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.

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

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

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

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

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/s². Table 1 summarizes property data for altitudes to 10 000 m.

Pressure values in Table 1 may be calculated from

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

The equation for temperature as a function of altitude is

$$t = 15 - 0.0065Z \tag{4}$$

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
1000	8.5	89.875
1500	5.2	84.556
2000	2.0	79.495
2500	–1.2	74.682
3000	–4.5	70.108
4000	–11.0	61.640
5000	–17.5	54.020
6000	–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).

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, m^3/kg_{da}.
v_{as} = $v_s - v_{da}$, difference between specific volume of moist air at saturation and that of dry air, m^3/kg_{da}, at same pressure and temperature.
v_s = specific volume of moist air at saturation, m^3/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, $kJ/(kg_{da}\cdot K)$. 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 $kJ/(kg_{da}\cdot K)$.

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). 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, two states (**saturated liquid** 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, 2008).

The saturation pressure over **ice** for the temperature range of −100 to 0°C is given by

$$\ln p_{ws} = C_1/T + C_2 + C_3T + C_4T^2 + C_5T^3 + C_6T^4 + C_7 \ln T \qquad (5)$$

where

C_1 = −5.674 535 9 E+03
C_2 = 6.392 524 7 E+00
C_3 = −9.677 843 0 E−03
C_4 = 6.221 570 1 E−07
C_5 = 2.074 782 5 E−09
C_6 = −9.484 024 0 E−13
C_7 = 4.163 501 9 E+00

The saturation pressure over **liquid water** for the temperature range of 0 to 200°C is given by

$$\ln p_{ws} = C_8/T + C_9 + C_{10}T + C_{11}T^2 + C_{12}T^3 + C_{13} \ln T \qquad (6)$$

where

C_8 = −5.800 220 6 E+03
C_9 = 1.391 499 3 E+00
C_{10} = −4.864 023 9 E−02
C_{11} = 4.176 476 8 E−05
C_{12} = −1.445 209 3 E−08
C_{13} = 6.545 967 3 E+00

In both Equations (5) and (6),

p_{ws} = saturation pressure, Pa
T = absolute temperature, K = °C + 273.15

The coefficients of Equations (5) and (6) were derived from the Hyland-Wexler equations. Because of rounding errors in the derivations and in some computers' calculating precision, results from Equations (5) and (6) may not agree precisely with Table 3 values.

The vapor pressure p_s of water in saturated moist air differs negligibly from the saturation vapor pressure p_{ws} of pure water at the same temperature. Consequently, p_s can be used in equations in place of p_{ws} with very little error:

$$p_s = x_{ws}p$$

where x_{ws} is the mole fraction of water vapor in saturated moist air at temperature t and pressure p, and p is the total barometric pressure of moist air.

HUMIDITY PARAMETERS

Basic Parameters

Humidity ratio W (alternatively, the moisture content or mixing ratio) of a given moist air sample is defined as the ratio of the mass of water vapor to the mass of dry air in the sample:

$$W = M_w/M_{da} \qquad (7)$$

W equals the mole fraction ratio x_w/x_{da} multiplied by the ratio of molecular masses (18.015 268/28.966 = 0.621 945):

$$W = 0.621\,945 x_w/x_{da} \qquad (8)$$

Specific humidity γ is the ratio of the mass of water vapor to total mass of the moist air sample:

$$\gamma = M_w/(M_w + M_{da}) \qquad (9a)$$

In terms of the humidity ratio,

$$\gamma = W/(1 + W) \qquad (9b)$$

Absolute humidity (alternatively, water vapor density) d_v is the ratio of the mass of water vapor to total volume of the sample:

$$d_v = M_w/V \qquad (10)$$

Density ρ of a moist air mixture is the ratio of total mass to total volume:

$$\rho = (M_{da} + M_w)/V = (1/v)(1 + W) \qquad (11)$$

where v is the moist air specific volume, m^3/kg_{da}, as defined by Equation (26).

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

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
–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	–38.212	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
–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	6.193	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	0.0037900	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	0.1337	13
14	0.010013	0.8131	0.0131	0.8262	14.081	25.290	39.371	0.0503	0.1430	14

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

Temp., °C	Humidity Ratio	Specific Volume, m^3/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
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	35.107	54.219	0.0676	0.1942	19
20	0.014761	0.8301	0.0196	0.8498	20.117	37.441	57.558	0.0711	0.2057	20
21	0.015724	0.8330	0.0210	0.8540	21.124	39.914	61.037	0.0745	0.2175	21
22	0.016744	0.8358	0.0224	0.8583	22.130	42.533	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	48.245	72.388	0.0847	0.2560	24
25	0.020173	0.8443	0.0273	0.8716	25.148	51.355	76.503	0.0881	0.2698	25
26	0.021451	0.8472	0.0291	0.8763	26.155	54.646	80.801	0.0915	0.2842	26
27	0.022802	0.8500	0.0311	0.8811	27.161	58.128	85.289	0.0948	0.2992	27
28	0.024229	0.8529	0.0331	0.8860	28.167	61.812	89.979	0.0982	0.3148	28
29	0.025738	0.8557	0.0353	0.8910	29.174	65.708	94.882	0.1015	0.3311	29
30	0.027333	0.8585	0.0376	0.8961	30.180	69.829	100.009	0.1048	0.3481	30
31	0.029018	0.8614	0.0400	0.9014	31.187	74.185	105.372	0.1081	0.3658	31
32	0.030797	0.8642	0.0426	0.9069	32.193	78.791	110.985	0.1115	0.3843	32
33	0.032677	0.8671	0.0454	0.9124	33.200	83.660	116.860	0.1147	0.4035	33
34	0.034663	0.8699	0.0483	0.9182	34.207	88.806	123.013	0.1180	0.4236	34
35	0.036760	0.8727	0.0514	0.9241	35.213	94.245	129.458	0.1213	0.4447	35
36	0.038975	0.8756	0.0547	0.9302	36.220	99.993	136.213	0.1246	0.4666	36
37	0.041313	0.8784	0.0581	0.9365	37.227	106.068	143.294	0.1278	0.4895	37
38	0.043783	0.8813	0.0618	0.9430	38.233	112.487	150.720	0.1311	0.5135	38
39	0.046391	0.8841	0.0657	0.9498	39.240	119.270	158.510	0.1343	0.5386	39
40	0.049145	0.8869	0.0698	0.9567	40.247	126.438	166.685	0.1375	0.5650	40
41	0.052053	0.8898	0.0741	0.9639	41.254	134.014	175.268	0.1407	0.5925	41
42	0.055124	0.8926	0.0788	0.9714	42.261	142.021	184.282	0.1439	0.6213	42
43	0.058368	0.8955	0.0837	0.9791	43.268	150.483	193.751	0.1471	0.6514	43
44	0.061795	0.8983	0.0888	0.9871	44.275	159.429	203.704	0.1503	0.6830	44
45	0.065416	0.9011	0.0943	0.9955	45.282	168.887	214.169	0.1535	0.7162	45
46	0.069242	0.9040	0.1002	1.0041	46.289	178.889	225.178	0.1566	0.7509	46
47	0.073286	0.9068	0.1063	1.0131	47.297	189.466	236.763	0.1598	0.7874	47
48	0.077561	0.9096	0.1129	1.0225	48.304	200.656	248.960	0.1629	0.8256	48
49	0.082081	0.9125	0.1198	1.0323	49.311	212.497	261.808	0.1660	0.8658	49
50	0.086863	0.9153	0.1272	1.0425	50.319	225.030	275.349	0.1692	0.9081	50
51	0.091922	0.9182	0.1350	1.0531	51.326	238.300	289.627	0.1723	0.9525	51
52	0.097278	0.9210	0.1433	1.0643	52.334	252.357	304.690	0.1754	0.9993	52
53	0.102949	0.9238	0.1521	1.0759	53.341	267.251	320.592	0.1785	1.0485	53
54	0.108958	0.9267	0.1614	1.0881	54.349	283.041	337.389	0.1816	1.1003	54
55	0.115326	0.9295	0.1714	1.1009	55.356	299.788	355.144	0.1846	1.1549	55
56	0.122080	0.9324	0.1819	1.1143	56.364	317.560	373.924	0.1877	1.2126	56
57	0.129248	0.9352	0.1932	1.1284	57.372	336.431	393.803	0.1908	1.2734	57
58	0.136858	0.9380	0.2051	1.1432	58.380	356.482	414.862	0.1938	1.3377	58
59	0.144945	0.9409	0.2179	1.1587	59.388	377.800	437.188	0.1968	1.4056	59
60	0.153545	0.9437	0.2315	1.1752	60.396	400.484	460.880	0.1999	1.4775	60
61	0.162697	0.9465	0.2460	1.1925	61.404	424.641	486.044	0.2029	1.5537	61
62	0.172446	0.9494	0.2615	1.2108	62.412	450.388	512.799	0.2059	1.6345	62
63	0.182842	0.9522	0.2780	1.2302	63.420	477.856	541.276	0.2089	1.7203	63
64	0.193937	0.9551	0.2957	1.2508	64.428	507.192	571.620	0.2119	1.8114	64
65	0.205794	0.9579	0.3147	1.2726	65.436	538.557	603.993	0.2149	1.9084	65
66	0.218478	0.9607	0.3350	1.2957	66.445	572.131	638.576	0.2179	2.0117	66
67	0.232067	0.9636	0.3568	1.3204	67.453	608.118	675.572	0.2208	2.1220	67
68	0.246645	0.9664	0.3803	1.3467	68.462	646.746	715.208	0.2238	2.2398	68
69	0.262309	0.9692	0.4056	1.3748	69.470	688.271	757.741	0.2268	2.3659	69
70	0.279167	0.9721	0.4328	1.4049	70.479	732.985	803.464	0.2297	2.5011	70
71	0.297343	0.9749	0.4622	1.4372	71.488	781.220	852.707	0.2326	2.6464	71
72	0.316979	0.9778	0.4941	1.4719	72.496	833.353	905.850	0.2356	2.8028	72
73	0.338237	0.9806	0.5287	1.5093	73.505	889.821	963.326	0.2385	2.9715	73
74	0.361304	0.9834	0.5663	1.5497	74.514	951.124	1025.638	0.2414	3.1539	74
75	0.386399	0.9863	0.6072	1.5935	75.523	1017.843	1093.367	0.2443	3.3517	75
76	0.413774	0.9891	0.6520	1.6411	76.532	1090.659	1167.191	0.2472	3.5668	76
77	0.443727	0.9919	0.7010	1.6930	77.542	1170.366	1247.907	0.2501	3.8014	77
78	0.476610	0.9948	0.7550	1.7497	78.551	1257.907	1336.458	0.2529	4.0581	78
79	0.512842	0.9976	0.8145	1.8121	79.560	1354.402	1433.962	0.2558	4.3401	79
80	0.552926	1.0005	0.8805	1.8809	80.569	1461.196	1541.765	0.2587	4.6511	80
81	0.597470	1.0033	0.9539	1.9572	81.579	1579.917	1661.496	0.2615	4.9956	81
82	0.647218	1.0061	1.0360	2.0421	82.589	1712.556	1795.145	0.2644	5.3794	82
83	0.703089	1.0090	1.1283	2.1373	83.598	1861.573	1945.171	0.2672	5.8091	83
84	0.766233	1.0118	1.2328	2.2446	84.608	2030.041	2114.649	0.2701	6.2933	84
85	0.838105	1.0146	1.3519	2.3665	85.618	2221.858	2307.476	0.2729	6.8430	85
86	0.920580	1.0175	1.4887	2.5062	86.628	2442.035	2528.662	0.2757	7.4721	86
87	1.016105	1.0203	1.6473	2.6676	87.638	2697.127	2784.764	0.2785	8.1987	87
88	1.127952	1.0232	1.8332	2.8564	88.648	2995.880	3084.528	0.2813	9.0472	88
89	1.260579	1.0260	2.0539	3.0799	89.658	3350.228	3439.885	0.2841	10.0508	89
90	1.420235	1.0288	2.3198	3.3487	90.668	3776.888	3867.556	0.2869	11.2558	90

Table 3 Thermodynamic Properties of Water at Saturation

Temp., °C t	Absolute Pressure p_{ws}, kPa	Specific Volume, m^3/kg_w Sat. Solid v_i/v_f	Specific Volume Evap. v_{ig}/v_{fg}	Specific Volume Sat. Vapor v_g	Specific Enthalpy, kJ/kg_w Sat. Solid h_i/h_f	Specific Enthalpy Evap. h_{ig}/h_{fg}	Specific Enthalpy Sat. Vapor h_g	Specific Entropy, $kJ/(kg_w \cdot K)$ Sat. Solid s_i/s_f	Specific Entropy Evap. s_{ig}/s_{fg}	Specific Entropy Sat. Vapor s_g	Temp., °C t
–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
Transition from saturated solid to saturated liquid											
0	0.6112	0.001000	206.139	206.140	–0.04	2500.93	2500.89	–0.0002	9.1559	9.1558	0
1	0.6571	0.001000	192.444	192.445	4.18	2498.55	2502.73	0.0153	9.1138	9.1291	1
2	0.7060	0.001000	179.763	179.764	8.39	2496.17	2504.57	0.0306	9.0721	9.1027	2

Table 3 Thermodynamic Properties of Water at Saturation (*Continued*)

Temp., °C t	Absolute Pressure p_{ws}, kPa	Specific Volume, m^3/kg_w Sat. Liquid v_i/v_f	Evap. v_{ig}/v_{fg}	Sat. Vapor v_g	Specific Enthalpy, kJ/kg_w Sat. Liquid h_i/h_f	Evap. h_{ig}/h_{fg}	Sat. Vapor h_g	Specific Entropy, $kJ/(kg_w \cdot K)$ Sat. Liquid s_i/s_f	Evap. s_{ig}/s_{fg}	Sat. Vapor s_g	Temp., °C t
3	0.7581	0.001000	168.013	168.014	12.60	2493.80	2506.40	0.0459	9.0306	9.0765	3
4	0.8135	0.001000	157.120	157.121	16.81	2491.42	2508.24	0.0611	8.9895	9.0506	4
5	0.8726	0.001000	147.016	147.017	21.02	2489.05	2510.07	0.0763	8.9486	9.0249	5
6	0.9354	0.001000	137.637	137.638	25.22	2486.68	2511.91	0.0913	8.9081	8.9994	6
7	1.0021	0.001000	128.927	128.928	29.43	2484.31	2513.74	0.1064	8.8678	8.9742	7
8	1.0730	0.001000	120.833	120.834	33.63	2481.94	2515.57	0.1213	8.8278	8.9492	8
9	1.1483	0.001000	113.308	113.309	37.82	2479.58	2517.40	0.1362	8.7882	8.9244	9
10	1.2282	0.001000	106.308	106.309	42.02	2477.21	2519.23	0.1511	8.7488	8.8998	10
11	1.3129	0.001000	99.792	99.793	46.22	2474.84	2521.06	0.1659	8.7096	8.8755	11
12	1.4028	0.001001	93.723	93.724	50.41	2472.48	2522.89	0.1806	8.6708	8.8514	12
13	1.4981	0.001001	88.069	88.070	54.60	2470.11	2524.71	0.1953	8.6322	8.8275	13
14	1.5989	0.001001	82.797	82.798	58.79	2467.75	2526.54	0.2099	8.5939	8.8038	14
15	1.7057	0.001001	77.880	77.881	62.98	2465.38	2528.36	0.2245	8.5559	8.7804	15
16	1.8188	0.001001	73.290	73.291	67.17	2463.01	2530.19	0.2390	8.5181	8.7571	16
17	1.9383	0.001001	69.005	69.006	71.36	2460.65	2532.01	0.2534	8.4806	8.7341	17
18	2.0647	0.001001	65.002	65.003	75.55	2458.28	2533.83	0.2678	8.4434	8.7112	18
19	2.1982	0.001002	61.260	61.261	79.73	2455.92	2535.65	0.2822	8.4064	8.6886	19
20	2.3392	0.001002	57.760	57.761	83.92	2453.55	2537.47	0.2965	8.3696	8.6661	20
21	2.4881	0.001002	54.486	54.487	88.10	2451.18	2539.29	0.3108	8.3331	8.6439	21
22	2.6452	0.001002	51.421	51.422	92.29	2448.81	2541.10	0.3250	8.2969	8.6218	22
23	2.8109	0.001003	48.551	48.552	96.47	2446.45	2542.92	0.3391	8.2609	8.6000	23
24	2.9856	0.001003	45.862	45.863	100.66	2444.08	2544.73	0.3532	8.2251	8.5783	24
25	3.1697	0.001003	43.340	43.341	104.84	2441.71	2546.54	0.3673	8.1895	8.5568	25
26	3.3637	0.001003	40.976	40.977	109.02	2439.33	2548.35	0.3813	8.1542	8.5355	26
27	3.5679	0.001004	38.757	38.758	113.20	2436.96	2550.16	0.3952	8.1192	8.5144	27
28	3.7828	0.001004	36.674	36.675	117.38	2434.59	2551.97	0.4091	8.0843	8.4934	28
29	4.0089	0.001004	34.718	34.719	121.56	2432.21	2553.78	0.4230	8.0497	8.4727	29
30	4.2467	0.001004	32.881	32.882	125.75	2429.84	2555.58	0.4368	8.0153	8.4521	30
31	4.4966	0.001005	31.153	31.154	129.93	2427.46	2557.39	0.4506	7.9812	8.4317	31
32	4.7592	0.001005	29.528	29.529	134.11	2425.08	2559.19	0.4643	7.9472	8.4115	32
33	5.0351	0.001005	28.000	28.001	138.29	2422.70	2560.99	0.4780	7.9135	8.3914	33
34	5.3247	0.001006	26.561	26.562	142.47	2420.32	2562.79	0.4916	7.8800	8.3715	34
35	5.6286	0.001006	25.207	25.208	146.64	2417.94	2564.58	0.5052	7.8467	8.3518	35
36	5.9475	0.001006	23.931	23.932	150.82	2415.56	2566.38	0.5187	7.8136	8.3323	36
37	6.2818	0.001007	22.728	22.729	155.00	2413.17	2568.17	0.5322	7.7807	8.3129	37
38	6.6324	0.001007	21.594	21.595	159.18	2410.78	2569.96	0.5457	7.7480	8.2936	38
39	6.9997	0.001007	20.525	20.526	163.36	2408.39	2571.75	0.5591	7.7155	8.2746	39
40	7.3844	0.001008	19.516	19.517	167.54	2406.00	2573.54	0.5724	7.6832	8.2557	40
41	7.7873	0.001008	18.564	18.565	171.72	2403.61	2575.33	0.5858	7.6512	8.2369	41
42	8.2090	0.001009	17.664	17.665	175.90	2401.21	2577.11	0.5990	7.6193	8.2183	42
43	8.6503	0.001009	16.815	16.816	180.08	2398.82	2578.89	0.6123	7.5876	8.1999	43
44	9.1118	0.001009	16.012	16.013	184.26	2396.42	2580.67	0.6255	7.5561	8.1816	44
45	9.5944	0.001010	15.252	15.253	188.44	2394.02	2582.45	0.6386	7.5248	8.1634	45
46	10.0988	0.001010	14.534	14.535	192.62	2391.61	2584.23	0.6517	7.4937	8.1454	46
47	10.6259	0.001011	13.855	13.856	196.80	2389.21	2586.00	0.6648	7.4628	8.1276	47
48	11.1764	0.001011	13.212	13.213	200.98	2386.80	2587.77	0.6778	7.4320	8.1099	48
49	11.7512	0.001012	12.603	12.604	205.16	2384.39	2589.54	0.6908	7.4015	8.0923	49
50	12.3513	0.001012	12.027	12.028	209.34	2381.97	2591.31	0.7038	7.3711	8.0749	50
51	12.9774	0.001013	11.481	11.482	213.52	2379.56	2593.08	0.7167	7.3409	8.0576	51
52	13.6305	0.001013	10.963	10.964	217.70	2377.14	2594.84	0.7296	7.3109	8.0405	52
53	14.3116	0.001014	10.472	10.473	221.88	2374.72	2596.60	0.7424	7.2811	8.0235	53
54	15.0215	0.001014	10.006	10.007	226.06	2372.30	2598.35	0.7552	7.2514	8.0066	54
55	15.7614	0.001015	9.5639	9.5649	230.24	2369.87	2600.11	0.7680	7.2219	7.9899	55
56	16.5322	0.001015	9.1444	9.1454	234.42	2367.44	2601.86	0.7807	7.1926	7.9733	56
57	17.3350	0.001016	8.7461	8.7471	238.61	2365.01	2603.61	0.7934	7.1634	7.9568	57
58	18.1708	0.001016	8.3678	8.3688	242.79	2362.57	2605.36	0.8060	7.1344	7.9405	58
59	19.0407	0.001017	8.0083	8.0093	246.97	2360.13	2607.10	0.8186	7.1056	7.9243	59
60	19.9458	0.001017	7.6666	7.6677	251.15	2357.69	2608.85	0.8312	7.0770	7.9082	60
61	20.8873	0.001018	7.3418	7.3428	255.34	2355.25	2610.58	0.8438	7.0485	7.8922	61
62	21.8664	0.001018	7.0328	7.0338	259.52	2352.80	2612.32	0.8563	7.0201	7.8764	62
63	22.8842	0.001019	6.7389	6.7399	263.71	2350.35	2614.05	0.8687	6.9919	7.8607	63
64	23.9421	0.001019	6.4591	6.4601	267.89	2347.89	2615.78	0.8811	6.9639	7.8451	64
65	25.0411	0.001020	6.1928	6.1938	272.08	2345.43	2617.51	0.8935	6.9361	7.8296	65
66	26.1827	0.001020	5.9392	5.9402	276.27	2342.97	2619.23	0.9059	6.9083	7.8142	66
67	27.3680	0.001021	5.6976	5.6986	280.45	2340.50	2620.96	0.9182	6.8808	7.7990	67
68	28.5986	0.001022	5.4674	5.4684	284.64	2338.03	2622.67	0.9305	6.8534	7.7839	68
69	29.8756	0.001022	5.2479	5.2490	288.83	2335.56	2624.39	0.9428	6.8261	7.7689	69

Table 3 Thermodynamic Properties of Water at Saturation (*Continued*)

Temp., °C t	Absolute Pressure p_{ws}, kPa	Specific Volume, m³/kg$_w$			Specific Enthalpy, kJ/kg$_w$			Specific Entropy, kJ/(kg$_w$·K)			Temp., °C t
		Sat. Liquid v_i/v_f	Evap. v_{ig}/v_{fg}	Sat. Vapor v_g	Sat. Liquid h_i/h_f	Evap. h_{ig}/h_{fg}	Sat. Vapor h_g	Sat. Liquid s_i/s_f	Evap. s_{ig}/s_{fg}	Sat. Vapor s_g	
70	31.2006	0.001023	5.0387	5.0397	293.02	2333.08	2626.10	0.9550	6.7990	7.7540	70
71	32.5750	0.001023	4.8392	4.8402	297.21	2330.60	2627.81	0.9672	6.7720	7.7392	71
72	34.0001	0.001024	4.6488	4.6498	301.40	2328.11	2629.51	0.9793	6.7452	7.7245	72
73	35.4775	0.001025	4.4671	4.4681	305.59	2325.62	2631.21	0.9915	6.7185	7.7100	73
74	37.0088	0.001025	4.2937	4.2947	309.78	2323.13	2632.91	1.0035	6.6920	7.6955	74
75	38.5954	0.001026	4.1281	4.1291	313.97	2320.63	2634.60	1.0156	6.6656	7.6812	75
76	40.2389	0.001026	3.9699	3.9709	318.17	2318.13	2636.29	1.0276	6.6393	7.6669	76
77	41.9409	0.001027	3.8188	3.8198	322.36	2315.62	2637.98	1.0396	6.6132	7.6528	77
78	43.7031	0.001028	3.6743	3.6754	326.56	2313.11	2639.66	1.0516	6.5872	7.6388	78
79	45.5271	0.001028	3.5363	3.5373	330.75	2310.59	2641.34	1.0635	6.5613	7.6248	79
80	47.4147	0.001029	3.4042	3.4053	334.95	2308.07	2643.01	1.0754	6.5356	7.6110	80
81	49.3676	0.001030	3.2780	3.2790	339.15	2305.54	2644.68	1.0873	6.5100	7.5973	81
82	51.3875	0.001030	3.1572	3.1582	343.34	2303.01	2646.35	1.0991	6.4846	7.5837	82
83	53.4762	0.001031	3.0415	3.0426	347.54	2300.47	2648.01	1.1109	6.4592	7.5701	83
84	55.6355	0.001032	2.9309	2.9319	351.74	2297.93	2649.67	1.1227	6.4340	7.5567	84
85	57.8675	0.001032	2.8249	2.8259	355.95	2295.38	2651.33	1.1344	6.4090	7.5434	85
86	60.1738	0.001033	2.7234	2.7244	360.15	2292.83	2652.98	1.1461	6.3840	7.5301	86
87	62.5565	0.001034	2.6262	2.6272	364.35	2290.27	2654.62	1.1578	6.3592	7.5170	87
88	65.0174	0.001035	2.5330	2.5341	368.56	2287.70	2656.26	1.1694	6.3345	7.5039	88
89	67.5587	0.001035	2.4437	2.4448	372.76	2285.14	2657.90	1.1811	6.3099	7.4909	89
90	70.1824	0.001036	2.3581	2.3591	376.97	2282.56	2659.53	1.1927	6.2854	7.4781	90
91	72.8904	0.001037	2.2760	2.2771	381.18	2279.98	2661.16	1.2042	6.2611	7.4653	91
92	75.6849	0.001037	2.1973	2.1983	385.38	2277.39	2662.78	1.2158	6.2368	7.4526	92
93	78.5681	0.001038	2.1217	2.1228	389.59	2274.80	2664.39	1.2273	6.2127	7.4400	93
94	81.5420	0.001039	2.0492	2.0502	393.81	2272.20	2666.01	1.2387	6.1887	7.4275	94
95	84.6089	0.001040	1.9796	1.9806	398.02	2269.60	2667.61	1.2502	6.1648	7.4150	95
96	87.7711	0.001040	1.9128	1.9138	402.23	2266.98	2669.22	1.2616	6.1411	7.4027	96
97	91.0308	0.001041	1.8486	1.8497	406.45	2264.37	2670.81	1.2730	6.1174	7.3904	97
98	94.3902	0.001042	1.7870	1.7880	410.66	2261.74	2672.40	1.2844	6.0938	7.3782	98
99	97.8518	0.001043	1.7277	1.7288	414.88	2259.11	2673.99	1.2957	6.0704	7.3661	99
100	101.4180	0.001043	1.6708	1.6719	419.10	2256.47	2675.57	1.3070	6.0471	7.3541	100
101	105.0910	0.001044	1.6161	1.6171	423.32	2253.83	2677.15	1.3183	6.0238	7.3421	101
102	108.8735	0.001045	1.5635	1.5645	427.54	2251.18	2678.72	1.3296	6.0007	7.3303	102
103	112.7678	0.001046	1.5129	1.5140	431.76	2248.52	2680.28	1.3408	5.9777	7.3185	103
104	116.7765	0.001047	1.4642	1.4653	435.99	2245.85	2681.84	1.3520	5.9548	7.3068	104
105	120.9021	0.001047	1.4174	1.4185	440.21	2243.18	2683.39	1.3632	5.9320	7.2951	105
106	125.1472	0.001048	1.3724	1.3734	444.44	2240.50	2684.94	1.3743	5.9092	7.2836	106
107	129.5145	0.001049	1.3290	1.3301	448.67	2237.81	2686.48	1.3854	5.8866	7.2721	107
108	134.0065	0.001050	1.2873	1.2883	452.90	2235.12	2688.02	1.3965	5.8641	7.2607	108
109	138.6261	0.001051	1.2471	1.2481	457.13	2232.41	2689.55	1.4076	5.8417	7.2493	109
110	143.3760	0.001052	1.2083	1.2094	461.36	2229.70	2691.07	1.4187	5.8194	7.2380	110
111	148.2588	0.001052	1.1710	1.1721	465.60	2226.99	2692.58	1.4297	5.7972	7.2268	111
112	153.2775	0.001053	1.1351	1.1362	469.83	2224.26	2694.09	1.4407	5.7750	7.2157	112
113	158.4348	0.001054	1.1005	1.1015	474.07	2221.53	2695.60	1.4517	5.7530	7.2047	113
114	163.7337	0.001055	1.0671	1.0681	478.31	2218.78	2697.09	1.4626	5.7310	7.1937	114
115	169.1770	0.001056	1.0349	1.0359	482.55	2216.03	2698.58	1.4735	5.7092	7.1827	115
116	174.7678	0.001057	1.0038	1.0049	486.80	2213.27	2700.07	1.4844	5.6874	7.1719	116
117	180.5090	0.001058	0.9739	0.9750	491.04	2210.51	2701.55	1.4953	5.6658	7.1611	117
118	186.4036	0.001059	0.9450	0.9461	495.29	2207.73	2703.02	1.5062	5.6442	7.1504	118
119	192.4547	0.001059	0.9171	0.9182	499.53	2204.94	2704.48	1.5170	5.6227	7.1397	119
120	198.6654	0.001060	0.8902	0.8913	503.78	2202.15	2705.93	1.5278	5.6013	7.1291	120
122	211.5782	0.001062	0.8392	0.8403	512.29	2196.53	2708.82	1.5494	5.5587	7.1081	122
124	225.1676	0.001064	0.7916	0.7927	520.80	2190.88	2711.69	1.5708	5.5165	7.0873	124
126	239.4597	0.001066	0.7472	0.7483	529.32	2185.19	2714.52	1.5922	5.4746	7.0668	126
128	254.4813	0.001068	0.7058	0.7068	537.85	2179.47	2717.32	1.6134	5.4330	7.0465	128
130	270.2596	0.001070	0.6670	0.6681	546.39	2173.70	2720.09	1.6346	5.3918	7.0264	130
132	286.8226	0.001072	0.6308	0.6318	554.93	2167.89	2722.83	1.6557	5.3508	7.0066	132
134	304.1989	0.001074	0.5969	0.5979	563.49	2162.04	2725.53	1.6767	5.3102	6.9869	134
136	322.4175	0.001076	0.5651	0.5662	572.05	2156.15	2728.20	1.6977	5.2698	6.9675	136
138	341.5081	0.001078	0.5353	0.5364	580.62	2150.22	2730.84	1.7185	5.2298	6.9483	138
140	361.5010	0.001080	0.5074	0.5085	589.20	2144.24	2733.44	1.7393	5.1900	6.9293	140
142	382.4271	0.001082	0.4813	0.4823	597.79	2138.22	2736.01	1.7600	5.1505	6.9105	142
144	404.3178	0.001084	0.4567	0.4577	606.39	2132.15	2738.54	1.7806	5.1112	6.8918	144
146	427.2053	0.001086	0.4336	0.4346	615.00	2126.04	2741.04	1.8011	5.0723	6.8734	146
148	451.1220	0.001088	0.4118	0.4129	623.62	2119.88	2743.50	1.8216	5.0335	6.8551	148
150	476.1014	0.001091	0.3914	0.3925	632.25	2113.67	2745.92	1.8420	4.9951	6.8370	150
152	502.1771	0.001093	0.3722	0.3733	640.89	2107.41	2748.30	1.8623	4.9569	6.8191	152
154	529.3834	0.001095	0.3541	0.3552	649.55	2101.10	2750.64	1.8825	4.9189	6.8014	154
156	557.7555	0.001097	0.3370	0.3381	658.21	2094.74	2752.95	1.9027	4.8811	6.7838	156
158	587.3287	0.001100	0.3209	0.3220	666.89	2088.32	2755.21	1.9228	4.8436	6.7664	158
160	618.1392	0.001102	0.3057	0.3068	675.57	2081.86	2757.43	1.9428	4.8063	6.7491	160

Humidity Parameters Involving Saturation

The following definitions of humidity parameters involve the concept of moist air saturation:

Saturation humidity ratio $W_s(t, p)$ is the humidity ratio of moist air saturated with respect to water (or ice) at the same temperature t and pressure p.

Degree of saturation μ is the ratio of air humidity ratio W to humidity ratio W_s of saturated moist air at the same temperature and pressure:

$$\mu = \left.\frac{W}{W_s}\right|_{t,p} \tag{12}$$

Relative humidity ϕ is the ratio of the mole fraction of water vapor x_w in a given moist air sample to the mole fraction x_{ws} in an air sample saturated at the same temperature and pressure:

$$\phi = \left.\frac{x_w}{x_{ws}}\right|_{t,p} \tag{13}$$

Combining Equations (8), (12), and (13)

$$\mu = \frac{\phi}{1 + (1 - \phi)W_s/(0.62\ 945)} \tag{14}$$

Dew-point temperature t_d is the temperature of moist air saturated at pressure p, with the same humidity ratio W as that of the given sample of moist air. It is defined as the solution $t_d(p, W)$ of the following equation:

$$W_s(p, t_d) = W \tag{15}$$

Thermodynamic wet-bulb temperature t^* is the temperature at which water (liquid or solid), by evaporating into moist air at dry-bulb temperature t and humidity ratio W, can bring air to saturation adiabatically at the same temperature t^* while total pressure p is constant. This parameter is considered separately in the section on Thermodynamic Wet-Bulb and Dew-Point Temperature.

PERFECT GAS RELATIONSHIPS FOR DRY AND MOIST AIR

When moist air is considered a mixture of independent perfect gases (i.e., dry air and water vapor), each is assumed to obey the perfect gas equation of state as follows:

$$\text{Dry air:} \quad p_{da}V = n_{da}RT \tag{16}$$

$$\text{Water vapor:} \quad p_wV = n_wRT \tag{17}$$

where

p_{da} = partial pressure of dry air
p_w = partial pressure of water vapor
V = total mixture volume
n_{da} = number of moles of dry air
n_w = number of moles of water vapor
R = universal gas constant, 8314.472 J/(kmol·K)
T = absolute temperature, K

The mixture also obeys the perfect gas equation:

$$pV = nRT \tag{18}$$

or

$$(p_{da} + p_w)V = (n_{da} + n_w)RT \tag{19}$$

where $p = p_{da} + p_w$ is the total mixture pressure and $n = n_{da} + n_w$ is the total number of moles in the mixture. From Equations (16) to (19), the mole fractions of dry air and water vapor are, respectively,

$$x_{da} = p_{da}/(p_{da} + p_w) = p_{da}/p \tag{20}$$

and

$$x_w = p_w/(p_{da} + p_w) = p_w/p \tag{21}$$

From Equations (8), (20), and (21), the **humidity ratio W** is

$$W = 0.621\ 945\ \frac{p_w}{p - p_w} \tag{22}$$

The degree of saturation μ is defined in Equation (12), where

$$W_s = 0.621\ 945\ \frac{p_{ws}}{p - p_{ws}} \tag{23}$$

The term p_{ws} represents the saturation pressure of water vapor in the absence of air at the given temperature t. This pressure p_{ws} is a function only of temperature and differs slightly from the vapor pressure of water in saturated moist air.

The **relative humidity** ϕ is defined in Equation (13). Substituting Equation (21) for x_w and x_{ws},

$$\phi = \left.\frac{p_w}{p_{ws}}\right|_{t,p} \tag{24}$$

Substituting Equation (23) for W_s into Equation (14),

$$\phi = \frac{\mu}{1 - (1 - \mu)(p_{ws}/p)} \tag{25}$$

Both ϕ and μ are zero for dry air and unity for saturated moist air. At intermediate states, their values differ, substantially so at higher temperatures.

The **specific volume v** of a moist air mixture is expressed in terms of a unit mass of dry air:

$$v = V/M_{da} = V/(28.966n_{da}) \tag{26}$$

where V is the total volume of the mixture, M_{da} is the total mass of dry air, and n_{da} is the number of moles of dry air. By Equations (16) and (26), with the relation $p = p_{da} + p_w$,

$$v = \frac{RT}{28.966(p - p_w)} = \frac{R_{da}T}{p - p_w} \tag{27}$$

Using Equation (22),

$$v = \frac{RT(1 + (1.607\ 858)W)}{28.966p} = \frac{R_{da}T(1 + (1.607\ 858)W)}{p} \tag{28}$$

In Equations (27) and (28), v is specific volume, T is absolute temperature, p is total pressure, p_w is partial pressure of water vapor, and W is humidity ratio.

In specific units, Equation (28) may be expressed as

$$v = 0.287\ 042(t + 273.15)(1 + 1.607\ 858W)/p$$

where

v = specific volume, m^3/kg_{da}
t = dry-bulb temperature, °C
W = humidity ratio, kg_w/kg_{da}
p = total pressure, kPa

The **enthalpy** of a mixture of perfect gases equals the sum of the individual partial enthalpies of the components. Therefore, the specific enthalpy of moist air can be written as follows:

$$h = h_{da} + Wh_g \tag{29}$$

where h_{da} is the specific enthalpy for dry air in kJ/kg$_{da}$ and h_g is the specific enthalpy for saturated water vapor in kJ/kg$_w$ at the mixture's temperature. As an approximation,

$$h_{da} \approx 1.006t \tag{30}$$

$$h_g \approx 2501 + 1.86t \tag{31}$$

where t is the dry-bulb temperature in °C. The moist air specific enthalpy in kJ/kg$_{da}$ then becomes

$$h = 1.006t + W(2501 + 1.86t) \tag{32}$$

THERMODYNAMIC WET-BULB AND DEW-POINT TEMPERATURE

For any state of moist air, a temperature t^* exists at which liquid (or solid) water evaporates into the air to bring it to saturation at exactly this same temperature and total pressure (Harrison 1965). During adiabatic saturation, saturated air is expelled at a temperature equal to that of the injected water. In this constant-pressure process,

- Humidity ratio increases from initial value W to W_s^*, corresponding to saturation at temperature t^*
- Enthalpy increases from initial value h to h_s^*, corresponding to saturation at temperature t^*
- Mass of water added per unit mass of dry air is $(W_s^* - W)$, which adds energy to the moist air of amount $(W_s^* - W)h_w^*$, where h_w^* denotes specific enthalpy in kJ/kg$_w$ of water added at temperature t^*

Therefore, if the process is strictly adiabatic, conservation of enthalpy at constant total pressure requires that

$$h + (W_s^* - W)h_w^* = h_s^* \tag{33}$$

W_s^*, h_w^*, and h_s^* are functions only of temperature t^* for a fixed value of pressure. The value of t^* that satisfies Equation (33) for given values of h, W, and p is the **thermodynamic wet-bulb temperature**.

A **psychrometer** consists of two thermometers; one thermometer's bulb is covered by a wick that has been thoroughly wetted with water. When the wet bulb is placed in an airstream, water evaporates from the wick, eventually reaching an equilibrium temperature called the **wet-bulb temperature**. This process is not one of adiabatic saturation, which defines the thermodynamic wet-bulb temperature, but one of simultaneous heat and mass transfer from the wet bulb. The fundamental mechanism of this process is described by the Lewis relation [Equation (38) in Chapter 6]. Fortunately, only small corrections must be applied to wet-bulb thermometer readings to obtain the thermodynamic wet-bulb temperature.

As defined, thermodynamic wet-bulb temperature is a unique property of a given moist air sample independent of measurement techniques.

Equation (33) is exact because it defines the thermodynamic wet-bulb temperature t^*. Substituting the approximate perfect gas relation [Equation (32)] for h, the corresponding expression for h_s^*, and the approximate relation for saturated liquid water

$$h_w^* \approx 4.186t^* \tag{34}$$

into Equation (33), and solving for the humidity ratio,

$$W = \frac{(2501 - 2.326t^*)W_s^* - 1.006(t - t^*)}{2501 + 1.86t - 4.186t^*} \tag{35}$$

where t and t^* are in °C. Below freezing, the corresponding equations are

$$h_w^* \approx -333.4 + 2.1t^* \tag{36}$$

$$W = \frac{(2830 - 0.24t^*)W_s^* - 1.006(t - t^*)}{2830 + 1.86t - 2.1t^*} \tag{37}$$

A wet/ice-bulb thermometer is imprecise when determining moisture content at 0°C.

The **dew-point temperature t_d** of moist air with humidity ratio W and pressure p was defined as the solution $t_d(p, w)$ of $W_s(p, t_d)$. For perfect gases, this reduces to

$$p_{ws}(t_d) = p_w = (pW)/(0.621\,945 + W) \tag{38}$$

where p_w is the water vapor partial pressure for the moist air sample and $p_{ws}(t_d)$ is the saturation vapor pressure at temperature t_d. The saturation vapor pressure is obtained from Table 3 or by using Equation (5) or (6). Alternatively, the dew-point temperature can be calculated directly by one of the following equations (Peppers 1988):

Between dew points of 0 and 93°C,

$$t_d = C_{14} + C_{15}\alpha + C_{16}\alpha^2 + C_{17}\alpha^3 + C_{18}(p_w)^{0.1984} \tag{39}$$

Below 0°C,

$$t_d = 6.09 + 12.608\alpha + 0.4959\alpha^2 \tag{40}$$

where

t_d = dew-point temperature, °C
α = ln p_w
p_w = water vapor partial pressure, kPa
C_{14} = 6.54
C_{15} = 14.526
C_{16} = 0.7389
C_{17} = 0.09486
C_{18} = 0.4569

NUMERICAL CALCULATION OF MOIST AIR PROPERTIES

The following are outlines, citing equations and tables already presented, for calculating moist air properties using perfect gas relations. These relations are accurate enough for most engineering calculations in air-conditioning practice, and are readily adapted to either hand or computer calculating methods. For more details, refer to Tables 15 through 18 in Chapter 1 of Olivieri (1996). Graphical procedures are discussed in the section on Psychrometric Charts.

SITUATION 1.

Given: Dry-bulb temperature t, Wet-bulb temperature t^*, Pressure p

To Obtain	Use	Comments
$p_{ws}(t^*)$	Table 3 or Equation (5) or (6)	Sat. press. for temp. t^*
W_s^*	Equation (23)	Using $p_{ws}(t^*)$
W	Equation (35) or (37)	
$p_{ws}(t)$	Table 3 or Equation (5) or (6)	Sat. press. for temp. t
W_s	Equation (23)	Using $p_{ws}(t)$
μ	Equation (12)	Using W_s
ϕ	Equation (25)	Using $p_{ws}(t)$
v	Equation (28)	
h	Equation (32)	
p_w	Equation (38)	
t_d	Table 3 with Equation (38), (39), or (40)	

SITUATION 2.

Given: Dry-bulb temperature t, Dew-point temperature t_d, Pressure p

To Obtain	Use	Comments
$p_w = p_{ws}(t_d)$	Table 3 or Equation (5) or (6)	Sat. press. for temp. t_d
W	Equation (22)	
$p_{ws}(t)$	Table 3 or Equation (5) or (6)	Sat. press. for temp. t_d
W_s	Equation (23)	Using $p_{ws}(t)$
μ	Equation (12)	Using W_s
ϕ	Equation (25)	Using $p_{ws}(t)$
v	Equation (28)	
h	Equation (32)	
t^*	Equation (23) and (35) or (37) with Table 3 or with Equation (5) or (6)	Requires trial-and-error or numerical solution method

SITUATION 3.

Given: Dry-bulb temperature t, Relative humidity ϕ, Pressure p

To Obtain	Use	Comments
$p_{ws}(t)$	Table 3 or Equation (5) or (6)	Sat. press. for temp. t
p_w	Equation (24)	
W	Equation (22)	
W_s	Equation (23)	Using $p_{ws}(t)$
μ	Equation (12)	Using W_s
v	Equation (28)	
h	Equation (32)	
t_d	Table 3 with Equation (38), (39), or (40)	
t^*	Equation (23) and (35) or (37) with Table 3 or with Equation (5) or (6)	Requires trial-and-error or numerical solution method

Moist Air Property Tables for Standard Pressure

Table 2 shows thermodynamic properties for standard atmospheric pressure at temperatures from –60 to 90°C. Properties of intermediate moist air states can be calculated using the degree of saturation μ:

$$\text{Volume} \qquad v = v_{da} + \mu v_{as} \tag{41}$$

$$\text{Enthalpy} \qquad h = h_{da} + \mu h_{as} \tag{42}$$

These equations are accurate to about 70°C. At higher temperatures, errors can be significant. Hyland and Wexler (1983a) include charts that can be used to estimate errors for v and h for standard barometric pressure. Nelson and Sauer (2002) provide psychrometric tables and charts up to 320°C and 1.0 kg_w/kg_{da}.

PSYCHROMETRIC CHARTS

A psychrometric chart graphically represents the thermodynamic properties of moist air.

The choice of coordinates for a psychrometric chart is arbitrary. A chart with coordinates of enthalpy and humidity ratio provides convenient graphical solutions of many moist air problems with a minimum of thermodynamic approximations. ASHRAE developed five such psychrometric charts. Chart 1 is shown as Figure 1; the others may be obtained through ASHRAE.

Charts 1, 2, 3 and 4 are for sea-level pressure (101.325 kPa). Chart 5 is for 750 m altitude (92.634 kPa), Chart 6 is for 1500 m altitude (84.54 kPa), and Chart 7 is for 2250 m altitude (77.058 kPa). All charts use oblique-angle coordinates of enthalpy and humidity ratio, and are consistent with the data of Table 2 and the properties computation methods of Goff (1949) and Goff and Gratch (1945), as well as Hyland and Wexler (1983a). Palmatier (1963) describes the geometry of chart construction applying specifically to Charts 1 and 4.

The dry-bulb temperature ranges covered by the charts are

Charts 1, 5, 6, 7	Normal temperature	0 to 50°C
Chart 2	Low temperature	–40 to 10°C
Chart 3	High temperature	10 to 120°C
Chart 4	Very high temperature	100 to 200°C

Charts 8 to 16 are for 200 to 320°C and cover the same pressures as 1, 5, 6, and 7 plus the additional pressures of 0.2, 0.5,1.0, 2.0, and 5.0 MPa. They were produced by Nelson and Sauer (2002) and are available on the CD-ROM included with Gatley (2013).

Psychrometric properties or charts for other barometric pressures can be derived by interpolation. Sufficiently exact values for most purposes can be derived by methods described in the section on Perfect Gas Relationships for Dry and Moist Air. Constructing charts for altitude conditions has been discussed by Haines (1961), Karig (1946), and Rohsenow (1946).

Comparison of charts 1 and 6 by overlay reveals the following:

- The dry-bulb lines coincide.
- Wet-bulb lines for a given temperature originate at the intersections of the corresponding dry-bulb line and the two saturation curves, and they have the same slope.
- Humidity ratio and enthalpy for a given dry- and wet-bulb temperature increase with altitude, but there is little change in relative humidity.
- Volume changes rapidly; for a given dry-bulb and humidity ratio, it is practically inversely proportional to barometric pressure.

The following table compares properties at sea level (chart 1) and 1500 m (chart 6):

Chart No.	db	wb	h	W	rh	v
1	40	30	99.5	23.0	49	0.920
6	40	30	114.1	28.6	50	1.111

Figure 1 shows humidity ratio lines (horizontal) for the range from 0 (dry air) to 30 grams moisture per kilogram dry air. Enthalpy lines are oblique lines across the chart precisely parallel to each other.

Dry-bulb temperature lines are straight, not precisely parallel to each other, and inclined slightly from the vertical position. Thermodynamic wet-bulb temperature lines are oblique and in a slightly different direction from enthalpy lines. They are straight but are not precisely parallel to each other.

Relative humidity lines are shown in intervals of 10%. The saturation curve is the line of 100% rh, whereas the horizontal line for $W = 0$ (dry air) is the line for 0% rh.

Specific volume lines are straight but are not precisely parallel to each other.

A narrow region above the saturation curve has been developed for fog conditions of moist air. This two-phase region represents a mechanical mixture of saturated moist air and liquid water, with the two components in thermal equilibrium. Isothermal lines in the fog region coincide with extensions of thermodynamic wet-bulb temperature lines. If required, the fog region can be further expanded by extending humidity ratio, enthalpy, and thermodynamic wet-bulb temperature lines.

The protractor to the left of the chart shows two scales: one for sensible/total heat ratio, and one for the ratio of enthalpy difference to humidity ratio difference. The protractor is used to establish the direction of a condition line on the psychrometric chart.

Example 1 illustrates use of the ASHRAE psychrometric chart to determine moist air properties.

Example 1. Moist air exists at 40°C dry-bulb temperature, 20°C thermodynamic wet-bulb temperature, and 101.325 kPa pressure. Determine the humidity ratio, enthalpy, dew-point temperature, relative humidity, and specific volume.

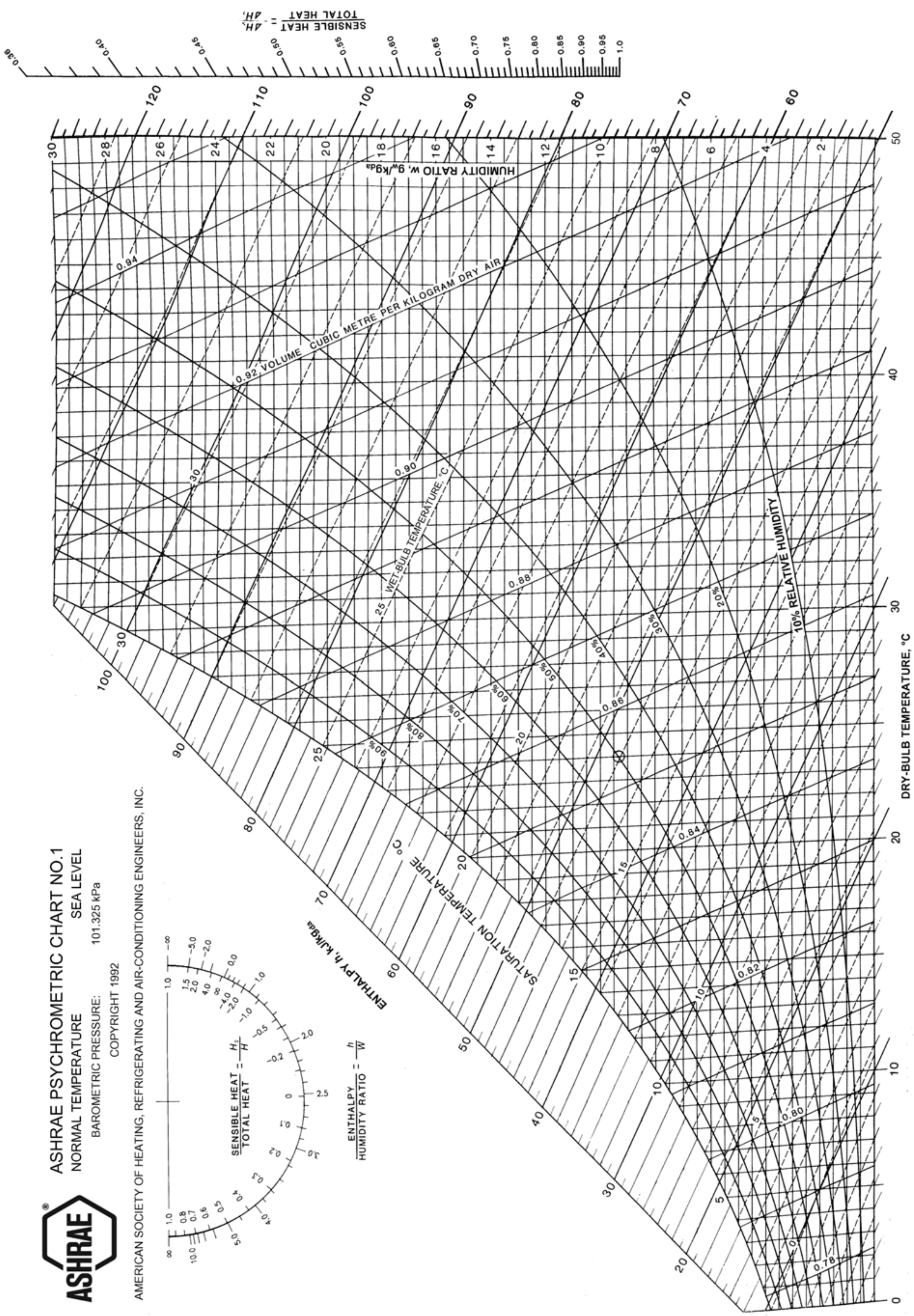

Fig. 1 ASHRAE Psychrometric Chart No. 1

Solution: Locate state point on chart 1 (Figure 1) at the intersection of 40°C dry-bulb temperature and 20°C thermodynamic wet-bulb temperature lines. Read **humidity ratio** $W = 6.5$ g_w/kg_{da}.

The **enthalpy** can be found by using two triangles to draw a line parallel to the nearest enthalpy line (60 kJ/kg_{da}) through the state point to the nearest edge scale. Read $h = 56.7$ kJ/kg_{da}.

Dew-point temperature can be read at the intersection of W = 6.5 g_w/kg_{da} with the saturation curve. Thus, $t_d = 7$°C.

Relative humidity ϕ can be estimated directly. Thus, $\phi = 14\%$.

Specific volume can be found by linear interpolation between the volume lines for 0.88 and 0.90 m^3/kg_{da}. Thus, $v = 0.896$ m^3/kg_{da}.

TYPICAL AIR-CONDITIONING PROCESSES

The ASHRAE psychrometric chart can be used to solve numerous process problems with moist air. Its use is best explained through illustrative examples. In each of the following examples, the process takes place at a constant total pressure of 101.325 kPa.

Moist Air Sensible Heating or Cooling

Adding heat alone to or removing heat alone from moist air is represented by a horizontal line on the ASHRAE chart, because the humidity ratio remains unchanged.

Figure 2 shows a device that adds heat to a stream of moist air. For steady-flow conditions, the required rate of heat addition is

$$ {}_1q_2 = \dot{m}_{da}(h_2 - h_1) \qquad (43) $$

Example 2. Moist air, saturated at 2°C, enters a heating coil at a rate of 10 m^3/s. Air leaves the coil at 40°C. Find the required rate of heat addition.

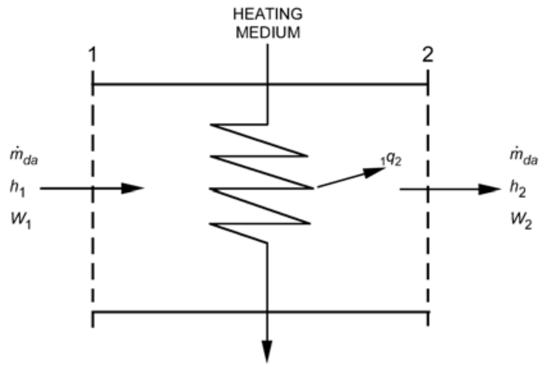

Fig. 2 Schematic of Device for Heating Moist Air

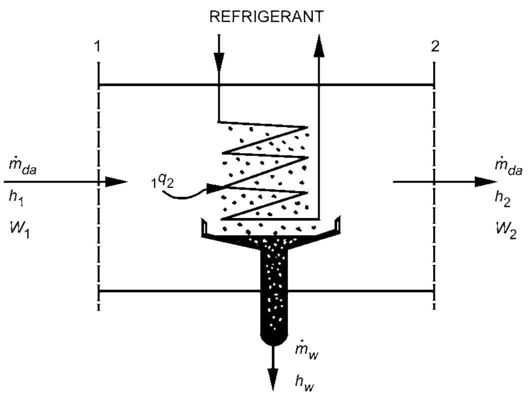

Fig. 3 Schematic of Device for Cooling Moist Air

Solution: Figure 3 schematically shows the solution. State 1 is located on the saturation curve at 2°C. Thus, $h_1 = 13.0$ kJ/kg_{da}, $W_1 = 4.38$ g_w/kg_{da}, and $v_1 = 0.785$ m^3/kg_{da}. State 2 is located at the intersection of $t = 40$°C and $W_2 = W_1 = 4.38$ g_{wT}/kg_{da}. Thus, $h_2 = 51.5$ kJ/kg_{da}. The mass flow of dry air is

$$ \dot{m}_{da} = 10/0.785 = 12.74\ kg_{da}/s $$

From Equation (43),

$$ {}_1q_2 = 12.74(51.5 - 13.0) = 490\ kW $$

Moist Air Cooling and Dehumidification

Moisture condensation occurs when moist air is cooled to a temperature below its initial dew point. Figure 4 shows a schematic cooling coil where moist air is assumed to be uniformly processed. Although water can be removed at various temperatures ranging from the initial dew point to the final saturation temperature, it is assumed that condensed water is cooled to the final air temperature t_2 before it drains from the system.

For the system in Figure 4, the steady-flow energy and material balance equations are

$$ \begin{aligned} \dot{m}_{da}h_1 &= \dot{m}_{da}h_2 + {}_1q_2 + \dot{m}_w h_{w2} \\ \dot{m}_{da}W_1 &= \dot{m}_{da}W_2 + \dot{m}_w \end{aligned} $$

Thus,

$$ \dot{m}_w = \dot{m}_{da}(W_1 - W_2) \qquad (44) $$

$$ {}_1q_2 = \dot{m}_{da}[(h_1 - h_2) - (W_1 - W_2)h_{w2}] \qquad (45) $$

Example 3. Moist air at 30°C dry-bulb temperature and 50% rh enters a cooling coil at 5 m^3/s and is processed to a final saturation condition at 10°C. Find the kW of refrigeration required.

Solution: Figure 5 shows the schematic solution. State 1 is located at the intersection of t = 30°C and ϕ = 50%. Thus, $h_1 = 64.3$ kJ/kg_{da}, $W_1 = 13.3$ g_w/kg_{da}, and $v_1 = 0.877$ m^3/kg_{da}. State 2 is located on the saturation curve at 10°C. Thus, $h_2 = 29.5$ kJ/kg_{da} and $W_2 = 7.66$ g_w/kg_{da}. From Table 3, $h_{w2} = 42.02$ kJ/kg_w. The mass flow of dry air is

$$ \dot{m}_{da} = 5/0.877 = 5.70\ kg_{da}/s $$

From Equation (45),

$$ \begin{aligned} {}_1q_2 &= 5.70[(64.3 - 29.5) - (0.0133 - 0.00766)42.02] \\ &= 197\ kW \end{aligned} $$

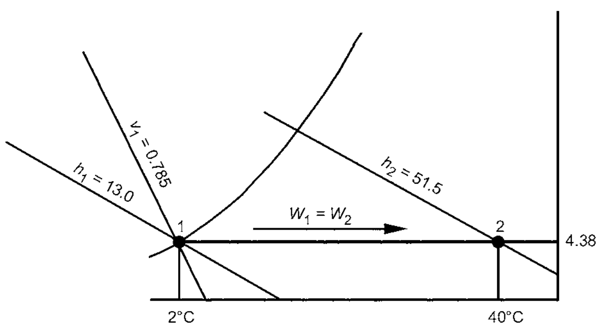

Fig. 4 Schematic Solution for Example 2

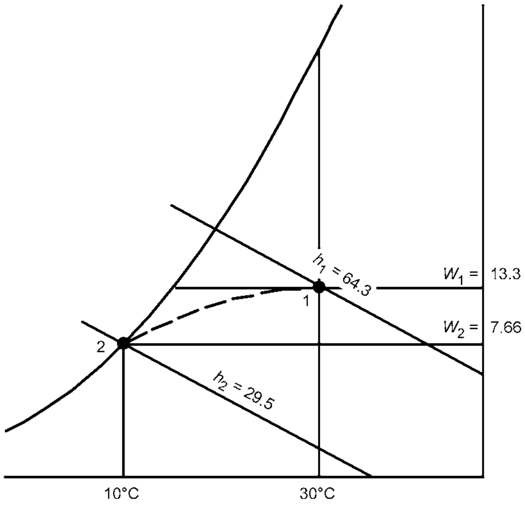

Fig. 5 Schematic Solution for Example 3

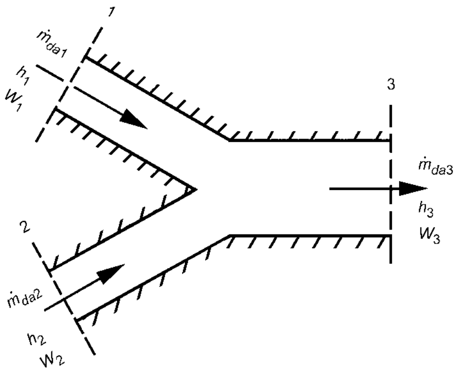

Fig. 6 Adiabatic Mixing of Two Moist Airstreams

Adiabatic Mixing of Two Moist Airstreams

A common process in air-conditioning systems is the adiabatic mixing of two moist airstreams. Figure 6 schematically shows the problem. Adiabatic mixing is governed by three equations:

$$\begin{aligned} \dot{m}_{da1}h_1 + \dot{m}_{da2}h_2 &= \dot{m}_{da3}h_3 \\ \dot{m}_{da1} + \dot{m}_{da2} &= \dot{m}_{da3} \\ \dot{m}_{da1}W_1 + \dot{m}_{da2}W_2 &= \dot{m}_{da3}W_3 \end{aligned}$$

Eliminating $\dot{m}_{da3}$ gives

$$\frac{h_2 - h_3}{h_3 - h_1} = \frac{W_2 - W_3}{W_3 - W_1} = \frac{\dot{m}_{da1}}{\dot{m}_{da2}} \tag{46}$$

according to which, on the ASHRAE chart, the state point of the resulting mixture lies on the straight line connecting the state points of the two streams being mixed, and divides the line into two segments, in the same ratio as the masses of dry air in the two streams.

Example 4. A stream of 2 m^3/s of outdoor air at 4°C dry-bulb temperature and 2°C thermodynamic wet-bulb temperature is adiabatically mixed with 6.25 m^3/s of recirculated air at 25°C dry-bulb temperature and 50% rh. Find the dry-bulb temperature and thermodynamic wet-bulb temperature of the resulting mixture.

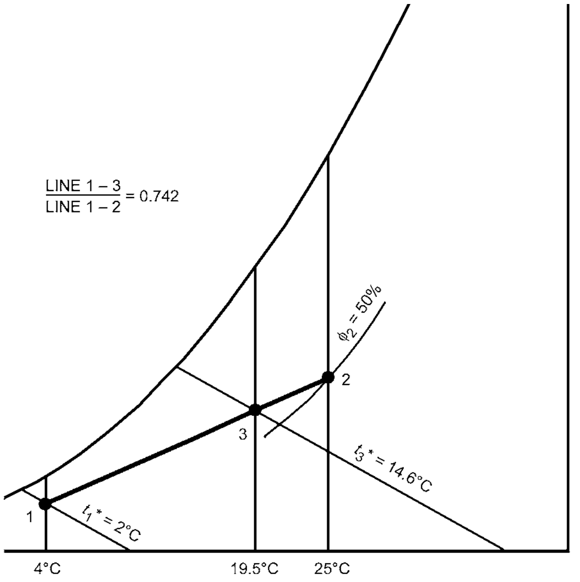

Fig. 7 Schematic Solution for Example 4

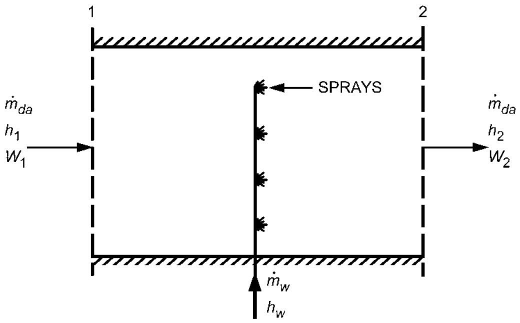

Fig. 8 Schematic Showing Injection of Water into Moist Air

Solution: Figure 7 shows the schematic solution. States 1 and 2 are located on the ASHRAE chart: v_1 = 0.789 m^3/kg_{da}, and v_2 = 0.858 m^3/kg_{da}. Therefore,

$$\dot{m}_{da1} = 2/0.789 = 2.535 \text{ kg}_{da}/\text{s}$$

$$\dot{m}_{da2} = 6.25/0.858 = 7.284 \text{ kg}_{da}/\text{s}$$

According to Equation (46),

$$\frac{\text{Line 3–2}}{\text{Line 1–3}} = \frac{\dot{m}_{da1}}{\dot{m}_{da2}} \text{ or } \frac{\text{Line 1–3}}{\text{Line 1–2}} = \frac{\dot{m}_{da2}}{\dot{m}_{da3}} = \frac{7.284}{9.819} = 0.742$$

Consequently, the length of line segment 1-3 is 0.742 times the length of entire line 1-2. Using a ruler, state 3 is located, and the values t_3 = 19.5°C and t_3^* = 14.6°C found.

Adiabatic Mixing of Water Injected into Moist Air

Steam or liquid water can be injected into a moist airstream to raise its humidity, as shown in Figure 8. If mixing is adiabatic, the following equations apply:

$$\begin{aligned} \dot{m}_{da}h_1 + \dot{m}_w h_w &= \dot{m}_{da}h_2 \\ \dot{m}_{da}W_1 + \dot{m}_w &= \dot{m}_{da}W_2 \end{aligned}$$

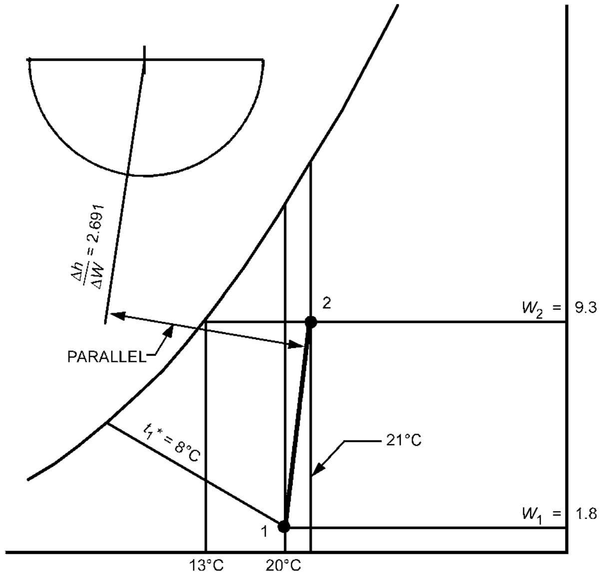

Fig. 9 Schematic Solution for Example 5

Therefore,

$$\frac{h_2 - h_1}{W_2 - W_1} = \frac{\Delta h}{\Delta W} = h_w \tag{47}$$

according to which, on the ASHRAE chart, the final state point of the moist air lies on a straight line in the direction fixed by the specific enthalpy of the injected water, drawn through the initial state point of the moist air.

Example 5. Moist air at 20°C dry-bulb and 8°C thermodynamic wet-bulb temperature is to be processed to a final dew-point temperature of 13°C by adiabatic injection of saturated steam at 110°C. The rate of dry airflow is 2 kg_{da}/s. Find the final dry-bulb temperature of the moist air and the rate of steam flow.

Solution: Figure 9 shows the schematic solution. By Table 3, the enthalpy of the steam h_g = 2691.07 kJ/kg_w. Therefore, according to Equation (47), the condition line on the ASHRAE chart connecting states 1 and 2 must have a direction:

$$\Delta h/\Delta W = 2.691 \text{ kJ/g}_w$$

The condition line can be drawn with the $\Delta h/\Delta W$ protractor. First, establish the reference line on the protractor by connecting the origin with the value $\Delta h/\Delta W$ = 2.691 kJ/g_w. Draw a second line parallel to the reference line and through the initial state point of the moist air. This second line is the condition line. State 2 is established at the intersection of the condition line with the horizontal line extended from the saturation curve at 13°C (t_{d2} = 13°C). Thus, t_2 = 21°C.

Values of W_2 and W_1 can be read from the chart. The required steam flow is

$$\dot{m}_w = \dot{m}_{da}(W_2 - W_1) = 2 \times 1000(0.0093 - 0.0018)$$
$$= 15.0 \text{ g}_w\text{/s, or } 0.015 \text{ kg}_w\text{/s}$$

Space Heat Absorption and Moist Air Moisture Gains

Air conditioning required for a space is usually determined by (1) the quantity of moist air to be supplied, and (2) the supply air condition necessary to remove given amounts of energy and water from the space at the exhaust condition specified.

Figure 10 shows a space with incident rates of energy and moisture gains. The quantity q_s denotes the net sum of all rates of heat gain in the space, arising from transfers through boundaries and from sources within the space. This heat gain involves energy addition alone and does not include energy contributions from

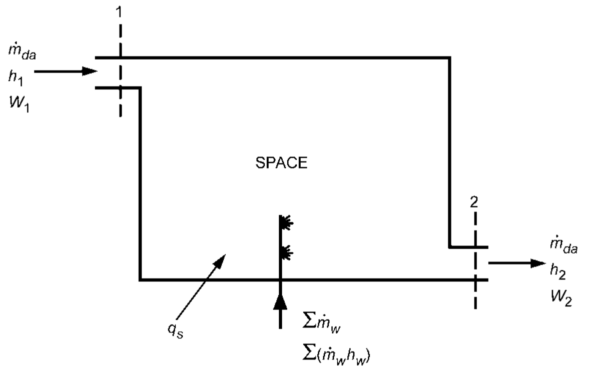

Fig. 10 Schematic of Air Conditioned Space

water (or water vapor) addition. It is usually called the **sensible heat gain**. The quantity $\Sigma\dot{m}_w$ denotes the net sum of all rates of moisture gain on the space arising from transfers through boundaries and from sources within the space. Each kilogram of water vapor added to the space adds an amount of energy equal to its specific enthalpy.

Assuming steady-state conditions, governing equations are

$$\dot{m}_{da}h_1 + q_s + \sum(\dot{m}_w h_w) = \dot{m}_{da}h_2$$

$$\dot{m}_{da}W_1 + \sum\dot{m}_w = \dot{m}_{da}W_2$$

or

$$q_s + \sum(\dot{m}_w h_w) = \dot{m}_{da}(h_2 - h_1) \tag{48}$$

$$\sum\dot{m}_w = \dot{m}_{da}(W_2 - W_1) \tag{49}$$

The left side of Equation (48) represents the total rate of energy addition to the space from all sources. By Equations (48) and (49),

$$\frac{h_2 - h_1}{W_2 - W_1} = \frac{\Delta h}{\Delta W} = \frac{q_s + \sum(\dot{m}_w h_w)}{\sum\dot{m}_w} \tag{50}$$

according to which, on the ASHRAE chart and for a given state of withdrawn air, all possible states (conditions) for supply air must lie on a straight line drawn through the state point of withdrawn air, with its direction specified by the numerical value of $[q_s + \Sigma(\dot{m}_w h_w)]/\Sigma\dot{m}_w$. This line is the condition line for the given problem.

Example 6. Moist air is withdrawn from a room at 25°C dry-bulb temperature and 19°C thermodynamic wet-bulb temperature. The sensible rate of heat gain for the space is 9 kW. A rate of moisture gain of 0.0015 kg_w/s occurs from the space occupants. This moisture is assumed as saturated water vapor at 30°C. Moist air is introduced into the room at a dry-bulb temperature of 15°C. Find the required thermodynamic wet-bulb temperature and volume flow rate of the supply air.

Solution: Figure 11 shows the schematic solution. State 2 is located on the ASHRAE chart. From Table 3, the specific enthalpy of the added water vapor is h_g = 2555.58 kJ/kg_w. From Equation (50),

$$\frac{\Delta h}{\Delta W} = \frac{9 + (0.0015 \times 2555.58)}{0.0015} = 8555 \text{ kJ/kg}_w$$

With the $\Delta h/\Delta W$ protractor, establish a reference line of direction $\Delta h/\Delta W$ = 8.555 kJ/g_w. Parallel to this reference line, draw a straight

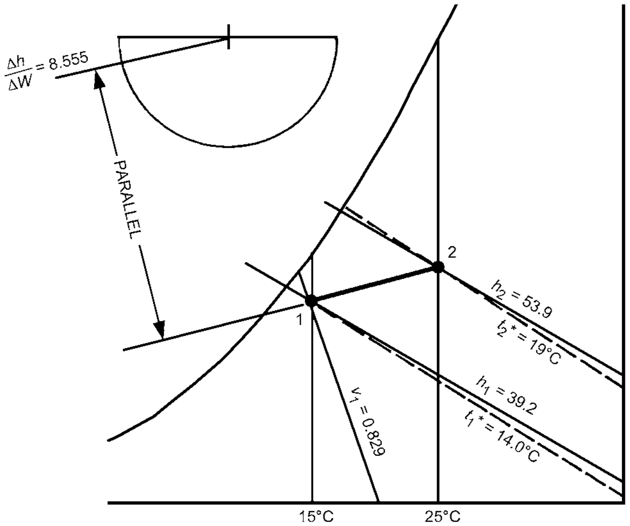

Fig. 11 Schematic Solution for Example 6

line on the chart through state 2. The intersection of this line with the 15°C dry-bulb temperature line is state 1. Thus, t_1^* = 14.0°C.

An alternative (and approximately correct) procedure in establishing the condition line is to use the protractor's sensible/total heat ratio scale instead of the $\Delta h/\Delta W$ scale. The quantity $\Delta H_s/\Delta H_t$ is the ratio of rate of sensible heat gain for the space to rate of total energy gain for the space. Therefore,

$$\frac{\Delta H_s}{\Delta H_t} = \frac{q_s}{q_s + \Sigma(\dot{m}_w h_w)} = \frac{9}{9 + (0.0015 \times 2555.58)} = 0.701$$

Note that $\Delta H_s/\Delta H_t$ = 0.701 on the protractor coincides closely with $\Delta h/\Delta W$ = 8.555 kJ/g$_w$.

The flow of dry air can be calculated from either Equation (48) or (49). From Equation (48),

$$\dot{m}_{da} = \frac{q_s + \Sigma(\dot{m}_w h_w)}{h_2 - h_1} = \frac{9 + (0.0015 \times 2555.58)}{53.9 - 39.2}$$
$$= 0.873 \text{ kg/s}$$

At state 1, v_1 = 0.829 m^3/kg$_{da}$.

Therefore, supply volume = $\dot{m}_{da} v_1$ = 0.873 × 0.829 = 0.724 m^3/s.

TRANSPORT PROPERTIES OF MOIST AIR

For certain scientific and experimental work, particularly in the heat transfer field, many other moist air properties are important. Generally classified as transport properties, these include diffusion coefficient, viscosity, thermal conductivity, and thermal diffusion factor. Mason and Monchick (1965) derive these properties by calculation. Table 4 and Figures 12 and 13 summarize the authors' results on the first three properties listed. Note that, within the boundaries of ASHRAE psychrometric charts 1, 2, and 3, viscosity varies little from that of dry air at normal atmospheric pressure, and thermal conductivity is essentially independent of moisture content.

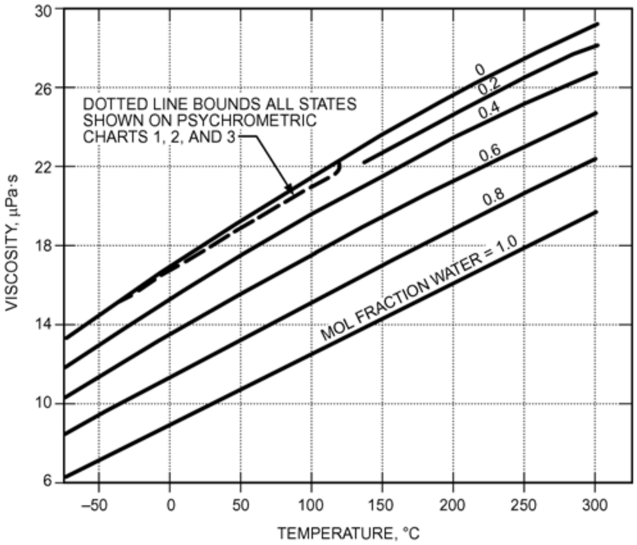

Fig. 12 Viscosity of Moist Air

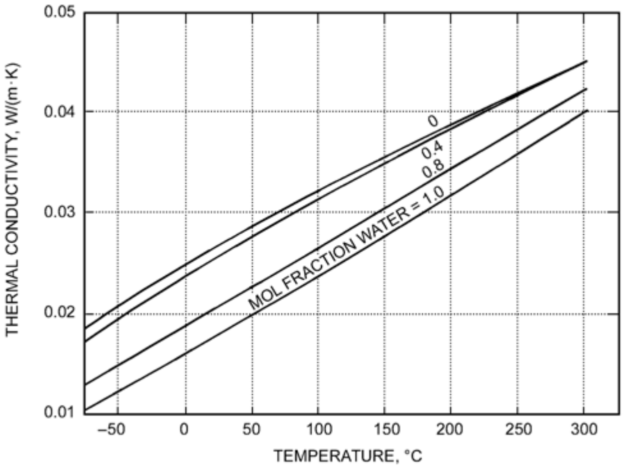

Fig. 13 Thermal Conductivity of Moist Air

Table 4 Calculated Diffusion Coefficients for Water/Air at 101.325 kPa

Temp., °C	mm²/s	Temp., °C	mm²/s	Temp., °C	mm²/s
–70	13.2	0	22.2	50	29.5
–50	15.6	5	22.9	55	30.3
–40	16.9	10	23.6	60	31.1
–35	17.5	15	24.3	70	32.7
–30	18.2	20	25.1	100	37.6
–25	18.8	25	25.8	130	42.8
–20	19.5	30	26.5	160	48.3
–15	20.2	35	27.3	190	54.0
–10	20.8	40	28.0	220	60.0
–5	21.5	45	28.8	250	66.3

SYMBOLS

C_1 to C_{18} = constants in Equations (5), (6), and (39)
d_v = absolute humidity of moist air, mass of water per unit volume of mixture, kg$_w$/m^3
h = specific enthalpy of moist air, kJ/kg$_{da}$
H_s = rate of sensible heat gain for space, kW
h_s^* = specific enthalpy of saturated moist air at thermodynamic wet-bulb temperature, kJ/kg$_{da}$
H_t = rate of total energy gain for space, kW
h_w^* = specific enthalpy of condensed water (liquid or solid) at thermodynamic wet-bulb temperature and a pressure of 101.325 kPa, kJ/kg$_w$
M_{da} = mass of dry air in moist air sample, kg$_{da}$
$\dot{m}_{da}$ = mass flow of dry air, per unit time, kg$_{da}$/s
M_w = mass of water vapor in moist air sample, kg$_w$

$\dot{m}_w$ = mass flow of water (any phase), per unit time, kg_w/s
n = $n_{da} + n_w$, total number of moles in moist air sample
n_{da} = moles of dry air
n_w = moles of water vapor
p = total pressure of moist air, kPa
p_{da} = partial pressure of dry air, kPa
p_s = vapor pressure of water in moist air at saturation, kPa. Differs slightly from saturation pressure of pure water because of presence of air.
p_w = partial pressure of water vapor in moist air, kPa
p_{ws} = pressure of saturated pure water, kPa
q_s = rate of addition (or withdrawal) of sensible heat, kW
R = universal gas constant, 8314.472 J/(kg mole·K)
R_{da} = gas constant for dry air, $kJ/(kg_{da}\cdot K)$
R_w = gas constant for water vapor, $kJ/(kg_w\cdot K)$
s = specific entropy, $kJ/(kg_{da}\cdot K)$ or $kJ/(kg_w\cdot K)$
T = absolute temperature, K
t = dry-bulb temperature of moist air, °C
t_d = dew-point temperature of moist air, °C
t^* = thermodynamic wet-bulb temperature of moist air, °C
V = total volume of moist air sample, m^3
v = specific volume, m^3/kg_{da} or m^3/kg_w
v_T = total gas volume, m^3
W = humidity ratio of moist air, kg_w/kg_{da} or g_w/kg_{da}
W_s^* = humidity ratio of moist air at saturation at thermodynamic wet-bulb temperature, kg_w/kg_{da} or g_w/kg_{da}
x_{da} = mole fraction of dry air, moles of dry air per mole of mixture
x_w = mole fraction of water, moles of water per mole of mixture
x_{ws} = mole fraction of water vapor under saturated conditions, moles of vapor per mole of saturated mixture
Z = altitude, m

Greek

α = $\ln(p_w)$, parameter used in Equations (39) and (40)
γ = specific humidity of moist air, mass of water per unit mass of mixture
μ = degree of saturation W/W_s, dimensionless
ρ = moist air density
ϕ = relative humidity, dimensionless

Subscripts

as = difference between saturated moist air and dry air
da = dry air
f = saturated liquid water
fg = difference between saturated liquid water and saturated water vapor
g = saturated water vapor
i = saturated ice
ig = difference between saturated ice and saturated water vapor
s = saturated moist air
t = total
w = water in any phase

REFERENCES

Gatley, D.P. 2013. *Understanding psychrometrics*, 3rd ed. ASHRAE.

Gatley, D.P., S. Herrmann, and H.J. Kretzschmar. 2008. A twenty-first century molar mass for dry air. *HVAC&R Research* 14:655-662.

Goff, J.A. 1949. Standardization of thermodynamic properties of moist air. *Heating, Piping, and Air Conditioning* 21(11):118-128.

Goff, J.A., and S. Gratch. 1945. Thermodynamic properties of moist air. *ASHVE Transactions* 51:125.

Haines, R.W. 1961. How to construct high altitude psychrometric charts. *Heating, Piping, and Air Conditioning* 33(10):144.

Harrison, L.P. 1965. Fundamental concepts and definitions relating to humidity. In *Humidity and moisture measurement and control in science and industry*, vol. 3. A. Wexler and W.A. Wildhack, eds. Reinhold, New York.

Herrmann, S., H.J. Kretzschmar, and D.P. Gatley. 2009. Thermodynamic properties of real moist air, dry air, steam, water, and ice. *HVAC&R Research* (forthcoming).

Hyland, R.W., and A. Wexler. 1983a. Formulations for the thermodynamic properties of dry air from 173.15 K to 473.15 K, and of saturated moist air from 173.15 K to 372.15 K, at pressures to 5 MPa. *ASHRAE Transactions* 89(2A):520-535.

Hyland, R.W., and A. Wexler. 1983b. Formulations for the thermodynamic properties of the saturated phases of H_2O from 173.15 K to 473.15 K. *ASHRAE Transactions* 89(2A):500-519.

IAPWS. 2007. *Revised release on the IAPWS industrial formulation 1997 for the thermodynamic properties of water and steam*. International Association for the Properties of Water and Steam, Oakville, ON, Canada.

IAPWS. 2008. *Revised release on the pressure along the melting and sublimation curves of ordinary water substance*. International Association for the Properties of Water and Steam, Oakville, ON, Canada.

Karig, H.E. 1946. Psychrometric charts for high altitude calculations. *Refrigerating Engineering* 52(11):433.

Keeling, C.D., and T.P. Whorf. 2005a. *Atmospheric carbon dioxide record from Mauna Loa*. Scripps Institution of Oceanography—CO_2 Research Group. (Available at http://cdiac.ornl.gov/trends/co2/sio-mlo.html)

Keeling, C.D., and T.P. Whorf. 2005b. Atmospheric CO_2 records from sites in the SIO air sampling network. *Trends: A compendium of data on global change.* Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory.

Kuehn, T.H., J.W. Ramsey, and J.L. Threlkeld. 1998. *Thermal environmental engineering*, 3rd ed. Prentice-Hall, Upper Saddle River, NJ.

Mason, E.A., and L. Monchick. 1965. Survey of the equation of state and transport properties of moist gases. In *Humidity and moisture measurement and control in science and industry*, vol. 3. A. Wexler and W.A. Wildhack, eds. Reinhold, New York.

Mohr, P.J., and P.N. Taylor. 2005. CODATA recommended values of the fundamental physical constants: 2002. *Reviews of Modern Physics* 77:1-107.

NASA. 1976. U.S. Standard atmosphere, 1976. National Oceanic and Atmospheric Administration, National Aeronautics and Space Administration, and the United States Air Force. Available from National Geophysical Data Center, Boulder, CO.

Nelson, H.F., and H.J. Sauer, Jr. 2002. Formulation of high-temperature properties for moist air. *International Journal of HVAC&R Research* 8(3):311-334.

Olivieri, J. 1996. *Psychrometrics—Theory and practice*. ASHRAE.

Palmatier, E.P. 1963. Construction of the normal temperature. ASHRAE psychrometric chart. *ASHRAE Journal* 5:55.

Peppers, V.W. 1988. *A new psychrometric relation for the dewpoint temperature.* Unpublished. Available from ASHRAE.

Preston-Thomas, H. 1990. The international temperature scale of 1990 (ITS-90). *Metrologia* 27(1):3-10.

Rohsenow, W.M. 1946. Psychrometric determination of absolute humidity at elevated pressures. *Refrigerating Engineering* 51(5):423.

BIBLIOGRAPHY

IAPWS. 1992. *Revised supplementary release on saturation properties of ordinary water system*. International Association for the Properties of Water and Steam, Oakville, ON, Canada.

IAPWS. 2006. *Release on an equation of state for H_2O ice Ih*. International Association for the Properties of Water and Steam, Oakville, ON, Canada.

Kusuda, T. 1970. Algorithms for psychrometric calculations. NBS *Publication* BSS21 (January) for sale by Superintendent of Documents, U.S. Government Printing Office, Washington, D.C.

Lemmon, E.W., R.T. Jacobsen, S.G. Penoncello, and D.G. Friend. 2000. Thermodynamic properties of air and mixture of nitrogen, argon, and oxygen from 60 to 2000 K at pressures to 2000 MPa. *Journal of Physical and Chemical Reference Data* 29:331-385.

NIST. 1990. Guidelines for realizing the international temperature scale of 1990 (ITS-90). NIST *Technical Note* 1265. National Institute of Technology and Standards, Gaithersburg, MD.