2013 ASHRAE HANDBOOK

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CHAPTER 1

PSYCHROMETRICS

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

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

COMPOSITION OF DRY AND MOIST AIR

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

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

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

Moist air is a binary (two-component) mixture of dry air and water vapor. The amount of water vapor varies from zero (dry air) to a maximum that depends on temperature and pressure. **Saturation** is a state of neutral equilibrium between moist air and the condensed water phase (liquid or solid); unless otherwise stated, it assumes a flat interface surface between moist air and the condensed phase.

Saturation conditions change when the interface radius is very small (e.g., with ultrafine water droplets). The relative molecular mass of water is 18.015 268 on the carbon-12 scale. The gas constant for water vapor is

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

U.S. STANDARD ATMOSPHERE

The temperature and barometric pressure of atmospheric air vary considerably with altitude as well as with local geographic and weather conditions. The standard atmosphere gives a standard of reference for estimating properties at various altitudes. At sea level, standard temperature is 15°C; standard barometric pressure is 101.325 kPa. Temperature is assumed to decrease linearly with increasing altitude throughout the troposphere (lower atmosphere), and to be constant in the lower reaches of the stratosphere. The lower atmosphere is assumed to consist of dry air that behaves as a perfect gas. Gravity is also assumed constant at the standard value, 9.806 65 m/s². Table 1 summarizes property data for altitudes to 10 000 m.

Pressure values in Table 1 may be calculated from

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

The equation for temperature as a function of altitude is

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

where

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

Table 1 Standard Atmospheric Data for Altitudes to 10 000 m

Altitude, m	Temperature, °C	Pressure, kPa
−500	18.2	107.478
0	15.0	101.325
500	11.8	95.461
1 000	8.5	89.875
1 500	5.2	84.556
2 000	2.0	79.495
2 500	−1.2	74.682
3 000	−4.5	70.108
4 000	−11.0	61.640
5 000	−17.5	54.020
6 000	−24.0	47.181
7 000	−30.5	41.061
8 000	−37.0	35.600
9 000	−43.5	30.742
10 000	−50	26.436

Source: Adapted from NASA (1976).

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

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

| Temp., °C | Humidity Ratio | Specific Volume, m³/kg_da | | | Specific Enthalpy, kJ/kg_da | | | Specific Entropy, kJ/(kg_da·K) | | Temp., °C |
t	W_s, kg_w/kg_da	v_{da}	v_{as}	v_s	h_{da}	h_{as}	h_s	s_{da}	s_s	t
−60	0.0000067	0.6027	0.0000	0.6027	−60.341	0.016	−60.325	−0.2494	−0.2494	−60
−59	0.0000076	0.6055	0.0000	0.6055	−59.335	0.018	−59.317	−0.2447	−0.2446	−59
−58	0.0000087	0.6084	0.0000	0.6084	−58.329	0.021	−58.308	−0.2400	−0.2399	−58
−57	0.0000100	0.6112	0.0000	0.6112	−57.323	0.024	−57.299	−0.2354	−0.2353	−57
−56	0.0000114	0.6141	0.0000	0.6141	−56.317	0.027	−56.289	−0.2307	−0.2306	−56
−55	0.0000129	0.6169	0.0000	0.6169	−55.311	0.031	−55.280	−0.2261	−0.2260	−55
−54	0.0000147	0.6198	0.0000	0.6198	−54.305	0.035	−54.269	−0.2215	−0.2213	−54
−53	0.0000167	0.6226	0.0000	0.6226	−53.299	0.040	−53.258	−0.2169	−0.2167	−53
−52	0.0000190	0.6255	0.0000	0.6255	−52.293	0.046	−52.247	−0.2124	−0.2121	−52
−51	0.0000215	0.6283	0.0000	0.6283	−51.287	0.052	−51.235	−0.2078	−0.2076	−51
−50	0.0000243	0.6312	0.0000	0.6312	−50.281	0.059	−50.222	−0.2033	−0.2030	−50
−49	0.0000275	0.6340	0.0000	0.6340	−49.275	0.066	−49.209	−0.1988	−0.1985	−49
−48	0.0000311	0.6369	0.0000	0.6369	−48.269	0.075	−48.194	−0.1943	−0.1940	−48
−47	0.0000350	0.6397	0.0000	0.6397	−47.263	0.085	−47.179	−0.1899	−0.1895	−47
−46	0.0000395	0.6425	0.0000	0.6426	−46.257	0.095	−46.162	−0.1854	−0.1850	−46
−45	0.0000445	0.6454	0.0000	0.6454	−45.252	0.107	−45.144	−0.1810	−0.1805	−45
−44	0.0000500	0.6482	0.0001	0.6483	−44.246	0.121	−44.125	−0.1766	−0.1761	−44
−43	0.0000562	0.6511	0.0001	0.6511	−43.240	0.136	−43.104	−0.1722	−0.1716	−43
−42	0.0000631	0.6539	0.0001	0.6540	−42.234	0.153	−42.081	−0.1679	−0.1672	−42
−41	0.0000708	0.6568	0.0001	0.6568	−41.229	0.172	−41.057	−0.1635	−0.1628	−41
−40	0.0000793	0.6596	0.0001	0.6597	−40.223	0.192	−40.031	−0.1592	−0.1583	−40
−39	0.0000887	0.6625	0.0001	0.6626	−39.217	0.215	−39.002	−0.1549	−0.1539	−39
−38	0.0000992	0.6653	0.0001	0.6654	−38.212	0.241	−37.970	−0.1506	−0.1495	−38
−37	0.0001108	0.6682	0.0001	0.6683	−37.206	0.269	−36.936	−0.1464	−0.1451	−37
−36	0.0001237	0.6710	0.0001	0.6711	−36.200	0.301	−35.899	−0.1421	−0.1408	−36
−35	0.0001379	0.6738	0.0001	0.6740	−35.195	0.336	−34.859	−0.1379	−0.1364	−35
−34	0.0001536	0.6767	0.0002	0.6769	−34.189	0.374	−33.815	−0.1337	−0.1320	−34
−33	0.0001710	0.6795	0.0002	0.6797	−33.183	0.417	−32.766	−0.1295	−0.1276	−33
−32	0.0001902	0.6824	0.0002	0.6826	−32.178	0.464	−31.714	−0.1253	−0.1232	−32
−31	0.0002113	0.6852	0.0002	0.6855	−31.172	0.516	−30.656	−0.1211	−0.1189	−31
−30	0.0002345	0.6881	0.0003	0.6883	−30.167	0.573	−29.593	−0.1170	−0.1145	−30
−29	0.0002602	0.6909	0.0003	0.6912	−29.161	0.636	−28.525	−0.1129	−0.1101	−29
−28	0.0002883	0.6938	0.0003	0.6941	−28.156	0.706	−27.450	−0.1088	−0.1057	−28
−27	0.0003193	0.6966	0.0004	0.6970	−27.150	0.782	−26.368	−0.1047	−0.1013	−27
−26	0.0003532	0.6994	0.0004	0.6998	−26.144	0.866	−25.278	−0.1006	−0.0969	−26
−25	0.0003905	0.7023	0.0004	0.7027	−25.139	0.958	−24.181	−0.0965	−0.0924	−25
−24	0.0004314	0.7051	0.0005	0.7056	−24.133	1.059	−23.074	−0.0925	−0.0880	−24
−23	0.0004761	0.7080	0.0005	0.7085	−23.128	1.170	−21.958	−0.0884	−0.0835	−23
−22	0.0005251	0.7108	0.0006	0.7114	−22.122	1.291	−20.831	−0.0844	−0.0790	−22
−21	0.0005787	0.7137	0.0007	0.7143	−21.117	1.424	−19.693	−0.0804	−0.0745	−21
−20	0.0006373	0.7165	0.0007	0.7172	−20.111	1.570	−18.542	−0.0765	−0.0699	−20
−19	0.0007013	0.7193	0.0008	0.7201	−19.106	1.728	−17.377	−0.0725	−0.0653	−19
−18	0.0007711	0.7222	0.0009	0.7231	−18.100	1.902	−16.198	−0.0685	−0.0607	−18
−17	0.0008473	0.7250	0.0010	0.7260	−17.095	2.091	−15.003	−0.0646	−0.0560	−17
−16	0.0009303	0.7279	0.0011	0.7290	−16.089	2.298	−13.791	−0.0607	−0.0513	−16
−15	0.0010207	0.7307	0.0012	0.7319	−15.084	2.523	−12.560	−0.0568	−0.0465	−15
−14	0.0011191	0.7336	0.0013	0.7349	−14.078	2.769	−11.310	−0.0529	−0.0416	−14
−13	0.0012261	0.7364	0.0014	0.7378	−13.073	3.036	−10.037	−0.0490	−0.0367	−13
−12	0.0013425	0.7392	0.0016	0.7408	−12.067	3.326	−8.741	−0.0452	−0.0317	−12
−11	0.0014689	0.7421	0.0017	0.7438	−11.062	3.642	−7.419	−0.0413	−0.0267	−11
−10	0.0016062	0.7449	0.0019	0.7468	−10.056	3.986	−6.070	−0.0375	−0.0215	−10
−9	0.0017551	0.7478	0.0021	0.7499	−9.050	4.358	−4.692	−0.0337	−0.0163	−9
−8	0.0019166	0.7506	0.0023	0.7529	−8.045	4.763	−3.282	−0.0299	−0.0110	−8
−7	0.0020916	0.7534	0.0025	0.7560	−7.039	5.202	−1.838	−0.0261	−0.0055	−7
−6	0.0022812	0.7563	0.0028	0.7591	−6.034	5.677	−0.356	−0.0223	0.0000	−6
−5	0.0024863	0.7591	0.0030	0.7622	−5.028	6.193	1.164	−0.0186	0.0057	−5
−4	0.0027083	0.7620	0.0033	0.7653	−4.023	6.750	2.728	−0.0148	0.0115	−4
−3	0.0029482	0.7648	0.0036	0.7684	−3.017	7.354	4.337	−0.0111	0.0175	−3
−2	0.0032076	0.7677	0.0039	0.7716	−2.011	8.007	5.995	−0.0074	0.0236	−2
−1	0.0034877	0.7705	0.0043	0.7748	−1.006	8.712	7.707	−0.0037	0.0299	−1
0	0.0037900	0.7733	0.0047	0.7780	0.000	9.475	9.475	0.0000	0.0364	0
1	0.004076	0.7762	0.0051	0.7813	1.006	10.198	11.203	0.0037	0.0427	1
2	0.004382	0.7790	0.0055	0.7845	2.011	10.970	12.981	0.0073	0.0492	2
3	0.004708	0.7819	0.0059	0.7878	3.017	11.794	14.811	0.0110	0.0559	3
4	0.005055	0.7847	0.0064	0.7911	4.023	12.673	16.696	0.0146	0.0627	4
5	0.005425	0.7875	0.0068	0.7944	5.029	13.611	18.639	0.0182	0.0697	5
6	0.005819	0.7904	0.0074	0.7978	6.034	14.610	20.644	0.0219	0.0769	6
7	0.006238	0.7932	0.0079	0.8012	7.040	15.674	22.714	0.0254	0.0843	7
8	0.006684	0.7961	0.0085	0.8046	8.046	16.807	24.853	0.0290	0.0919	8
9	0.007158	0.7989	0.0092	0.8081	9.052	18.013	27.065	0.0326	0.0997	9
10	0.007663	0.8017	0.0098	0.8116	10.058	19.297	29.354	0.0362	0.1078	10
11	0.008199	0.8046	0.0106	0.8152	11.063	20.661	31.724	0.0397	0.1162	11
12	0.008768	0.8074	0.0113	0.8188	12.069	22.111	34.181	0.0432	0.1248	12
13	0.009372	0.8103	0.0122	0.8224	13.075	23.653	36.728	0.0468	0.1337	13
14	0.010013	0.8131	0.0131	0.8262	14.081	25.290	39.371	0.0503	0.1430	14

Table 3 Thermodynamic Properties of Water at Saturation

Temp., °C t	Absolute Pressure p_{ws}, kPa	Specific Volume, m³/kg$_w$			Specific Enthalpy, kJ/kg$_w$			Specific Entropy, kJ/(kg$_w$·K)			Temp., °C t
		Sat. Solid v_i/v_f	Evap. v_{ig}/v_{fg}	Sat. Vapor v_g	Sat. Solid h_i/h_f	Evap. h_{ig}/h_{fg}	Sat. Vapor h_g	Sat. Solid s_i/s_f	Evap. s_{ig}/s_{fg}	Sat. Vapor s_g	
−60	0.00108	0.001081	90971.58	90971.58	−446.12	2836.27	2390.14	−1.6842	13.3064	11.6222	−60
−59	0.00124	0.001082	79885.31	79885.31	−444.46	2836.45	2391.99	−1.6764	13.2452	11.5687	−59
−58	0.00141	0.001082	70235.77	70235.78	−442.79	2836.63	2393.85	−1.6687	13.1845	11.5158	−58
−57	0.00161	0.001082	61826.23	61826.24	−441.11	2836.81	2395.70	−1.6609	13.1243	11.4634	−57
−56	0.00184	0.001082	54488.28	54488.28	−439.42	2836.97	2397.55	−1.6531	13.0646	11.4115	−56
−55	0.00209	0.001082	48077.54	48077.54	−437.73	2837.13	2399.40	−1.6453	13.0054	11.3601	−55
−54	0.00238	0.001082	42470.11	42470.11	−436.03	2837.28	2401.25	−1.6375	12.9468	11.3092	−54
−53	0.00271	0.001082	37559.49	37559.50	−434.32	2837.42	2403.10	−1.6298	12.8886	11.2589	−53
−52	0.00307	0.001083	33254.07	33254.07	−432.61	2837.56	2404.95	−1.6220	12.8310	11.2090	−52
−51	0.00348	0.001083	29474.87	29474.87	−430.88	2837.69	2406.81	−1.6142	12.7738	11.1596	−51
−50	0.00394	0.001083	26153.80	26153.80	−429.16	2837.81	2408.66	−1.6065	12.7171	11.1106	−50
−49	0.00445	0.001083	23232.03	23232.04	−427.42	2837.93	2410.51	−1.5987	12.6609	11.0622	−49
−48	0.00503	0.001083	20658.70	20658.70	−425.68	2838.04	2412.36	−1.5909	12.6051	11.0142	−48
−47	0.00568	0.001083	18389.75	18389.75	−423.93	2838.14	2414.21	−1.5832	12.5498	10.9666	−47
−46	0.00640	0.001083	16387.03	16387.03	−422.17	2838.23	2416.06	−1.5754	12.4950	10.9196	−46
−45	0.00720	0.001084	14617.39	14617.39	−420.40	2838.32	2417.91	−1.5677	12.4406	10.8729	−45
−44	0.00810	0.001084	13052.07	13052.07	−418.63	2838.39	2419.76	−1.5599	12.3867	10.8267	−44
−43	0.00910	0.001084	11666.02	11666.02	−416.85	2838.47	2421.62	−1.5522	12.3331	10.7810	−43
−42	0.01022	0.001084	10437.46	10437.46	−415.06	2838.53	2423.47	−1.5444	12.2801	10.7356	−42
−41	0.01146	0.001084	9347.38	9347.38	−413.27	2838.59	2425.32	−1.5367	12.2274	10.6907	−41
−40	0.01284	0.001084	8379.20	8379.20	−411.47	2838.64	2427.17	−1.5289	12.1752	10.6462	−40
−39	0.01437	0.001085	7518.44	7518.44	−409.66	2838.68	2429.02	−1.5212	12.1234	10.6022	−39
−38	0.01607	0.001085	6752.43	6752.43	−407.85	2838.72	2430.87	−1.5135	12.0720	10.5585	−38
−37	0.01795	0.001085	6070.08	6070.08	−406.02	2838.74	2432.72	−1.5057	12.0210	10.5152	−37
−36	0.02004	0.001085	5461.68	5461.68	−404.19	2838.76	2434.57	−1.4980	11.9704	10.4724	−36
−35	0.02234	0.001085	4918.69	4918.69	−402.36	2838.78	2436.42	−1.4903	11.9202	10.4299	−35
−34	0.02489	0.001085	4433.64	4433.64	−400.51	2838.78	2438.27	−1.4825	11.8703	10.3878	−34
−33	0.02771	0.001085	3999.95	3999.95	−398.66	2838.78	2440.12	−1.4748	11.8209	10.3461	−33
−32	0.03081	0.001086	3611.82	3611.82	−396.80	2838.77	2441.97	−1.4671	11.7718	10.3047	−32
−31	0.03423	0.001086	3264.15	3264.16	−394.94	2838.75	2443.82	−1.4594	11.7231	10.2638	−31
−30	0.03801	0.001086	2952.46	2952.46	−393.06	2838.73	2445.67	−1.4516	11.6748	10.2232	−30
−29	0.04215	0.001086	2672.77	2672.77	−391.18	2838.70	2447.51	−1.4439	11.6269	10.1830	−29
−28	0.04672	0.001086	2421.58	2421.58	−389.29	2838.66	2449.36	−1.4362	11.5793	10.1431	−28
−27	0.05173	0.001086	2195.80	2195.80	−387.40	2838.61	2451.21	−1.4285	11.5321	10.1036	−27
−26	0.05724	0.001087	1992.68	1992.68	−385.50	2838.56	2453.06	−1.4208	11.4852	10.0644	−26
−25	0.06327	0.001087	1809.79	1809.79	−383.59	2838.49	2454.91	−1.4131	11.4386	10.0256	−25
−24	0.06989	0.001087	1644.99	1644.99	−381.67	2838.42	2456.75	−1.4054	11.3925	9.9871	−24
−23	0.07714	0.001087	1496.36	1496.36	−379.75	2838.35	2458.60	−1.3977	11.3466	9.9489	−23
−22	0.08508	0.001087	1362.21	1362.21	−377.81	2838.26	2460.45	−1.3899	11.3011	9.9111	−22
−21	0.09376	0.001087	1241.03	1241.03	−375.88	2838.17	2462.29	−1.3822	11.2559	9.8736	−21
−20	0.10324	0.001087	1131.49	1131.49	−373.93	2838.07	2464.14	−1.3745	11.2110	9.8365	−20
−19	0.11360	0.001088	1032.38	1032.38	−371.98	2837.96	2465.98	−1.3668	11.1665	9.7996	−19
−18	0.12490	0.001088	942.64	942.65	−370.01	2837.84	2467.83	−1.3591	11.1223	9.7631	−18
−17	0.13722	0.001088	861.34	861.34	−368.05	2837.72	2469.67	−1.3514	11.0784	9.7269	−17
−16	0.15065	0.001088	787.61	787.61	−366.07	2837.59	2471.51	−1.3437	11.0348	9.6910	−16
−15	0.16527	0.001088	720.70	720.70	−364.09	2837.45	2473.36	−1.3360	10.9915	9.6554	−15
−14	0.18119	0.001088	659.94	659.94	−362.10	2837.30	2475.20	−1.3284	10.9485	9.6201	−14
−13	0.19849	0.001089	604.72	604.73	−360.10	2837.14	2477.04	−1.3207	10.9058	9.5851	−13
−12	0.21729	0.001089	554.51	554.51	−358.10	2836.98	2478.88	−1.3130	10.8634	9.5504	−12
−11	0.23771	0.001089	508.81	508.81	−356.08	2836.80	2480.72	−1.3053	10.8213	9.5160	−11
−10	0.25987	0.001089	467.19	467.19	−354.06	2836.62	2482.56	−1.2976	10.7795	9.4819	−10
−9	0.28391	0.001089	429.25	429.26	−352.04	2836.44	2484.40	−1.2899	10.7380	9.4481	−9
−8	0.30995	0.001089	394.66	394.66	−350.00	2836.24	2486.23	−1.2822	10.6967	9.4145	−8
−7	0.33817	0.001090	363.09	363.09	−347.96	2836.03	2488.07	−1.2745	10.6558	9.3812	−7
−6	0.36871	0.001090	334.26	334.26	−345.91	2835.82	2489.91	−1.2668	10.6151	9.3482	−6
−5	0.40174	0.001090	307.92	307.92	−343.86	2835.60	2491.74	−1.2592	10.5747	9.3155	−5
−4	0.43745	0.001090	283.82	283.83	−341.79	2835.37	2493.57	−1.2515	10.5345	9.2830	−4
−3	0.47604	0.001090	261.78	261.78	−339.72	2835.13	2495.41	−1.2438	10.4946	9.2508	−3
−2	0.51770	0.001091	241.60	241.60	−337.64	2834.88	2497.24	−1.2361	10.4550	9.2189	−2
−1	0.56266	0.001091	223.10	223.11	−335.56	2834.63	2499.07	−1.2284	10.4157	9.1872	−1
0	0.61115	0.001091	206.15	206.15	−333.47	2834.36	2500.90	−1.2208	10.3766	9.1558	0

Transition from saturated solid to saturated liquid

0	0.6112	0.001000	206.139	206.140	−0.04	2500.93	2500.89	−0.0002	9.1559	9.1558	0
1	0.6571	0.001000	192.444	192.445	4.18	2498.55	2502.73	0.0153	9.1138	9.1291	1
2	0.7060	0.001000	179.763	179.764	8.39	2496.17	2504.57	0.0306	9.0721	9.1027	2