2017 Fundamentals (SI Edition)

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BUILDING ENVELOPE

MATERIALS

GENERAL

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ASHRAE Research: Improving the Quality of Life

ASHRAE is the world's foremost technical society in the fields of heating, ventilation, air conditioning, and refrigeration. Its members worldwide are individuals who share ideas, identify needs, support research, and write the industry's standards for testing and practice. The result is that engineers are better able to keep indoor environments safe and productive while protecting and preserving the outdoors for generations to come.

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Preface

The 2017 *ASHRAE Handbook—Fundamentals* covers basic principles and data used in the HVAC&R industry. The ASHRAE Technical Committees that prepare these chapters provide new information, clarify existing content, delete obsolete materials, and reorganize chapters to make the Handbook more understandable and easier to use. An accompanying CD-ROM contains all the volume's chapters in both I-P and SI units.

This edition includes a new chapter:

- Chapter 36, Moisture Management in Buildings, presents data on indoor vapor release and measured indoor/outdoor vapor pressure/concentration differences, and discusses moisture sources and sinks that can reduce materials' durability, as well as the negative effects of insufficient or excessive indoor relative humidity.

Other selected highlights include the following:

- Chapter 7, Fundamentals of Control, has new content on thermostatic valve actuators, placement of sensors, auxiliary control devices, and network architecture.
- Chapter 9, Thermal Comfort, has new content from ASHRAE research project RP-1504 on nonwestern clothing; combined chilled-ceiling, displacement ventilation, and vertical radiant temperature asymmetry effects on sedentary office work; and updates to align with ASHRAE Standard 55-2013.
- Chapter 10, Indoor Environmental Health, has updates on bioaerosols, plus new content on electronic cigarettes and on climate change.
- Chapter 11, Air Contaminants, has new content on particle sizes and settling times, particulate contaminant effects, polymerase chain reaction (PCR) measurement, volatility, mercury, e-cigarettes, and 3D printers.
- Chapter 14, Climatic Design Information, includes new data for 8118 locations worldwide—an increase of 1675 locations from the 2013 edition of the chapter—as a result of ASHRAE research project RP-1699.
- Chapter 15, Fenestration, has updated discussion on U-factor, solar-optical glazing properties, complex glazings and window coverings, tubular daylighting devices (TDDs), and spectrally selective glazing.
- Chapter 16, Ventilation and Infiltration, has been updated and revised for clarity throughout, including recent research results on envelope air leakage.
- Chapter 17, Residential Cooling and Heating Load Calculations, has updates for 2017 climate data and current standards.
- Chapter 18, Nonresidential Cooling and Heating Load Calculations, has new design data for lighting power densities, motors, kitchen equipment, LED lighting, walls and roofs, and an updated example calculation.
- Chapter 19, Energy Estimating and Modeling Methods, extensively revised, has new sections on method development history, using models, uncertainty, thermal loads and model inputs, envelope components, HVAC components, terminal components, low-energy systems, natural and hybrid ventilation, daylighting, passive heating, hybrid inverse method, and model calibration.
- Chapter 20, Space Air Diffusion, has new content on outlet types and characteristics, air curtains, thermal plumes, and air movement in occupied zones.
- Chapter 21, Duct Design, was reorganized for ease of use, and updated for data from the latest version of the *ASHRAE Duct Fitting Database*.
- Chapter 22, Pipe Design, has a new title and now incorporates the content of its sister chapter, Pipes, Tubes, and Fittings, from *HVAC Systems and Equipment*. Also added are content on PEX pipe, plus expanded applications.
- Chapter 24, Airflow Around Buildings, has new content on flow patterns around building groups and isolated buildings, environmental impacts, pollutant dispersion and exhaust reentrainment, pedestrian wind comfort and safety, and wind-driven rain.
- Chapter 30, Thermophysical Properties of Refrigerants, has new or revised data for R-1233zd(E), R-245fa, R-1234ze(E), and R-1234yf.
- Chapter 34, Energy Resources, has extensive updates for new statistics on worldwide energy use and resources.
- Chapter 35, Sustainability, has new content on the water/energy nexus, embodied energy, and climate change.

This volume is published, as a bound print volume and in electronic format on CD-ROM and online, in two editions: one using inch-pound (I-P) units of measurement, the other using the International System of Units (SI).

Corrections to the 2014, 2015, and 2016 Handbook volumes can be found on the ASHRAE website at www.ashrae.org and in the Additions and Corrections section of this volume. Corrections for this volume will be listed in subsequent volumes and on the ASHRAE website.

Reader comments are enthusiastically invited. To suggest improvements for a chapter, **please comment using the form on the ASHRAE website** or, using the cutout page(s) at the end of this volume's index, write to Handbook Editor, ASHRAE, 1791 Tullie Circle, Atlanta, GA 30329, or fax 678-539-2187, or e-mail mowen@ashrae.org.

Mark S. Owen
Editor

Related Commercial Resources

CHAPTER 1

PSYCHROMETRICS

PSYCHROMETRICS uses thermodynamic properties to analyze conditions and processes involving moist air. This chapter discusses perfect gas relations and their use in common heating, cooling, and humidity control problems. Formulas developed by Herrmann et al. (2009) may be used where greater precision is required.

Herrmann et al. (2009), Hyland and Wexler (1983a, 1983b), and Nelson and Sauer (2002) developed formulas for thermodynamic properties of moist air and water modeled as real gases. However, perfect gas relations can be substituted in most air-conditioning problems. Kuehn et al. (1998) showed that errors are less than 0.7% in calculating humidity ratio, enthalpy, and specific volume of saturated air at standard atmospheric pressure for a temperature range of –50 to 50°C. Furthermore, these errors decrease with decreasing pressure.

1. COMPOSITION OF DRY AND MOIST AIR

Atmospheric air contains many gaseous components as well as water vapor and miscellaneous contaminants (e.g., smoke, pollen, and gaseous pollutants not normally present in free air far from pollution sources).

Dry air is atmospheric air with all water vapor and contaminants removed. Its composition is relatively constant, but small variations in the amounts of individual components occur with time, geographic location, and altitude. Harrison (1965) lists the approximate percentage composition of dry air by volume as: nitrogen, 78.084; oxygen, 20.9476; argon, 0.934; neon, 0.001818; helium, 0.000524; methane, 0.00015; sulfur dioxide, 0 to 0.0001; hydrogen, 0.00005; and minor components such as krypton, xenon, and ozone, 0.0002. Harrison (1965) and Hyland and Wexler (1983a) used a value 0.0314 (circa 1955) for carbon dioxide. Carbon dioxide reached 0.0379 in 2005, is currently increasing by 0.00019 percent per year and is projected to reach 0.0438 in 2036 (Gatley et al. 2008; Keeling and Whorf 2005a, 2005b). Increases in carbon dioxide are offset by decreases in oxygen; consequently, the oxygen percentage in 2036 is projected to be 20.9352. Using the projected changes, the relative molecular mass for dry air for at least the first half of the 21st century is 28.966, based on the carbon-12 scale. The gas constant for dry air using the current Mohr and Taylor (2005) value for the universal gas constant is

$$R_{da} = 8314.472/28.966 = 287.042 \text{ J/(kg}_{da}\cdot\text{K)} \quad (1)$$

Moist air is a binary (two-component) mixture of dry air and water vapor. The amount of water vapor varies from zero (dry air) to a maximum that depends on temperature and pressure. **Saturation** is a state of neutral equilibrium between moist air and the condensed water phase (liquid or solid); unless otherwise stated, it assumes a flat interface surface between moist air and the condensed phase. Saturation conditions change when the interface radius is very small (e.g., with ultrafine water droplets). The relative molecular mass of water is 18.015 268 on the carbon-12 scale. The gas constant for water vapor is

$$R_w = 8314.472/18.015\,268 = 461.524 \text{ J/(kg}_w\cdot\text{K)} \quad (2)$$

2. U.S. STANDARD ATMOSPHERE

The temperature and barometric pressure of atmospheric air vary considerably with altitude as well as with local geographic and weather conditions. The standard atmosphere gives a standard of reference for estimating properties at various altitudes. At sea level, standard temperature is 15°C; standard barometric pressure is 101.325 kPa. Temperature is assumed to decrease linearly with increasing altitude throughout the troposphere (lower atmosphere), and to be constant in the lower reaches of the stratosphere. The lower atmosphere is assumed to consist of dry air that behaves as a perfect gas. Gravity is also assumed constant at the standard value, 9.806 65 m/s^2. Table 1 summarizes property data for altitudes to 10 000 m.

Pressure values in Table 1 may be calculated from

$$p = 101.325(1 - 2.25577 \times 10^{-5}Z)^{5.2559} \quad (3)$$

The equation for temperature as a function of altitude is

$$t = 15 - 0.0065Z \quad (4)$$

where

Z = altitude, m
p = barometric pressure, kPa
t = temperature, °C

Table 1 Standard Atmospheric Data for Altitudes to 10 000 m

Altitude, m	Temperature, °C	Pressure, kPa
–500	18.2	107.478
0	15.0	101.325
500	11.8	95.461
1 000	8.5	89.875
1500	5.2	84.556
2 000	2.0	79.495
2 500	–1.2	74.682
3 000	–4.5	70.108
4 000	–11.0	61.640
5 000	–17.5	54.020
6 000	–24.0	47.181
7000	–30.5	41.061
8000	–37.0	35.600
9000	–43.5	30.742
10 000	–50	26.436

Source: Adapted from NASA (1976).

The preparation of this chapter is assigned to TC 1.1, Thermodynamics and Psychrometrics.

Equations (3) and (4) are accurate from –5000 m to 11 000 m. For higher altitudes, comprehensive tables of barometric pressure and other physical properties of the standard atmosphere, in both SI and I-P units, can be found in NASA (1976).

3. THERMODYNAMIC PROPERTIES OF MOIST AIR

Table 2, developed from formulas by Herrmann et al. (2009), shows values of thermodynamic properties of moist air based on the International Temperature Scale of 1990 (ITS-90). This ideal scale differs slightly from practical temperature scales used for physical measurements. For example, the standard boiling point for water (at 101.325 kPa) occurs at 99.97°C on this scale rather than at the traditional 100°C. Most measurements are currently based on ITS-90 (Preston-Thomas 1990).

The following properties are shown in Table 2:

t = Celsius temperature, based on the ITS-90 and expressed relative to absolute temperature T in kelvins (K) by the following relation:

$$T = t + 273.15$$

W_s = humidity ratio at saturation; gaseous phase (moist air) exists in equilibrium with condensed phase (liquid or solid) at given temperature and pressure (standard atmospheric pressure). At given values of temperature and pressure, humidity ratio W can have any value from zero to W_s.

v_{da} = specific volume of dry air, m³/kg$_{da}$.

v_{as} = $v_s - v_{da}$, difference between specific volume of moist air at saturation and that of dry air, m³/kg$_{da}$, at same pressure and temperature.

v_s = specific volume of moist air at saturation, m³/kg$_{da}$.

h_{da} = specific enthalpy of dry air, kJ/kg$_{da}$. In Table 2, h_{da} is assigned a value of 0 at 0°C and standard atmospheric pressure.

h_{as} = $h_s - h_{da}$, difference between specific enthalpy of moist air at saturation and that of dry air, kJ/kg$_{da}$, at same pressure and temperature.

h_s = specific enthalpy of moist air at saturation, kJ/kg$_{da}$.

s_{da} = specific entropy of dry air, kJ/(kg$_{da}$·K). In Table 2, s_{da} is assigned a value of 0 at 0°C and standard atmospheric pressure.

s_s = specific entropy of moist air at saturation kJ/(kg$_{da}$·K).

Table 2 Thermodynamic Properties of Moist Air at Standard Atmospheric Pressure, 101.325 kPa

Temp., °C	Humidity Ratio	Specific Volume, m³/kg$_{da}$			Specific Enthalpy, kJ/kg$_{da}$			Specific Entropy, kJ/(kg$_{da}$·K)		Temp., °C
t	W_s, kg$_w$/kg$_{da}$	v_{da}	v_{as}	v_s	h_{da}	h_{as}	h_s	s_{da}	s_s	t
–60	0.0000067	0.6027	0.0000	0.6027	–60.341	0.016	–60.325	–0.2494	–0.2494	–60
–59	0.0000076	0.6055	0.0000	0.6055	–59.335	0.018	–59.317	–0.2447	–0.2446	–59
–58	0.0000087	0.6084	0.0000	0.6084	–58.329	0.021	–58.308	–0.2400	–0.2399	–58
–57	0.0000100	0.6112	0.0000	0.6112	–57.323	0.024	–57.299	–0.2354	–0.2353	–57
–56	0.0000114	0.6141	0.0000	0.6141	–56.317	0.027	–56.289	–0.2307	–0.2306	–56
–55	0.0000129	0.6169	0.0000	0.6169	–55.311	0.031	–55.280	–0.2261	–0.2260	–55
–54	0.0000147	0.6198	0.0000	0.6198	–54.305	0.035	–54.269	–0.2215	–0.2213	–54
–53	0.0000167	0.6226	0.0000	0.6226	–53.299	0.040	–53.258	–0.2169	–0.2167	–53
–52	0.0000190	0.6255	0.0000	0.6255	–52.293	0.046	–52.247	–0.2124	–0.2121	–52
–51	0.0000215	0.6283	0.0000	0.6283	–51.287	0.052	–51.235	–0.2078	–0.2076	–51
–50	0.0000243	0.6312	0.0000	0.6312	–50.281	0.059	–50.222	–0.2033	–0.2030	–50
–49	0.0000275	0.6340	0.0000	0.6340	–49.275	0.066	–49.209	–0.1988	–0.1985	–49
–48	0.0000311	0.6369	0.0000	0.6369	–48.269	0.075	–48.194	–0.1943	–0.1940	–48
–47	0.0000350	0.6397	0.0000	0.6397	–47.263	0.085	–47.179	–0.1899	–0.1895	–47
–46	0.0000395	0.6425	0.0000	0.6426	–46.257	0.095	–46.162	–0.1854	–0.1850	–46
–45	0.0000445	0.6454	0.0000	0.6454	–45.252	0.107	–45.144	–0.1810	–0.1805	–45
–44	0.0000500	0.6482	0.0001	0.6483	–44.246	0.121	–44.125	–0.1766	–0.1761	–44
–43	0.0000562	0.6511	0.0001	0.6511	–43.240	0.136	–43.104	–0.1722	–0.1716	–43
–42	0.0000631	0.6539	0.0001	0.6540	–42.234	0.153	–42.081	–0.1679	–0.1672	–42
–41	0.0000708	0.6568	0.0001	0.6568	–41.229	0.172	–41.057	–0.1635	–0.1628	–41
–40	0.0000793	0.6596	0.0001	0.6597	–40.223	0.192	–40.031	–0.1592	–0.1583	–40
–39	0.0000887	0.6625	0.0001	0.6626	–39.217	0.215	–39.002	–0.1549	–0.1539	–39
–38	0.0000992	0.6653	0.0001	0.6654	–38.211	0.241	–37.970	–0.1506	–0.1495	–38
–37	0.0001108	0.6682	0.0001	0.6683	–37.206	0.269	–36.936	–0.1464	–0.1451	–37
–36	0.0001237	0.6710	0.0001	0.6711	–36.200	0.301	–35.899	–0.1421	–0.1408	–36
–35	0.0001379	0.6738	0.0001	0.6740	–35.195	0.336	–34.859	–0.1379	–0.1364	–35
–34	0.0001536	0.6767	0.0002	0.6769	–34.189	0.374	–33.815	–0.1337	–0.1320	–34
–33	0.0001710	0.6795	0.0002	0.6797	–33.183	0.417	–32.766	–0.1295	–0.1276	–33
–32	0.0001902	0.6824	0.0002	0.6826	–32.178	0.464	–31.714	–0.1253	–0.1232	–32
–31	0.0002113	0.6852	0.0002	0.6855	–31.172	0.516	–30.656	–0.1211	–0.1189	–31
–30	0.0002345	0.6881	0.0003	0.6883	–30.167	0.573	–29.593	–0.1170	–0.1145	–30
–29	0.0002602	0.6909	0.0003	0.6912	–29.161	0.636	–28.525	–0.1129	–0.1101	–29
–28	0.0002883	0.6938	0.0003	0.6941	–28.156	0.706	–27.450	–0.1088	–0.1057	–28
–27	0.0003193	0.6966	0.0004	0.6970	–27.150	0.782	–26.368	–0.1047	–0.1013	–27
–26	0.0003532	0.6994	0.0004	0.6998	–26.144	0.866	–25.278	–0.1006	–0.0969	–26
–25	0.0003905	0.7023	0.0004	0.7027	–25.139	0.958	–24.181	–0.0965	–0.0924	–25
–24	0.0004314	0.7051	0.0005	0.7056	–24.133	1.059	–23.074	–0.0925	–0.0880	–24
–23	0.0004761	0.7080	0.0005	0.7085	–23.128	1.170	–21.958	–0.0884	–0.0835	–23
–22	0.0005251	0.7108	0.0006	0.7114	–22.122	1.291	–20.831	–0.0844	–0.0790	–22
–21	0.0005787	0.7137	0.0007	0.7143	–21.117	1.424	–19.693	–0.0804	–0.0745	–21
–20	0.0006373	0.7165	0.0007	0.7172	–20.111	1.570	–18.542	–0.0765	–0.0699	–20

Table 2 Thermodynamic Properties of Moist Air at Standard Atmospheric Pressure, 101.325 kPa (*Continued*)

Temp., °C	Humidity Ratio	Specific Volume, m^3/kg_{da}			Specific Enthalpy, kJ/kg_{da}			Specific Entropy, $kJ/(kg_{da}\cdot K)$		Temp., °C
t	W_s, kg_w/kg_{da}	v_{da}	v_{as}	v_s	h_{da}	h_{as}	h_s	s_{da}	s_s	t
–19	0.0007013	0.7193	0.0008	0.7201	–19.106	1.728	–17.377	–0.0725	–0.0653	–19
–18	0.0007711	0.7222	0.0009	0.7231	–18.100	1.902	–16.198	–0.0685	–0.0607	–18
–17	0.0008473	0.7250	0.0010	0.7260	–17.095	2.091	–15.003	–0.0646	–0.0560	–17
–16	0.0009303	0.7279	0.0011	0.7290	–16.089	2.298	–13.791	–0.0607	–0.0513	–16
–15	0.0010207	0.7307	0.0012	0.7319	–15.084	2.523	–12.560	–0.0568	–0.0465	–15
–14	0.0011191	0.7336	0.0013	0.7349	–14.078	2.769	–11.310	–0.0529	–0.0416	–14
–13	0.0012261	0.7364	0.0014	0.7378	–13.073	3.036	–10.037	–0.0490	–0.0367	–13
–12	0.0013425	0.7392	0.0016	0.7408	–12.067	3.326	–8.741	–0.0452	–0.0317	–12
–11	0.0014689	0.7421	0.0017	0.7438	–11.062	3.642	–7.419	–0.0413	–0.0267	–11
–10	0.0016062	0.7449	0.0019	0.7468	–10.056	3.986	–6.070	–0.0375	–0.0215	–10
–9	0.0017551	0.7478	0.0021	0.7499	–9.050	4.358	–4.692	–0.0337	–0.0163	–9
–8	0.0019166	0.7506	0.0023	0.7529	–8.045	4.763	–3.282	–0.0299	–0.0110	–8
–7	0.0020916	0.7534	0.0025	0.7560	–7.039	5.202	–1.838	–0.0261	–0.0055	–7
–6	0.0022812	0.7563	0.0028	0.7591	–6.034	5.677	–0.356	–0.0223	0.0000	–6
–5	0.0024863	0.7591	0.0030	0.7622	–5.028	6.192	1.164	–0.0186	0.0057	–5
–4	0.0027083	0.7620	0.0033	0.7653	–4.023	6.750	2.728	–0.0148	0.0115	–4
–3	0.0029482	0.7648	0.0036	0.7684	–3.017	7.354	4.337	–0.0111	0.0175	–3
–2	0.0032076	0.7677	0.0039	0.7716	–2.011	8.007	5.995	–0.0074	0.0236	–2
–1	0.0034877	0.7705	0.0043	0.7748	–1.006	8.712	7.707	–0.0037	0.0299	–1
0	0.003790	0.7733	0.0047	0.7780	0.000	9.475	9.475	0.0000	0.0364	0
1	0.004076	0.7762	0.0051	0.7813	1.006	10.198	11.203	0.0037	0.0427	1
2	0.004382	0.7790	0.0055	0.7845	2.011	10.970	12.981	0.0073	0.0492	2
3	0.004708	0.7819	0.0059	0.7878	3.017	11.794	14.811	0.0110	0.0559	3
4	0.005055	0.7847	0.0064	0.7911	4.023	12.673	16.696	0.0146	0.0627	4
5	0.005425	0.7875	0.0068	0.7944	5.029	13.611	18.639	0.0182	0.0697	5
6	0.005819	0.7904	0.0074	0.7978	6.034	14.610	20.644	0.0219	0.0769	6
7	0.006238	0.7932	0.0079	0.8012	7.040	15.674	22.714	0.0254	0.0843	7
8	0.006684	0.7961	0.0085	0.8046	8.046	16.807	24.853	0.0290	0.0919	8
9	0.007158	0.7989	0.0092	0.8081	9.052	18.013	27.065	0.0326	0.0997	9
10	0.007663	0.8017	0.0098	0.8116	10.058	19.297	29.354	0.0362	0.1078	10
11	0.008199	0.8046	0.0106	0.8152	11.063	20.661	31.724	0.0397	0.1162	11
12	0.008768	0.8074	0.0113	0.8188	12.069	22.111	34.181	0.0432	0.1248	12
13	0.009372	0.8103	0.0122	0.8224	13.075	23.653	36.728	0.0468	0.1338	13
14	0.010013	0.8131	0.0131	0.8262	14.081	25.290	39.371	0.0503	0.1430	14
15	0.010694	0.8159	0.0140	0.8299	15.087	27.028	42.115	0.0538	0.1525	15
16	0.011415	0.8188	0.0150	0.8338	16.093	28.873	44.966	0.0573	0.1624	16
17	0.012181	0.8216	0.0160	0.8377	17.099	30.830	47.929	0.0607	0.1726	17
18	0.012991	0.8245	0.0172	0.8416	18.105	32.906	51.011	0.0642	0.1832	18
19	0.013851	0.8273	0.0184	0.8457	19.111	35.108	54.219	0.0676	0.1942	19
20	0.014761	0.8301	0.0196	0.8498	20.117	37.441	57.559	0.0711	0.2057	20
21	0.015724	0.8330	0.0210	0.8540	21.124	39.914	61.038	0.0745	0.2175	21
22	0.016744	0.8358	0.0224	0.8583	22.130	42.534	64.663	0.0779	0.2298	22
23	0.017823	0.8387	0.0240	0.8626	23.136	45.308	68.444	0.0813	0.2426	23
24	0.018965	0.8415	0.0256	0.8671	24.142	48.246	72.388	0.0847	0.2560	24
25	0.020173	0.8443	0.0273	0.8716	25.148	51.355	76.504	0.0881	0.2698	25
26	0.021451	0.8472	0.0291	0.8763	26.155	54.647	80.801	0.0915	0.2842	26
27	0.022802	0.8500	0.0311	0.8811	27.161	58.129	85.290	0.0948	0.2992	27
28	0.024229	0.8529	0.0331	0.8860	28.167	61.813	89.980	0.0982	0.3148	28
29	0.025738	0.8557	0.0353	0.8910	29.174	65.709	94.883	0.1015	0.3311	29
30	0.027333	0.8585	0.0376	0.8961	30.180	69.829	100.010	0.1048	0.3481	30
31	0.029018	0.8614	0.0400	0.9014	31.187	74.186	105.373	0.1081	0.3658	31
32	0.030797	0.8642	0.0426	0.9069	32.193	78.792	110.986	0.1115	0.3843	32
33	0.032677	0.8671	0.0454	0.9124	33.200	83.661	116.861	0.1147	0.4035	33
34	0.034663	0.8699	0.0483	0.9182	34.207	88.807	123.014	0.1180	0.4236	34
35	0.036760	0.8727	0.0514	0.9241	35.213	94.247	129.460	0.1213	0.4447	35
36	0.038975	0.8756	0.0546	0.9302	36.220	99.995	136.215	0.1246	0.4666	36
37	0.041313	0.8784	0.0581	0.9365	37.227	106.069	143.296	0.1278	0.4895	37
38	0.043783	0.8813	0.0618	0.9430	38.233	112.488	150.722	0.1311	0.5135	38
39	0.046391	0.8841	0.0657	0.9498	39.240	119.272	158.512	0.1343	0.5386	39
40	0.049145	0.8869	0.0698	0.9567	40.247	126.440	166.687	0.1375	0.5649	40
41	0.052053	0.8898	0.0741	0.9639	41.254	134.016	175.270	0.1407	0.5923	41
42	0.055124	0.8926	0.0788	0.9714	42.261	142.023	184.284	0.1439	0.6211	42

Table 2 Thermodynamic Properties of Moist Air at Standard Atmospheric Pressure, 101.325 kPa (*Continued*)

Temp., °C	Humidity Ratio	Specific Volume, m^3/kg_{da}			Specific Enthalpy, kJ/kg_{da}			Specific Entropy, $kJ/(kg_{da} \cdot K)$		Temp., °C
t	W_s, kg_w/kg_{da}	v_{da}	v_{as}	v_s	h_{da}	h_{as}	h_s	s_{da}	s_s	t
43	0.058368	0.8955	0.0837	0.9791	43.268	150.486	193.754	0.1471	0.6512	43
44	0.061795	0.8983	0.0888	0.9871	44.275	159.432	203.707	0.1503	0.6828	44
45	0.065416	0.9011	0.0943	0.9955	45.282	168.890	214.172	0.1535	0.7159	45
46	0.069242	0.9040	0.1002	1.0041	46.289	178.892	225.181	0.1566	0.7507	46
47	0.073286	0.9068	0.1063	1.0131	47.297	189.470	236.766	0.1598	0.7871	47
48	0.077561	0.9096	0.1129	1.0225	48.304	200.660	248.964	0.1629	0.8254	48
49	0.082081	0.9125	0.1198	1.0323	49.311	212.501	261.812	0.1660	0.8655	49
50	0.086863	0.9153	0.1272	1.0425	50.319	225.034	275.353	0.1692	0.9078	50
51	0.091922	0.9182	0.1350	1.0531	51.326	238.305	289.631	0.1723	0.9522	51
52	0.097278	0.9210	0.1433	1.0643	52.334	252.362	304.695	0.1754	0.9989	52
53	0.102949	0.9238	0.1521	1.0759	53.341	267.256	320.598	0.1785	1.0481	53
54	0.108958	0.9267	0.1614	1.0881	54.349	283.047	337.395	0.1816	1.0999	54
55	0.115326	0.9295	0.1714	1.1009	55.356	299.794	355.151	0.1846	1.1545	55
56	0.122080	0.9324	0.1819	1.1143	56.364	317.567	373.931	0.1877	1.2121	56
57	0.129248	0.9352	0.1932	1.1284	57.372	336.439	393.811	0.1908	1.2729	57
58	0.136858	0.9380	0.2051	1.1432	58.380	356.490	414.869	0.1938	1.3371	58
59	0.144945	0.9409	0.2179	1.1587	59.388	377.809	437.197	0.1968	1.4050	59
60	0.153545	0.9437	0.2315	1.1752	60.396	400.493	460.889	0.1999	1.4769	60
61	0.162697	0.9465	0.2460	1.1925	61.404	424.650	486.054	0.2029	1.5530	61
62	0.172446	0.9494	0.2615	1.2108	62.412	450.398	512.810	0.2059	1.6338	62
63	0.182842	0.9522	0.2780	1.2302	63.420	477.868	541.287	0.2089	1.7195	63
64	0.193937	0.9551	0.2957	1.2508	64.428	507.204	571.632	0.2119	1.8105	64
65	0.205794	0.9579	0.3147	1.2726	65.436	538.570	604.006	0.2149	1.9075	65
66	0.218478	0.9607	0.3350	1.2957	66.445	572.145	638.590	0.2179	2.0107	66
67	0.232067	0.9636	0.3568	1.3204	67.453	608.133	675.587	0.2208	2.1209	67
68	0.246645	0.9664	0.3803	1.3467	68.462	646.762	715.224	0.2238	2.2386	68
69	0.262309	0.9692	0.4056	1.3748	69.470	688.288	757.759	0.2268	2.3647	69
70	0.279167	0.9721	0.4328	1.4049	70.479	733.004	803.483	0.2297	2.4998	70
71	0.297343	0.9749	0.4622	1.4372	71.488	781.240	852.728	0.2326	2.6449	71
72	0.316979	0.9778	0.4941	1.4719	72.496	833.375	905.872	0.2356	2.8012	72
73	0.338237	0.9806	0.5287	1.5093	73.505	889.844	963.350	0.2385	2.9697	73
74	0.361304	0.9834	0.5663	1.5497	74.514	951.149	1025.663	0.2414	3.1520	74
75	0.386399	0.9863	0.6072	1.5935	75.523	1017.871	1093.394	0.2443	3.3497	75
76	0.413774	0.9891	0.6520	1.6411	76.532	1090.688	1167.220	0.2472	3.5645	76
77	0.443727	0.9919	0.7010	1.6930	77.542	1170.398	1247.939	0.2501	3.7989	77
78	0.476610	0.9948	0.7550	1.7497	78.551	1257.941	1336.492	0.2529	4.0554	78
79	0.512842	0.9976	0.8145	1.8121	79.560	1354.439	1433.999	0.2558	4.3371	79
80	0.552926	1.0005	0.8805	1.8809	80.570	1461.236	1541.806	0.2587	4.6478	80
81	0.597470	1.0033	0.9539	1.9572	81.579	1579.961	1661.540	0.2615	4.9921	81
82	0.647218	1.0061	1.0360	2.0421	82.589	1712.604	1795.193	0.2644	5.3755	82
83	0.703089	1.0090	1.1283	2.1373	83.598	1861.625	1945.223	0.2672	5.8048	83
84	0.766233	1.0118	1.2328	2.2446	84.608	2030.099	2114.707	0.2701	6.2886	84
85	0.838105	1.0146	1.3519	2.3665	85.618	2221.922	2307.539	0.2729	6.8377	85
86	0.920580	1.0175	1.4887	2.5062	86.628	2442.105	2528.732	0.2757	7.4661	86
87	1.016105	1.0203	1.6473	2.6676	87.638	2697.204	2784.842	0.2785	8.1920	87
88	1.127952	1.0232	1.8332	2.8564	88.648	2995.967	3084.614	0.2813	9.0397	88
89	1.260579	1.0260	2.0539	3.0799	89.658	3350.325	3439.983	0.2841	10.0422	89
90	1.420235	1.0288	2.3198	3.3487	90.668	3776.998	3867.666	0.2869	11.2459	90

4. THERMODYNAMIC PROPERTIES OF WATER AT SATURATION

Table 3 shows thermodynamic properties of water at saturation for temperatures from –60 to 160°C, calculated by the formulations described by IAPWS (2007, 2009, 2011, 2014). Symbols in the table follow standard steam table nomenclature. These properties are based on ITS-90. The internal energy and entropy of saturated liquid water are both assigned the value zero at the triple point, 0.01°C. Between the triple-point and critical-point temperatures of water, both **saturated liquid** and **saturated vapor** may coexist in equilibrium; below the triple-point temperature, both **saturated ice** and **saturated vapor** may coexist in equilibrium.

The **water vapor saturation pressure** is required to determine a number of moist air properties, principally the saturation humidity ratio. Values may be obtained from Table 3 or calculated from the following formulas (Hyland and Wexler 1983b). The 1983 formulas are within 300 ppm of the latest IAPWS formulations. For higher accuracy, developers of software and others are referred to IAPWS (2007, 2011).

Table 3 Thermodynamic Properties of Water at Saturation

Temp., °C t	Absolute Pressure p_{ws}, kPa	Specific Volume, m^3/kg$_w$			Specific Enthalpy, kJ/kg$_w$			Specific Entropy, kJ/(kg$_w$·K)			Temp., °C t
		Sat. Solid v_i/v_f	Evap. v_{ig}/v_{fg}	Sat. Vapor v_g	Sat. Solid h_i/h_f	Evap. h_{ig}/h_{fg}	Sat. Vapor h_g	Sat. Solid s_i/s_f	Evap. s_{ig}/s_{fg}	Sat. Vapor s_g	
–60	0.00108	0.001081	90971.58	90971.58	–446.12	2836.27	2390.14	–1.6842	13.3064	11.6222	–60
–59	0.00124	0.001082	79885.31	79885.31	–444.46	2836.45	2391.99	–1.6764	13.2452	11.5687	–59
–58	0.00141	0.001082	70235.77	70235.78	–442.79	2836.63	2393.85	–1.6687	13.1845	11.5158	–58
–57	0.00161	0.001082	61826.23	61826.24	–441.11	2836.81	2395.70	–1.6609	13.1243	11.4634	–57
–56	0.00184	0.001082	54488.28	54488.28	–439.42	2836.97	2397.55	–1.6531	13.0646	11.4115	–56
–55	0.00209	0.001082	48077.54	48077.54	–437.73	2837.13	2399.40	–1.6453	13.0054	11.3601	–55
–54	0.00238	0.001082	42470.11	42470.11	–436.03	2837.28	2401.25	–1.6375	12.9468	11.3092	–54
–53	0.00271	0.001082	37559.49	37559.50	–434.32	2837.42	2403.10	–1.6298	12.8886	11.2589	–53
–52	0.00307	0.001083	33254.07	33254.07	–432.61	2837.56	2404.95	–1.6220	12.8310	11.2090	–52
–51	0.00348	0.001083	29474.87	29474.87	–430.88	2837.69	2406.81	–1.6142	12.7738	11.1596	–51
–50	0.00394	0.001083	26153.80	26153.80	–429.16	2837.81	2408.66	–1.6065	12.7171	11.1106	–50
–49	0.00445	0.001083	23232.03	23232.04	–427.42	2837.93	2410.51	–1.5987	12.6609	11.0622	–49
–48	0.00503	0.001083	20658.70	20658.70	–425.68	2838.04	2412.36	–1.5909	12.6051	11.0142	–48
–47	0.00568	0.001083	18389.75	18389.75	–423.93	2838.14	2414.21	–1.5832	12.5498	10.9666	–47
–46	0.00640	0.001083	16387.03	16387.03	–422.17	2838.23	2416.06	–1.5754	12.4950	10.9196	–46
–45	0.00720	0.001084	14617.39	14617.39	–420.40	2838.32	2417.91	–1.5677	12.4406	10.8729	–45
–44	0.00810	0.001084	13052.07	13052.07	–418.63	2838.39	2419.76	–1.5599	12.3867	10.8267	–44
–43	0.00910	0.001084	11666.02	11666.02	–416.85	2838.47	2421.62	–1.5522	12.3331	10.7810	–43
–42	0.01022	0.001084	10437.46	10437.46	–415.06	2838.53	2423.47	–1.5444	12.2801	10.7356	–42
–41	0.01146	0.001084	9347.38	9347.38	–413.27	2838.59	2425.32	–1.5367	12.2274	10.6907	–41
–40	0.01284	0.001084	8379.20	8379.20	–411.47	2838.64	2427.17	–1.5289	12.1752	10.6462	–40
–39	0.01437	0.001085	7518.44	7518.44	–409.66	2838.68	2429.02	–1.5212	12.1234	10.6022	–39
–38	0.01607	0.001085	6752.43	6752.43	–407.85	2838.72	2430.87	–1.5135	12.0720	10.5585	–38
–37	0.01795	0.001085	6070.08	6070.08	–406.02	2838.74	2432.72	–1.5057	12.0210	10.5152	–37
–36	0.02004	0.001085	5461.68	5461.68	–404.19	2838.76	2434.57	–1.4980	11.9704	10.4724	–36
–35	0.02234	0.001085	4918.69	4918.69	–402.36	2838.78	2436.42	–1.4903	11.9202	10.4299	–35
–34	0.02489	0.001085	4433.64	4433.64	–400.51	2838.78	2438.27	–1.4825	11.8703	10.3878	–34
–33	0.02771	0.001085	3999.95	3999.95	–398.66	2838.78	2440.12	–1.4748	11.8209	10.3461	–33
–32	0.03081	0.001086	3611.82	3611.82	–396.80	2838.77	2441.97	–1.4671	11.7718	10.3047	–32
–31	0.03423	0.001086	3264.15	3264.16	–394.94	2838.75	2443.82	–1.4594	11.7231	10.2638	–31
–30	0.03801	0.001086	2952.46	2952.46	–393.06	2838.73	2445.67	–1.4516	11.6748	10.2232	–30
–29	0.04215	0.001086	2672.77	2672.77	–391.18	2838.70	2447.51	–1.4439	11.6269	10.1830	–29
–28	0.04672	0.001086	2421.58	2421.58	–389.29	2838.66	2449.36	–1.4362	11.5793	10.1431	–28
–27	0.05173	0.001086	2195.80	2195.80	–387.40	2838.61	2451.21	–1.4285	11.5321	10.1036	–27
–26	0.05724	0.001087	1992.68	1992.68	–385.50	2838.56	2453.06	–1.4208	11.4852	10.0644	–26
–25	0.06327	0.001087	1809.79	1809.79	–383.59	2838.49	2454.91	–1.4131	11.4386	10.0256	–25
–24	0.06989	0.001087	1644.99	1644.99	–381.67	2838.42	2456.75	–1.4054	11.3925	9.9871	–24
–23	0.07714	0.001087	1496.36	1496.36	–379.75	2838.35	2458.60	–1.3977	11.3466	9.9489	–23
–22	0.08508	0.001087	1362.21	1362.21	–377.81	2838.26	2460.45	–1.3899	11.3011	9.9111	–22
–21	0.09376	0.001087	1241.03	1241.03	–375.88	2838.17	2462.29	–1.3822	11.2559	9.8736	–21
–20	0.10324	0.001087	1131.49	1131.49	–373.93	2838.07	2464.14	–1.3745	11.2110	9.8365	–20
–19	0.11360	0.001088	1032.38	1032.38	–371.98	2837.96	2465.98	–1.3668	11.1665	9.7996	–19
–18	0.12490	0.001088	942.64	942.65	–370.01	2837.84	2467.83	–1.3591	11.1223	9.7631	–18
–17	0.13722	0.001088	861.34	861.34	–368.05	2837.72	2469.67	–1.3514	11.0784	9.7269	–17
–16	0.15065	0.001088	787.61	787.61	–366.07	2837.59	2471.51	–1.3437	11.0348	9.6910	–16
–15	0.16527	0.001088	720.70	720.70	–364.09	2837.45	2473.36	–1.3360	10.9915	9.6554	–15
–14	0.18119	0.001088	659.94	659.94	–362.10	2837.30	2475.20	–1.3284	10.9485	9.6201	–14
–13	0.19849	0.001089	604.72	604.73	–360.10	2837.14	2477.04	–1.3207	10.9058	9.5851	–13
–12	0.21729	0.001089	554.51	554.51	–358.10	2836.98	2478.88	–1.3130	10.8634	9.5504	–12
–11	0.23771	0.001089	508.81	508.81	–356.08	2836.80	2480.72	–1.3053	10.8213	9.5160	–11
–10	0.25987	0.001089	467.19	467.19	–354.06	2836.62	2482.56	–1.2976	10.7795	9.4819	–10
–9	0.28391	0.001089	429.25	429.26	–352.04	2836.44	2484.40	–1.2899	10.7380	9.4481	–9
–8	0.30995	0.001089	394.66	394.66	–350.00	2836.24	2486.23	–1.2822	10.6967	9.4145	–8
–7	0.33817	0.001090	363.09	363.09	–347.96	2836.03	2488.07	–1.2745	10.6558	9.3812	–7
–6	0.36871	0.001090	334.26	334.26	–345.91	2835.82	2489.91	–1.2668	10.6151	9.3482	–6
–5	0.40174	0.001090	307.92	307.92	–343.86	2835.60	2491.74	–1.2592	10.5747	9.3155	–5
–4	0.43745	0.001090	283.82	283.83	–341.79	2835.37	2493.57	–1.2515	10.5345	9.2830	–4
–3	0.47604	0.001090	261.78	261.78	–339.72	2835.13	2495.41	–1.2438	10.4946	9.2508	–3
–2	0.51770	0.001091	241.60	241.60	–337.64	2834.88	2497.24	–1.2361	10.4550	9.2189	–2
–1	0.56266	0.001091	223.10	223.11	–335.56	2834.63	2499.07	–1.2284	10.4157	9.1872	–1
0	0.61115	0.001091	206.15	206.15	–333.47	2834.36	2500.90	–1.2208	10.3766	9.1558	0