CHAPTER 6

PSYCHROMETRICS

PSYCHROMETRICS deals with the thermodynamic properties of moist air and uses these properties to analyze conditions and processes involving moist air.

Hyland and Wexler (1983a,b) developed formulas for thermodynamic properties of moist air and water. However, perfect gas relations can be used instead of these formulas 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.

This chapter discusses perfect gas relations and describes their use in common air-conditioning problems. The formulas developed by Hyland and Wexler (1983a) and discussed by Olivieri (1996) may be used where greater precision is required.

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 exists when all water vapor and contaminants have been removed from atmospheric air. The composition of dry air 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; carbon dioxide, 0.0314; 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. The relative molecular mass of all components for dry air is 28.9645, based on the carbon-12 scale (Harrison 1965). The gas constant for dry air, based on the carbon-12 scale, is

$$R_{da} = 8314.41/28.9645 = 287.055\ \mathrm{J/(kg\cdot K)} \qquad (1)$$

Moist air is a binary (two-component) mixture of dry air and water vapor. The amount of water vapor in moist air varies from zero (dry air) to a maximum that depends on temperature and pressure. The latter condition refers to **saturation**, a state of neutral equilibrium between moist air and the condensed water phase (liquid or solid). Unless otherwise stated, saturation refers to a flat interface surface between the moist air and the condensed phase. Saturation conditions will change when the interface radius is very small such as with ultrafine water droplets. The relative molecular mass of water is 18.01528 on the carbon-12 scale. The gas constant for water vapor is

$$R_w = 8314.41/18.01528 = 461.520\ \mathrm{J/(kg\cdot K)} \qquad (2)$$

UNITED STATES 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. The 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, $9.806\,65\ \mathrm{m/s^2}$. Table 1 summarizes property data for altitudes to 10 000 m.

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
1 500	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
7 000	−30.5	41.061
8 000	−37.0	35.600
9 000	−43.5	30.742
10 000	−50	26.436
12 000	−63	19.284
14 000	−76	13.786
16 000	−89	9.632
18 000	−102	6.556
20 000	−115	4.328

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

The 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 given as

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

where

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

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 can be found in NASA (1976).

THERMODYNAMIC PROPERTIES OF MOIST AIR

Table 2, developed from formulas by Hyland and Wexler (1983a,b), shows values of thermodynamic properties of **moist air** based on the **thermodynamic temperature scale**. 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 value of 100°C. Most measurements are currently based on the International Temperature Scale of 1990 (ITS-90) (Preston-Thomas 1990).

The following paragraphs briefly describe each column of Table 2:

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

$$T = t + 273.15$$

W_s = humidity ratio at saturation, condition at which 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 (dry air).
v_{as} = $v_s - v_{da}$, difference between specific volume of moist air at saturation and that of dry air itself, m^3/kg (dry air), at same pressure and temperature.
v_s = specific volume of moist air at saturation, m^3/kg (dry air).
h_{da} = specific enthalpy of dry air, kJ/kg (dry air). In Table 2, h_{da} has been 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 itself, kJ/kg (dry air), at same pressure and temperature.
h_s = specific enthalpy of moist air at saturation, kJ/kg (dry air).
s_{da} = specific entropy of dry air, kJ/(kg·K) (dry air). In Table 2, s_{da} has been assigned a value of 0 at 0°C and standard atmospheric pressure.
s_{as} = $s_s - s_{da}$, difference between specific entropy of moist air at saturation and that of dry air itself, kJ/(kg·K) (dry air), at same pressure and temperature.
s_s = specific entropy of moist air at saturation kJ/(kg·K) (dry air).
h_w = specific enthalpy of condensed water (liquid or solid) in equilibrium with saturated moist air at specified temperature and pressure, kJ/kg (water). In Table 2, h_w is assigned a value of 0 at its triple point (0.01°C) and saturation pressure.

Note that h_w is greater than the steam-table enthalpy of saturated pure condensed phase by the amount of enthalpy increase governed by the pressure increase from saturation pressure to 101.325 kPa, plus influences from presence of air.

s_w = specific entropy of condensed water (liquid or solid) in equilibrium with saturated air, kJ/(kg·K) (water); s_w differs from entropy of pure water at saturation pressure, similar to h_w.
p_s = vapor pressure of water in saturated moist air, kPa. Pressure p_s differs negligibly from saturation vapor pressure of pure water p_{ws} for conditions shown. Consequently, values of p_s can be used at same pressure and temperature in equations where p_{ws} appears. Pressure p_s is defined as $p_s = x_{ws}p$, where x_{ws} is mole fraction of water vapor in moist air saturated with water at temperature t and pressure p, and where p is total barometric pressure of moist air.

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 Hyland and Wexler (1983b). Symbols in the table follow standard steam table nomenclature. These properties are based on the thermodynamic temperature scale. The enthalpy 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—liquid and vapor—may coexist in equilibrium. These states are called **saturated liquid** and **saturated vapor**.

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

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

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

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

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),

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

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

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

Temp., °C	Humidity Ratio, kg(w)/kg(da)	Specific Volume, m^3/kg (dry air)			Specific Enthalpy, kJ/kg (dry air)			Specific Entropy, kJ/(kg · K) (dry air)			Condensed Water			Temp., °C
											Specific Enthalpy, kJ/kg	Specific Entropy, kJ/(kg·K)	Vapor Pressure, kPa	
t	W_s	v_{da}	v_{as}	v_s	h_{da}	h_{as}	h_s	s_{da}	s_{as}	s_s	h_w	s_w	p_s	t
–60	0.0000067	0.6027	0.0000	0.6027	–60.351	0.017	–60.334	–0.2495	0.0001	–0.2494	–446.29	–1.6854	0.00108	–60
–59	0.0000076	0.6056	0.0000	0.6056	–59.344	0.018	–59.326	–0.2448	0.0001	–0.2447	–444.63	–1.6776	0.00124	–59
–58	0.0000087	0.6084	0.0000	0.6084	–58.338	0.021	–58.317	–0.2401	0.0001	–0.2400	–442.95	–1.6698	0.00141	–58
–57	0.0000100	0.6113	0.0000	0.6113	–57.332	0.024	–57.308	–0.2354	0.0001	–0.2353	–441.27	–1.6620	0.00161	–57
–56	0.0000114	0.6141	0.0000	0.6141	–56.326	0.028	–56.298	–0.2308	0.0001	–0.2306	–439.58	–1.6542	0.00184	–56
–55	0.0000129	0.6170	0.0000	0.6170	–55.319	0.031	–55.288	–0.2261	0.0002	–0.2260	–437.89	–1.6464	0.00209	–55
–54	0.0000147	0.6198	0.0000	0.6198	–54.313	0.036	–54.278	–0.2215	0.0002	–0.2214	–436.19	–1.6386	0.00238	–54
–53	0.0000167	0.6226	0.0000	0.6227	–53.307	0.041	–53.267	–0.2170	0.0002	–0.2168	–434.48	–1.6308	0.00271	–53
–52	0.0000190	0.6255	0.0000	0.6255	–52.301	0.046	–52.255	–0.2124	0.0002	–0.2122	–432.76	–1.6230	0.00307	–52
–51	0.0000215	0.6283	0.0000	0.6284	–51.295	0.052	–51.243	–0.2079	0.0002	–0.2076	–431.03	–1.6153	0.00348	–51
–50	0.0000243	0.6312	0.0000	0.6312	–50.289	0.059	–50.230	–0.2033	0.0003	–0.2031	–429.30	–1.6075	0.00394	–50
–49	0.0000275	0.6340	0.0000	0.6341	–49.283	0.067	–49.216	–0.1988	0.0003	–0.1985	–427.56	–1.5997	0.00445	–49
–48	0.0000311	0.6369	0.0000	0.6369	–48.277	0.075	–48.202	–0.1944	0.0004	–0.1940	–425.82	–1.5919	0.00503	–48
–47	0.0000350	0.6397	0.0000	0.6398	–47.271	0.085	–47.186	–0.1899	0.0004	–0.1895	–424.06	–1.5842	0.00568	–47
–46	0.0000395	0.6426	0.0000	0.6426	–46.265	0.095	–46.170	–0.1855	0.0004	–0.1850	–422.30	–1.5764	0.00640	–46
–45	0.0000445	0.6454	0.0000	0.6455	–45.259	0.108	–45.151	–0.1811	0.0005	–0.1805	–420.54	–1.5686	0.00721	–45
–44	0.0000500	0.6483	0.0001	0.6483	–44.253	0.121	–44.132	–0.1767	0.0006	–0.1761	–418.76	–1.5609	0.00811	–44
–43	0.0000562	0.6511	0.0001	0.6512	–43.247	0.137	–43.111	–0.1723	0.0006	–0.1716	–416.98	–1.5531	0.00911	–43
–42	0.0000631	0.6540	0.0001	0.6540	–42.241	0.153	–42.088	–0.1679	0.0007	–0.1672	–415.19	–1.5453	0.01022	–42
–41	0.0000708	0.6568	0.0001	0.6569	–41.235	0.172	–41.063	–0.1636	0.0008	–0.1628	–413.39	–1.5376	0.01147	–41
–40	0.0000793	0.6597	0.0001	0.6597	–40.229	0.192	–40.037	–0.1592	0.0009	–0.1584	–411.59	–1.5298	0.01285	–40
–39	0.0000887	0.6625	0.0001	0.6626	–39.224	0.216	–39.007	–0.1549	0.0010	–0.1540	–409.77	–1.5221	0.01438	–39
–38	0.0000992	0.6653	0.0001	0.6654	–38.218	0.241	–37.976	–0.1507	0.0011	–0.1496	–407.96	–1.5143	0.01608	–38
–37	0.0001108	0.6682	0.0001	0.6683	–37.212	0.270	–36.942	–0.1464	0.0012	–0.1452	–406.13	–1.5066	0.01796	–37
–36	0.0001237	0.6710	0.0001	0.6712	–36.206	0.302	–35.905	–0.1421	0.0014	–0.1408	–404.29	–1.4988	0.02005	–36
–35	0.0001379	0.6739	0.0001	0.6740	–35.200	0.336	–34.864	–0.1379	0.0015	–0.1364	–402.45	–1.4911	0.02235	–35
–34	0.0001536	0.6767	0.0002	0.6769	–34.195	0.375	–33.820	–0.1337	0.0017	–0.1320	–400.60	–1.4833	0.02490	–34
–33	0.0001710	0.6796	0.0002	0.6798	–33.189	0.417	–32.772	–0.1295	0.0018	–0.1276	–398.75	–1.4756	0.02772	–33
–32	0.0001902	0.6824	0.0002	0.6826	–32.183	0.464	–31.718	–0.1253	0.0020	–0.1233	–396.89	–1.4678	0.03082	–32
–31	0.0002113	0.6853	0.0002	0.6855	–31.178	0.517	–30.661	–0.1212	0.0023	–0.1189	–395.01	–1.4601	0.03425	–31
–30	0.0002346	0.6881	0.0003	0.6884	–30.171	0.574	–29.597	–0.1170	0.0025	–0.1145	–393.14	–1.4524	0.03802	–30
–29	0.0002602	0.6909	0.0003	0.6912	–29.166	0.636	–28.529	–0.1129	0.0028	–0.1101	–391.25	–1.4446	0.04217	–29
–28	0.0002883	0.6938	0.0003	0.6941	–28.160	0.707	–27.454	–0.1088	0.0031	–0.1057	–389.36	–1.4369	0.04673	–28
–27	0.0003193	0.6966	0.0004	0.6970	–27.154	0.782	–26.372	–0.1047	0.0034	–0.1013	–387.46	–1.4291	0.05175	–27
–26	0.0003533	0.6995	0.0004	0.6999	–26.149	0.867	–25.282	–0.1006	0.0037	–0.0969	–385.55	–1.4214	0.05725	–26
–25	0.0003905	0.7023	0.0004	0.7028	–25.143	0.959	–24.184	–0.0965	0.0041	–0.0924	–383.63	–1.4137	0.06329	–25
–24	0.0004314	0.7052	0.0005	0.7057	–24.137	1.059	–23.078	–0.0925	0.0045	–0.0880	–381.71	–1.4059	0.06991	–24
–23	0.0004762	0.7080	0.0005	0.7086	–23.132	1.171	–21.961	–0.0885	0.0050	–0.0835	–379.78	–1.3982	0.07716	–23
–22	0.0005251	0.7109	0.0006	0.7115	–22.126	1.292	–20.834	–0.0845	0.0054	–0.0790	–377.84	–1.3905	0.08510	–22
–21	0.0005787	0.7137	0.0007	0.7144	–21.120	1.425	–19.695	–0.0805	0.0060	–0.0745	–375.90	–1.3828	0.09378	–21
–20	0.0006373	0.7165	0.0007	0.7173	–20.115	1.570	–18.545	–0.0765	0.0066	–0.0699	–373.95	–1.3750	0.10326	–20
–19	0.0007013	0.7194	0.0008	0.7202	–19.109	1.729	–17.380	–0.0725	0.0072	–0.0653	–371.99	–1.3673	0.11362	–19
–18	0.0007711	0.7222	0.0009	0.7231	–18.103	1.902	–16.201	–0.0686	0.0079	–0.0607	–370.02	–1.3596	0.12492	–18
–17	0.0008473	0.7251	0.0010	0.7261	–17.098	2.092	–15.006	–0.0646	0.0086	–0.0560	–368.04	–1.3518	0.13725	–17
–16	0.0009303	0.7279	0.0011	0.7290	–16.092	2.299	–13.793	–0.0607	0.0094	–0.0513	–366.06	–1.3441	0.15068	–16
–15	0.0010207	0.7308	0.0012	0.7320	–15.086	2.524	–12.562	–0.0568	0.0103	–0.0465	–364.07	–1.3364	0.16530	–15
–14	0.0011191	0.7336	0.0013	0.7349	–14.080	2.769	–11.311	–0.0529	0.0113	–0.0416	–362.07	–1.3287	0.18122	–14
–13	0.0012262	0.7364	0.0014	0.7379	–13.075	3.036	–10.039	–0.0490	0.0123	–0.0367	–360.07	–1.3210	0.19852	–13
–12	0.0013425	0.7393	0.0016	0.7409	–12.069	3.327	–8.742	–0.0452	0.0134	–0.0318	–358.06	–1.3132	0.21732	–12
–11	0.0014690	0.7421	0.0017	0.7439	–11.063	3.642	–7.421	–0.0413	0.0146	–0.0267	–356.04	–1.3055	0.23775	–11
–10	0.0016062	0.7450	0.0019	0.7469	–10.057	3.986	–6.072	–0.0375	0.0160	–0.0215	–354.01	–1.2978	0.25991	–10
–9	0.0017551	0.7478	0.0021	0.7499	–9.052	4.358	–4.693	–0.0337	0.0174	–0.0163	–351.97	–1.2901	0.28395	–9
–8	0.0019166	0.7507	0.0023	0.7530	–8.046	4.764	–3.283	–0.0299	0.0189	–0.0110	–349.93	–1.2824	0.30999	–8
–7	0.0020916	0.7535	0.0025	0.7560	–7.040	5.202	–1.838	–0.0261	0.0206	–0.0055	–347.88	–1.2746	0.33821	–7
–6	0.0022811	0.7563	0.0028	0.7591	–6.035	5.677	–0.357	–0.0223	0.0224	–0.0000	–345.82	–1.2669	0.36874	–6
–5	0.0024862	0.7592	0.0030	0.7622	–5.029	6.192	1.164	–0.0186	0.0243	–0.0057	–343.76	–1.2592	0.40178	–5
–4	0.0027081	0.7620	0.0033	0.7653	–4.023	6.751	2.728	–0.0148	0.0264	–0.0115	–341.69	–1.2515	0.43748	–4
–3	0.0029480	0.7649	0.0036	0.7685	–3.017	7.353	4.336	–0.0111	0.0286	–0.0175	–339.61	–1.2438	0.47606	–3
–2	0.0032074	0.7677	0.0039	0.7717	–2.011	8.007	5.995	–0.0074	0.0310	–0.0236	–337.52	–1.2361	0.51773	–2
–1	0.0034874	0.7705	0.0043	0.7749	–1.006	8.712	7.706	–0.0037	0.0336	–0.0299	–335.42	–1.2284	0.56268	–1
0	0.0037895	0.7734	0.0047	0.7781	0.000	9.473	9.473	0.0000	0.0364	0.0364	–333.32	–1.2206	0.61117	0
0*	0.003789	0.7734	0.0047	0.7781	0.000	9.473	9.473	0.0000	0.0364	0.0364	0.06	–0.0001	0.6112	0
1	0.004076	0.7762	0.0051	0.7813	1.006	10.197	11.203	0.0037	0.0391	0.0427	4.28	0.0153	0.6571	1
2	0.004381	0.7791	0.0055	0.7845	2.012	10.970	12.982	0.0073	0.0419	0.0492	8.49	0.0306	0.7060	2
3	0.004707	0.7819	0.0059	0.7878	3.018	11.793	14.811	0.0110	0.0449	0.0559	12.70	0.0459	0.7581	3
4	0.005054	0.7848	0.0064	0.7911	4.024	12.672	16.696	0.0146	0.0480	0.0627	16.91	0.0611	0.8135	4
5	0.005424	0.7876	0.0068	0.7944	5.029	13.610	18.639	0.0182	0.0514	0.0697	21.12	0.0762	0.8725	5
6	0.005818	0.7904	0.0074	0.7978	6.036	14.608	20.644	0.0219	0.0550	0.0769	25.32	0.0913	0.9353	6
7	0.006237	0.7933	0.0079	0.8012	7.041	15.671	22.713	0.0255	0.0588	0.0843	29.52	0.1064	1.0020	7
8	0.006683	0.7961	0.0085	0.8046	8.047	16.805	24.852	0.0290	0.0628	0.0919	33.72	0.1213	1.0729	8
9	0.007157	0.7990	0.0092	0.8081	9.053	18.010	27.064	0.0326	0.0671	0.0997	37.92	0.1362	1.1481	9
10	0.007661	0.8018	0.0098	0.8116	10.059	19.293	29.352	0.0362	0.0717	0.1078	42.11	0.1511	1.2280	10
11	0.008197	0.8046	0.0106	0.8152	11.065	20.658	31.724	0.0397	0.0765	0.1162	46.31	0.1659	1.3128	11
12	0.008766	0.8075	0.0113	0.8188	12.071	22.108	34.179	0.0433	0.0816	0.1248	50.50	0.1806	1.4026	12
13	0.009370	0.8103	0.0122	0.8225	13.077	23.649	36.726	0.0468	0.0870	0.1337	54.69	0.1953	1.4979	13

*Extrapolated to represent metastable equilibrium with undercooled liquid.

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

Temp., °C	Humidity Ratio, kg(w)/kg(da)	Specific Volume, m^3/kg (dry air)			Specific Enthalpy, kJ/kg (dry air)			Specific Entropy, kJ/(kg · K) (dry air)			Condensed Water			Temp., °C
											Specific Enthalpy, kJ/kg	Specific Entropy, kJ/(kg·K)	Vapor Pressure, kPa	
t	W_s	v_{da}	v_{as}	v_s	h_{da}	h_{as}	h_s	s_{da}	s_{as}	s_s	h_w	s_w	p_s	t
14	0.010012	0.8132	0.0131	0.8262	14.084	25.286	39.370	0.0503	0.0927	0.1430	58.88	0.2099	1.5987	14
15	0.010692	0.8160	0.0140	0.8300	15.090	27.023	42.113	0.0538	0.0987	0.1525	63.07	0.2244	1.7055	15
16	0.011413	0.8188	0.0150	0.8338	16.096	28.867	44.963	0.0573	0.1051	0.1624	67.26	0.2389	1.8185	16
17	0.012178	0.8217	0.0160	0.8377	17.102	30.824	47.926	0.0607	0.1119	0.1726	71.44	0.2534	1.9380	17
18	0.012989	0.8245	0.0172	0.8417	18.108	32.900	51.008	0.0642	0.1190	0.1832	75.63	0.2678	2.0643	18
19	0.013848	0.8274	0.0184	0.8457	19.114	35.101	54.216	0.0677	0.1266	0.1942	79.81	0.2821	2.1979	19
20	0.014758	0.8302	0.0196	0.8498	20.121	37.434	57.555	0.0711	0.1346	0.2057	84.00	0.2965	2.3389	20
21	0.015721	0.8330	0.0210	0.8540	21.127	39.908	61.035	0.0745	0.1430	0.2175	88.18	0.3107	2.4878	21
22	0.016741	0.8359	0.0224	0.8583	22.133	42.527	64.660	0.0779	0.1519	0.2298	92.36	0.3249	2.6448	22
23	0.017821	0.8387	0.0240	0.8627	23.140	45.301	68.440	0.0813	0.1613	0.2426	96.55	0.3390	2.8105	23
24	0.018963	0.8416	0.0256	0.8671	24.146	48.239	72.385	0.0847	0.1712	0.2559	100.73	0.3531	2.9852	24
25	0.020170	0.8444	0.0273	0.8717	25.153	51.347	76.500	0.0881	0.1817	0.2698	104.91	0.3672	3.1693	25
26	0.021448	0.8472	0.0291	0.8764	26.159	54.638	80.798	0.0915	0.1927	0.2842	109.09	0.3812	3.3633	26
27	0.022798	0.8501	0.0311	0.8811	27.165	58.120	85.285	0.0948	0.2044	0.2992	113.27	0.3951	3.5674	27
28	0.024226	0.8529	0.0331	0.8860	28.172	61.804	89.976	0.0982	0.2166	0.3148	117.45	0.4090	3.7823	28
29	0.025735	0.8558	0.0353	0.8910	29.179	65.699	94.878	0.1015	0.2296	0.3311	121.63	0.4229	4.0084	29
30	0.027329	0.8586	0.0376	0.8962	30.185	69.820	100.006	0.1048	0.2432	0.3481	125.81	0.4367	4.2462	30
31	0.029014	0.8614	0.0400	0.9015	31.192	74.177	105.369	0.1082	0.2576	0.3658	129.99	0.4505	4.4961	31
32	0.030793	0.8643	0.0426	0.9069	32.198	78.780	110.979	0.1115	0.2728	0.3842	134.17	0.4642	4.7586	32
33	0.032674	0.8671	0.0454	0.9125	33.205	83.652	116.857	0.1148	0.2887	0.4035	138.35	0.4779	5.0345	33
34	0.034660	0.8700	0.0483	0.9183	34.212	88.799	123.011	0.1180	0.3056	0.4236	142.53	0.4915	5.3242	34
35	0.036756	0.8728	0.0514	0.9242	35.219	94.236	129.455	0.1213	0.3233	0.4446	146.71	0.5051	5.6280	35
36	0.038971	0.8756	0.0546	0.9303	36.226	99.983	136.209	0.1246	0.3420	0.4666	150.89	0.5186	5.9468	36
37	0.041309	0.8785	0.0581	0.9366	37.233	106.058	143.290	0.1278	0.3617	0.4895	155.07	0.5321	6.2812	37
38	0.043778	0.8813	0.0618	0.9431	38.239	112.474	150.713	0.1311	0.3824	0.5135	159.25	0.5456	6.6315	38
39	0.046386	0.8842	0.0657	0.9498	39.246	119.258	158.504	0.1343	0.4043	0.5386	163.43	0.5590	6.9988	39
40	0.049141	0.8870	0.0698	0.9568	40.253	126.430	166.683	0.1375	0.4273	0.5649	167.61	0.5724	7.3838	40
41	0.052049	0.8898	0.0741	0.9640	41.261	134.005	175.265	0.1407	0.4516	0.5923	171.79	0.5857	7.7866	41
42	0.055119	0.8927	0.0788	0.9714	42.268	142.007	184.275	0.1439	0.4771	0.6211	175.97	0.5990	8.2081	42
43	0.058365	0.8955	0.0837	0.9792	43.275	150.475	193.749	0.1471	0.5041	0.6512	180.15	0.6122	8.6495	43
44	0.061791	0.8983	0.0888	0.9872	44.282	159.417	203.699	0.1503	0.5325	0.6828	184.33	0.6254	9.1110	44
45	0.065411	0.9012	0.0943	0.9955	45.289	168.874	214.164	0.1535	0.5624	0.7159	188.51	0.6386	9.5935	45
46	0.069239	0.9040	0.1002	1.0042	46.296	178.882	225.179	0.1566	0.5940	0.7507	192.69	0.6517	10.0982	46
47	0.073282	0.9069	0.1063	1.0132	47.304	189.455	236.759	0.1598	0.6273	0.7871	196.88	0.6648	10.6250	47
48	0.077556	0.9097	0.1129	1.0226	48.311	200.644	248.955	0.1629	0.6624	0.8253	201.06	0.6778	11.1754	48
49	0.082077	0.9125	0.1198	1.0323	49.319	212.485	261.803	0.1661	0.6994	0.8655	205.24	0.6908	11.7502	49
50	0.086858	0.9154	0.1272	1.0425	50.326	225.019	275.345	0.1692	0.7385	0.9077	209.42	0.7038	12.3503	50
51	0.091918	0.9182	0.1350	1.0532	51.334	238.290	289.624	0.1723	0.7798	0.9521	213.60	0.7167	12.9764	51
52	0.097272	0.9211	0.1433	1.0643	52.341	252.340	304.682	0.1754	0.8234	0.9988	217.78	0.7296	13.6293	52
53	0.102948	0.9239	0.1521	1.0760	53.349	267.247	320.596	0.1785	0.8695	1.0480	221.97	0.7424	14.3108	53
54	0.108954	0.9267	0.1614	1.0882	54.357	283.031	337.388	0.1816	0.9182	1.0998	226.15	0.7552	15.0205	54
55	0.115321	0.9296	0.1713	1.1009	55.365	299.772	355.137	0.1847	0.9698	1.1544	230.33	0.7680	15.7601	55
56	0.122077	0.9324	0.1819	1.1143	56.373	317.549	373.922	0.1877	1.0243	1.2120	234.52	0.7807	16.5311	56
57	0.129243	0.9353	0.1932	1.1284	57.381	336.417	393.798	0.1908	1.0820	1.2728	238.70	0.7934	17.3337	57
58	0.136851	0.9381	0.2051	1.1432	58.389	356.461	414.850	0.1938	1.1432	1.3370	242.88	0.8061	18.1691	58
59	0.144942	0.9409	0.2179	1.1588	59.397	377.788	437.185	0.1969	1.2081	1.4050	247.07	0.8187	19.0393	59
60	0.15354	0.9438	0.2315	1.1752	60.405	400.458	460.863	0.1999	1.2769	1.4768	251.25	0.8313	19.9439	60
61	0.16269	0.9466	0.2460	1.1926	61.413	424.624	486.036	0.2029	1.3500	1.5530	255.44	0.8438	20.8858	61
62	0.17244	0.9494	0.2614	1.2109	62.421	450.377	512.798	0.2059	1.4278	1.6337	259.62	0.8563	21.8651	62
63	0.18284	0.9523	0.2780	1.2303	63.429	477.837	541.266	0.2089	1.5104	1.7194	263.81	0.8688	22.8826	63
64	0.19393	0.9551	0.2957	1.2508	64.438	507.177	571.615	0.2119	1.5985	1.8105	268.00	0.8812	23.9405	64
65	0.20579	0.9580	0.3147	1.2726	65.446	538.548	603.995	0.2149	1.6925	1.9074	272.18	0.8936	25.0397	65
66	0.21848	0.9608	0.3350	1.2958	66.455	572.116	638.571	0.2179	1.7927	2.0106	276.37	0.9060	26.1810	66
67	0.23207	0.9636	0.3568	1.3204	67.463	608.103	675.566	0.2209	1.8999	2.1208	280.56	0.9183	27.3664	67
68	0.24664	0.9665	0.3803	1.3467	68.472	646.724	715.196	0.2238	2.0147	2.2385	284.75	0.9306	28.5967	68
69	0.26231	0.9693	0.4055	1.3749	69.481	688.261	757.742	0.2268	2.1378	2.3646	288.94	0.9429	29.8741	69
70	0.27916	0.9721	0.4328	1.4049	70.489	732.959	803.448	0.2297	2.2699	2.4996	293.13	0.9551	31.1986	70
71	0.29734	0.9750	0.4622	1.4372	71.498	781.208	852.706	0.2327	2.4122	2.6448	297.32	0.9673	32.5734	71
72	0.31698	0.9778	0.4941	1.4719	72.507	833.335	905.842	0.2356	2.5655	2.8010	301.51	0.9794	33.9983	72
73	0.33824	0.9807	0.5287	1.5093	73.516	889.807	963.323	0.2385	2.7311	2.9696	305.70	0.9916	35.4759	73
74	0.36130	0.9835	0.5662	1.5497	74.525	951.077	1025.603	0.2414	2.9104	3.1518	309.89	1.0037	37.0063	74
75	0.38641	0.9863	0.6072	1.5935	75.535	1017.841	1093.375	0.2443	3.1052	3.3496	314.08	1.0157	38.5940	75
76	0.41377	0.9892	0.6519	1.6411	76.543	1090.628	1167.172	0.2472	3.3171	3.5644	318.28	1.0278	40.2369	76
77	0.44372	0.9920	0.7010	1.6930	77.553	1170.328	1247.881	0.2501	3.5486	3.7987	322.47	1.0398	41.9388	77
78	0.47663	0.9948	0.7550	1.7498	78.562	1257.921	1336.483	0.2530	3.8023	4.0553	326.67	1.0517	43.7020	78
79	0.51284	0.9977	0.8145	1.8121	79.572	1354.347	1433.918	0.2559	4.0810	4.3368	330.86	1.0636	45.5248	79
80	0.55295	1.0005	0.8805	1.8810	80.581	1461.200	1541.781	0.2587	4.3890	4.6477	335.06	1.0755	47.4135	80
81	0.59751	1.0034	0.9539	1.9572	81.591	1579.961	1661.552	0.2616	4.7305	4.9921	339.25	1.0874	49.3670	81
82	0.64724	1.0062	1.0360	2.0422	82.600	1712.547	1795.148	0.2644	5.1108	5.3753	343.45	1.0993	51.3860	82
83	0.70311	1.0090	1.1283	2.1373	83.610	1861.548	1945.158	0.2673	5.5372	5.8045	347.65	1.1111	53.4746	83
84	0.76624	1.0119	1.2328	2.2446	84.620	2029.983	2114.603	0.2701	6.0181	6.2882	351.85	1.1228	55.6337	84
85	0.83812	1.0147	1.3518	2.3666	85.630	2221.806	2307.436	0.2729	6.5644	6.8373	356.05	1.1346	57.8658	85
86	0.92062	1.0175	1.4887	2.5062	86.640	2442.036	2528.677	0.2757	7.1901	7.4658	360.25	1.1463	60.1727	86
87	1.01611	1.0204	1.6473	2.6676	87.650	2697.016	2784.666	0.2785	7.9128	8.1914	364.45	1.1580	62.5544	87
88	1.12800	1.0232	1.8333	2.8565	88.661	2995.890	3084.551	0.2813	8.7580	9.0393	368.65	1.1696	65.0166	88
89	1.26064	1.0261	2.0540	3.0800	89.671	3350.254	3439.925	0.2841	9.7577	10.0419	372.86	1.1812	67.5581	89
90	1.42031	1.0289	2.3199	3.3488	90.681	3776.918	3867.599	0.2869	10.9586	11.2455	377.06	1.1928	70.1817	90

Table 3 Thermodynamic Properties of Water at Saturation

Temp., °C t	Absolute Pressure, kPa p	Specific Volume, m^3/kg (water)			Specific Enthalpy, kJ/kg (water)			Specific Entropy, kJ/(kg·K) (water)			Temp., °C t
		Sat. Solid v_i	Evap. v_{ig}	Sat. Vapor v_g	Sat. Solid h_i	Evap. h_{ig}	Sat. Vapor h_g	Sat. Solid s_i	Evap. s_{ig}	Sat. Vapor s_g	
–60	0.00108	0.001082	90942.00	90942.00	–446.40	2836.27	2389.87	–1.6854	13.3065	11.6211	–60
–59	0.00124	0.001082	79858.69	79858.69	–444.74	2836.46	2391.72	–1.7667	13.2452	11.5677	–59
–58	0.00141	0.001082	70212.37	70212.37	–443.06	2836.64	2393.57	–1.6698	13.8145	11.5147	–58
–57	0.00161	0.001082	61805.35	61805.35	–441.38	2836.81	2395.43	–1.6620	13.1243	11.4623	–57
–56	0.00184	0.001082	54469.39	54469.39	–439.69	2836.97	2397.28	–1.6542	13.0646	11.4104	–56
–55	0.00209	0.001082	48061.05	48061.05	–438.00	2837.13	2399.12	–1.6464	13.0054	11.3590	–55
–54	0.00238	0.001082	42455.57	42455.57	–436.29	2837.27	2400.98	–1.6386	12.9468	11.3082	–54
–53	0.00271	0.001083	37546.09	37546.09	–434.59	2837.42	2402.83	–1.6308	12.8886	11.2578	–53
–52	0.00307	0.001083	33242.14	33242.14	–432.87	2837.55	2404.68	–1.6230	12.8309	11.2079	–52
–51	0.00348	0.001083	29464.67	29464.67	–431.14	2837.68	2406.53	–1.6153	12.7738	11.1585	–51
–50	0.00394	0.001083	26145.01	26145.01	–429.41	2837.80	2408.39	–1.6075	12.7170	11.1096	–50
–49	0.00445	0.001083	23223.69	23223.70	–427.67	2837.91	2410.24	–1.5997	12.6608	11.0611	–49
–48	0.00503	0.001083	20651.68	20651.69	–425.93	2838.02	2412.09	–1.5919	12.6051	11.0131	–48
–47	0.00568	0.001083	18383.50	18383.51	–424.27	2838.12	2413.94	–1.5842	12.5498	10.9656	–47
–46	0.00640	0.001083	16381.35	16381.36	–422.41	2838.21	2415.79	–1.5764	12.4949	10.9185	–46
–45	0.00721	0.001984	14612.35	14512.36	–420.65	2838.29	2417.65	–1.5686	12.4405	10.8719	–45
–44	0.00811	0.001084	13047.65	13047.66	–418.87	2838.37	2419.50	–1.5609	12.3866	10.8257	–44
–43	0.00911	0.001084	11661.85	11661.85	–417.09	2838.44	2421.35	–1.5531	12.3330	10.7799	–43
–42	0.01022	0.001084	10433.85	10433.85	–415.30	2838.50	2423.20	–1.5453	12.2799	10.7346	–42
–41	0.01147	0.001084	9344.25	9344.25	–413.50	2838.55	2425.05	–1.5376	12.2273	10.6897	–41
–40	0.01285	0.001084	8376.33	8376.33	–411.70	2838.60	2426.90	–1.5298	12.1750	10.6452	–40
–39	0.01438	0.001085	7515.86	7515.87	–409.88	2838.64	2428.76	–1.5221	12.1232	10.6011	–39
–38	0.01608	0.001085	6750.36	6750.36	–508.07	2838.67	1430.61	–1.5143	12.0718	10.5575	–38
–37	0.01796	0.001085	6068.16	6068.17	–406.24	2838.70	2432.46	–1.5066	12.0208	10.5142	–37
–36	0.02004	0.001085	5459.82	5459.82	–404.40	2838.71	2434.31	–1.4988	11.9702	10.4713	–36
–35	0.02235	0.001085	4917.09	4917.10	–402.56	2838.73	2436.16	–1.4911	11.9199	10.4289	–35
–34	0.02490	0.001085	4432.36	4432.37	–400.72	2838.73	2438.01	–1.4833	11.8701	10.3868	–34
–33	0.02771	0.001085	3998.71	3998.71	–398.86	2838.72	2439.86	–1.4756	11.8207	10.3451	–33
–32	0.03082	0.001086	3610.71	3610.71	–397.00	2838.71	2441.72	–1.4678	11.7716	10.3037	–32
–31	0.03424	0.001086	3263.20	3263.20	–395.12	2838.69	2443.57	–1.4601	11.7229	10.2628	–31
–30	0.03802	0.001086	2951.64	2951.64	–393.25	2838.66	2445.42	–1.4524	11.6746	10.2222	–30
–29	0.04217	0.001086	2672.03	2672.03	–391.36	2838.63	2447.27	–1.4446	11.6266	10.1820	–29
–28	0.04673	0.001086	2420.89	2420.89	–389.47	2838.59	2449.12	–1.4369	11.4790	10.1421	–28
–27	0.05174	0.001086	2195.23	2195.23	–387.57	2838.53	2450.97	–1.4291	11.5318	10.1026	–27
–26	0.05725	0.001087	1992.15	1992.15	–385.66	2838.48	2452.82	–1.4214	11.4849	10.0634	–26
–25	0.06329	0.001087	1809.35	1809.35	–383.74	2838.41	2454.67	–1.4137	11.4383	10.0246	–25
–24	0.06991	0.001087	1644.59	1644.59	–381.34	2838.34	2456.52	–1.4059	11.3921	9.9862	–24
–23	0.07716	0.001087	1495.98	1495.98	–379.89	2838.26	2458.37	–1.3982	11.3462	9.9480	–23
–22	0.08510	0.001087	1361.94	1361.94	–377.95	2838.17	2460.22	–1.3905	11.3007	9.9102	–22
–21	0.09378	0.001087	1240.77	1240.77	–376.01	2838.07	2462.06	–1.3828	11.2555	9.8728	–21
–20	0.10326	0.001087	1131.27	1131.27	–374.06	2837.97	2463.91	–1.3750	11.2106	9.8356	–20
–19	0.11362	0.001088	1032.18	1032.18	–372.10	2837.86	2465.76	–1.3673	11.1661	9.7988	–19
–18	0.12492	0.001088	942.46	942.47	–370.13	2837.74	2467.61	–1.3596	11.1218	9.7623	–18
–17	0.13725	0.001088	861.17	861.18	–368.15	2837.61	2469.46	–1.3518	11.0779	9.7261	–17
–16	0.15068	0.001088	787.48	787.49	–366.17	2837.47	2471.30	–1.3441	11.0343	9.6902	–16
–15	0.16530	0.001088	720.59	720.59	–364.18	2837.33	2473.15	–1.3364	10.9910	9.6546	–15
–14	0.18122	0.001088	659.86	659.86	–362.18	2837.18	2474.99	–1.3287	10.9480	9.6193	–14
–13	0.19852	0.001089	604.65	604.65	–360.18	2837.02	2476.84	–1.3210	10.9053	9.5844	–13
–12	0.21732	0.001089	554.45	554.45	–358.17	2836.85	2478.68	–1.3232	10.8629	9.5497	–12
–11	0.23774	0.001089	508.75	508.75	–356.15	2836.68	2480.53	–1.3055	10.8208	9.5153	–11
–10	0.25990	0.001089	467.14	467.14	–354.12	2836.49	2482.37	–1.2978	10.7790	9.4812	–10
–9	0.28393	0.001089	429.21	429.21	–352.08	2836.30	2484.22	–1.2901	10.7375	9.4474	–9
–8	0.30998	0.001090	394.64	394.64	–350.04	2836.10	2486.06	–1.2824	10.6962	9.4139	–8
–7	0.33819	0.001090	363.07	363.07	–347.99	2835.89	2487.90	–1.2746	10.6552	9.3806	–7
–6	0.36874	0.001090	334.25	334.25	–345.93	2835.68	2489.74	–1.2669	10.6145	9.3476	–6
–5	0.40176	0.001090	307.91	307.91	–343.87	2835.45	2491.58	–2.2592	10.4741	9.3149	–5
–4	0.43747	0.001090	283.83	283.83	–341.80	2835.22	2493.42	–1.2515	10.5340	9.2825	–4
–3	0.47606	0.001090	261.79	261.79	–339.72	2834.98	2495.26	–1.2438	10.4941	9.2503	–3
–2	0.51772	0.001091	241.60	241.60	–337.63	2834.72	2497.10	–1.2361	10.4544	9.2184	–2
–1	0.56267	0.001091	223.11	223.11	–335.53	2834.47	2498.93	–1.2284	10.4151	9.1867	–1
0	0.61115	0.001091	206.16	206.16	–333.43	2834.20	2500.77	–1.2206	10.3760	9.1553	0

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

Temp., °C	Absolute Pressure, kPa	Specific Volume, m^3/kg (water)			Specific Enthalpy, kJ/kg (water)			Specific Entropy, kJ/(kg·K) (water)			Temp., °C
t	p	Sat. Liquid v_f	Evap. v_{fg}	Sat. Vapor v_g	Sat. Liquid h_f	Evap. h_{fg}	Sat. Vapor h_g	Sat. Liquid s_f	Evap. s_{fg}	Sat. Vapor s_g	t
0	0.6112	0.001000	206.141	206.143	–0.04	2500.81	2500.77	–0.0002	9.1555	9.1553	0
1	0.6571	0.001000	192.455	192.456	4.18	2498.43	2502.61	0.0153	9.1134	9.1286	1
2	0.7060	0.001000	179.769	179.770	8.39	2496.05	2504.45	0.0306	9.0716	9.1022	2
3	0.7580	0.001000	168.026	168.027	12.60	2493.68	2506.28	0.0459	9.0302	9.0761	3
4	0.8135	0.001000	157.137	157.138	16.81	2491.31	2508.12	0.0611	8.9890	9.0501	4
5	0.8725	0.001000	147.032	147.033	21.02	2488.94	2509.96	0.0763	8.9482	9.0244	5
6	0.9353	0.001000	137.653	137.654	25.22	2486.57	2511.79	0.0913	8.9077	8.9990	6
7	1.0020	0.001000	128.947	128.948	29.42	2484.20	2513.62	0.1064	8.8674	8.9738	7
8	1.0728	0.001000	120.850	120.851	33.62	2481.84	2515.46	0.1213	8.8273	8.9488	8
9	1.1481	0.001000	113.326	113.327	37.82	2479.47	2517.29	0.1362	8.7878	8.9245	9
10	1.2280	0.001000	106.328	106.329	42.01	2477.11	2519.12	0.1511	8.7484	8.8995	10
11	1.3127	0.001000	99.812	99.813	46.21	2474.74	2520.95	0.1659	8.7093	8.8752	11
12	1.4026	0.001001	93.743	93.744	50.40	2472.38	2522.78	0.1806	8.6705	8.8511	12
13	1.4978	0.001001	88.088	88.089	54.59	2470.02	2524.61	0.1953	8.6319	8.8272	13
14	1.5987	0.001001	82.815	82.816	58.78	2467.66	2526.44	0.2099	8.5936	3.8035	14
15	1.7055	0.001001	77.897	77.898	62.97	2465.30	2528.26	0.2244	8.5556	8.7801	15
16	1.8184	0.001001	73.307	73.308	67.16	2462.93	2530.09	0.2389	8.5178	8.7568	16
17	1.9380	0.001001	69.021	69.022	71.34	2460.57	2531.92	0.2534	8.4804	8.7338	17
18	2.0643	0.001002	65.017	65.018	75.53	2458.21	2533.74	0.2678	8.4431	8.7109	18
19	2.1978	0.001002	65.274	61.273	79.72	2455.85	2535.56	0.2821	8.4061	8.6883	19
20	2.3388	0.001002	57.774	57.773	83.90	2453.48	2537.38	0.2964	8.3694	8.6658	20
21	2.4877	0.001002	54.450	54.500	88.08	2451.12	2539.20	0.3107	8.3329	8.6436	21
22	2.6448	0.001002	51.433	51.434	92.27	2448.75	2541.02	0.3249	8.2967	8.6215	22
23	2.8104	0.001003	48.562	48.563	96.45	2446.39	2542.84	0.3390	8.2607	8.5996	23
24	2.9851	0.001003	45.872	45.873	100.63	2444.02	2544.65	0.3531	8.2249	8.5780	24
25	3.1692	0.001003	43.350	43.351	104.81	2441.66	2546.47	0.3672	8.1894	8.5565	25
26	3.3631	0.001003	40.985	40.986	108.99	2439.29	2548.28	0.3812	8.1541	8.5352	26
27	3.5673	0.001004	38.766	38.767	113.18	2436.92	2550.09	0.3951	8.1190	8.5141	27
28	3.7822	0.001004	36.682	36.683	117.36	2434.55	2551.90	0.4090	8.0842	8.4932	28
29	4.0083	0.001004	34.726	34.727	121.54	2432.17	2553.71	0.4229	8.0496	8.4724	29
30	4.2460	0.001004	32.889	32.889	125.72	2429.80	2555.52	0.4367	8.0152	8.4519	30
31	4.4959	0.001005	31.160	31.161	129.90	2427.43	2557.32	0.4505	7.9810	8.4315	31
32	4.7585	0.001005	29.535	29.536	134.08	2425.05	2559.13	0.4642	7.9471	8.4112	32
33	5.0343	0.001005	28.006	28.007	138.26	2422.67	2560.93	0.4779	7.9133	8.3912	33
34	5.3239	0.001006	26.567	26.568	142.44	2410.29	2562.73	0.4915	7.8790	8.3713	34
35	5.6278	0.001006	25.212	25.213	146.62	2417.91	2564.53	0.5051	7.8465	8.3516	35
36	5.9466	0.001006	23.935	23.936	150.80	2415.53	2566.33	0.5186	7.8134	8.3320	36
37	6.2810	0.001007	22.733	22.734	154.98	2413.14	2568.12	0.5321	7.7805	8.3127	37
38	6.6315	0.001007	21.599	21.600	159.16	2410.76	2569.91	0.5456	7.7479	8.2934	38
39	6.9987	0.001008	20.529	20.530	163.34	2408.37	2571.71	0.5590	7.7154	8.2744	39
40	7.3835	0.001008	19.520	19.521	167.52	2405.98	2573.50	0.5724	7.6831	8.2555	40
41	7.7863	0.001008	18.567	18.568	171.70	2403.58	2575.28	0.5857	7.6510	8.2367	41
42	8.2080	0.001009	17.667	17.668	175.88	2401.19	2577.07	0.5990	7.6191	8.2181	42
43	8.6492	0.001009	16.818	16.819	180.06	2398.79	2578.85	0.6122	7.5875	8.1997	43
44	9.1107	0.001010	16.014	16.015	184.24	2396.39	2580.63	0.6254	7.3560	8.1814	44
45	9.5932	0.001010	15.255	15.256	188.42	2393.99	2582.41	0.6386	7.5247	8.1632	45
46	10.0976	0.001010	14.537	14.538	192.60	2391.59	2584.19	0.6517	7.4936	8.1452	46
47	10.6246	0.001011	13.858	13.859	196.78	2389.18	2585.96	0.6648	7.4626	8.1274	47
48	11.1751	0.001011	13.214	13.215	200.97	2386.77	2587.74	0.6778	7.4319	8.1097	48
49	11.7500	0.001012	12.606	12.607	205.15	2384.36	2589.51	0.6908	7.4013	8.0921	49
50	12.3499	0.001012	12.029	12.029	209.33	2381.94	2591.27	0.7038	7.3709	8.0747	50
51	12.9759	0.001013	11.482	11.483	213.51	2379.53	2593.04	0.7167	7.3407	8.0574	51
52	13.6290	0.001013	10.964	10.965	217.70	2377.10	2594.80	0.7296	7.3107	8.0403	52
53	14.3100	0.001014	10.473	10.474	221.88	2374.68	2596.56	0.7424	7.2809	8.0233	53
54	15.0200	0.001014	10.001	10.008	226.06	2372.26	2598.32	0.7552	7.2512	8.0064	54
55	15.7597	0.001015	9.563	9.5663	230.25	2369.83	2600.07	0.7680	7.2217	7.9897	55
56	16.5304	0.001015	9.147	9.1468	234.43	2367.39	2601.82	0.7807	7.1924	7.9731	56
57	17.3331	0.001016	8.744	8.7489	238.61	2364.96	2603.57	0.7934	7.1632	7.9566	57
58	18.1690	0.001016	8.3690	8.3700	242.80	2362.52	2605.32	0.8061	7.1342	7.9403	58
59	19.0387	0.001017	8.0094	8.0114	246.99	2360.08	2607.06	0.8187	7.1054	7.9240	59
60	19.944	0.001017	7.6677	7.6697	251.17	2357.63	2608.80	0.8313	7.0767	7.9079	60
61	20.885	0.001018	7.3428	7.3438	255.36	2355.19	2610.54	0.8438	7.0482	7.8920	61
62	21.864	0.001018	7.0337	7.0347	259.54	2352.73	2612.28	0.8563	7.0198	7.8761	62
63	22.882	0.001019	6.7397	6.7407	263.73	2350.28	2614.01	0.8688	6.9916	7.8604	63
64	23.940	0.001019	6.4599	6.4609	267.92	2347.82	2615.74	0.8812	6.9636	7.8448	64
65	25.040	0.001020	6.1935	6.1946	272.11	2345.36	2617.46	0.8936	6.9357	7.8293	65
66	26.180	0.001020	5.9397	5.9409	276.30	2342.89	2619.19	0.9060	6.9080	7.8140	66
67	27.366	0.001021	5.6982	5.6992	280.49	2340.42	2620.90	0.9183	6.8804	7.7987	67
68	28.596	0.001022	5.4680	5.4690	284.68	2337.95	2622.62	0.9306	2.8530	7.7836	68
69	29.873	0.001022	5.2485	5.2495	288.87	2335.47	2624.33	0.9429	6.8257	7.7686	69

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

Temp., °C *t*	Absolute Pressure, kPa *p*	Specific Volume, m^3/kg (water) Sat. Liquid v_f	Specific Volume, m^3/kg (water) Evap. v_{fg}	Specific Volume, m^3/kg (water) Sat. Vapor v_g	Specific Enthalpy, kJ/kg (water) Sat. Liquid h_f	Specific Enthalpy, kJ/kg (water) Evap. h_{fg}	Specific Enthalpy, kJ/kg (water) Sat. Vapor h_g	Specific Entropy, kJ/(kg·K) (water) Sat. Liquid s_f	Specific Entropy, kJ/(kg·K) (water) Evap. s_{fg}	Specific Entropy, kJ/(kg·K) (water) Sat. Vapor s_g	Temp., °C *t*
70	31.198	0.001023	5.0392	5.0402	293.06	2332.99	2626.04	0.9551	6.7986	7.7537	70
71	32.572	0.001023	4.8396	4.8407	297.25	2330.50	2627.75	0.9673	6.7716	7.7389	71
72	33.997	0.001024	4.6492	4.6502	301.44	2328.01	2629.45	0.9795	6.7448	7.7242	72
73	35.475	0.001025	4.4675	4.4685	305.63	2325.51	2631.15	0.9916	6.7181	7.7097	73
74	37.006	0.001025	4.2940	4.2951	309.83	2323.02	2632.84	1.0037	6.6915	7.6952	74
75	38.592	0.001026	4.1284	4.1294	314.02	2320.51	2634.53	1.0157	6.6651	7.6809	75
76	40.236	0.001026	3.9702	3.9712	318.22	2318.01	2636.22	1.0278	6.6389	7.6666	76
77	41.938	0.001027	3.8190	3.8201	322.41	2315.49	2637.90	1.0398	6.6127	7.6525	77
78	43.700	0.001028	3.6746	3.6756	326.61	2312.98	2639.58	1.0517	6.5867	7.6384	78
79	45.524	0.001028	3.5365	3.5375	330.81	2310.46	2641.26	1.0636	6.5609	7.6245	79
80	47.412	0.001029	3.4044	3.4055	335.00	2307.93	2642.93	1.0755	6.5351	7.6107	80
81	49.364	0.001030	3.2781	3.2792	339.20	2305.40	2644.60	1.0874	6.5095	7.5969	81
82	51.384	0.001030	3.1573	3.1583	343.40	2902.86	2646.26	1.0993	6.4841	7.5833	82
83	53.473	0.001031	3.0417	3.0427	347.60	2300.32	2647.92	1.1111	6.4587	7.5698	83
84	55.633	0.001032	2.9310	2.9320	351.80	2297.78	2649.58	1.1228	6.4335	7.5563	84
85	57.865	0.001032	2.8250	2.8260	356.01	2295.22	2651.23	1.1346	6.4084	7.5430	85
86	60.171	0.001033	2.7235	2.7245	350.21	2292.67	2652.88	1.1463	6.3834	7.5297	86
87	62.554	0.001034	2.6263	2.6273	364.41	2290.11	2654.52	1.1580	6.3586	7.5166	87
88	65.015	0.001035	2.5331	2.5341	368.62	2287.54	2656.16	1.1696	6.3339	7.5035	88
89	67.556	0.001035	2.4438	2.4448	372.82	2284.97	2657.79	1.1812	6.3093	7.4905	89
90	70.180	0.001036	2.3582	2.3592	377.03	2282.39	2659.42	1.1928	6.2848	7.4776	90
91	72.888	0.001037	2.2760	2.2771	381.24	2279.81	2661.04	1.2044	6.2605	7.4648	91
92	75.683	0.001037	2.1973	2.1983	385.45	2277.22	2662.66	1.2159	6.2362	7.4521	92
93	78.566	0.001038	2.1217	2.1228	389.66	2274.62	2664.28	1.2274	6.2121	7.4395	93
94	81.541	0.001039	2.0492	2.0502	393.87	2272.02	2665.89	1.2389	6.1881	7.4270	94
95	84.608	0.001040	1.9796	1.9806	398.08	2269.41	2667.49	1.2504	6.1642	7.4146	95
96	87.770	0.001040	1.9128	1.9138	402.29	2266.80	2669.09	1.2618	6.1404	7.4022	96
97	91.030	0.001041	1.8486	1.8496	406.51	2264.18	2670.69	1.2732	6.1168	7.3899	97
98	94.390	0.001042	1.7869	1.7880	410.72	2261.55	2672.28	1.2845	6.0932	7.3777	98
99	97.852	0.001044	1.7277	1.7287	414.94	2258.92	2673.86	1.2959	6.0697	7.3656	99
100	101.419	0.001044	1.6708	1.6718	419.16	2256.28	2675.44	1.3072	6.0464	7.3536	100
101	105.092	0.001044	1.6161	1.6171	423.38	2253.64	2677.02	1.3185	6.0232	7.3416	101
102	108.875	0.001045	1.5635	1.5645	427.60	2250.99	2678.58	1.3297	6.0000	7.3298	102
103	112.770	0.001046	1.5129	1.5139	431.82	2248.33	2680.15	1.3410	5.9770	7.3180	103
104	116.779	0.001047	1.4642	1.4652	436.04	2245.66	2681.71	1.3522	5.9541	7.3062	104
105	120.906	0.001047	1.4174	1.4184	440.27	2242.99	2683.26	1.3634	5.9313	7.2946	105
106	125.152	0.001048	1.3723	1.3734	444.49	2240.31	2684.80	1.3745	5.9086	7.2830	106
107	129.520	0.001049	1.3290	1.3300	448.72	2237.63	2686.35	1.3856	5.8860	7.2716	107
108	134.012	0.001050	1.2872	1.2883	452.95	2234.93	2687.88	1.3967	5.8635	7.2601	108
109	138.633	0.001051	1.2470	1.2481	457.18	2232.23	2689.41	1.4078	5.8410	7.2488	109
110	143.384	0.001052	1.2083	1.2093	461.41	2229.52	2690.93	1.4188	5.8187	7.2375	110
111	148.267	0.001052	1.1710	1.1720	465.64	2226.81	2692.45	1.4298	5.7965	7.2263	111
112	153.287	0.001053	1.1350	1.1361	469.88	2224.09	2693.96	1.4408	5.7744	7.2152	112
113	158.445	0.001054	1.1004	1.1015	474.11	2221.35	2695.47	1.4518	5.7524	7.2402	113
114	163.745	0.001055	1.0670	1.0681	478.35	2218.62	2696.97	1.4627	5.7304	7.1931	114
115	169.190	0.001056	1.0348	1.0359	482.59	2215.87	2698.46	1.4737	5.7086	7.1822	115
116	174.782	0.001057	1.0038	1.0048	486.83	2213.12	2699.95	1.4846	5.6868	7.1714	116
117	180.525	0.001058	0.9739	0.9749	491.07	2210.35	2701.43	1.4954	5.6652	7.1606	117
118	186.420	0.001059	0.9450	0.9460	495.32	2207.58	2702.90	1.5063	5.6436	7.1499	118
119	192.473	0.001059	0.9171	0.9182	499.56	2204.80	2704.37	1.5171	5.6221	7.1392	119
120	198.685	0.001060	0.8902	0.8913	503.81	2202.02	2705.83	1.5279	5.6007	7.1286	120
122	211.601	0.001062	0.8391	0.8402	512.31	2196.42	2706.73	1.5494	5.5582	7.1076	122
124	225.194	0.001064	0.7916	0.7927	520.82	2190.78	2711.60	1.5709	5.5160	7.0869	124
126	239.490	0.001066	0.7472	0.7483	529.33	2185.11	2714.44	1.5922	5.4742	7.0664	126
128	254.515	0.001068	0.7057	0.7068	537.86	2179.40	2717.26	1.6135	5.4326	7.0461	128
130	270.298	0.001070	0.6670	0.6681	546.39	2173.66	2720.05	1.6347	5.3914	7.0261	130
132	286.866	0.001072	0.6308	0.6318	554.93	2167.87	2722.80	1.6557	5.3505	7.0063	132
134	304.247	0.001074	0.5969	0.5979	563.48	2162.05	2725.53	1.6767	5.3099	6.9867	134
136	322.470	0.001076	0.5651	0.5662	572.04	2156.18	2728.22	1.6977	5.2697	6.9673	136
138	341.566	0.001078	0.5354	0.5364	580.60	2150.28	2730.88	1.7185	5.2296	6.9481	138
140	361.565	0.001080	0.5075	0.5085	589.18	2144.33	2733.51	1.7393	5.1899	6.9292	140
142	382.497	0.001082	0.4813	0.4824	597.76	2138.34	2736.11	1.7599	5.1505	6.9104	142
144	404.394	0.001084	0.4567	0.4578	606.36	2132.31	2738.67	1.7805	5.1113	6.8918	144
146	427.288	0.001086	0.4336	0.4347	614.97	2126.23	2741.19	1.8011	5.0724	6.8735	146
148	451.211	0.001088	0.4119	0.4130	623.58	2120.10	2743.68	1.8215	5.0338	6.8553	148
150	476.198	0.001091	0.3914	0.3925	632.21	2113.92	2746.13	1.8419	4.9954	6.8373	150
152	502.281	0.001093	0.3722	0.3733	640.85	2107.70	2748.55	1.8622	4.9573	6.8194	152
154	529.495	0.001095	0.3541	0.3552	649.50	2101.43	2750.93	1.8824	4.9194	6.8017	154
156	557.875	0.001097	0.3370	0.3381	658.16	2095.11	2753.27	1.9026	4.8817	6.7842	156
158	587.456	0.001100	0.3209	0.3220	666.83	2088.73	2755.57	1.9226	4.8443	6.7669	158
160	618.275	0.001102	0.3058	0.3069	675.52	2082.31	2757.82	1.9427	4.8070	6.7497	160

HUMIDITY PARAMETERS

Basic Parameters

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

$$W = M_w / M_{da} \tag{7}$$

The humidity ratio W is equal to the mole fraction ratio x_w/x_{da} multiplied by the ratio of molecular masses, namely, 18.01528/28.9645 = 0.62198:

$$W = 0.62198 x_w / x_{da} \tag{8}$$

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

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

In terms of the humidity ratio,

$$\gamma = W / (1 + W) \tag{9b}$$

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

$$d_v = M_w / V \tag{10}$$

The **density** ρ of a moist air mixture is the ratio of the total mass to the total volume:

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

where v is the moist air specific volume, m^3/kg (dry air), as defined by Equation (27).

Humidity Parameters Involving Saturation

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

Saturation humidity ratio $\boldsymbol{W_s(t, p)}$ 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 the air humidity ratio W to the 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),

$$\mu = \frac{\phi}{1 + (1 - \phi)W_s / 0.62198} \tag{14}$$

Dew-point temperature $\boldsymbol{t_d}$ is the temperature of moist air saturated at the same 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 $\boldsymbol{t^*}$ is the temperature at which water (liquid or solid), by evaporating into moist air at a given dry-bulb temperature t and humidity ratio W, can bring air to saturation adiabatically at the same temperature t^* while the total pressure p is maintained constant. This parameter is considered separately in the section on Thermodynamic Wet-Bulb Temperature 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:

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

$$\text{Water vapor:} \quad p_w V = n_w R T \tag{17}$$

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, 8314.41 J/(kg mol·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) through (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 given by

$$W = 0.62198 \frac{p_w}{p - p_w} \tag{22}$$

The degree of saturation μ is, by definition, Equation (12):

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

where

$$W_s = 0.62198 \frac{p_{ws}}{p - p_{ws}} \tag{23}$$

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, by definition, Equation (13):

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

Substituting Equation (21) for x_w and x_{ws},

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

Substituting Equation (21) for x_{ws} 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** $\boldsymbol{v}$ of a moist air mixture is expressed in terms of a unit mass of dry air:

$$v = V/M_{da} = V/(28.9645n_{da}) \tag{26}$$

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 $p = p_{da} + p_w$,

$$v = \frac{RT}{28.9645(p-p_w)} = \frac{R_{da}T}{p-p_w} \tag{27}$$

Using Equation (22),

$$v = \frac{RT(1+1.6078W)}{28.964p} = \frac{R_{da}T(1+1.6078W)}{p} \tag{28}$$

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

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

$$v = 0.2871(t+273.15)(1+1.6078W)/p$$

where

v = specific volume, m^3/kg (dry air)
t = dry-bulb temperature, °C
W = humidity ratio, kg (water)/kg (dry air)
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 (dry air) and h_g is the specific enthalpy for saturated water vapor in kJ/kg (water) at the temperature of the mixture. As an approximation,

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

$$h_g \approx 2501 + 1.805t \tag{31}$$

where t is the dry-bulb temperature in °C. The moist air specific enthalpy in kJ/kg (dry air) then becomes

$$h = 1.006t + W(2501+1.805t) \tag{32}$$

THERMODYNAMIC WET-BULB TEMPERATURE 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 the adiabatic saturation process, the saturated air is expelled at a temperature equal to that of the injected water. In this constant pressure process,

- Humidity ratio is increased from a given initial value W to the value W_s^* corresponding to saturation at the temperature t^*
- Enthalpy is increased from a given initial value h to the value h_s^* corresponding to saturation at the 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 the specific enthalpy in kJ/kg (water) of the water added at the temperature t^*

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

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

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

The **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 (39) in Chapter 5]. 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 since 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

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

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

$$W = \frac{(2501 - 2.381t^*)W_s^* - 1.006(t - t^*)}{2501 + 1.805t - 4.186t^*} \tag{35}$$

where t and t^* are in °C.

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

$$p_{ws}(t_d) = p_w = (pW)/(0.62198 + W) \tag{36}$$

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 derived from Table 3 or from Equation

(5) or (6). Alternatively, the dew-point temperature can be calculated directly by one of the following equations (Peppers 1988):

For the dew-point temperature range of 0 to 93°C,

$$t_d = C_{14} + C_{15}\alpha + C_{16}\alpha^2 + C_{17}\alpha^3 + C_{18}(p_w)^{0.1984} \tag{37}$$

For temperatures below 0°C,

$$t_d = 6.09 + 12.608\alpha + 0.4959\alpha^2 \tag{38}$$

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 sufficiently accurate 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)	
$p_{ws}(t)$	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 (36)	
t_d	Table 3 with Equation (36), (37), or (38)	

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) 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 (36), (37), or (38)	
t^*	Equation (23) and (35) with Table 3 or with Equation (5) or (6)	Requires trial-and-error or numerical solution method

Exact Relations for Computing W_s and ϕ

Corrections that account for (1) the effect of dissolved gases on properties of condensed phase; (2) the effect of pressure on properties of condensed phase; and (3) the effect of intermolecular force on properties of moisture itself, can be applied to Equations (23) and (25):

$$W_s = 0.62198\frac{fp_{ws}}{p - fp_{ws}} \tag{23a}$$

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

Table 4 lists *f* values for a number of pressure and temperature combinations. Hyland and Wexler (1983a) give additional values.

Table 4 Values of *f* and Estimated Maximum Uncertainties (EMUs)

	0.1 MPa		0.5 MPa		1 MPa	
***T*, K**	***f***	**EMU E+04**	***f***	**EMU E+04**	***f***	**EMU E+04**
173.15	1.0105	134	1.0540	66	1.1130	136
273.15	1.0039	2	1.0177	10	1.0353	19
373.15	1.0039	0.1	1.0180	4	1.0284	11

Moist Air Property Tables for Standard Pressure

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

$$\text{Volume} \qquad v = v_{da} + \mu v_{as} \tag{39}$$

$$\text{Enthalpy} \qquad h = h_{da} + \mu h_{as} \tag{40}$$

$$\text{Entropy} \qquad s = s_{da} + \mu s_{as} \tag{41}$$

These equations are accurate to about 70°C. At higher temperatures, the errors can be significant. Hyland and Wexler (1983a) include charts that can be used to estimate errors for *v*, *h*, and *s* for standard barometric pressure.

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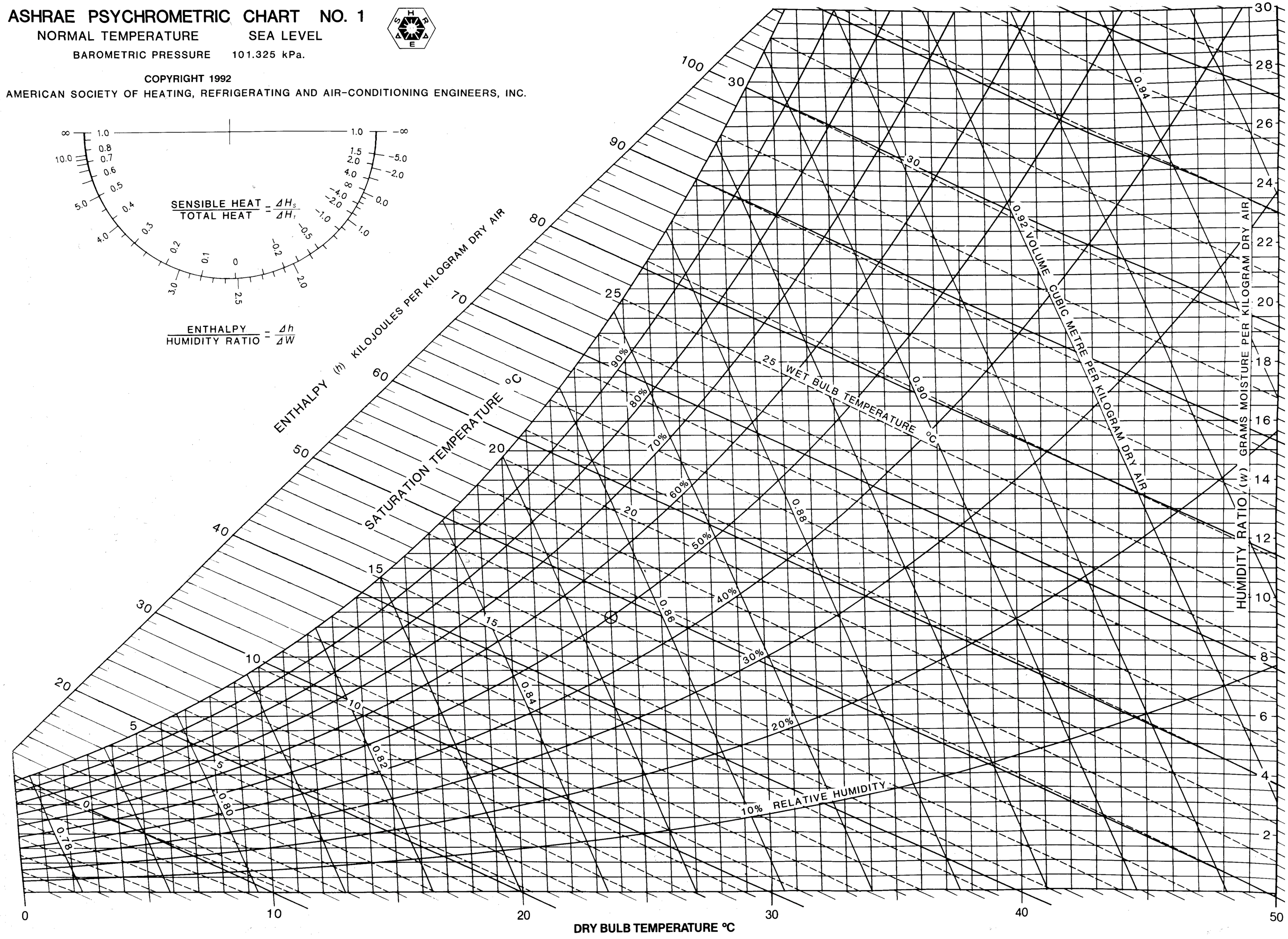

Fig. 1 ASHRAE Psychrometric Chart No. 1

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 seven such psychrometric charts. Chart No. 1 is shown as Figure 1; the others may be obtained through ASHRAE.

Charts 1 through 4 are for sea level pressure (101.325 kPa). Chart 5 is for 750 m altitude (92.66 kPa), Chart 6 is for 1500 m altitude (84.54 kPa), and Chart 7 is for 2250 m altitude (77.04 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 and Gratch (1945), and Goff (1949) 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

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. The construction of charts for altitude conditions has been treated by Haines (1961), Rohsenow (1946), and Karig (1946).

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

1. The dry-bulb lines coincide.
2. 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.
3. Humidity ratio and enthalpy for a given dry- and wet-bulb temperature increase with altitude, but there is little change in relative humidity.
4. 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, which is ASHRAE Psychrometric Chart No. 1, shows humidity ratio lines (horizontal) for the range from 0 (dry air) to 30 g (water)/kg (dry air). Enthalpy lines are oblique lines drawn across the chart precisely parallel to each other.

Dry-bulb temperature lines are drawn straight, not precisely parallel to each other, and inclined slightly from the vertical position. Thermodynamic wet-bulb temperature lines are oblique lines that differ slightly in direction from that of 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, while 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 extension of 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.

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 (water)/kg (dry air).

The **enthalpy** can be found by using two triangles to draw a line parallel to the nearest enthalpy line [60 kJ/kg (dry air)] through the state point to the nearest edge scale. Read $h = 56.7$ kJ/kg (dry air).

Dew-point temperature can be read at the intersection of $W = 6.5$ g (water)/kg (dry air) 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 (dry air). Thus, $v = 0.896$ m^3/kg (dry air).

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

The process of adding heat alone to or removing heat alone from moist air is represented by a horizontal line on the ASHRAE chart, since 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

$$ {}_1q_2 = m_{da}(h_2 - h_1) \qquad (42) $$

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.

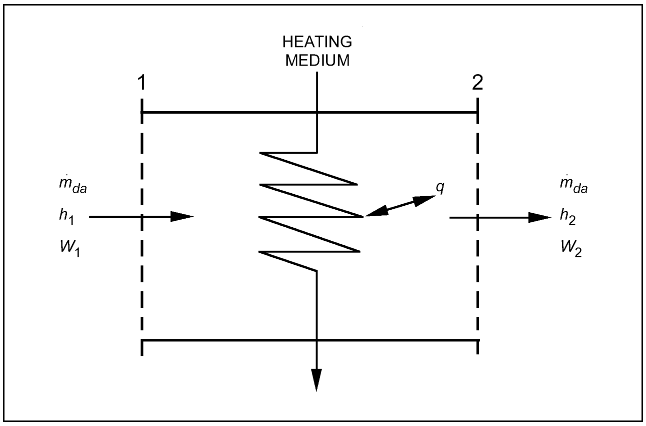

Fig. 2 Schematic of Device for Heating Moist Air

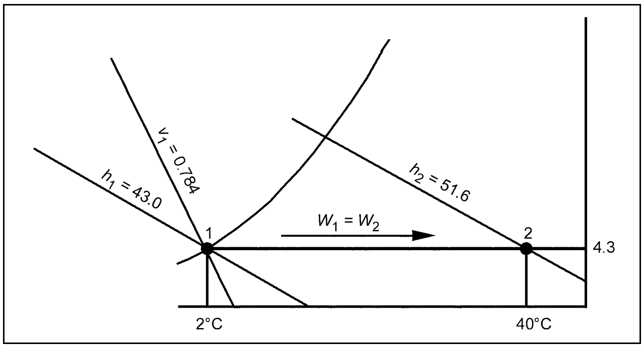

Fig. 3 Schematic Solution for Example 2

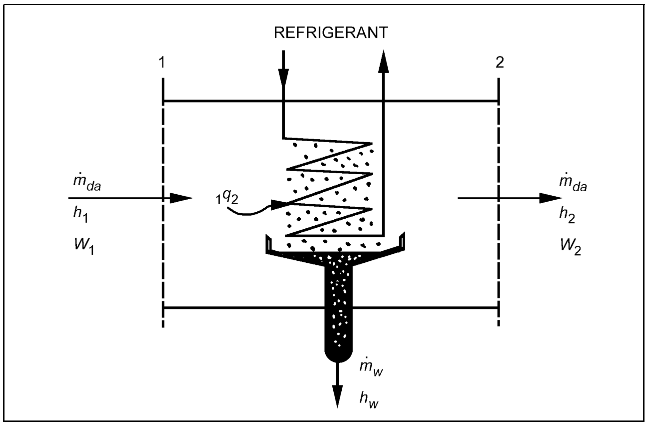

Fig. 4 Schematic of Device for Cooling Moist Air

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 (dry air), W_1 = 4.3 g (water)/kg (dry air), and v_1 = 0.784 m^3/kg (dry air). State 2 is located at the intersection of t = 40°C and $W_2 = W_1$ = 4.3 g (water)/kg (dry air). Thus, h_2 = 51.6 kJ/kg (dry air). The mass flow of dry air is

$$\dot{m}_{da} = 10/0.784 = 12.76 \text{ kg/s (dry air)}$$

From Equation (42),

$${}_1q_2 = 12.76(51.6 - 13.0) = 492 \text{ kW}$$

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 of Figure 4, the steady flow energy and material balance equations are

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

Thus,

$$\dot{m}_w = \dot{m}_{da}(W_1 - W_2) \tag{43}$$

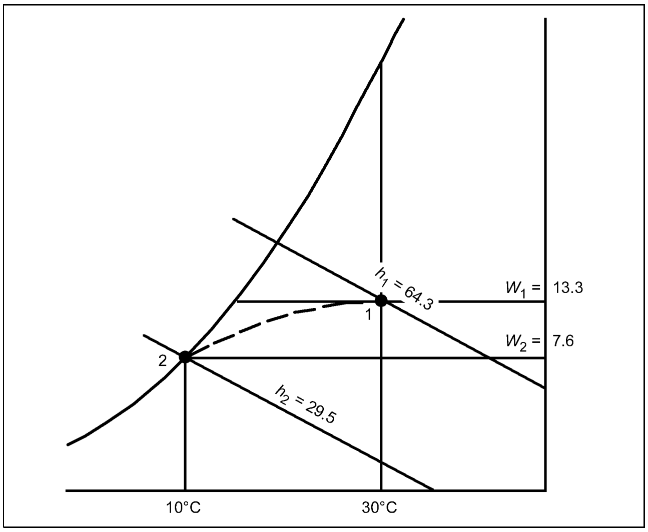

Fig. 5 Schematic Solution for Example 3

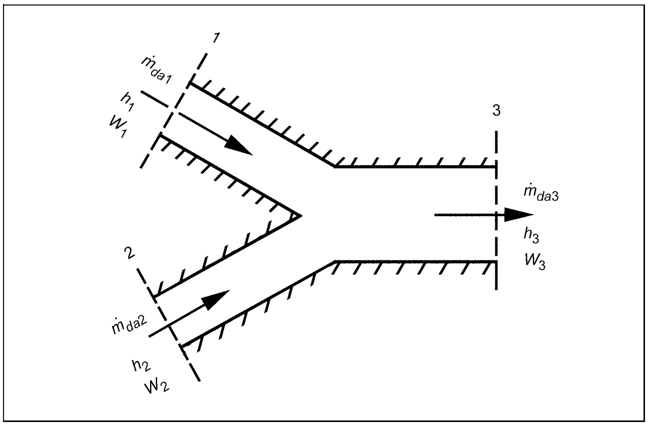

Fig. 6 Adiabatic Mixing of Two Moist Airstreams

$${}_1q_2 = \dot{m}_{da}[(h_1 - h_2) - (W_1 - W_2)h_{w2}] \tag{44}$$

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 (dry air), W_1 = 13.3 g (water)/kg (dry air), and v_1 = 0.877 m^3/kg (dry air). State 2 is located on the saturation curve at 10°C. Thus, h_2 = 29.5 kJ/kg (dry air) and W_2 = 7.66 g (water)/kg (dry air). From Table 2, h_{w2} = 42.11 kJ/kg (water). The mass flow of dry air is

$$\dot{m}_{da} = 5/0.877 = 5.70 \text{ kg/s (dry air)}$$

From Equation (44),

$$\begin{aligned} {}_1q_2 &= 5.70[(64.3 - 29.5) - (0.0133 - 0.00766)42.11] \\ &= 197 \text{ kW} \end{aligned}$$

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:

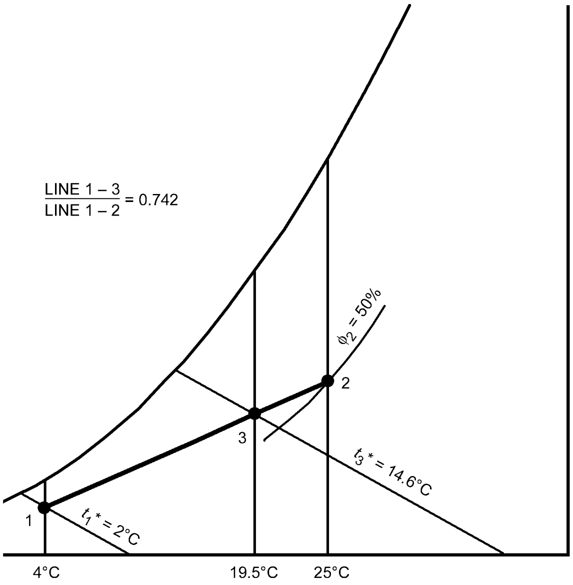

Fig. 7 Schematic Solution for Example 4

$$\dot{m}_{da1}h_1 + \dot{m}_{da2}h_2 = \dot{m}_{da3}h_3$$

$$\dot{m}_{da1} + \dot{m}_{da2} = \dot{m}_{da3}$$

$$\dot{m}_{da1}W_1 + \dot{m}_{da2}W_2 = \dot{m}_{da3}W_3$$

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

$$\frac{h_2 - h_3}{h_3 - h_1} = \frac{W_2 - W_3}{W_3 - W_1} = \frac{\dot{m}_{da1}}{\dot{m}_{da2}} \tag{45}$$

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.

Solution: Figure 7 shows the schematic solution. States 1 and 2 are located on the ASHRAE chart, revealing that v_1 = 0.789 m^3/kg (dry air), and v_2 = 0.858 m^3/kg (dry air). Therefore,

$$\dot{m}_{da1} = 2/0.789 = 2.535 \text{ kg/s (dry air)}$$

$$\dot{m}_{da2} = 6.25/0.858 = 7.284 \text{ kg/s (dry air)}$$

According to Equation (45),

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

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. Figure 8 represents a diagram of this common air-conditioning process. If the mixing is adiabatic, the following equations apply:

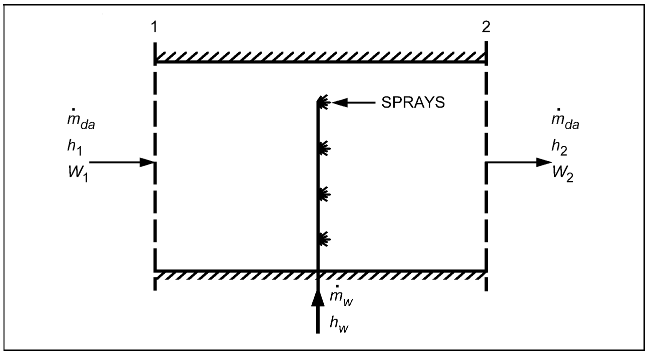

Fig. 8 Schematic Showing Injection of Water into Moist Air

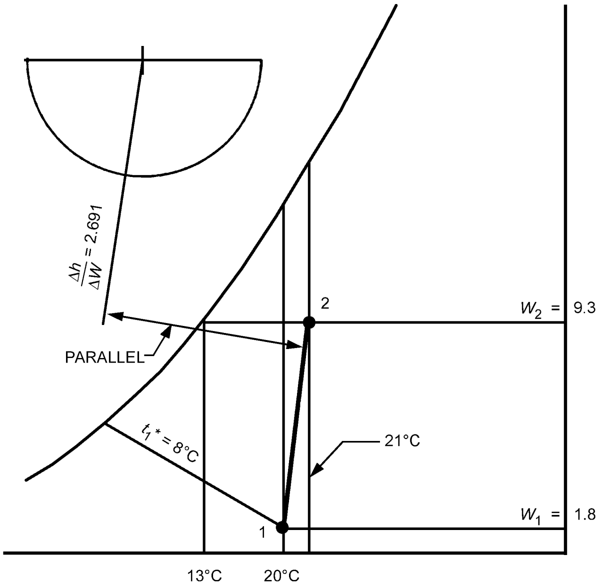

Fig. 9 Schematic Solution for Example 5

$$\dot{m}_{da}h_1 + \dot{m}_w h_w = \dot{m}_{da}h_2$$

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

Therefore,

$$\frac{h_2 - h_1}{W_2 - W_1} = \frac{\Delta h}{\Delta W} = h_w \tag{46}$$

according to which, on the ASHRAE chart, the final state point of the moist air lies on a straight line whose direction is 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/s (dry air). 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 kJ/kg (water). Therefore, according to Equation (46), the condition line on the ASHRAE chart connecting States 1 and 2 must have a direction:

$$\Delta h/\Delta W = 2.691 \text{ kJ/g (water)}$$

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 (water). 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,

$$\begin{aligned}\dot{m}_w &= \dot{m}_{da}(W_2 - W_1) = 2 \times 1000(0.0093 - 0.0018)\\ &= 15.0 \text{ kg/s (steam)}\end{aligned}$$

Space Heat Absorption and Moist Air Moisture Gains

Air conditioning 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 schematically 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 addition of energy alone and does not include energy contributions due to addition of water (or water vapor). 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

$$q_s + \sum(\dot{m}_w h_w) = \dot{m}_{da}(h_2 - h_1) \qquad (47)$$

$$\sum\dot{m}_w = \dot{m}_{da}(W_2 - W_1) \qquad (48)$$

The left side of Equation (47) represents the total rate of energy addition to the space from all sources. By Equations (47) and (48),

$$\frac{h_2 - h_1}{W_2 - W_1} = \frac{\Delta h}{\Delta W} = \frac{q_s + \sum(\dot{m}_w h_w)}{\sum\dot{m}_w} \qquad (49)$$

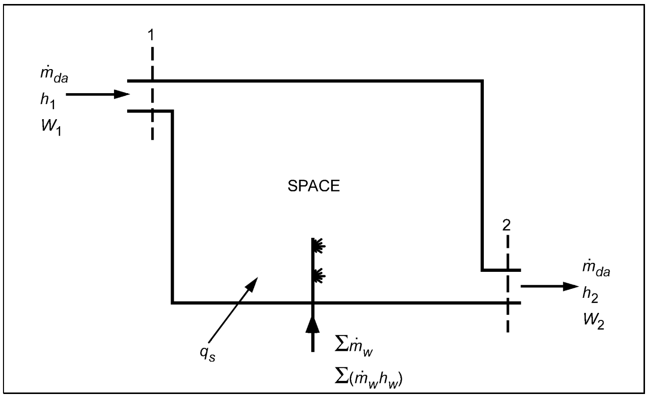

Fig. 10 Schematic of Air Conditioned Space

according to which, on the ASHRAE chart and for a given state of the withdrawn air, all possible states (conditions) for the supply air must lie on a straight line drawn through the state point of the withdrawn air, that has a 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/s (water) 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 = 2555.52 kJ/kg (water). From Equation (49),

$$\frac{\Delta h}{\Delta W} = \frac{9 + (0.0015 \times 2555.52)}{0.0015} = 8555 \text{ kJ/kg (water)}$$

With the $\Delta h/\Delta W$ protractor, establish a reference line of direction $\Delta h/\Delta W$ = 8.555 kJ/g (water). Parallel to this reference line, draw a straight 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^* = 13.8°C.

An alternate (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 the rate of sensible heat gain for the space to the rate of total energy gain for the space. Therefore,

$$\frac{\Delta H_s}{\Delta H_t} = \frac{q_s}{q_s + \Sigma(\dot{m}_w h_w)} = \frac{9}{9 + (0.0015 \times 2555.52)} = 0.701$$

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

The flow of dry air can be calculated from either Equation (47) or (48). From Equation (47),

$$\begin{aligned}\dot{m}_{da} &= \frac{q_s + \Sigma(\dot{m}_w h_w)}{h_2 - h_1} = \frac{9 + (0.0015 \times 2555.52)}{54.0 - 39.0}\\ &= 0.856 \text{ kg/s (dry air)}\end{aligned}$$

At State 1, v_1 = 0.859 m^3/kg (dry air)

Therefore, supply volume = $\dot{m}_{da}v_1$ = 0.856 × 0.859 = 0.735 m^3/s

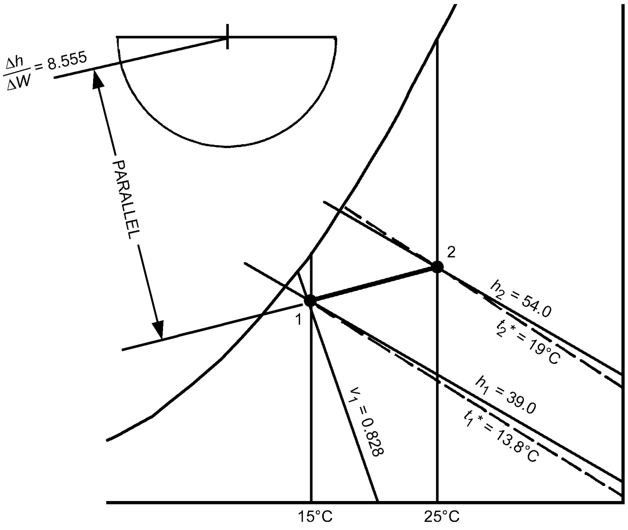

Fig. 11 Schematic Solution for Example 6

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 5 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, the viscosity varies little from that of dry air at normal atmospheric pressure, and the thermal conductivity is essentially independent of moisture content.

Table 5 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

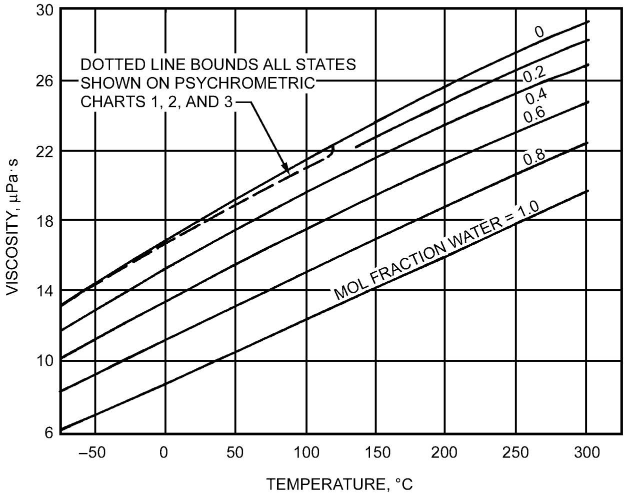

Fig. 12 Viscosity of Moist Air

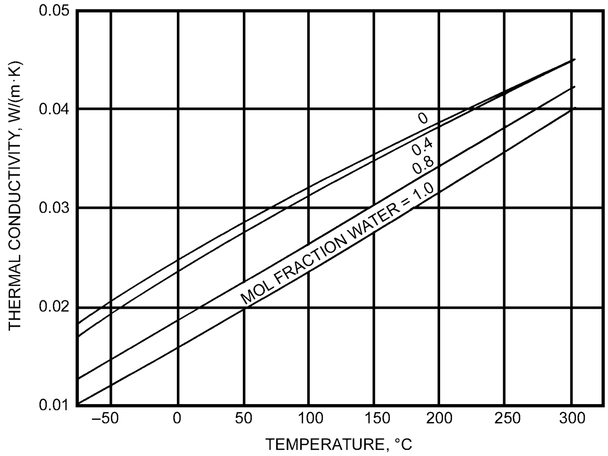

Fig. 13 Thermal Conductivity of Moist Air

REFERENCES FOR AIR, WATER, AND STEAM PROPERTIES

Coefficient f_w (over water) at pressures from 0.5 to 110 kPa for temperatures from −50 to 60°C (Smithsonian Institution).

Coefficient f_i (over ice) at pressures from 0.5 to 110 kPa for temperatures from 0 to 100°C (Smithsonian Institution).

Compressibility factor of dry air at pressures from 1 kPa to 10 MPa and at temperatures from 50 to 3000 K (Hilsenrath et al. 1960).

Compressibility factor of moist air at pressures from 0 to 10 MPa, at values of degree of saturation from 0 to 100, and for temperatures from 0 to 60°C (Smithsonian Institution). [Note: At the time the Smithsonian Meteorological Tables were published, the value $\mu = W/W_s$ was known as relative humidity, in terms of a percentage. Since that time, there has been general agreement to designate the value μ as degree of saturation, usually expressed as a decimal and sometimes as a percentage. See Goff (1949) for more recent data and formulations.]

Compressibility factor for steam at pressures from 100 kPa to 30 MPa and at temperatures from 380 to 850 K (Hilsenrath et al. 1960).

Density, enthalpy, entropy, Prandtl number, specific heat, specific heat ratio, and viscosity of dry air (Hilsenrath et al. 1960).

Density, enthalpy, entropy, specific heat, viscosity, thermal conductivity, and free energy of steam (Hilsenrath et al. 1960).

Dry air. Thermodynamic properties over a wide range of temperature (Keenan and Kaye 1945).

Enthalpy of saturated steam (Osborne et al. 1939).

Ideal-gas thermodynamic functions of dry air at temperatures from 10 to 3000 K (Hilsenrath et al. 1960).

Ideal-gas thermodynamic functions of steam at temperatures from 50 to 5000 K. Functions included are specific heat, enthalpy, free energy, and entropy (Hilsenrath et al. 1960).

Moist air properties from tabulated virial coefficients (Chaddock 1965).

Saturation humidity ratio over ice at pressures from 30 to 100 kPa and for temperatures from −88.8 to 0°C (Smithsonian Institution).

Saturation humidity ratio over water at pressures from 6 to 105 kPa and for temperatures from −50 to 59°C (Smithsonian Institution).

Saturation vapor pressure over water for temperatures from −50 to 102°C (Smithsonian Institution).

Speed of sound in dry air at pressures from 0.001 to 10 MPa for temperatures from 50 to 3000 K (Hilsenrath et al. 1960). At atmospheric pressure for temperatures from −90 to 60°C (Smithsonian Institution).

Speed of sound in moist air. Relations using the formulation of Goff and Gratch and studies by Hardy et al. (1942) give methods for calculating this speed (Smithsonian Institution).

Steam tables covering the range from –40 to 1315°C (Keenan et al. 1969).

Transport properties of moist air. Diffusion coefficient, viscosity, thermal conductivity, and thermal diffusion factor of moist air are listed (Mason and Monchick 1965). The authors' results are summarized in Table 5 and Figures 12 and 13.

Virial coefficients and other information for use with Goff and Gratch formulation (Goff 1949).

Volume of water in cubic metres for temperatures from −10 to 250°C (Smithsonian Institution 1954).

Water properties. Includes properties of ordinary water substance for the gaseous, liquid, and solid phases (Dorsey 1940).

SYMBOLS

C_1 to C_{18} = constants in Equations (5), (6), and (37)

d_v = absolute humidity of moist air, mass of water per unit volume of mixture
f = enhancement factor, used in Equations (23a) and (25a)
h = specific enthalpy of moist air
h_s^* = specific enthalpy of saturated moist air at thermodynamic wet-bulb temperature
h_w^* = specific enthalpy of condensed water (liquid or solid) at thermodynamic wet-bulb temperature and pressure of 101.325 kPa
H_s = rate of sensible heat gain for space
H_t = rate of total energy gain for space
$\dot{m}_{da}$ = mass flow of dry air, per unit time
$\dot{m}_w$ = mass flow of water (any phase), per unit time
M_{da} = mass of dry air in moist air sample
M_w = mass of water vapor in moist air sample
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
p_{da} = partial pressure of dry air
p_s = vapor pressure of water in moist air at saturation. Differs from saturation pressure of pure water because of presence of air.
p_w = partial pressure of water vapor in moist air
p_{ws} = pressure of saturated pure water
q_s = rate of addition (or withdrawal) of sensible heat
R = universal gas constant, 8314.41 J/(kg mole·K)
R_{da} = gas constant for dry air
R_w = gas constant for water vapor
s = specific entropy
t = dry-bulb temperature of moist air
t_d = dew-point temperature of moist air
t^* = thermodynamic wet-bulb temperature of moist air
T = absolute temperature
v = specific volume
v_T = total gas volume
V = total volume of moist air sample
W = humidity ratio of moist air, mass of water per unit mass of dry air
W_s^* = humidity ratio of moist air at saturation at thermodynamic wet-bulb temperature
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
α = $\ln(p_w)$, parameter used in Equations (37) and (38)
γ = specific humidity of moist air, mass of water per unit mass of mixture
μ = degree of saturation W/W_s
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

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