in gas, m/sec	223.	221.	221.	270.
Thermal and Thermodynamic Properties				
Specific heat, c_p, Btu/b·deg F or cal/g·degC	0.327	0.365	0.37	0.205
Specific heat, c_p, J/kg·K	1 368.	1 527.	1 548.	876.
Specific heat ratio, c_p/c_{pv}	1.121	1.107	1.10	1.30
Gas constant R, ft-lb/lb·deg F				35.1
Gas constant R, J/kg·deg C				189.
Thermal conductivity, Btu/hr·ft·deg F				0.01
Thermal conductivity, W/m·deg C				0.017
Boiling point (sat 14.7 psia), deg F	38.6	33.6	19.2	–109.4[b]
Boiling point (sat 760 mm), deg C	3.7	0.9	–7.1	–78.5
Latent heat of evap (at bp), Btu/lb	178.9	174.4	169.	246.
Latent heat of evap (at bp), J/kg	416 000.	406 000.	393 000.	572 000.
Freezing (melting) point, deg F (1 atm)	–218.	–158.		
Freezing (melting) point, deg C (1 atm)	–138.9	–105.5		
Latent heat of fusion, Btu/lb	31.2	41.6	25.3	—
Latent heat of fusion, J/kg	72 600.	96 800.	58 800.	—
Critical temperature, deg F				88.
Critical temperature, deg C	160.	155.		31.
Critical pressure, psia	595.	610.		1 072.
Critical pressure, MN/m^2	4.10	4.20		7.4
Critical volume, ft^3/lb				
Critical volume, m^3/kg				
Flammable (yes or no)	Yes	Yes	Yes	No
Heat of combustion, Btu/ft^3	3 150.	3 150.	3 150.	—
Heat of combustion, Btu/lb	21 000.	21 000.	21 000.	—
Heat of combustion, kJ/kg	48 800.	48 800.	48 800.	—

[a] For $N{\cdot}sec/m^2$ divide by 1 000.
[b] Sublimes.

Common Name(s)	Carbon Monoxide	Chlorine	Deuterium	Ethane
Chemical Formula	CO	Cl_2	D_2	C_2H_6
Refrigerant Number	—	—	—	170
Chemical and Physical Properties				
Molecular weight	28.011	70.906	2.014	30.070
Specific gravity, air = 1	0.967	2.45	0.070	1.04
Specific volume, ft^3/lb	14.0	5.52	194.5	13.025
Specific volume, m^3/kg	0.874	0.344	12.12	0.815
Density of liquid (at atm bp), lb/ft^3		97.3		28.
Density of liquid (at atm bp), kg/m^3		1 559.		449.

Properties of Gases (continued)

Vapor pressure at 25 deg C, psia			0.756	
Vapor pressure at 25 deg C, MN/m^2			0.005 2	
Viscosity (abs), lbm/ft·sec	12.1 × 10^{-6}	9.4 × 10^{-6}	8.75 × 10^{-6}	64. × 10^{-6}
Viscosity (abs), centipoises[a]	0.018	0.014	0.013	0.095
Sound velocity in gas, m/sec	352.	215.	930.	316.
Thermal and Thermodynamic Properties				
Specific heat, c_p, Btu/b·deg F or cal/g·degC	0.25	0.114	1.73	0.41
Specific heat, c_p, J/kg·K	1 046.	477.	7 238.	1 715.
Specific heat ratio, c_p/c_{pv}	1.40	1.35	1.40	1.20
Gas constant R, ft-lb/lb·deg F	55.2	21.8	384.	51.4
Gas constant R, J/kg·deg C	297.	117.	2 066.	276.
Thermal conductivity, Btu/hr·ft·deg F	0.014	0.005	0.081	0.010
Thermal conductivity, W/m·deg C	0.024	0.008 7	0.140	0.017
Boiling point (sat 14.7 psia), deg F	–312.7	–29.2		–127.
Boiling point (sat 760 mm), deg C	–191.5	–34.	—	–88.3
Latent heat of evap (at bp), Btu/lb	92.8	123.7		210.
Latent heat of evap (at bp), J/kg	216 000.	288 000.		488 000.
Freezing (melting) point, deg F (1 atm)	–337.	–150.		–278.
Freezing (melting) point, deg C (1 atm)	–205.	–101.		–172.2
Latent heat of fusion, Btu/lb	12.8	41.0		41.
Latent heat of fusion, J/kg		95 400.		95 300.
Critical temperature, deg F	–220.	291.	–390.6	90.1
Critical temperature, deg C	–140.	144.	–234.8	32.2
Critical pressure, psia	507.	1 120.	241.	709.
Critical pressure, MN/m^2	3.49	7.72	1.66	4.89
Critical volume, ft^3/lb	0.053	0.028	0.239	0.076
Critical volume, m^3/kg	0.003 3	0.001 75	0.014 9	0.004 7
Flammable (yes or no)	Yes	No		Yes
Heat of combustion, Btu/ft^3	310.	—		
Heat of combustion, Btu/lb	4 340.	—		22 300.
Heat of combustion, kJ/kg	10 100.	—		51 800.

[a] For N·sec/m^2 divide by 1 000.

Common Name(s)	Ethyl Chloride	Ethylene (Ethene)	Fluorine
Chemical Formula	C_2H_5Cl	C_2H_4	F_2
Refrigerant Number	160	1150	—
Chemical and Physical Properties			
Molecular weight	64.515	28.054	37.996
Specific gravity, air = 1	2.23	0.969	1.31
Specific volume, ft^3/lb	6.07	13.9	10.31
Specific volume, m^3/kg	0.378	0.87	0.706
Density of liquid (at atm bp), lb/ft^3	56.5	35.5	
Density of liquid (at atm bp), kg/m^3	905.	569.	
Vapor pressure at 25 deg C, psia			
Vapor pressure at 25 deg C, MN/m^2			
Viscosity (abs), lbm/ft·sec		6.72 × 10^{-6}	16.1 × 10^{-6}
Viscosity (abs), centipoises[a]		0.010	0.024
Sound velocity in gas, m/sec	204.	331.	290.
Thermal and Thermodynamic Properties			
Specific heat, c_p, Btu/b·deg F or cal/g·degC	0.27	0.37	0.198
Specific heat, c_p, J/kg·K	1 130.	1 548.	828.
Specific heat ratio, c_p/c_p	1.13	1.24	1.35
Gas constant R, ft-lb/lb·deg F	24.0	55.1	40.7
Gas constant R, J/kg·deg C	129.	296.	219.

Properties of Gases (continued)

Thermal conductivity, Btu/hr·ft·deg F		0.010	0.016
Thermal conductivity, W/m·deg C		0.017	0.028
Boiling point (sat 14.7 psia), deg F	54.	–155.	–306.4
Boiling point (sat 760 mm), deg C	12.2	–103.8	–188.
Latent heat of evap (at bp), Btu/lb	166.	208.	74.
Latent heat of evap (at bp), J/kg	386 000.	484 000.	172 000.
Freezing (melting) point, deg F (1 atm)	–218.	–272.	–364.
Freezing (melting) point, deg C (1 atm)	–138.9	–169.	–220.
Latent heat of fusion, Btu/lb	29.3	51.5	11.
Latent heat of fusion, J/kg	68 100.	120 000.	25 600.
Critical temperature, deg F	368.6	49.	–200
Critical temperature, deg C	187.	9.5	–129.
Critical pressure, psia	764.	741.	810.
Critical pressure, MN/m^2	5.27	5.11	5.58
Critical volume, ft^3/lb	0.049	0.073	
Critical volume, m^3/kg	0.003 06	0.004 6	
Flammable (yes or no)	No	Yes	
Heat of combustion, Btu/ft^3	—	1 480.	
Heat of combustion, Btu/lb	—	20 600.	
Heat of combustion, kJ/kg	—	47 800.	

[a] For $N·sec/m^2$ divide by 1 000.

Common Name(s)	Fluorocarbons			
Chemical Formula	CCl_3F	CCl_2F_2	$CClF_3$	$CBrF_3$
Refrigerant Number	11	12	13	13B1
Chemical and Physical Properties				
Molecular weight	137.37	120.91	104.46	148.91
Specific gravity, air = 1	4.74	4.17	3.61	5.14
Specific volume, ft^3/lb	2.74	3.12	3.58	2.50
Specific volume, m^3/kg	0.171	0.195	0.224	0.975
Density of liquid (at atm bp), lb/ft^3	92.1	93.0	95.0	124.4
Density of liquid (at atm bp), kg/m^3	1 475.	1 490.	1 522.	1 993.
Vapor pressure at 25 deg C, psia		94.51	516.	234.8
Vapor pressure at 25 deg C, MN/m^2		0.652	3.56	1.619
Viscosity (abs), lbm/ft·sec	7.39×10^{-6}	8.74×10^{-6}		
Viscosity (abs), centipoises[a]	0.011	0.013		
Sound velocity in gas, m/sec				
Thermal and Thermodynamic Properties				
Specific heat, c_p, Btu/b·deg F or cal/g·degC	0.14	0.146	0.154	
Specific heat, c_p, J/kg·K	586.	611.	644.	
Specific heat ratio, c_p/c_{pv}	1.14	1.14	1.145	
Gas constant R, ft-lb/lb·deg F				
Gas constant R, J/kg·deg C				
Thermal conductivity, Btu/hr·ft·deg F	0.005	0.006		
Thermal conductivity, W/m·deg C	0.008 7	0.010 4		
Boiling point (sat 14.7 psia), deg F	74.9	–21.8	–114.6	–72
Boiling point (sat 760 mm), deg C	23.8	–29.9	–81.4	–57.8
Latent heat of evap (at bp), Btu/lb	77.5	71.1	63.0	51.1
Latent heat of evap (at bp), J/kg	180 000.	165 000.	147 000.	119 000.
Freezing (melting) point, deg F (1 atm)	–168.	–252.	–294.	–270.
Freezing (melting) point, deg C (1 atm)	–111.	–157.8	–181.1	–167.8
Latent heat of fusion, Btu/lb				
Latent heat of fusion, J/kg				

Properties of Gases (continued)

Critical temperature, deg F	388.4	233.	83.9	152.
Critical temperature, deg C	198.	111.7	28.8	66.7
Critical pressure, psia	635.	582.	559.	573.
Critical pressure, MN/m^2	4.38	4.01	3.85	3.95
Critical volume, ft^3/lb	0.028 9	0.287	0.027 7	0.021 5
Critical volume, m^3/kg	0.001 80	0.018	0.001 73	0.001 34
Flammable (yes or no)	No	No	No	No
Heat of combustion, Btu/ft^3	—	—	—	—
Heat of combustion, Btu/lb	—	—	—	—
Heat of combustion, kJ/kg	—	—	—	—

[a] For $N \cdot sec/m^2$ divide by 1 000.

Common Name(s)	Fluorocarbons			
Chemical Formula	CF_4	$CHCl_2F$	$CHClF_2$	$C_2Cl_2F_4$
Refrigerant Number	14	21	22	114
Chemical and Physical Properties				
Molecular weight	88.00	102.92	86.468	170.92
Specific gravity, air = 1	3.04	3.55	2.99	5.90
Specific volume, ft^3/lb	4.34	3.7	4.35	2.6
Specific volume, m^3/kg	0.271	0.231	0.271	0.162
Density of liquid (at atm bp), lb/ft^3	102.0	87.7	88.2	94.8
Density of liquid (at atm bp), kg/m^3	1 634.	1 405.	1 413.	1 519.
Vapor pressure at 25 deg C, psia		26.4	151.4	30.9
Vapor pressure at 25 deg C, MN/m^2		0.182	1.044	0.213
Viscosity (abs), lbm/ft·sec		8.06×10^{-6}	8.74×10^{-6}	8.06×10^{-6}
Viscosity (abs), centipoises[a]		0.012	0.013	0.012
Sound velocity in gas, m/sec				
Thermal and Thermodynamic Properties				
Specific heat, c_p, Btu/b·deg F or cal/g·degC		0.139	0.157	0.158
Specific heat, c_p, J/kg·K		582.	657.	661.
Specific heat ratio, c_p/c_{pv}		1.18	1.185	1.09
Gas constant R, ft-lb/lb·deg F				
Gas constant R, J/kg·deg C				
Thermal conductivity, Btu/hr·ft·deg F			0.007	0.006
Thermal conductivity, W/m·deg C			0.012	0.010
Boiling point (sat 14.7 psia), deg F	–198.2	48.1	–41.3	38.4
Boiling point (sat 760 mm), deg C	–127.9	9.0	–40.7	3.55
Latent heat of evap (at bp), Btu/lb	58.5	104.1	100.4	58.4
Latent heat of evap (at bp), J/kg	136 000.	242 000.	234 000.	136 000.
Freezing (melting) point, deg F (1 atm)	–299.	–211.	–256.	–137.
Freezing (melting) point, deg C (1 atm)	–183.8	–135.	–160.	–93.8
Latent heat of fusion, Btu/lb	2.53			
Latent heat of fusion, J/kg	5 880			
Critical temperature, deg F	–49.9	353.3	204.8	294.
Critical temperature, deg C	–45.5	178.5	96.5	
Critical pressure, psia	610.	750.	715.	475.
Critical pressure, MN/m^2	4.21	5.17	4.93	3.28
Critical volume, ft^3/lb	0.025	0.030 7	0.030 5	0.027 5
Critical volume, m^3/kg	0.001 6	0.001 91	0.001 90	0.001 71
Flammable (yes or no)	No	No	No	No
Heat of combustion, Btu/ft^3	—	—	—	—
Heat of combustion, Btu/lb	—	—	—	—
Heat of combustion, kJ/kg	—	—	—	—

[a] For $N \cdot sec/m^2$ divide by 1 000.

Properties of Gases (continued)

Common Name(s)	Fluorocarbons			Helium
Chemical Formula	C_2ClF_5	$C_2H_3ClF_2$	$C_2H_4F_2$	He
Refrigerant Number	115	142b	152a	704
Chemical and Physical Properties				
Molecular weight	154.47	100.50	66.05	4.002 6
Specific gravity, air = 1	5.33	3.47	2.28	0.138
Specific volume, ft³/lb	2.44	3.7	5.9	97.86
Specific volume, m³/kg	0.152	0.231	0.368	6.11
Density of liquid (at atm bp), lb/ft³	96.5	74.6	62.8	7.80
Density of liquid (at atm bp), kg/m³	1 546.	1 195.	1 006.	125.
Vapor pressure at 25 deg C, psia	132.1	49.1	86.8	
Vapor pressure at 25 deg C, MN/m²	0.911	0.338 5	0.596	
Viscosity (abs), lbm/ft·sec				13.4×10^{-6}
Viscosity (abs), centipoises[a]				0.02
Sound velocity in gas, m/sec				1 015.
Thermal and Thermodynamic Properties				
Specific heat, c_p, Btu/b·deg F or cal/g·degC	0.161			1.24
Specific heat, c_p, J/kg·K	674.			5 188.
Specific heat ratio, c_p/c_{pv}	1.091			1.66
Gas constant R, ft-lb/lb·deg F				386.
Gas constant R, J/kg·deg C				2 077.
Thermal conductivity, Btu/hr·ft·deg F				0.086
Thermal conductivity, W/m·deg C				0.149
Boiling point (sat 14.7 psia), deg F	–38.0	14.	–13.	–452.
Boiling point (sat 760 mm), deg C	–38.9	–10.0	–25.0	4.22 K
Latent heat of evap (at bp), Btu/lb	53.4	92.5	137.1	10.0
Latent heat of evap (at bp), J/kg	124 000.	215 000.	319 000.	23 300.
Freezing (melting) point, deg F (1 atm)	–149.			[b]
Freezing (melting) point, deg C (1 atm)	–100.6			—
Latent heat of fusion, Btu/lb				
Latent heat of fusion, J/kg				
Critical temperature, deg F	176.		387.	–450.3
Critical temperature, deg C				5.2 K
Critical pressure, psia	457.6			33.22
Critical pressure, MN/m²	3.155			
Critical volume, ft³/lb	0.026 1			0.231
Critical volume, m³/kg	0.001 63			0.014 4
Flammable (yes or no)	No	No	No	No
Heat of combustion, Btu/ft³	—	—	—	—
Heat of combustion, Btu/lb	—	—	—	—
Heat of combustion, kJ/kg	—	—	—	—

[a] For N·sec/m² divide by 1 000.
[b] Helium cannot be solidified at atmospheric pressure.

Common Name(s)	Hydrogen	Hydrogen Chloride	Hydrogen Sulfide	Krypton
Chemical Formula	H_2	HCl	H_2S	Kr
Refrigerant Number	702	—	—	—
Chemical and Physical Properties				
Molecular weight	2.016	36.461	34.076	83.80
Specific gravity, air = 1	0.070	1.26	1.18	2.89
Specific volume, ft³/lb	194.	10.74	11.5	4.67
Specific volume, m³/kg	12.1	0.670	0.093 0	0.291
Density of liquid (at atm bp), lb/ft³	4.43	74.4	62.	150.6
Density of liquid (at atm bp), kg/m³	71.0	1 192.	993.	2 413.

Properties of Gases (continued)

Vapor pressure at 25 deg C, psia				
Vapor pressure at 25 deg C, MN/m^2				
Viscosity (abs), lbm/ft Viscosity (abs), lbm/ft× 10^{-6}	6.05×10^{-6}	10.1×10^{-6}	8.74×10^{-6}	16.8×10^{-6}
Viscosity (abs), centipoises[a]	0.009	0.015	0.013	0.025
Sound velocity in gas, m/sec	1 315.	310.	302.	223.
Thermal and Thermodynamic Properties				
Specific heat, c_p, Btu/b·deg F or cal/g·degC	3.42	0.194	0.23	0.059
Specific heat, c_p, J/kg·K	14 310.	812.	962.	247.
Specific heat ratio, c_p/c_{pv}	1.405	1.39	1.33	1.68
Gas constant R, ft-lb/lb·deg F	767.	42.4	45.3	18.4
Gas constant R, J/kg·deg C	4 126.	228.	244.	99.0
Thermal conductivity, Btu/hr·ft·deg F	0.105	0.008	0.008	0.005 4
Thermal conductivity, W/m·deg C	0.018 2	0.014	0.014	0.009 3
Boiling point (sat 14.7 psia), deg F	–423.	–121.	–76.	–244.
Boiling point (sat 760 mm), deg C	20.4 K	–85.	–60.	–153.
Latent heat of evap (at bp), Btu/lb	192.	190.5	234.	46.4
Latent heat of evap (at bp), J/kg	447 000.	443 000.	544 000.	108 000.
Freezing (melting) point, deg F (1 atm)	–434.6	–169.6	–119.2	–272.
Freezing (melting) point, deg C (1 atm)	–259.1	–112.	–84.	–169.
Latent heat of fusion, Btu/lb	25.0	23.4	30.2	4.7
Latent heat of fusion, J/kg	58 000.	54 400.	70 200.	10 900.
Critical temperature, deg F	–399.8	124.	213.	
Critical temperature, deg C	–240.0	51.2	100.4	–63.8
Critical pressure, psia	189.	1 201.	1 309.	800.
Critical pressure, MN/m^2	1.30	8.28	9.02	5.52
Critical volume, ft^3/lb	0.53	0.038	0.046	0.017 7
Critical volume, m^3/kg	0.033	0.002 4	0.002 9	0.001 1
Flammable (yes or no)	Yes	No	Yes	No
Heat of combustion, Btu/ft^3	320.	—	700.	—
Heat of combustion, Btu/lb	62 050.	—	8 000.	—
Heat of combustion, kJ/kg	144 000.	—	18 600.	—

[a] For $N{\cdot}sec/m^2$ divide by 1 000.

Common Name(s)	Methane	Methyl Chloride	Neon	Nitric Oxcide
Chemical Formula	CH_4	CH_3Cl	NE	NO
Refrigerant Number	50	40	720	—
Chemical and Physical Properties				
Molecular weight	16,044	50,488	20.179	30.006
Specific gravity, air = 1	0.554	1.74	0.697	1.04
Specific volume, ft^3/lb	24.2	7.4	19.41	13.05
Specific volume, m^3/kg	1.51	0.462	1.211	0.814
Density of liquid (at atm bp), lb/ft^3	26.3	62.7	75.35	
Density of liquid (at atm bp), kg/m^3	421.	1 004.	1 207.	
Vapor pressure at 25 deg C, psia		82.2		
Vapor pressure at 25 deg C, MN/m^2		0.567		
Viscosity (abs), lbm/ft·sec	7.39×10^{-6}	7.39×10^{-6}	21.5×10^{-6}	12.8×10^{-6}
Viscosity (abs), centipoises[a]	0.011	0.011	0.032	0.019
Sound velocity in gas, m/sec	446.	251.	454.	341.
Thermal and Thermodynamic Properties				
Specific heat, c_p, Btu/b·deg F or cal/g·degC	0.54	0.20	0.246	0.235
Specific heat, c_p, J/kg·K	2 260.	837.	1 030.	983.
Specific heat ratio, c_p/c_{pv}	1.31	1.28	1.64	1.40
Gas constant R, ft-lb/lb·deg F	96.	30.6	76.6	51.5
Gas constant R, J/kg·deg C	518.	165.	412.	277.

Properties of Gases (continued)

Thermal conductivity, Btu/hr·ft·deg F	0.02	0.006	0.028	0.015
Thermal conductivity, W/m·deg C	0.035	0.010	0.048	0.026
Boiling point (sat 14.7 psia), deg F	–259.	–10.7	–410.9	–240.
Boiling point (sat 760 mm), deg C	–434.2	–23.7	–246.	–151.5
Latent heat of evap (at bp), Btu/lb	219.2	184.1	37.	
Latent heat of evap (at bp), J/kg	510 000.	428 000.	86 100.	
Freezing (melting) point, deg F (1 atm)	–296.6	–144.	–415.6	–258.
Freezing (melting) point, deg C (1 atm)	–182.6	–97.8	–248.7	–161.
Latent heat of fusion, Btu/lb	14.	56.	6.8	32.9
Latent heat of fusion, J/kg	32 600.	130 000.	15 800.	76 500.
Critical temperature, deg F	–116.	289.4	–379.8	–136.
Critical temperature, deg C	–82.3	143.	–228.8	–93.3
Critical pressure, psia	673.	968.	396.	945.
Critical pressure, MN/m^2	4.64	6.67	2.73	6.52
Critical volume, ft^3/lb	0.099	0.043	0.033	0.033 2
Critical volume, m^3/kg	0.006 2	0.002 7	0.002 0	0.002 07
Flammable (yes or no)	Yes	Yes	No	No
Heat of combustion, Btu/ft^3	985.		—	—
Heat of combustion, Btu/lb	2 290.		—	—
Heat of combustion, kJ/kg				—

[a] For N·sec/m^2 divide by 1 000.

Common Name(s)	Nitrogen	Nitrous Oxide	Oxygen	Ozone
Chemical Formula	N_2	N_2O	O_2	O_3
Refrigerant Number	728	744A	732	—
Chemical and Physical Properties				
Molecular weight	28.013 4	44.012	31.998 8	47.998
Specific gravity, air = 1	0.967	1.52	1.105	1.66
Specific volume, ft^3/lb	13.98	8.90	12.24	8.16
Specific volume, m^3/kg	0.872	0.555	0.764	0.509
Density of liquid (at atm bp), lb/ft^3	50.46	76.6	71.27	
Density of liquid (at atm bp), kg/m^3	808.4	1 227.	1 142.	
Vapor pressure at 25 deg C, psia				
Vapor pressure at 25 deg C, MN/m^2				
Viscosity (abs), lbm/ft·sec	12.1×10^{-6}	10.1×10^{-6}	13.4×10^{-6}	8.74×10^{-6}
Viscosity (abs), centipoises[a]	0.018	0.015	0.020	0.013
Sound velocity in gas, m/sec	353.	268.	329.	
Thermal and Thermodynamic Properties				
Specific heat, c_p, Btu/b·deg F or cal/g·degC	0.249	0.21	0.220	0.196
Specific heat, c_p, J/kg·K	1040.	879.	920.	820.
Specific heat ratio, c_p/c_{pv}	1.40	1.31	1.40	
Gas constant R, ft-lb/lb·deg F	55.2	35.1	48.3	32.2
Gas constant R, J/kg·deg C	297.	189.	260.	173.
Thermal conductivity, Btu/hr·ft·deg F	0.015	0.010	0.015	0.019
Thermal conductivity, W/m·deg C	0.026	0.017	0.026	0.033
Boiling point (sat 14.7 psia), deg F	–320.4	–127.3	–297.3	–170.
Boiling point (sat 760 mm), deg C	–195.8	–88.5	–182.97	–112.
Latent heat of evap (at bp), Btu/lb	85.5	161.8	91.7	
Latent heat of evap (at bp), J/kg	199 000.	376 000.	213 000.	
Freezing (melting) point, deg F (1 atm)	–346.	–131.5	361.1	–315.5
Freezing (melting) point, deg C (1 atm)	–210.	–90.8	–218.4	–193.
Latent heat of fusion, Btu/lb	11.1	63.9	5.9	97.2
Latent heat of fusion, J/kg	25 800.	149 000.	13 700.	226 000.
Critical temperature, deg F	–232.6	97.7	–181.5	16.
Critical temperature, deg C	–147.	36.5	–118.6	–9.

Properties of Gases (continued)

Critical pressure, psia	493.	1 052.	726.	800.
Critical pressure, MN/m²	3.40	7.25	5.01	5.52
Critical volume, ft³/lb	0.051	0.036	0.040	0.029 8
Critical volume, m³/kg	0.003 18	0.002 2	0.002 5	0.001 86
Flammable (yes or no)	No	No	No	No
Heat of combustion, Btu/ft³	—	—	—	—
Heat of combustion, Btu/lb	—	—	—	—
Heat of combustion, kJ/kg	—	—	—	—

[a] For N·sec/m² divide by 1 000.

Common Name(s)	Propane	Propylene (Propene)	Sulfur Dioxide	Xenon
Chemical Formula	C_3H_8	C_3H_6	SO_2	Xe
Refrigerant Number	290	1 270	764	—
Chemical and Physical Properties				
Molecular weight	44.097	42.08	64.06	131.30
Specific gravity, air = 1	1.52	1.45	2.21	4.53
Specific volume, ft³/lb	8.84	9.3	6.11	2.98
Specific volume, m³/kg	0.552	0.58		
Density of liquid (at atm bp), lb/ft³	36.2	37.5	42.8	190.8
Density of liquid (at atm bp), kg/m³	580.	601.	585.	3 060.
Vapor pressure at 25 deg C, psia	135.7	166.4	56.6	
Vapor pressure at 25 deg C, MN/m²	0.936	1.147	0.390	
Viscosity (abs), lbm/ft·sec	53.8×10^{-6}	57.1×10^{-6}	8.74×10^{-6}	15.5×10^{-6}
Viscosity (abs), centipoises[a]	0.080	0.085	0.013	0.023
Sound velocity in gas, m/sec	253.	261.	220.	177.
Thermal and Thermodynamic Properties				
Specific heat, c_p, Btu/b·deg F or cal/g·degC	0.39	0.36	0.11	0.115
Specific heat, c_p, J/kg·K	1 630.	1 506.	460.	481.
Specific heat ratio, c_p/c_{pv}	1.2	1.16	1.29	1.67
Gas constant R, ft-lb/lb·deg F	35.0	36.7	24.1	11.8
Gas constant R, J/kg·deg C	188.	197.	130.	63.5
Thermal conductivity, Btu/hr·ft·deg F	0.010	0.010	0.006	0.003
Thermal conductivity, W/m·deg C	0.017	0.017	0.010	0.005 2
Boiling point (sat 14.7 psia), deg F	–44.	–54.	14.0	–162.5
Boiling point (sat 760 mm), deg C	–42.2	–48.3	–10.	–108.
Latent heat of evap (at bp), Btu/lb	184.	188.2	155.5	41.4
Latent heat of evap (at bp), J/kg	428 000.	438 000.	362 000.	96 000.
Freezing (melting) point, deg F (1 atm)	–309.8	–301.	–104.	–220.
Freezing (melting) point, deg C (1 atm)	–189.9	–185.	–75.5	–140.
Latent heat of fusion, Btu/lb	19.1		58.0	10.
Latent heat of fusion, J/kg	44 400.		135 000.	23 300.
Critical temperature, deg F	205.	197.	315.5	61.9
Critical temperature, deg C	96.	91.7	157.6	16.6
Critical pressure, psia	618.	668.	1 141.	852.
Critical pressure, MN/m²	4.26	4.61	7.87	5.87
Critical volume, ft³/lb	0.073	0.069	0.03	0.014 5
Critical volume, m³/kg	0.004 5	0.004 3	0.001 9	0.000 90
Flammable (yes or no)	Yes	Yes		Yes
Heat of combustion, Btu/ft³	2 450.	2 310.	—	—
Heat of combustion, Btu/lb	21 660.	21 500.	—	—
Heat of combustion, kJ/kg	50 340.	50 000.	—	—

[a] For N·sec/m² divide by 1 000.

From Bolz, R.E. and Tuve, G.L., Gases and vapors, in *CRC Handbook of Tables for Applied Engineering Science*, CRC Press, Boca Raton, FL, 1973, pp. 38–49.

Typical Composition, Properties, and Uses of Common Materials

For MN/m² multiply strength in thousands of psi by 6.895.

FERROUS ALLOYS

Ferrous alloys comprise the largest volume of metal alloys used in engineering. The actual range of mechanical properties in any particular grade of alloy steel depends on the particular history and heat treatment. The steels listed in this table are intended to give some idea of the range of properties readily obtainable. Many hundreds of steels are available. Cost is frequently an important criterion in the choice of material; in general the greater the percentage of alloying elements present in the alloy, the greater will be the cost.

No.	Material	Nominal Composition				Form and Condition	Typical Mechanical Properties: Yield Strength (0.2% offset), 1000 lb/sq in.	Tensile Strength 1000 lb/sq in.	Elongation in 2 in., %	Harness, Brinell	Comments
	Iron										
1	Ingot iron (Included for comparison)	Fe	99.9			Hot-rolled	29	45	26	90	
						Annealed	19	38	45	67	
	Plain Carbon Steels										
2	AISI-SAE 1020	C	0.20	Mn	0.45	Hot-rolled	30	55	25	111	Bolts, crankshafts,
		Si	0.25	Fe bal.		Hardened (water-quenched, 1000˚F-tempered)	62	90	25	179	gears, connecting rods; easily weldable
3	AISI 1025	C	0.25	Fe bal.		Bar stock					
		Mn	0.45			Hot-rolled	32	58	25	116	
						Cold-drawn	54	64	15	126	
4	AISI-SAE 1035	C	0.35	Mn	0.75	Hot-rolled	39	72	18	143	Medium-strength,
						Cold-rolled	67	80	12	163	engineering steel
5	AISI-SAE 1045	C	0.45	Fe bal.		Bar stock					
		Mn	0.75			Annealed	73	80	12	170	
						Hot-rolled	45	82	16	163	
						Cold-drawn	77	91	12	179	
6	AISI-SAE 1078	C	0.78	Fe bal.		Bar stock					
		Mn	0.45			Hot-rolled; spheroidized	55	100	12	207	
						Annealed	72	94	10	192	
7	AISI-SAE 1095	C	0.95	Fe bal.							
		Mn	0.40								

8	AISI-SAE 1120	C	0.2	Mn	0.8	Cold-drawn	58	69	—	137	Free-cutting, leaded,
		S	0.1								resulphurized steel;
											high-speed, automatic
											machining
	Alloy Steels										
9	ASTM A202/56	C	0.17	Mn	1.2	Stress-relieved	45	75	18	—	Low alloy; boilers,
		Cr	0.5	Si	0.75						pressure vessels
10	AISI 4140	C	0.40	Si	0.3	Fully-tempered	95	108	22	240	High strength; gears,
		Cr	1.0	Mo	0.2	Optimum properties	132	150	18	—	shafts
		Mn	0.9								
11	12% Manganese steel	12%	Mn	C		Tempered 600°F	200	220	10	—	Machine tool parts;
						Rolled and heat-treated stock	44	160	40	170	wear, abrasion-
											resistant
12	VASCO 300	Ni	18.5	Ti	0.6	Solution treatment 1 500°F;	110	150	18	—	Very high strength,
		Co	9.0	C	0.03	aged 900·F					maraging, good
		Mo	4.8								machining properties
											in annealed state
13	TI (AISI)	W	18.0	V	1.0	Quenched; tempered				R(c)	High speed tool steel,
		Cr	4.0	C	0.7						cutting tools, punches,
											etc.
14	M2 (AISI)	W	6.5	Mo	5.0	Quenched; tempered				65–66	M-grade, cheaper,
		Cr	4.0	C	0.85						tougher
		V	2.0								
15	Stainless steel type 304	Ni	9.0	C	0.08	Annealed; cold-rolled	35–160	85–185	60	160–400	General purpose,
		Cr	19.0		max				8		weldable;
											nonmagnetic
											austenitic steel
16	Stainless steel type 316	Cr	18.0	C	0.10	Annealed	30–120	90–150	50	165	For severe corrosive
		Ni	11.0		max				8		media, under stress;
		Mo	2.5	Fe bal.							nonmagnetic
											austenitic steel
17	Stainless steel type 431	Cr	16.0	Si	1.0	Annealed	85	120	25	250	Heat-treated stainless
		Ni	2.0	C	0.20	Heat-treated	150	195	20	400	steel, with good
		Mn	1.0	Fe bal.							mechanical strength;
											magnetic
18	Stainless steel 17–4 PH	Cr	17.0	Co	0.35	Annealed	110	150	10	363	Precipitation
		Ni	4.0	C	0.07						hardening; heat-
		Cu	4.0	Fe bal.							resisting type; retains
											strength up to approx.
											600°F

Mechanical Properties of Metals and Alloys (continued)

No.	Material	Nominal Composition				Form and Condition	Typical Mechanical Properties: Yield Strength (0.2% offset), 1000 lb/sq in.	Typical Mechanical Properties: Tensile Strength 1000 lb/sq in.	Typical Mechanical Properties: Elongation in 2 in., %	Typical Mechanical Properties: Harness, Brinell	Comments
	CAST IRONS AND CAST STEELS										
	These alloys are used where large and/or intricate-shaped articles are required or where overall dimensional tolerances are not critical. Thus the article can be produced with the fabrication and machining costs held to a minimum. Except for a few heat-treatable cast steels, this class of alloys does not demonstrate high-strength qualities.										
	Cast Irons										
19	Cast gray iron	C	34	Si	1.8	Cast (as cast)	—	25 min	0.5 max	180	Engine blocks, fly-
	ASTM A48–48, Class 25	Mn	0.5								wheels, gears,
											machine-tool bases
20	White	C	3.4	Si	0.7	Cast	—	25	0	450	
		Mn	0.6								
21	Malleable iron	C	2.5	Si	1.0	Cast (annealed)	33	52	12	130	Automotives, axle
	ASTM A47	Mn	0.55								bearings, track wheels,
			max								crankshafts
22	Ductile or nodular	C	3.4	P	0.1	Cast	53	70	18	170	Heavy-duty machines,
	iron (Mg-containing)	Mn	0.40		max	Cast (as cast)	68	90	7	235	gears, cams,
	ASTM A339	Ni	1%	Mg	0.06	Cast (quenched, tempered)	108	135	5	310	crankshafts
	ASTM A395	Si	2.5	Fe bal.							
23	Ni-hard type 2	C	2.7	Si	0.6	Sand-cast	—	55	—	550	Strength, with heat-
		Mn	0.5	Ni	4.5	Chill-cast (tempered)	—	75	—	625	and corrosion-
		Cr	2.0	Fe bal.							resistance
24	Ni-resist type 2	C	3.0	Si	2.0	Cast (as cast)	—	27	2	140	
		Mn	1.0	Ni	20.0						
		Cr	2.5	Fe bal.							
	Cast Steels										
25	ASTM A27-62 (60-30)	C	0.3	Mn	0.6		30	60	24	—	Low alloy, medium
		Si	0.8	Ni	0.5						strength, general
		Cr	0.4	Mo	0.2						application
26	ASTM A148-60 (105-85)						85	105	17	—	High strength;
											structural application

27	Cast 12 Cr alloy (CA-15)	C 0.15 max	Mn 1.00 max	Air-cooled from 1800°F; tempered at 600°F	150	200	7	390	Stainless, corrosion-resistant to mildly corrosive alkalis and acids
		Si 150 max	Cr 11.5–14	Air-cooled from 1800°F; tempered at 1400°F	75	100	30	185	
		Ni 1.00 max	Fe bal.						
28	Cast 29-9 alloy (CE-30) ASTM–A296 63T	C 0.30 max	Min 1.50 max	As cast	60	95	15	170	Greater corrosion resistance, especially for oxidizing condition
		Si 2.00 max	Cr 26–30						
			Fe bal.						
		Ni 8–11							
29	Cast 28-7 alloy (HD) ASTM–A97-63T	C 0.50 max	Mn 1.50 max	As cast	48	85	16	190	Heat-resistant
		Si 2.00	Cr 26–30						
		Ni 4–7	Fe bal.						

SUPER ALLOYS

The advent of engineering applications requiring high temperature and high strength, as in jet engines and rocket motors, has lead to the development of a range of alloys collectively called super alloys. These alloys require excellent resistance to oxidation together with strength at high temperatures, typically 1800°F in existing engines. These alloys are continually being modified to develop better specific properties, and therefore entries in this group of alloys should be considered “fluid”. Both wrought and casting-type alloys are represented. As the high temperature properties of cast materials improve, these alloys become more attractive, since great dimensional precision is now attainable in investment castings.

	Nickel Base							
30	Hastelloy X	Co 1.5 max	Fe 18.5	Wrought sheet	52	113.2	43	194
			Mo 9.0	Mill-annealed	—	67	17	172
		Cr 22.0	C 0.15 max (wrought)	As investment cast	46.5	—	—	—
		W 0.6						
		C 0.20 max (cast)	Ni bal.					
31	Hastelloy C	Cr 16.0	Fe 6.0	Sand-cast (annealed)	50	78	5	199
				Rolled (annealed)	71	130	45	204
		W 4.0	C 0.15 max	Investment cast	50	80	10	215
		Mo 17.0	Ni bal.					
32	Inconel 712C	Ni (+Co) bal.	Cr 13.0	Investment cast	102	120	6	—
			Cb 2.0					
		Mo 4.5	Ti 0.6					
		Al 6.0						
33	In 100	C 18.0	Cr 10.0	Cast				
		Mo 3.0	Ti 4.7					
		Al 55.0	Co 15.0					
		V 1.0						

Mechanical Properties of Metals and Alloys (continued)

No.	Material	Nominal Composition				Form and Condition	Typical Mechanical Properties: Yield Strength (0.2% offset), 1000 lb/sq in.	Typical Mechanical Properties: Tensile Strength 1000 lb/sq in.	Typical Mechanical Properties: Elongation in 2 in., %	Typical Mechanical Properties: Harness, Brinell	Comments
34	Taz 8	C	125.0	Cr	6.0	Cast					
		Mo	4.0	Al	6.0						
		W	4.0	Zr	1.0						
		Ta	8.0	V	2.5						
35	Nimonic 90	Ni (+Co)		C	0.05	Annealed; wrought	90	155	—	260	General elevated temperature applications
			57.00	Fe	0.45						
		Mn	0.50	Si	0.20						
		S	0.007	Cr	20.55						
		Cu	0.05	Ti	2.60						
		Al	1.65								
		Co	16.90								
36	Inconel X	Ni (+Co)		C	0.04	Annealed	50	115	50	150	
			72.85	Fe							
		Mn	0.65	Si	6.80	Annealed; age hardened	115	175	25	300	
		S	0.007	Cr	0.30						
		Cu	0.05	Ti	15.0						
		Al	0.75		2.50						
		Cb (+Ta)									
			0.85								
37	Waspaloy	C	0.08	Cr	19.5	Cold-rolled	270	275	8	Rc 51	
		Mo	4.3	Ti	3.0						
		Co	13.5								
38	Rene 41	C	0.09	Cr	19.0	Wrought	100	145	—	—	
		Mo	10.0	Ti	3.1						
		Al	1.5	Co	11.0						
39	Udimet 700	C	0.08	Cr	15.0	Cold-rolled	280	285	6	Rc 53	
		Mo	5.0	Ti	3.5						
		Al	4.3	Co	18.5						
40	T.D. Nickel	Ni	97.5	ThO_2	2.4	Extended and cold-worked	85	100	13	—	High temperature; jet engine parts

	Cobalt Base										
41	Haynes Stellite alloy 25	C	0.15	Cr	20.0	Wrought sheet; mill annealed	63	140	60	244	
	(L605)		max	W	15.0						
		Ni	10.0	Co bal.							
		Mn	1.5	Mo	5.5						
42	Haynes Stellite alloy 21	C	0.25	Co. bal.		As investment cast	82	103	8	313 max	For castings
	AMS 5385 (cast)	Ni	2.5								
		Cr	28.5								

ALUMINUM ALLOYS

Although the strength of aluminum alloys is in general less than that attainable in ferrous alloys or copper-base alloys, their major advantage lies in their high strength-to-weight ratio due to the low density of aluminum. Aluminum alloys have good corrosion resistance for most applications except in alkaline solutions.

43	3003	Cu	0.12	Al bal.		Annealed-O	6	16	40	28	Good formability,
	ASTM B221	Mn	1.2			Cold-rolled-H14	21	22	16	40	weldable, medium
						Cold-rolled-H18	27	29	10	55	strength; chemical
											equipment
44	2017	Mn	0.5	Mg	0.5	Annealed-O	10	26	22	45	High strength;
	ASTM B221	Cu	4.0	Al bal.		Heat-treated-T4	40	62	22	105	structural parts,
											aircraft, heavy
											forgings
45	2024	Cu	4.5	Mg	1.5	Heat-treated-T4	47	68	19	120	
	ASTM B211	Mn	0.6	Al bal.							
46	5052	Cr	0.25	Al bal.		Annealed-O	13	28	30	47	Medium strength, good
	ASTM B211	Mg	2.5			Cold-rolled and stabilized H34	31	38	14	68	fatigue properties;
											street-light standards
47	ASTM B208					Cold-rolled and stabilized H38	37	42	8	77	
48	7075	Cu	1.6	Mg	2.5	Annealed-O	15	33	17	60	High strength, good
	ASTM B211	Cr	0.3	Al bal.		Heat-treated and artificially	73	83	11	150	corrosion resistance
		Zn	5.6			aged-T6					
49	380	Si	9.0	Al bal.		Die-cast	24	48	3	—	General purpose die
	ASTM SC84B	Cu	3.5								casting
50	195	Si	0.8	Al bal.		Sand-cast; heat-treated-T4	16	32	8.5	60	Structural elements,
	ASTM C4A	Cu	4.5			Sand-cast; heat-treated and	24	36	5	75	aircraft, and machines
						artificially aged-T6					
51	214	Mg	3.8	Al bal.		Sand-cast-F	12	25	9	50	Chemical equipment,
	ASTM G4A										marine hardware,
											architectural
52	220	Mg	10.0	Al bal.		Sand-cast; heat-treated-T4	26	48	16	75	Strength with shock
	ASTM G10A										resistance; aircraft

No.	Material	Nominal Composition				Form and Condition	Typical Mechanical Properties: Yield Strength (0.2% offset), 1000 lb/sq in.	Tensile Strength 1000 lb/sq in.	Elongation in 2 in., %	Harness, Brinell	Comments
	COPPER ALLOYS										

Because of their corrosion resistance and the fact that copper alloys have been used for many thousands of years, the number of copper alloys available is second only to the ferrous alloys. In general copper alloys do not have the high-strength qualities of the ferrous alloys, while their density is comparable. The cost per strength-weight ratio is high; however, they have the advantage of ease of joining by soldering, which is not shared by other metals that have reasonable corrosion resistance.

No.	Material	Nominal Composition				Form and Condition	Yield Strength (0.2% offset), 1000 lb/sq in.	Tensile Strength 1000 lb/sq in.	Elongation in 2 in., %	Harness, Brinell	Comments
53	Copper	Cu	99.9 plus			Annealed	10	32	45	42	Bus-bars, switches, architectural, roofing, screens
	ASTM B152					Cold-drawn	40	45	15	90	
	ASTM B124, B133					Cold-rolled	40	46	5	100	
	ASTM B1, B2, B3										
54	Gilding metal	Cu	95.0	Zn	5.0	Cold-rolled	50	56	5	114	Coinage, ammunition
	ASTM B36										
55	Cartridge 70-30 brass	Cu	70.0	Zn	30.0	Cold-rolled	63	76	8	155	Good cold-working poperties; radiator covers, hardware, electrical
	ASTM B14										
	ASTM B19										
	ASTM B36										
	ASTM B134										
	ASTM B135										
56	Phosphor bronze 10%	Cu	90.0	Sn	10.0	Spring temper	—	122	4	241	Good spring qualities, high-fatigue strength
	ASTM B103	P	0.25								
	ASTM B130										
	ASTM B159										
57	Yellow brass (high brass)	Cu	65.0	Zn	35.0	Annealed	18	48	60	55	Good corrosion resistance; plumbing, architectural
	ASTM B36					Cold-drawn	55	70	15	115	
	ASTM B134					Cold-rolled (HT)	60	74	10	180	
	ASTM B135										
58	Manganese bronze	Cu	58.5	Zn	39.2	Annealed	30	60	30	95	Forgings
	ASTM B138	Fe	1.0	Sn	1.0	Cold-drawn	50	80	20	180	
		Mn	0.3								
59	Naval brass	Cu	60.0	Zn	39.25	Annealed	22	56	40	90	Condensor tubing; high resistance to salt-water corrosion
	ASTM B21	Sn	0.75			Cold-drawn	40	65	35	150	
60	Muntz metal	Cu	60.0	Zn	40.0	Annealed	20	54	45	80	Condensor tubes; valve stress
	ASTM B111										

61	Aluminum bronze	Cu	92.0	Al	8.0	Annealed	25	70	60	80	
	ASTM B169, alloy A					Hard	65	105	7	210	
	ASTM B124										
	ASTM B150										
62	Beryllium copper 25	Be	1.9	Cu bal.		Annealed, solution-treated	32	70	45	B60	Bellows, fuse clips,
	ASTM B194	Co or Ni								(Rockwell)	electrical relay parts,
	ASTM B197		0.25			Cold-rolled	104	110	5	B81	valves, pumps
	ASTM B196					Cold-rolled	70	190	3	C40	
63	Free-cutting brass	Cu	62.0	Zn	35.5	Cold-drawn	44	70	18	B80	Screws, nuts, gears, keys
		Pb	2.5							(Rockwell)	
64	Nickel silver 18%	Cu	65.0	Zn	17.0	Annealed	25	58	40	70	Hardware, optical
	Alloy A (wrought)	Ni	18.0			Cold-rolled	70	85	4	170	goods, camera parts
	ASTM B122, No. 2					Cold-drawn wire	—	105	—	—	
65	Nickel silver 13% (cast)	Ni	12.5	Pb	9.0	Cast	18	35	15	55	Ornamental castings,
	10A	Sn	2.0	Cu bal.							plumbing; good
	ASTM B149, No. 10A	Zn	20.0								machining qualities
66	Cupronickel 10%	Cu	88.35	Ni	10.0	Annealed	22	44	45	—	Condensor, salt-water
	ASTM B111	Fe	1.25	Mn	0.4	Cold-drawn tube	57	60	15	—	piping
	ASTM B171										
67	Cupronickel	Cu	70.0	Ni	30.0	Wrought					Heat-exchanger process equipment, valves
68	Red brass (cast)	Cu	85.0	Zn	5.0	As-cast	17	35	25	60	
	ASTM B30, No. 4A	Pb	5.0	Sn	5.0						
69	Silicon bronze	Si	4.0	Fe	2.0	Castings					Cheaper substitute for
	ASTM B30, alloy 12A	Zn	4.0	Al	1.0						tin bronze
		Mn	1.0								
70	Tin bronze	Sn	8%	Zn	4.0	Castings					Bearings, high-pressure
	ASTM B30, alloy B										brushings, pump impellers
71	Navy bronze					Cast					

TIN AND LEAD-BASE ALLOYS

Major uses for these alloys are as "white"-metal bearing alloys, extruded cable sheathing, and solders. Tin forms the basis of pewter used for culinary applications.

72	Lead-base Babbitt	Pb	85.0	Sn	5.0	Chill east	—	10	5	19	Bearings, light loads
	ASTM B23, alloy 19	Sb	10.0	As	0.6						and low speeds
		Cu	0.5								
73	Arsenical-lead Babbitt	Pb	83.0	Sn	1.0	Chill cast	—	10.3	2	20	Bearings, high loads
	ASTM B23, alloy 15	Sb	16.0	As	1.1						and speeds, diesel
		Cu	0.6								engines, steel mills

No.	Material	Nominal Composition	Form and Condition	Typical Mechanical Properties: Yield Strength (0.2% offset), 1000 lb/sq in.	Tensile Strength 1000 lb/sq in.	Elongation in 2 in., %	Harness, Brinell	Comments
74	Chemical lead	Pb 99.9 Cu 0.06 Bi 0.005 max	Rolled 95%	1.9	2.5	50	5	
75	Antimonial lead (hard lead)	Pb 94.0 Sb 6.0	Chill east Rolled 95%	— —	6.8 4.1	22 47	(500 kg) 9	Good corrosion resistance and strength
76	Calcium lead	Pb 99.9 Ca 0.025 Cu 0.10	Extruded and aged	—	4.5	25	—	Cable sheathing, creep-resistant pipe
77	Tin Babbitt alloy ASTM B23–61, grade 1	Sb 4.5 Sn bal. Cu 4.5	Chill east	—	9.3	2	17	General bearings and die casting
78	Tin die-casting alloy ASTM B102–52	Sb 13.0 Sn bal. Cu 5.0	Die-cast	—	10	1	29	Die-casting alloy
79	Pewter	Sn 91.0 Sb 7.0 Cu 2.0	Rolled sheet, annealed	—	8.6	40	9.5	Ornamental and household items
80	Solder 50-50	Sn 50.0 Pb 50.0	Cast	4.8	6.1	60	14	General-purpose solder
81	Solder	Sn 20.0 Pb 80.0	Cast	3.6	5.8	16	11	Coating and joining, filling seams on automobile bodies

MAGNESIUM ALLOYS

Because of their low density these alloys are attractive for use where weight is at a premium. The major drawback to the use of these alloys is their ability to ignite in air (this can be a problem in machining); they are also costly. Magnesium alloys are used in both the wrought and die-cast forms, the latter being the most frequently used form.

No.	Material	Nominal Composition	Form and Condition	Yield Strength (0.2% offset), 1000 lb/sq in.	Tensile Strength 1000 lb/sq in.	Elongation in 2 in., %	Harness, Brinell	Comments
82	Magnesium alloy AZ31B	Zn 1.0 Mn 0.20 Al 3.0 min Mg. bal.	Rolled-plate (strain-hardened, then partially annealed)	24	37	18	—	Structural applications of medium strength
			Rolled-sheet (strain-hardened, then partially annealed)	32	42	15	73	
			Annealed	22	37	21	56	
			Extruded	28	38	14	—	
83	Magnesium alloy AZ80A	Zn 0.5 Mn 0.15 Al 8.5 min Mg. bal.	Extruded Extruded (age-hardened) Forged (age-hardened)	36 39 34	49 53 50	11 6 6	60 82 72	General extruded and forged products

84	Magnesium alloy AZ92A	Zn	2.0	Mn	0.10	Sand-cast (as cast)	14	24	6	50	
		Al	9.0		min	Sand-cast (solution heat-treated)	14	40	12	55	
				Mg bal.							
						Sand-cast (solution heat-treated and aged)	19	40	5	83	
						Sand-cast (age-hardened)	16	30	18	—	
						Sand-cast and tempered	22	40	3	81	Pressure-tight sand and permanent mold castings; high UTS and good yield strength
85	Magnesium alloy ZK60A	Zn	5.7	Mg bal.		Extruded	43	52	12	82	
		Zr	0.55								
86	Magnesium alloy AZ91A and AZl91B	Zn	0.6	Mn	0.13	Die-cast (as cast)	22	33	3	67	General die-casting applications
		Al	9.0		min						
				Mg bal.							
						BERYLLIUM					
87	Beryllium						27	33	1–3	—	Windows, X-ray tubes
						Hot-pressed	38	51			
						Cross-rolled	40	60	10–40	—	Moderator- and reflector-cladding nuclear reactors; heat-shield and structural-member missiles
							60	90			
						NICKEL ALLOYS					
	Nickel and its alloys are expensive and used mainly either for their high-corrosion resistance in many environments or for high-temperature and strength applications. (See Super Alloys, above.)										
88	Nickel (cast)	Ni	95.6	Cu	0.5	As cast	25	57	22	110	Good corrosion-resistance applications
		Fe	0.5	Mn	0.8						
		Si	1.5	C	0.8						
89	K Monel	Ni(+ Co) 65.25		C	0.15	Annealed	45	100	40	155	High strength and corrosion resistance; aircraft parts, valve stems, pumps
				Fe	1.00	Annealed, age-hardened	100	155	25	270	
		Mn	0.60	Si	0.15	Spring	140	150	5	300	
		S	0.005	Al	2.75	Spring, age-hardened	160	185	10	335	
		Cu	29.60								
		Ti	0.45								

No.	Material	Nominal Composition				Form and Condition	Typical Mechanical Properties: Yield Strength (0.2% offset), 1000 lb/sq in.	Tensile Strength 1000 lb/sq in.	Elongation in 2 in., %	Harness, Brinell	Comments
90	A nickel	Ni(+ Co)		C	0.06	Annealed	20	70	40	100	Chemical industry for
	ASTM B160		99.40	Fe	0.15	Hot-rolled	25	75	40	110	resistance to strong
	ASTM B161	Mn	0.25	Si	0.05	Cold-drawn	70	95	25	170	alkalis, plating nickel
	ASTM B162	S	0.005			Cold-rolled	95	105	5	210	
		Cu	0.05								
91	Duranickel	Ni(+ Co)		C	0.15	Annealed	45	100	40	160	High strength and
			93.90	Fe	0.15	Annealed, age-hardened	125	170	25	330	corrosion resistance;
		Mn	0.25	Si	0.55	Spring	—	175	5	320	pump rods, shafts,
		S	0.005	Al	4.50	Spring, age-hardened	—	205	10	370	springs
		Cu	0.05								
		Ti	0.45								
92	Cupronickel 55–45	Cu	55.0	Ni	45.0	Annealed	30	60	45	—	Electrical-resistance
	(Constantan)					Cold-drawn	50	65	30	—	wire; low temperature
						Cold-rolled	65	85	20	—	coefficient, high
											resistivity
93	Nichrome	Ni	80.0	Cr	20.0						Heating elements for
											furnaces
94	"S" Monel	Ni	60.0	Cu	29.0	Sand-casting	80–115	110–145	2	270–350	High-strength casting
		Fe	2.50	Mn	1.5						alloy; good bearing
			max		max						properties for valve
		Si	4.0	Al	0.5						seats
					max						

TITANIUM ALLOYS

The main application for these alloys is in the aerospace industry. Because of the low density and high strength of titanium alloys, they present excellent strength-to-weight ratios.

No.	Material	Nominal Composition		Form and Condition	Yield Strength	Tensile Strength	Elongation	Harness, Brinell	Comments
95	Commercial titanium	Ti	99.4	Annealed at 1100 to 1350°F	70	80	20	—	Moderate strength,
	ASTM B265-58T			(593 to 732°C)					excellent fabricability;
									chemical industry
									pipes
96	Titanium alloy			Water-quenched from 1750°F	160	170	13	—	High-temperature
	ASTM B265-58T-5			(954°C); aged at 1000°F					strength needed in
	Ti-6-Al-4V			(538°C) for 2 hr					gas-turbine
									compressor blades

97	Titanium alloy Ti-4 Al-4Mn					Water-quenched from 1450°C); aged at 900°F (482°C) for 8 hr	170	185	13	—	Aircraft forgings and compressor parts
98	Ti-Mn alloy ASTM B265-58T-7	Fe Mn	0.5 7.0–8.0	Ti bal.		Sheet	140	150	18	—	Good formability, moderate high-temperature strength; aircraft skin
						ZINC ALLOYS					
	A major use for these alloys is for low-cost die-cast products, such as household fixtures, automotive, parts, and trim.										
99	Zinc ASTM B69	Cd Pb	0.35 0.08	Zn bal.		Hot-rolled	—	19.5	65	38	Battery cans, grommets, lithographer's sheet
100	Zilloy–15	Cu Mg	1.00 0.010	Zn lbal.		Hot-rolled Cold-rolled	— —	29 36	20 25	61 80	Corrugated roofs, articles with maximum stiffness
101	Zilloy–40	Cu	1.00	Zn bal.		Hot-rolled Cold-rolled	— —	24 31	50 40	52 60	Weatherstrip, spun articles
102	Zamac–5 ASTM 25	Zn (99.99% pure reminder) Mg	 0.03–0.08	Al Cu	3.5–4.3 0.75–1.25	Die-cast	—	47.6	7	91	Die casting for automobile parts, padlocks; used also for die material.
						ZIRCONIUM ALLOYS					
	These alloys have good corrosion resistance but are easily oxidized at elevated temperatures in air: The major application is for use in nuclear reactors.										
103	Zirconium, commercial	O2 Hf	0.07 1.90	C Zr bal.	0.15	Annealed	40	65	27	B80 (Rockwell)	
104	Zircaloy 2	Hf Fe Sn	0.02 0.15 1.46	Ni Other Zr bal.	0.05 0.25	Annealed	50	75	22	B90 (Rockwell)	Nuclear power-reactor cores at elevated temperatures

From Bolz, R.E. and Tuve, G.L., Solids — Metals, in *CRC Handbook of Tables for Applied Engineering Science,* CRC Press, Boca Raton, FL, 1973, pp. 103–115.

Thermal Properties of Pure Metals—Metric Units

	At Atmospheric Pressure								Liquid Metal			
				At 100°K		At 25°C (77°F)				Vapor Pressure		
										10^{-3} atm	10^{-6} atm	10^{-9} atm
Metal	Melting Point, °C	Boiling Point, °C	Latent Heat of Fusion cal/g	Thermal Conductivity, watts/cm°C	Specific Heat, cal/g°C	Specific Heat, cal/g°C	Coeff. of Linear Expansion ($\times 10^6$) $(°C)^{-1}$	Thermal Conductivity, watts/cm°C	Specific Heat (Liquid) at 2000°K, calg°C	Boiling Point Temperature, °K		
Aluminum	660.	2441.	95	3.00*	.115	0.215	25	2.37	.26	1,782	1,333	1,063
Antimony	630.	1440.	38.5	—	.040	.050	9	.185	.062	1,007	741	612
Beryllium	1285.	2475.	324.	—	.049	.436	12	2.18	.78	1,793	1,347	1,085
Bismuth	271.4	1660.	12.4	—	.026	.030	13	.084	.036	1,155	851	677
Cadmium	321.	767.	13.2	1.03	.047	.055	30	.93	.063	655	486	388
Chromium	1860.	2670.	79	1.58	.046	.110	6	.91	.224	1,992	1,530	1,247
Cobalt	1495.	2925.	66	—	.057	.10	12	.69	.164	2,167	1,652	1,345
Copper	1084.	2575.	49	4.83*	.061	.092	16.6	3.98	.118	1,862	1,391	1,120
Gold	1063.	2800.	15	3.45*	.026	.031	14.2	3.15	.0355	2,023	1,510	1,211
Iridium	2450.	4390.	33	—	.022	.031	6	1.47	.0434	3,253	2,515	2,062
Iron	1536.	2870.	65	1.32*	.052	.108	12	.803	.197	2,093	1,594	1,297
Lead	327.5	1750.	5.5	0.396	.028	.031	29	.346	.033	1,230	889	698
Magnesium	650.	1090.	88.0	1.69	.016	.243	25	1.59	.32	857	638	509
Manganese	1244.	2060.	64	—	.064	.114	22	—	.20	1,495	1,131	913
Mercury	−38.86	356.55	2.7	—	.029	.033	—	.0839	—	393	287	227
Molybdenum	2620.	4651.	69	1.79	.033	.060	5	1.4	.089	3,344	2,558	2,079

Nickel	1453.	2800.	71	1.58	.055	.106	13	.899	.175	2,156	1,646	1,343
Niobium (Columbium)	2470.	4740.	68	0.552	.045	.064	7	.52	.083	3,523	2,721	2,232
Osmium	3025.	4225.	34	—	—	.031	5	.61	.039	—	—	—
Platinum	1770.	3825.	24	0.79*	.024	.032	9	.73	.043	2,817	2,155	1,757
Plutonium	640.	3230.	3	—	.019	.032	54	.08	.041	2,200	1,596	1,252
Potassium	63.3	760.	14.5	—	.150	.180	83	.99	—	606	430	335
Rhodium	1965.	3700.	50	—	—	.058	8	1.50	.092	—	—	—
Selenium	217.	700.	16	—	—	.077	37	.005	—	—	—	—
Silicon	1411.	3280.	430	—	.062	.17	3	.835	.217	2,340	1,749	1,427
Silver	961.	2212.	26.5	4.50*	.045	.057	19	4.27	.068	1,582	1,179	952
Sodium	97.83	884.	27	—	.234	.293	70	1.34	—	701	504	394
Tantalum	2980.	5365.	41	0.592	.026	.034	6.5	.54	.040	3,959	3,052	2,495
Thorium	1750.	4800.	17	—	.024	.03	12	.41	.047	3,251	2,407	1,919
Tin	232.	2600.	14.1	0.85	.039	.054	20	.64	.058	1,857	1,366	1,080
Titanium	1670.	3290.	100	0.312	.072	.125	8.5	.2	.188	2,405	1,827	1,484
Tungsten	3400.	5550.	46	2.35*	.021	.032	4.5	1.78	.040	4,139	3,228	2,656
Uranium	1132.	4240.	12	—	.022	.028	13.4	.25	.048	2,861	2,128	1,699
Vanadium	1900.	3400.	98	—	.061	.116	8	.60	.207	2,525	1,948	1,591
Zinc	419.5	910.	27	1.32	.063	.093	35	1.15	—	752	559	449

* Temperatures of maximum thermal conductivity (conductivity values in watts/cm°C): Aluminum 13°K, cond. = 71.5; copper 10°K, cond. = 196; gold 10°K, cond. = 28.2; iron 20°K, cond. = 9.97; platinum 8°K, cond. = 12.9; silver 7°K, cond. = 193; tungsten 8°K, cond. = 85.3.

From Bolz, R.E. and Tuve, G.L., Solids — Metals, in *CRC Handbook of Tables for Applied Engineering Science*, CRC Boca Raton, FL, 1973, p. 119.

Terms and Units for Radiant Energy and Illumination

Note: Any of the following quantities may be restricted to a narrow wavelength interval by addition of the world *spectral*.

Measure of	Terms in Use	Meaning or Definition	Usual Units
Quantity	Radiant energy Luminous energy	Total quantity of radiant energy	Erg, joule, calorie, kilowatt-hour, Btu
Rate	Radiant flux Luminous flux	Time rate of flow of radiant energy (power)	Erg/sec, watt, Bu/hr, lumen
Intensity	Radiant intensity Luminous intensity	Radiant flux per unit solid angle (point source)	Watts per steradian, candela* = lumens/steradian
Density at surface	Radiant emittance Radiant excitance Irradiance Illumination Illuminance (Emittance)	Density of radiant flux incident upon (or emitted from) a surface	Watts/sq cm, foot-candle = lumens/sq ft, lux = lumens/sq m, phot = lumens sq cm, Btu/hr × sq ft
Density of beam (at surface)	Radiance	Unit intensity normal to the beam per unit of projected area in that direction	$\text{Watts/sr} \times \text{sq cm}, \dfrac{\text{Btu/hr}}{\text{sr} \times \text{sq ft}}$
Effectiveness (radiating)	Emissivity (Absorptivity)	Ratio of radiant emittance (or absorptance) to that of a perfect blackbody	Dimensionless
Brightness	Luminance	Photometric brightness per unit area	Candela/sq ft, stilb = cd/sq cm, nit = cd/sq m, foot-lambert = cd/π sq ft, lambert = cd/π sq cm, apostilb = cd/π sq m

* The candela (cd) was formerly called "candlepower." (One international candle will illuminate a sphere at one foot distance with 4π lumens, or one sq ft of the sphere with one lumen.)

From Bolz, R.E. and Tuve, G.L., Electromagnetic radiation, in *CRC Handbook of Tables for Applied Engineering Science*, CRC Press, Boca Raton, FL, 1973, p. 205.

Blackbody Radiation

Temperature		Wavelength of Maximum Intensity, Microns, μ	Maximum Normal Intensity†		Total Maximum Hemispherical Radiation†	
°K	°R		W/cm² μ	Btu/hr ft² μ	W/cm²	Btu/hr ft²
10	18	290	1.290×10^{-10}	4.092×10^{-7}	5.679×10^{-8}	1.801×10^{-4}
50	90	58.0	4.030×10^{-7}	1.278×10^{-3}	3.549×10^{-5}	1.126×10^{-1}
100	180	29.0	1.290×10^{-5}	4.092×10^{-2}	5.679×10^{-4}	1.801
200	360	14.5	4.127×10^{-4}	1.309	9.086×10^{-3}	2.882×10
300	540	9.66	3.134×10^{-3}	9.941	4.600×10^{-2}	1.459×10^{2}
350	630	8.28	6.774×10^{-3}	2.149×10	8.522×10^{-2}	2.703×10^{2}
400	720	7.25	1.321×10^{-2}	4.190×10	1.454×10^{-1}	4.612×10^{2}
450	810	6.44	2.380×10^{-2}	7.550×10	2.328×10^{-1}	7.385×10^{2}
500	900	5.80	4.030×10^{-2}	1.278×10^{2}	3.549×10^{-1}	1.126×10^{3}
550	990	5.27	6.484×10^{-2}	2.057×10^{2}	5.207×10^{-1}	1.652×10^{3}
600	1080	4.83	1.003×10^{-1}	3.181×10^{2}	7.360×10^{-1}	2.335×10^{3}
700	1260	4.14	2.168×10^{-1}	6.877×10^{2}	1.364	4.327×10^{3}
800	1440	3.63	4.226×10^{-1}	1.341×10^{3}	2.326	7.378×10^{3}
900	1620	3.22	7.616×10^{-1}	2.417×10^{3}	3.726	1.182×10^{4}
1000	1800	2.90	1.290	4.092×10^{3}	5.679	1.801×10^{4}
1200	2160	2.42	3.209	1.018×10^{4}	1.178×10	3.737×10^{4}
1400	2520	2.07	6.936	2.200×10^{4}	2.181×10	6.918×10^{4}
1600	2880	1.81	1.352×10	4.289×10^{4}	3.722×10	1.181×10^{5}
1800	3240	1.61	2.437×10	7.730×10^{4}	5.961×10	1.891×10^{5}
2000	3600	1.49	4.127×10	1.309×10^{5}	9.096×10	2.882×10^{5}
2500	4500	1.156	1.260×10^{2}	3.997×10^{5}	2.218×10^{2}	7.036×10^{5}
3000	5400	0.966	3.134×10^{2}	9.941×10^{5}	4.600×10^{2}	1.459×10^{6}
4000	7200	0.725	1.321×10^{3}	4.190×10^{6}	1.454×10^{3}	4.612×10^{6}
6000	10,800	0.483	1.003×10^{4}	3.181×10^{7}	7.360×10^{3}	2.335×10^{7}
8000	14,400	0.363	4.226×10^{4}	1.340×10^{8}	2.326×10^{4}	7.378×10^{7}

Notes: One half of the blackbody radiation lies on either side of the wavelength computed from $\lambda = 4107/T$, where λ is in microns and T is °K.

1 cm = 0.3937 in. = 10,000 microns = 10^8 Angstrom units. To convert Btu/hr·ft² to W/m², multiply by 3.1525.

† Zero temperature receiver; no reradiation.

From Bolz, R.E. and Tuve, G.L., Electromagnetic radiation, in *CRC Handbook of Tables for Applied Engineering Science*, CRC Press, Boca Raton, FL, 1973, p. 207.

Thermodynamic Nonflow Process Equations

For a System Containing a Perfect Gas with Constant Specific Heats

$_1Q_2 = {_1W_2} + (U_2 - U_1)$

Process	Constant Pressure	Constant Volume	Isothermal	Isentropic S = constant	Polytropic pV^n = constant
p, V, T $pV = mRT$‡	p = constant $p = p_1 = p_2$	V = constant $V = V_1 = V_2$	T = constant $T = T_1 = T_2$	$p_1V_1^k = p_2V_2^k$ = constant	$p_1V_1^n = p_2V_2^n$ = constant
$pu = RT$‡	$\frac{V}{T} = constant$ $\frac{V_1}{T_1} = \frac{V_2}{T_2}$	$\frac{P}{T} = constant$ $\frac{P_1}{T_1} = \frac{P_2}{T_2}$	pV = constant $p_1V_1 = p_2V_2$	$\frac{T_2}{T_1} = \left(\frac{p_2}{p_1}\right)^{\frac{k-1}{k}}$ $\frac{T_2}{T_1} = \left(\frac{V_1}{V_2}\right)^{k-1}$	$\frac{T_2}{T_1} = \left(\frac{p_2}{p_1}\right)^{\frac{n-1}{n}}$ $\frac{T_2}{T_1} = \left(\frac{V_1}{V_2}\right)^{n-1}$
Specific heat $c = {_1Q_2}/(T_2 - T_1)$‡	$c_p = \left(\frac{kR‡}{k-1}\right)$	$c_p = \left(\frac{R‡}{k-1}\right)$	∞	0	$c_n = c_v\frac{(k-n)}{(1-n)}$
Exponent n for polytropic process	0	∞	1	$k = \left(\frac{c_p†}{c_v}\right)$	n = any value
Quantity of heat $_1Q_2 = \int TdS$ positive for heat into system from surroundings	$mc_p(T_2 - T_1)$ $c_p(p/R)(V_2 - V_1)$ $\frac{k}{k-1}\,{_1W_2}$ $H_2 - H_1$	$mc_v(T_2 - T_1)$ $\frac{V(p_2 - p_1)}{k-1}$ $U_2 - U_1$	$p_1V_1 \ln(V_2/V_1)$ $p_1V_1 \ln(p_1/p_2)$ $mRT \ln(V_2/V_1)$ $mRT \ln(p_1/p_2)$ $_1Q_2 = {_1W_2}$	Adiabatic 0	$mc_n(T_2 - T_1)$
Quantity of work $_1W_2 = \int pdV$ positive for work done by system on surroundings	$p(V_2/V_1)$ $mR(T_2 - T_1)$ $\frac{k-1}{k}\,{_1Q_2}$	0		$\frac{p_2V_2 - p_1V_1}{1-k}$ $mc_v(T_1 - T_2)$ $U_1 - U_2$ $\frac{p_1V_1}{k-1}\left[1 - \left(\frac{p_2}{p_1}\right)^{\frac{k-1}{k}}\right]$	$\frac{p_2V_2 - p_1V_1}{1-n}$ $\frac{mR(T_2 - T_1)}{1-n}$ $\frac{p_1V_1}{n-1}\left[1 - \left(\frac{p_2}{p_1}\right)^{\frac{n-1}{n}}\right]$
Internal energy $U_2 - U_1$ $dU = mc_u dT$‡	$mc_v(T_2 - T_1)$† $\frac{p(V_2 - V_1)‡}{(k-1)}$	$mc_v(T_2 - T_1)$† $\frac{V(p_2 - p_1)‡}{(k-1)}$	0	$mc_v(T_2 - T_1)$† $\frac{p_2V_2 - p_1V_1‡}{(k-1)}$	$mc_v(T_2 - T_1)$† $\frac{p_2V_2 - p_1V_1‡}{(k-1)}$
Enthalpy $H_2 - H_1$ d $H = mc_p dT$‡	$mc_p(T_2 - T_1)$† $\frac{kp(V_2 - V_1)‡}{(k-1)}$	$mc_p(T_2 - T_1)$† $\frac{kV(p_2 - p_1)‡}{(k-1)}$	0	$mc_p(T_2 - T_1)$† $\frac{k(p_2V_2 - p_1V_1)‡}{(k-1)}$	$mc_p(T_2 - T_1)$† $\frac{k(p_2V_2 - p_1V_1)‡}{(k-1)}$
Entropy $S_2 - S_1$ $ds = \frac{dH}{T} - \frac{Vdp†}{T}$ $= \frac{dU}{TG} + \frac{pdV†}{T}$	$mc_p \ln(T_2/T_1)$ $mc_p \ln(V_2/V_1)$	$mc_\upsilon \ln(T_2/T_1)$ $mc_\upsilon \ln(p_2/p_1)$	$mR \ln(V_2/V_1)$ $mR \ln(p_1/p_2)$	0	$mc_n \ln(T_2/T_1)$

† Valid in general, not only for process or processes listed, and not only for perfect gases.

‡ Valid in general for perfect gases, not only for process listed.

From Bolz, R.E. and Tuve, G.L., Thermodynamics, in *CRC Handbook of Tables for Applied Engineering Science*, CRC Press, Boca Raton, FL, 1973, p. 473.

Thermodynamic Cycle Efficiencies

Symbols: $\eta_c = (T_H - T_L)/T_H$ = Carnot cycle efficiency, present

$\eta_o = 1 - r^{1-k}$ = Otto cycle efficiency, percent

$\eta_D = 1 - r^{1-k} \frac{(S^k - 1)}{k(S-1)}$ = Diesel cycle efficiency, percent

$\eta_\beta = 1 - r_p^{(1-k)/k}$ = Brayton (or Joule) cycle efficiency, percent

where T_H = absolute temperature of energy reservoir from which energy is drawn
T_L = absolute temperatue of energy reservoir to which energy is rejected
r = compression ratio for Otto and Diesel cycles, maximum volume/minimum volume
r_p = pressure ratio for Brayton (or Joule) cycle, maximum pressure/minimum pressure
S = cut-off ratio for Diesel cycle, volume at end of constant pressure heat addition process/minimum volume
$k = C_p/C_v$ = specific heat ratio

Otto Cycle Efficiency, η_o, Percent

$k = \frac{c_p}{c_v}$	Compression Ratio, r												
	5	6	7	8	9	10	11	12	13	14	15	20	50
1.30	38.3	41.6	44.2	46.4	48.3	49.9	51.3	52.5	53.7	54.7	55.6	59.3	69.1
1.35	43.1	46.6	49.4	51.7	53.7	55.3	56.8	58.1	59.3	60.3	61.2	65.0	74.6
1.40	47.5	51.2	54.1	56.5	58.5	60.2	61.7	63.0	64.2	65.2	66.1	69.8	79.1
5/3	65.8	69.7	72.7	75.0	76.9	78.5	79.8	80.9	81.9	82.7	83.6	86.4	92.6

Diesel Cycle Efficiency, η_D, Percent

$k = \frac{c_p}{c_v}$	Cut-Off Ratio, S	Compression Ratio, r											
		5	10	14	15	16	17	18	19	20	25	30	50
1.30	2	30.6	43.6	49.0	50.1	51.0	51.9	52.7	53.5	54.2	57.2	59.5	65.2
1.30	3	24.7	38.9	44.7	45.9	46.9	47.9	48.8	49.6	50.3	53.6	56.0	62.3
1.30	4	19.9	34.9	41.2	42.4	43.5	44.5	45.5	46.3	47.2	50.6	53.2	59.9
1.30	5	15.7	31.5	38.1	39.4	40.5	41.6	42.6	43.5	44.4	48.0	50.8	57.8
1.35	2	34.7	48.7	54.4	55.5	56.5	57.4	58.3	59.1	59.8	62.8	65.1	70.8
1.35	3	28.2	43.6	49.9	51.1	52.2	53.2	54.1	55.0	55.8	59.1	61.6	67.9
1.35	4	22.7	39.4	46.1	47.4	48.6	49.6	50.6	51.6	52.4	56.0	58.7	65.5
1.35	5	18.0	35.6	42.8	44.1	45.4	46.5	47.6	48.6	49.5	53.3	56.2	63.3
1.40	2	38.5	53.4	59.3	60.4	61.4	62.3	63.2	63.9	64.7	67.7	70.0	75.5
1.40	3	31.4	48.0	54.6	55.8	56.9	58.0	58.9	59.8	60.6	64.0	66.5	72.7
1.40	4	25.4	43.5	50.6	51.9	53.2	54.3	55.3	56.3	57.2	60.8	63.6	70.3
1.40	5	20.1	39.4	47.1	48.5	49.8	51.0	52.1	53.2	54.1	58.0	61.0	68.2

Brayton (or Joule) Cycle Efficiency, η_β, Percent

$k = \frac{c_p}{c_v}$	Pressure Ratio, r_p												
	3	4	5	6	7	8	9	10	12	14	15	20	50
1.30	22.4	27.4	31.0	33.9	36.2	38.1	39.8	41.2	43.6	45.5	46.5	49.9	59.5
1.35	24.8	30.2	34.1	37.2	39.6	41.7	43.4	45.0	47.5	49.4	50.4	54.0	63.7
1.40	27.0	32.7	36.9	40.1	42.7	44.8	46.6	48.2	50.8	52.9	53.9	57.5	67.3
5/3	35.6	42.6	47.5	51.2	54.1	56.5	58.5	60.2	63.0	65.1	66.1	69.8	79.1

Carnot Cycle Efficiency, η_c, Percent[a]

T_L		T_H, K(R)										
K	R	200 (360)	300 (540)	400 (720)	500 (900)	1000 (1800)	1500 (2700)	2000 (3600)	2500 (4500)	3000 (5400)	4000 (7200)	5000 (9000)
100	180	50.0	66.7	75.0	80.0	90.0	93.3	95.0	96.0	96.7	97.5	98.0
200	360	0	33.3	50.0	60.0	80.0	86.7	90.0	92.0	93.3	95.0	96.0
300	540	—	0	25.0	40.0	70.0	80.0	85.0	88.0	90.0	92.5	94.0

Thermodynamic Cycle Efficiencies (continued)

T_L K	T_L R	T_H, K(R) 200 (360)	300 (540)	400 (720)	500 (900)	1000 (1800)	1500 (2700)	2000 (3600)	2500 (4500)	3000 (5400)	4000 (7200)	5000 (9000)
400	720	—	—	0	20.0	60.0	73.3	80.0	84.0	86.7	90.0	92.0
500	900	—	—	—	0	50.0	66.7	75.0	80.0	83.3	87.5	90.0
1000	1800	—	—	—	—	0	33.3	50.0	40.0	66.7	75.0	80.0

[a] These values are valid for any reversible cycle with heat addition at T_H and heat rejection at T_L. Stirling and Ericcson cycles with ideal regeneration meet this requirement, for example.

Otto Cycle. The Otto cycle consists of isentropic compression, constant-volume heat addition, isentropic expansion, and constant-volume heat rejection.
Diesel Cycle. The Diesel cycle consists of isentropic compression, constant-pressure heat addition, isentropic expansion, and constant-volume heat rejection.
Brayton Cycle. The Brayton, or Joule, cycle consists of isentropic compression, constant-pressure heat addition, isentropic expansion, and constant-pressure heat rejection.
Carnot Cycle. The Carnot cycle consists of isothermal compression (with heat rejection), isentropic compression, isothermal expansion (with heat addition), and isentropic expansion.
Stirling Cycle. The Stirling cycle consists of isothermal compression (with heat rejection), constant-volume heat addition, isothermal expansion (with heat addition), and constant-volume heat rejection.
Ericcson Cycle. The Ericcson cycle consists of isothermal compression (with heat rejection), constant-pressure heat addition, isothermal expansion (with heat addition), and constant-pressure heat rejection.

From Bolz, R.E. and Tuve, G.L., Thermodynamics, in *CRC Handbook of Tables for Applied Engineering Science*, CRC Press, Boca Raton, FL, 1973, pp. 477–478.

Heat of Fusion of Some Inorganic Compounds*

For heat of fusion in J/kg, multiply values in cal/g by 4184. For heat of fusion in J/mol, multiply values in cal/g·mol (= cal/mol) by 4.184. For melting point in K, add 273.15 to values in ˚C. Values in parentheses are of uncertain reliability.

Compound	Formula	Melting Point, ˚C	Heat of Fusion Btu/lb	cal/g	cal/g Mole
Actinium[227]	Ac	1050 ± 50	(20.)	(11.0)	(3400)
Aluminum	Al	658.5	170.	94.5	2250
Aluminum bromide	Al_2Br_6	87.4	18.2	10.1	5420
Aluminum chloride	Al_2Cl_6	192.4	114.	63.6	19600
Aluminum iodide	Al_2I_6	190.9	17.6	9.8	7960
Aluminum oxide	Al_2O_3	2045.0	(461.)	(256.0)	(26000)
Antimony	Sb	630	70.4	39.1	4770
Antimony pentachloride	$SbCl_5$	4.0	14.4	8.0	2400
Antimony tribromide	$SbBr_3$	96.8	17.5	9.7	3510
Antimony trichloride	$SbCl_3$	73.3	23.9	13.3	3030
Antimony trioxide	Sb_4O_6	655.0	(83.3)	(46.3)	(26990)
Antimony trisulfide	Sb_4S_6	546.0	59.4	33.0	11200
Argon	Ar	–190.2	13.1	7.25	290
Arsenic	As	816.8	(39.6)	(22.0)	(6620)
Arsenic pentafluoride	AsF_5	–80.8	29.7	16.5	2800
Arsenic tribromide	$AsBr_3$	30.0	16.0	8.9	2810
Arsenic trichloride	$AsCl_3$	–16.0	23.9	13.3	2420
Arsenic trifluoride	AsF_3	–6.0	34.0	18.9	2486
Arsenic trioxide	As_4O_6	312.8	40.0	22.2	8000
Barium	Ba	725	23.9	13.3	1830
Barium bromide	$BaBr_2$	846.8	39.4	21.9	6000

Heat of Fusion of Some Inorganic Compounds* (continued)

Compound	Formula	Melting Point, °C	Heat of Fusion Btu/lb	cal/g	cal/g Mole
Barium chloride	$BaCl_2$	959.8	46.6	25.9	5370
Barium fluoride	BaF_2	1286.8	30.8	17.1	3000
Barium iodide	BaI_2	710.8	(31.1)	(17.3)	(6800)
Barium nitrate	$Ba(NO_3)_2$	594.8	(40.7)	(22.6)	(5900)
Barium oxide	BaO	1922.8	168.	93.2	13800
Barium phosphate	$Ba_3(PO_4)_2$	1727	55.6	30.9	18600
Barium sulfate	$BaSO_4$	1350	74.9	41.6	9700
Beryllium	Be	1278	468.	260.0	—
Beryllium bromide	$BeBr_2$	487.8	(47.9)	(26.6)	(4500)
Beryllium chloride	$BeCl_2$	404.8	(54)	(30)	(3000)
Beryllium oxide	BeO	2550.0	1223.	679.7	17000
Bismuth	Bi	271	21.6	12.0	2505
Bismuth trichloride	$BiCl_3$	223.8	14.8	8.2	2600
Bismuth trifluoride	BiF_3	726.0	(41.9)	(23.3)	(6200)
Bismuth trioxide	Bi_2O_3	815.8	26.3	14.6	6800
Boron	B	2300	(882)	(490)	(5300)
Boron tribromide	BBr_3	–48.8	(5.2)	(2.9)	(700)
Boron trichloride	BCl_3	–107.8	(7.7)	(4.3)	(500)
Boron trifluoride	BF_3	–128.0	12.6	7.0	480
Boron trioxide	B_2O_3	448.8	142.	78.9	5500
Bromine	Br_2	–7.2	29.0	16.1	2580
Bromine pentafluoride	BrF_5	–61.4	12.7	7.07	1355
Cadmium	Cd	320.8	23.2	12.9	1460
Cadmium bromide		567.8	(33.1)	(18.4)	(5000)
Cadmium chloride	$CdCl_2$	567.8	51.8	28.8	5300
Cadmium fluoride	CdF_2	1110	(64.6)	(35.9)	(5400)
Cadmium iodide	CdI_2	386.8	18.0	10.0	3660
Cadmium sulfate	$CdSO_4$	1000	41.2	22.9	4790
Calcium	Ca	851	100.	55.7	2230
Calcium bromide	$CaBr_2$	729.8	37.6	20.9	4180
Calcium carbonate	$CaCO_3$	1282	(227)	(126)	(12700)
Calcium chloride	$CaCl_2$	782	99	55	6100
Calcium fluoride	CaF_2	1382	94.5	52.5	4100
Calcium metasilicate	$CaSiO_2$	1512	208.	115.4	13400
Calcium nitrate	$Ca(NO_3)_2$	560.8	56.2	31.2	5120
Calcium oxide	CaO	2707	(393.)	(218.1)	(12240)
Calcium sulfate	$CaSO_4$	1297	88.6	49.2	6700
Carbon dioxide	CO_2	–57.6	77.8	43.2	1900.
Carbon monoxide	CO	–205	12.8	7.13	199.7
Cerium	Ce	775	27.2	15.1	2120
Cesium	Cs	28.3	6.7	3.7	500
Cesium chloride	CsCl	641.8	38.5	21.4	3600
Cesium nitrate	$CsNO_3$	406.8	29.9	16.6	3250
Chlorine	Cl_2	–103 ± 5	41.0	22.8	1531
Chromium	Cr	1890	112.	62.1	3600
Chromium (II) chloride	$CrCl_2$	814	119.	65.9	7700
Chromium (III) sequioxide	Cr_2O_3	2279	49.7	27.6	4200
Chromium trioxide	CrO_3	197	67.9	37.7	3770
Cobalt	Co	1490	112.	62.1	3640
Cobalt (II) chloride	$CoCl_2$	727	102.	56.9	7390
Copper	Cu	1083	88.2	49.0	3110
Copper (I) chloride	CuCl	429	47.5	26.4	2620
Copper (I) cyanide	$Cu_2(CN)_2$	473	(54.2)	(30.1)	(5400)
Copper (I) iodide	CuI	587	(24.5)	(13.6)	(2600)
Copper (I) oxide	Cu_2O	1230	(168.)	(93.6)	(13400)

Heat of Fusion of Some Inorganic Compounds* (continued)

Compound	Formula	Melting Point, ˚C	Heat of Fusion Btu/lb	cal/g	cal/g Mole
Copper (I) sulfide	Cu_2S	1129	62.3	34.6	5500
Copper (II) chloride	$CuCl_2$	430	44.5	24.7	4890
Copper (II) oxide	CuO	1446	63.7	35.4	2820
Cyanogen	C_2N2	–27.2	71.3	39.6	2060
Cyanogen chloride	CNCl	–5.2	65.5	36.4	2240
Deuterium oxide	D_2O	3.78	136.	75.8	1516
Dysprosium	Dy	1407	45.4	25.2	4100
Erbium	Er	1496	44.1	24.5	4100
Europium	Eu	826	29.5	16.4	2500
Europium trichloride	$EuCl_3$	622	(37.6)	(20.9)	(8000)
Fluorine	F_2	–219.6	11.5	6.4	244.0
Gadolinium	Gd	1312	42.8	23.8	3700
Gallium	Ga	29	(34.4)	19.1	1336
Germanium	Ge	959	(206.)	(114.3)	(8300)
Gold	Au	1063	(27.5)	15.3	3030
Hafnium	Hf	2214	(61.4)	(34.1)	(6000)
Holmium	Ho	1461	44.6	24.8	4100
Hydrogen	H_2	–259.25	24.8	13.8	28
Hydrogen bromide	HBr	–86.96	12.8	7.1	575.1
Hydrogen chloride	HCl	–114.3	23.4	13.0	476.0
Hydrogen fluoride	HF	–83.11	98.5	54.7	1094
Hydrogen iodide	HI	–50.91	9.7	5.4	686.3
Hydrogen nitrate	HNO_3	–47.2	17.1	9.5	601
Hydrogen oxide (water)	H_2O	0	138.	79.72	1436
Hydrogen peroxide	H_2O_2	–0.7	15.4	8.58	2920
Hydrogen selenate	H_2SeO_4	57.8	42.8	23.8	3450
Hydrogen sulfate	H_2SO_4	10.4	43.2	24.0	2360
Hydrogen sulfide	H_2S	–85.6	30.2	16.8	5683
Hydrogen sulfide, di-	H_2S_2	–89.7	49.1	27.3	1805
Hydrogen telluride	H_2Te	–49.0	23.2	12.9	1670
Indium	In	156.3	12.2	6.8	781
Iodine	I_2	112.9	25.7	14.3	3650
Iodine chloride (α)	ICl	17.1	29.5	16.4	2660
Iodine chloride (β)	ICl	13.8	23.9	13.3	2270
Iron	Fe	1530.0	115.	63.7	3560
Iron (II) chloride	$FeCl^2$	677	111.	61.5	7800
Iron (II) oxide	FeO	1380	(193.)	(107.2)	(7700)
Iron (II) sulfide	FeS	1195	102.	56.9	5000
Iron (III) chloride	Fe_2Cl_6	303.8	114.	63.2	20500
Iron carbide	Fe_3C	1226.8	123.	68.6	12330
Iron oxide	Fe_3O_4	1596	257.	142.5	33000
Iron pentacarbonyl	$Fe(CO)_2$	–21.2	29.7	16.5	3250
Lanthanum	La	920	31.3	17.4	2400
Lead	Pb	327.3	10.6	5.9	1224
Lead bromide	$PbBr_2$	487.8	21.1	11.7	4290
Lead chloride	$PbCl_2$	497.8	36.5	20.3	5650
Lead fluoride	PbF_2	823	13.7	7.6	1860
Lead iodide	Pbl2	412	32.2	17.9	5970
Lead molybdate	$PbMoO_4$	1065	(127.)	70.8	(25800)
Lead oxide	PbO	890	22.7	12.6	2820
Lead sulfate	$PbSO_4$	1087	56.9	31.6	9600
Lead sulfide	PbS	1114	31.1	17.3	4150
Lithium	Li	178.8	285.	158.5	1100
Lithium bromide	LiBr	552	60.1	33.4	2900
Lithium chloride	LiCl	614	136.	75.5	3200

Heat of Fusion of Some Inorganic Compounds* (continued)

Compound	Formula	Melting Point, °C	Heat of Fusion Btu/lb	cal/g	cal/g Mole
Lithium fluoride	LiF	896	(164.)	(91.1)	(2360)
Lithium hydroxide	LiOH	462	186.	103.3	2480
Lithium iodide	Lil	440	(19.1)	(10.6)	(1420)
Lithium metasilicate	Li_2SiO_3	1177	144.	80.2	7210
Lithium molybdate	Li_2MoO_4	705	43.4	24.1	4200
Lithium nitrate	$LiNO_3$	250	158.	87.8	6060
Lithium orthosilicate	Li_4SiO_4	1249	109.	60.5	7340
Lithium sulfate	Li_2SO_4	857	49.7	27.6	3040
Lithium tungstate	Li_2WO_4	742	(46.1)	(25.6)	(6700)
Lutetium	Lu	1651	47.3	26.3	4600
Magnesium	Mg	650	160.	88.9	2160
Magnesium bromide	$MgBr_2$	711	81.0	45.0	8300
Magnesium chloride	$MgCl_2$	712	149.	82.9	8100
Magnesium fluoride	MgF_2	1221	170.	94.7	5900
Magnesium oxide	MgO	2642	826.	459.0	18500
Magnesium silicate	$MgSiO_3$	1524	264.	146.4	14700
Magnesium sulfate	$MgSO_4$	1327	52.0	28.9	3500
Manganese	Mn	1220	113.	62.7	3450
Manganese (II) oxide	MnO	1784	330.	183.3	13000
Manganese dichloride	$MnCl_2$	650	105.	58.4	7340
Manganese metasilicate	$MnSiO_3$	1274	(113.)	(62.6)	(8200)
Manganese oxide	Mn_3O_4	1590	(307.)	(170.4)	(39000)
Mercury	Hg	–39	4.9	2.7	557.2
Mercury bromide	$HgBr_2$	241	19.6	10.9	3960
Mercury chloride	$HgCl_2$	276.8	27.5	15.3	4150
Mercury iodide	HgI_2	250	17.8	9.9	4500
Mercury sulfate	$HgSO_4$	850	8.6	(4.8)	(1440)
Molybdenum	Mo	2622	(123.)	(68.4)	(6600)
Molybdenum dichloride	$MoCl_2$	726.8	64.4	3.58	6000
Molybdenum hexafluoride	MoF_4	17	21.4	11.9	2500
Molybdenum trioxide	MoO_3	795	(31.1)	(17.3)	(2500)
Neodymium	Nd	1020	21.2	11.8	1700
Neon	Ne	–248.6	6.89	3.83	77.4
Nickel	Ni	1452	129.	71.5	4200
Nickel chloride	$NiCl_2$	1030	257.	142.5	18470
Nickel subsulfide	Ni_3S_2	790	46.4	25.8	5800
Niobium	Nb	2496	(124.)	(68.9)	(6500)
Niobium pentachloride	$NbCl_5$	211	55.4	30.8	8400
Niobium pentoxide	Nb_2O_5	1511	164.	91.0	24200
Nitric oxide	NO	–163.7	32.9	18.3	549.5
Nitrogen	N_2	–210	11.1	6.15	172.3
Nitrogen tetroxide	N_2O_4	–13.2	108.	60.2	5540
Nitrous oxide	N_2O	–90.9	63.9	35.5	1563
Osmium	Os	2700	(66.1)	(36.7)	(7000)
Osmium tetroxide (white)	OsO_4	41.8	16.6	9.2	2340
Osmium tetroxide (yellow)	OsO_4	55.8	27.9	15.5	4060
Oxygen	O_2	–218.8	5.9	3.3	106.3
Palladium	Pd	1555	69.5	38.6	4120
Phosphoric acid	H_3PO_4	42.3	46.4	25.8	2520
Phosphoric acid, hypo-	$H_4P_2O_6$	54.8	92.2	51.2	8300
Phosphorus acid, hypo	H_3PO_2	17.3	63.0	35.0	2310
Phosphorus acid, ortho-	H_3PO_3	73.8	67.3	37.4	3070
Phosphorus oxychloride	$POCl_3$	1.0	36.5	20.3	3110
Phosphorus pentoxide	P_4O_{10}	569.0	108.	60.1	17080
Phosphorus trioxide	P_4O_6	23.7	27.5	15.3	3360

Heat of Fusion of Some Inorganic Compounds* (continued)

Compound	Formula	Melting Point, °C	Heat of Fusion Btu/lb	Heat of Fusion cal/g	Heat of Fusion cal/g Mole
Phosphorus, yellow	P_4	44.1	8.6	4.8	600
Platinum	Pt	1770	43.4	24.1	4700
Potassium	K	63.4	26.3	14.6	574
Potassium borate, meta-	KBO_2	947	(124.)	(69.1)	(5600)
Potassium bromide	KBr	742	75.6	42.0	5000
Potassium carbonate	K_2CO_3	897	102.	56.4	7800
Potassium chloride	KCl	770	155.	85.9	6410
Potassium chromate	K_2CrO_4	984	64.1	35.6	6920
Potassium cyanide	KCN	623	(96.7)	(53.7)	(3500)
Potassium dichromate	$K_2Cr_2O_7$	398	53.6	29.8	8770
Potassium fluoride	KF	875	201.	111.9	6500
Potassium hydroxide	KOH	360	(63.5)	(35.3)	(1980)
Potassium iodide	KI	682	44.5	24.7	4100
Potassium nitrate	KNO_3	338	50.6	28.1	2840
Potassium peroxide	K_2O_2	490	99.5	55.3	6100
Potassium phosphate	K_3PO_4	1340	75.4	41.9	8900
Potassium pyrophosphate	$K_4P_2O_7$	1092	76.3	42.4	14000
Potassium sulfate	K_2SO_4	1074	83.5	46.4	8100
Potassium thiocyanate	KSCN	179	41.6	23.1	2250
Praseodymium	Pr	931	34.2	19.0	2700
Rhenium	Re	3167 ± 60	(76.3)	(42.4)	(7900)
Rhenium heptoxide	Re_2O_7	296	54.2	30.1	15340
Rhenium hexafluoride	ReF_6	19.0	29.9	16.6	5000
Rubidium	Rb	38.9	11.0	6.1	525
Rubidium bromide	RbBr	677	40.3	22.4	3700
Rubidium chloride	RbCl	717	65.5	36.4	4400
Rubidium fluoride	RbF	833	71.1	39.5	4130
Rubidium iodide	RbI	638	25.2	14.0	2990
Rubidium nitrate	$RbNO_3$	305	16.4	9.1	1340
Samarium	Sm	1072	31.1	17.3	2600
Scandium	Sc	1538	152.	84.4	3800
Selenium	Se	217	27.7	15.4	1220
Selenium oxychloride	$SeOCl_3$	9.8	11.0	6.1	1010
Silane, hexafluoro-	Si_2F_6	–28.6	41.2	22.9	3900
Silicon	Si	1427	607.	337.0	9470
Silicon dioxide (Cristobalite)	SiO_2	2100	63.0	35.0	2100
Silicon dioxide (Quartz)	SiO_2	1470	102.	56.7	3400
Silicon tetrachloride	$SiCl_4$	–67.7	19.4	10.8	1845
Silver	Ag	961	45.0	25.0	2700
Silver bromide	AgBr	430	20.9	11.6	2180
Silver chloride	AgCl	455	39.6	22.0	3155
Silver cyanide	AgCN	350	36.9	20.5	2750
Silver iodide	AgI	557	17.1	9.5	2250
Silver nitrate	$AgNO_3$	209	29.2	16.2	2755
Silver sulfate	Ag_2SO_4	657	(24.7)	(13.7)	(4280)
Silver sulfide	Ag_2S	841	24.3	13.5	3360
Sodium	Na	97.8	49.3	27.4	630
Sodium borate, meta-	$NaBO_2$	966	242.	134.6	8600
Sodium bromide	NaBr	747	107.	59.7	6140
Sodium carbonate	Na_2CO_3	854	119.	66.0	7000
Sodium chlorate	$NaClO_3$	255	89.5	49.7	5290
Sodium chloride	NaCl	800	222.	123.5	7220
Sodium cyanide	NaCN	562	(160.)	(88.9)	(4360)
Sodium fluoride	NaF	992	300.	166.7	7000
Sodium hydroxide	NaOH	322	90.0	50.0	2000

Heat of Fusion of Some Inorganic Compounds* (continued)

Compound	Formula	Melting Point, °C	Heat of Fusion Btu/lb	cal/g	cal/g Mole
Sodium iodide	NaI	662	63.2	35.1	5340
Sodium molybdate	Na_2MoO_4	687	31.5	17.5	3600
Sodium nitrate	NaNO3	310	79.6	44.2	3760
Sodium peroxide	Na_2O_2	460	135.	75.1	5860
Sodium phosphate, meta-	$NaPO_3$	988	(87.5)	(48.6)	(4960)
Sodium pyrophosphate	$Na_4P_2O_7$	970	(92.7)	(51.5)	(13700)
Sodium silicate, aluminum-	$NaAlSi_3O_8$	1107	90.2	50.1	13150
Sodium silicate, di-	$Na_2Si_2O_5$	884	83.5	46.4	8460
Sodium silicate, meta-	Na_2SiO_3	1087	152.	84.4	10300
Sodium sulfate	Na_2SO_4	884	73.8	41.0	5830
Sodium sulfide	Na_2S	920	(27.7)	15.4	(1200)
Sodium thiocyanate	NaSCN	323	98.6	54.8	4450
Sodium tungstate	Na_2WO_4	702	35.3	19.6	5800
Strontium	Sr	757	45.0	25.0	2190
Strontium bromide	$SrBr_2$	643	34.7	19.3	4780
Strontium chloride	$SrCl_2$	872	47.7	26.5	4100
Strontium fluoride	SrF_2	1400	61.2	34.0	4260
Strontium oxide	SrO	2430	290.	161.2	16700
Sulfur (monatomic)	S	119	16.6	9.2	295
Sulfur dioxide	SO_2	–73.2	58.0	32.2	2060
Sulfur trioxide (α)	SO_3	16.8	46.4	25.8	2060
Sulfur trioxide (β)	SO_3	32.3	65.0	36.1	2890
Sulfur trioxide (γ)	SO_3	62.1	142.	79.0	6310
Tantalum	Ta	2996 ± 50	(62.3) 74.7	34.6–41.5	(7500)
Tantalum pentachloride	$TaCl_5$	206.8	45.2	25.1	9000
Tantalum pentoxide	Ta_2O_5	1877	195.	108.6	48000
Tellurium	Te	453	45.5	25.3	3230
Terbium	Tb	1356	44.3	24.6	3900
Thallium	Tl	302.4	9.0	5.0	1030
Thallium bromide, mono-	TlBr	460	37.8	21.0	5990
Thallium carbonate	Tl_2CO_3	273	17.1	9.5	4400
Thallium chloride, mono-	TlCl	427	31.9	17.7	4260
Thallium iodide, mono-	TlI	440	16.9	9.4	3125
Thallium nitrate	$TlNO_3$	207	15.5	8.6	2290
Thallium sulfate	Tl_2SO_4	632	19.6	10.9	5500
Thallium sulfide	Tl_2S	449	12.2	6.8	3000
Thorium	Th	1845	(<35.6)	(<19.8)	(<4600)
Thorium chloride	$ThCl_4$	765	111.	61.6	22500
Thorium dioxide	ThO_2	2952	1984.	1102.0	291100
Thulium	Tm	1545	46.8	26.0	4400
Tin	Sn	231.7	25.9	14.4	1720
Tin bromide, di-	$SnBr_2$	231.8	(11.0)	(6.1)	(1720)
Tin bromide, tetra-	$SnBr_4$	29.8	12.2	6.8	3000
Tin chloride, di-	$SnCl_2$	247	28.8	16.0	3050
Tin chloride, tetra-	$SnCl_4$	–33.3	15.1	8.4	2190
Tin iodide, tetra-	SnI_4	143.4	(12.4)	(6.9)	(4330)
Tin oxide	SnO	1042	(84.2)	(46.8)	(6400)
Titanium	Ti	1800	(188.)	(104.4)	(5000)
Titanium bromide, tetra-	$TiBr_4$	38	(10.1)	(5.6)	(2060)
Titanium chloride, tetra-	$TiCl_4$	–23.2	21.4	11.9	2240
Titanium dioxide	TiO_2	1825	(257.)	(142.7)	(11400)
Titanium oxide	TiO	991	394	219	14000
Tungsten	W	3387	(82.4)	(45.8)	(8420)
Tungsten dioxide	WO_2	1270	108.	60.1	13940
Tungsten hexafluoride	WF_6	–0.5	10.8	6.0	1800

Heat of Fusion of Some Inorganic Compounds* (continued)

Compound	Formula	Melting Point, °C	Heat of Fusion Btu/lb	cal/g	cal/g Mole
Tungsten tetrachloride	WCl_4	327	33.1	18.4	6000
Tungsten trioxide	WO_3	1470	108.	60.1	13940
Uranium^{235}	U	~1133	36	20	3700
Uranium tetrachloride	UCl_4	590	48.8	27.1	10300
Vanadium	V	1917	(126)	(70)	(4200)
Vanadium dichloride	VCl_2	1027	118.	65.6	8000
Vanadium oxide	VO	2077	403.	224.0	15000
Vanadium pentoxide	V_2O_5	670	154.	85.5	15560
Xenon	Xe	–111.6	10.1	5.6	740
Ytterbium	Yb	823	22.9	12.7	2200
Yttrium	Y	1504	83.0	46.1	4100
Yttrium oxide	Y_2O_3	2227	199.	110.7	25000
Zinc	Zn	419.4	43.9	24.4	1595
Zinc chloride	$ZnCl_2$	283	(73.1)	(40.6)	(5540)
Zinc oxide	ZnO	1975	98.8	54.9	4470
Zinc sulfide	ZnS	1745	168.	(93.3)	(9100)
Zirconium	Zr	1857	(108)	(60)	(5500)
Zirconium dichloride	$ZrCl_2$	727	81.0	45.0	7400
Zirconium oxide	ZrO_2	2715	304.	168.8	20800

From Bolz, R.E. and Tuve, G.L., Thermodynamics, in *CRC Handbook of Tables for Applied Engineering Science*, CRC Press, Boca Raton, FL, 1973, pp. 479–483.

Conservation Equations of a Viscous, Heat-Conducting Fluid

In Curvillnear Orthogonal Coordinates

NOMENCLATURE:

e_{ij} = components of rate of strain tensor
E = internal energy per unit mass
f = scalar
F = body force per unit volume
$h_1 h_2 h_3$ = scale factors
H = static enthalpy per unit mass
H_t = total enthalpy, $H_t = H + V^2/2$
k = thermal conductivity
p = static pressure
q = heat-flux vector
q_β = heat-flux component normal to the surface
t = time
T = temperature
u = velocity component in α direction
v = velocity component in β direction
V = velocity vector
w = velocity component in y direction
W = heat generation per unit volume
α, β, γ = orthogonal coordinates
κ = bulk viscosity
λ = second viscosity coefficient
μ = shear viscosity
ρ = density
τ = viscous stress tensor

I. Introduction

Although formulation of the conservation equations of a viscous, heat-conducting fluid in curvilinear orthogonal coordinates is well known through vector and tensor analysis (Refs. 1 and 2), a complete, written-out set of equations, including the energy equation, is not readily available in any given source. The momentum equation was given by Goldstein (Ref. 3) in curvilinear orthogonal coordinates for an incompressible, constant-property fluid, and by Tsien (Ref. 4) for a compressible, variable-property fluid. Only the commonly used special cases of the set of equations in rectangular, cylindrical, and spherical coordinates appear in the literature (e.g., Ref. 5). The purpose of this paper is to briefly present the complete set of equations in stationary, curvilinear orthogonal coordinates. For convenience in expressing the equations in various coordinates, scale factors for eleven coordinate systems are tabulated.

II. Conservation Equations

Three forms of the energy equation are considered, one form of which may be best suited for a particular application. These relations involve the total enthalpy H_t,

$$\rho\frac{\partial H_t}{\partial t}+\rho(\mathbf{V}\cdot\nabla)H_t=\frac{\partial p}{\partial t}-\nabla\cdot\mathbf{q}+\nabla\cdot(\tau\cdot\mathbf{V})+\mathbf{F}\cdot\mathbf{V}+W$$

the internal energy E,

$$\rho\frac{\partial E}{\partial t}+\rho(\mathbf{V}\cdot\nabla)E+p\nabla\cdot\mathbf{V}=-\nabla\cdot\mathbf{q}+\tau:(\nabla\mathbf{V})+W$$

and the enthalpy H,

$$\rho\frac{\partial H}{\partial t}+\rho(\mathbf{V}\cdot\nabla)H-\left[\frac{\partial p}{\partial t}+(\mathbf{V}\cdot\nabla)p\right]=-\nabla\cdot\mathbf{q}+\tau:(\nabla\mathbf{V})+W$$

To complete the set of conservation equations, the continuity and momentum equations are, respectively,

$$\frac{\partial\rho}{\partial t}+\nabla\cdot(\rho\mathbf{V})=0$$

$$\frac{\partial\mathbf{V}}{\partial t}+(\mathbf{V}\cdot\nabla)\mathbf{V}=-\frac{1}{\rho}\nabla p+\frac{\mathbf{F}}{\rho}+\frac{1}{\rho}\nabla\cdot\tau$$

The quantities that appear in these equations are identified in the nomenclature.

By use of the same notation as used by Goldstein (Ref. 3), the orthogonal coordinates are taken as α, β, and γ such that the elements of length at α, β, and γ in the directions of increasing α, β, and γ are $h_1 d\alpha$, $h_2 d\beta$, and $h_2 d\gamma$, respectively. The differential arc length ds is, then,

$$(ds)^2=h_1^2(d\alpha)^2+h_2^2(d\beta)^2+h_3^2(d\gamma)^2$$

Conservation Equations of a Viscous, Heat-Conducting Fluid (continued)

u, *v*, and *w* are components of the velocity vector **V** in the direction of increasing α, β, and γ, the continuity equation is

$$+\frac{1}{h_1h_2h_3}\times\left[\frac{\partial}{\partial\alpha}(h_2h_3\rho u)+\frac{\partial}{\partial\beta}(h_1h_3\rho v)+\frac{\partial}{\partial\gamma}(h_1h_2\rho w)\right]=0$$

the momentum equation written in the α, β, and γ directions is

$$\frac{\partial u}{\partial t}+\frac{u}{h_1}\frac{\partial u}{\partial\alpha}+\frac{v}{h_2}\frac{\partial u}{\partial\beta}+\frac{w}{h_2}\frac{\partial u}{\partial\gamma}+\frac{uv}{h_1h_2}\frac{\partial h_1}{\partial\beta}+\frac{uw}{h_1h_3}\frac{\partial h_1}{\partial\gamma}$$

$$\frac{v^2}{h_1h_2}\frac{\partial h_2}{\partial\alpha}-\frac{w^2}{h_1h_3}\frac{\partial h_3}{\partial\alpha}=-\frac{1}{\rho}\frac{1}{h_1}\frac{\partial p}{\partial\alpha}+\frac{F_\alpha}{\rho}+\frac{1}{\rho}(\nabla\cdot\tau)_\alpha$$

$$\frac{\partial v}{\partial t}+\frac{u}{h_1}\frac{\partial v}{\partial\alpha}+\frac{v}{h_2}\frac{\partial v}{\partial\beta}+\frac{w}{h_3}\frac{\partial v}{\partial\gamma}+\frac{vu}{h_1h_2}\frac{\partial h_2}{\partial\alpha}+\frac{vw}{h_2h_3}\frac{\partial h_2}{\partial\gamma}$$

$$\frac{u^2}{h_1h_2}\frac{\partial h_1}{\partial\beta}-\frac{w^2}{h_2h_3}\frac{\partial h_3}{\partial\beta}=-\frac{1}{\rho}\frac{1}{h_2}\frac{\partial p}{\partial\beta}+\frac{F_\beta}{\rho}+\frac{1}{\rho}(\nabla\cdot\tau)_\beta$$

$$\frac{\partial w}{\partial t}+\frac{u}{h_1}\frac{\partial w}{\partial\alpha}+\frac{v}{h_2}\frac{\partial w}{\partial\beta}+\frac{w}{h_3}\frac{\partial w}{\partial\gamma}+\frac{wu}{h_1h_3}\frac{\partial h_3}{\partial\alpha}+\frac{wv}{h_2h_3}\frac{\partial h_2}{\partial\beta}$$

$$\frac{u^2}{h_1h_3}\frac{\partial h_1}{\partial\beta}-\frac{v^2}{h_2h_3}\frac{\partial h_2}{\partial\gamma}=-\frac{1}{\rho}\frac{1}{h_3}\frac{\partial p}{\partial\gamma}+\frac{F_\gamma}{\rho}+\frac{1}{\rho}(\nabla\cdot\tau)_\gamma$$

ε components of the divergence of the symmetric stress tensor τ in the α, β, and γ direction (Ref. 6)[1] are:

$$(\nabla\cdot\tau)_\alpha=\frac{1}{h_1h_2h_3}\left[\frac{\partial}{\partial\alpha}(h_2h_3\tau_{\alpha\alpha})+\frac{\partial}{\partial\beta}(h_1h_3\tau_{\alpha\beta})+\frac{\partial}{\partial\gamma}(h_1h_2\tau_{\gamma\alpha})\right]$$
$$+\tau_{\alpha\beta}\frac{1}{h_1h_2}\frac{\partial h_1}{\partial\beta}+\tau_{\gamma c}\frac{1}{h_1h_3}\frac{\partial h_1}{\partial\gamma}$$
$$-\tau_{\beta\beta}\frac{1}{h_1h_2}\frac{\partial h_2}{\partial\alpha}-\tau_{\gamma\gamma}\frac{1}{h_1h_3}\frac{\partial h_3}{\partial\alpha}$$

$$(\nabla\cdot\tau)_\beta=\frac{1}{h_1h_2h_3}\left[\frac{\partial}{\partial\alpha}(h_2h_3\tau_{\alpha\beta})+\frac{\partial}{\partial\beta}(h_1h_3\tau_{\beta\beta})+\frac{\partial}{\partial\gamma}(h_1h_2\tau_{\beta\gamma})\right]$$
$$+\tau_{\alpha\beta}\frac{1}{h_1h_2}\frac{\partial h_2}{\partial\alpha}+\tau_{\beta\gamma}\frac{1}{h_2h_3}\frac{\partial h_2}{\partial\gamma}$$
$$-\tau_{\alpha\alpha}\frac{1}{h_1h_2}\frac{\partial h_1}{\partial\beta}-\tau_{\gamma\gamma}\frac{1}{h_2h_3}\frac{\partial h_3}{\partial\beta}$$

[1]ε, h_1, h_2, and h_3 used by Love are the reciprocals of those used herein.

Conservation Equations of a Viscous, Heat-Conducting Fluid (continued)

$$(\nabla \cdot \tau)_\gamma =$$

$$\frac{1}{h_1 h_2 h_3}\left[\frac{\partial}{\partial \alpha}\left(h_2 h_3 \tau_{\gamma\alpha}\right)+\frac{\partial}{\partial \beta}\left(h_1 h_3 \tau_{\beta\gamma}\right)+\frac{\partial}{\partial \gamma}\left(h_1 h_2 \tau_{\gamma\gamma}\right)\right]$$

$$+\tau_{\gamma\alpha}\frac{1}{h_1 h_3}\frac{\partial h_3}{\partial \alpha}+\tau_{\beta\gamma}\frac{1}{h_2 h_3}\frac{\partial h_3}{\partial \beta}$$

$$-\tau_{\alpha\alpha}\frac{1}{h_1 h_3}\frac{\partial h_1}{\partial \gamma}-\tau_{\beta\beta}\frac{1}{h_2 h_3}\frac{\partial h_2}{\partial \gamma}$$

The components of the viscous stress tensor for a Stokes' fluid are related to the components of the rate of strain tensor by

$$\tau_{\alpha\alpha} = \lambda \nabla \cdot \mathbf{V} + \mu e_{\alpha\alpha}$$

$$\tau_{\beta\beta} = \lambda \nabla \cdot \mathbf{V} + \mu e_{\beta\beta}$$

$$\tau_{\gamma\gamma} = \lambda \nabla \cdot \mathbf{V} + \mu e_{\gamma\gamma}$$

$$\tau_{\alpha\beta} = \tau_{\beta\alpha} = \mu e_{\alpha\beta}$$

$$\tau_{\alpha\gamma} = \tau_{\gamma\alpha} = \mu e_{\alpha\gamma}$$

$$\tau_{\beta\gamma} = \tau_{\gamma\beta} = \mu e_{\beta\gamma}$$

where the divergence of the velocity vector is

$$\nabla \cdot \mathbf{V} = \frac{1}{h_1 h_2 h_3}\left[\frac{\partial}{\partial \alpha}\left(h_2 h_3 u\right)+\frac{\partial}{\partial \beta}\left(h_1 h_3 v\right)+\frac{\partial}{\partial \gamma}\left(h_1 h_2 w\right)\right]$$

and the components of the rate of strain tensor are (Ref. 3):

$$\frac{1}{2}e_{\alpha\alpha} = \frac{1}{h_1}\frac{\partial u}{\partial \alpha}+\frac{v}{h_1 h_2}\frac{\partial h_1}{\partial \beta}+\frac{w}{h_3 h_1}\frac{\partial h_1}{\partial \gamma}$$

$$\frac{1}{2}e_{\beta\beta} = \frac{1}{h_2}\frac{\partial v}{\partial \beta}+\frac{w}{h_2 h_3}\frac{\partial h_2}{\partial \gamma}+\frac{u}{h_1 h_2}\frac{\partial h_2}{\partial \alpha}$$

$$\frac{1}{2}e_{\gamma\gamma} = \frac{1}{h_3}\frac{\partial w}{\partial y}+\frac{u}{h_1 h_3}\frac{\partial h_3}{\partial \alpha}+\frac{v}{h_2 h_3}\frac{\partial h_3}{\partial \beta}$$

$$e_{\alpha\beta} = \frac{h_2}{h_1}\frac{\partial}{\partial \alpha}\left(\frac{v}{h_2}\right)+\frac{h_1}{h_2}\frac{\partial}{\partial \beta}\left(\frac{u}{h_1}\right)$$

$$e_{\alpha\gamma} = \frac{h_1}{h_3}\frac{\partial}{\partial \gamma}\left(\frac{u}{h_1}\right)+\frac{h_3}{h_1}\frac{\partial}{\partial \alpha}\left(\frac{w}{h_3}\right)$$

$$e_{\beta\gamma} = \frac{h_3}{h_2}\frac{\partial}{\partial \beta}\left(\frac{w}{h_3}\right)+\frac{h_2}{h_3}\frac{\partial}{\partial \gamma}\left(\frac{v}{h_2}\right)$$

The second viscosity coefficient λ is related to the shear viscosity μ (first viscosity coefficient) by $\lambda = 2/3\ \mu$ if the bulk viscosity coefficient defined by $\kappa = \lambda + 2/3\ \mu$ is *zero*. Otherwise, λ is given by

$$\lambda = \kappa - \frac{2}{3}\mu$$

Conservation Equations of a Viscous, Heat-Conducting Fluid (continued)

In the various forms of the energy equations, the operator $(\mathbf{V}\cdot\nabla)$ applied to a scalar f, such as H_t, E, p, or H, gives the convection of that quantity by the flow,

$$(\mathbf{V}\cdot\nabla)f = u\frac{1}{h_1}\frac{\partial f}{\partial\alpha} + v\frac{1}{h_2}\frac{\partial f}{\partial\beta} + w\frac{1}{h_3}\frac{\partial f}{\partial\gamma}$$

The divergence of the heat flux vector **q** is

$$\nabla\cdot\mathbf{q} = \frac{1}{h_1h_2h_3}\left[\frac{\partial}{\partial\alpha}(h_2h_3q_\alpha) + \frac{\partial}{\partial\beta}(h_1h_3q_\beta) + \frac{\partial}{\partial\gamma}(h_1h_2q_\gamma)\right]$$

In particular, if the heat flux vector is given by Fourier's heat-conduction law, $\mathbf{q} = k\,\nabla\,T$, then the components are

$$q_\alpha = -k\frac{1}{h_1}\frac{\partial T}{\partial\alpha}, \quad q_\beta = -k\frac{1}{h_2}\frac{\partial T}{\partial\beta}, \quad q_\gamma = -k\frac{1}{h_3}\frac{\partial T}{\partial\gamma}$$

The rate at which work is done by body forces is, simply,

$$\mathbf{F}\cdot\mathbf{V} = F_\alpha u + F_\beta v + F_\gamma w$$

The rate at which work is done by the viscous stresses is given by

$$\begin{aligned}\nabla\cdot(\tau\cdot\mathbf{V}) = \frac{1}{h_1h_2h_3}\Bigg\{&\frac{\partial}{\partial\alpha}\left[h_2h_3(\tau_{\alpha\alpha}u + \tau_{\beta\alpha}v + \tau_{\gamma\alpha}w)\right]\\ &+ \frac{\partial}{\partial\beta}\left[h_1h_3(\tau_{\alpha\beta}u + \tau_{\beta\beta}v + \tau_{\gamma\beta}w)\right]\\ &+ \frac{\partial}{\partial\gamma}\left[h_1h_2(\tau_{\alpha\gamma}u + \tau_{\beta\gamma}v + \tau_{\gamma\gamma}w)\right]\Bigg\}\end{aligned}$$

Lastly, the rate of dissipation of energy takes the form

$$\begin{aligned}\tau:(\nabla\mathbf{V}) = {}&\tau_{\alpha\alpha}\left(\frac{1}{h_1}\frac{\partial u}{\partial\alpha} + \frac{v}{h_1h_2}\frac{\partial h_1}{\partial\beta} + \frac{w}{h_1h_3}\frac{\partial h_1}{\partial\gamma}\right)\\ &+ \tau_{\beta\beta}\left(\frac{1}{h_2}\frac{\partial v}{\partial\beta} + \frac{u}{h_1h_2}\frac{\partial h_2}{\partial\alpha} + \frac{w}{h_2h_3}\frac{\partial h_2}{\partial\gamma}\right)\\ &+ \tau_{\gamma\gamma}\left(\frac{1}{h_3}\frac{\partial w}{\partial\gamma} + \frac{u}{h_1h_3}\frac{\partial h_2}{\partial\alpha} + \frac{v}{h_2h_3}\frac{\partial h_3}{\partial\beta}\right)\\ &+ \tau_{\alpha\beta}\left(\frac{1}{h_2}\frac{\partial u}{\partial\beta} + \frac{1}{h_1}\frac{\partial v}{\partial\alpha} - \frac{v}{h_1h_2}\frac{\partial h_2}{\partial\alpha} - \frac{u}{h_1h_2}\frac{\partial h_1}{\partial\beta}\right)\\ &+ \tau_{\alpha\gamma}\left(\frac{1}{h_3}\frac{\partial u}{\partial\gamma} + \frac{1}{h_1}\frac{\partial w}{\partial\alpha} - \frac{w}{h_1h_3}\frac{\partial h_3}{\partial\alpha} - \frac{u}{h_1h_2}\frac{\partial h_1}{\partial\gamma}\right)\\ &+ \tau_{\beta\gamma}\left(\frac{1}{h_3}\frac{\partial v}{\partial\gamma} + \frac{1}{h_2}\frac{\partial w}{\partial\beta} - \frac{w}{h_2h_3}\frac{\partial h_2}{\partial\beta} - \frac{v}{h_2h_3}\frac{\partial h_2}{\partial\gamma}\right)\end{aligned}$$

This rate of dissipation of energy term usually appears in the literature as Φ.

Table 1 presents descriptive information on a number of orthogonal coordinate systems for which the conservation equations can be readily written by use of the foregoing relations. The last two entries in Table 1, in which the coordinates are taken along and normal to the surface, are useful in analyzing internal and external boundary-layer flows. For many flow problems in these coordinates, the dominant viscous stress is the shear stress that lies in the plane of β = const ($\tau_{\alpha\beta}$ for a two-dimensional flow and $\tau_{\alpha\beta}$, $\tau_{\gamma\beta}$ for a three-dimensional flow), and the important heat-flux component is normal to the surface, q_β.

Table 1. COORDINATE SYSTEMS AND SCALE FACTORS

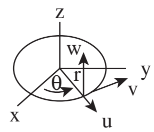
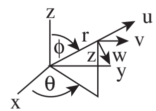
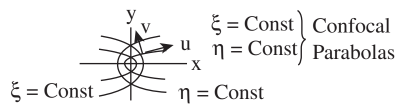
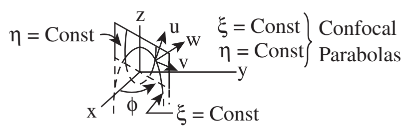
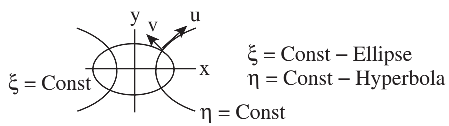
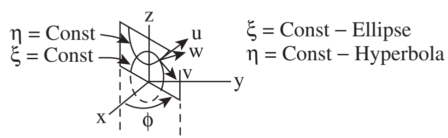
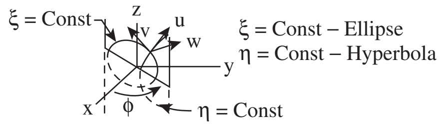
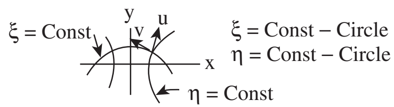
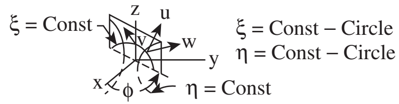
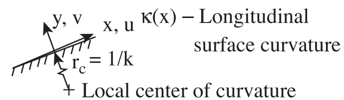
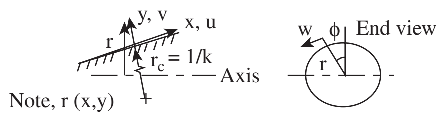
1. Orthogonal Coordinate System, and 2. Orthogonal coordinates α, β, γ	Rectangular Coordinates			Scale Factors h_1, h_2, h_α			
	x	y	z	h_1	h_2	h_3	Coordinate Configuration
Cylindrical r, θ, z	$r \cos q$	$r \sin q$	z	1	r	1	
Spherical r, ϕ, θ	$r \cos\theta \sin\phi$	$r \sin\theta \sin\phi$	$r \cos\phi$	1	r	$r \sin\theta$	
Parabolic cylindrical ξ, η, z	$\frac{1}{2}(\xi^2 - \eta^2)$	$\zeta\eta$	z	$\sqrt{\xi^2 + \eta^2}$	$\sqrt{\xi^2 + \eta^2}$	1	
Paraboloidal ξ, η, ϕ	$\xi\eta \cos\phi$	$\xi\eta \sin\phi$	$\frac{1}{2}(\xi^2 - \eta^2)$	$\sqrt{\xi^2 + \eta^2}$	$\sqrt{\xi^2 + \eta^2}$	$\xi\eta$	
Elliptic cylindrical ξ, η, z	$\alpha \cosh\xi \cos\eta$ α = const	$\alpha \sinh\xi \sin\eta$	z	$\alpha\sqrt{\sinh^2\xi + \sin^2\eta}$	$\alpha\sqrt{\sinh^2\xi + \sin^2\eta}$	1	
Prolate spheroidal ξ, η, ϕ	$\alpha \sinh\xi \sin\eta$ $\cos\phi$ α = const	$\alpha \sinh\xi \sin\eta$ $\sin\phi$	$\alpha \cosh\xi \cos\eta$	$\alpha\sqrt{\sinh^2\xi + \sin^2\eta}$	$\alpha\sqrt{\sinh^2\xi + \sin^2\eta}$	$\alpha \sinh\xi \sin\eta$	

Table 1. COORDINATE SYSTEMS AND SCALE FACTORS (continued)

Oblate spheroidal ξ, η, ϕ	$\alpha \cosh \xi \cos \eta \cos \phi$ α = const	$\alpha \cosh \xi \cos \eta \sin \phi$	$\alpha \sinh \xi \sin \eta$	$\alpha\sqrt{\sinh^2 \xi + \sin^2 \eta}$	$\alpha\sqrt{\sinh^2 \xi + \sin^2 \eta}$	$\alpha \cosh \xi \cos \eta$	
Bipolar ξ, η, x	$\frac{\alpha \sinh \eta}{\cosh \eta - \cos \xi}$ $\alpha = \text{const}$	$\frac{\alpha \sinh \xi}{\cosh \eta - \cos \xi}$	z	$\frac{\alpha}{\cosh \eta - \cos \xi}$	$\frac{\alpha}{\cosh \eta - \cos \xi}$	1	
Toroidal ξ, η, ϕ	$\frac{\alpha \sinh \eta \cos \phi}{\cosh \eta - \cos \xi}$ $\alpha = \text{const}$	$\frac{\alpha \sinh \eta \sin \phi}{\cosh \eta - \cos \xi}$	$\frac{\alpha \sinh \xi}{\cosh \eta - \cos \xi}$	$\frac{\alpha}{\cosh \eta - \cos \xi}$	$\frac{\alpha}{\cosh \eta - \cos \xi}$	$\frac{\alpha \sinh \eta}{\cosh \eta - \cos \xi}$	
Local coordinates along surface (Ref. 3) x, y, z	—	—	—	$1 + \kappa\gamma$	1	1	
Local coordinates along surface (Ref. 3) Symmetric about axis x, y, ϕ	—	—	—	$1 + \kappa\gamma$	1	r	

References
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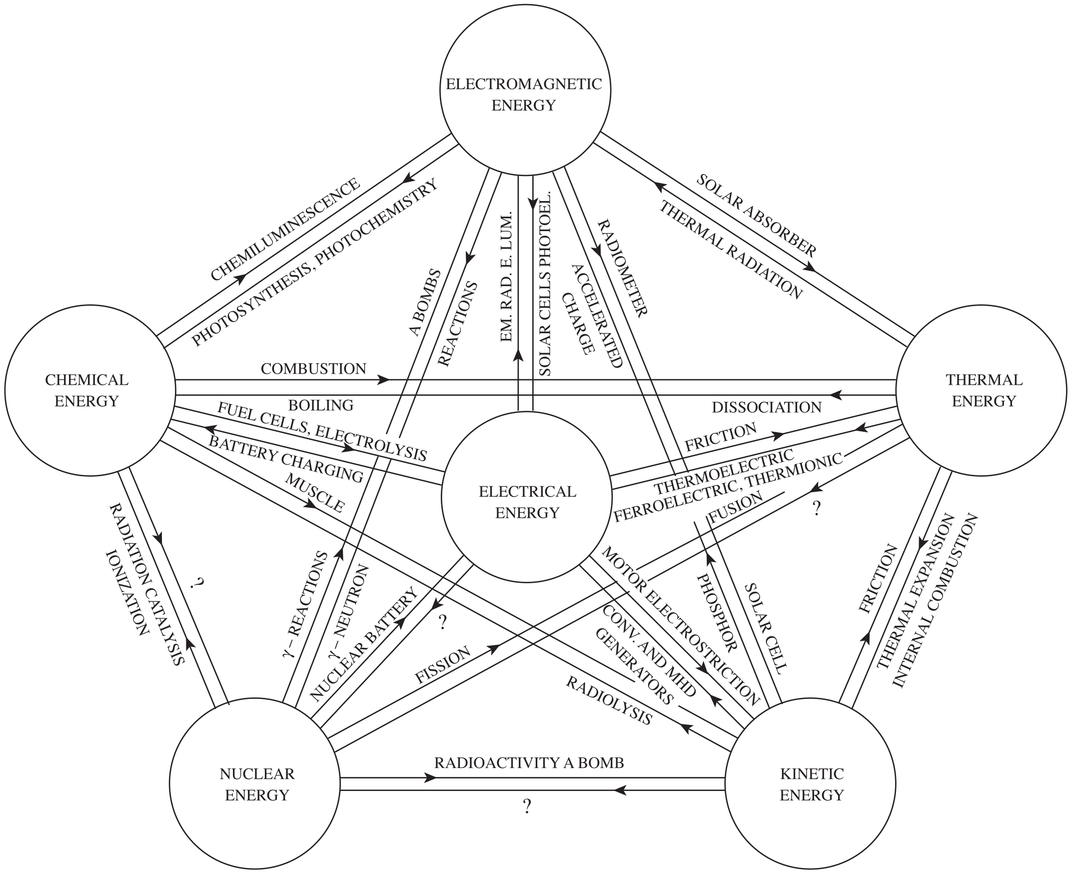
5. "Transport Phenomena," R.B. Bird, W.E. Stewart, and E.N. Lightfoot, John Wiley & Sons, 1960.
6. "Treatise on the Mathematical Theory of Elasticity," A.E.H. Love, Dover Publications, 1944, p. 90.

From Bolz, R.E. and Tuve, G.L., Fluid and aero mechanics, in *CRC Handbook of Tables for Applied Engineering Science*, CRC Press, Boca Raton, FL, 1973, pp. 496–501. Originally from "JPL Technical Report 32–1332," L.H. Back, Jet Propulsion Laboratory, California Institute of Technology, 1968.

Energy Conversions

Directions and Methods for Energy Conversion



Energy conversion chart. The circles represent the different forms of energy and the arrows the ways of converting energy from one form to another.

From Bolz, R.E. and Tuve, G.L., Fluid and aero mechanics, in *CRC Handbook of Tables for Applied Engineering Science*, CRC Press, Boca Raton, FL, 1973, p. 550. Originally from Kettani, M.A., *Direct Energy Conversion,* Addison-Wesley Publishing Company, 1970, p. 6.

Helical Steel Springs*

Compression or Tension

The upper figure is the load in pounds at 100 000 psi (689 MN/m^2) stress by the "corrected" stress equation. The lower figure gives spring stiffness in lb/in per single coil, based on a shear modulus of 11.5×10^6 psi (79.3 GN/M^2). The stiffness is independent of load. Both figures may be adjusted in direct proportion to selected stress or modulus. For multicoil springs divide the stiffness per coil by the number of active coils. For load in N, multiply the values in lbf by 4.4482. For stiffness in N/m, multiply the values in lbf/in. by 175.13.

Helical Springs—Load and Stiffness

Wire Diam. in.	Outside Diameter of Coil, in.												
	1/8	3/16	1/4	5/16	3/8	7/16	1/2	9/16	5/8	11/16	3/4	7/8	1
.010	.305												
	9.47												
.012	.522	.350											
	20.7	5.43											
.014	.823	.560	.422										
	40.3	10.5	4.18										
.016	1.21	.824	.626										
	72.9	18.4	7.37										
.018	1.71	1.17	.889										
	124	30.7	12.1										
.020	2.32	1.60	1.22	.972									
	200	48.6	18.9	9.06									
.022	3.03	2.12	1.60	1.30									
	306	73.9	28.2	13.7									
.024	3.90	2.72	2.09	1.68	1.41	1.21							
	464	108	41.4	19.9	11.1	6.67							
.028	5.98	4.25	3.29	2.65	2.24	1.92	1.69	1.51					
	965	216	80.6	38.0	21.1	12.9	8.37	5.79					
.032		6.25	4.84	3.95	3.33	2.85	2.51	2.24	2.03				
		398	146	68.0	37.5	22.4	14.8	10.0	7.27				
.037		9.42	7.41	6.01	5.07	4.41	3.88	3.44	3.10	2.83	2.61		
		785	280	128	69.6	42.2	27.3	18.5	13.3	9.77	7.43		
.043		14.4	11.4	9.33	7.91	6.82	6.07	5.36	4.89	4.44	4.10	3.52	
		1618	559	249	134	80.0	51.6	34.9	25.0	18.3	14.0	8.60	
.049			16.4	13.7	11.6	10.1	8.84	7.95	7.14	6.54	6.00	5.17	4.55
			1019	452	240	141	90.8	60.7	43.2	32.0	24.1	14.6	9.66
.055			22.8	18.9	16.2	14.1	12.4	11.2	10.0	9.23	8.50	7.32	6.40
			1767	768	401	234	149	101	70.4	51.9	39.5	23.9	15.6
.063				27.9	23.8	20.9	18.6	16.6	15.1	13.8	12.7	10.9	9.60
				1461	721	429	272	181	128	92.6	70.0	42.3	27.5
.071				38.7	33.4	29.4	26.1	23.6	21.3	19.5	18.0	15.5	13.6
				2563	1295	741	463	307	215	156	117	70.6	45.3
.080					47.1	41.3	36.9	33.4	30.2	27.8	25.7	22.2	19.5
					2300	1285	795	525	364	262	196	117	75.6
.090						57.9	51.7	46.9	42.9	39.0	36.2	31.2	27.6
						2236	1368	890	617	442	329	195	125
.100						77.5	69.7	63.3	58.0	53.0	49.2	42.6	37.6
						3726	2248	1449	993	707	525	309	197
.112							95.6	87.4	79.7	73.8	68.1	59.3	52.2
							3886	2462	1678	1186	871	509	323
.125							130	119	109	101	93.8	81.9	72.5
							6701	4205	2817	1977	1436	832	525
.148									175	163	151	133	119
									6350	4380	3166	1802	1119
.177											250	222	198
											7485	4150	2526
.207												341	307
												8857	5266
.244													484
													11,805

Helical Steel Springs*

Wire Diam. in.	Outside Diameter of Coil, in. 1 1/8	1 1/4	1 3/8	1 1/2	1 3/4	2	2 1/4	2 1/2	2 3/4	3	3 1/4	3 1/2	4
.055	5.70												
	10.7												
.063	8.55	7.75											
	18.8	13.6											
.071	12.2	11.1	9.97	9.21									
	31.5	22.4	16.4	12.6									
.080	17.3	15.7	14.2	13.1									
	51.4	37.0	27.0	20.5									
.090	24.7	22.2	20.2	18.6									
	85.1	60.3	44.3	33.5									
.100	33.5	30.5	27.7	25.5	22.1	19.3							
	132	94.5	69.0	52.4	32.1	20.9							
.112	47.0	42.4	38.6	35.8	30.7	27.0	24.1						
	218	152	112	84.5	51.7	33.5	23.1						
.125	65.0	58.8	53.9	49.4	42.6	37.6	33.4	30.2					
	350	246	180	135	82.0	53.3	36.6	26.2					
.148	106	96.3	88.0	81.2	70.5	62.0	55.1	49.7	45.3	41.7			
	741	514	375	279	168	109	74.3	53.1	39.1	29.7			
.177	178	163	149	137	119	105	94.0	84.7	77.2	71.0	65.5	61.2	
	1664	1145	819	609	361	234	159	113	83.3	63.2	48.4	38.4	
.207	279	255	235	217	188	166	150	134	122	113	104	97.2	85.2
	3419	2320	1658	1218	716	457	310	218	160	121	93.6	74.1	48.5
.244	444	406	376	306	349	269	241	218	199	183	170	158	139
	7462	4988	3498	2562	1488	941	631	443	322	243	188	148	95.9
.283		614	574	534	467	415	374	338	309	285	263	247	216
		10,199	7086	5154	2919	1820	1210	849	616	460	352	276	180
.331			882	824	733	652	589	534	491	453	421	391	343
			15,207	10,785	6048	3713	2449	1693	1217	911	694	543	348
.375				1166	1038	932	844	767	704	652	605	567	497
				19,966	10,903	6652	4302	2960	2124	1575	1195	933	597
.437					1587	1433	1307	1201	1102	1019	951	888	783
					23,202	13,859	8861	6005	4243	3132	2367	1835	1166
.500						2073	1897	1742	1617	1500	1396	1310	1160
						26,645	16,817	11,268	7880	5736	4325	3330	2097
.562							2623	2426	2251	2096	1956	1832	1628
							29,977	19,533	13,751	9957	7412	5686	3546
.625								3239	3010	2825	2649	2491	2221
								33,289	22,872	16,386	12,135	9240	5710

From Bolz, R.E. and Tuve, G.L., Dynamics and vibration, in *CRC Handbook of Tables for Applied Engineering Science,* CRC Press, Boca Raton, FL, 1973, pp. 605–606. Originally from Ross, H.F., *Trans. ASME*, 69, 727, 1947.

Ultrasonic Energy and Applications

Table A. Applications of Ultrasonics

Processes	Typical Frequencies, kc/s
HIGH POWER RANGE[a]	
Surface cleaning; grease and film removal	15–60
Emulsifying; homogenizing; production of dispersions	10–40
Degassing of liquids and molten metals (grain refinement)	10–40
Stimulating mechanical processes; mixing, diffusion, defoaming, atomizing, drying, plastic sealing, particle agglomeration, flow of powders, adhesion in soldering and welding, grain refinement in casting	10–500
Cutting and forming; impact grinding of brittle materials; abrasive cutting; die forming with reduced friction	15–100
Stimulating chemical processes; combustion and other reactions	10–200
LOW POWER RANGE (ABSORPTION AND ECHO)	
Inspection and flow detection	500–5000
Pulse-echo counting and inspection	700–10,000
Medical examination, diagnosis, and therapy	500–2500
Measurement and control (flow, thickness, density, liquid level, viscosity)	500–20,000
Sonic detection and ranging; command signaling; delay lines	10 000–20 000

[a] The desired effects in this range are largely accomplished by cavitation (in a liquid) or by vibrations and high accelerations that affect materials in contact with each other. *Cavitation* is bubble formation at a nucleus (such as a particle), followed by bubble growth and collapse. High pressures and temperatures occur at the instant of collapse, and the number of bubbles collapsing can be millions per second. Cavitation is suppressed by high static pressure and varies with liquid temperature. As the ultrasonic frequency is increased, up to a practical limit of about 10^7 cps (hz), the sound intensity must be increased to pass the threshold at which cavitation begins. Intensities very much above the threshold are not advantageous. Cavitation is increased in a liquid of low viscosity, low vapor pressure, and high surface tension.

Transmission and matching of acoustics power to the load is often not simple; in fact this step is an art in itself (see references).

Table B. Generators or Transducers

Type of Generator	Typical Limits		
	Mechanical Power,[a] W	Frequency, kc/s	Efficiency,[b] %
Air whistles	75	40	15
Jet-edge vibrators (gas or liquid)	50	20	15
Cavity resonators	500	12	15
Sirens (jet interruption)	1000	25	70
Piezoelectric-quartz		5000	90
Piezoelectric-ceramic (e.g., barium titanate)	4000	5000	75
Magnetostrictive (Ni, Fe, Co, ferrites)	5000	90	50
Electron tube	1000	30	50
Rotating alternator	25,000	25	50

[a] Power intensity per unit area at point of use depends on methods for transmission and focusing.
[b] The efficiencies of available equipment for industrial use are often much below these values.

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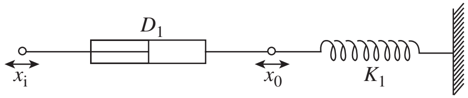
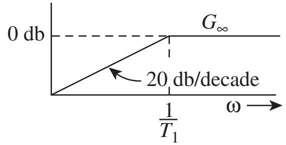
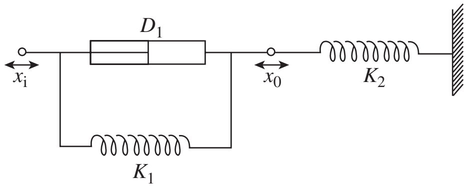
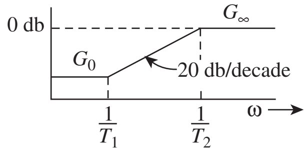
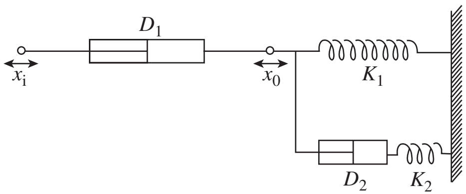
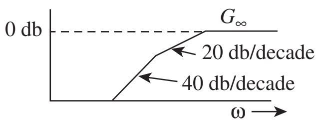
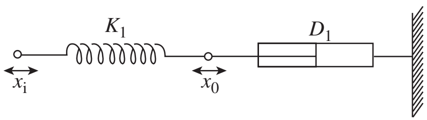
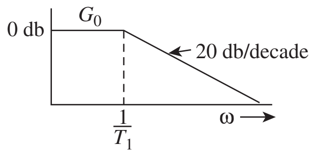
"Sources of High-Intensity Ultrasound," L.D. Rozenberg, Ed., 2 volumes, Plenum Press, 1968.
"Ultrasonic Engineering," J.R. Frederick, John Wiley & Sons, Inc., 1965.
"Ultrasonic Machining of Intractable Materials," A.I. Markov, Ed., Butterworth & Co., 1967.
"Ultrasonics: Theory and Application," G.L. Gooberman, English Universities Press, 1968.

From Bolz, R.E. and Tuve, G.L., Dynamics and vibration, in *CRC Handbook of Tables for Applied Engineering Science*, CRC Press, Boca Raton, FL, 1973, p. 607.

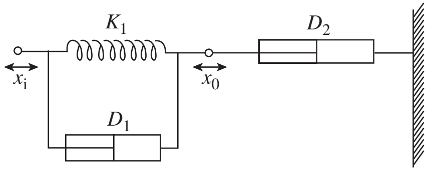
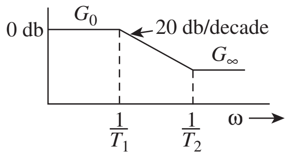
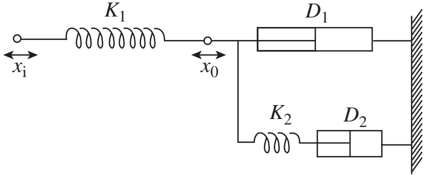
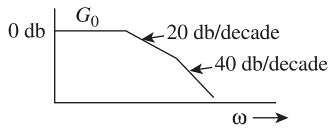
LEAD

Mechanical Lead Network	Log Magnitude Characteristic	Transfer Function	T_1	T_2
	 $G_0 = 0$ $G_\infty = 1$	$\frac{T_1 s}{T_1 s + 1}$	$\frac{D_1}{K_1}$	…
	 $G_0 = \frac{1}{1 + \frac{K_2}{K_1}}$ $G_\infty = 1$	$G_0 \frac{T_1 s + 1}{T_2 s + 1}$	$\frac{D_1}{K_1}$	$G_0 T_1$
	 $G_0 = 0$ $G_\infty = 1$	$\frac{T_1 T_2 s^2}{T_1 T_2 s^2 + \left[T_1 + \left(1 + \frac{K_2}{K_1}\right) T_2\right] s + 1}$	$\frac{D_1}{K_1}$	$\frac{D_2}{K_2}$

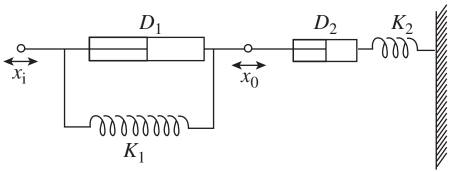
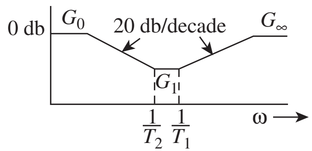
LAG

Mechanical Lag Network	Log Magnitude Characteristic	Transfer Function	T_1	T_2
	 $G_0 = 1$ $G_\infty = 0$	$\frac{1}{T_1 s + 1}$	$\frac{D_1}{K_1}$	…

Mechanical Components (continued)

Mechanical Lag Network	Log Magnitude Characteristic	Transfer Function	T_1	T_2
	 $G_0 = 1$ $G_\infty = \frac{1}{1 + D_2/D_1}$	$\frac{T_2 s+1}{T_1 s+1}$	$\frac{T_2}{G_\infty}$	$\frac{D_1}{K_1}$
	 $G_0 = 1$ $G_\infty = 0$	$\frac{1}{T_1T_2s^2+\left[T_1+\left(1+\frac{K_2}{K_1}\right)T_2\right]s+1}$	$\frac{D_1}{K_1}$	$\frac{D_2}{K_2}$

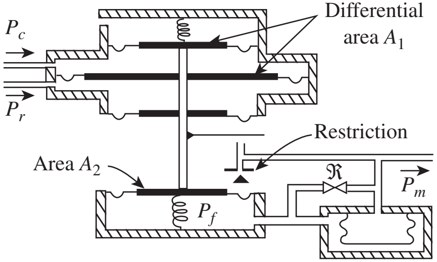
LAG-LEAD

Mechanical Lag-Lead Network	Log Magnitude Characteristic	Transfer Function	T_1	T_2
	 $G_0 = G_\infty = 1$ $G_1 = \frac{T_1 + T_2}{T_1 + (1 + \frac{K_2}{K_1})\, T_2}$	$\frac{(T_1 s+1)(T_2 s+1)}{T_1T_2s^2+\left[T_1+\left(1+\frac{K_2}{K_1}\right)T_2\right]s+1}$	$\frac{D_1}{K_1}$	$\frac{D_2}{K_2}$

From Bolz, R.E. and Tuve, G.L., Automatic control, in *CRC Handbook of Tables for Applied Engineering Science*, CRC Press, Boca Raton, FL, 1973, pp. 1088–1089. Originally from *Handbook of Automation, Computation, and Control*, Vol. 1, Grabbe, E.M., Ramo, S., and Wooldridge, D.E., Eds., John Wiley & Sons, New York, 1958.

Approximate Relationships for High Loop Gain Controllers, $\varepsilon \ll 1$

LEAD



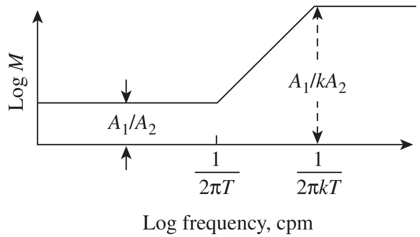
▲ = Pressure source

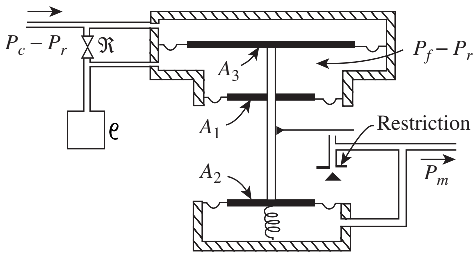
$$\frac{P_m - P_0}{P_c - P_r} = \frac{A_1}{A_2}\left[\frac{1 + T_1 s}{1 + kT_1 s}\right]$$

$$T_1 = \mathfrak{R}\mathscr{C}$$

k = change in P_f for a unit change in P_m when $\mathfrak{R}$ is completely closed.

Plot for $T = T_1$

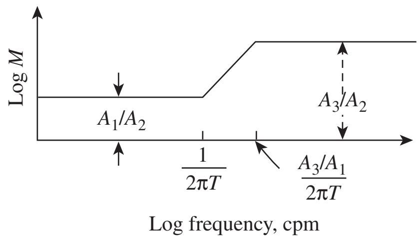




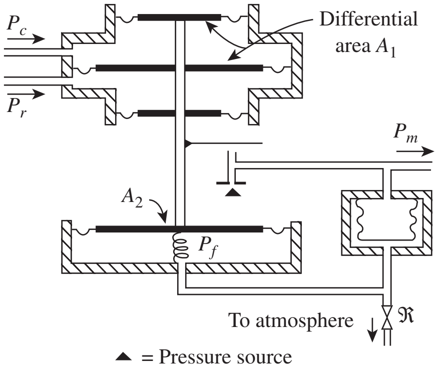
$$\frac{P_m - P_0}{P_c - P_r} = \frac{A_1}{A_2}\left[\frac{1 + \left(A_3/A_2\right)T_1 s}{1 + kT_1 s}\right]$$

$$T_1 = \mathfrak{R}\mathscr{C}$$

Plot for $T = T_1$



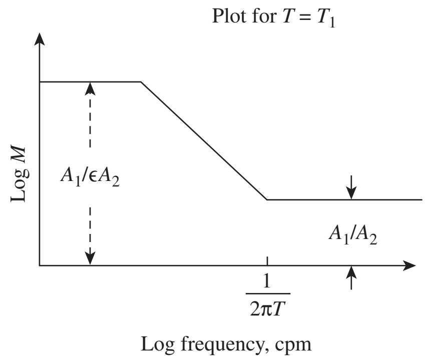
LAG



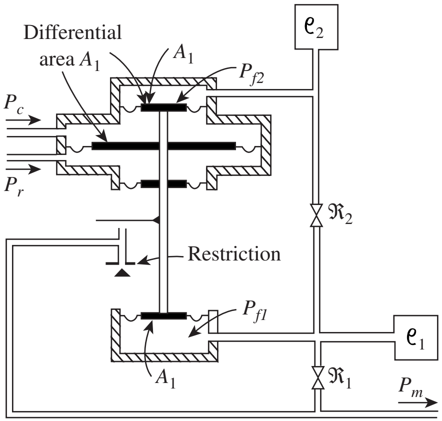
$$\frac{P_m - P_0}{P_c - P_r} = \frac{A_1}{A_2 k}\left[\frac{1+1/T_1 s}{1+\epsilon/kT_1 s}\right]$$

$$T_1 = \Re e$$

ϵ = a system constant related to the loop gain.



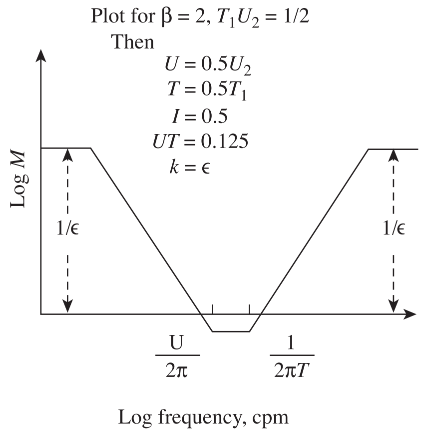
LAG-LEAD



$$\frac{P_m - P_0}{P_c - P_r}$$

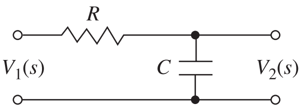
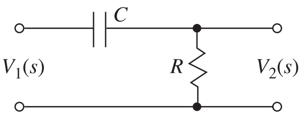
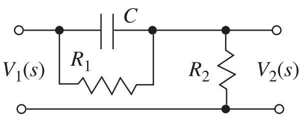
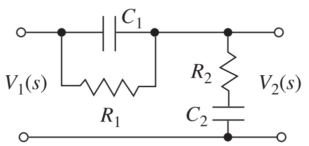
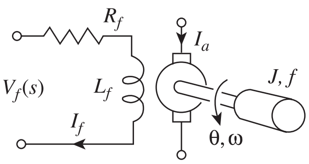
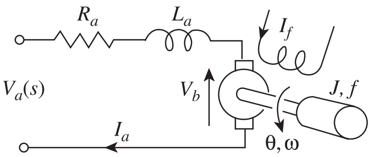
$$= \left(1+\beta T_1 U_2\right)\cdot\left[\frac{\dfrac{U_2/s}{1+\beta T_1 U_2} + 1 + \dfrac{T_1 s}{1+\beta T_1 U_2}}{\epsilon U_2/s + \epsilon T_1 s + 1}\right],$$

where $\epsilon\beta T_1 U_2 \ll 1$, $T_1 = \Re_1\mathscr{C}_1$, $U_2 = 1/\Re_2\mathscr{C}_2$, $\beta = 1 + \mathscr{C}_2/\mathscr{C}_1$, I = interaction factor.



From Bolz, R.E. and Tuve, G.L., Automatic control, in *CRC Handbook of Tables for Applied Engineering Science*, CRC Press, Boca Raton, FL, 1973, pp. 1090–1091. Originally from *Handbook of Automation, Computation, and Control*, Vol. 1, Grabbe, E.M., Ramo, S., and Wooldridge, D.E., Eds., John Wiley & Sons, New York, 1958, pp. **23**-46 and **23**-47.

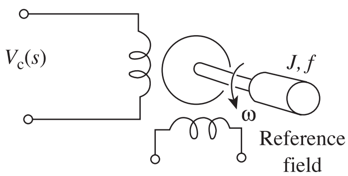
Dynamic Elements and Networks

Element or System	G(s)
1. Integrating circuit	
	$\frac{V_2(s)}{V_1(s)} = \frac{1}{RCS+1}$
2. Differentiating circuit	
	$\frac{V_2(s)}{V_1(s)} = \frac{RCS}{RCS+1}$
3. Differentiating circuit	
	$\frac{V_2(s)}{V_1(s)} = \frac{s+1/RCS}{s+(R_1+R_2)/R_1R_2C}$
4. Lead-lag filter circuit	
 $\tau_a = R_1C_1,$ $\tau_b = R_2C_2$ $\tau_{ab} = R_1C_1$ $\tau_1\tau_2 = \tau_a\tau_b,$ $\tau_1 + \tau_2 = \tau_a + \tau_b + \tau_{ab}$	$\frac{V_2(s)}{V_1(s)} = \frac{(1+s\tau_a)(1+s\tau_b)}{\tau_a\tau_b s^2 + (\tau_a+\tau_b+\tau_{ab})s+1}$ $= \frac{(1+s\tau_a)(1+s\tau_b)}{(1+s\tau_1)(1+s\tau_2)}$
5. dc-motor, field controlled	
	$\frac{\theta(s)}{V_f(s)} = \frac{K_m}{s(Js+f)(L_f s+R_f)}$
6. dc-motor, armature controlled	
	$\frac{\theta(s)}{V_a(s)} = \frac{K_m}{s[(R_a+L_a s)(J_s+f)+K_bK_m]}$

Dynamic Elements and Networks (continued)

Element or System	G(s)

7. ac-motor, two-phase control field

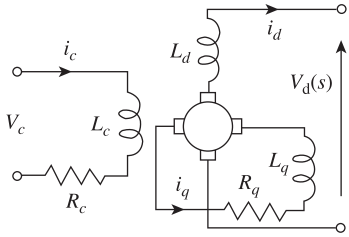


$$\frac{\theta(s)}{V_c(s)} = \frac{K_m}{s(\tau s+1)}$$

$$\tau = J/(f-m)$$

$m =$ slope of linearized torque-speed curve (normally negative)

8. Amplidyne



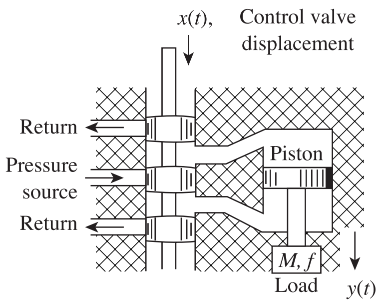
$$\frac{V_d(s)}{V_c(s)} = \frac{(K/R_cR_q)}{(s\tau_c+1)(s\tau_q+1)}$$

$$\tau_c = L_c/R_c, \quad \tau_q = L_q/R_q$$

For the unloaded case, $i_d \simeq 0, \tau_c \simeq \tau_q$,

$0.05 \text{ sec} < \tau_c < 0.5 \text{ sec}$

9. Hydraulic actuator



$$\frac{Y(s)}{X(s)} = \frac{K}{s(Ms+B)}$$

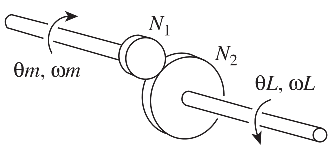
$$K = \frac{Ak_z}{k_p}, \quad B = \left(f + \frac{A^2}{k_p}\right)$$

$$k_z = \left.\frac{\partial g}{\partial x}\right|_{x_0}, \quad k_p = \left.\frac{\partial g}{\partial P}\right|_{P_0},$$

$$g = g(x, P)$$

$A =$ area of piston

10. Gear Train

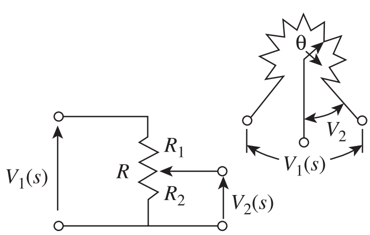


$$\text{Gear ratio} = n = \frac{N_1}{N_2}$$

$$N_2\theta_L = N_1\theta_m, \quad \theta_L = n\theta_m$$

$$\omega_L = n\omega_M$$

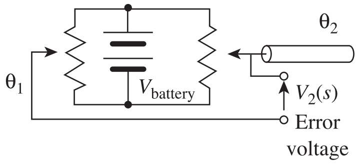
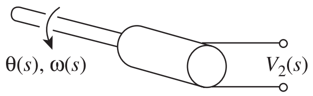
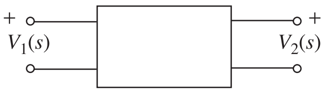
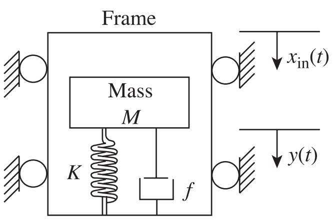
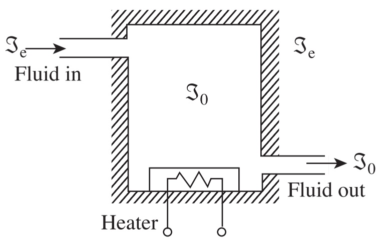
11. Potentiometer



$$\frac{V_2(s)}{V_1(s)} = \frac{R_2}{R} = \frac{R_2}{R_1+R_2}$$

$$\frac{R_2}{R} = \frac{\theta}{\theta_{max}}$$

Dynamic Elements and Networks (continued)

Element or System	G(s)
12. Potentiometer error detector bridge  	$V_2(s) = k_s(\theta_1(s) - \theta_2(s))$ $V_2(s) = k_s\theta_{error}(s)$ $k_2 = \frac{V_{battery}}{\theta_{max}}$
13. Tachometer  	$V_2(s) = K_t\omega(s)$ $= K_t s\theta(s)$
14. dc-amplifier  	$\frac{V_2(s)}{V_1(s)} = \frac{k_a}{s\tau + 1}$ R_0 = output resistance C_0 = output capacitance $\tau = R_0C_0$, $\tau \ll 1$ and is often negligible for servomechanism amplifier
15. Accelerometer  	$x_0(t) = y(t) - x_{in}(t)$, $\frac{X_0(s)}{X_{in}(s)} = \frac{-s^2}{s^2 + (f/M)s + K/M}$ For low-frequency oscillations, where $\omega < \omega_n$, $\frac{X_0(j\omega)}{X_{in}(j\omega)} \simeq \frac{\omega^2}{K/M}$
16. Thermal Heating System  	$\frac{\Im(s)}{q(s)} = \frac{1}{C_t s + (QS + 1/R)}$, where $\Im = \Im_0 - \Im_e$ = temperature difference due to thermal process C_t = thermal capacitance Q = fluid flow rate = constant S = specific heat of water R_t = thermal resistance of insulation $q(s)$ = rate of heat flow of heating element

From Bolz, R.E. and Tuve, G.L., Automatic control, in *CRC Handbook of Tables for Applied Engineering Science*, CRC Press, Boca Raton, FL, 1973, pp. 1092–1094. Originally from Dorf, R.C., *Modern Control Systems*, Addison-Wesley, Reading, MA, 1967.

Properties of Saturated Water and Steam (Temperature)

t (°C)	Pressure MPa	Volume, m³/kg			Enthalpy, kJ/kg			Entropy, kJ/(kg°K)			t (°C)
		v_L	Δv	v_v	h_L	Δh	h_v	s_L	Δs	s_v	
0	*0.000 611 2	0.001 000 2	206.14	206.14	–0.042	2500.9	2500.9	–0.0002	9.1559	9.1558	0
0.01	0.000 611 7	0.001 000 2	206.00	206.00	0.001	2500.9	2500.9	0.0000	9.1555	9.1555	0.01
1	0.000 657 1	0.001 000 1	192.44	192.44	4.177	2498.6	2502.7	0.0153	9.1138	9.1291	1
2	0.000 706 0	0.001 000 1	179.76	179.76	8.392	2496.2	2504.6	0.0306	9.0721	9.1027	2
3	0.000 758 1	0.001 000 1	168.01	168.01	12.604	2493.8	2506.4	0.0459	9.0306	9.0765	3
4	0.000 813 5	0.001 000 1	157.12	157.12	16.813	2491.4	2508.2	0.0611	8.9895	9.0506	4
5	0.000 872 6	0.001 000 1	147.02	147.02	21.019	2489.1	2510.1	0.0763	8.9486	9.0249	5
6	0.000 935 4	0.001 000 1	137.64	137.64	25.224	2486.7	2511.9	0.0913	8.9081	8.9994	6
7	0.001 002	0.001 000 1	128.93	128.93	29.426	2484.3	2513.7	0.1064	8.8678	8.9742	7
8	0.001 073	0.001 000 2	120.83	120.83	33.626	2481.9	2515.6	0.1213	8.8278	8.9492	8
9	0.001 148	0.001 000 3	113.31	113.31	37.824	2479.6	2517.4	0.1362	8.7882	8.9244	9
10	0.001 228	0.001 000 3	106.31	106.31	42.021	2477.2	2519.2	0.1511	8.7488	8.8998	10
11	0.001 313	0.001 000 4	99.792	99.792	46.216	2474.8	2521.1	0.1659	8.7096	8.8755	11
12	0.001 403	0.001 000 5	93.723	93.724	50.410	2472.5	2522.9	0.1806	8.6708	8.8514	12
13	0.001 498	0.001 000 7	88.059	88.070	54.602	2470.1	2524.7	0.1953	8.6322	8.8275	13
14	0.001 599	0.001 000 8	82.797	82.798	58.794	2467.7	2526.5	0.2099	8.5939	8.8038	14
15	0.001 706	0.001 000 9	77.880	77.881	62.984	2465.4	2528.4	0.2245	8.5559	8.7804	15
16	0.001 819	0.001 001 1	73.290	73.291	67.173	2463.0	2530.2	0.2390	8.5181	8.7571	16
17	0.001 938	0.001 001 3	69.005	69.006	71.361	2460.6	2532.0	0.2534	8.4806	8.7341	17
18	0.002 065	0.001 001 5	65.002	65.003	75.548	2458.3	2533.8	0.2678	8.4434	8.7112	18
19	0.002 198	0.001 001 6	61.260	61.261	79.734	2455.9	2535.7	0.2822	8.4064	8.6886	19
20	0.002 339	0.001 001 8	57.760	57.761	83.920	2453.5	2537.5	0.2965	8.3696	8.6661	20
21	0.002 488	0.001 002 1	54.486	54.487	88.105	2451.2	2539.3	0.3108	8.3331	8.6439	21
22	0.002 645	0.001 002 3	51.421	51.422	92.289	2448.8	2541.1	0.3250	8.2969	8.6218	22
23	0.002 811	0.001 002 5	48.551	48.552	96.473	2446.4	2542.9	0.3391	8.2609	8.6000	23
24	0.002 986	0.001 002 8	45.862	45.863	100.66	2444.1	2544.7	0.3532	8.2251	8.5783	24
25	0.003 170	0.001 003 0	43.340	43.341	104.84	2441.7	2546.5	0.3673	8.1895	8.5568	25
26	0.003 364	0.001 003 3	40.976	40.977	109.92	2439.3	2548.4	0.3813	8.1542	8.5355	26
27	0.003 568	0.001 003 5	38.757	38.758	113.20	2437.0	2550.2	0.3952	8.1192	8.5144	27
28	0.003 783	0.001 003 8	36.674	36.675	117.38	2434.6	2552.0	0.4091	8.0843	8.4934	28
29	0.004 009	0.001 004 1	34.718	34.719	121.56	2432.2	2553.8	0.4230	8.0497	8.4727	29
30	0.004 247	0.001 004 4	32.881	32.882	125.75	2429.8	2555.6	0.4368	8.0153	8.4521	30
31	0.004 497	0.001 004 7	31.153	31.154	129.93	2427.5	2557.4	0.4506	7.9812	8.4317	31
32	0.004 759	0.001 005 0	29.528	29.529	134.11	2425.1	2559.2	0.4643	7.9472	8.4115	32
33	0.005 035	0.001 005 4	28.000	28.001	138.29	2422.7	2561.0	0.4780	7.9135	8.3914	33
34	0.005 325	0.001 005 7	26.561	26.562	142.47	2420.3	2562.8	0.4916	7.8800	8.3715	34
35	0.005 629	0.001 006 0	25.207	25.208	146.64	2417.9	2564.6	0.5052	7.8467	8.3518	35
36	0.005 947	0.001 006 4	23.931	23.932	150.82	2415.6	2566.4	0.5187	7.8136	8.3323	36
37	0.006 282	0.001 006 8	22.728	22.729	155.00	2413.2	2568.2	0.5322	7.7807	8.3129	37
38	0.006 632	0.001 007 1	21.594	21.595	159.18	2410.8	2570.0	0.5457	7.7480	8.2936	38
39	0.007 000	0.001 007 5	20.525	20.526	163.36	2408.4	2571.8	0.5591	7.7155	8.2746	39
40	0.007 384	0.001 007 9	19.516	19.517	167.54	2406.0	2573.5	0.5724	7.6832	8.2557	40
41	0.007 787	0.001 008 3	18.564	18.565	171.72	2403.6	2575.3	0.5858	7.6512	8.2369	41
42	0.008 209	0.001 008 7	17.664	17.665	175.90	2401.2	2577.1	0.5990	7.6193	8.2183	42
43	0.008 650	0.001 009 1	16.815	16.816	180.08	2398.8	2578.9	0.6123	7.5876	8.1999	43
44	0.009 112	0.001 009 5	16.012	16.013	184.26	2396.4	2580.7	0.6255	7.5561	8.1816	44
45	0.009 594	0.001 009 9	15.252	15.253	188.44	2394.0	2582.5	0.6386	7.5248	8.1634	45
46	0.010 099	0.001 010 3	14.534	14.535	192.62	2391.6	2584.2	0.6517	7.4937	8.1454	46
47	0.010 626	0.001 010 8	13.855	13.856	196.80	2389.2	2586.0	0.6648	7.4628	8.1276	47
48	0.011 176	0.001 011 2	13.212	13.213	200.98	2386.8	2587.8	0.6778	7.4320	8.1099	48
49	0.011 751	0.001 011 7	12.603	12.604	205.16	2384.4	2589.5	0.6908	7.4015	8.0923	49
50	0.012 351	0.001 012 1	12.027	12.028	209.34	2382.0	2591.3	0.7038	7.3711	8.0749	50
51	0.012 977	0.001 012 6	11.481	11.482	213.52	2379.6	2593.1	0.7167	7.3409	8.0576	51
52	0.013 631	0.001 031 1	10.963	10.964	217.70	2377.1	2594.8	0.7296	7.3109	8.0405	52
53	0.014 312	0.001 013 6	10.472	10.473	221.88	2374.7	2596.6	0.7424	7.2811	8.0235	53
54	0.015 022	0.001 014 0	10.006	10.007	226.06	2372.3	2598.4	0.7552	7.2514	8.0066	54
55	0.015 761	0.001 014 5	9.5639	9.5649	230.24	2369.9	2600.1	0.7680	7.2219	7.9899	55

Properties of Saturated Water and Steam (Temperature) (continued)

t (°C)	Pressure MPa	Volume, m³/kg v_L	Δv	v_v	Enthalpy, kJ/kg h_L	Δh	h_v	Entropy, kJ/(kg°K) s_L	Δs	s_v	t (°C)
56	0.016 532	0.001 015 0	9.1444	9.1454	234.42	2367.4	2601.9	0.7807	7.1926	7.9733	56
57	0.017 335	0.001 015 5	8.7461	8.7471	238.61	2365.0	2603.6	0.7934	7.1634	7.9568	57
58	0.018 171	0.001 016 1	8.3678	8.3688	242.79	2362.6	2605.4	0.8060	7.1344	7.9405	58
59	0.019 041	0.001 016 6	8.0083	8.0093	246.97	2360.1	2607.1	0.8186	7.1056	7.9243	59
60	0.019 946	0.001 017 1	7.6666	7.6677	251.15	2357.7	2608.8	0.8312	7.0770	7.9082	60
61	0.020 887	0.001 017 6	7.3418	7.3428	255.34	2355.2	2610.6	0.8438	7.0485	7.8922	61
62	0.021 866	0.001 018 2	7.0328	7.0338	259.52	2352.8	2612.3	0.8563	7.0201	7.8764	62
63	0.022 884	0.001 018 7	6.7389	6.7399	263.71	2350.3	2614.1	0.8687	6.9919	7.8607	63
64	0.023 942	0.001 019 3	6.4591	6.4601	267.89	2347.9	2615.8	0.8811	6.9639	7.8451	64
65	0.025 041	0.001 019 9	6.1928	6.1938	272.08	2345.4	2617.5	0.8935	6.9361	7.8296	65
66	0.026 183	0.001 020 4	5.9392	5.9402	276.27	2343.0	2619.2	0.9059	6.9083	7.8142	66
67	0.027 368	0.001 021 0	5.6976	5.6986	280.45	2340.5	2621.0	0.9182	6.8808	7.7990	67
68	0.028 599	0.001 021 6	5.4674	5.4684	284.64	2338.0	2622.7	0.9305	6.8534	7.7839	68
69	0.029 876	0.001 022 2	5.2479	5.2490	288.83	2335.6	2624.4	0.9428	6.8261	7.7689	69
70	0.031 201	0.001 022 8	5.0387	5.0397	293.02	2333.1	2626.1	0.9550	6.7990	7.7540	70
71	0.032 575	0.001 023 4	4.8392	4.8402	297.21	2330.6	2627.8	0.9672	6.7720	7.7392	71
72	0.034 000	0.001 024 0	4.6488	4.6498	301.40	2328.1	2629.5	0.9793	6.7452	7.7245	72
73	0.035 478	0.001 024 6	4.4671	4.4681	305.59	2325.6	2631.2	0.9915	6.7185	7.7100	73
74	0.037 009	0.001 025 2	4.2937	4.2947	309.78	2323.1	2632.9	1.0035	6.6920	7.6955	74
75	0.038 595	0.001 025 8	4.1281	4.1291	313.97	2320.6	2634.6	1.0156	6.6656	7.6812	75
76	0.040 239	0.001 026 5	3.9699	3.9709	318.17	2318.1	2636.3	1.0276	6.6393	7.6669	76
77	0.041 941	0.001 027 1	3.8188	3.8198	322.36	2315.6	2638.0	1.0396	6.6132	7.6528	77
78	0.043 703	0.001 027 7	3.6743	3.6754	326.56	2313.1	2639.7	1.0516	6.5872	7.6388	78
79	0.045 527	0.001 028 4	3.5363	3.5373	330.75	2310.6	2641.3	1.0635	6.5613	7.6248	79
80	0.047 415	0.001 029 0	3.4042	3.4053	334.95	2308.1	2643.0	1.0754	6.5356	7.6110	80
81	0.049 368	0.001 029 7	3.2780	3.2790	339.15	2305.5	2644.7	1.0873	6.5100	7.5973	81
82	0.051 387	0.001 030 4	3.1572	3.1582	343.34	2303.0	2646.4	1.0991	6.4846	7.5837	82
83	0.053 476	0.001 031 0	3.0415	3.0426	347.54	2300.5	2648.0	1.1109	6.4592	7.5701	83
84	0.055 636	0.001 031 7	2.9309	2.9319	351.74	2297.9	2649.7	1.1227	6.4340	7.5567	84
85	0.057 867	0.001 032 4	2.8249	2.8259	355.95	2295.4	2651.3	1.1344	6.4090	7.5434	85
86	0.060 174	0.001 033 1	2.7234	2.7244	360.15	2292.8	2653.0	1.1461	6.3840	7.5301	86
87	0.062 556	0.001 033 8	2.6262	2.6272	364.35	2290.3	2654.6	1.1578	6.3592	7.5170	87
88	0.065 017	0.001 034 5	2.5330	2.5341	368.56	2287.7	2656.3	1.1694	6.3345	7.7039	88
89	0.067 559	0.001 035 2	2.4437	2.4448	372.76	2285.1	2657.9	1.1811	6.3099	7.4909	89
90	0.070 182	0.001 035 9	2.3581	2.3591	376.97	2282.6	2659.5	1.1927	6.2854	7.4781	90
91	0.072 890	0.001 036 7	2.2760	2.2771	381.18	2280.0	2661.2	1.2042	6.2611	7.4653	91
92	0.075 685	0.001 037 4	2.1973	2.1983	385.38	2277.4	2662.8	1.2158	6.2368	7.4526	92
93	0.078 568	0.001 038 1	2.1217	2.1228	389.59	2274.8	2664.4	1.2273	6.2127	7.4400	93
94	0.081 542	0.001 038 9	2.0492	2.0502	393.81	2272.2	2666.0	1,2387	6.1887	7.4275	94
95	0.084 609	0.001 039 6	1.9796	1.9806	398.02	2269.6	2667.6	1.2502	6.1648	7.4150	95
96	0.087 771	0.001 040 4	1.9128	1.9138	402.23	2267.0	2669.2	1.2616	6.1411	7.4027	96
97	0.091 031	0.001 041 1	1.8486	1.8497	406.45	2264.4	2670.8	1.2730	6.1174	7.3904	97
98	0.094 390	0.001 041 9	1.7870	1.7880	410.66	2261.7	2672.4	1.2844	6.0938	7.3782	98
99	0.097 852	0.001 042 7	1.7277	1.7288	414.88	2259.1	2674.0	1.2957	6.0704	7.3661	99
100	0.101 42	0.001 043 5	1.6708	1.6719	419.10	2256.5	2675.6	1.3070	6.0471	7.3541	100
101	0.105 09	0.001 044 2	1.6161	1.6171	423.32	2253.8	2677.1	1.3183	6.0238	7.3421	101
102	0.108 87	0.001 045 0	1.5635	1.5645	427.54	2251.2	2678.7	1.3296	6.0007	7.3303	102
103	0.112 77	0.001 045 8	1.5129	1.5140	431.76	2248.5	2680.3	1.3408	5.9777	7.3185	103
104	0.116 78	0.001 046 6	1.4642	1.4653	435.99	2245.9	2681.8	1.3520	5.9548	7.3068	104
105	0.120 90	0.001 047 4	1.4174	1.4185	440.21	2243.2	2683.4	1.3632	5.9320	7.2951	105
106	0.125 15	0.001 048 3	1.3724	1.3734	444.44	2240.5	2684.9	1.3743	5.9092	7.2836	106
107	0.129 51	0.001 049 1	1.3290	1.3301	448.67	2237.8	2686.5	1.3854	5.8866	7.2721	107
108	0.134 01	0.001 049 9	1.2873	1.2883	452.90	2235.1	2588.0	1.3965	5.8641	7.2607	108
109	0.138 63	0.001 050 7	1.2471	1.2481	457.13	2232.4	2689.5	1.4076	5.8417	7.2493	109
110	0.143 38	0.001 051 6	1.2083	1.2094	461.36	2229.7	2691.1	1.4187	5.8194	7.2380	110

Properties of Saturated Water and Steam (Temperature) (continued)

t (°C)	Pressure MPa	Volume, m³/kg v_L	Volume Δv	Volume v_v	Enthalpy, kJ/kg h_L	Enthalpy Δh	Enthalpy h_v	Entropy, kJ/(kg°K) s_L	Entropy Δs	Entropy s_v	t (°C)
111	0.148 26	0.001 052 4	1.1710	1.1721	465.60	2227.0	2692.6	1.4297	5.7972	7.2268	111
112	0.153 28	0.001 053 3	1.1351	1.1362	469.83	2224.3	2694.1	1.4407	5.7750	7.2157	112
113	0.158 43	0.001 054 1	1.1005	1.1015	474.07	2221.5	5695.6	1.4517	5.7530	7.2047	113
114	0.163 73	0.001 055 0	1.0671	1.0681	478.31	2218.8	2697.1	1.4626	5.7310	7.1937	114
115	0.169 18	0.001 055 9	1.0349	1.0359	482.55	2216.0	2698.6	1.4735	5.7092	7.1827	115
116	0.174 77	0.001 056 8	1.0038	1.0049	486.80	2213.3	2700.1	1.4844	5.6874	7.1719	116
117	0.180 51	0.001 057 6	0.973 90	0.974 95	491.04	2210.5	2701.5	1.4953	5.6658	7.1611	117
118	0.186 40	0.001 058 5	0.945 01	0.946 07	495.29	2207.7	2703.0	1.5062	5.6442	7.1504	118
119	0.192 45	0.001 059 4	0.917 14	0.918 20	499.53	2204.9	2704.5	1.5170	5.6227	7.1397	119
120	0.198 67	0.001 060 3	0.890 24	0.891 30	503.78	2202.1	2705.9	1.5278	5.6013	7.1291	120
121	0.205 04	0.001 061 2	0.864 28	0.865 34	508.04	2199.3	2707.4	1.5386	5.5800	7.1186	121
122	0.211 58	0.001 062 2	0.839 21	0.840 28	512.29	2196.5	2708.8	1.5494	5.5587	7.1081	122
123	0.218 29	0.001 063 1	0.815 01	0.816 07	516.55	2193.7	2710.3	1.5601	5.5376	7.0977	123
124	0.225 17	0.001 064 0	0.791 63	0.792 69	520.80	2190.9	2711.7	1.5708	5.5165	7.0873	124
125	0.232 22	0.001 064 9	0.769 05	0.770 11	525.06	2188.0	2713.1	1.5815	5.4955	7.0770	125
126	0.239 46	0.001 065 9	0.747 23	0.748 29	529.32	2185.2	2714.5	1.5922	5.4746	7.0668	126
127	0.246 88	0.001 066 8	0.726 14	0.727 21	533.59	2182.3	2715.9	1.6028	5.4538	7.0566	127
128	0.254 48	0.001 067 8	0.705 76	0.706 83	537.85	2179.5	2717.3	1.6134	5.4330	7.0465	128
129	0.262 27	0.001 068 7	0.686 06	0.687 13	542.12	2176.6	2718.7	1.6240	5.4124	7.0364	129
130	0.270 26	0.001 069 7	0.667 01	0.668 08	546.39	2173.7	2720.1	1.6346	5.3918	7.0264	130
131	0.278 44	0.001 070 7	0.648 59	0.649 66	550.66	2170.8	2721.5	1.6452	5.3713	7.0165	131
132	0.286 82	0.001 071 7	0.630 78	0.631 85	554.93	2167.9	2722.8	1.6557	5.3508	7.0066	132
133	0.295 41	0.001 072 7	0.613 54	0.614 61	559.21	2165.0	2724.2	1.6662	5.5305	6.9967	133
134	0.304 20	0.001 073 6	0.596 87	0.597 94	563.49	2162.0	2725.5	1.6767	5.3102	6.9869	134
135	0.313 20	0.001 074 7	0.580 73	0.581 80	567.77	2159.1	2726.9	1.6872	5.2900	6.9772	135
136	0.322 42	0.001 075 7	0.565 11	0.566 18	572.05	2156.2	2728.2	1.6977	5.2698	6.9675	136
137	0.331 85	0.001 076 7	0.549 99	0.551 06	576.33	2153.2	2729.5	1.7081	5.2498	6.9579	137
138	0.341 51	0.001 077 7	0.535 35	0.536 42	580.62	2150.2	2730.8	1.7185	5.2298	6.9483	138
139	0.351 39	0.001 078 7	0.521 17	0.522 25	584.91	2147.2	2732.1	1.7289	5.2098	6.9388	139
140	0.361 50	0.001 079 8	0.507 44	0.508 52	589.20	2144.2	2733.4	1.7393	5.1900	6.9293	140
141	0.371 85	0.001 080 8	0.494 14	0.495 22	593.49	2141.2	2734.7	1.7496	5.1702	6.9198	141
142	0.382 43	0.001 081 9	0.481 25	0.482 33	597.79	2138.2	2736.0	1,7600	5.1505	6.9105	142
143	0.393 25	0.001 082 9	0.468 77	0.469 85	602.09	2135.2	2737.3	1.7703	5.1308	6.9011	143
144	0.404 32	0.001 084 0	0.456 66	0.457 75	606.39	2132.2	2738.5	1,7806	5.1112	6.8918	144
145	0.415 63	0.001 085 0	0.444 93	0.446 02	610.69	2129.1	2739.8	1,7909	5.0917	6.8826	145
146	0.427 21	0.001 086 1	0.433 56	0.434 65	615.00	2126.0	2741.0	1.8011	5.0723	6.8734	146
147	0.439 03	0.001 087 2	0.422 54	0.423 62	619.31	2123.0	2742.3	1.8114	5.0529	6.8642	147
148	0.451 12	0.001 088 3	0.411 84	0.412 93	623.62	2119.9	2743.5	1.8216	5.0335	6.8551	148
149	0.463 48	0.001 089 4	0.401 47	0.402 56	627.93	2116.8	2744.7	1.8318	5.0143	6.8461	149
150	0.476 10	0.001 090 5	0.391 41	0.392 50	632.25	2113.7	2745.9	1.8420	4.9951	6.8370	150
152	0.502 18	0.001 092 7	0.372 18	0.373 27	640.89	2107.4	2748.3	1.8623	4.9569	6.8191	152
154	0.529 38	0.001 095 0	0.354 07	0.355 16	649.55	2101.1	2750.6	1.8825	4.9189	6.8014	154
156	0.557 76	0.001 097 3	0.337 00	0.338 09	658.21	2094.7	2752.9	1.9027	4.8811	6.7838	156
158	0.587 33	0.001 099 6	0.320 90	0.322 00	666.89	2088.3	2755.2	1.9228	4.8436	6.7664	158
160	0.618 14	0.001 102 0	0.305 72	0.306 82	675.57	2081.9	2757.4	1.9428	4.8063	6.7491	160
162	0.650 22	0.001 104 4	0.291 38	0.292 49	684.28	2075.3	2759.6	1.9627	4.7693	6.7320	162
164	0.683 62	0.001 106 8	0.277 84	0.278 95	692.99	2068.8	2761.7	1.9826	4.7324	6.7150	164
166	0.718 36	0.001 109 3	0.265 05	0.266 16	701.71	2062.1	2763.8	2.0025	4.6957	6.6982	166
168	0.754 50	0.001 111 7	0.252 95	0.254 06	710.45	2055.4	2765.9	2.0222	4.6593	6.6815	168
170	0.792 05	0.001 114 3	0.241 50	0.242 62	719.21	2048.7	2767.9	2.0419	4.6230	6.6649	170
172	0.831 08	0.001 116 8	0.230 67	0.231 78	727.97	2041.9	2769.9	2.0616	4.5870	6.6485	172
174	0.871 61	0.001 119 4	0.220 41	0.221 53	736.75	2035.0	2771.8	2.0811	4.5511	6.6322	174
176	0.913 68	0.001 122 0	0.210 69	0.211 81	745.55	2028.1	2773.6	2.1007	4.5154	6.6161	176
178	0.957 34	0.001 124 7	0.201 47	0.202 60	754.36	2021.1	2775.4	2.1201	4.4799	6.6000	178
180	1.0026	0.001 127 4	0.192 73	0.193 86	763.19	2014.0	2777.2	2.1395	4.4445	6.5841	180

Properties of Saturated Water and Steam (Temperature) (continued)

	Pressure	Volume, m³/kg			Enthalpy, kJ/kg			Entropy, kJ/(kg°K)			
t (°C)	MPa	v_L	Δv	v_v	h_L	Δh	h_v	s_L	Δs	s_v	t (°C)
182	1.0496	0.001 130 1	0.184 44	0.185 57	772.03	2006.9	2778.9	2.1589	4.4094	6.5682	182
184	1.0983	0.001 132 9	0.176 57	0.177 70	780.89	1999.7	2780.6	2.1782	4.3743	6.5525	184
186	1.1487	0.001 135 7	0.169 09	0.170 23	789.76	1992.5	2782.2	2.1974	4.3395	6.5369	186
188	1.2009	0.001 138 6	0.161 99	0.163 13	798.66	1985.1	2783.8	2.2166	4.3048	6.5214	188
190	1.2550	0.001 141 4	0.155 24	0.156 38	807.57	1977.7	2785.3	2.2358	4.2702	6.5060	190
192	1.3110	0.001 144 4	0.148 81	0.149 96	816.49	1970.3	2786.8	2.2549	4.2358	6.4907	192
194	1.3689	0.001 147 3	0.142 70	0.143 85	825.44	1962.7	2788.2	2.2739	4.2015	6.4755	194
196	1.4288	0.001 150 4	0.136 88	0.138 03	834.40	1955.1	2789.5	2.2929	4.1674	6.4603	196
198	1.4907	0.001 153 4	0.131 34	0.132 50	843.39	1947.4	2790.8	2.3119	4.1334	6.4453	198
200	1.5547	0.001 156 5	0.126 07	0.127 22	852.39	1939.7	2792.1	2.3308	4.0995	6.4303	200
202	1.6208	0.001 160	0.121 04	0.122 20	861.42	1931.8	2793.2	2.3497	4.0657	6.4154	202
204	1.6891	0.001 163	0.116 24	0.117 40	870.46	1923.9	2794.4	2.3685	4.0321	6.4006	204
206	1.7596	0.001 166	0.111 66	0.112 83	879.53	1915.9	2795.4	2.3873	3.9985	6.3858	206
208	1.8323	0.001 169	0.107 30	0.108 47	888.62	1907.8	2796.4	2.4060	3.9651	6.3711	208
210	1.9074	0.001 173	0.103 13	0.104 30	897.73	1899.6	2797.4	2.4248	3.9318	6.3565	210
212	1.9848	0.001 176	0.009 15	0.100 32	906.86	1891.4	2798.2	2.4434	3.8985	6.3420	212
214	2.0647	0.001 180	0.095 345	0.096 525	916.02	1883.0	2799.0	2.4621	3.8654	6.3275	214
216	2.1470	0.001 183	0.091 710	0.092 893	925.20	1874.6	2799.8	2.4807	3.8323	6.3130	216
218	2.2319	0.001 187	0.088 235	0.089 421	934.41	1866.0	2800.4	2.4883	3.7993	6.2986	218
220	2.3193	0.001 190	0.084 911	0.086 101	943.64	1857.4	2801.1	2.5178	3.7664	6.2842	220
222	2.4093	0.001 194	0.081 730	0.082 924	952.90	1848.7	2801.6	2.5363	3.7336	6.2699	222
224	2.5020	0.001 198	0.078 685	0.079 883	962.19	1839.9	2802.1	2.5548	3.7008	6.2557	224
226	2.5975	0.001 201	0.075 770	0.076 971	971.50	1830.9	2802.4	2.5733	3.6681	6.2414	226
228	2.6957	0.001 205	0.072 977	0.074 182	980.84	1821.9	2802.8	2.5917	3.6355	6.2272	228
230	2.7968	0.001 209	0.070 301	0.071 510	990.21	1812.8	2803.0	2.6102	3.6029	6.2131	230
232	2.9008	0.001 213	0.067 736	0.068 949	999.61	1803.6	2803.2	2.6285	3.5704	6.1989	232
234	3.0077	0.001 217	0.065 277	0.066 494	1009.0	1794.2	2803.3	2.6469	3.5379	6.1848	234
236	3.1176	0.001 221	0.062 917	0.064 138	1018.5	1784.8	2803.3	2.6653	3.5054	6.1707	236
238	3.2306	0.001 225	0.060 654	0.061 879	1028.0	1775.2	2803.2	2.6836	3.4730	6.1566	238
240	3.3467	0.001 229	0.058 481	0.059 710	1037.5	1765.5	2803.1	2.7019	3.4406	6.1425	240
242	3.4659	0.001 234	0.056 394	0.057 628	1047.1	1757.7	2802.8	2.7203	3.4082	6.1285	242
244	3.5884	0.001 238	0.054 390	0.055 628	1056.7	1745.8	2802.5	2.7385	3.3759	6.1144	244
246	3.7142	0.001 243	0.052 465	0.053 707	1066.3	1735.8	2802.1	2.7568	3.3435	6.1003	246
248	3.8434	0.001 247	0.050 614	0.051 861	1076.0	1725.6	2801.6	2.7751	3.3112	6.0863	248
250	3.9759	0.001 252	0.048 835	0.050 087	1085.7	1715.3	2801.0	2.7934	3.2788	6.0722	250
252	4.1120	0.001 256	0.047 124	0.048 380	1095.4	1704.9	2800.3	2.8117	3.2465	6.0582	252
254	4.2515	0.001 261	0.045 477	0.046 739	1105.2	1694.3	2799.6	2.8299	3.2141	6.0441	254
256	4.3947	0.001 266	0.043 893	0.045 159	1115.0	1683.6	2798.7	2.8482	3.1818	6.0300	256
258	4.5415	0.001 271	0.042 368	0.043 639	1124.9	1672.8	2797.7	2.8664	3.1494	6.0158	258
260	4.6921	0.001 276	0.040 899	0.042 175	1134.8	1661.8	2796.6	2.8847	3.1170	6.0017	260
262	4.8464	0.001 281	0.039 485	0.040 766	1144.8	1650.7	2795.5	2.9030	3.0845	5.9875	262
264	5.0046	0.001 287	0.038 122	0.039 408	1154.8	1639.4	2794.2	2.9213	3.0520	5.9733	264
266	5.1667	0.001 292	0.036 808	0.038 100	1164.8	1628.0	2792.8	2.9396	3.0195	5.9590	266
368	5.3327	0.001 297	0.035 541	0.036 839	1174.9	1616.4	2791.3	2.9579	2.9869	5.9448	268
270	5.5028	0.001 303	0.034 319	0.035 622	1185.1	1604.6	2789.7	2.9762	2.9542	5.9304	270
272	5.671	0.001 309	0.033 141	0.034 450	1195.3	1592.7	2788.0	2.9945	2.9215	5.9160	272
274	5.8555	0.001 315	0.032 003	0.033 318	1205.6	1580.6	2786.1	3.0129	2.8887	5.9016	274
276	6.0381	0.001 321	0.030 905	0.032 226	1215.9	1568.3	2784.1	3.0312	2.8558	5.8871	276
278	6.2251	0.001 327	0.029 845	0.031 172	1226.2	1555.8	2782.0	3.0496	3.8228	5.8725	278
280	6.4165	0.001 333	0.028 821	0.030 154	1236.7	1543.2	2779.8	3.0681	2.7898	5.8578	280
282	6.6123	0.001 339	0.027 832	0.029 171	1247.2	1530.3	2777.5	3.0865	2.7566	5.8431	282
284	6.8126	0.001 346	0.026 875	0.028 221	1257.7	1517.3	2775.0	3.1050	2.7232	5.8283	284
286	7.0176	0.001 352	0.025 950	0.027 303	1268.3	1504.0	2772.3	3.1236	2.6898	5.8134	286
288	7.2272	0.001 359	0.025 056	0.026 415	1279.0	1490.5	2769.6	3.1421	2.6562	5.7984	288
290	7.4416	0.001 366	0.024 191	0.025 557	1289.8	1476.8	2766.6	3.1608	2.6225	5.7832	290

Properties of Saturated Water and Steam (Temperature) (continued)

t (°C)	Pressure MPa	Volume, m³/kg v_L	Δv	v_v	Enthalpy, kJ/kg h_L	Δh	h_v	Entropy, kJ/(kg°K) s_L	Δs	s_v	t (°C)
292	7.6609	0.001 373	0.023 353	0.024 727	1300.6	1462.9	2763.6	3.1794	2.5886	5.7680	292
294	7.8850	0.001 381	0.022 542	0.023 923	1311.5	1448.8	2760.3	3.1982	2.5545	5.7526	294
296	8.1142	0.001 388	0.021 757	0.023 145	1322.5	1434.4	2756.9	3.2170	2.5202	5.7372	296
298	8.3484	0.001 396	0.020 996	0.022 392	1333.6	1419.7	2753.3	3.2358	2.4857	5.7215	298
300	8.5877	0.001 404	0.020 259	0.021 663	1344.8	1404.8	2749.6	3.2547	2.4510	5.7058	300
302	8.8323	0.001 412	0.019 544	0.020 956	1356.0	1389.6	2745.6	3.2737	2.4161	5.6898	302
304	9.0822	0.001 421	0.018 851	0.020 272	1367.4	1374.1	2741.5	3.2928	2.3809	5.6737	304
306	9.3375	0.001 430	0.018 178	0.019 608	1378.8	1358.4	2737.2	3.3120	2.3455	5.6575	306
308	9.5983	0.001 439	0.017 525	0.018 964	1390.4	1342.3	2732.7	3.3312	2.3098	5.6410	308
310	9.8647	0.001 448	0.016 891	0.018 339	1402.0	1325.9	2727.9	3.3506	2.2737	5.6243	310
312	10.137	0.001 457	0.016 275	0.017 732	1413.8	1309.2	2723.0	3.3700	2.2374	5.6074	312
314	10.415	0.001 467	0.015 676	0.017 144	1425.6	1292.1	2717.8	3.3896	2.2007	5.5903	314
316	10.698	0.001 478	0.015 094	0.016 572	1437.6	1274.7	2712.3	3.4093	2.1636	5.5729	316
318	10.988	0.001 488	0.014 528	0.016 016	1449.8	1256.8	2706.6	3.4291	2.1261	5.5553	318
320	11.284	0.001 499	0.013 977	0.015 476	1462.1	1238.6	2700.7	3.4491	2.0882	5.5373	320
322	11.586	0.001 510	0.013 440	0.014 951	1474.5	1220.0	2694.4	3.4692	2.0498	5.5191	322
324	11.894	0.001 522	0.012 917	0.014 439	1487.0	1200.8	2687.9	3.4895	2.0110	5.5005	324
326	12.209	0.001 534	0.012 407	0.013 941	1499.8	1181.3	2681.0	3.5100	1.9715	5.4816	326
328	12.530	0.001 547	0.011 909	0.013 457	1512.7	1161.2	2673.8	3.5307	1.9316	5.4622	328
330	12.858	0.001 561	0.011 423	0.012 984	1525.7	1140.5	2666.2	3.5516	1.8909	5.4425	330
332	13.192	0.001 575	0.010 949	0.012 523	1539.0	1119.3	2658.3	3.5727	1.8496	5.4223	332
334	13.533	0.001 589	0.010 484	0.012 073	1552.5	1097.4	2649.9	3.5940	1.8075	5.4016	334
336	13.882	0.001 604	0.010 029	0.011 634	1566.2	1074.9	2641.1	3.6157	1.7646	5.3803	336
338	14.237	0.001 621	0.009 584	0.011 204	1580.2	1051.7	2631.9	3.6376	1.7208	5.3584	338
340	14.600	0.001 638	0.009 146	0.010 784	1594.4	1027.6	2622.1	3.6599	1.6760	5.3359	340
342	14.970	0.001 655	0.008 717	0.010 372	1609.0	1002.7	2611.7	3.6826	1.6300	5.3127	342
344	15.348	0.001 675	0.008 294	0.009 969	1623.9	976.87	2600.7	3.7058	1.5829	5.2886	344
346	15.734	0.001 695	0.007 878	0.009 573	1639.1	950.00	2589.1	3.7294	1.5344	5.2637	346
348	16.127	0.001 717	0.007 467	0.009 184	1654.8	921.99	2576.7	3.7535	1.4843	5.2378	348
350	16.529	0.001 740	0.007 061	0.008 801	1670.9	892.73	2563.6	3.7783	1.4326	5.2109	350
352	16.939	0.001 765	0.006 659	0.008 424	1687.5	862.02	2549.6	3.8039	1.3789	5.1828	352
354	17.358	0.001 793	0.006 258	0.008 051	1704.8	829.63	2534.4	3.8302	1.3229	5.1531	354
356	17.785	0.001 823	0.005 858	0.007 681	1722.8	795.33	2518.1	3.8577	1.2641	5.1218	356
358	18.221	0.001 857	0.005 456	0.007 313	1741.6	758.77	2500.4	3.8863	1.2022	5.0885	358
360	18.666	0.001 895	0.005 050	0.006 945	1761.5	719.50	2481.0	3.9164	1.1364	5.0527	360
361	18.893	0.001 915	0.004 845	0.006 760	1771.9	698.65	2470.5	3.9321	1.1017	5.0338	361
362	19.121	0.001 937	0.004 637	0.006 574	1782.6	676.87	2459.5	3.9483	1.0657	5.0140	362
363	19.352	0.001 961	0.004 425	0.006 387	1793.8	654.01	2447.8	3.9651	1.0281	4.9932	363
364	19.586	0.001 987	0.004 210	0.006 197	1805.4	629.93	2435.3	3.9827	0.9887	4.9714	364
365	19.822	0.002 016	0.003 989	0.006 004	1817.6	604.41	2422.0	4.0011	0.9471	4.9482	365
366	20.061	0.002 047	0.003 761	0.005 808	1830.4	577.19	2407.6	4.0204	0.9031	4.9235	366
367	20.302	0.002 082	0.003 524	0.005 606	1844.1	547.89	2392.0	4.0410	0.8559	4.8968	367
368	20.546	0.002 122	0.003 276	0.005 398	1858.8	515.99	2374.8	4.0631	0.8048	4.8679	368
369	20.793	0.002 167	0.003 012	0.005 179	1874.8	480.72	2355.5	4.0872	0.7486	4.8358	369
370	21.043	0.002 222	0.002 724	0.004 946	1892.6	440.86	2333.5	4.1142	0.6855	4.7996	370
371	21.296	0.002 290	0.002 401	0.004 691	1913.3	394.20	2307.5	4.1453	0.6120	4.7573	371
372	21.553	0.002 382	0.002 017	0.004 398	1938.5	336.15	2274.7	4.1836	0.5210	4.7046	372
373	21.813	0.002 526	0.001 495	0.004 021	1974.1	253.42	2227.6	4.2377	0.3922	4.6299	373.
373.5	21.945	0.002 658	0.001 087	0.003 745	2003.0	186.19	2189.1	4.2818	0.2879	4.5697	373.5
T_c	22.064	0.003 106	0.	0.003 106	2087.5	0.	2087.5	4.4120	0.	4.4120	T_c

* Values in italics indicate points where thermodynamic equilibrium state is a solid; computed values are for the metastable liquid.

T_c 373.946°C

From ASME International Steam Tables for Industrial Use, pp. 55–59.

Properties of Saturated Water and Steam (Pressure)

p MPa	t (°C)	Volume, m³/kg v_L	Δv	v_v	Enthalpy, kJ/kg h_L	Δh	h_v	Entropy, kJ/(kg°K) s_L	Δs	s_v	p MPa
$^*p_t$	0.010	0.001 000 2	206.00	206.00	0.001	2500.9	2500.9	0.0000	9.1555	9.1555	$^*p_t$
0.0007	1.881	0.001 000 1	181.22	181.22	7.890	2496.5	2504.3	0.0288	9.0770	9.1058	0.0007
0.0008	3.761	0.001 000 1	159.65	159.65	15.809	2492.0	2507.8	0.0575	8.9992	9.0567	0.0008
0.0009	5.444	0.001 000 1	142.76	142.76	22.888	2488.0	2510.9	0.0830	8.9305	9.0135	0.0009
0.0010	6.970	0.001 000 1	129.18	129.18	29.298	2484.4	2513.7	0.1059	8.8690	8.9749	0.0010
0.0012	9.654	0.001 000 3	108.67	108.67	40.569	2478.0	2518.6	0.1460	8.7624	8.9083	0.0012
0.0014	11.969	0.001 000 5	93.902	93.903	50.282	2472.5	2522.8	0.1802	8.6720	8.8521	0.0014
0.0016	14.010	0.001 000 8	82.745	82.746	58.836	2467.7	2526.6	0.2101	8.5935	8.8036	0.0016
0.0018	15.838	0.001 001 1	74.013	74.014	66.494	2463.4	2529.9	0.2366	8.5242	8.7609	0.0018
0.0020	17.495	0.001 001 4	66.989	66.990	73.435	2459.5	2532.9	0.2606	8.4621	8.7227	0.0020
0.0022	19.013	0.001 001 6	61.212	61.213	79.790	2455.9	2535.7	0.2824	8.4059	8.6883	0.0022
0.0024	20.415	0.001 001 9	56.376	56.377	85.656	3452.6	2538.2	0.3024	8.3545	8.6569	0.0024
0.0026	21.718	0.001 002 2	52.266	52.267	91.108	2449.5	2540.6	0.3210	8.3071	8.6280	0.0026
0.0028	22.936	0.001 002 5	48.730	48.731	96.204	2446.6	2542.8	0.3382	8.2632	8.6014	0.0028
0.0030	24.080	0.001 002 8	45.654	45.655	100.99	2443.9	2544.9	0.3543	8.2222	8.5766	0.0030
0.0032	25.159	0.001 003 0	42.953	42.954	105.51	2441.3	2546.8	0.3695	8.1839	8.5534	0.0032
0.0034	26.182	0.001 003 3	40.562	40.563	109.78	2438.9	2548.7	0.3838	8.1479	8.5316	0.0034
0.0036	27.153	0.001 003 6	38.431	38.432	113.84	2436.6	2550.4	0.3973	8.1138	8.5112	0.0036
0.0038	28.078	0.001 003 8	36.518	36.519	117.71	2434.4	2552.1	0.4102	8.0816	8.4918	0.0038
0.0040	28.962	0.001 004 1	34.791	34.792	121.40	2432.3	2553.7	0.4224	8.0510	8.4735	0.0040
0.0042	29.808	0.001 004 4	33.225	33.226	124.94	2430.3	2555.2	0.4341	8.0219	8.4561	0.0042
0.0044	30.619	0.001 004 6	31.798	31.799	128.33	2428.4	2556.7	0.4453	7.9941	8.4395	0.0044
0.0046	31.400	0.001 004 8	30.492	30.493	131.60	2426.5	2558.1	0.4560	7.9676	8.4236	0.0046
0.0048	32.151	0.001 005 1	29.292	29.293	134.74	2424.7	2559.5	0.4663	7.9421	8.4084	0.0048
0.0050	32.875	0.001 005 3	28.185	28.186	137.77	2423.0	2560.8	0.4763	7.9177	8.3939	0.0050
0.0055	34.583	0.001 005 9	25.762	25.763	144.90	2418.9	2563.8	0.4995	7.8605	8.3600	0.0055
0.0060	36.160	0.001 006 4	23.733	23.734	151.49	2415.2	2566.7	0.5209	7.8083	8.3291	0.0060
0.0065	37.628	0.001 007 0	22.009	22.010	157.63	2411.7	2569.3	0.5407	7.7601	8.3008	0.0065
0.0070	39.001	0.001 007 5	20.524	20.525	163.37	2408.4	2571.8	0.5591	7.7155	8.2746	0.0070
0.0075	40.292	0.001 008 0	19.233	19.234	168.76	2405.3	2574.1	0.5763	7.6739	8.2502	0.0075
0.0080	41.510	0.001 008 5	18.098	18.099	173.85	2402.4	2576.2	0.5925	7.6349	8.2274	0.0080
0.0085	42.665	0.001 008 9	17.094	17.095	178.68	2399.6	2578.3	0.6078	7.5982	8.2060	0.0085
0.0090	43.762	0.001 009 4	16.199	16.200	183.26	2397.0	2580.3	0.6223	7.5636	8.1859	0.0090
0.0095	44.808	0.001 009 8	15.395	15.396	187.63	2394.5	2582.1	0.6361	7.5308	8.1669	0.0095
0.010	45.808	0.001 010 3	14.670	14.671	191.81	2392.1	2583.9	0.6492	7.4997	8.1489	0.010
0.011	47.684	0.001 011 1	13.411	13.412	199.66	2387.6	2587.2	0.6737	7.4417	8.1155	0.011
0.012	49.420	0.001 011 9	12.358	12.359	206.91	2383.4	2590.3	0.6963	7.3887	8.0850	0.012
0.013	51.035	0.001 012 6	11.462	11.463	213.66	2379.5	2593.1	0.7172	7.3399	8.0570	0.013
0.014	52.548	0.001 013 3	10.690	10.691	219.99	2375.8	2595.8	0.7366	7.2945	8.0312	0.014
0.015	53.970	0.001 014 0	10.019	10.020	225.94	2372.4	2598.3	0.7548	7.2523	8.0071	0.015
0.016	55.314	0.001 014 7	9.4299	9.4309	231.55	2369.1	2600.7	0.7720	7.2127	7.9847	0.016
0.017	56.588	0.001 015 3	8.9079	8.9089	236.88	2366.0	2602.9	0.7882	7.1754	7.9636	0.017
0.018	57.799	0.001 016 0	8.4423	8.4433	241.95	2363.1	2605.0	0.8035	7.1403	7.9437	0.018
0.019	58.954	0.001 016 6	8.0244	8.0254	246.78	2360.2	2607.0	0.8181	7.1069	7.9250	0.019
0.020	60.059	0.001 017 1	7.6471	7.6482	251.40	2357.5	2608.9	0.8320	7.0753	7.9072	0.020
0.022	62.133	0.001 018 3	6.9927	6.9938	260.08	2352.5	2612.6	0.8579	7.0164	7.8743	0.022
0.024	64.054	0.001 019 3	6.4445	6.4455	268.12	2347.8	2615.9	0.8818	6.9624	7.8442	0.024
0.026	65.843	0.001 020 3	5.9783	5.9793	275.61	2343.4	2619.0	0.9040	6.9127	7.8167	0.026
0.028	67.518	0.001 021 3	5.5769	5.5779	282.62	2339.2	2621.8	0.9246	6.8666	7.7912	0.028
0.030	69.095	0.001 022 2	5.2275	5.2286	289.23	2335.3	2624.6	0.9439	6.8235	7.7675	0.030

Properties of Saturated Water and Steam (Pressure) (continued)

		Volume, m^3/kg			Enthalpy, kJ/kg			Entropy, kJ/(kg°K)			p
p MPa	t (°C)	v_L	Δv	v_v	h_L	Δh	h_v	s_L	Δs	s_v	MPa
0.032	70.586	0.001 023 1	4.9206	4.9216	295.47	2331.6	2627.1	0.9621	6.7832	7.7453	0.032
0.034	72.000	0.001 024 0	4.6488	4.6498	301.40	2328.1	2629.5	0.9793	6.7452	7.7245	0.034
0.036	73.345	0.001 024 8	4.4063	4.4073	307.04	2324.8	2631.8	0.9956	6.7093	7.7050	0.036
0.038	74.629	0.001 025 6	4.1886	4.1897	312.42	2321.6	2634.0	1.0111	6.6754	7.6865	0.038
0.040	75.857	0.001 026 4	3.9921	3.9931	317.57	2318.5	2636.1	1.0259	6.6431	7.6690	0.040
0.042	77.034	0.001 027 1	3.8137	3.8147	322.50	2315.5	2638.0	1.0400	6.6123	7.6523	0.042
0.044	78.165	0.001 027 8	3.6511	3.6521	327.25	2312.7	2639.9	1.0535	6.5829	7.6365	0.044
0.046	79.254	0.001 028 6	3.5022	3.5032	331.82	2309.9	2641.8	1.0665	6.5548	7.6213	0.046
0.048	80.303	0.001 029 2	3.3653	3.3664	336.22	2307.3	2643.5	1.0790	6.5279	7.6068	0.048
0.050	81.317	0.001 029 9	3.2391	3.2401	340.48	2304.7	2645.2	1.0910	6.5020	7.5930	0.050
0.055	83.709	0.001 031 5	2.9626	2.9636	350.52	2298.7	2649.2	1.1192	6.4414	7.5606	0.055
0.060	85.926	0.001 033 1	2.7308	2.7318	359.84	2293.0	2652.9	1.1452	6.3859	7.5311	0.060
0.065	87.993	0.001 034 5	2.5337	2.5347	368.53	2287.7	2656.2	1.1694	6.3346	7.5040	0.065
0.070	89.932	0.001 035 9	2.3639	2.3649	376.68	2282.7	2659.4	1.1919	6.2871	7.4790	0.070
0.075	91.758	0.001 037 2	2.2160	2.2171	384.37	2278.0	2662.4	1.2130	6.2427	7.4557	0.075
0.080	93.485	0.001 038 5	2.0862	2.0872	391.64	2273.5	2665.2	1.2328	6.2011	7.4339	0.080
0.085	95.125	0.001 039 7	1.9711	1.9721	398.55	2269.3	2667.8	1.2516	6.1618	7.4135	0.085
0.090	96.687	0.001 040 9	1.8684	1.8695	405.13	2265.2	2670.3	1.2694	6.1248	7.3942	0.090
0.095	98.178	0.001 042 0	1.7762	1.7773	411.42	2261.3	2672.7	1.2864	6.0897	7.3760	0.095
0.10	99.606	0.001 043 1	1.6930	1.6940	417.44	2257.5	2674.9	1.3026	6.0562	7.3588	0.10
0.11	102.292	0.001 045 3	1.5485	1.5496	428.77	2250.4	2679.2	1.3328	5.9940	7.3268	0.11
0.12	104.784	0.001 047 3	1.4274	1.4284	439.30	2243.8	2683.1	1.3608	5.9369	7.2976	0.12
0.13	107.109	0.001 049 2	1.3244	1.3254	449.13	2237.5	2686.6	1.3867	5.8842	7.2708	0.13
0.14	109.292	0.001 051 0	1.2356	1.2366	458.37	2231.6	2690.0	1.4109	5.8352	7.2460	0.14
0.15	111.350	0.001 052 7	1.1583	1.1594	467.08	2226.0	2693.1	1.4335	5.7894	7.2229	0.15
0.16	113.298	0.001 054 4	1.0904	1.0914	475.34	2220.7	2696.0	1.4549	5.7464	7.2014	0.16
0.17	115.149	0.001 056 0	1.0302	1.0312	483.18	2215.6	2698.8	1.4752	5.7059	7.1811	0.17
0.18	116.912	0.001 057 6	0.976 48	0.977 53	490.67	2210.7	2701.4	1.4944	5.6677	7.1620	0.18
0.19	118.597	0.001 059 1	0.928 24	0.929 30	497.82	2206.1	2703.9	1.5127	5.6313	7.1440	0.19
0.20	120.212	0.001 060 5	0.884 67	0.885 74	504.68	2201.6	2706.2	1.5301	5.5968	7.1269	0.20
0.21	121.761	0.001 061 9	0.845 13	0.846 19	511.27	2197.2	2708.5	1.5468	5.5638	7.1106	0.21
0.22	123.251	0.001 063 3	0.809 06	0.810 12	517.62	2193.0	2710.6	1.5628	5.5323	7.0951	0.22
0.23	124.688	0.001 064 6	0.776 02	0.777 09	523.73	2188.9	2712.7	1.5782	5.5021	7.0802	0.23
0.24	126.074	0.001 065 9	0.745 65	0.746 72	529.64	2185.0	2714.6	1.5930	5.4731	7.0660	0.24
0.25	127.414	0.001 067 2	0.717 63	0.718 70	535.35	2181.2	2716.5	1.6072	5.4452	7.0524	0.25
0.26	128.711	0.001 068 5	0.691 69	0.692 76	540.88	2177.4	2718.3	1.6210	5.4183	7.0393	0.26
0.27	129.968	0.001 069 7	0.667 62	0.668 69	546.25	2173.8	2720.0	1.6343	5.3924	7.0267	0.27
0.28	131.188	0.001 070 9	0.645 20	0.646 27	551.46	2170.3	2721.7	1.6472	5.3674	7.0146	0.28
0.29	132.373	0.001 072 0	0.624 28	0.625 36	556.53	2166.8	2723.3	1.6597	5.3432	7.0029	0.29
0.30	133.525	0.001 073 2	0.604 71	0.605 79	561.46	2163.4	2724.9	1.6718	5.3198	6.9916	0.30
0.31	136.647	0.001 074 3	0.586 36	0.587 44	566.26	2160.1	2726.4	1.6835	5.2971	6.9806	0.31
0.32	135.740	0.001 075 4	0.569 12	0.570 20	570.93	2156.9	2727.9	1.6950	5.2751	6.9700	0.32
0.33	136.806	0.001 076 5	0.552 89	0.553 97	575.50	2153.8	2729.3	1.7061	5.2537	6.9597	0.33
0.34	137.845	0.001 077 5	0.537 58	0.538 66	579.96	2150.7	2730.6	1.7169	5.2329	6.9498	0.34
0.35	138.861	0.001 078 6	0.523 12	0.524 20	584.31	2147.7	2732.0	1.7275	5.2126	6.9401	0.35
0.36	139.853	0.001 079 6	0.509 43	0.510 51	588.57	2144.7	2733.3	1.7378	5.1929	6.9307	0.36
0.37	140.823	0.001 080 6	0.496 46	0.497 54	592.74	2141.8	2734.5	1.7478	5.1737	6.9215	0.37
0.38	141.773	0.001 081 6	0.484 15	0.485 23	596.81	2138.9	2735.7	1.7576	5.1550	6.9126	0.38
0.39	142.702	0.001 082 6	0.472 44	0.473 53	600.81	2136.1	2736.9	1.7672	5.1367	6.9039	0.39
0.40	143.613	0.001 083 6	0.461 31	0.462 39	604.72	2133.3	2738.1	1.7766	5.1188	6.8954	0.40

Properties of Saturated Water and Steam (Pressure) (continued)

		Volume, m³/kg			Enthalpy, kJ/kg			Entropy, kJ/(kg°K)			p
p MPa	t (°C)	v_L	Δv	v_v	h_L	Δh	h_v	s_L	Δs	s_v	MPa
0.42	145.380	0.001 085 5	0.440 57	0.441 66	612.33	2127.9	2740.3	1.7948	5.0843	6.8791	0.42
0.44	147.081	0.001 087 3	0.421 66	0.422 75	619.66	2122.7	2742.4	1.8122	5.0513	6.8635	0.44
0.46	148.721	0.001 089 1	0.404 34	0.405 43	626.73	2117.6	2744.4	1.8289	5.0197	6.8486	0.46
0.48	150.305	0.001 090 8	0.388 41	0.389 50	633.57	2112.7	2746.3	1.8450	4.9892	6.8343	0.48
0.50	151.836	0.001 092 6	0.373 71	0.374 80	640.19	2107.9	2748.1	1.8606	4.9600	6.8206	0.50
0.52	153.320	0.001 094 2	0.360 11	0.361 20	646.60	2103.2	2749.9	1.8756	4.9318	6.8074	0.52
0.54	154.758	0.001 095 9	0.347 48	0.348 57	652.83	2098.7	2751.5	1.8901	4.9045	6.7947	0.54
0.56	156.155	0.001 097 5	0.335 72	0.336 82	658.88	2094.2	2753.1	1.9042	4.8782	6.7824	0.56
0.58	157.512	0.001 099 1	0.324 74	0.325 84	664.77	2089.9	2754.7	1.9179	4.8528	6.7706	0.58
0.60	158.832	0.001 100 6	0.314 47	0.315 58	670.50	2085.6	2756.1	1.9311	4.8281	6.7592	0.60
0.62	160.118	0.001 102 1	0.304 85	0.305 95	676.09	2081.5	2757.6	1.9440	4.8041	6.7481	0.62
0.64	161.371	0.001 103 6	0.295 80	0.296 90	681.54	2077.4	2758.9	1.9565	4.7809	6.7374	0.64
0.66	162.594	0.001 105 1	0.287 28	0.288 39	686.86	2073.4	2760.2	1.9686	4.7583	6.7269	0.66
0.68	163.787	0.001 106 5	0.279 25	0.280 35	692.06	2069.5	2761.5	1.9805	4.7363	6.7168	0.68
0.70	164.953	0.001 108 0	0.271 66	0.272 76	697.14	2065.6	2762.7	1.9921	4.7149	6.7070	0.70
0.72	166.092	0.001 109 4	0.264 47	0.265 58	702.12	2061.8	2763.9	2.0034	4.6940	6.6974	0.72
0.74	167.207	0.001 110 8	0.257 66	0.268 77	706.99	2058.1	2765.1	2.0144	4.6737	6.6881	0.74
0.76	168.298	0.001 112 1	0.251 20	0.252 31	711.76	2054.4	2766.2	2.0252	4.6539	6.6790	0.76
0.78	169.366	0.001 113 5	0.245 06	0.246 17	716.43	2050.8	2767.3	2.0357	4.6345	6.6702	0.78
0.80	170.414	0.001 114 8	0.239 21	0.240 33	721.02	2047.3	2768.3	2.0460	4.6156	6.6615	0.80
0.82	171.440	0.001 116 1	0.233 64	0.234 76	725.52	2043.8	2769.3	2.0561	4.5970	6.6531	0.82
0.84	172.447	0.001 117 4	0.228 33	0.229 44	729.93	2040.4	2770.3	2.0659	4.5789	6.6449	0.84
0.86	173.435	0.001 118 7	0.223 25	0.224 37	734.27	2037.0	2771.2	2.0756	4.5612	6.6368	0.86
0.88	174.405	0.001 119 9	0.218 40	0.219 52	738.53	2033.6	2772.1	2.0851	4.5438	6.6289	0.88
0.90	175.358	0.001 121 2	0.213 75	0.214 87	742.72	2030.3	2773.0	2.0944	4.5268	6.6212	0.90
0.92	176.294	0.001 122 4	0.209 30	0.210 42	746.85	2027.1	2773.9	2.1035	4.5102	6.6137	0.92
0.94	177.214	0.001 123 6	0.205 03	0.206 16	750.90	2023.8	2774.7	2.1125	4.4938	6.6063	0.94
0.96	178.119	0.001 124 9	0.200 94	0.202 06	754.89	2020.7	2775.6	2.1213	4.4778	6.5991	0.96
0.98	179.010	0.001 126 0	0.197 00	0.198 13	758.82	2017.5	2776.3	2.1299	4.4620	6.5919	0.98
1.00	179.886	0.001 127 2	0.193 22	0.194 35	762.58	2014.4	2777.1	2.1384	4.4465	6.5850	1.00
1.05	182.017	0.001 130 1	0.184 37	0.185 50	772.10	2006.8	2779.0	2.1591	4.4091	6.5681	1.05
1.10	184.070	0.001 133 0	0.176 30	0.177 44	781.20	1999.5	2780.7	2.1789	4.3731	6.5520	1.10
1.15	186.050	0.001 135 8	0.168 91	0.170 05	789.99	1992.3	2782.3	2.1979	4.3386	6.5365	1.15
1.20	187.965	0.001 138 5	0.161 11	0.163 25	798.50	1985.3	2783.8	2.2163	4.3054	6.5217	1.20
1.25	189.817	0.001 141 2	0.155 84	0.156 98	806.75	1978.4	2785.2	2.2340	4.2734	6.5074	1.25
1.30	191.613	0.001 143 8	0.150 03	0.151 17	814.76	1971.7	2786.5	2.2512	4.2425	6.4936	1.30
1.35	193.355	0.001 146 4	0.144 64	0.145 79	822.55	1965.2	2787.7	2.2678	4.2126	6.4804	1.35
1.40	195.047	0.001 148 9	0.139 62	0.140 77	830.13	1958.8	2788.9	2.2839	4.1836	6.4675	1.40
1.45	196.693	0.001 151 4	0.134 93	0.136 08	837.52	1952.5	2790.0	2.2995	4.1556	6.4551	1.45
1.50	198.295	0.001 153 9	0.130 55	0.131 70	844.72	1946.3	2791.0	2.3147	4.1284	6.4431	1.50
1.55	199.856	0.001 156 3	0.126 44	0.127 59	851.74	1940.2	2792.0	2.3294	4.1019	6.4314	1.55
1.60	201.378	0.001 158 7	0.122 57	0.123 73	858.61	1934.3	2792.9	2.3438	4.0762	6.4200	1.60
1.65	202.864	0.001 161 0	0.118 94	0.120 10	865.32	1928.4	2793.7	2.3578	4.0512	6.4090	1.65
1.70	204.315	0.001 163 4	0.115 50	0.116 67	871.89	1922.6	2794.5	2.3715	4.0268	6.3983	1.70
1.75	205.733	0.001 165 7	0.112 26	0.113 43	878.32	1917.0	2795.3	2.3848	4.0030	6.3878	1.75
1.80	207.120	0.001 167 9	0.109 19	0.110 36	884.61	1911.4	2796.0	2.3978	3.9798	6.3776	1.80
1.85	208.477	0.001 170 2	0.106 29	0.107 46	890.79	1905.9	2796.6	2.4105	3.9571	6.3676	1.85
1.90	209.806	0.001 172 4	0.103 53	0.104 70	896.84	1900.4	2797.3	2.4229	3.9350	6.3579	1.90
1.95	211.108	0.001 174 6	0.100 90	0.102 08	902.79	1895.1	2797.8	2.4351	3.9133	6.3484	1.95
2.0	212.385	0.001 176 8	0.098 404	0.099 581	908.62	1889.8	2798.4	2.4470	3.8921	6.3392	2.0

Properties of Saturated Water and Steam (Pressure) (continued)

		Volume, m^3/kg			Enthalpy, kJ/kg			Entropy, kJ/(kg°K)			
p MPa	*t* (°C)	v_L	Δv	v_v	h_L	Δ*h*	h_v	s_L	Δ*s*	s_v	*p* MPa
2.1	214.865	0.001 181 0	0.093 753	0.094 934	919.99	1879.4	2799.4	2.4701	3.8511	6.3212	2.1
2.2	217.256	0.001 185 2	0.089 510	0.090 695	930.98	1869.2	2800.2	2.4924	3.8116	6.3040	2.2
2.3	219.564	0.001 189 4	0.085 623	0.086 812	941.63	1859.3	2800.9	2.5138	3.7736	6.2874	2.3
2.4	221.795	0.001 193 4	0.082 049	0.083 242	951.95	1849.6	2801.5	2.5244	3.7370	6.2714	2.4
2.5	223.956	0.001 197 4	0.078 750	0.079 947	961.98	1840.1	2802.0	2.5544	3.7015	6.2560	2.5
2.6	226.052	0.001 201 4	0.075 696	0.076 897	971.74	1830.7	2802.5	2.5738	3.6673	6.2411	2.6
2.7	228.086	0.001 205 3	0.072 860	0.074 065	981.24	1821.5	2802.8	2.5925	3.6341	6.2266	2.7
2.8	230.063	0.001 209 1	0.070 219	0.071 428	990.50	1812.5	2803.0	2.6107	3.6019	6.2126	2.8
2.9	231.986	0.001 212 9	0.067 754	0.068 967	999.54	1803.6	2803.2	2.6284	3.5706	6.1990	2.9
3.0	233.858	0.001 216 7	0.065 447	0.066 664	1008.4	1794.9	2803.3	2.6456	3.5402	6.1878	3.0
3.1	235.684	0.001 220 4	0.063 284	0.064 504	1017.0	1786.3	2803.3	2.6624	3.5105	6.1729	3.1
3.2	237.464	0.001 224 1	0.061 251	0.062 475	1025.5	1777.8	2803.2	2.6787	3.4817	6.1604	3.2
3.3	239.203	0.001 227 8	0.059 336	0.060 564	1033.7	1769.4	2803.1	2.6946	3.4535	6.1481	3.3
3.4	240.901	0.001 231 4	0.057 530	0.058 761	1041.8	1761.1	2803.0	2.7102	3.4260	6.1362	3.4
3.5	242.562	0.001 235 0	0.055 823	0.057 058	1049.8	1753.0	2802.7	2.7254	3.3991	6.1245	3.5
3.6	244.186	0.001 238 5	0.054 208	0.055 446	1057.6	1744.9	2802.5	2.7403	3.3728	6.1131	3.6
3.7	245.776	0.001 242 1	0.052 676	0.053 918	1065.2	1736.9	2802.1	2.7548	3.3471	6.1019	3.7
3.8	247.334	0.001 245 6	0.051 222	0.052 468	1072.8	1729.0	2801.8	2.7690	3.3219	6.0910	3.8
3.9	248.861	0.001 249 1	0.049 840	0.051 089	1080.2	1721.2	2801.4	2.7830	3.2973	6.0802	3.9
4.0	250.358	0.001 252 6	0.048 524	0.049 777	1087.4	1713.5	2800.9	2.7967	3.2731	6.0697	4.0
4.1	251.826	0.001 256 0	0.047 270	0.048 526	1094.6	1705.8	2800.4	2.8101	3.2493	6.0594	4.1
4.2	253.267	0.001 259 5	0.046 073	0.047 333	1101.6	1698.2	2799.9	2.8232	3.2260	6.0492	4.2
4.3	254.683	0.001 262 9	0.044 930	0.046 193	1108.6	1690.7	2799.3	2.8362	3.2031	6.0393	4.3
4.4	256.073	0.001 206 3	0.043 836	0.045 103	1115.4	1683.2	2798.7	2.8488	3.1806	6.0294	4.4
4.5	257.439	0.001 269 7	0.042 790	0.044 059	1122.1	1675.9	2798.0	2.8613	3.1585	6.0198	4.5
4.6	258.783	0.001 273	0.041 787	0.043 060	1128.8	1668.5	2797.3	2.8736	3.1367	6.0103	4.6
4.7	260.104	0.001 276	0.040 825	0.042 101	1135.3	1661.2	2796.6	2.8857	3.1153	6.0010	4.7
4.8	261.404	0.001 280	0.039 901	0.041 181	1141.8	1654.0	2795.8	2.8975	3.0942	5.9917	4.8
4.9	262.683	0.001 283	0.039 013	0.040 296	1148.2	1646.8	2795.0	2.9092	3.0734	5.9827	4.9
5.0	263.943	0.001 286	0.038 160	0.039 446	1154.5	1639.7	2794.2	2.9207	3.0530	5.9737	5.0
5.1	265.183	0.001 290	0.037 338	0.038 628	1160.7	1632.7	2793.4	2.9321	3.0328	5.9649	5.1
5.2	266.405	0.001 293	0.036 547	0.037 840	1166.9	1625.6	2792.5	2.9433	3.0129	5.9562	5.2
5.3	267.610	0.001 296	0.035 785	0.037 081	1173.0	1618.6	2791.6	2.9543	2.9933	5.9475	5.3
5.4	268.797	0.001 300	0.035 049	0.036 349	1179.0	1611.7	2790.7	2.9652	2.9739	5.9390	5.4
5.5	269.967	0.001 303	0.034 339	0.035 642	1184.9	1604.8	2789.7	2.9759	3.9548	5.9307	5.5
5.6	271.121	0.001 306	0.033 654	0.034 960	1190.8	1597.9	2788.7	2.9865	2.9359	5.9224	5.6
5.7	272.260	0.001 309	0.032 991	0.034 300	1196.6	1591.1	2787.7	2.9969	2.9173	5.9141	5.7
5.8	273.383	0.001 313	0.032 350	0.033 663	1202.4	1584.3	2786.7	3.0072	2.8988	5.9060	5.8
5.9	274.492	0.001 316	0.031 730	0.033 046	1208.1	1577.6	2785.6	3.0174	2.8806	5.8980	5.9
6.0	275.586	0.001 319	0.031 129	0.032 449	1213.7	1570.8	2784.6	3.0274	2.8626	5.8901	6.0
6.1	276.667	0.001 323	0.030 548	0.031 870	1219.3	1564.1	2783.5	3.0374	2.8448	5.8822	6.1
6.2	277.734	0.001 326	0.029 984	0.031 310	1224.9	1557.5	2782.3	3.0472	2.8272	5.8744	6.2
6.3	278.788	0.001 329	0.029 437	0.030 766	1230.3	1550.8	2781.2	3.0569	2.8098	5.8667	6.3
6.4	279.830	0.001 332	0.028 907	0.030 239	1235.8	1544.2	2780.0	3.0665	2.7926	5.8591	6.4
6.5	280.859	0.001 336	0.028 392	0.029 728	1241.2	1537.7	2778.8	3.0760	2.7755	5.8515	6.5
6.6	281.876	0.001 339	0.027 892	0.029 231	1246.5	1531.1	2777.6	3.0854	2.7586	5.8440	6.6
6.7	282.881	0.001 342	0.027 406	0.028 748	1251.8	1524.6	2776.4	3.0947	2.7419	5.8366	6.7
6.8	283.875	0.001 345	0.026 934	0.028 279	1257.1	1518.1	2775.1	3.1039	2.7253	5.8292	6.8
6.9	284.858	0.001 349	0.026 475	0.027 823	1262.3	1511.6	2773.9	3.1130	2.7089	5.8219	6.9
7.0	285.830	0.001 352	0.026 028	0.027 380	1267.4	1505.1	2772.6	3.1220	2.6926	5.8146	7.0

Properties of Saturated Water and Steam (Pressure) (continued)

		Volume, m³/kg			Enthalpy, kJ/kg			Entropy, kJ/(kg°K)			p
p MPa	t (°C)	v_L	Δv	v_v	h_L	Δh	h_v	s_L	Δs	s_v	MPa
7.1	286.791	0.001 355	0.025 593	0.026 948	1272.6	1498.7	2771.3	3.1309	2.6765	5.8074	7.1
7.2	287.743	0.001 358	0.025 169	0.026 528	1277.7	1492.3	2769.9	3.1398	2.6605	5.8003	7.2
7.3	288.684	0.001 362	0.024 757	0.026 119	1282.7	1485.9	2768.6	3.1485	2.6447	5.7932	7.3
7.4	289.615	0.001 365	0.024 355	0.025 720	1287.7	1479.5	2767.2	3.1572	2.6290	5.7862	7.4
7.5	290.537	0.001 368	0.023 963	0.025 331	1292.7	1473.1	2765.8	3.1658	2.6134	5.7792	7.5
7.6	291.449	0.001 371	0.023 581	0.024 952	1297.6	1466.8	2764.4	3.1743	2.5979	5.7722	7.6
7.7	292.352	0.001 375	0.023 208	0.024 583	1302.5	1460.4	2763.0	3.1827	2.5826	5.7653	7.7
7.8	293.247	0.001 378	0.022 845	0.024 223	1307.4	1454.1	2761.5	3.1911	2.5673	5.7584	7.8
7.9	294.132	0.001 381	0.022 490	0.023 871	1312.3	1447.8	2760.1	3.1994	2.5522	5.7516	7.9
8.0	295.009	0.001 385	0.022 143	0.023 528	1317.1	1441.5	2758.6	3.2077	2.5372	5.7448	8.0
8.1	295.878	0.001 388	0.021 804	0.023 192	1321.9	1435.3	2757.1	3.2158	2.5223	5.7381	8.1
8.2	296.738	0.001 391	0.021 473	0.022 865	1326.6	1429.0	2755.6	3.2239	2.5075	5.7314	8.2
8.3	297.591	0.001 395	0.021 150	0.022 545	1331.3	1422.7	2754.1	3.2320	2.4928	5.7247	8.3
8.4	298.435	0.001 398	0.020 834	0.022 232	1336.0	1416.5	2752.5	3.2399	2.4782	5.7181	8.4
8.5	299.272	0.001 401	0.020 525	0.021 926	1340.7	1410.3	2751.0	3.2478	2.4637	5.7115	8.5
8.6	300.102	0.001 405	0.020 222	0.021 627	1345.3	1404.0	2749.4	3.2557	2.4493	5.7050	8.6
8.7	300.924	0.001 408	0.019 926	0.021 334	1350.0	1397.8	2747.8	3.2635	2.4349	5.6984	8.7
8.8	301.738	0.001 411	0.019 636	0.021 048	1354.5	1391.6	2746.2	3.2712	2.4207	5.6919	8.8
8.9	302.546	0.001 415	0.019 353	0.020 767	1359.1	1385.4	2744.5	3.2789	2.4065	5.6855	8.9
9.0	303.347	0.001 418	0.019 075	0.020 493	1363.7	1379.2	2742.9	3.2866	2.3924	5.6790	9.0
9.1	304.141	0.001 422	0.018 803	0.020 224	1368.2	1373.0	2741.2	3.2942	2.3784	5.6726	9.1
9.2	304.928	0.001 425	0.018 536	0.019 961	1372.7	1366.9	2739.5	3.3017	2.3645	5.6662	9.2
9.3	305.709	0.001 428	0.018 275	0.019 703	1371.1	1360.7	2737.8	3.3092	2.3507	5.6598	9.3
9.4	306.483	0.001 432	0.018 019	0.019 450	1381.6	1354.5	2736.1	3.3166	2.3369	5.6535	9.4
9.5	307.251	0.001 435	0.017 767	0.019 203	1386.0	1348.4	2734.4	3.3240	2.3232	5.6472	9.5
9.6	308.013	0.001 439	0.017 521	0.018 960	1390.4	1342.2	2732.6	3.3313	2.3095	5.6409	9.6
9.7	308.768	0.001 442	0.017 279	0.018 721	1394.8	1336.1	2730.9	3.3386	2.2960	5.6346	9.7
9.8	309.518	0.001 446	0.017 042	0.018 488	1399.2	1329.9	2729.1	3.3459	2.2824	5.6283	9.8
9.9	310.262	0.001 449	0.016 809	0.018 259	1403.5	1323.8	2727.3	3.3531	2.2690	5.6221	9.9
10.0	310.999	0.001 453	0.016 581	0.018 034	1407.9	1317.6	2725.5	3.3603	2.2556	5.6159	10.0
10.2	312.458	0.001 460	0.016 136	0.017 596	1416.5	1305.3	2721.8	3.3745	2.2290	5.6035	10.2
10.4	313.895	0.001 467	0.015 707	0.017 174	1425.0	1293.0	2718.0	3.3886	2.2026	5.5912	10.4
10.6	315.311	0.001 474	0.015 293	0.016 767	1433.5	1280.7	2714.2	3.4025	2.1764	5.5789	10.6
10.8	316.706	0.001 481	0.014 893	0.016 374	1441.9	1268.4	2710.3	3.4163	2.1504	5.5667	10.8
11.0	318.081	0.001 489	0.014 505	0.015 994	1450.3	1256.1	2706.4	3.4300	2.1246	5.5545	11.0
11.2	319.437	0.001 496	0.014 130	0.015 626	1458.6	1243.8	2702.4	3.4435	2.0989	5.5424	11.2
11.4	320.774	0.001 503	0.013 767	0.015 271	1466.8	1231.4	2698.3	3.4569	2.0734	5.5303	11.4
11.6	322.093	0.001 511	0.013 415	0.014 926	1475.0	1219.1	2694.1	3.4702	2.0480	5.5182	11.6
11.8	323.394	0.001 519	0.013 074	0.014 593	1483.2	1206.7	2689.9	3.4834	2.0228	5.5062	11.8
12.0	324.678	0.001 526	0.012 743	0.014 269	1491.3	1194.3	2685.6	3.4965	1.9977	5.4941	12.0
12.2	325.946	0.001 534	0.012 421	0.013 955	1499.4	1181.8	2681.2	3.5095	1.9726	5.4821	12.2
12.4	327.197	0.001 542	0.012 108	0.013 650	1507.5	1169.3	2676.7	3.5224	1.9477	5.4700	12.4
12.6	328.432	0.001 550	0.011 803	0.013 354	1515.5	1156.7	2672.2	3.5352	1.9228	5.4580	12.6
12.8	329.652	0.001 558	0.011 507	0.013 065	1523.4	1144.1	2667.6	3.5479	1,8980	5.4459	12.8
13.0	330.857	0.001 506	0.011 219	0.012 785	1531.4	1131.5	2662.9	3.5606	1.8733	5.4339	13.0
13.2	332.047	0.001 575	0.010 937	0.012 512	1539.3	1118.8	2658.1	3.5732	1.8486	5.4218	13.2
13.4	333.223	0.001 583	0.010 663	0.012 247	1547.2	1106.0	2653.2	3.5857	1.8240	5.4097	13.4
13.6	334.385	0.001 592	0.010 396	0.011 988	1555.1	1093.1	2648.3	3.5982	1.7993	5.3975	13.6
13.8	335.534	0.001 601	0.010 134	0.011 735	1563.0	1080.2	2643.2	3.6106	1.7747	5.3853	13.8
14.0	336.669	0.001 610	0.009 879	0.011 489	1570.9	1067.2	2638.1	3.6230	1.7500	5.3730	14.0

Properties of Saturated Water and Steam (Pressure) (continued)

		Volume, m^3/kg			Enthalpy, kJ/kg			Entropy, kJ/(kg°K)			p
p MPa	t (°C)	v_L	Δv	v_v	h_L	Δh	h_v	s_L	Δs	s_v	MPa
14.2	337.792	0.001 619	0.009 630	0.011 248	1578.7	1054.1	2632.9	3.6353	1.7254	5.3607	14.2
14.4	338.902	0.001 628	0.009 385	0.011 014	1586.6	1040.9	2627.5	3.6477	1.7007	5.3484	14.4
14.6	339.999	0.001 638	0.009 147	0.010 784	1594.4	1027.6	2622.1	3.6599	1.6760	5.3359	14.6
14.8	341.084	0.001 647	0.008 912	0.010 560	1602.3	1014.2	2616.5	3.6722	1.6512	5.3234	14.8
15.0	342.158	0.001 657	0.008 683	0.010 340	1610.2	1000.7	2610.9	3.6844	1.6264	5.3108	15.0
15.2	343.220	0.001 667	0.008 458	0.010 125	1618.0	987.07	2605.1	3.6967	1.6014	5.2981	15.2
15.4	344.270	0.001 677	0.008 237	0.009 915	1625.9	973.30	2599.2	3.7089	1.5764	5.2853	15.4
15.6	345.310	0.001 688	0.008 021	0.009 709	1633.8	959.39	2593.2	3.7212	1.5513	5.2724	15.6
15.8	346.339	0.001 699	0.007 808	0.009 506	1641.7	945.34	2587.1	3.7334	1.5260	5.2594	15.8
16.0	347.357	0.001 710	0.007 599	0.009 308	1649.7	931.13	2580.8	3.7457	1.5006	5.2463	16.0
16.2	348.364	0.001 721	0.007 393	0.009 114	1657.6	916.76	2574.4	3.7580	1.4750	5.2330	16.2
16.4	349.361	0.001 732	0.007 190	0.008 923	1665.7	902.22	2567.9	3.7703	1.4493	5.2196	16.4
16.6	350.349	0.001 744	0.006 991	0.008 736	1673.8	887.50	2561.2	3.7827	1.4234	5.2061	16.6
16.8	351.326	0.001 757	0.006 794	0.008 551	1681.9	872.55	2554.4	3.7952	1.3973	5.1924	16.8
17.0	352.293	0.001 769	0.006 600	0.008 369	1690.0	857.38	2547.4	3.8077	1.3708	5.1785	17.0
17.2	353.252	0.001 782	0.006 408	0.008 190	1698.3	841.96	2540.2	3.8203	1.3441	5.1644	17.2
17.4	354.200	0.001 796	0.006 218	0.008 014	1706.6	826.29	2532.9	3.8329	1.3171	5.1501	17.2
17.6	355.140	0.001 810	0.006 030	0.007 840	1715.0	810.34	2525.3	3.8457	1.2898	5.1355	17.6
17.8	356.070	0.001 824	0.005 844	0.007 668	1723.4	794.09	2517.5	3.8586	1.2620	5.1206	17.8
18.0	356.992	0.001 839	0.005 659	0.007 499	1732.0	777.51	2509.5	3.8717	12339	5.1055	18.0
18.2	357.905	0.001 855	0.005 476	0.007 331	1740.7	760.57	2501.3	3.8849	1.2052	5.0901	18.2
18.4	358.809	0.001 872	0.005 293	0.007 164	1749.5	743.24	2492.8	3.8982	1.1761	5.0743	18.4
18.6	359.704	0.001 889	0.005 111	0.006 999	1785.5	752.49	2484.0	3.9118	1.1464	5.0582	18.6
18.8	360.592	0.001 907	0.004 929	0.006 836	1767.6	707.27	2474.9	3.9256	1.1160	5.0416	18.8
19.0	361.471	0.001 925	0.004 747	0.006 673	1776.9	688.52	2465.4	3.9396	1.0849	5.0246	19.0
19.2	362.342	0.001 945	0.004 565	0.006 510	1786.4	669.18	2455.6	3.9540	1.0530	5.0070	19.2
19.4	363.205	0.001 966	0.004 381	0.006 348	1796.1	649.19	2445.3	3.9687	1.0202	4.9888	19.4
19.6	364.060	0.001 989	0.004 197	0.006 186	1806.1	628.46	2434.6	3.9838	0.9863	4.9700	19.6
19.8	364.907	0.002 013	0.004 010	0.006 022	1816.4	606.87	2423.3	3.9993	0.9511	4.9299	19.8
20.0	365.746	0.002 039	0.003 820	0.005 858	1827.1	584.29	2411.4	4.0154	0.9145	4.9299	20.0
20.2	366.577	0.002 067	0.003 626	0.005 692	1838.2	560.55	2398.8	4.0321	0.8762	4.9083	20.2
20.4	367.401	0.002 097	0.003 426	0.005 523	1849.8	535.43	2385.3	4.0496	0.8359	4.8855	20.4
20.6	368.218	0.002 131	0.003 220	0.005 351	1862.1	508.63	2370.8	4.0681	0.7930	4.8612	20.6
20.8	369.026	0.002 169	0.003 004	0.005 173	1875.2	479.74	2355.0	4.0879	0.7471	4.8349	20.8
21.0	369.827	0.002 212	0.002 776	0.004 988	1889.4	448.15	2337.5	4.1093	0.6970	4.8062	21.0
21.2	370.621	0.002 262	0.002 529	0.004 791	1905.0	412.91	2317.9	4.1328	0.6414	4.7742	21.2
21.4	371.406	0.002 324	0.002 255	0.004 579	1922.8	372.44	2295.2	4.1597	0.5778	4.7375	21.4
21.6	372.182	0.002 403	0.001 936	0.004 338	1944.0	323.61	2267.6	4.1918	0.5015	4.6933	21.6
21.8	372.950	0.002 517	0.001 527	0.004 044	1971.9	258.69	2230.6	4.2343	0.4004	4.6347	21.8
22.0	373.707	0.002 750	0.000 826	0.003 577	2021.9	142.27	2164.2	4.3109	0.2199	4.5308	22.0
p_c	373.946	0.003 106	0	0.003 106	2087.5	0	2087.5	4.4120	0	4.4120	p_c

*P_t = 611.657 Pa
p_c = 22.064 MPa
From ASME International Steam Tables for Industrial Use, pp. 60–64.

Thermal Conductivity of Water and Steam ($mW \cdot m^{-1} \cdot K^{-1}$)

	Pressure (MPa)													
t (°C)	0.01	0.02	0.05	0.1	0.2	0.5	1	2	5	10	20	50	75	100
Sat Liq.	635.7	650.8	667.8	677.6	683.6	683.6	674.7	654.4	600.5	524.5	403.7			
Sat. Vap.	19.9	21.1	23.0	24.8	27.0	31.0	35.4	41.6	55.6	79.0	226.5			
0	562.0	562.0	562.0	562.0	562.1	562.3	562.6	563.2	564.9	567.8	573.6	590.6	603.5	616.0
10	581.9	581.9	581.9	582.0	582.0	582.2	582.5	583.0	584.7	587.5	593.0	608.8	621.4	633.4
20	599.5	599.5	599.5	599.5	599.6	599.7	600.0	600.6	602.2	604.8	610.1	625.4	637.5	649.1
25	607.5	607.5	607.5	607.5	607.6	607.7	608.0	608.5	610.1	612.7	617.9	633.0	645.0	656.4
30	615.0	615.0	615.0	615.0	615.1	615.2	615.5	616.0	617.6	620.2	625.3	640.2	652.1	663.4
40	628.6	628.6	628.6	628.6	628.7	628.8	629.1	629.6	631.1	633.7	638.8	633.5	665.1	676.3
50	20.3	640.5	640.5	640.5	640.6	640.7	641.0	641.5	643.0	645.6	650.6	665.2	676.8	687.8
60	21.0	650.8	650.8	650.8	650.9	651.0	651.3	651.8	653.3	655.9	661.0	675.5	687.1	698.1
70	21.8	21.9	659.6	659.6	659.7	659.8	660.1	660.6	662.2	664.8	669.8	684.5	696.1	707.2
80	22.6	22.7	667.0	667.0	667.0	667.2	667.5	668.0	669.6	672.2	677.4	692.2	703.9	715.1
90	23.4	23.5	23.6	673.0	673.1	673.2	673.5	674.1	675.7	678.3	683.6	698.7	710.5	721.8
100	24.3	24.3	24.4	24.8	677.8	678.0	678.3	678.8	680.5	683.2	688.6	704.0	716.0	727.5
110	25.1	25.1	25.2	25.5	681.3	681.5	681.8	682.3	684.1	686.9	692.4	708.2	720.5	732.1
120	26.0	26.0	26.1	26.3	683.6	683.8	684.1	684.7	686.4	689.4	695.1	711.3	723.8	735.7
130	26.8	26.8	26.9	27.1	27.6	684.9	685.2	685.9	687.7	690.7	696.6	713.3	726.2	738.4
140	27.7	27.7	27.8	27.9	28.4	685.0	685.3	685.9	687.8	691.0	697.1	714.3	727.7	740.2
150	28.6	28.6	28.7	28.8	29.2	683.9	684.2	684.9	686.9	690.2	696.5	714.4	728.2	741.0
160	29.5	29.5	29.6	29.7	30.0	31.4	682.1	682.8	684.9	688.3	695.0	713.6	727.8	741.0
170	30.4	30.4	30.5	30.6	30.8	32.0	678.9	679.6	681.8	685.4	692.4	711.8	726.5	740.2
180	31.4	31.4	31.4	31.5	31.7	32.7	35.4	675.4	677.7	681.5	688.9	709.1	724.5	738.6
190	32.3	32.3	32.3	32.4	32.6	33.4	35.6	670.1	672.6	676.6	684.4	705.6	721.6	736.2
200	33.2	33.3	33.3	33.4	33.5	34.2	36.1	663.8	666.4	670.7	678.9	701.3	717.9	733.2
220	35.2	35.2	35.2	35.3	35.4	36.0	37.3	41.5	650.9	655.8	665.2	690.2	708.4	724.9
240	37.2	37.2	37.2	37.3	37.4	37.8	38.8	41.8	630.9	636.7	647.5	675.8	696.0	714.0
260	39.2	39.2	39.2	39.3	39.4	39.8	40.6	42.8	606.0	613.0	625.8	658.4	681.0	700.8
280	41.3	41.3	41.3	41.4	41.5	41.8	42.5	44.2	53.7	584.0	599.7	637.8	663.3	685.2
300	43.4	43.4	43.4	43.5	43.6	43.9	44.5	46.0	53.0	548.1	568.3	614.0	643.0	667.4
320	45.6	45.6	45.6	45.7	45.7	46.0	46.6	47.8	53.5	74.7	530.4	586.8	620.3	647.6
340	47.8	47.8	47.8	47.9	47.9	48.2	48.7	49.8	54.5	69.8	483.1	556.0	595.1	625.9
360	50.0	50.0	50.1	50.1	50.2	50.4	50.9	51.9	56.0	67.7	419.8	521.1	567.4	602.3
380	52.3	52.3	52.3	52.4	52.5	52.7	53.1	54.1	57.6	66.7	129.4	481.7	537.2	576.9
400	54.6	54.7	54.7	54.7	54.8	55.0	55.4	56.3	59.5	67.2	103.4	438.3	504.7	550.0
420	57.0	57.0	57.0	57.1	57.2	57.4	57.8	58.6	61.6	68.3	94.6	391.5	470.4	521.9
440	59.4	59.4	59.4	59.5	59.5	59.8	60.1	60.9	63.7	69.7	90.8	342.0	434.7	492.7
460	61.9	61.9	61.9	61.9	62.0	62.2	62.6	63.3	65.9	71.4	89.1	289.0	398.9	463.1
480	64.3	64.3	64.4	64.4	64.5	64.7	65.0	65.8	68.2	73.3	88.7	240.3	363.9	433.5
500	66.8	66.8	66.9	66.9	67.0	67.2	67.5	68.2	70.6	75.3	89.1	205.5	330.9	404.8
520	69.4	69.4	69.4	69.4	69.5	69.7	70.0	70.7	73.0	77.5	90.0	182.8	300.6	377.7
540	72.0	72.0	72.0	72.0	72.1	72.3	72.6	73.3	75.4	79.7	91.2	168.2	273.8	352.7
560	74.6	74.6	74.6	74.6	74.7	74.9	75.2	75.8	77.9	82.0	92.7	158.5	251.4	329.9
580	77.2	77.2	77.2	77.2	77.3	77.5	77.8	78.4	80.5	84.3	94.4	152.0	233.4	309.6
600	79.8	79.9	79.9	79.9	80.0	80.1	80.4	81.0	83.0	86.8	96.2	147.7	219.2	291.7
620	82.5	82.5	82.6	82.6	82.6	82.8	83.1	83.7	85.6	89.2	98.2	144.8	208.2	276.2
640	85.2	85.3	85.3	85.3	85.4	85.5	85.8	86.4	88.2	91.7	100.3	142.9	199.8	263.0
660	88.0	88.0	88.0	88.0	88.1	88.2	88.5	89.1	90.9	94.3	102.5	141.9	193.3	252.0
680	90.7	90.7	90.8	90.8	90.8	91.0	91.3	91.8	93.6	96.9	104.7	141.4	188.3	242.7
700	93.5	93.5	93.5	93.6	93.6	93.8	94.0	94.6	96.3	99.5	107.0	141.4	184.5	235.0

Thermal Conductivity of Water and Steam (mW·m^{-1}·K^{-1}) (continued)

	Pressure (MPa)													
t (°C)	0.01	0.02	0.05	0.1	0.2	0.5	1	2	5	10	20	50	75	100
720	96.3	96.3	96.3	96.4	96.4	96.6	96.8	97.4	99.0	102.1	109.4	141.8	181.7	228.7
740	99.1	99.1	99.2	99.2	99.2	99.4	99.6	100.2	101.8	104.8	111.8	142.5	179.6	223.5
760	102.0	102.0	102.0	102.0	102.1	102.2	102.5	103.0	104.6	107.5	114.3	143.5	178.2	219.3
780	104.8	104.8	104.8	104.9	104.9	105.1	105.3	105.8	107.4	110.2	116.8	144.6	177.2	215.9
800	107.7	107.7	107.7	107.7	107.8	107.9	108.2	108.6	110.2	113.0	119.3	145.9	176.7	213.2

From ASME International Steam Tables for Industrial Use, p. 149.