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 –60 to 120°F. 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 apparent molecular mass (weighted average molecular weight 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

$$R_{da} = 1545.32/28.9645 = 53.352 \text{ ft}\cdot\text{lb}_f/\text{lb}_m\cdot{}^\circ\text{R} \qquad (1)$$

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

$$R_w = 1545.32/18.01528 = 85.778 \text{ ft}\cdot\text{lb}_f/\text{lb}_m\cdot{}^\circ\text{R} \qquad (2)$$

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

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 59°F; standard barometric pressure is 29.921 in. Hg. 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, 32.1740 ft/s^2. Table 1 summarizes property data for altitudes to 60,000 ft.

Table 1 Standard Atmospheric Data for Altitudes to 60,000 ft

Altitude, ft	Temperature, °F	Pressure in. Hg	Pressure psia
−1000	62.6	31.02	15.236
−500	60.8	30.47	14.966
0	59.0	29.921	14.696
500	57.2	29.38	14.430
1,000	55.4	28.86	14.175
2,000	51.9	27.82	13.664
3,000	48.3	26.82	13.173
4,000	44.7	25.82	12.682
5,000	41.2	24.90	12.230
6,000	37.6	23.98	11.778
7,000	34.0	23.09	11.341
8,000	30.5	22.22	10.914
9,000	26.9	21.39	10.506
10,000	23.4	20.58	10.108
15,000	5.5	16.89	8.296
20,000	−12.3	13.76	6.758
30,000	−47.8	8.90	4.371
40,000	−69.7	5.56	2.731
50,000	−69.7	3.44	1.690
60,000	−69.7	2.14	1.051

Source: Adapted from NASA (1976).

The pressure values in Table 1 may be calculated from

$$p = 29.92(1 - 6.8753 \times 10^{-6} Z)^{5.2559} \quad (3)$$

The equation for temperature as a function of altitude is given as

$$t = 59 - 0.00356616Z \quad (4)$$

where

Z = altitude, ft
p = barometric pressure, in. Hg.
t = temperature, °F

Equations (3) and (4) are accurate from −16,500 ft to 36,000 ft. For higher altitudes, comprehensive tables of barometric pressure and other physical properties of the standard atmosphere, in both SI and inch-pound units, 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 14.696 psia or 29.921 in. Hg) occurs at 211.95°F on this scale rather than at the traditional value of 212°F. 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 = Fahrenheit temperature, based on thermodynamic temperature scale and expressed relative to absolute temperature T in degrees Rankine (°R) by the following relation:

$$T = t + 459.67$$

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, ft^3/lb_{da}.
v_{as} = $v_s - v_{da}$, difference between specific volume of moist air at saturation and that of dry air itself, ft^3/lb_{da}, at same pressure and temperature.
v_s = specific volume of moist air at saturation, ft^3/lb_{da}.
h_{da} = specific enthalpy of dry air, Btu/lb_{da}. In Table 2, h_{da} has been assigned a value of 0 at 0°F 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, Btu/lb_{da}, at same pressure and temperature.
h_s = specific enthalpy of moist air at saturation, Btu/lb_{da}.
s_{da} = specific entropy of dry air, $Btu/lb_{da} \cdot °R$. In Table 2, s_{da} has been assigned a value of 0 at 0°F 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, $Btu/lb_{da} \cdot °R$, at same pressure and temperature.
s_s = specific entropy of moist air at saturation $Btu/lb_{da} \cdot °R$.
h_w = specific enthalpy of condensed water (liquid or solid) in equilibrium with saturated moist air at specified temperature and pressure, Btu/lb_w. In Table 2, h_w is assigned a value of 0 at its triple point (32.018°F) 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 1 atm. plus influences from presence of air.
s_w = specific entropy of condensed water (liquid or solid) in equilibrium with saturated air, $Btu/lb_w \cdot °R$; 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, in. Hg. 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 −80 to 300°F, 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, 32.018°F. 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 −148 to 32°F is given by

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

where

C_1 = −1.021 416 5 E+04
C_2 = −4.893 242 8 E+00
C_3 = −5.376 579 4 E−03
C_4 = 1.920 237 7 E−07
C_5 = 3.557 583 2 E−10
C_6 = −9.034 468 8 E−14
C_7 = 4.163 501 9 E+00

The saturation pressure over **liquid water** for the temperature range of 32 to 392°F is given by

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

where

C_8 = −1.044 039 7 E+04
C_9 = −1.129 465 0 E+01
C_{10} = −2.702 235 5 E−02
C_{11} = 1.289 036 0 E−05
C_{12} = −2.478 068 1 E−09
C_{13} = 6.545 967 3 E+00

In both Equations (5) and (6),

ln = natural logarithm
p_{ws} = saturation pressure, psia
T = absolute temperature, °R = °F + 459.67

The coefficients of Equations (5) and (6) have been derived from the Hyland-Wexler equations, which are given in SI units. 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, 14.696 psi (29.921 in. Hg)

Temp., °F	Humidity Ratio, lb_w/lb_{da}	Specific Volume, ft^3/lb_{da}			Specific Enthalpy, Btu/lb_{da}			Specific Entropy, $Btu/lb_{da}\cdot°F$			Condensed Water Specific Enthalpy, Btu/lb_w	Condensed Water Specific Entropy, $Btu/lb_w\cdot°F$	Condensed Water Vapor Pressure, in. Hg	Temp., °F
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
−80	0.0000049	9.553	0.000	9.553	−19.221	0.005	−19.215	−0.04594	0.00001	−0.04592	−193.45	−0.4067	0.000236	−80
−79	0.0000053	9.579	0.000	9.579	−18.980	0.005	−18.975	−0.04531	0.00002	−0.04529	−193.06	−0.4056	0.000255	−79
−78	0.0000057	9.604	0.000	9.604	−18.740	0.006	−18.734	−0.04468	0.00002	−0.04466	−192.66	−0.4046	0.000275	−78
−77	0.0000062	9.629	0.000	9.629	−18.500	0.007	−18.493	−0.04405	0.00002	−0.04403	−192.27	−0.4036	0.000296	−77
−76	0.0000067	9.655	0.000	9.655	−18.259	0.007	−18.252	−0.04342	0.00002	−0.04340	−191.87	−0.4025	0.000319	−76
−75	0.0000072	9.680	0.000	9.680	−18.019	0.007	−18.011	−0.04279	0.00002	−0.04277	−191.47	−0.4015	0.000344	−75
−74	0.0000078	9.705	0.000	9.705	−17.778	0.008	−17.770	−0.04217	0.00002	−0.04215	−191.07	−0.4005	0.000371	−74
−73	0.0000084	9.731	0.000	9.731	−17.538	0.009	−17.529	−0.04155	0.00002	−0.04152	−190.68	−0.3994	0.000400	−73
−72	0.0000090	9.756	0.000	9.756	−17.298	0.010	−17.288	−0.04093	0.00003	−0.04090	−190.27	−0.3984	0.000430	−72
−71	0.0000097	9.781	0.000	9.782	−17.057	0.010	−17.047	−0.04031	0.00003	−0.04028	−189.87	−0.3974	0.000463	−71
−70	0.0000104	9.807	0.000	9.807	−16.806	0.011	−16.817	−0.03969	0.00003	−0.03966	−189.47	−0.3963	0.000498	−70
−69	0.0000112	9.832	0.000	9.832	−16.577	0.012	−16.565	−0.03907	0.00003	−0.03904	−189.07	−0.3953	0.000536	−69
−68	0.0000120	9.857	0.000	9.858	−16.336	0.013	−16.324	−0.03846	0.00003	−0.03843	−188.66	−0.3943	0.000576	−68
−67	0.0000129	9.883	0.000	9.883	−16.096	0.013	−16.083	−0.03785	0.00004	−0.03781	−188.26	−0.3932	0.000619	−67
−66	0.0000139	9.908	0.000	9.908	−15.856	0.015	−15.841	−0.03724	0.00004	−0.03720	−187.85	−0.3922	0.000665	−66
−65	0.0000149	9.933	0.000	9.934	−15.616	0.015	−15.600	−0.03663	0.00004	−0.03659	−187.44	−0.3912	0.000714	−65
−64	0.0000160	9.959	0.000	9.959	−15.375	0.017	−15.359	−0.03602	0.00005	−0.03597	−187.04	−0.3901	0.000766	−64
−63	0.0000172	9.984	0.000	9.984	−15.117	0.018	−15.135	−0.03541	0.00005	−0.03536	−186.63	−0.3891	0.000822	−63
−62	0.0000184	10.009	0.000	10.010	−14.895	0.019	−14.876	−0.03481	0.00005	−0.03476	−186.22	−0.3881	0.000882	−62
−61	0.0000198	10.035	0.000	10.035	−14.654	0.021	−14.634	−0.03420	0.00006	−0.03415	−185.81	−0.3870	0.000945	−61
−60	0.0000212	10.060	0.000	10.060	−14.414	0.022	−14.392	−0.03360	0.00006	−0.03354	−185.39	−0.3860	0.001013	−60
−59	0.0000227	10.085	0.000	10.086	−14.174	0.024	−14.150	−0.03300	0.00006	−0.03294	−184.98	−0.3850	0.001086	−59
−58	0.0000243	10.111	0.000	10.111	−13.933	0.025	−13.908	−0.03240	0.00007	−0.03233	−184.57	−0.3839	0.001163	−58
−57	0.0000260	10.136	0.000	10.137	−13.693	0.027	−13.666	−0.03180	0.00007	−0.03173	−184.15	−0.3829	0.001246	−57
−56	0.0000279	10.161	0.000	10.162	−13.453	0.029	−13.424	−0.03121	0.00008	−0.03113	−183.74	−0.3819	0.001333	−56
−55	0.0000298	10.187	0.000	10.187	−13.213	0.031	−13.182	−0.03061	0.00008	−0.03053	−183.32	−0.3808	0.001427	−55
−54	0.0000319	10.212	0.001	10.213	−12.972	0.033	−12.939	−0.03002	0.00009	−0.02993	−182.90	−0.3798	0.001526	−54
−53	0.0000341	10.237	0.001	10.238	−12.732	0.035	−12.697	−0.02943	0.00009	−0.02934	−182.48	−0.3788	0.001632	−53
−52	0.0000365	10.263	0.001	10.263	−12.492	0.038	−12.454	−0.02884	0.00010	−0.02874	−182.06	−0.3778	0.001745	−52
−51	0.0000390	10.288	0.001	10.289	−12.251	0.041	−12.211	−0.02825	0.00011	−0.02814	−181.64	−0.3767	0.001865	−51
−50	0.0000416	10.313	0.001	10.314	−12.011	0.043	−11.968	−0.02766	0.00011	−0.02755	−181.22	−0.3757	0.001992	−50
−49	0.0000445	10.339	0.001	10.340	−11.771	0.046	−11.725	−0.02708	0.00012	−0.02696	−180.80	−0.3747	0.002128	−49
−48	0.0000475	10.364	0.001	10.365	−11.531	0.050	−11.481	−0.02649	0.00013	−0.02636	−180.37	−0.3736	0.002272	−48
−47	0.0000507	10.389	0.001	10.390	−11.290	0.053	−11.237	−0.02591	0.00014	−0.02577	−179.95	−0.3726	0.002425	−47
−46	0.0000541	10.415	0.001	10.416	−11.050	0.056	−10.994	−0.02533	0.00015	−0.02518	−179.52	−0.3716	0.002587	−46
−45	0.0000577	10.440	0.001	10.441	−10.810	0.060	−10.750	−0.02475	0.00016	−0.02459	−179.10	−0.3705	0.002760	−45
−44	0.0000615	10.465	0.001	10.466	−10.570	0.064	−10.505	−0.02417	0.00017	−0.02400	−178.67	−0.3695	0.002943	−44
−43	0.0000656	10.491	0.001	10.492	−10.329	0.068	−10.261	−0.02359	0.00018	−0.02342	−178.24	−0.3685	0.003137	−43
−42	0.0000699	10.516	0.001	10.517	−10.089	0.073	−10.016	−0.02302	0.00019	−0.02283	−177.81	−0.3675	0.003343	−42
−41	0.0000744	10.541	0.001	10.543	−9.849	0.078	−9.771	−0.02244	0.00020	−0.02224	−177.38	−0.3664	0.003562	−41
−40	0.0000793	10.567	0.001	10.568	−9.609	0.083	−9.526	−0.02187	0.00021	−0.02166	−176.95	−0.3654	0.003793	−40
−39	0.0000844	10.592	0.001	10.593	−9.368	0.088	−9.280	−0.02130	0.00022	−0.02107	−176.52	−0.3644	0.004039	−39
−38	0.0000898	10.617	0.002	10.619	−9.128	0.094	−9.034	−0.02073	0.00024	−0.02049	−176.08	−0.3633	0.004299	−38
−37	0.0000956	10.643	0.002	10.644	−8.888	0.100	−8.788	−0.02016	0.00025	−0.01991	−175.65	−0.3623	0.004575	−37
−36	0.0001017	10.668	0.002	10.670	−8.648	0.106	−8.541	−0.01959	0.00027	−0.01932	−175.21	−0.3613	0.004866	−36
−35	0.0001081	10.693	0.002	10.695	−8.407	0.113	−8.294	−0.01902	0.00028	−0.01874	−174.78	−0.3603	0.005175	−35
−34	0.0001150	10.719	0.002	10.721	−8.167	0.120	−8.047	−0.01846	0.00030	−0.01816	−174.34	−0.3529	0.005502	−34
−33	0.0001222	10.744	0.002	10.746	−7.927	0.128	−7.799	−0.01790	0.00032	−0.01758	−173.90	−0.3582	0.005848	−33
−32	0.0001298	10.769	0.002	10.772	−7.687	0.136	−7.551	−0.01733	0.00034	−0.01699	−173.46	−0.3572	0.006214	−32
−31	0.0001379	10.795	0.002	10.797	−7.447	0.145	−7.302	−0.01677	0.00036	−0.01641	−173.02	−0.3561	0.006601	−31
−30	0.0001465	10.820	0.003	10.822	−7.206	0.154	−7.053	−0.01621	0.00038	−0.01583	−172.58	−0.3551	0.007009	−30
−29	0.0001555	10.845	0.003	10.848	−6.966	0.163	−6.803	−0.01565	0.00040	−0.01525	−172.14	−0.3541	0.007442	−29
−28	0.0001650	10.871	0.003	10.873	−6.726	0.173	−6.553	−0.01510	0.00043	−0.01467	−171.70	−0.3531	0.007898	−28
−27	0.0001751	10.896	0.003	10.899	−6.486	0.184	−6.302	−0.01454	0.00045	−0.01409	−171.25	−0.3520	0.008381	−27
−26	0.0001858	10.921	0.003	10.924	−6.245	0.195	−6.051	−0.01399	0.00048	−0.01351	−170.81	−0.3510	0.008890	−26
−25	0.0001970	10.947	0.003	10.950	−6.005	0.207	−5.798	−0.01343	0.00051	−0.01293	−170.36	−0.3500	0.009428	−25
−24	0.0002088	10.972	0.004	10.976	−5.765	0.220	−5.545	−0.01288	0.00054	−0.01235	−169.92	−0.3489	0.009995	−24
−23	0.0002214	10.997	0.004	11.001	−5.525	0.233	−5.292	−0.01233	0.00057	−0.01176	−169.47	−0.3479	0.010594	−23
−22	0.0002346	11.022	0.004	11.027	−5.284	0.247	−5.038	−0.01178	0.00060	−0.01118	−169.02	−0.3469	0.011226	−22
−21	0.0002485	11.048	0.004	11.052	−5.044	0.261	−4.783	−0.01123	0.00063	−0.01060	−168.57	−0.3459	0.011893	−21
−20	0.0002632	11.073	0.005	11.078	−4.804	0.277	−4.527	−0.01069	0.00067	−0.01002	−168.12	−0.3448	0.012595	−20
−19	0.0002786	11.098	0.005	11.103	−4.564	0.293	−4.271	−0.01014	0.00071	−0.00943	−167.67	−0.3438	0.013336	−19
−18	0.0002950	11.124	0.005	11.129	−4.324	0.311	−4.013	−0.00960	0.00075	−0.00885	−167.21	−0.3428	0.014117	−18
−17	0.0003121	11.149	0.006	11.155	−4.084	0.329	−3.754	−0.00905	0.00079	−0.00826	−166.76	−0.3418	0.014939	−17
−16	0.0003303	11.174	0.006	11.180	−3.843	0.348	−3.495	−0.00851	0.00083	−0.00768	−166.30	−0.3407	0.015806	−16
−15	0.0003493	11.200	0.006	11.206	−3.603	0.368	−3.235	−0.00797	0.00088	−0.00709	−165.85	−0.3397	0.016718	−15
−14	0.0003694	11.225	0.007	11.232	−3.363	0.390	−2.973	−0.00743	0.00093	−0.00650	−165.39	−0.3387	0.017679	−14
−13	0.0003905	11.250	0.007	11.257	−3.123	0.412	−2.710	−0.00689	0.00098	−0.00591	−164.93	−0.3377	0.018690	−13
−12	0.0004128	11.276	0.007	11.283	−2.882	0.436	−2.447	−0.00635	0.00103	−0.00532	−164.47	−0.3366	0.019754	−12
−11	0.0004362	11.301	0.008	11.309	−2.642	0.460	−2.182	−0.00582	0.00109	−0.00473	−164.01	−0.3356	0.020873	−11

Table 2 Thermodynamic Properties of Moist Air at Standard Atmospheric Pressure, 14.696 psi (29.921 in. Hg) (*Continued*)

Temp., °F	Humidity Ratio, lb_w/lb_{da}	Specific Volume, ft^3/lb_{da}			Specific Enthalpy, Btu/lb_{da}			Specific Entropy, $Btu/lb_{da} \cdot °F$			Condensed Water: Specific Enthalpy, Btu/lb_w	Condensed Water: Specific Entropy, $Btu/lb_w \cdot °F$	Condensed Water: Vapor Pressure, in. Hg	Temp., °F
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
−10	0.0004608	11.326	0.008	11.335	−2.402	0.487	−1.915	−0.00528	0.00115	−0.00414	−163.55	−0.3346	0.022050	−10
−9	0.0004867	11.351	0.009	11.360	−2.162	0.514	−1.647	−0.00475	0.00121	−0.00354	−163.09	−0.3335	0.023289	−9
−8	0.0005139	11.377	0.009	11.386	−1.922	0.543	−1.378	−0.00422	0.00127	−0.00294	−162.63	−0.3325	0.024591	−8
−7	0.0005425	11.402	0.010	11.412	−1.681	0.574	−1.108	−0.00369	0.00134	−0.00234	−162.17	−0.3315	0.025959	−7
−6	0.0005726	11.427	0.010	11.438	−1.441	0.606	−0.835	−0.00316	0.00141	−0.00174	−161.70	−0.3305	0.027397	−6
−5	0.0006041	11.453	0.011	11.464	−1.201	0.640	−0.561	−0.00263	0.00149	−0.00114	−161.23	−0.3294	0.028907	−5
−4	0.0006373	11.478	0.012	11.490	−0.961	0.675	−0.286	−0.00210	0.00157	−0.00053	−160.77	−0.3284	0.030494	−4
−3	0.0006722	11.503	0.012	11.516	−0.721	0.712	−0.008	−0.00157	0.00165	0.00008	−160.30	−0.3274	0.032160	−3
−2	0.0007088	11.529	0.013	11.542	−0.480	0.751	0.271	−0.00105	0.00174	0.00069	−159.83	−0.3264	0.033909	−2
−1	0.0007472	11.554	0.014	11.568	−0.240	0.792	0.552	−0.00052	0.00183	0.00130	−159.36	−0.3253	0.035744	−1
0	0.0007875	11.579	0.015	11.594	0.0	0.835	0.835	0.00000	0.00192	0.00192	−158.89	−0.3243	0.037671	0
1	0.0008298	11.604	0.015	11.620	0.240	0.880	1.121	0.00052	0.00202	0.00254	−158.42	−0.3233	0.039694	1
2	0.0008742	11.630	0.016	11.646	0.480	0.928	1.408	0.00104	0.00212	0.00317	−157.95	−0.3223	0.041814	2
3	0.0009207	11.655	0.017	11.672	0.721	0.978	1.699	0.00156	0.00223	0.00380	−157.47	−0.3212	0.044037	3
4	0.0009695	11.680	0.018	11.699	0.961	1.030	1.991	0.00208	0.00235	0.00443	−157.00	−0.3202	0.046370	4
5	0.0010207	11.706	0.019	11.725	1.201	1.085	2.286	0.00260	0.00247	0.00506	−156.52	−0.3192	0.048814	5
6	0.0010743	11.731	0.020	11.751	1.441	1.143	2.584	0.00311	0.00259	0.00570	−156.05	−0.3182	0.051375	6
7	0.0011306	11.756	0.021	11.778	1.681	1.203	2.884	0.00363	0.00635	0.00272	−155.57	−0.3171	0.054060	7
8	0.0011895	11.782	0.022	11.804	1.922	1.266	3.188	0.00414	0.00286	0.00700	−155.09	−0.3161	0.056872	8
9	0.0012512	11.807	0.024	11.831	2.162	1.332	3.494	0.00466	0.00300	0.00766	−154.61	−0.3151	0.059819	9
10	0.0013158	11.832	0.025	11.857	2.402	1.402	3.804	0.00517	0.00315	0.00832	−154.13	−0.3141	0.062901	10
11	0.0013835	11.857	0.026	11.884	2.642	1.474	4.117	0.00568	0.00330	0.00898	−153.65	−0.3130	0.066131	11
12	0.0014544	11.883	0.028	11.910	2.882	1.550	4.433	0.00619	0.00347	0.00966	−153.17	−0.3120	0.069511	12
13	0.0015286	11.908	0.029	11.937	3.123	1.630	4.753	0.00670	0.00364	0.01033	−152.68	−0.3110	0.073049	13
14	0.0016062	11.933	0.031	11.964	3.363	1.714	5.077	0.00721	0.00381	0.01102	−152.20	−0.3100	0.076751	14
15	0.0016874	11.959	0.032	11.991	3.603	1.801	5.404	0.00771	0.00400	0.01171	−151.71	−0.3089	0.080623	15
16	0.0017724	11.984	0.034	12.018	3.843	1.892	5.736	0.00822	0.00419	0.01241	−151.22	−0.3079	0.084673	16
17	0.0018613	12.009	0.036	12.045	4.084	1.988	6.072	0.00872	0.00439	0.01312	−150.74	−0.3069	0.088907	17
18	0.0019543	12.035	0.038	12.072	4.324	2.088	6.412	0.00923	0.00460	0.01383	−150.25	−0.3059	0.093334	18
19	0.0020515	12.060	0.040	12.099	4.564	2.193	6.757	0.00973	0.00482	0.01455	−149.76	−0.3049	0.097962	19
20	0.0021531	12.085	0.042	12.127	4.804	2.303	7.107	0.01023	0.00505	0.01528	−149.27	−0.3038	0.102798	20
21	0.0022592	12.110	0.044	12.154	5.044	2.417	7.462	0.01073	0.00529	0.01602	−148.78	−0.3028	0.107849	21
22	0.0023703	12.136	0.046	12.182	5.285	2.537	7.822	0.01123	0.00554	0.01677	−148.28	−0.3018	0.113130	22
23	0.0024863	12.161	0.048	12.209	5.525	2.662	8.187	0.01173	0.00580	0.01753	−147.79	−0.3008	0.118645	23
24	0.0026073	12.186	0.051	12.237	5.765	2.793	8.558	0.01223	0.00607	0.01830	−147.30	−0.2997	0.124396	24
25	0.0027339	12.212	0.054	12.265	6.005	2.930	8.935	0.01272	0.00636	0.01908	−146.80	−0.2987	0.130413	25
26	0.0028660	12.237	0.056	12.293	6.246	3.073	9.318	0.01322	0.00665	0.01987	−146.30	−0.2977	0.136684	26
27	0.0030039	12.262	0.059	12.321	6.486	3.222	9.708	0.01371	0.00696	0.02067	−145.81	−0.2967	0.143233	27
28	0.0031480	12.287	0.062	12.349	6.726	3.378	10.104	0.01420	0.00728	0.02148	−145.31	−0.2956	0.150066	28
29	0.0032984	12.313	0.065	12.378	6.966	3.541	10.507	0.01470	0.00761	0.02231	−144.81	−0.2946	0.157198	29
30	0.0034552	12.338	0.068	12.406	7.206	3.711	10.917	0.01519	0.00796	0.02315	−144.31	−0.2936	0.164631	30
31	0.0036190	12.363	0.072	12.435	7.447	3.888	11.335	0.01568	0.00832	0.02400	−143.80	−0.2926	0.172390	31
32	0.0037895	12.389	0.075	12.464	7.687	4.073	11.760	0.01617	0.00870	0.02487	−143.30	−0.2915	0.180479	32
32*	0.003790	12.389	0.075	12.464	7.687	4.073	11.760	0.01617	0.00870	0.02487	0.02	0.0000	0.18050	32
33	0.003947	12.414	0.079	12.492	7.927	4.243	12.170	0.01665	0.00905	0.02570	1.03	0.0020	0.18791	33
34	0.004109	12.439	0.082	12.521	8.167	4.420	12.587	0.01714	0.00940	0.02655	2.04	0.0041	0.19559	34
35	0.004277	12.464	0.085	12.550	8.408	4.603	13.010	0.01763	0.00977	0.02740	3.05	0.0061	0.20356	35
36	0.004452	12.490	0.089	12.579	8.648	4.793	13.441	0.01811	0.01016	0.02827	4.05	0.0081	0.21181	36
37	0.004633	12.515	0.093	12.608	8.888	4.990	13.878	0.01860	0.01055	0.02915	5.06	0.0102	0.22035	37
38	0.004820	12.540	0.097	12.637	9.128	5.194	14.322	0.01908	0.01096	0.03004	6.06	0.0122	0.22920	38
39	0.005014	12.566	0.101	12.667	9.369	5.405	14.773	0.01956	0.01139	0.03095	7.07	0.0142	0.23835	39
40	0.005216	12.591	0.105	12.696	9.609	5.624	15.233	0.02004	0.01183	0.03187	8.07	0.0162	0.24784	40
41	0.005424	12.616	0.110	12.726	9.849	5.851	15.700	0.02052	0.01228	0.03281	9.08	0.0182	0.25765	41
42	0.005640	12.641	0.114	12.756	10.089	6.086	16.175	0.02100	0.01275	0.03375	10.08	0.0202	0.26781	42
43	0.005863	12.667	0.119	12.786	10.330	6.330	16.660	0.02148	0.01324	0.03472	11.09	0.0222	0.27831	43
44	0.006094	12.692	0.124	12.816	10.570	6.582	17.152	0.02196	0.01374	0.03570	12.09	0.0242	0.28918	44
45	0.006334	12.717	0.129	12.846	10.810	6.843	17.653	0.02244	0.01426	0.03669	13.09	0.0262	0.30042	45
46	0.006581	12.743	0.134	12.877	11.050	7.114	18.164	0.02291	0.01479	0.03770	14.10	0.0282	0.31206	46
47	0.006838	12.768	0.140	12.908	11.291	7.394	18.685	0.02339	0.01534	0.03873	15.10	0.0302	0.32408	47
48	0.007103	12.793	0.146	12.939	11.531	7.684	19.215	0.02386	0.01592	0.03978	16.10	0.0321	0.33651	48
49	0.007378	12.818	0.152	12.970	11.771	7.984	19.756	0.02433	0.01651	0.04084	17.10	0.0341	0.34937	49
50	0.007661	12.844	0.158	13.001	12.012	8.295	20.306	0.02480	0.01712	0.04192	18.11	0.0361	0.36264	50
51	0.007955	12.869	0.164	13.033	12.252	8.616	20.868	0.02528	0.01775	0.04302	19.11	0.0381	0.37636	51
52	0.008259	12.894	0.171	13.065	12.492	8.949	21.441	0.02575	0.01840	0.04415	20.11	0.0400	0.39054	52
53	0.008573	12.920	0.178	13.097	12.732	9.293	22.025	0.02622	0.01907	0.04529	21.11	0.0420	0.40518	53
54	0.008897	12.945	0.185	13.129	12.973	9.648	22.621	0.02668	0.01976	0.04645	22.11	0.0439	0.42030	54
55	0.009233	12.970	0.192	13.162	13.213	10.016	23.229	0.02715	0.02048	0.04763	23.11	0.0459	0.43592	55
56	0.009580	12.995	0.200	13.195	13.453	10.397	23.850	0.02762	0.02122	0.04884	24.11	0.0478	0.45205	56
57	0.009938	13.021	0.207	13.228	13.694	10.790	24.484	0.02808	0.02198	0.05006	25.11	0.0497	0.46870	57
58	0.010309	13.046	0.216	13.262	13.934	11.197	25.131	0.02855	0.02277	0.05132	26.11	0.0517	0.48589	58
59	0.010692	13.071	0.224	13.295	14.174	11.618	25.792	0.02901	0.02358	0.05259	27.11	0.0536	0.50363	59

*Extrapolated to represent metastable equilibrium with undercooled liquid.

Table 2 Thermodynamic Properties of Moist Air at Standard Atmospheric Pressure, 14.696 psi (29.921 in. Hg) (*Continued*)

Temp., °F	Humidity Ratio, lb_w/lb_{da}	Specific Volume, ft^3/lb_{da}			Specific Enthalpy, Btu/lb_{da}			Specific Entropy, $Btu/lb_{da}\cdot°F$			Condensed Water: Specific Enthalpy, Btu/lb_w	Condensed Water: Specific Entropy, $Btu/lb_w\cdot°F$	Condensed Water: Vapor Pressure, in. Hg	Temp., °F
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	0.011087	13.096	0.233	13.329	14.415	12.052	26.467	0.02947	0.02442	0.05389	28.11	0.0555	0.52193	60
61	0.011496	13.122	0.242	13.364	14.655	12.502	27.157	0.02994	0.02528	0.05522	29.12	0.0575	0.54082	61
62	0.011919	13.147	0.251	13.398	14.895	12.966	27.862	0.03040	0.02617	0.05657	30.11	0.0594	0.56032	62
63	0.012355	13.172	0.261	13.433	15.135	13.446	28.582	0.03086	0.02709	0.05795	31.11	0.0613	0.58041	63
64	0.012805	13.198	0.271	13.468	15.376	13.942	29.318	0.03132	0.02804	0.05936	32.11	0.0632	0.60113	64
65	0.013270	13.223	0.281	13.504	15.616	14.454	30.071	0.03178	0.02902	0.06080	33.11	0.0651	0.62252	65
66	0.013750	13.248	0.292	13.540	15.856	14.983	30.840	0.03223	0.03003	0.06226	34.11	0.0670	0.64454	66
67	0.014246	13.273	0.303	13.577	16.097	15.530	31.626	0.03269	0.03107	0.06376	35.11	0.0689	0.66725	67
68	0.014758	13.299	0.315	13.613	16.337	16.094	32.431	0.03315	0.03214	0.06529	36.11	0.0708	0.69065	68
69	0.015286	13.324	0.326	13.650	16.577	16.677	33.254	0.03360	0.03325	0.06685	37.11	0.0727	0.71479	69
70	0.015832	13.349	0.339	13.688	16.818	17.279	34.097	0.03406	0.03438	0.06844	38.11	0.0746	0.73966	70
71	0.016395	13.375	0.351	13.726	17.058	17.901	34.959	0.03451	0.03556	0.07007	39.11	0.0765	0.76567	71
72	0.016976	13.400	0.365	13.764	17.299	18.543	35.841	0.03496	0.03677	0.07173	40.11	0.0783	0.79167	72
73	0.017575	13.425	0.378	13.803	17.539	19.204	36.743	0.03541	0.03801	0.07343	41.11	0.0802	0.81882	73
74	0.018194	13.450	0.392	13.843	17.779	19.889	37.668	0.03586	0.03930	0.07516	42.11	0.0821	0.84684	74
75	0.018833	13.476	0.407	13.882	18.020	20.595	38.615	0.03631	0.04062	0.07694	43.11	0.0840	0.87567	75
76	0.019491	13.501	0.422	13.923	18.260	21.323	39.583	0.03676	0.04199	0.07875	44.10	0.0858	0.90533	76
77	0.020170	13.526	0.437	13.963	18.500	22.075	40.576	0.03721	0.04339	0.08060	45.10	0.0877	0.93589	77
78	0.020871	13.551	0.453	14.005	18.741	22.851	41.592	0.03766	0.04484	0.08250	46.10	0.0896	0.96733	78
79	0.021594	13.577	0.470	14.046	18.981	23.652	42.633	0.03811	0.04633	0.08444	47.10	0.0914	0.99970	79
80	0.022340	13.602	0.487	14.089	19.222	24.479	43.701	0.03855	0.04787	0.08642	48.10	0.0933	1.03302	80
81	0.023109	13.627	0.505	14.132	19.462	25.332	44.794	0.03900	0.04945	0.08844	49.10	0.0951	1.06728	81
82	0.023902	13.653	0.523	14.175	19.702	26.211	45.913	0.03944	0.05108	0.09052	50.10	0.0970	1.10252	82
83	0.024720	13.678	0.542	14.220	19.943	27.120	47.062	0.03988	0.05276	0.09264	51.09	0.0988	1.13882	83
84	0.025563	13.703	0.561	14.264	20.183	28.055	48.238	0.04033	0.05448	0.09481	52.09	0.1006	1.17608	84
85	0.026433	13.728	0.581	14.310	20.424	29.021	49.445	0.04077	0.05626	0.09703	53.09	0.1025	1.21445	85
86	0.027329	13.754	0.602	14.356	20.664	30.017	50.681	0.04121	0.05809	0.09930	54.09	0.1043	1.25388	86
87	0.028254	13.779	0.624	14.403	20.905	31.045	51.949	0.04165	0.05998	0.10163	55.09	0.1061	1.29443	87
88	0.029208	13.804	0.646	14.450	21.145	32.105	53.250	0.04209	0.06192	0.10401	56.09	0.1080	1.33613	88
89	0.030189	13.829	0.669	14.498	21.385	33.197	54.582	0.04253	0.06392	0.10645	57.09	0.1098	1.37893	89
90	0.031203	13.855	0.692	14.547	21.626	34.325	55.951	0.04297	0.06598	0.10895	58.08	0.1116	1.42298	90
91	0.032247	13.880	0.717	14.597	21.866	35.489	57.355	0.06810	0.04340	0.11150	59.08	0.1134	1.46824	91
92	0.033323	13.905	0.742	14.647	22.107	36.687	58.794	0.04384	0.07028	0.11412	60.08	0.1152	1.51471	92
93	0.034433	13.930	0.768	14.699	22.347	37.924	60.271	0.04427	0.07253	0.11680	61.08	0.1170	1.56248	93
94	0.035577	13.956	0.795	14.751	22.588	39.199	61.787	0.04471	0.07484	0.11955	62.08	0.1188	1.61154	94
95	0.036757	13.981	0.823	14.804	22.828	40.515	63.343	0.04514	0.07722	0.12237	63.08	0.1206	1.66196	95
96	0.037972	14.006	0.852	14.858	23.069	41.871	64.940	0.04558	0.07968	0.12525	64.07	0.1224	1.71372	96
97	0.039225	14.032	0.881	14.913	23.309	43.269	66.578	0.04601	0.08220	0.12821	65.07	0.1242	1.76685	97
98	0.040516	14.057	0.912	14.969	23.550	44.711	68.260	0.04644	0.08480	0.13124	66.07	0.1260	1.82141	98
99	0.041848	14.082	0.944	15.026	23.790	46.198	69.988	0.04687	0.08747	0.13434	67.07	0.1278	1.87745	99
100	0.043219	14.107	0.976	15.084	24.031	47.730	71.761	0.04730	0.09022	0.13752	68.07	0.1296	1.93492	100
101	0.044634	14.133	1.010	15.143	24.271	49.312	73.583	0.04773	0.09306	0.14079	69.07	0.1314	1.99396	101
102	0.046090	14.158	1.045	15.203	24.512	50.940	75.452	0.04816	0.09597	0.14413	70.06	0.1332	2.05447	102
103	0.047592	14.183	1.081	15.264	24.752	52.621	77.373	0.04859	0.09897	0.14756	71.06	0.1349	2.11661	103
104	0.049140	14.208	1.118	15.326	24.993	54.354	79.346	0.04901	0.10206	0.15108	72.06	0.1367	2.18037	104
105	0.050737	14.234	1.156	15.390	25.233	56.142	81.375	0.04944	0.10525	0.15469	73.06	0.1385	2.24581	105
106	0.052383	14.259	1.196	15.455	25.474	57.986	83.460	0.04987	0.10852	0.15839	74.06	0.1402	2.31297	106
107	0.054077	14.284	1.236	15.521	25.714	59.884	85.599	0.05029	0.11189	0.16218	75.06	0.1420	2.38173	107
108	0.055826	14.309	1.279	15.588	25.955	61.844	87.799	0.05071	0.11537	0.16608	76.05	0.1438	2.45232	108
109	0.057628	14.335	1.322	15.657	26.195	63.866	90.061	0.05114	0.11894	0.17008	77.05	0.1455	2.52473	109
110	0.059486	14.360	1.367	15.727	26.436	65.950	92.386	0.05156	0.12262	0.17418	78.05	0.1473	2.59891	110
111	0.061401	14.385	1.414	15.799	26.677	68.099	94.776	0.05198	0.12641	0.17839	79.05	0.1490	2.67500	111
112	0.063378	14.411	1.462	15.872	26.917	70.319	97.237	0.05240	0.13032	0.18272	80.05	0.1508	2.75310	112
113	0.065411	14.436	1.511	15.947	27.158	72.603	99.760	0.05282	0.13434	0.18716	81.05	0.1525	2.83291	113
114	0.067512	14.461	1.562	16.023	27.398	74.964	102.362	0.05324	0.13847	0.19172	82.04	0.1543	2.91491	114
115	0.069676	14.486	1.615	16.101	27.639	77.396	105.035	0.05366	0.14274	0.19640	83.04	0.1560	2.99883	115
116	0.071908	14.512	1.670	16.181	27.879	79.906	107.786	0.05408	0.14713	0.20121	84.04	0.1577	3.08488	116
117	0.074211	14.537	1.726	16.263	28.120	82.497	110.617	0.05450	0.15165	0.20615	85.04	0.1595	3.17305	117
118	0.076586	14.562	1.784	16.346	28.361	85.169	113.530	0.05492	0.15631	0.21122	86.04	0.1612	3.26335	118
119	0.079036	14.587	1.844	16.432	28.601	87.927	116.528	0.05533	0.16111	0.21644	87.04	0.1629	3.35586	119
120	0.081560	14.613	1.906	16.519	28.842	90.770	119.612	0.05575	0.16605	0.22180	88.04	0.1647	3.45052	120
121	0.084169	14.638	1.971	16.609	29.083	93.709	122.792	0.05616	0.17115	0.22731	89.04	0.1664	3.54764	121
122	0.086860	14.663	2.037	16.700	29.323	96.742	126.065	0.05658	0.17640	0.23298	90.03	0.1681	3.64704	122
123	0.089633	14.688	2.106	16.794	29.564	99.868	129.432	0.05699	0.18181	0.23880	91.03	0.1698	3.74871	123
124	0.092500	14.714	2.176	16.890	29.805	103.102	132.907	0.05740	0.18739	0.24480	92.03	0.1715	3.85298	124
125	0.095456	14.739	2.250	16.989	30.045	106.437	136.482	0.05781	0.19314	0.25096	93.03	0.1732	3.95961	125
126	0.098504	14.764	2.325	17.090	30.286	109.877	140.163	0.05823	0.19907	0.25729	94.03	0.1749	4.06863	126
127	0.101657	14.789	2.404	17.193	30.527	113.438	143.965	0.05864	0.20519	0.26382	95.03	0.1766	4.18046	127
128	0.104910	14.815	2.485	17.299	30.767	117.111	147.878	0.05905	0.21149	0.27054	96.03	0.1783	4.29477	128
129	0.108270	14.840	2.569	17.409	31.008	120.908	151.916	0.21800	0.21810	0.27745	97.03	0.1800	4.41181	129

Table 2 Thermodynamic Properties of Moist Air at Standard Atmospheric Pressure, 14.696 psi (29.921 in. Hg) (*Continued*)

Temp., °F	Humidity Ratio, lb_w/lb_{da}	Specific Volume, ft^3/lb_{da}			Specific Enthalpy, Btu/lb_{da}			Specific Entropy, $Btu/lb_{da}\cdot°F$			Condensed Water Specific Enthalpy, Btu/lb_w	Condensed Water Specific Entropy, $Btu/lb_w\cdot°F$	Vapor Pressure, in. Hg	Temp., °F
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
130	0.111738	14.865	2.655	17.520	31.249	124.828	156.076	0.05986	0.22470	0.28457	98.03	0.1817	4.53148	130
131	0.115322	14.891	2.745	17.635	31.489	128.880	160.370	0.06027	0.23162	0.29190	99.02	0.1834	4.65397	131
132	0.119023	14.916	2.837	17.753	31.730	133.066	164.796	0.06068	0.23876	0.29944	100.02	0.1851	4.77919	132
133	0.122855	14.941	2.934	17.875	31.971	137.403	169.374	0.06109	0.24615	0.30723	101.02	0.1868	4.90755	133
134	0.126804	14.966	3.033	17.999	32.212	141.873	174.084	0.06149	0.25375	0.31524	102.02	0.1885	5.03844	134
135	0.130895	14.992	3.136	18.127	32.452	146.504	178.957	0.06190	0.26161	0.32351	103.02	0.1902	5.17258	135
136	0.135124	15.017	3.242	18.259	32.693	151.294	183.987	0.06230	0.26973	0.33203	104.02	0.1919	5.30973	136
137	0.139494	15.042	3.352	18.394	32.934	156.245	189.179	0.06271	0.27811	0.34082	105.02	0.1935	5.44985	137
138	0.144019	15.067	3.467	18.534	33.175	161.374	194.548	0.06311	0.28707	0.35018	106.02	0.1952	5.59324	138
139	0.148696	15.093	3.585	18.678	33.415	166.677	200.092	0.06351	0.29602	0.35954	107.02	0.1969	5.73970	139
140	0.153538	15.118	3.708	18.825	33.656	172.168	205.824	0.06391	0.30498	0.36890	108.02	0.1985	5.88945	140
141	0.158643	15.143	3.835	18.978	33.897	177.857	211.754	0.06431	0.31456	0.37887	109.02	0.2002	6.04256	141
142	0.163748	15.168	3.967	19.135	34.138	183.754	217.892	0.06471	0.32446	0.38918	110.02	0.2019	6.19918	142
143	0.169122	15.194	4.103	19.297	34.379	189.855	224.233	0.06511	0.33470	0.39981	111.02	0.2035	6.35898	143
144	0.174694	15.219	4.245	19.464	34.620	196.183	230.802	0.06551	0.34530	0.41081	112.02	0.2052	6.52241	144
145	0.180467	15.244	4.392	19.637	34.860	202.740	237.600	0.06591	0.35626	0.42218	113.02	0.2068	6.68932	145
146	0.186460	15.269	4.545	19.815	35.101	209.550	244.651	0.06631	0.36764	0.43395	114.02	0.2085	6.86009	146
147	0.192668	15.295	4.704	19.999	35.342	216.607	251.949	0.06671	0.37941	0.44611	115.02	0.2101	7.03435	147
148	0.199110	15.320	4.869	20.189	35.583	223.932	259.514	0.06710	0.39160	0.45871	116.02	0.2118	7.21239	148
149	0.205792	15.345	5.040	20.385	35.824	231.533	267.356	0.06750	0.40424	0.47174	117.02	0.2134	7.39413	149
150	0.212730	15.370	5.218	20.589	36.064	239.426	275.490	0.06790	0.41735	0.48524	118.02	0.2151	7.57977	150
151	0.219945	15.396	5.404	20.799	36.305	247.638	283.943	0.06829	0.43096	0.49925	119.02	0.2167	7.76958	151
152	0.227429	15.421	5.596	21.017	36.546	256.158	292.705	0.06868	0.44507	0.51375	120.02	0.2184	7.96306	152
153	0.235218	15.446	5.797	21.243	36.787	265.028	301.816	0.06908	0.45973	0.52881	121.02	0.2200	8.16087	153
154	0.243309	15.471	6.005	21.477	37.028	274.245	311.273	0.06947	0.47494	0.54441	122.02	0.2216	8.36256	154
155	0.251738	15.497	6.223	21.720	37.269	283.849	321.118	0.06986	0.49077	0.56064	123.02	0.2233	8.56871	155
156	0.260512	15.522	6.450	21.972	37.510	293.849	331.359	0.07025	0.50723	0.57749	124.02	0.2249	8.77915	156
157	0.269644	15.547	6.686	22.233	37.751	304.261	342.012	0.07065	0.52434	0.59499	125.02	0.2265	8.99378	157
158	0.279166	15.572	6.933	22.505	37.992	315.120	353.112	0.07104	0.54217	0.61320	126.02	0.2281	9.21297	158
159	0.289101	15.598	7.190	22.788	38.233	326.452	364.685	0.07143	0.56074	0.63216	127.02	0.2297	9.43677	159
160	0.29945	15.623	7.459	23.082	38.474	338.263	376.737	0.07181	0.58007	0.65188	128.02	0.2314	9.6648	160
161	0.31027	15.648	7.740	23.388	38.715	350.610	389.325	0.07220	0.60025	0.67245	129.02	0.2330	9.8978	161
162	0.32156	15.673	8.034	23.707	38.956	363.501	402.457	0.07259	0.62128	0.69388	130.03	0.2346	10.1353	162
163	0.33336	15.699	8.341	24.040	39.197	376.979	416.175	0.07298	0.64325	0.71623	131.03	0.2362	10.3776	163
164	0.34572	15.724	8.664	24.388	39.438	391.095	430.533	0.07337	0.66622	0.73959	132.03	0.2378	10.6250	164
165	0.35865	15.749	9.001	24.750	39.679	405.865	445.544	0.07375	0.69022	0.76397	133.03	0.2394	10.8771	165
166	0.37220	15.774	9.355	25.129	39.920	421.352	461.271	0.07414	0.71535	0.78949	134.03	0.2410	11.1343	166
167	0.38639	15.800	9.726	25.526	40.161	437.578	477.739	0.07452	0.74165	0.81617	135.03	0.2426	11.3965	167
168	0.40131	15.825	10.117	25.942	40.402	454.630	495.032	0.07491	0.76925	0.84415	136.03	0.2442	11.6641	168
169	0.41698	15.850	10.527	26.377	40.643	472.554	513.197	0.07529	0.79821	0.87350	137.04	0.2458	11.9370	169
170	0.43343	15.875	10.959	26.834	40.884	491.372	532.256	0.07567	0.82858	0.90425	138.04	0.2474	12.2149	170
171	0.45079	15.901	11.414	27.315	41.125	511.231	552.356	0.07606	0.86058	0.93664	139.04	0.2490	12.4988	171
172	0.46905	15.926	11.894	27.820	41.366	532.138	573.504	0.07644	0.89423	0.97067	140.04	0.2506	12.7880	172
173	0.48829	15.951	12.400	28.352	41.607	554.160	595.767	0.07682	0.92962	1.00644	141.04	0.2521	13.0823	173
174	0.50867	15.976	12.937	28.913	41.848	577.489	619.337	0.07720	0.96707	1.04427	142.04	0.2537	13.3831	174
175	0.53019	16.002	13.504	29.505	42.089	602.139	644.229	0.07758	1.00657	1.08416	143.05	0.2553	13.6894	175
176	0.55294	16.027	14.103	30.130	42.331	628.197	670.528	0.07796	1.04828	1.12624	144.05	0.2569	14.0010	176
177	0.57710	16.052	14.741	30.793	42.572	655.876	698.448	0.07834	1.09253	1.17087	145.05	0.2585	14.3191	177
178	0.60274	16.078	15.418	31.496	42.813	685.260	728.073	0.07872	1.13943	1.21815	146.05	0.2600	14.6430	178
179	0.63002	16.103	16.139	32.242	43.054	716.524	759.579	0.07910	1.18927	1.26837	147.06	0.2616	14.9731	179
180	0.65911	16.128	16.909	33.037	43.295	749.871	793.166	0.07947	1.24236	1.32183	148.06	0.2632	15.3097	180
181	0.69012	16.153	17.730	33.883	43.536	785.426	828.962	0.07985	1.29888	1.37873	149.06	0.2647	15.6522	181
182	0.72331	16.178	18.609	34.787	43.778	823.487	867.265	0.08023	1.35932	1.43954	150.06	0.2663	16.0014	182
183	0.75885	16.204	19.551	35.755	44.019	864.259	908.278	0.08060	1.42396	1.50457	151.07	0.2679	16.3569	183
184	0.79703	16.229	20.564	36.793	44.260	908.061	952.321	0.08098	1.49332	1.57430	152.07	0.2694	16.7190	184
185	0.83817	16.254	21.656	37.910	44.501	955.261	999.763	0.08135	1.56797	1.64932	153.07	0.2710	17.0880	185
186	0.88251	16.280	22.834	39.113	44.742	1006.149	1050.892	0.08172	1.64834	1.73006	154.08	0.2725	17.4634	186
187	0.93057	16.305	24.111	40.416	44.984	1061.314	1106.298	0.08210	1.73534	1.81744	155.08	0.2741	17.8462	187
188	0.98272	16.330	25.498	41.828	45.225	1121.174	1166.399	0.08247	1.82963	1.91210	156.08	0.2756	18.2357	188
189	1.03951	16.355	27.010	43.365	45.466	1186.382	1231.848	0.08284	1.93221	2.01505	157.09	0.2772	18.6323	189
190	1.10154	16.381	28.661	45.042	45.707	1257.614	1303.321	0.08321	2.04412	2.12733	158.09	0.2787	19.0358	190
191	1.16965	16.406	30.476	46.882	45.949	1335.834	1381.783	0.08359	2.16684	2.25043	159.09	0.2803	19.4468	191
192	1.24471	16.431	32.477	48.908	46.190	1422.047	1468.238	0.08396	2.30193	2.38589	160.10	0.2818	19.8652	192
193	1.32788	16.456	34.695	51.151	46.431	1517.581	1564.013	0.08433	2.45144	2.53576	161.10	0.2834	20.2913	193
194	1.42029	16.481	37.161	53.642	46.673	1623.758	1670.430	0.08470	2.61738	2.70208	162.11	0.2849	20.7244	194
195	1.52396	16.507	39.928	56.435	46.914	1742.879	1789.793	0.08506	2.80332	2.88838	163.11	0.2864	21.1661	195
196	1.64070	16.532	43.046	59.578	47.155	1877.032	1924.188	0.08543	3.01244	3.09787	164.12	0.2880	21.6152	196
197	1.77299	16.557	46.580	63.137	47.397	2029.069	2076.466	0.08580	3.24914	3.33494	165.12	0.2895	22.0714	197
198	1.92472	16.583	50.636	67.218	47.638	2203.464	2251.102	0.08617	3.52030	3.60647	166.13	0.2910	22.5367	198
199	2.09975	16.608	55.316	71.923	47.879	2404.668	2452.547	0.08653	3.83275	3.91929	167.13	0.2926	23.0092	199
200	2.30454	16.633	60.793	77.426	48.121	2640.084	2688.205	0.08690	4.19787	4.28477	168.13	0.2941	23.4906	200

Table 3 Thermodynamic Properties of Water at Saturation

Temp., °F	Absolute Pressure		Specific Volume, ft³/lb$_w$			Specific Enthalpy, Btu/lb$_w$			Specific Entropy, Btu/lb$_w$·°F			Temp., °F
			Sat. Solid	Evap.	Sat. Vapor	Sat. Solid	Evap.	Sat. Vapor	Sat. Solid	Evap.	Sat. Vapor	
t	p, psi	p, in. Hg	v_i	v_{ig}	v_g	h_i	h_{ig}	h_g	s_i	s_{ig}	s_g	t
−80	0.000116	0.000236	0.01732	1953234	1953234	−193.50	1219.19	1025.69	−0.4067	3.2112	2.8045	−80
−79	0.000125	0.000254	0.01732	1814052	1814052	−193.11	1219.24	1026.13	−0.4056	3.2029	2.7972	−79
−78	0.000135	0.000275	0.01732	1685445	1685445	−192.71	1219.28	1026.57	−0.4046	3.1946	2.7900	−78
−77	0.000145	0.000296	0.01732	1566663	1566663	−192.31	1219.33	1027.02	−0.4036	3.1964	2.7828	−77
−76	0.000157	0.000319	0.01732	1456752	1456752	−191.92	1219.38	1027.46	−0.4025	3.1782	2.7757	−76
−75	0.000169	0.000344	0.01733	1355059	1355059	−191.52	1219.42	1027.90	−0.4015	3.1701	2.7685	−75
−74	0.000182	0.000371	0.01733	1260977	1260977	−191.12	1219.47	1028.34	−0.4005	3.1619	2.7615	−74
−73	0.000196	0.000399	0.01733	1173848	1173848	−190.72	1219.51	1028.79	−0.3994	3.1539	2.7544	−73
−72	0.000211	0.000430	0.01733	1093149	1093149	−190.32	1219.55	1029.23	−0.3984	3.1459	2.7475	−72
−71	0.000227	0.000463	0.01733	1018381	1018381	−189.92	1219.59	1029.67	−0.3974	3.1379	2.7405	−71
−70	0.000245	0.000498	0.01733	949067	949067	−189.52	1219.63	1030.11	−0.3963	3.1299	2.7336	−70
−69	0.000263	0.000536	0.01733	884803	884803	−189.11	1219.67	1030.55	−0.3953	3.1220	2.7267	−69
−68	0.000283	0.000576	0.01733	825187	825187	−188.71	1219.71	1031.00	−0.3943	3.1141	2.7199	−68
−67	0.000304	0.000619	0.01734	769864	769864	−188.30	1219.74	1031.44	−0.3932	3.1063	2.7131	−67
−66	0.000326	0.000664	0.01734	718508	718508	−187.90	1219.78	1031.88	−0.3922	3.0985	2.7063	−66
−65	0.000350	0.000714	0.01734	670800	670800	−187.49	1219.82	1032.32	−0.3912	3.0907	2.6996	−65
−64	0.000376	0.000766	0.01734	626503	626503	−187.08	1219.85	1032.77	−0.3901	3.0830	2.6929	−64
−63	0.000404	0.000822	0.01734	585316	585316	−186.67	1219.88	1033.21	−0.3891	3.0753	2.6862	−63
−62	0.000433	0.000882	0.01734	548041	547041	−186.26	1219.91	1033.65	−0.3881	3.0677	2.6730	−62
−61	0.000464	0.000945	0.01734	511446	511446	−185.85	1219.95	1034.09	−0.3870	3.0601	2.6730	−61
−60	0.000498	0.001013	0.01734	478317	478317	−185.44	1219.98	1034.54	−0.3860	3.0525	2.6665	−60
−59	0.000533	0.001086	0.01735	447495	447495	−185.03	1220.01	1034.98	−0.3850	3.0449	2.6600	−59
−58	0.000571	0.001163	0.01735	418803	418803	−184.61	1220.03	1035.42	−0.3839	3.0374	2.6535	−58
−57	0.000612	0.001246	0.01735	392068	392068	−184.20	1220.06	1035.86	−0.3829	3.0299	2.6470	−57
−56	0.000655	0.001333	0.01735	367172	367172	−183.78	1220.09	1036.30	−0.3819	3.0225	2.6406	−56
−55	0.000701	0.001427	0.01735	343970	343970	−183.37	1220.11	1036.75	−0.3808	3.0151	2.6342	−55
−54	0.000750	0.001526	0.01735	322336	322336	−182.95	1220.14	1037.19	−0.3798	3.0077	2.6279	−54
−53	0.000802	0.001632	0.01735	302157	302157	−182.53	1220.16	1037.63	−0.3788	3.0004	2.6216	−53
−52	0.000857	0.001745	0.01735	283335	283335	−182.11	1220.18	1038.07	−0.3778	2.9931	2.6153	−52
−51	0.000916	0.001865	0.01736	265773	265773	−181.69	1220.21	1038.52	−0.3767	2.9858	2.6091	−51
−50	0.000979	0.001992	0.01736	249381	249381	−181.27	1220.23	1038.96	−0.3757	2.9786	2.6029	−50
−49	0.001045	0.002128	0.01736	234067	234067	−180.85	1220.25	1039.40	−0.3747	2.9714	2.5967	−49
−48	0.001116	0.002272	0.01736	219766	219766	−180.42	1220.26	1039.84	−0.3736	2.9642	2.5906	−48
−47	0.001191	0.002425	0.01736	206398	206398	−180.00	1220.28	1040.28	−0.3726	2.9570	2.5844	−47
−46	0.001271	0.002587	0.01736	193909	193909	−179.57	1220.30	1040.73	−0.3716	2.9499	2.5784	−46
−45	0.001355	0.002760	0.01736	182231	182231	−179.14	1220.31	1041.17	−0.3705	2.9429	2.5723	−45
−44	0.001445	0.002943	0.01736	171304	171304	−178.72	1220.33	1041.61	−0.3695	2.9358	2.5663	−44
−43	0.001541	0.003137	0.01737	161084	161084	−178.29	1220.34	1042.05	−0.3685	2.9288	2.5603	−43
−42	0.001642	0.003343	0.01737	151518	151518	−177.86	1220.36	1042.50	−0.3675	2.9218	2.5544	−42
−41	0.001749	0.003562	0.01737	142566	142566	−177.43	1220.37	1042.94	−0.3664	2.9149	2.5485	−41
−40	0.001863	0.003793	0.01737	134176	134176	−177.00	1220.38	1043.38	−0.3654	2.9080	2.5426	−40
−39	0.001984	0.004039	0.01737	126322	126322	−176.57	1220.39	1043.82	−0.3644	2.9011	2.5367	−39
−38	0.002111	0.004299	0.01737	118959	118959	−176.13	1220.40	1044.27	−0.3633	2.8942	2.5309	−38
−37	0.002247	0.004574	0.01737	112058	112058	−175.70	1220.40	1044.71	−0.3623	2.8874	2.5251	−37
−36	0.002390	0.004866	0.01738	105592	105592	−175.26	1220.41	1045.15	−0.3613	2.8806	2.5193	−36
−35	0.002542	0.005175	0.01738	99522	99522	−174.83	1220.42	1045.59	−0.3603	2.8738	2.5136	−35
−34	0.002702	0.005502	0.01738	93828	93828	−174.39	1220.42	1046.03	−0.3592	2.8671	2.5078	−34
−33	0.002872	0.005848	0.01738	88489	88489	−173.95	1220.43	1046.48	−0.3582	2.8604	2.5022	−33
−32	0.003052	0.006213	0.01738	83474	83474	−173.51	1220.43	1046.92	−0.3572	2.8537	2.4965	−32
−31	0.003242	0.006600	0.01738	78763	78763	−173.07	1220.43	1047.36	−0.3561	2.8470	2.4909	−31
−30	0.003443	0.007009	0.01738	74341	74341	−172.63	1220.43	1047.80	−0.3551	2.8404	2.4853	−30
−29	0.003655	0.007441	0.01738	70187	70187	−172.19	1220.43	1048.25	−0.3541	2.8338	2.4797	−29
−28	0.003879	0.007898	0.01739	66282	66282	−171.74	1220.43	1048.69	−0.3531	2.8272	2.4742	−28
−27	0.004116	0.008380	0.01739	62613	62613	−171.30	1220.43	1049.13	−0.3520	2.8207	2.4687	−27
−26	0.004366	0.008890	0.01739	59161	59161	−170.86	1220.43	1049.57	−0.3510	2.8142	2.4632	−26
−25	0.004630	0.009428	0.01739	55915	55915	−170.41	1220.42	1050.01	−0.3500	2.8077	2.4577	−25
−24	0.004909	0.009995	0.01739	52861	52861	−169.96	1220.42	1050.46	−0.3489	2.8013	2.4523	−24
−23	0.005203	0.010594	0.01739	49986	49986	−169.51	1220.41	1050.90	−0.3479	2.7948	2.4469	−23
−22	0.005514	0.011226	0.01739	47281	47281	−169.07	1220.41	1051.34	−0.3469	2.7884	2.4415	−22
−21	0.005841	0.011892	0.01740	44733	44733	−168.62	1220.40	1051.78	−0.3459	2.7820	2.4362	−21
−20	0.006186	0.012595	0.01740	42333	42333	−168.16	1220.39	1052.22	−0.3448	2.7757	2.4309	−20
−19	0.006550	0.013336	0.01740	40073	40073	−167.71	1220.38	1052.67	−0.3438	2.7694	2.4256	−19
−18	0.006933	0.014117	0.01740	37943	37943	−167.26	1220.37	1053.11	−0.3428	2.7631	2.4203	−18
−17	0.007337	0.014939	0.01740	35934	35934	−166.81	1220.36	1053.55	−0.3418	2.7568	2.4151	−17
−16	0.007763	0.015806	0.01740	34041	34041	−166.35	1220.34	1053.99	−0.3407	2.7506	2.4098	−16
−15	0.008211	0.016718	0.01740	32256	32256	−165.90	1220.33	1054.43	−0.3397	2.7444	2.4046	−15
−14	0.008683	0.017678	0.01741	30572	30572	−165.44	1220.31	1054.87	−0.3387	2.7382	2.3995	−14

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

Temp., °F	Absolute Pressure		Specific Volume, ft^3/lb_w			Specific Enthalpy, Btu/lb_w			Specific Entropy, $Btu/lb_w \cdot °F$			Temp., °F
			Sat. Solid/Liq.	Evap.	Sat. Vapor	Sat. Solid/Liq.	Evap.	Sat. Vapor	Sat. Solid/Liq.	Evap.	Sat. Vapor	
t	p, psi	p, in. Hg	v_i/v_f	v_{ig}	v_g	h_i/h_f	h_{ig}	h_g	s_i/s_f	s_{ig}	s_g	t
−13	0.009179	0.018689	0.01741	28983	28983	−164.98	1220.30	1055.32	−0.3377	2.7320	2.3943	−13
−12	0.009702	0.019753	0.01741	27483	27483	−164.52	1220.28	1055.76	−0.3366	2.7259	2.3892	−12
−11	0.010252	0.020873	0.01741	26067	26067	−164.06	1220.26	1056.20	−0.3356	2.7197	2.3841	−11
−10	0.010830	0.022050	0.01741	24730	24730	−163.60	1220.24	1056.64	−0.3346	2.7136	2.3791	−10
−9	0.011438	0.023288	0.01741	23467	23467	−163.14	1220.22	1057.08	−0.3335	2.7076	2.3740	−9
−8	0.012077	0.024590	0.01741	22274	22274	−162.68	1220.20	1057.53	−0.3325	2.7015	2.3690	−8
−7	0.012749	0.025958	0.01742	21147	21147	−162.21	1220.18	1057.97	−0.3315	2.6955	2.3640	−7
−6	0.013456	0.027396	0.01742	20081	20081	−161.75	1220.16	1058.41	−0.3305	2.6895	2.3591	−6
−5	0.014197	0.028906	0.01742	19074	19074	−161.28	1220.13	1058.85	−0.3294	2.6836	2.3541	−5
−4	0.014977	0.030493	0.01742	18121	18121	−160.82	1220.11	1059.29	−0.3284	2.6776	2.3492	−4
−3	0.015795	0.032159	0.01742	17220	17220	−160.35	1220.08	1059.73	−0.3274	2.6717	2.3443	−3
−2	0.016654	0.033908	0.01742	16367	16367	−159.88	1220.05	1060.17	−0.3264	2.6658	2.3394	−2
−1	0.017556	0.035744	0.01742	15561	15561	−159.41	1220.02	1060.62	−0.3253	2.6599	2.3346	−1
0	0.018502	0.037671	0.01743	14797	14797	−158.94	1220.00	1061.06	−0.3243	2.6541	2.3298	0
1	0.019495	0.039693	0.01743	14073	14073	−158.47	1219.96	1061.50	−0.3233	2.6482	2.3249	1
2	0.020537	0.041813	0.01743	13388	13388	−157.99	1219.93	1061.94	−0.3223	2.6424	2.3202	2
3	0.021629	0.044037	0.01743	12740	12740	−157.52	1219.90	1062.38	−0.3212	2.6367	2.3154	3
4	0.022774	0.046369	0.01743	12125	12125	−157.05	1219.87	1062.82	−0.3202	2.6309	2.3107	4
5	0.023975	0.048813	0.01743	11543	11543	−156.57	1219.83	1063.26	−0.3192	2.6252	2.3060	5
6	0.025233	0.051375	0.01743	10991	10991	−156.09	1219.80	1063.70	−0.3182	2.6194	2.3013	6
7	0.026552	0.054059	0.01744	10468	10468	−155.62	1219.76	1064.14	−0.3171	2.6138	2.2966	7
8	0.027933	0.056872	0.01744	9971	9971	−155.14	1219.72	1064.58	−0.3161	2.6081	2.2920	8
9	0.029379	0.059817	0.01744	9500	9500	−154.66	1219.68	1065.03	−0.3151	2.6024	2.2873	9
10	0.030894	0.062901	0.01744	9054	9054	−154.18	1219.64	1065.47	−0.3141	2.5968	2.2827	10
11	0.032480	0.066131	0.01744	8630	8630	−153.70	1219.60	1065.91	−0.3130	2.5912	2.2782	11
12	0.034140	0.069511	0.01744	8228	8228	−153.21	1219.56	1066.35	−0.3120	2.5856	2.2736	12
13	0.035878	0.073047	0.01745	7846	7846	−152.73	1219.52	1066.79	−0.3110	2.5801	2.2691	13
14	0.037696	0.076748	0.01745	7483	7483	−152.24	1219.47	1067.23	−0.3100	2.5745	2.2645	14
15	0.039597	0.080621	0.01745	7139	7139	−151.76	1219.43	1067.67	−0.3089	2.5690	2.2600	15
16	0.041586	0.084671	0.01745	6811	6811	−151.27	1219.38	1068.11	−0.3079	2.5635	2.2556	16
17	0.043666	0.088905	0.01745	6501	6501	−150.78	1219.33	1068.55	−0.3069	2.5580	2.2511	17
18	0.045841	0.093332	0.01745	6205	6205	−150.30	1219.28	1068.99	−0.3059	2.5526	2.2467	18
19	0.048113	0.097960	0.01745	5924	5924	−149.81	1219.23	1069.43	−0.3049	2.5471	2.2423	19
20	0.050489	0.102796	0.01746	5657	5657	−149.32	1219.18	1069.87	−0.3038	2.5417	2.2379	20
21	0.052970	0.107849	0.01746	5404	5404	−148.82	1219.13	1070.31	−0.3028	2.5363	2.2335	21
22	0.055563	0.113128	0.01746	5162	5162	−148.33	1219.08	1070.75	−0.3018	2.5309	2.2292	22
23	0.058271	0.118641	0.01746	4932	4932	−147.84	1219.02	1071.19	−0.3008	2.5256	2.2248	23
24	0.061099	0.124398	0.01746	4714	4714	−147.34	1218.97	1071.63	−0.2997	2.5203	2.2205	24
25	0.064051	0.130408	0.01746	4506	4506	−146.85	1218.91	1072.07	−0.2987	2.5149	2.2162	25
26	0.067133	0.136684	0.01747	4308	4308	−146.35	1218.85	1072.50	−0.2977	2.5096	2.2119	26
27	0.070349	0.143233	0.01747	4119	4119	−145.85	1218.80	1072.94	−0.2967	2.5044	2.2077	27
28	0.073706	0.150066	0.01747	3940	3940	−145.35	1218.74	1073.38	−0.2956	2.4991	2.2035	28
29	0.077207	0.157195	0.01747	3769	3769	−144.85	1218.68	1073.82	−0.2946	2.4939	2.1992	29
30	0.080860	0.164632	0.01747	3606	3606	−144.35	1218.61	1074.26	−0.2936	2.4886	2.1951	30
31	0.084669	0.172387	0.01747	3450	3450	−143.85	1218.55	1074.70	−0.2926	2.4834	2.1909	31
32	0.088640	0.180474	0.01747	3302	3302	−143.35	1218.49	1075.14	−0.2915	2.4783	2.1867	32
32*	0.08865	0.18049	0.01602	3302.07	3302.09	−0.02	1075.15	1075.14	0.0000	2.1867	2.1867	32
33	0.09229	0.18791	0.01602	3178.15	3178.16	0.99	1074.59	1075.58	0.0020	2.1811	2.1832	33
34	0.09607	0.19559	0.01602	3059.47	3059.49	2.00	1074.02	1076.01	0.0041	2.1756	2.1796	34
35	0.09998	0.20355	0.01602	2945.66	2945.68	3.00	1073.45	1076.45	0.0061	2.1700	2.1761	35
36	0.10403	0.21180	0.01602	2836.60	2836.61	4.01	1072.88	1076.89	0.0081	2.1645	2.1726	36
37	0.10822	0.22035	0.01602	2732.13	2732.15	5.02	1072.32	1077.33	0.0102	2.1590	2.1692	37
38	0.11257	0.22919	0.01602	2631.88	2631.89	6.02	1071.75	1077.77	0.0122	2.1535	2.1657	38
39	0.11707	0.23835	0.01602	2535.86	2535.88	7.03	1071.18	1078.21	0.0142	2.1481	2.1623	39
40	0.12172	0.24783	0.01602	2443.67	2443.69	8.03	1070.62	1078.65	0.0162	2.1426	2.1589	40
41	0.12654	0.25765	0.01602	2355.22	2355.24	9.04	1070.05	1079.09	0.0182	2.1372	2.1554	41
42	0.13153	0.26780	0.01602	2270.42	2270.43	10.04	1069.48	1079.52	0.0202	2.1318	2.1521	42
43	0.13669	0.27831	0.01602	2189.02	2189.04	11.04	1068.92	1079.96	0.0222	2.1265	2.1487	43
44	0.14203	0.28918	0.01602	2110.92	2110.94	12.05	1068.35	1080.40	0.0242	2.1211	2.1454	44
45	0.14755	0.30042	0.01602	2035.91	2035.92	13.05	1067.79	1080.84	0.0262	2.1158	2.1420	45
46	0.15326	0.31205	0.01602	1963.85	1963.87	14.05	1067.22	1081.28	0.0282	2.1105	2.1387	46
47	0.15917	0.32407	0.01602	1894.71	1894.73	15.06	1066.66	1081.71	0.0302	2.1052	2.1354	47
48	0.16527	0.33650	0.01602	1828.28	1828.30	16.06	1066.09	1082.15	0.0321	2.1000	2.1321	48
49	0.17158	0.34935	0.01602	1764.44	1764.46	17.06	1065.53	1082.59	0.0341	2.0947	2.1288	49
50	0.17811	0.36263	0.01602	1703.18	1703.20	18.06	1064.96	1083.03	0.0361	2.0895	2.1256	50
51	0.18484	0.37635	0.01602	1644.25	1644.26	19.06	1064.40	1083.46	0.0381	2.0843	2.1224	51
52	0.19181	0.39053	0.01603	1587.64	1587.65	20.07	1063.83	1083.90	0.0400	2.0791	2.1191	52

*Extrapolated to represent metastable equilibrium with undercooled liquid.

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

Temp., °F	Absolute Pressure		Specific Volume, ft^3/lb_w			Specific Enthalpy, Btu/lb_w			Specific Entropy, $Btu/lb_w \cdot °F$			Temp., °F
t	p, psi	p, in. Hg	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
53	0.19900	0.40516	0.01603	1533.22	1533.24	21.07	1063.27	1084.34	0.0420	2.0740	2.1159	53
54	0.20643	0.42029	0.01603	1480.89	1480.91	22.07	1062.71	1084.77	0.0439	2.0689	2.1128	54
55	0.21410	0.43591	0.01603	1430.61	1430.62	23.07	1062.14	1085.21	0.0459	2.0637	2.1096	55
56	0.22202	0.45204	0.01603	1382.19	1382.21	24.07	1061.58	1085.65	0.0478	2.0586	2.1064	56
57	0.23020	0.46869	0.01603	1335.65	1335.67	25.07	1061.01	1086.08	0.0497	2.0536	2.1033	57
58	0.23864	0.48588	0.01603	1290.85	1290.87	26.07	1060.45	1086.52	0.0517	2.0485	2.1002	58
59	0.24735	0.50362	0.01603	1247.76	1247.78	27.07	1059.89	1086.96	0.0536	2.0435	2.0971	59
60	0.25635	0.52192	0.01604	1206.30	1206.32	28.07	1059.32	1087.39	0.0555	2.0385	2.0940	60
61	0.26562	0.54081	0.01604	1166.38	1166.40	29.07	1058.76	1087.83	0.0575	2.0334	2.0909	61
62	0.27519	0.56029	0.01604	1127.93	1127.95	30.07	1058.19	1088.27	0.0594	2.0285	2.0878	62
63	0.28506	0.58039	0.01604	1090.94	1090.96	31.07	1057.63	1088.70	0.0613	2.0235	2.0848	63
64	0.29524	0.60112	0.01604	1055.32	1055.33	32.07	1057.07	1089.14	0.0632	2.0186	2.0818	64
65	0.30574	0.62249	0.01604	1020.98	1021.00	33.07	1056.50	1089.57	0.0651	2.0136	2.0787	65
66	0.31656	0.64452	0.01604	987.95	987.97	34.07	1055.94	1090.01	0.0670	2.0087	2.0758	66
67	0.32772	0.66724	0.01605	956.11	956.12	35.07	1055.37	1090.44	0.0689	2.0039	2.0728	67
68	0.33921	0.69065	0.01605	925.44	925.45	36.07	1054.81	1090.88	0.0708	1.9990	2.0698	68
69	0.35107	0.71478	0.01605	895.86	895.87	37.07	1054.24	1091.31	0.0727	1.9941	2.0668	69
70	0.36328	0.73964	0.01605	867.34	867.36	38.07	1053.68	1091.75	0.0746	1.9893	2.0639	70
71	0.37586	0.76526	0.01605	839.87	839.88	39.07	1053.11	1092.18	0.0765	1.9845	2.0610	71
72	0.38882	0.79164	0.01606	813.37	813.39	40.07	1052.55	1092.61	0.0783	1.9797	2.0580	72
73	0.40217	0.81883	0.01606	787.85	787.87	41.07	1051.98	1093.05	0.0802	1.9749	2.0552	73
74	0.41592	0.84682	0.01606	763.19	763.21	42.06	1051.42	1093.48	0.0821	1.9702	2.0523	74
75	0.43008	0.87564	0.01606	739.42	739.44	43.06	1050.85	1093.92	0.0840	1.9654	2.0494	75
76	0.44465	0.90532	0.01606	716.51	726.53	44.06	1050.29	1094.35	0.0858	1.9607	2.0465	76
77	0.45966	0.93587	0.01607	694.38	699.80	45.06	1049.72	1094.78	0.0877	1.9560	2.0437	77
78	0.47510	0.96732	0.01607	673.05	673.06	46.06	1049.16	1095.22	0.0896	1.9513	2.0409	78
79	0.49100	0.99968	0.01607	652.44	652.46	47.06	1048.59	1095.65	0.0914	1.9466	2.0380	79
80	0.50736	1.03298	0.01607	632.54	632.56	48.06	1048.03	1096.08	0.0933	1.9420	2.0352	80
81	0.52419	1.06725	0.01608	613.35	613.37	49.06	1047.46	1096.51	0.0951	1.9373	2.0324	81
82	0.54150	1.10250	0.01608	594.82	594.84	50.05	1046.89	1096.95	0.0970	1.9327	2.0297	82
83	0.55931	1.13877	0.01608	576.90	576.92	51.05	1046.33	1097.38	0.0988	1.9281	2.0269	83
84	0.57763	1.17606	0.01608	559.63	559.65	52.05	1045.76	1097.81	0.1006	1.9235	2.0242	84
85	0.59647	1.21442	0.01609	542.93	542.94	53.05	1045.19	1098.24	0.1025	1.9189	2.0214	85
86	0.61584	1.25385	0.01609	526.80	526.81	54.05	1044.63	1098.67	0.1043	1.9144	2.0187	86
87	0.63575	1.29440	0.01609	511.21	511.22	55.05	1044.06	1099.11	0.1061	1.9098	2.0160	87
88	0.65622	1.33608	0.01609	496.14	496.15	56.05	1043.49	1099.54	0.1080	1.9053	2.0133	88
89	0.67726	1.37892	0.01610	481.60	481.61	57.04	1042.92	1099.97	0.1098	1.9008	2.0106	89
90	0.69889	1.42295	0.01610	467.52	467.53	58.04	1042.36	1100.40	0.1116	1.8963	2.0079	90
91	0.72111	1.46820	0.01610	453.91	453.93	59.04	1041.79	1100.83	0.1134	1.8918	2.0053	91
92	0.74394	1.51468	0.01611	440.76	440.78	60.04	1041.22	1101.26	0.1152	1.8874	2.0026	92
93	0.76740	1.56244	0.01611	428.04	428.06	61.04	1040.65	1101.69	0.1170	1.8829	2.0000	93
94	0.79150	1.61151	0.01611	415.74	415.76	62.04	1040.08	1102.12	0.1188	1.8785	1.9973	94
95	0.81625	1.66189	0.01612	403.84	403.86	63.03	1039.51	1102.55	0.1206	1.8741	1.9947	95
96	0.84166	1.71364	0.01612	392.33	392.34	64.03	1038.95	1102.98	0.1224	1.8697	1.9921	96
97	0.86776	1.76678	0.01612	381.20	381.21	65.03	1038.38	1103.41	0.1242	1.8653	1.9895	97
98	0.89456	1.82134	0.01612	370.42	370.44	66.03	1037.81	1103.84	0.1260	1.8610	1.9870	98
99	0.92207	1.87736	0.01613	359.99	360.01	67.03	1037.24	1104.26	0.1278	1.8566	1.9844	99
100	0.95031	1.93485	0.01613	349.91	349.92	68.03	1036.67	1104.69	0.1296	1.8523	1.9819	100
101	0.97930	1.99387	0.01613	340.14	340.15	69.03	1036.10	1105.12	0.1314	1.8479	1.9793	101
102	1.00904	2.05443	0.01614	330.69	330.71	70.02	1035.53	1105.55	0.1332	1.8436	1.9768	102
103	1.03956	2.11667	0.01614	321.53	321.55	71.02	1034.95	1105.98	0.1349	1.8393	1.9743	103
104	1.07088	2.18034	0.01614	312.67	312.69	72.02	1034.38	1106.40	0.1367	1.8351	1.9718	104
105	1.10301	2.24575	0.01615	304.08	304.10	73.02	1033.81	1106.83	0.1385	1.8308	1.9693	105
106	1.13597	2.31285	0.01615	295.76	295.77	74.02	1033.24	1107.26	0.1402	1.8266	1.9668	106
107	1.16977	2.38168	0.01616	287.71	287.73	75.01	1032.67	1107.68	0.1420	1.8223	1.9643	107
108	1.20444	2.45226	0.01616	279.91	279.92	76.01	1032.10	1108.11	0.1438	1.8181	1.9619	108
109	1.23999	2.52464	0.01616	272.34	272.36	77.01	1031.52	1108.54	0.1455	1.8139	1.9594	109
110	1.27644	2.59885	0.01617	265.02	265.03	78.01	1030.95	1108.96	0.1473	1.8097	1.9570	110
111	1.31381	2.67494	0.01617	257.91	257.93	79.01	1030.38	1109.39	0.1490	1.8055	1.9546	111
112	1.35212	2.75293	0.01617	251.02	251.04	80.01	1029.80	1109.81	0.1508	1.8014	1.9521	112
113	1.39138	2.83288	0.01618	244.36	244.38	81.01	1029.23	1110.24	0.1525	1.7972	1.9497	113
114	1.43162	2.91481	0.01618	237.89	237.90	82.00	1028.66	1110.66	0.1543	1.7931	1.9474	114
115	1.47286	2.99878	0.01619	231.62	231.63	83.00	1028.08	1111.09	0.1560	1.7890	1.9450	115
116	1.51512	3.08481	0.01619	225.53	225.55	84.00	1027.51	1111.51	0.1577	1.7849	1.9426	116
117	1.55842	3.17296	0.01619	219.63	219.65	85.00	1026.93	1111.93	0.1595	1.7808	1.9402	117
118	1.60277	3.26327	0.01620	213.91	213.93	86.00	1026.36	1112.36	0.1612	1.7767	1.9379	118
119	1.64820	3.35577	0.01620	208.36	208.37	87.00	1025.78	1112.78	0.1629	1.7726	1.9356	119
120	1.69474	3.45052	0.01620	202.98	202.99	88.00	1025.20	1113.20	0.1647	1.7686	1.9332	120

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

Temp., °F	Absolute Pressure		Specific Volume, ft³/lb_w			Specific Enthalpy, Btu/lb_w			Specific Entropy, Btu/lb_w·°F			Temp., °F
			Sat. Liquid	Evap.	Sat. Vapor	Sat. Liquid	Evap.	Sat. Vapor	Sat. Liquid	Evap.	Sat. Vapor	
t	p, psi	p, in. Hg	v_f	v_{fg}	v_g	h_f	h_{fg}	h_g	s_f	s_{fg}	s_g	t
121	1.74240	3.54755	0.01621	197.76	197.76	89.00	1024.63	1113.62	0.1664	1.7645	1.9309	121
122	1.79117	3.64691	0.01621	192.69	192.69	90.00	1024.05	1114.05	0.1681	1.7605	1.9286	122
123	1.84117	3.74863	0.01622	187.78	187.78	90.99	1023.47	1114.47	0.1698	1.7565	1.9263	123
124	1.89233	3.85282	0.01622	182.98	182.99	91.99	1022.90	1114.89	0.1715	1.7525	1.9240	124
125	1.94470	3.95945	0.01623	178.34	178.36	92.99	1022.32	1115.31	0.1732	1.7485	1.9217	125
126	1.99831	4.06860	0.01623	173.85	173.86	93.99	1021.74	1115.73	0.1749	1.7445	1.9195	126
127	2.05318	4.18032	0.01623	169.47	169.49	94.99	1021.16	1116.15	0.1766	1.7406	1.9172	127
128	2.10934	4.29465	0.01624	165.23	165.25	95.99	1020.58	1116.57	0.1783	1.7366	1.9150	128
129	2.16680	4.41165	0.01624	161.11	161.12	96.99	1020.00	1116.99	0.1800	1.7327	1.9127	129
130	2.22560	4.53136	0.01625	157.11	157.12	97.99	1019.42	1117.41	0.1817	1.7288	1.9105	130
131	2.28576	4.65384	0.01625	153.22	153.23	98.99	1018.84	1117.83	0.1834	1.7249	1.9083	131
132	2.34730	4.77914	0.01626	149.44	149.46	99.99	1018.26	1118.25	0.1851	1.7210	1.9061	132
133	2.41025	4.90730	0.01626	145.77	145.78	100.99	1017.68	1118.67	0.1868	1.7171	1.9039	133
134	2.47463	5.03839	0.01627	142.21	142.23	101.99	1017.10	1119.08	0.1885	1.7132	1.9017	134
135	2.54048	5.17246	0.01627	138.74	138.76	102.99	1016.52	1119.50	0.1902	1.7093	1.8995	135
136	2.60782	5.30956	0.01627	135.37	135.39	103.98	1015.93	1119.92	0.1919	1.7055	1.8974	136
137	2.67667	5.44975	0.01628	132.10	132.12	104.98	1015.35	1120.34	0.1935	1.7017	1.8952	137
138	2.74707	5.59308	0.01628	128.92	128.94	105.98	1014.77	1120.75	0.1952	1.6978	1.8930	138
139	2.81903	5.73961	0.01629	125.83	125.85	106.98	1014.18	1121.17	0.1969	1.6940	1.8909	139
140	2.89260	5.88939	0.01629	122.82	122.84	107.98	1013.60	1121.58	0.1985	1.6902	1.8888	140
141	2.96780	6.04250	0.01630	119.90	119.92	108.98	1013.01	1122.00	0.2002	1.6864	1.8867	141
142	3.04465	6.19897	0.01630	117.05	117.07	109.98	1012.43	1122.41	0.2019	1.6827	1.8845	142
143	3.12320	6.35888	0.01631	114.29	114.31	110.98	1011.84	1122.83	0.2035	1.6789	1.8824	143
144	3.20345	6.52229	0.01631	111.60	111.62	111.98	1011.26	1123.24	0.2052	1.6752	1.8803	144
145	3.28546	6.68926	0.01632	108.99	109.00	112.98	1010.67	1123.66	0.2068	1.6714	1.8783	145
146	3.36924	6.85984	0.01632	106.44	106.45	113.98	1010.09	1124.07	0.2085	1.6677	1.8762	146
147	3.45483	7.03410	0.01633	103.96	103.98	114.98	1009.50	1124.48	0.2101	1.6640	1.8741	147
148	3.54226	7.21211	0.01633	101.55	101.57	115.98	1008.91	1124.89	0.2118	1.6603	1.8721	148
149	3.63156	7.39393	0.01634	99.21	99.22	116.98	1008.32	1125.31	0.2134	1.6566	1.8700	149
150	3.72277	7.57962	0.01634	96.93	96.94	117.98	1007.73	1125.72	0.2151	1.6529	1.8680	150
151	3.81591	7.76925	0.01635	94.70	94.72	118.99	1007.14	1126.13	0.2167	1.6492	1.8659	151
152	3.91101	7.96289	0.01635	92.54	92.56	119.99	1006.55	1126.54	0.2184	1.6455	1.8639	152
153	4.00812	8.16061	0.01636	90.44	90.46	120.99	1005.96	1126.95	0.2200	1.6419	1.8619	153
154	4.10727	8.36247	0.01636	88.39	88.41	121.99	1005.37	1127.36	0.2216	1.6383	1.8599	154
155	4.20848	8.56854	0.01637	86.40	86.41	122.99	1004.78	1127.77	0.2233	1.6346	1.8579	155
156	4.31180	8.77890	0.01637	84.45	84.47	123.99	1004.19	1128.18	0.2249	1.6310	1.8559	156
157	4.41725	8.99360	0.01638	82.56	82.58	124.99	1003.60	1128.59	0.2265	1.6274	1.8539	157
158	4.52488	9.21274	0.01638	80.72	80.73	125.99	1003.00	1128.99	0.2281	1.6238	1.8519	158
159	4.63472	9.43637	0.01639	78.92	78.94	126.99	1002.41	1129.40	0.2297	1.6202	1.8500	159
160	4.7468	9.6646	0.01639	77.175	77.192	127.99	1001.82	1129.81	0.2314	1.6167	1.8480	160
161	4.8612	9.8974	0.01640	75.471	75.488	128.99	1001.22	1130.22	0.2330	1.6131	1.8461	161
162	4.9778	10.1350	0.01640	73.812	73.829	130.00	1000.63	1130.62	0.2346	1.6095	1.8441	162
163	5.0969	10.3774	0.01641	72.196	72.213	131.00	1000.03	1131.03	0.2362	1.6060	1.8422	163
164	5.2183	10.6246	0.01642	70.619	70.636	132.00	999.43	1131.43	0.2378	1.6025	1.8403	164
165	5.3422	10.8768	0.01642	69.084	69.101	133.00	998.84	1131.84	0.2394	1.5989	1.8383	165
166	5.4685	11.1340	0.01643	67.587	67.604	134.00	998.24	1132.24	0.2410	1.5954	1.8364	166
167	5.5974	11.3963	0.01643	66.130	66.146	135.00	997.64	1132.64	0.2426	1.5919	1.8345	167
168	5.7287	11.6638	0.01644	64.707	64.723	136.01	997.04	1133.05	0.2442	1.5884	1.8326	168
169	5.8627	11.9366	0.01644	63.320	63.336	137.01	996.44	1133.45	0.2458	1.5850	1.8308	169
170	5.9993	12.2148	0.01645	61.969	61.986	138.01	995.84	1133.85	0.2474	1.5815	1.8289	170
171	6.1386	12.4983	0.01646	60.649	60.666	139.01	995.24	1134.25	0.2490	1.5780	1.8270	171
172	6.2806	12.7874	0.01646	59.363	59.380	140.01	994.64	1134.66	0.2506	1.5746	1.8251	172
173	6.4253	13.0821	0.01647	58.112	58.128	141.02	994.04	1135.06	0.2521	1.5711	1.8233	173
174	6.5729	13.3825	0.01647	56.887	56.904	142.02	993.44	1135.46	0.2537	1.5677	1.8214	174
175	6.7232	13.6886	0.01648	55.694	55.711	143.02	992.83	1135.86	0.2553	1.5643	1.8196	175
176	6.8765	14.0006	0.01648	54.532	54.549	144.02	992.23	1136.26	0.2569	1.5609	1.8178	176
177	7.0327	14.3186	0.01649	53.397	53.414	145.03	991.63	1136.65	0.2585	1.5575	1.8159	177
178	7.1918	14.6426	0.01650	52.290	52.307	146.03	991.02	1137.05	0.2600	1.5541	1.8141	178
179	7.3539	14.9727	0.01650	51.210	51.226	147.03	990.42	1137.45	0.2616	1.5507	1.8123	179
180	7.5191	15.3091	0.01651	50.155	50.171	148.04	989.81	1137.85	0.2632	1.5473	1.8105	180
181	7.6874	15.6518	0.01651	49.126	49.143	149.04	989.20	1138.24	0.2647	1.5440	1.8087	181
182	7.8589	16.0008	0.01652	48.122	48.138	150.04	988.60	1138.64	0.2663	1.5406	1.8069	182
183	8.0335	16.3564	0.01653	47.142	47.158	151.05	987.99	1139.03	0.2679	1.5373	1.8051	183
184	8.2114	16.7185	0.01653	46.185	46.202	152.05	987.38	1139.43	0.2694	1.5339	1.8034	184
185	8.3926	17.0874	0.01654	45.251	45.267	153.05	986.77	1139.82	0.2710	1.5306	1.8016	185
186	8.5770	17.4630	0.01654	44.339	44.356	154.06	986.16	1140.22	0.2725	1.5273	1.7998	186
187	8.7649	17.8455	0.01655	43.448	43.465	155.06	985.55	1140.61	0.2741	1.5240	1.7981	187
188	8.9562	18.2350	0.01656	42.579	42.595	156.07	984.94	1141.00	0.2756	1.5207	1.7963	188
189	9.1510	18.6316	0.01656	41.730	41.746	157.07	984.32	1141.39	0.2772	1.5174	1.7946	189

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

Temp., °F	Absolute Pressure		Specific Volume, ft^3/lb_w			Specific Enthalpy, Btu/lb_w			Specific Entropy, $Btu/lb_w \cdot °F$			Temp., °F
t	p, psi	p, in. Hg	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
190	9.3493	19.0353	0.01657	40.901	40.918	158.07	983.71	1141.78	0.2787	1.5141	1.7929	190
191	9.5512	19.4464	0.01658	40.092	40.108	159.08	983.10	1142.18	0.2803	1.5109	1.7911	191
192	9.7567	19.8648	0.01658	39.301	39.317	160.08	982.48	1142.57	0.2818	1.5076	1.7894	192
193	9.9659	20.2907	0.01659	38.528	38.544	161.09	981.87	1142.95	0.2834	1.5043	1.7877	193
194	10.1788	20.7242	0.01659	37.774	37.790	162.09	981.25	1143.34	0.2849	1.5011	1.7860	194
195	10.3955	21.1653	0.01660	37.035	37.052	163.10	980.63	1143.73	0.2864	1.4979	1.7843	195
196	10.6160	21.6143	0.01661	36.314	36.331	164.10	980.02	1144.12	0.2880	1.4946	1.7826	196
197	10.8404	22.0712	0.01661	35.611	35.628	165.11	979.40	1144.51	0.2895	1.4914	1.7809	197
198	11.0687	22.5361	0.01662	34.923	34.940	166.11	978.78	1144.89	0.2910	1.4882	1.7792	198
199	11.3010	23.0091	0.01663	34.251	34.268	167.12	978.16	1145.28	0.2926	1.4850	1.7776	199
200	11.5374	23.4904	0.01663	33.594	33.610	168.13	977.54	1145.66	0.2941	1.4818	1.7759	200
201	11.7779	23.9800	0.01664	32.951	32.968	169.13	976.92	1146.05	0.2956	1.4786	1.7742	201
202	12.0225	24.4780	0.01665	32.324	32.340	170.14	976.29	1146.43	0.2971	1.4755	1.7726	202
203	12.2713	24.9847	0.01665	31.710	31.726	171.14	975.67	1146.81	0.2986	1.4723	1.7709	203
204	12.5244	25.5000	0.01666	31.110	31.127	172.15	975.05	1147.20	0.3002	1.4691	1.7693	204
205	12.7819	26.0241	0.01667	30.523	30.540	173.16	974.42	1147.58	0.3017	1.4660	1.7677	205
206	13.0436	26.5571	0.01667	29.949	29.965	174.16	973.80	1147.96	0.3032	1.4628	1.7660	206
207	13.3099	27.0991	0.01668	29.388	29.404	175.17	973.17	1148.34	0.3047	1.4597	1.7644	207
208	13.5806	27.6503	0.01669	28.839	28.856	176.18	972.54	1148.72	0.3062	1.4566	1.7628	208
209	13.8558	28.2108	0.01669	28.303	28.319	177.18	971.92	1149.10	0.3077	1.4535	1.7612	209
210	14.1357	28.7806	0.01670	27.778	27.795	178.19	971.29	1149.48	0.3092	1.4503	1.7596	210
212	14.7096	29.9489	0.01671	26.763	26.780	180.20	970.03	1150.23	0.3122	1.4442	1.7564	212
214	15.3025	31.1563	0.01673	25.790	25.807	182.22	968.76	1150.98	0.3152	1.4380	1.7532	214
216	15.9152	32.4036	0.01674	24.861	24.878	184.24	967.50	1151.73	0.3182	1.4319	1.7501	216
218	16.5479	33.6919	0.01676	23.970	23.987	186.25	966.23	1152.48	0.3212	1.4258	1.7469	218
220	17.2013	35.0218	0.01677	23.118	23.134	188.27	964.95	1153.22	0.3241	1.4197	1.7438	220
222	17.8759	36.3956	0.01679	22.299	22.316	190.29	963.67	1153.96	0.3271	1.4136	1.7407	222
224	18.5721	37.8131	0.01680	21.516	21.533	192.31	962.39	1154.70	0.3301	1.4076	1.7377	224
226	19.2905	39.2758	0.01682	20.765	20.782	194.33	961.11	1155.43	0.3330	1.4016	1.7347	226
228	20.0316	40.7848	0.01683	20.045	20.062	196.35	959.82	1156.16	0.3359	1.3957	1.7316	228
230	20.7961	42.3412	0.01684	19.355	19.372	198.37	958.52	1156.89	0.3389	1.3898	1.7287	230
232	21.5843	43.9461	0.01686	18.692	18.709	200.39	957.22	1157.62	0.3418	1.3839	1.7257	232
234	22.3970	45.6006	0.01688	18.056	18.073	202.41	955.92	1158.34	0.3447	1.3780	1.7227	234
236	23.2345	47.3060	0.01689	17.446	17.463	204.44	954.62	1159.06	0.3476	1.3722	1.7198	236
238	24.0977	49.0633	0.01691	16.860	16.877	206.46	953.31	1159.77	0.3505	1.3664	1.7169	238
240	24.9869	50.8738	0.01692	16.298	16.314	208.49	952.00	1160.48	0.3534	1.3606	1.7140	240
242	25.9028	52.7386	0.01694	15.757	15.774	210.51	950.68	1161.19	0.3563	1.3548	1.7111	242
244	26.8461	54.6591	0.01695	15.238	15.255	212.54	949.35	1161.90	0.3592	1.3491	1.7083	244
246	27.8172	56.6364	0.01697	14.739	14.756	214.57	948.03	1162.60	0.3621	1.3434	1.7055	246
248	28.8169	58.6717	0.01698	14.259	14.276	216.60	946.70	1163.29	0.3649	1.3377	1.7026	248
250	29.8457	60.7664	0.01700	13.798	13.815	218.63	945.36	1163.99	0.3678	1.3321	1.6998	250
252	30.9043	62.9218	0.01702	13.355	13.372	220.66	944.02	1164.68	0.3706	1.3264	1.6971	252
254	31.9934	65.1391	0.01703	12.928	12.945	222.69	942.68	1165.37	0.3735	1.3208	1.6943	254
256	33.1135	67.4197	0.01705	12.526	12.147	226.73	939.99	1166.72	0.3764	1.3153	1.6916	256
258	34.2653	69.7649	0.01707	12.123	12.140	226.76	939.97	1166.73	0.3792	1.3097	1.6889	258
260	35.4496	72.1760	0.01708	11.742	11.759	228.79	938.61	1167.40	0.3820	1.3042	1.6862	260
262	36.6669	74.6545	0.01710	11.376	11.393	230.83	937.25	1168.08	0.3848	1.2987	1.6835	262
264	37.9180	77.2017	0.01712	11.024	11.041	232.87	935.88	1168.74	0.3876	1.2932	1.6808	264
266	39.2035	79.8190	0.01714	10.684	10.701	234.90	934.50	1169.41	0.3904	1.2877	1.6781	266
268	40.5241	82.5078	0.01715	10.357	10.374	236.94	933.12	1170.07	0.3932	1.2823	1.6755	268
270	41.8806	85.2697	0.01717	10.042	10.059	238.98	931.74	1170.72	0.3960	1.2769	1.6729	270
272	43.2736	88.1059	0.01719	9.737	9.755	241.03	930.35	1171.38	0.3988	1.2715	1.6703	272
274	44.7040	91.0181	0.01721	9.445	9.462	243.07	928.95	1172.02	0.4016	1.2661	1.6677	274
276	46.1723	94.0076	0.01722	9.162	9.179	245.11	927.55	1172.67	0.4044	1.2608	1.6651	276
278	47.6794	97.0761	0.01724	8.890	8.907	247.16	926.15	1173.31	0.4071	1.2554	1.6626	278
280	49.2260	100.2250	0.01726	8.627	8.644	249.20	924.74	1173.94	0.4099	1.2501	1.6600	280
282	50.8128	103.4558	0.01728	8.373	8.390	251.25	923.32	1174.57	0.4127	1.2448	1.6575	282
284	52.4406	106.7701	0.01730	8.128	8.146	253.30	921.90	1175.20	0.4154	1.2396	1.6550	284
286	54.1103	110.1695	0.01731	7.892	7.910	255.35	920.47	1175.82	0.4182	1.2343	1.6525	286
288	55.8225	113.6556	0.01733	7.664	7.681	257.40	919.03	1176.44	0.4209	1.2291	1.6500	288
290	57.5780	117.2299	0.01735	7.444	7.461	259.45	917.59	1177.05	0.4236	1.2239	1.6476	290
292	59.3777	120.8941	0.01737	7.231	7.248	261.51	916.15	1177.66	0.4264	1.2187	1.6451	292
294	61.2224	124.6498	0.01739	7.026	7.043	263.56	914.69	1178.26	0.4291	1.2136	1.6427	294
296	63.1128	128.4987	0.01741	6.827	6.844	265.62	913.24	1178.86	0.4318	1.2084	1.6402	296
298	65.0498	132.4425	0.01743	6.635	6.652	267.68	911.77	1179.45	0.4345	1.2033	1.6378	298
300	67.0341	136.4827	0.01745	6.450	6.467	269.74	910.30	1180.04	0.4372	1.1982	1.6354	300

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, ft^3/lb_{da}, 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, 1545.32 $ft \cdot lb_f / lb\ mol \cdot °R$
T = absolute temperature, °R

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:

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

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

$$v = 0.7543(t+459.67)(1+1.6078W)/p$$

where

v = specific volume, ft^3/lb_{da}
t = dry-bulb temperature, °F
W = humidity ratio, lb_w/lb_{da}
p = total pressure, in. Hg

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 Btu/lb_{da} and h_g is the specific enthalpy for saturated water vapor in Btu/lb_w at the temperature of the mixture. As an approximation,

$$h_{da} \approx 0.240t \tag{30}$$

$$h_g \approx 1061 + 0.444t \tag{31}$$

where t is the dry-bulb temperature in °F. The moist air specific enthalpy in Btu/lb_{da} then becomes

$$h = 0.240t + W(1061 + 0.444t) \tag{32}$$

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 Btu/lb_w 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

$$h_w^* \approx t^* - 32 \tag{34}$$

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

$$W = \frac{(1093 - 0.556t^*)W_s^* - 0.240(t - t^*)}{1093 + 0.444t - t^*} \tag{35}$$

where t and t^* are in °F.

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 32 to 200°F,

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

For temperatures below 32°F,

$$t_d = 90.12 + 26.142\alpha + 0.8927\alpha^2 \quad (38)$$

where

t_d = dew-point temperature, °F
α = ln p_w
p_w = water vapor partial pressure, psia
C_{14} = 100.45
C_{15} = 33.193
C_{16} = 2.319
C_{17} = 0.17074
C_{18} = 1.2063

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):

$$W_s = 0.62198 \frac{f p_{ws}}{p - f p_{ws}} \quad (23a)$$

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

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)

	14.50 psia		72.52 psia		145.04 psia	
T, °R	*f*	EMU E+04	*f*	EMU E+04	*f*	EMU E+04
311.67	1.0105	134	1.0540	66	1.1130	136
491.67	1.0039	2	1.0177	10	1.0353	19
671.67	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 –80 to 200°F. The properties of intermediate moist air states can be calculated using the degree of saturation μ:

$$\text{Volume} \quad v = v_{da} + \mu v_{as} \quad (39)$$

$$\text{Enthalpy} \quad h = h_{da} + \mu h_{as} \quad (40)$$

$$\text{Entropy} \quad s = s_{da} + \mu s_{as} \quad (41)$$

These equations are accurate to about 160°F. 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.

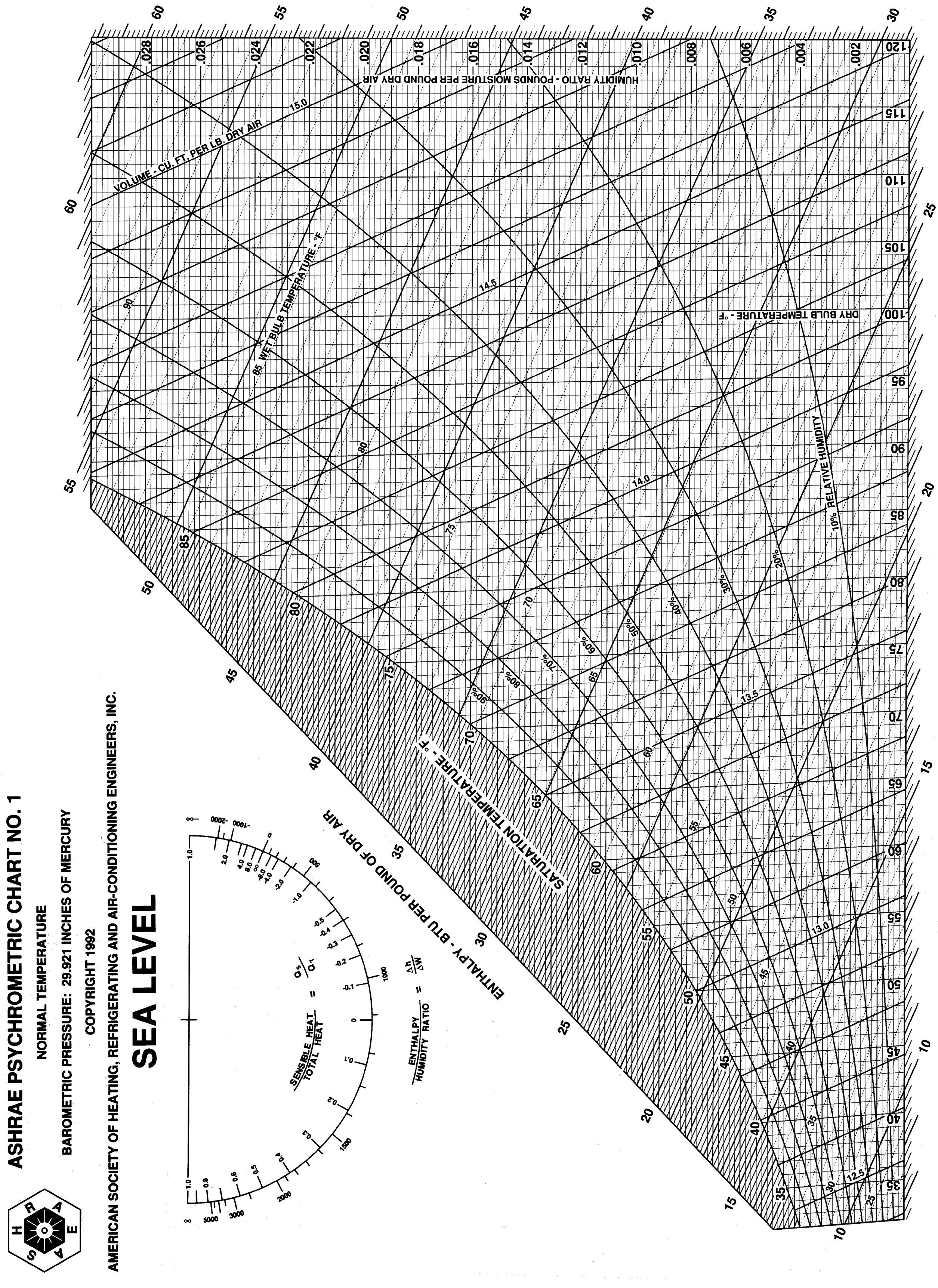

Fig. 1 ASHRAE Psychrometric Chart No. 1

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

Charts 1, 2, and 3 are for sea level pressure, Chart 4 is for 5000 ft altitude (24.89 in. Hg), and Chart 5 is for 7500 ft altitude (22.65 in. Hg). 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, 4, 5	Normal temperature	32 to 120°F
Chart 2	Low temperature	–40 to 50°F
Chart 3	High temperature	60 to 250°F

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 4 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 5000 ft (Chart 4):

Chart No.	db	wb	h	W	rh	v
1	100	81	44.6	0.0186	45	14.5
4	100	81	49.8	0.0234	46	17.6

Figure 1, which is ASHRAE Psychrometric Chart No. 1, shows humidity ratio lines (horizontal) for the range from 0 (dry air) to 0.03 lb_w/lb_{da}. 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 100°F dry-bulb temperature, 65°F thermodynamic wet-bulb temperature, and 29.921 in. Hg 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 100°F dry-bulb temperature and 65°F thermodynamic wet-bulb temperature lines. Read **humidity ratio** $W = 0.00523$ lb_w/lb_{da}.

The **enthalpy** can be found by using two triangles to draw a line parallel to the nearest enthalpy line [30 Btu/lb_{da}] through the state point to the nearest edge scale. Read $h = 29.80$ Btu/lb_{da}.

Dew-point temperature can be read at the intersection of $W = 0.00523$ lb_w/lb_{da} with the saturation curve. Thus, $t_d = 40$°F.

Relative humidity ϕ can be estimated directly. Thus, $\phi = 13\%$.

Specific volume can be found by linear interpolation between the volume lines for 14.0 and 14.5 ft^3/lb_{da}. Thus, $v = 14.22$ ft^3/lb_{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 29.921 in. Hg.

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

$$_1q_2 = \dot{m}_{da}(h_2 - h_1) \qquad (42)$$

Example 2. Moist air, saturated at 35°F, enters a heating coil at a rate of 20,000 cfm. Air leaves the coil at 100°F. Find the required rate of heat addition.

Solution: Figure 3 schematically shows the solution. State 1 is located on the saturation curve at 35°F. Thus, $h_1 = 13.01$ Btu/lb_{da}, $W_1 = 0.00428$ lb_w/lb_{da}, and $v_1 = 12.55$ ft^3/lb_{da}. State 2 is located at the intersection of $t = 100$°F and $W_2 = W_1 = 0.00428$ lb_w/lb_{da}. Thus, $h_2 = 28.77$ Btu/lb_{da}. The mass flow of dry air is

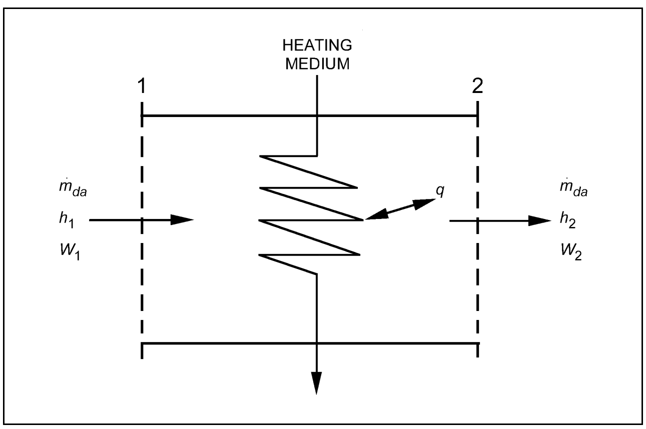

Fig. 2 Schematic of Device for Heating Moist Air

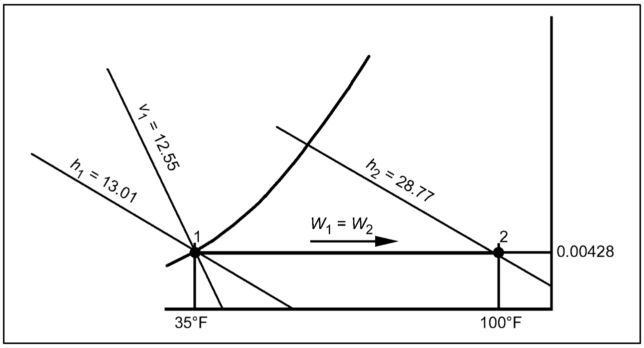

Fig. 3 Schematic Solution for Example 2

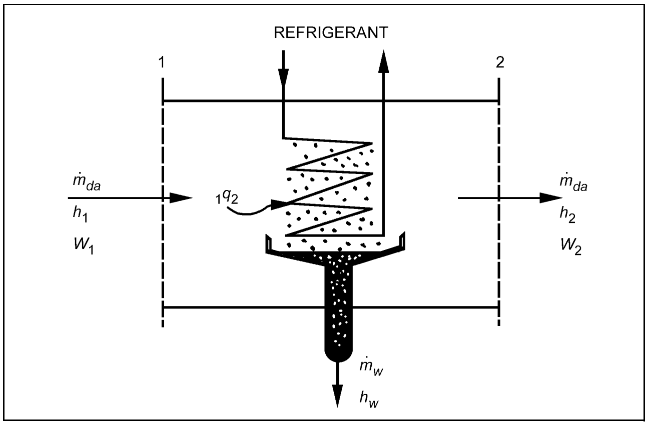

Fig. 4 Schematic of Device for Cooling Moist Air

$$\dot{m}_{da} = (20{,}000 \times 60)/12.55 = 95{,}620 \text{ lb}_{da}/\text{h}$$

From Equation (42),

$${}_1q_2 = (95{,}620)(28.77 - 13.01) = 1{,}507{,}000 \text{ Btu/h}$$

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,

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

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

Example 3. Moist air at 85°F dry-bulb temperature and 50% rh enters a cooling coil at 10,000 cfm and is processed to a final saturation condition at 50°F. Find the tons of refrigeration required.

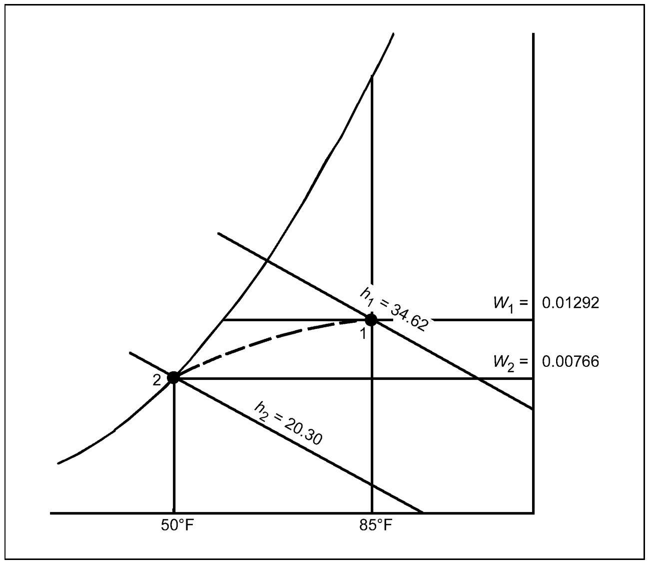

Fig. 5 Schematic Solution for Example 3

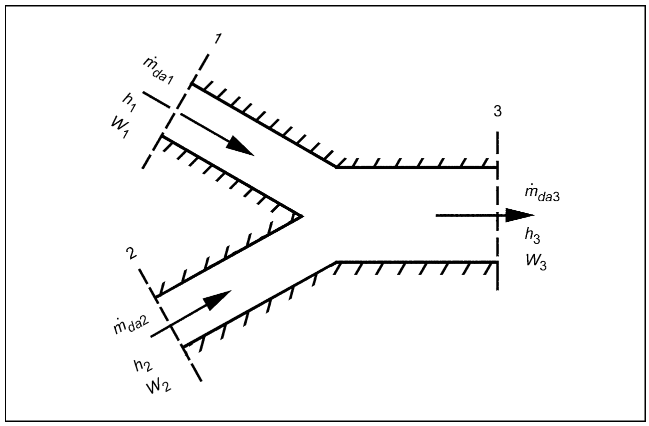

Fig. 6 Adiabatic Mixing of Two Moist Airstreams

Solution: Figure 5 shows the schematic solution. State 1 is located at the intersection of t = 85°F and ϕ = 50%. Thus, h_1 = 34.62 Btu/lb$_{da}$, W_1 = 0.01292 lb$_w$/lb$_{da}$, and v_1 = 14.01 ft^3/lb$_{da}$. State 2 is located on the saturation curve at 50°F. Thus, h_2 = 20.30 Btu/lb$_{da}$ and W_2 = 0.00766 lb$_w$/lb$_{da}$. From Table 2, h_{w2} = 18.11 Btu/lb$_w$. The mass flow of dry air is

$$\dot{m}_{da} = 10{,}000/14.01 = 713.8 \text{ lb}_{da}/\text{min}$$

From Equation (44),

$$\begin{aligned} {}_1q_2 &= 713.8[(34.62 - 20.30) - (0.01292 - 0.00766)(18.11)] \\ &= 10{,}150 \text{ Btu/min, or } 50.75 \text{ tons of refrigeration} \end{aligned}$$

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:

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

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

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

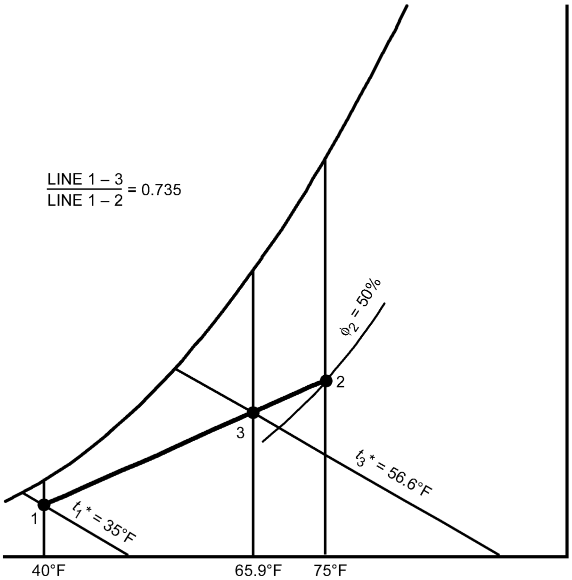

Fig. 7 Schematic Solution for Example 4

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 5000 cfm of outdoor air at 40°F dry-bulb temperature and 35°F thermodynamic wet-bulb temperature is adiabatically mixed with 15,000 cfm of recirculated air at 75°F 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 = 12.65 ft³/lb$_{da}$, and v_2 = 13.68 ft³/lb$_{da}$. Therefore,

$$\dot{m}_{da1} = 5000/12.65 = 395 \text{ lb}_{da}/\text{min}$$

$$\dot{m}_{da2} = 15{,}000/13.68 = 1096 \text{ lb}_{da}/\text{min}$$

According to Equation (45),

$$\frac{\text{Line 3–2}}{\text{Line 1–3}} = \frac{\dot{m}_{da1}}{\dot{m}_{da2}} \text{ or } \frac{\text{Line 1–3}}{\text{Line 1–2}} = \frac{\dot{m}_{da2}}{\dot{m}_{da3}} = \frac{1096}{1491} = 0.735$$

Consequently, the length of line segment 1–3 is 0.735 times the length of entire line 1–2. Using a ruler, State 3 is located, and the values t_3 = 65.9°F and t_3^* = 56.6°F 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:

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

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

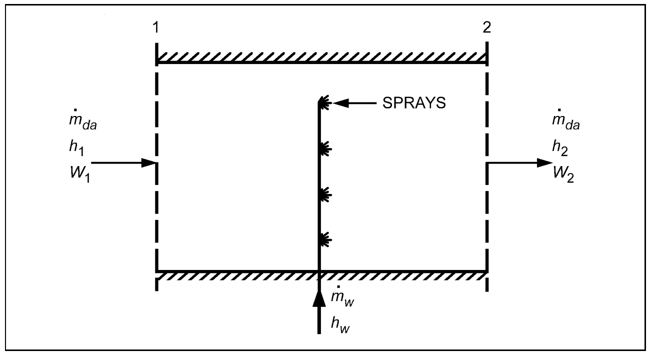

Fig. 8 Schematic Showing Injection of Water into Moist Air

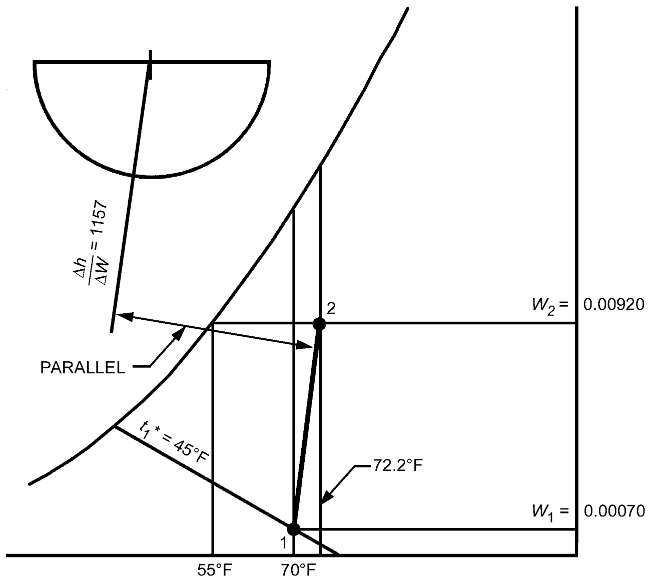

Fig. 9 Schematic Solution for Example 5

Therefore,

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

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 70°F dry-bulb and 45°F thermodynamic wet-bulb temperature is to be processed to a final dew-point temperature of 55°F by adiabatic injection of saturated steam at 230°F. The rate of dry airflow $\dot{m}_{da}$ is 200 lb$_{da}$/min. Find the final dry-bulb temperature of the moist air and the rate of steam flow required.

Solution: Figure 9 shows the schematic solution. By Table 3, the enthalpy of the steam h_g = 1157 Btu/lb$_w$. Therefore, according to Equation (46), the condition line on the ASHRAE chart connecting States 1 and 2 must have a direction:

$$\Delta h/\Delta W = 1157 \text{ Btu/lb}_w$$

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 $\Delta h/\Delta W$ = 1157. 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 55°F (t_{d2} = 55°F). Thus, t_2 = 72.2°F.

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

$$\dot{m}_w = \dot{m}_{da}(W_2 - W_1) = (200)(60)(0.00920 - 0.00070)$$
$$= 102\ \text{lb}_{steam}/\text{h}$$

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 pound 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

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

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

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

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

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.

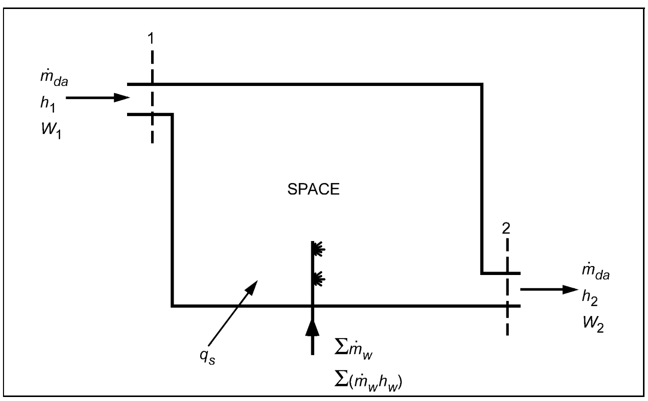

Fig. 10 Schematic of Air Conditioned Space

Example 6. Moist air is withdrawn from a room at 80°F dry-bulb temperature and 66°F thermodynamic wet-bulb temperature. The sensible rate of heat gain for the space is 30,000 Btu/h. A rate of moisture gain of 10 lb_w/h occurs from the space occupants. This moisture is assumed as saturated water vapor at 90°F. Moist air is introduced into the room at a dry-bulb temperature of 60°F. 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 = 1100.40 Btu/lb_w. From Equation (49),

$$\frac{\Delta h}{\Delta W} = \frac{30{,}000 + (10)(1100.40)}{10} = 4100\ \text{Btu/lb}_w$$

With the $\Delta h/\Delta W$ protractor, establish a reference line of direction $\Delta h/\Delta W$ = 4100 Btu/lb_w. Parallel to this reference line, draw a straight line on the chart through State 2. The intersection of this line with the 60°F dry-bulb temperature line is State 1. Thus, t_1^* = 56.4°F.

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,

$$\frac{\Delta H_s}{\Delta H_t} = \frac{q_s}{q_s + \Sigma(\dot{m}_w h_w)} = \frac{30{,}000}{30{,}000 + (10 \times 1100.40)} = 0.732$$

Note that $\Delta H_s/\Delta H_t$ = 0.732 on the protractor coincides closely with $\Delta h/\Delta W$ = 4100 Btu/lb_w.

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

$$\dot{m}_{da} = \frac{q_s + \Sigma(\dot{m}_w h_w)}{h_2 - h_1} = \frac{30{,}000 + (10 \times 1100.40)}{(60)(30.73 - 24.00)}$$
$$= 101.5\ \text{lb}_{da}/\text{min}$$

At State 1, $v_1 = 13.29\ \text{ft}^3/\text{lb}_{da}$

Therefore, supply volume = $\dot{m}_{da}v_1$ = 101.5 × 13.29 = 1349 cfm

TRANSPORT PROPERTIES OF MOIST AIR

For certain scientific and experimental work, particularly in the heat transfer field, many other moist air properties are important.

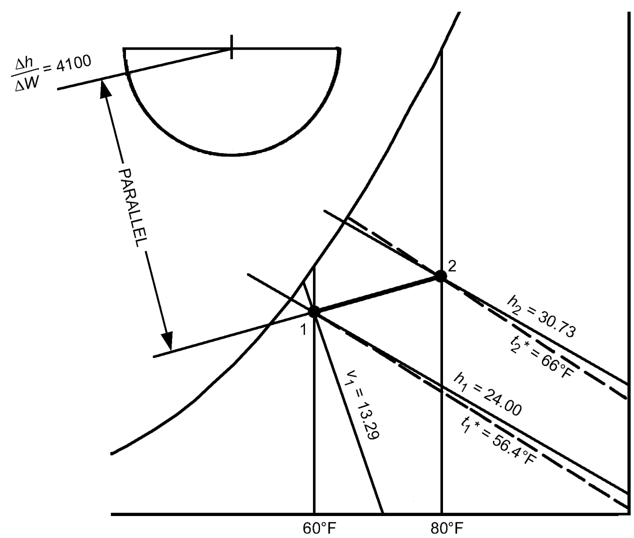

Fig. 11 Schematic Solution for Example 6

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 29.921 in. Hg Barometric Pressure

Temp., °F	ft²/h	Temp., °F	ft²/h	Temp., °F	ft²/h
−100	0.504	40	0.884	140	1.205
−50	0.600	50	0.915	150	1.240
−40	0.655	60	0.942	200	1.414
−30	0.682	70	0.973	250	1.600
−20	0.709	80	1.008	300	1.794
−10	0.736	90	1.042	350	1.996
0	0.767	100	1.073	400	2.205
10	0.794	110	1.104	450	2.422
20	0.825	120	1.139	500	2.647
30	0.853	130	1.170		

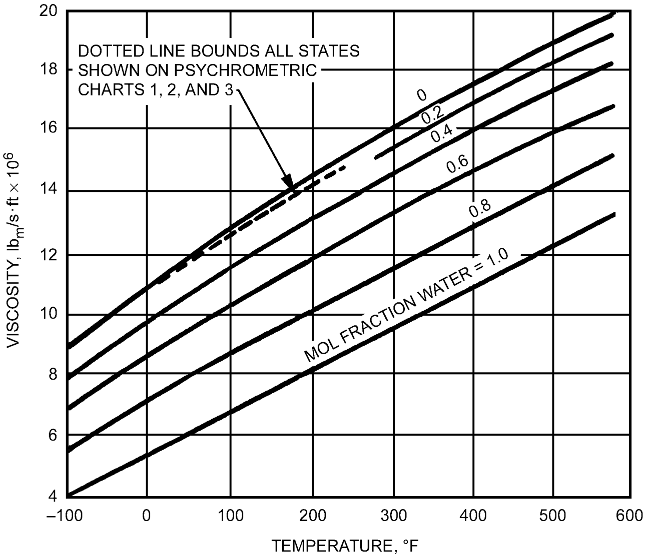

Fig. 12 Viscosity of Moist Air

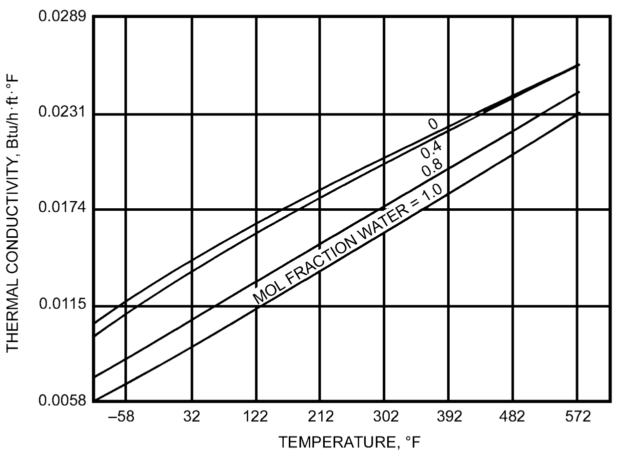

Fig. 13 Thermal Conductivity of Moist Air

REFERENCES FOR AIR, WATER, AND STEAM PROPERTIES

Coefficient f_w (over water) at pressures from 0.145 to 31.799 in. Hg for temperatures from −58 to 140°F (Smithsonian Institution).

Coefficient f_i (over ice) at pressures from 0.145 to 31.799 in. Hg for temperatures from 32 to 212°F (Smithsonian Institution).

Compressibility factor of dry air at pressures from 0.147 to 1470 psi and at temperatures from 90 to 5400°R (Hilsenrath et al. 1960).

Compressibility factor of moist air at pressures from 25 to 31 in. Hg at humidity ratios from 0.006 to 0.30 lb_w/lb_{da}, and for temperatures from 40 to 100°F. At pressures from 0 to 31.799 in. Hg, at values of degree of saturation from 0 to 100, and for temperatures from 32 to 140°F (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 14.696 to 440 psi and at temperatures from 684 to 1530°R (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 18 to 5400°R (Hilsenrath et al. 1960).

Ideal-gas thermodynamic functions of steam at temperatures from 90 to 9000°R. 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 8.672 to 28.908 in. Hg and for temperatures from −128 to 32°F (Smithsonian Institution).

Saturation humidity ratio over water at pressures from 1.73 to 30.35 in. Hg and for temperatures from −58 to 138.2°F (Smithsonian Institution).

Saturation vapor pressure over water in in. Hg andfor temperatures from −60 to 212°F (Smithsonian Institution).

Speed of sound in dry air at pressures from 0.147 to 1470 psi for temperatures from 90 to 5400°R (Hilsenrath et al. 1960). At atmospheric pressure for temperatures from −130 to 140°F (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 2400°F (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 feet for temperatures from 14 to 482°F (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 29.921 in. Hg
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, 1545.32 ft·lb$_f$/lb mole·°R
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, dimensionless
ρ = moist air density
ϕ = relative humidity

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

Chaddock, J.B. 1965. Moist air properties from tabulated virial coefficients. *Humidity and moisture measurement and control in science and industry* 3:273. A. Wexler and W.A. Wildhack, eds. Reinhold Publishing, New York.

Dorsey, N.E. 1940. *Properties of ordinary water substance*. Reinhold Publishing, New York.

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

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

Goff, J.A., J.R. Anderson, and S. Gratch. 1943. Final values of the interaction constant for moist air. *ASHVE Transactions* 49:269.

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

Hardy, H.C., D. Telfair, and W.H. Pielemeier. 1942. The velocity of sound in air. *Journal of the Acoustical Society of America* 13:226.

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

Hilsenrath, J. et al. 1960. Tables of thermodynamic and transport properties of air, argon, carbon dioxide, carbon monoxide, hydrogen, nitrogen, oxygen, and steam. National Bureau of Standards. *Circular* 564, Pergamon Press, New York.

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):520-35.

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.

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

Keenan, J.H. and J. Kaye. 1945. *Gas tables.* John Wiley and Sons, New York.

Keenan, J.H., F.G. Keyes, P.G. Hill, and J.G. Moore. 1969. *Steam tables.* John Wiley and Sons, New York.

Kuehn, T.H., J.W. Ramsey, and J.L. Threlkeld. 1998. *Thermal environmental engineering*, 3rd ed., p. 188. Prentice-Hall, Upper Saddle River, NJ.

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.

Mason, E.A. and L. Monchick. 1965. Survey of the equation of state and transport properties of moist gases. *Humidity and moisture measurement and control in science and industry* 3:257. Reinhold Publishing, New York.

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.

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.

Osborne, N.S. 1939. Stimson and Ginnings. Thermal properties of saturated steam. *Journal of Research*, National Bureau of Standards, 23(8):261.

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

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

Peppers, V.W. 1988. Unpublished paper. 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.

Smithsonian Institution. 1954. *Smithsonian physical tables*, 9th rev. ed. Available from the Smithsonian Institution, Washington, D.C.

Smithsonian Institution. *Smithsonian meteorological tables*, 6th rev. ed. Out of print, but available in many libraries. Washington, D.C.