Psychrometrics

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8.1 INTRODUCTION

8.1.1 Background of Psychrometrics

Psychrometrics is the study of vaporized liquids in gases, with the most frequently studied and applied system being water vapor in air. Psychrometrics has a long history with many early documents exploring the relationships of moisture and air (Noble, 1854). At the heart of psychrometrics is the concept that, when the atmospheric pressure is known, two measured parameters can be used to determine the physical properties of a water/air mixture. For example, by measuring dry-bulb temperature and wet-bulb temperature, all of the important physical properties of the water-air mixture can be determined, such as relative humidity, dew point temperature, enthalpy, specific volume, etc. (ASHRAE, 2017; Gatley, 2013; Olivieri and Singh, 1996)

8.1.2 Importance to Postharvest Practices

Postharvest practices are primarily focused on preserving and delivering the highest quality of product possible to the market with minimal losses and at a reasonable cost. As a result the measurement and control of temperature (to control respiration) and humidity (to control water loss and prevent disease) are important components of the postharvest value chain (Donald and Hochmuth, 2006; Gross, 2014). As we will see in this chapter, psychrometrics is the link between temperature and humidity; it is a tool with great value for the world of postharvest systems (Bartsch and Blanpied, 1990).

8.2 FUNDAMENTALS OF POSTHARVEST PSYCHROMETRICS

8.2.1 The Moisture-Carrying Capacity of Air

The air around us has a remarkable property that much of terrestrial life depends on yet is oblivious to its presence. In addition to being made up primarily of nitrogen (N_2), oxygen (O_2), and other trace inert gases, air carries water vapor (H_2O). We refer to this property as the moisture-carrying capacity of air. This property, along with air current and changes in temperature and pressure, is important to weather systems and meteorology, as well as life in general. Warm air can carry more moisture than cold air (Fig. 8.1). As the accompanying chapters indicate, it is also important when considering the postharvest handling and storage of horticultural crops.

8.2.2 Moisture Loss of Crops

Harvested horticultural crops are living organisms in which cellular respiration continues. The result of this respiration process (i.e., a chemical reaction) is heat production; conversion of sugars (e.g., glucose) into water vapor (H_2O) and carbon dioxide (CO_2); and, generally, a decline in product quality (Gross, 2014). The rate of this chemical reaction is reduced by lowering the temperature. These crops are also mostly comprised of water. It is important to retain this water in the crop to support quality and weight retention. Water loss leads to weight loss and reduced crop value at market, but it also leads to poor appearance quality, which can impact marketability. Wilting and shriveling are physical evidence of water loss, and few customers desire product with obvious appearance defects. To reduce the loss of water into the air from the product, we usually maintain a high relative humidity depending on the specific crop. In other words, we aim to have sufficient water vapor in the air surrounding the product to limit the loss of water from the product (e.g., by evaporation, diffusion, and/or transpiration).
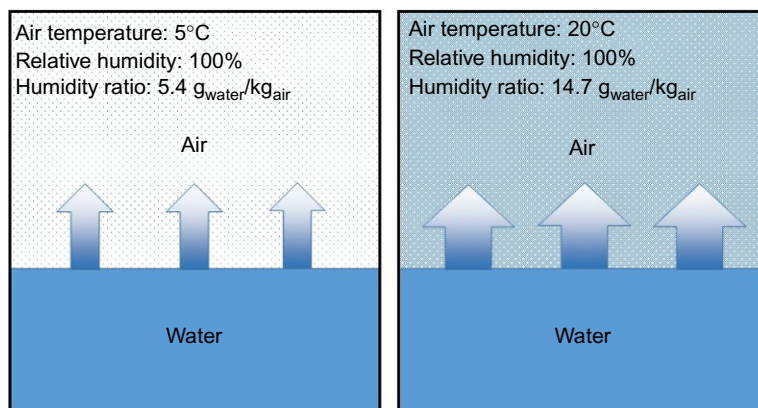

FIG. 8.1   The absolute maximum amount of water vapor that can be carried by air (i.e., 100% RH) depends on the temperature of the air. Air at 20°C can carry almost three times the amount of water vapor as air at 5°C.

8.2.3 Postharvest Pathology

On the other end of the humidity spectrum, excessive humidity and resulting moisture (e.g., from condensation) can lead to increased plant diseases, such as molds and mildews, as well as the risk of human pathogens. It is therefore important to maintain the level of water vapor in air between a specific band where it is neither too high nor too low. Psychrometrics is the tool we use to enable this control.

8.2.4 Psychrometric Parameters

As noted above, if we can measure two state variables of water-air mixture, then we can determine several others to provide value in system design, operation, and maintenance in support of postharvest quality. This section will discuss these variables.

8.2.4.1 Dry-Bulb Temperature

Dry-bulb temperature (T_{db}) is the term we use to refer to the air "temperature" without any modifying adjectives. This is the temperature reported by a thermometer resting in air. It is called the "dry-bulb" temperature to differentiate it from the wet-bulb temperature, which we will discuss below. Dry-bulb temperature is one of the easiest and most reliable postharvest variables we can measure with accuracy and precision. This is one reason we use dry-bulb temperature as the horizontal, or X, axis of the psychrometric chart.

8.2.4.2 Vapor Pressure

Vapor pressure (p_v) refers to the specific pressure experienced by a specific gaseous component in a mixture of gases. Some readers may have been wondering, for example, how water vapor can exist in air that is below the 100°C boiling point of water? This is because the boiling point of water is actually a function of both temperature and pressure. The 100°C boiling point of water is at 1 bar of atmospheric pressure. If the pressure is reduced to 0.5 bar, the boiling point is depressed to 81°C, and at 0.25 bar it is further depressed to 65°C. At even lower pressures the boiling point is depressed even lower. In short the boiling point of water is a function of the effective, or specific, pressure exerted by the vapor phase over the liquid phase. Vapor pressure is the pressure exerted by a gas over its condensed phase. It is important to remember that saturation vapor pressure represents 100% relative humidity at a given dry-bulb temperature; that is, when the vapor exerts this pressure on the liquid surface, the air is fully saturated and cannot carry any more vapor. Vapor pressure is represented on the psychrometric chart as the top curved line (i.e., the 100% RH line). It is this nonlinear relation of the vapor pressure to the dry-bulb temperature that gives the psychrometric chart its characteristic form.

8.2.4.3 Humidity Ratio (Moisture Content)

The humidity ratio (w) is the ratio of water mass to air mass in a water-air mixture (e.g., kg water vapor per kg of air, or kg_v/kg_a). The humidity ratio is sometimes referred to as absolute humidity or moisture content. For a given vapor pressure the humidity ratio is constant

regardless of the dry-bulb temperature. Both the vapor pressure and the humidity ratio are shown as horizontal lines on the psychrometric chart, which is discussed below.

8.2.4.4 Relative Humidity

Relative humidity (RH) is a measure of how much water vapor is in a water-air mixture compared to the maximum amount possible. RH is a ratio of the humidity ratio of a particular water-air mixture compared to the saturation humidity ratio at a given temperature (dry-bulb). It is important to note that the relevance of relative humidity to a particular application depends on knowing both the dry-bulb temperature as well as the RH. For example the amount of moisture in a water-air mixture at 80% RH at 40°C is different from the amount of water vapor in a water-air mixture at 80% RH at 10°C (38.5 vs. 6.1 g_{H_2O}/kg_{air}, respectively). This is why postharvest storage guidance, for example, includes both relative humidity and temperature. When shown on the psychrometric chart, lines of constant relative humidity follow the nonlinear characteristic of vapor pressure relative to dry-bulb temperature. Note that as the dry-bulb temperature increases the same difference in RH translates to a larger difference in actual humidity ratio. In other words the space between lines of constant RH narrows at lower dry-bulb temperatures.

Although relative humidity is technically the result of a calculation, it can be measured (Farahani et al., 2014). The most widespread approach to RH measurement uses absorptive polymers, whose conductive or capacitive properties change depending on how much moisture they have absorbed from the air. That amount of absorption is proportional to the level of humidity in the air. For postharvest applications, particularly ones involving very high humidity and low temperature, this approach can be problematic. Most of these types of sensors have poor accuracy in the higher RH range and are not recommended for condensing environments, such as coolers with high RH and low temperature. The traditional approach to RH measurement is the sling psychrometer, which is explained below as part of the discussion on wet-bulb temperature (ASHRAE, 1994).

8.2.4.5 Wet-Bulb Temperature

The wet-bulb temperature (T_{wb}) is important in determining relative humidity. In practical terms, it is one of the only independent variables other than dry-bulb temperature that we can actually measure directly. The term is derived from the way it is measured. A moistened wick is placed over the bulb of a thermometer. When this "wet-bulb" thermometer is used in conjunction with a typical dry-bulb thermometer and there is air flow over the wick, the wet-bulb temperature becomes depressed relative to the dry-bulb temperature (Fig. 8.2). This is due to the evaporative heat loss from the wick as liquid water is vaporized into the sample air. The rate of water vaporization into the air and therefore the equilibrium wet-bulb temperature is directly related to the amount of moisture in the air relative to the saturation moisture content. The difference in these temperatures at steady state is used to calculate relative humidity. This difference (dry-bulb vs. wet-bulb temperatures) is referred to as the "wet-bulb depression."

The sling psychrometer is a device that employs the approach noted above to determine the wet-bulb depression and thus the RH. There are both manual and automated versions. In the manual version, two thermometers are attached to a frame that can be rotated on its handle rapidly by the user to induce air flow over the moist wet-bulb. This is done until a steady wet-bulb depression is noted and both the dry-bulb and wet-bulb are recorded. A chart, table,
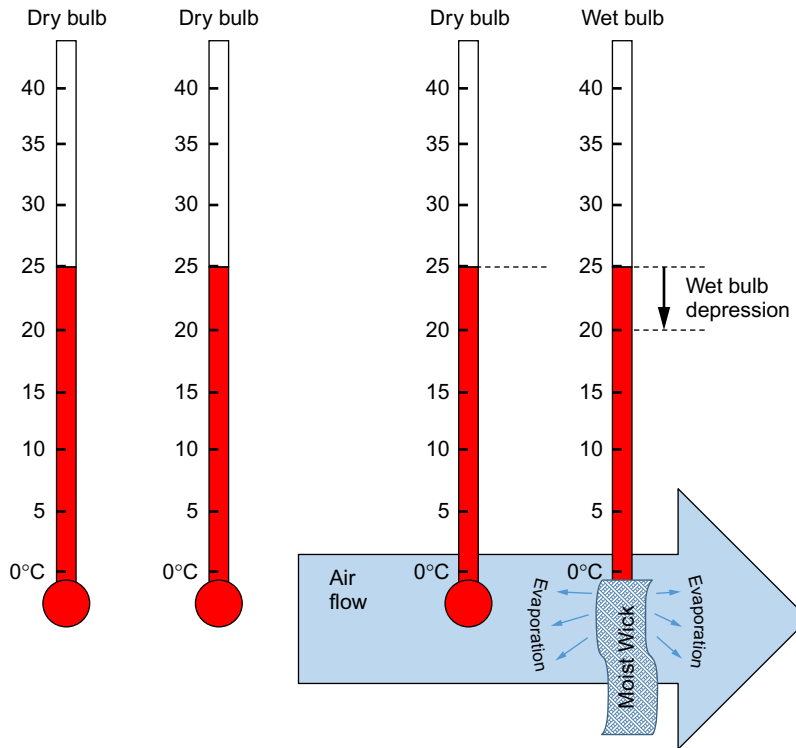
FIG. 8.2   Two thermostats side by side should show the same temperature. But when we put a moist wick around the bulb of one of the thermostats and provide air flow, the evaporation of moisture into the air results in heat loss from the bulb. This heat loss results in a temperature depression known as "wet-bulb depression." The degree of wet-bulb depression depends on the amount of water vapor already in the air. As a result the comparison of wet-bulb to dry-bulb can be used to determine the moisture content of the air and other psychometric properties. For example the measurements shown above, 25°C dry-bulb and 20°C wet-bulb, indicate 63.5% relative humidity at standard altitude and pressure.

slide calculator or computer-based calculator can be used to determine the RH based on the recorded temperatures as noted below. The main drawbacks to the manual sling psychrometer are the inconvenience of use and the fact that user error can be significant (Waite, 1971). Automated versions of the sling psychrometer vary from stationary versions that simply automate the induction of air flow over the wet-bulb to systems that use high-precision thermistors and embedded microprocessors to automate the air flow, measurement of dry- and wet-bulb temperatures, and the calculation of RH and other psychrometric properties (Callahan, 2017).

8.2.4.6 Dew Point Temperature

The dew point temperature (T_{dp}) is the temperature at which water vapor in air will start to condense. This property is important to postharvest practices for several reasons. First the control of condensation in postharvest facilities can help minimize standing water in storage

rooms and other areas where it can become a safety risk to both personnel and produce. Secondly the control of elevated relative humidity can be passively achieved with careful attention to evaporator sizing and design refrigerant temperature to avoid excessive condensation of water from the air when it is cooled at the evaporator. Conversely the reduction of humidity depends on the removal of water vapor from the air; this can be enhanced with careful attention to dew point. Third the control of condensation on the product is an important part of quality control.

Dew point can also be measured, which makes it another parameter that can be used in conjunction with dry-bulb temperature to determine the other state properties of air using psychrometric charts or calculations. Dew point is typically measured using a chilled mirror or other optical approach that determines the start of condensation as the reflective surface is slowly cooled. This approach tends to be more expense and complex than a dry-bulb/wet-bulb psychrometer.

8.2.4.7 Specific Enthalpy

Specific enthalpy (h) is a measure of the energy embodied in air (kJ/kg) at a given state of temperature and moisture content. This property is most useful when used to compare two sets of conditions, such as the enthalpy of the mixture at one lower temperature and the enthalpy at an elevated temperature or moisture content. Using enthalpy in the two states, one can determine the energy addition required to cause the change (e.g., by adding heat).

8.2.4.8 Specific Volume

The specific volume (v) of an air mixture (m^3/kg) is a measure of how much volume is associated with a unit of mass. It is the inverse of density, which provides a measure of the amount mass in a unit of volume. The specific volume is a useful parameter for converting between mass flows (kg/h) to volumetric flows (m^3/h) of air. The inclusion of the specific volume in psychrometric charts, tables, and calculators allows for proper sizing of equipment.

8.2.5 Psychrometric Data

Fortunately for those applying psychrometric design principles the properties of moist air have been well studied and documented. Tables exist which provide thermodynamic properties of saturated air (Table 8.1; ASHRAE, 2017, pp. 1.2–1.6) and for water at saturation (Table 8.2; ASHRAE, 2017, pp. 1.7–1.11). Using these tables and appropriate formulae from the same reference, one can determine the psychrometric properties of moist air with accuracy. However, the psychrometric charts and calculators presented in the next two sections are generally more convenient for typical use.

8.2.6 Psychrometric Charts

8.2.6.1 A Simplified Psychrometric Chart

The calculation of psychrometric properties can be complex, time consuming, and inconvenient in the field. One portable and efficient method of determining properties is to use the

TABLE 8.1 Thermodynamic Properties of Moist Air at Standard Atmospheric Pressure, 101.325 kPa

Temp. (°C t)	Humidity Ratio W_s (kg$_w$/kg$_{da}$)	Specific Volume (m³/kg$_{da}$)			Specific Enthalpy (kJ/kg$_{da}$)			Specific Entropy, kJ/(kg$_{da}$ K)		Temp., t (°C)
		v_{da}	v_{as}	v_s	h_{da}	h_{as}	h_s	s_{da}	s_s	
−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

Continued

TABLE 8.1 Thermodynamic Properties of Moist Air at Standard Atmospheric Pressure, 101.325 kPa—cont'd

Temp. (°C t)	Humidity Ratio W_s (kg$_w$/kg$_{da}$)	Specific Volume (m³/kg$_{da}$)			Specific Enthalpy (kJ/kg$_{da}$)			Specific Entropy, kJ/(kg$_{da}$ K)		Temp., t (°C)
		v_{da}	v_{as}	v_s	h_{da}	h_{as}	h_s	s_{da}	s_s	
−39	0.0000887	0.6625	0.0001	0.6626	−39.217	0.215	−39.002	−0.1549	−0.1539	−39
−38	0.0000992	0.6653	0.0001	0.6654	−38.211	0.241	−37.970	−0.1506	−0.1495	−38
−37	0.0001108	0.6682	0.0001	0.6683	−37.206	0.269	−36.936	−0.1464	−0.1451	−37
−36	0.0001237	0.6710	0.0001	0.6711	−36.200	0.301	−35.899	−0.1421	−0.1408	−36
−35	0.0001379	0.6738	0.0001	0.6740	−35.195	0.336	−34.859	−0.1379	−0.1364	−35
−34	0.0001536	0.6767	0.0002	0.6769	−34.189	0.374	−33.815	−0.1337	−0.1320	−34
−33	0.0001710	0.6795	0.0002	0.6797	−33.183	0.417	−32.766	−0.1295	−0.1276	−33
−32	0.0001902	0.6824	0.0002	0.6826	−32.178	0.464	−31.714	−0.1253	−0.1232	−32
−31	0.0002113	0.6852	0.0002	0.6855	−31.172	0.516	−30.656	−0.1211	−0.1189	−31
−30	0.0002345	0.6881	0.0003	0.6883	−30.167	0.573	−29.593	−0.1170	−0.1145	−30
−29	0.0002602	0.6909	0.0003	0.6912	−29.161	0.636	−28.525	−0.1129	−0.1101	−29
−28	0.0002883	0.6938	0.0003	0.6941	−28.156	0.706	−27.450	−0.1088	−0.1057	−28
−27	0.0003193	0.6966	0.0004	0.6970	−27.150	0.782	−26.368	−0.1047	−0.1013	−27
−26	0.0003532	0.6994	0.0004	0.6998	−26.144	0.866	−25.278	−0.1006	−0.0969	−26
−25	0.0003905	0.7023	0.0004	0.7027	−25.139	0.958	−24.181	−0.0965	−0.0924	−25
−24	0.0004314	0.7051	0.0005	0.7056	−24.133	1.059	−23.074	−0.0925	−0.0880	−24
−23	0.0004761	0.7080	0.0005	0.7085	−23.128	1.170	−21.958	−0.0884	−0.0835	−23
−22	0.0005251	0.7108	0.0006	0.7114	−22.122	1.291	−20.831	−0.0844	−0.0790	−22
−21	0.0005787	0.7137	0.0007	0.7143	−21.117	1.424	−19.693	−0.0804	−0.0745	−21
−20	0.0006373	0.7165	0.0007	0.7172	−20.111	1.570	−18.542	−0.0765	−0.0699	−20
−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

Temp. (°C t)	Humidity Ratio W_s (kg$_w$/kg$_{da}$)	Specific Volume (m³/kg$_{da}$)			Specific Enthalpy (kJ/kg$_{da}$)			Specific Entropy, kJ/(kg$_{da}$ K)		Temp., t (°C)
		v_{da}	v_{as}	v_s	h_{da}	h_{as}	h_s	s_{da}	s_s	
−17	0.0008473	0.7250	0.0010	0.7260	−17.095	2.091	−15.003	−0.0646	−0.0560	−17
−16	0.0009303	0.7279	0.0011	0.7290	−16.089	2.298	−13.791	−0.0607	−0.0513	−16
−15	0.0010207	0.7307	0.0012	0.7319	−15.084	2.523	−12.560	−0.0568	−0.0465	−15
−14	0.0011191	0.7336	0.0013	0.7349	−14.078	2.769	−11.310	−0.0529	−0.0416	−14
−13	0.0012261	0.7364	0.0014	0.7378	−13.073	3.036	−10.037	−0.0490	−0.0367	−13
−12	0.0013425	0.7392	0.0016	0.7408	−12.067	3.326	−8.741	−0.0452	−0.0317	−12
−11	0.0014689	0.7421	0.0017	0.7438	−11.062	3.642	−7.419	−0.0413	−0.0267	−11
−10	0.0016062	0.7449	0.0019	0.7468	−10.056	3.986	−6.070	−0.0375	−0.0215	−10
−9	0.0017551	0.7478	0.0021	0.7499	−9.050	4.358	−4.692	−0.0337	−0.0163	−9
−8	0.0019166	0.7506	0.0023	0.7529	−8.045	4.763	−3.282	−0.0299	−0.0110	−8
−7	0.0020916	0.7534	0.0025	0.7560	−7.039	5.202	−1.838	−0.0261	−0.0055	−7
−6	0.0022812	0.7563	0.0028	0.7591	−6.034	5.677	−0.356	−0.0223	0.0000	−6
−5	0.0024863	0.7591	0.0030	0.7622	−5.028	6.192	1.164	−0.0186	0.0057	−5
−4	0.0027083	0.7620	0.0033	0.7653	−4.023	6.750	2.728	−0.0148	0.0115	−4
−3	0.0029482	0.7648	0.0036	0.7684	−3.017	7.354	4.337	−0.0111	0.0175	−3
−2	0.0032076	0.7677	0.0039	0.7716	−2.011	8.007	5.995	−0.0074	0.0236	−2
−1	0.0034877	0.7705	0.0043	0.7748	−1.006	8.712	7.707	−0.0037	0.0299	−1
0	0.003790	0.7733	0.0047	0.7780	0.000	9.475	9.475	0.0000	0.0364	0
1	0.004076	0.7762	0.0051	0.7813	1.006	10.198	11.203	0.0037	0.0427	1
2	0.004382	0.7790	0.0055	0.7845	2.011	10.970	12.981	0.0073	0.0492	2
3	0.004708	0.7819	0.0059	0.7878	3.017	11.794	14.811	0.0110	0.0559	3

Continued

TABLE 8.1 Thermodynamic Properties of Moist Air at Standard Atmospheric Pressure, 101.325 kPa—cont'd

Temp. (°C t)	Humidity Ratio W_s (kg$_w$/kg$_{da}$)	Specific Volume (m³/kg$_{da}$)			Specific Enthalpy (kJ/kg$_{da}$)			Specific Entropy, kJ/(kg$_{da}$ K)		Temp., t (°C)
		v_{da}	v_{as}	v_s	h_{da}	h_{as}	h_s	s_{da}	s_s	
4	0.005055	0.7847	0.0064	0.7911	4.023	12.673	16.696	0.0146	0.0627	4
5	0.005425	0.7875	0.0068	0.7944	5.029	13.611	18.639	0.0182	0.0697	5
6	0.005819	0.7904	0.0074	0.7978	6.034	14.610	20.644	0.0219	0.0769	6
7	0.006238	0.7932	0.0079	0.8012	7.040	15.674	22.714	0.0254	0.0843	7
8	0.006684	0.7961	0.0085	0.8046	8.046	16.807	24.853	0.0290	0.0919	8
9	0.007158	0.7989	0.0092	0.8081	9.052	18.013	27.065	0.0326	0.0997	9
10	0.007663	0.8017	0.0098	0.8116	10.058	19.297	29.354	0.0362	0.1078	10
11	0.008199	0.8046	0.0106	0.8152	11.063	20.661	31.724	0.0397	0.1162	11
12	0.008768	0.8074	0.0113	0.8188	12.069	22.111	34.181	0.0432	0.1248	12
13	0.009372	0.8103	0.0122	0.8224	13.075	23.653	36.728	0.0468	0.1338	13
14	0.010013	0.8131	0.0131	0.8262	14.081	25.290	39.371	0.0503	0.1430	14
15	0.010694	0.8159	0.0140	0.8299	15.087	27.028	42.115	0.0538	0.1525	15
16	0.011415	0.8188	0.0150	0.8338	16.093	28.873	44.966	0.0573	0.1624	16
17	0.012181	0.8216	0.0160	0.8377	17.099	30.830	47.929	0.0607	0.1726	17
18	0.012991	0.8245	0.0172	0.8416	18.105	32.906	51.011	0.0642	0.1832	18
19	0.013851	0.8273	0.0184	0.8457	19.111	35.108	54.219	0.0676	0.1942	19
20	0.014761	0.8301	0.0196	0.8498	20.117	37.441	57.559	0.0711	0.2057	20
21	0.015724	0.8330	0.0210	0.8540	21.124	39.914	61.038	0.0745	0.2175	21
22	0.016744	0.8358	0.0224	0.8583	22.130	42.534	64.663	0.0779	0.2298	22
23	0.017823	0.8387	0.0240	0.8626	23.136	45.308	68.444	0.0813	0.2426	23
24	0.018965	0.8415	0.0256	0.8671	24.142	48.246	72.388	0.0847	0.2560	24
25	0.020173	0.8443	0.0273	0.8716	25.148	51.355	76.504	0.0881	0.2698	25

Temp. (°C t)	Humidity Ratio W_s (kg$_w$/kg$_{da}$)	Specific Volume (m³/kg$_{da}$)			Specific Enthalpy (kJ/kg$_{da}$)			Specific Entropy, kJ/(kg$_{da}$ K)		Temp., t (°C)
		v_{da}	v_{as}	v_s	h_{da}	h_{as}	h_s	s_{da}	s_s	
26	0.021451	0.8472	0.0291	0.8763	26.155	54.647	80.801	0.0915	0.2842	26
27	0.022802	0.8500	0.0311	0.8811	27.161	58.129	85.290	0.0948	0.2992	27
28	0.024229	0.8529	0.0331	0.8860	28.167	61.813	89.980	0.0982	0.3148	28
29	0.025738	0.8557	0.0353	0.8910	29.174	65.709	94.883	0.1015	0.3311	29
30	0.027333	0.8585	0.0376	0.8961	30.180	69.829	100.010	0.1048	0.3481	30
31	0.029018	0.8614	0.0400	0.9014	31.187	74.186	105.373	0.1081	0.3658	31
32	0.030797	0.8642	0.0426	0.9069	32.193	78.792	110.986	0.1115	0.3843	32
33	0.032677	0.8671	0.0454	0.9124	33.200	83.661	116.861	0.1147	0.4035	33
34	0.034663	0.8699	0.0483	0.9182	34.207	88.807	123.014	0.1180	0.4236	34
35	0.036760	0.8727	0.0514	0.9241	35.213	94.247	129.460	0.1213	0.4447	35
36	0.038975	0.8756	0.0546	0.9302	36.220	99.995	136.215	0.1246	0.4666	36
37	0.041313	0.8784	0.0581	0.9365	37.227	106.069	143.296	0.1278	0.4895	37
38	0.043783	0.8813	0.0618	0.9430	38.233	112.488	150.722	0.1311	0.5135	38
39	0.046391	0.8841	0.0657	0.9498	39.240	119.272	158.512	0.1343	0.5386	39
40	0.049145	0.8869	0.0698	0.9567	40.247	126.440	166.687	0.1375	0.5649	40
41	0.052053	0.8898	0.0741	0.9639	41.254	134.016	175.270	0.1407	0.5923	41
42	0.055124	0.8926	0.0788	0.9714	42.261	142.023	184.284	0.1439	0.6211	42
43	0.058368	0.8955	0.0837	0.9791	43.268	150.486	193.754	0.1471	0.6512	43
44	0.061795	0.8983	0.0888	0.9871	44.275	159.432	203.707	0.1503	0.6828	44
45	0.065416	0.9011	0.0943	0.9955	45.282	168.890	214.172	0.1535	0.7159	45
46	0.069242	0.9040	0.1002	1.0041	46.289	178.892	225.181	0.1566	0.7507	46

Continued

TABLE 8.1 Thermodynamic Properties of Moist Air at Standard Atmospheric Pressure, 101.325 kPa—cont'd

Temp. (°C t)	Humidity Ratio W_s (kg$_w$/kg$_{da}$)	Specific Volume (m³/kg$_{da}$)			Specific Enthalpy (kJ/kg$_{da}$)			Specific Entropy, kJ/(kg$_{da}$ K)		Temp., t (°C)
		v_{da}	v_{as}	v_s	h_{da}	h_{as}	h_s	s_{da}	s_s	
47	0.073286	0.9068	0.1063	1.0131	47.297	189.470	236.766	0.1598	0.7871	47
48	0.077561	0.9096	0.1129	1.0225	48.304	200.660	248.964	0.1629	0.8254	48
49	0.082081	0.9125	0.1198	1.0323	49.311	212.501	261.812	0.1660	0.8655	49
50	0.086863	0.9153	0.1272	1.0425	50.319	225.034	275.353	0.1692	0.9078	50
51	0.091922	0.9182	0.1350	1.0531	51.326	238.305	289.631	0.1723	0.9522	51
52	0.097278	0.9210	0.1433	1.0643	52.334	252.362	304.695	0.1754	0.9989	52
53	0.102949	0.9238	0.1521	1.0759	53.341	267.256	320.598	0.1785	1.0481	53
54	0.108958	0.9267	0.1614	1.0881	54.349	283.047	337.395	0.1816	1.0999	54
55	0.115326	0.9295	0.1714	1.1009	55.356	299.794	355.151	0.1846	1.1545	55
56	0.122080	0.9324	0.1819	1.1143	56.364	317.567	373.931	0.1877	1.2121	56
57	0.129248	0.9352	0.1932	1.1284	57.372	336.439	393.811	0.1908	1.2729	57
58	0.136858	0.9380	0.2051	1.1432	58.380	356.490	414.869	0.1938	1.3371	58
59	0.144945	0.9409	0.2179	1.1587	59.388	377.809	437.197	0.1968	1.4050	59
60	0.153545	0.9437	0.2315	1.1752	60.396	400.493	460.889	0.1999	1.4769	60
61	0.162697	0.9465	0.2460	1.1925	61.404	424.650	486.054	0.2029	1.5530	61
62	0.172446	0.9494	0.2615	1.2108	62.412	450.398	512.810	0.2059	1.6338	62
63	0.182842	0.9522	0.2780	1.2302	63.420	477.868	541.287	0.2089	1.7195	63
64	0.193937	0.9551	0.2957	1.2508	64.428	507.204	571.632	0.2119	1.8105	64
65	0.205794	0.9579	0.3147	1.2726	65.436	538.570	604.006	0.2149	1.9075	65
66	0.218478	0.9607	0.3350	1.2957	66.445	572.145	638.590	0.2179	2.0107	66
67	0.232067	0.9636	0.3568	1.3204	67.453	608.133	675.587	0.2208	2.1209	67
68	0.246645	0.9664	0.3803	1.3467	68.462	646.762	715.224	0.2238	2.2386	68

Temp. (°C t)	Humidity Ratio W_s (kg$_w$/kg$_{da}$)	Specific Volume (m³/kg$_{da}$)			Specific Enthalpy (kJ/kg$_{da}$)			Specific Entropy, kJ/(kg$_{da}$ K)		Temp., t (°C)
		v_{da}	v_{as}	v_s	h_{da}	h_{as}	h_s	s_{da}	s_s	
69	0.262309	0.9692	0.4056	1.3748	69.470	688.288	757.759	0.2268	2.3647	69
70	0.279167	0.9721	0.4328	1.4049	70.479	733.004	803.483	0.2297	2.4998	70
71	0.297343	0.9749	0.4622	1.4372	71.488	781.240	852.728	0.2326	2.6449	71
72	0.316979	0.9778	0.4941	1.4719	72.496	833.375	905.872	0.2356	2.8012	72
73	0.338237	0.9806	0.5287	1.5093	73.505	889.844	963.350	0.2385	2.9697	73
74	0.361304	0.9834	0.5663	1.5497	74.514	951.149	1025.663	0.2414	3.1520	74
75	0.386399	0.9863	0.6072	1.5935	75.523	1017.871	1093.394	0.2443	3.3497	75
76	0.413774	0.9891	0.6520	1.6411	76.532	1090.688	1167.220	0.2472	3.5645	76
77	0.443727	0.9919	0.7010	1.6930	77.542	1170.398	1247.939	0.2501	3.7989	77
78	0.476610	0.9948	0.7550	1.7497	78.551	1257.941	1336.492	0.2529	4.0554	78
79	0.512842	0.9976	0.8145	1.8121	79.560	1354.439	1433.999	0.2558	4.3371	79
80	0.552926	1.0005	0.8805	1.8809	80.570	1461.236	1541.806	0.2587	4.6478	80
81	0.597470	1.0033	0.9539	1.9572	81.579	1579.961	1661.540	0.2615	4.9921	81
82	0.647218	1.0061	1.0360	2.0421	82.589	1712.604	1795.193	0.2644	5.3755	82
83	0.703089	1.0090	1.1283	2.1373	83.598	1861.625	1945.223	0.2672	5.8048	83
84	0.766233	1.0118	1.2328	2.2446	84.608	2030.099	2114.707	0.2701	6.2886	84
85	0.838105	1.0146	1.3519	2.3665	85.618	2221.922	2307.539	0.2729	6.8377	85
86	0.920580	1.0175	1.4887	2.5062	86.628	2442.105	2528.732	0.2757	7.4661	86
87	1.016105	1.0203	1.6473	2.6676	87.638	2697.204	2784.842	0.2785	8.1920	87
88	1.127952	1.0232	1.8332	2.8564	88.648	2995.967	3084.614	0.2813	9.0397	88
89	1.260579	1.0260	2.0539	3.0799	89.658	3350.325	3439.983	0.2841	10.0422	89
90	1.420235	1.0288	2.3198	3.3487	90.668	3776.998	3867.666	0.2869	11.2459	90

ASHRAE, 2017. Psychrometrics. In: ASHRAE Fundamentals. ASHRAE (Chapter 1; Table 2).

TABLE 8.2 Thermodynamic Properties of Water at Saturation

Temp., t (°C)	Absolute Pressure, p_{ws} (kPa)	Specific Volume (m³/kg$_w$)			Specific Enthalpy (kJ/kg$_w$)			Specific Entropy (kJ/(kg$_w$ K))			Temp., t (°C)
		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	−442.19	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

TABLE 8.2 Thermodynamic Properties of Water at Saturation—cont'd

Temp., t (°C)	Absolute Pressure, p_{ws} (kPa)	Specific Volume (m³/kg$_w$)			Specific Enthalpy (kJ/kg$_w$)			Specific Entropy (kJ/(kg$_w$ K))			Temp., t (°C)
		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	
−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

Continued

TABLE 8.2 Thermodynamic Properties of Water at Saturation—cont'd

Temp., t (°C)	Absolute Pressure, p_{ws} (kPa)	Specific Volume (m³/kg$_w$)			Specific Enthalpy (kJ/kg$_w$)			Specific Entropy (kJ/(kg$_w$ K))			Temp., t (°C)
		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	
−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

TABLE 8.2 Thermodynamic Properties of Water at Saturation—cont'd

		Specific Volume (m³/kg$_w$)			Specific Enthalpy (kJ/kg$_w$)			Specific Entropy (kJ/(kg$_w$ K))			
Temp., t (°C)	Absolute Pressure, p_{ws} (kPa)	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	Temp., t (°C)
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
3	0.7581	0.001000	168.013	168.014	12.60	2493.80	2506.40	0.0459	9.0306	9.0765	3
4	0.8135	0.001000	157.120	157.121	16.81	2491.42	2508.24	0.0611	8.9895	9.0506	4
5	0.8726	0.001000	147.016	147.017	21.02	2489.05	2510.07	0.0763	8.9486	9.0249	5
6	0.9354	0.001000	137.637	137.638	25.22	2486.68	2511.91	0.0913	8.9081	8.9994	6
7	1.0021	0.001000	128.927	128.928	29.43	2484.31	2513.74	0.1064	8.8678	8.9742	7
8	1.0730	0.001000	120.833	120.834	33.63	2481.94	2515.57	0.1213	8.8278	8.9492	8
9	1.1483	0.001000	113.308	113.309	37.82	2479.58	2517.40	0.1362	8.7882	8.9244	9
10	1.2282	0.001000	106.308	106.309	42.02	2477.21	2519.23	0.1511	8.7488	8.8998	10
11	1.3129	0.001000	99.792	99.793	46.22	2474.84	2521.06	0.1659	8.7096	8.8755	11
12	1.4028	0.001001	93.723	93.724	50.41	2472.48	2522.89	0.1806	8.6708	8.8514	12
13	1.4981	0.001001	88.069	88.070	54.60	2470.11	2524.71	0.1953	8.6322	8.8275	13
14	1.5989	0.001001	82.797	82.798	58.79	2467.75	2526.54	0.2099	8.5939	8.8038	14
15	1.7057	0.001001	77.880	77.881	62.98	2465.38	2528.36	0.2245	8.5559	8.7804	15
16	1.8188	0.001001	73.290	73.291	67.17	2463.01	2530.19	0.2390	8.5181	8.7571	16
17	1.9383	0.001001	69.005	69.006	71.36	2460.65	2532.01	0.2534	8.4806	8.7341	17
18	2.0647	0.001001	65.002	65.003	75.55	2458.28	2533.83	0.2678	8.4434	8.7112	18

Continued

TABLE 8.2 Thermodynamic Properties of Water at Saturation—cont'd

Temp., t (°C)	Absolute Pressure, p_{ws} (kPa)	Specific Volume (m³/kg$_w$)			Specific Enthalpy (kJ/kg$_w$)			Specific Entropy (kJ/(kg$_w$ K))			Temp., t (°C)
		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	
19	2.1982	0.001002	61.260	61.261	79.73	2455.92	2535.65	0.2822	8.4064	8.6886	19
20	2.3392	0.001002	57.760	57.761	83.92	2453.55	2537.47	0.2965	8.3696	8.6661	20
21	2.4881	0.001002	54.486	54.487	88.10	2451.18	2539.29	0.3108	8.3331	8.6439	21
22	2.6452	0.001002	51.421	51.422	92.29	2448.81	2541.10	0.3250	8.2969	8.6218	22
23	2.8109	0.001003	48.551	48.552	96.47	2446.45	2542.92	0.3391	8.2609	8.6000	23
24	2.9856	0.001003	45.862	45.863	100.66	2444.08	2544.73	0.3532	8.2251	8.5783	24
25	3.1697	0.001003	43.340	43.341	104.84	2441.71	2546.54	0.3673	8.1895	8.5568	25
26	3.3637	0.001003	40.976	40.977	109.02	2439.33	2548.35	0.3813	8.1542	8.5355	26
27	3.5679	0.001004	38.757	38.758	113.20	2436.96	2550.16	0.3952	8.1192	8.5144	27
28	3.7828	0.001004	36.674	36.675	117.38	2434.59	2551.97	0.4091	8.0843	8.4934	28
29	4.0089	0.001004	34.718	34.719	121.56	2432.21	2553.78	0.4230	8.0497	8.4727	29
30	4.2467	0.001004	32.881	32.882	125.75	2429.84	2555.58	0.4368	8.0153	8.4521	30
31	4.4966	0.001005	31.153	31.154	129.93	2427.46	2557.39	0.4506	7.9812	8.4317	31
32	4.7592	0.001005	29.528	29.529	134.11	2425.08	2559.19	0.4643	7.9472	8.4115	32
33	5.0351	0.001005	28.000	28.001	138.29	2422.70	2560.99	0.4780	7.9135	8.3914	33
34	5.3247	0.001006	26.561	26.562	142.47	2420.32	2562.79	0.4916	7.8800	8.3715	34
35	5.6286	0.001006	25.207	25.208	146.64	2417.94	2564.58	0.5052	7.8467	8.3518	35
36	5.9475	0.001006	23.931	23.932	150.82	2415.56	2566.38	0.5187	7.8136	8.3323	36
37	6.2818	0.001007	22.728	22.729	155.00	2413.17	2568.17	0.5322	7.7807	8.3129	37
38	6.6324	0.001007	21.594	21.595	159.18	2410.78	2569.96	0.5457	7.7480	8.2936	38

TABLE 8.2 Thermodynamic Properties of Water at Saturation—cont'd

Temp., t (°C)	Absolute Pressure, p_{ws} (kPa)	Specific Volume (m³/kg$_w$)			Specific Enthalpy (kJ/kg$_w$)			Specific Entropy (kJ/(kg$_w$ K))			Temp., t (°C)
		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	
39	6.9997	0.001007	20.525	20.526	163.36	2408.39	2571.75	0.5591	7.7155	8.2746	39
40	7.3844	0.001008	19.516	19.517	167.54	2406.00	2573.54	0.5724	7.6832	8.2557	40
41	7.7873	0.001008	18.564	18.565	171.72	2403.61	2575.33	0.5858	7.6512	8.2369	41
42	8.2090	0.001009	17.664	17.665	175.90	2401.21	2577.11	0.5990	7.6193	8.2183	42
43	8.6503	0.001009	16.815	16.816	180.08	2398.82	2578.89	0.6123	7.5876	8.1999	43
44	9.1118	0.001009	16.012	16.013	184.26	2396.42	2580.67	0.6255	7.5561	8.1816	44
45	9.5944	0.001010	15.252	15.253	188.44	2394.02	2582.45	0.6386	7.5248	8.1634	45
46	10.0988	0.001010	14.534	14.535	192.62	2391.61	2584.23	0.6517	7.4937	8.1454	46
47	10.6259	0.001011	13.855	13.856	196.80	2389.21	2586.00	0.6648	7.4628	8.1276	47
48	11.1764	0.001011	13.212	13.213	200.98	2386.80	2587.77	0.6778	7.4320	8.1099	48
49	11.7512	0.001012	12.603	12.604	205.16	2384.39	2589.54	0.6908	7.4015	8.0923	49
50	12.3513	0.001012	12.027	12.028	209.34	2381.97	2591.31	0.7038	7.3711	8.0749	50
51	12.9774	0.001013	11.481	11.482	213.52	2379.56	2593.08	0.7167	7.3409	8.0576	51
52	13.6305	0.001013	10.963	10.964	217.70	2377.14	2594.84	0.7296	7.3109	8.0405	52
53	14.3116	0.001014	10.472	10.473	221.88	2374.72	2596.60	0.7424	7.2811	8.0235	53
54	15.0215	0.001014	10.006	10.007	226.06	2372.30	2598.35	0.7552	7.2514	8.0066	54
55	15.7614	0.001015	9.5639	9.5649	230.24	2369.87	2600.11	0.7680	7.2219	7.9899	55
56	16.5322	0.001015	9.1444	9.1454	234.42	2367.44	2601.86	0.7807	7.1926	7.9733	56
57	17.3350	0.001016	8.7461	8.7471	238.61	2365.01	2603.61	0.7934	7.1634	7.9568	57
58	18.1708	0.001016	8.3678	8.3688	242.79	2362.57	2605.36	0.8060	7.1344	7.9405	58

TABLE 8.2 Thermodynamic Properties of Water at Saturation—cont'd

Temp., t (°C)	Absolute Pressure, p_{ws} (kPa)	Specific Volume (m³/kg$_w$)			Specific Enthalpy (kJ/kg$_w$)			Specific Entropy (kJ/(kg$_w$ K))			Temp., t (°C)
		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	
59	19.0407	0.001017	8.0083	8.0093	246.97	2360.13	2607.10	0.8186	7.1056	7.9243	59
60	19.9458	0.001017	7.6666	7.6677	251.15	2357.69	2608.85	0.8312	7.0770	7.9082	60
61	20.8873	0.001018	7.3418	7.3428	255.34	2355.25	2610.58	0.8438	7.0485	7.8922	61
62	21.8664	0.001018	7.0328	7.0338	259.52	2352.80	2612.32	0.8563	7.0201	7.8764	62
63	22.8842	0.001019	6.7389	6.7399	263.71	2350.35	2614.05	0.8687	6.9919	7.8607	63
64	23.9421	0.001019	6.4591	6.4601	267.89	2347.89	2615.78	0.8811	6.9639	7.8451	64
65	25.0411	0.001020	6.1928	6.1938	272.08	2345.43	2617.51	0.8935	6.9361	7.8296	65
66	26.1827	0.001020	5.9392	5.9402	276.27	2342.97	2619.23	0.9059	6.9083	7.8142	66
67	27.3680	0.001021	5.6976	5.6986	280.45	2340.50	2620.96	0.9182	6.8808	7.7990	67
68	28.5986	0.001022	5.4674	5.4684	284.64	2338.03	2622.67	0.9305	6.8534	7.7839	68
69	29.8756	0.001022	5.2479	5.2490	288.83	2335.56	2624.39	0.9428	6.8261	7.7689	69
70	31.2006	0.001023	5.0387	5.0397	293.02	2333.08	2626.10	0.9550	6.7990	7.7540	70
71	32.5750	0.001023	4.8392	4.8402	297.21	2330.60	2627.81	0.9672	6.7720	7.7392	71
72	34.0001	0.001024	4.6488	4.6498	301.40	2328.11	2629.51	0.9793	6.7452	7.7245	72
73	35.4775	0.001025	4.4671	4.4681	305.59	2325.62	2631.21	0.9915	6.7185	7.7100	73
74	37.0088	0.001025	4.2937	4.2947	309.78	2323.13	2632.91	1.0035	6.6920	7.6955	74
75	38.5954	0.001026	4.1281	4.1291	313.97	2320.63	2634.60	1.0156	6.6656	7.6812	75
76	40.2389	0.001026	3.9699	3.9709	318.17	2318.13	2636.29	1.0276	6.6393	7.6669	76
77	41.9409	0.001027	3.8188	3.8198	322.36	2315.62	2637.98	1.0396	6.6132	7.6528	77
78	43.7031	0.001028	3.6743	3.6754	326.56	2313.11	2639.66	1.0516	6.5872	7.6388	78

TABLE 8.2 Thermodynamic Properties of Water at Saturation—cont'd

Temp., t (°C)	Absolute Pressure, p_{ws} (kPa)	Specific Volume (m³/kg$_w$)			Specific Enthalpy (kJ/kg$_w$)			Specific Entropy (kJ/(kg$_w$ K))			Temp., t (°C)
		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	
79	45.5271	0.001028	3.5363	3.5373	330.75	2310.59	2641.34	1.0635	6.5613	7.6248	79
80	47.4147	0.001029	3.4042	3.4053	334.95	2308.07	2643.01	1.0754	6.5356	7.6110	80
81	49.3676	0.001030	3.2780	3.2790	339.15	2305.54	2644.68	1.0873	6.5100	7.5973	81
82	51.3875	0.001030	3.1572	3.1582	343.34	2303.01	2646.35	1.0991	6.4846	7.5837	82
83	53.4762	0.001031	3.0415	3.0426	347.54	2300.47	2648.01	1.1109	6.4592	7.5701	83
84	55.6355	0.001032	2.9309	2.9319	351.74	2297.93	2649.67	1.1227	6.4340	7.5567	84
85	57.8675	0.001032	2.8249	2.8259	355.95	2295.38	2651.33	1.1344	6.4090	7.5434	85
86	60.1738	0.001033	2.7234	2.7244	360.15	2292.83	2652.98	1.1461	6.3840	7.5301	86
87	62.5565	0.001034	2.6262	2.6272	364.35	2290.27	2654.62	1.1578	6.3592	7.5170	87
88	65.0174	0.001035	2.5330	2.5341	368.56	2287.70	2656.26	1.1694	6.3345	7.5039	88
89	67.5587	0.001035	2.4437	2.4448	372.76	2285.14	2657.90	1.1811	6.3099	7.4909	89
90	70.1824	0.001036	2.3581	2.3591	376.97	2282.56	2659.53	1.1927	6.2854	7.4781	90
91	72.8904	0.001037	2.2760	2.2771	381.18	2279.98	2661.16	1.2042	6.2611	7.4653	91
92	75.6849	0.001037	2.1973	2.1983	385.38	2277.39	2662.78	1.2158	6.2368	7.4526	92
93	78.5681	0.001038	2.1217	2.1228	389.59	2274.80	2664.39	1.2273	6.2127	7.4400	93
94	81.5420	0.001039	2.0492	2.0502	393.81	2272.20	2666.01	1.2387	6.1887	7.4275	94
95	84.6089	0.001040	1.9796	1.9806	398.02	2269.60	2667.61	1.2502	6.1648	7.4150	95
96	87.7711	0.001040	1.9128	1.9138	402.23	2266.98	2669.22	1.2616	6.1411	7.4027	96
97	91.0308	0.001041	1.8486	1.8497	406.45	2264.37	2670.81	1.2730	6.1174	7.3904	97
98	94.3902	0.001042	1.7870	1.7880	410.66	2261.74	2672.40	1.2844	6.0938	7.3782	98
99	97.8518	0.001043	1.7277	1.7288	414.88	2259.11	2673.99	1.2957	6.0704	7.3661	99

Continued

TABLE 8.2 Thermodynamic Properties of Water at Saturation—cont'd

Temp., t (°C)	Absolute Pressure, p_{ws} (kPa)	Specific Volume (m³/kg$_w$)			Specific Enthalpy (kJ/kg$_w$)			Specific Entropy (kJ/(kg$_w$ K))			Temp., t (°C)
		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	
100	101.4180	0.001043	1.6708	1.6719	419.10	2256.47	2675.57	1.3070	6.0471	7.3541	100
101	105.0910	0.001044	1.6161	1.6171	423.32	2253.83	2677.15	1.3183	6.0238	7.3421	101
102	108.8735	0.001045	1.5635	1.5645	427.54	2251.18	2678.72	1.3296	6.0007	7.3303	102
103	112.7678	0.001046	1.5129	1.5140	431.76	2248.52	2680.28	1.3408	5.9777	7.3185	103
104	116.7765	0.001047	1.4642	1.4653	435.99	2245.85	2681.84	1.3520	5.9548	7.3068	104
105	120.9021	0.001047	1.4174	1.4185	440.21	2243.18	2683.39	1.3632	5.9320	7.2951	105
106	125.1472	0.001048	1.3724	1.3734	444.44	2240.50	2684.94	1.3743	5.9092	7.2836	106
107	129.5145	0.001049	1.3290	1.3301	448.67	2237.81	2686.48	1.3854	5.8866	7.2721	107
108	134.0065	0.001050	1.2873	1.2883	452.90	2235.12	2688.02	1.3965	5.8641	7.2607	108
109	138.6261	0.001051	1.2471	1.2481	457.13	2232.41	2689.55	1.4076	5.8417	7.2493	109
110	143.3760	0.001052	1.2083	1.2094	461.36	2229.70	2691.07	1.4187	5.8194	7.2380	110
111	148.2588	0.001052	1.1710	1.1721	465.60	2226.99	2692.58	1.4297	5.7972	7.2268	111
112	153.2775	0.001053	1.1351	1.1362	469.83	2224.26	2694.09	1.4407	5.7750	7.2157	112
113	158.4348	0.001054	1.1005	1.1015	474.07	2221.53	2695.60	1.4517	5.7530	7.2047	113
114	163.7337	0.001055	1.0671	1.0681	478.31	2218.78	2697.09	1.4626	5.7310	7.1937	114
115	169.1770	0.001056	1.0349	1.0359	482.55	2216.03	2698.58	1.4735	5.7092	7.1827	115
116	174.7678	0.001057	1.0038	1.0049	486.80	2213.27	2700.07	1.4844	5.6874	7.1719	116
117	180.5090	0.001058	0.9739	0.9750	491.04	2210.51	2701.55	1.4953	5.6658	7.1611	117
118	186.4036	0.001059	0.9450	0.9461	495.29	2207.73	2703.02	1.5062	5.6442	7.1504	118
119	192.4547	0.001059	0.9171	0.9182	499.53	2204.94	2704.48	1.5170	5.6227	7.1397	119
120	198.6654	0.001060	0.8902	0.8913	503.78	2202.15	2705.93	1.5278	5.6013	7.1291	120
122	211.5782	0.001062	0.8392	0.8403	512.29	2196.53	2708.82	1.5494	5.5587	7.1081	122

TABLE 8.2   Thermodynamic Properties of Water at Saturation—cont'd

Temp., t (°C)	Absolute Pressure, p_{ws} (kPa)	Specific Volume (m³/kg$_w$)			Specific Enthalpy (kJ/kg$_w$)			Specific Entropy (kJ/(kg$_w$ K))			Temp., t (°C)
		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	
124	225.1676	0.001064	0.7916	0.7927	520.80	2190.88	2711.69	1.5708	5.5165	7.0873	124
126	239.4597	0.001066	0.7472	0.7483	529.32	2185.19	2714.52	1.5922	5.4746	7.0668	126
128	254.4813	0.001068	0.7058	0.7068	537.85	2179.47	2717.32	1.6134	5.4330	7.0465	128
130	270.2596	0.001070	0.6670	0.6681	546.39	2173.70	2720.09	1.6346	5.3918	7.0264	130
132	286.8226	0.001072	0.6308	0.6318	554.93	2167.89	2722.83	1.6557	5.3508	7.0066	132
134	304.1989	0.001074	0.5969	0.5979	563.49	2162.04	2725.53	1.6767	5.3102	6.9869	134
136	322.4175	0.001076	0.5651	0.5662	572.05	2156.15	2728.20	1.6977	5.2698	6.9675	136
138	341.5081	0.001078	0.5353	0.5364	580.62	2150.22	2730.84	1.7185	5.2298	6.9483	138
140	361.5010	0.001080	0.5074	0.5085	589.20	2144.24	2733.44	1.7393	5.1900	6.9293	140
142	382.4271	0.001082	0.4813	0.4823	597.79	2138.22	2736.01	1.7600	5.1505	6.9105	142
144	404.3178	0.001084	0.4567	0.4577	606.39	2132.15	2738.54	1.7806	5.1112	6.8918	144
146	427.2053	0.001086	0.4336	0.4346	615.00	2126.04	2741.04	1.8011	5.0723	6.8734	146
148	451.1220	0.001088	0.4118	0.4129	623.62	2119.88	2743.50	1.8216	5.0335	6.8551	148
150	476.1014	0.001091	0.3914	0.3925	632.25	2113.67	2745.92	1.8420	4.9951	6.8370	150
152	502.1771	0.001093	0.3722	0.3733	640.89	2107.41	2748.30	1.8623	4.9569	6.8191	152
154	529.3834	0.001095	0.3541	0.3552	649.55	2101.10	2750.64	1.8825	4.9189	6.8014	154
156	557.7555	0.001097	0.3370	0.3381	658.21	2094.74	2752.95	1.9027	4.8811	6.7838	156
158	587.3287	0.001100	0.3209	0.3220	666.89	2088.32	2755.21	1.9228	4.8436	6.7664	158
160	618.1392	0.001102	0.3057	0.3068	675.57	2081.86	2757.43	1.9428	4.8063	6.7491	160

ASHRAE, 2017. Psychrometrics. In: ASHRAE Fundamentals. ASHRAE (Chapter 1; Table 3).

psychrometric chart. These charts are available in different ranges of temperature, at different altitudes, and with different units of measure.

To understand how to use a psychrometric chart, it is best to build a simplified one.

The first step is to plot the vapor pressure of water in air over a range of temperatures. This line represents 100% relative humidity (RH) at each given temperature (Fig. 8.3).

Next, we can add a line that represents 50% RH by plotting points that are 50% of the vapor pressure at saturation (Fig. 8.4).

We now have a chart that easily relates temperature, RH, and vapor pressure. We could also add curves showing many other levels of RH, but we will keep it simple for now.

How do we know how much water vapor is actually in the air? For many psychrometric applications, this is the most important part. When moving from one set of conditions to another, the amount of water that has either been added or removed from the air is of interest.

The vapor pressure actually provides this information when we remember that the vapor pressure is also a measure of the partial pressure of water vapor in air. We can convert this pressure to a volume ratio (of water to air) and eventually to a mass ratio. Therefore for a given vapor pressure, the ratio of water mass to air mass in a given mixture is constant, and so we can plot a line of this humidity ratio on our chart as shown in Fig. 8.5. We can also add a second vertical axis to explicitly show the humidity ratio.

All of this may start to feel a little confusing and abstract. After all, what good is it to have this information if we cannot measure something that helps us know what conditions we actually have. This is where wet-bulb temperature comes in. As shown in Fig. 8.2 above, we can use dry-bulb and wet-bulb temperature measurements to determine the state condition of our air. The wet-bulb depression is a measure of how much water vapor is in the air, so our
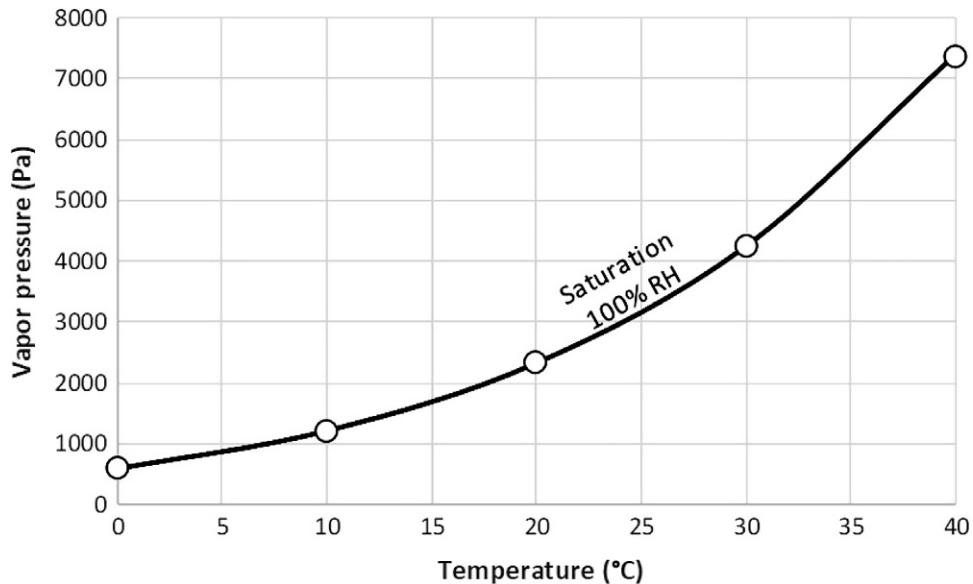
FIG. 8.3   The start of a psychrometric chart. This step shows the vapor pressure of water in air plotted against air temperature. This is the "saturation" line or the line of 100% relative humidity.
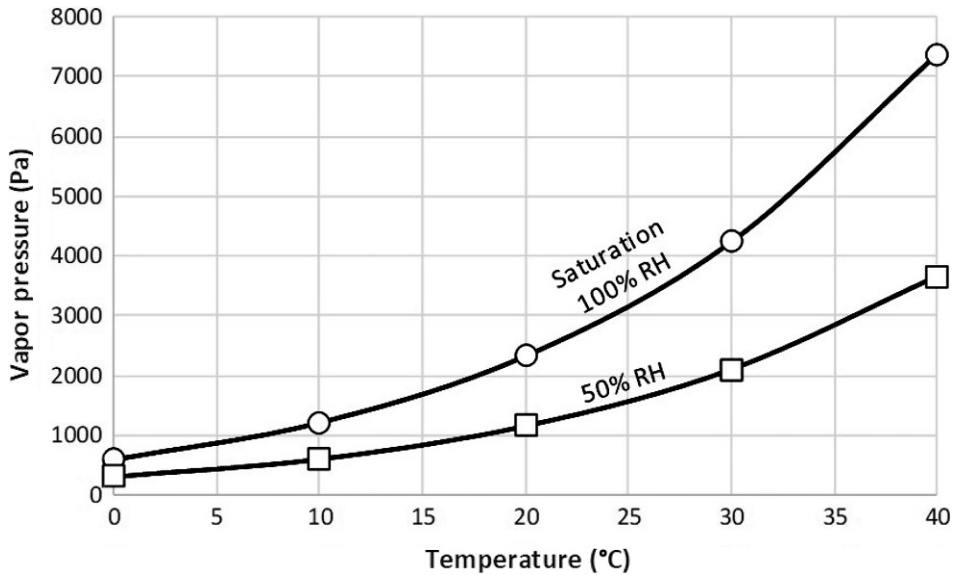
FIG. 8.4 Adding a 50% RH line to our psychrometric chart.
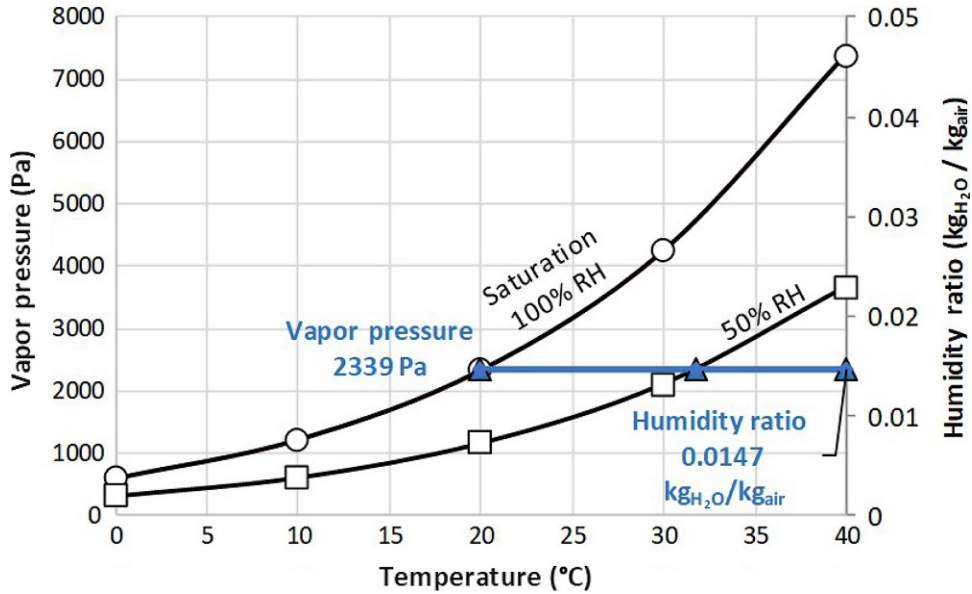
FIG. 8.5 The blue line is a line of constant vapor pressure of 2339 Pa, which is also a line of constant mass ratio of water to air of 0.0147 kg_{H_2O}/kg_{air}. We have also added a second vertical axis so we can easily read the mass ratio values at any point on the chart.

psychrometric chart should also indicate wet-bulb temperature. Other references provide extensive background on how to relate dry-bulb, wet-bulb, and relative humidity (ASHRAE, 2017). For our purposes, it is enough to know that this relationship exists and can be calculated or found in tables. As shown in Fig. 8.6, we have added a line of constant 20°C wet-bulb temperature. You can see from this addition that at any dry-bulb temperature from 20°C to 40°C, we can draw an imaginary vertical line up to the 20°C wet-bulb temperature line; with enough RH and humidity ratio lines, we can then determine the RH and humidity ratio at that point very precisely.

We can add many more lines to ease the actual use of such a chart. For example, we would want more lines of the relative humidity, wet-bulb temperature, and humidity ratio in order to use the chart over a wide range of conditions. The addition of a few more lines is shown in Fig. 8.7.

In fact, published psychrometric charts include many, many lines to provide the capability of assessing conditions over a broad set of conditions.

8.2.6.2 Published Psychrometric Charts

Published psychrometric charts, such as those from ASHRAE, include many lines to allow the user to determine properties over a broad set of conditions. These charts are provided for different temperature ranges and altitudes (pressures) and are available in different units of measure. The two included in this chapter are for normal temperature (Fig. 8.8) and low temperature (Fig. 8.9) at sea level with SI units of measure.
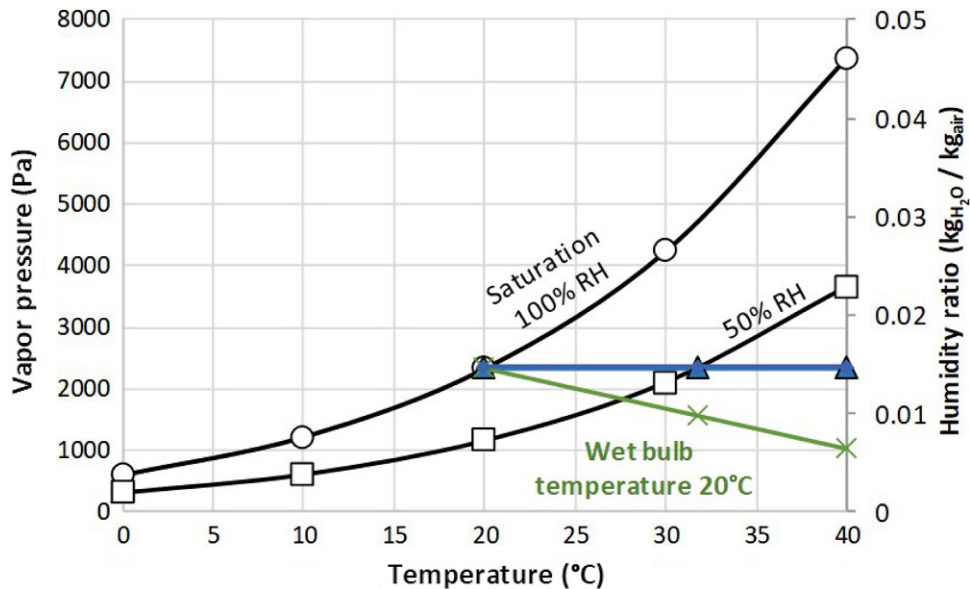
FIG. 8.6 Adding a line of constant 20°C wet-bulb temperature to the chart to allow for the use of dry-bulb and wet-bulb temperature to determine psychrometric properties.
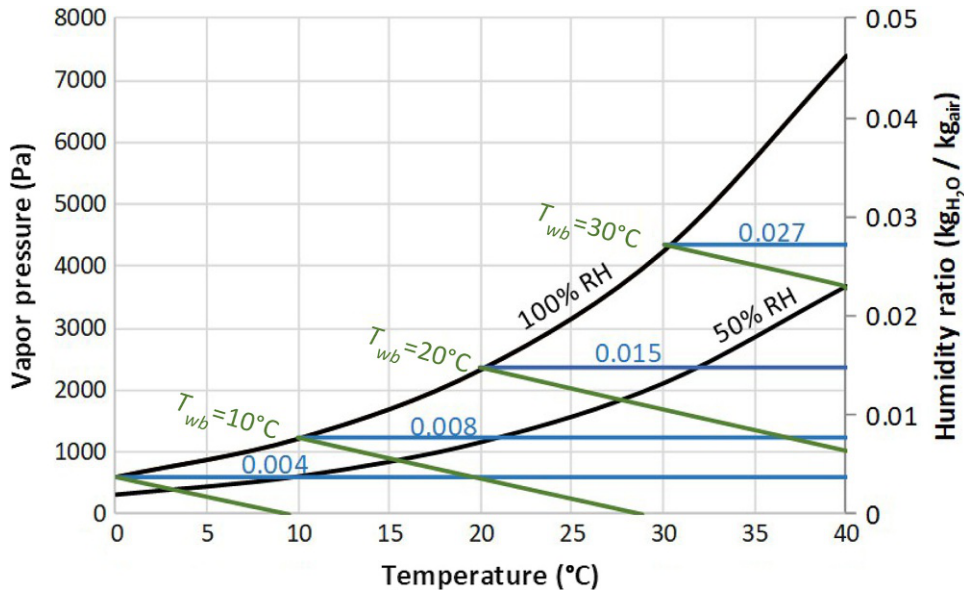
FIG. 8.7 A nearly complete psychrometric chart, looking much more complicated than when we started. We have now added several wet-bulb lines and several humidity ratio lines.

8.2.6.3 Navigating the Psychrometric Chart

One of the most challenging parts of psychrometric charts for new users is to understand where to begin and in which direction to travel. Generally speaking, in postharvest applications, we know the dry-bulb air temperature, so we are usually able to start on the horizontal axis and draw a vertical line straight up from there to an intersection with either wet-bulb temperature or relative humidity for our starting point. The other trick is to look for the chart labels; for example, "wet-bulb temperature" or "specific volume." These labels remind you which lines provide which information. Pay attention to their labeling and the associated orientation of the lines. The lines of constant dry-bulb temperature are generally vertical and march horizontally in parallel. The lines of constant relative humidity follow the characteristic curve of saturation temperature that we started with above in Fig. 8.3 (bottom left to upper right). The lines of constant wet-bulb temperature are diagonal from the upper left to the lower right and usually have specific temperature labels along the 100% RH, or "saturation" line where dry-bulb and wet-bulb temperatures are equal. The lines of constant humidity ratio are horizontal and march vertically in parallel. Enthalpy basically follows the orientation of wet-bulb temperature (diagonal from upper left to lower right.)

For example, let us assume you just took a dry-bulb/wet-bulb sling psychrometer reading. The results were 25°C dry-bulb and 20°C wet-bulb. Starting at 25°C dry-bulb in Fig. 8.10, follow the vertical dry-bulb line *(red)* to the diagonal 20°C wet-bulb line *(red)*. You now can determine the relative humidity is about 63% based on where this point is between

FIG. 8.8 ASHRAE psychrometric chart 1 normal temperature—sea level (0–50°C db).

ASHRAE psychrometric chart no. 2
Low temperature –40°C to 10°C   Sea level
Barometric pressure   101.325 kPa.
Copyright 1981
American society of heating, refrigerating and air-conditioning engineers, inc.

$$\frac{\text{Sensible heat}}{\text{Total heat}} = \frac{\Delta H_S}{\Delta H_T}$$

$$\frac{\text{Enthalpy}}{\text{Humidity ratio}} = \frac{\Delta h}{\Delta W}$$

Enthalpy (h) kilojoules per kilogram dry air

Saturation temperature (°C)

Wet bulb temperature (°C)

Volume cubic metre per kilogram dry air

Humidity ratio (W) grams moisture per kilogram dry air

Relative humidity

Dry bulb temperature (°C)

$$\frac{\text{Sensible heat}}{\text{Total heat}} = \frac{\Delta H_S}{\Delta H_T}$$
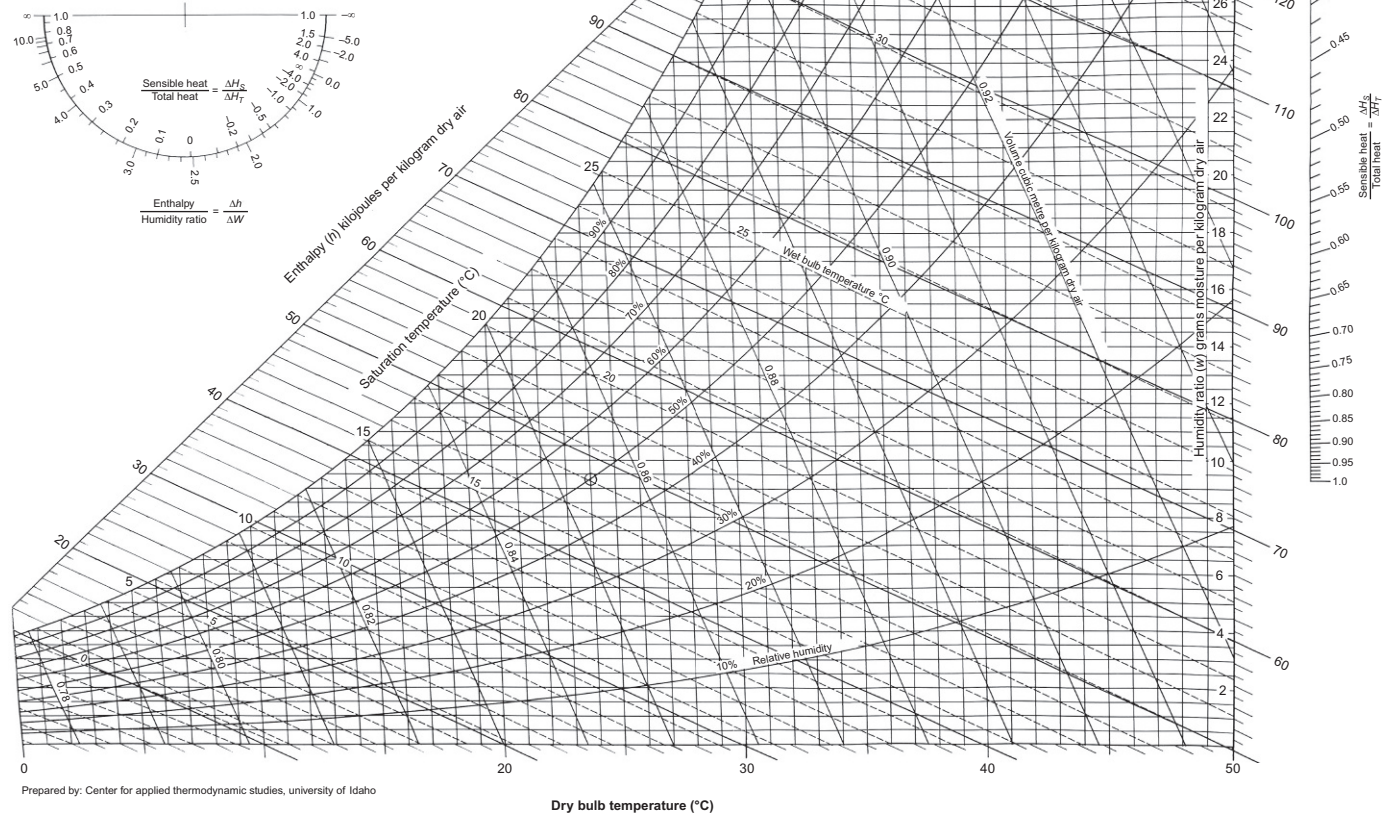
Prepared by: Center for applied thermodynamic studies, university of Idaho

FIG. 8.9   ASHRAE psychrometric chart 2 low temperature—sea level (−40°C to 10°C db).

FIG. 8.10   Using a published psychrometric chart to find air properties for 25°C dry-bulb and 20°C wet-bulb.

the 60% and 70% curved RH lines *(blue)*. This point is very close to $0.86 \, \text{m}^3/\text{kg}$ specific volume diagonal line *(green)*, so you can estimate the specific volume as that value. You can follow the humidity ratio lines horizontally to determine the value of approximately $12.6 \, \text{g}_{\text{water}}/\text{kg}_{\text{air}}$ *(brown)*. Finally, you can estimate the enthalpy as $57.5 \, \text{kJ/kg}$ of dry air *(purple)*. That is a lot of new information that we determined from just two temperatures.

What if we want to move around on the psychrometric chart to understand how changes we make to the air will change the properties? The psychrometric "compass" in Fig. 8.11 should help. This shows how different processes (e.g., heating, cooling, humidifying, etc.) translate to movement on the psychrometric chart.

8.2.7 Psychrometric Calculators

In addition to psychrometric charts noted above, there are also calculators available to determine psychrometric properties. These calculators are available online with web-based interfaces, such as for downloadable mobile phone applications (apps) and as add-ins for common spreadsheet applications.

8.2.7.1 Web-Based Calculators

The Sugar Engineers Psychrometric Calculator. http://www.sugartech.co.za/psychro/index.php
Tornado Psychrometric Calculator. http://www.hvac-calculator.net/index.php?v=2
MegaWatSoft Humid Air Calculator. https://www.psychrometric-calculator.com/HumidAirWeb.aspx

8.2.7.2 Mobile App Calculators

HVAC Psychrometric Chart—ASHRAE—https://itunes.apple.com/us/app/hvac-psychrometric-chart/id584295008?mt=8
HVAC Psychrometric Plus—Carmel Software—https://itunes.apple.com/us/app/hvac-psychrometric-plus/id348669031?mt=8
Munters PsychroApp—https://itunes.apple.com/us/app/hvac-psychrometric-chart/id584295008?mt=8
Psychrometric Chart. Pheinix, LLC—https://itunes.apple.com/us/app/psychrometric-chart/id1026273214?mt=8

8.2.7.3 Desktop Client Calculators

Greenheck Calculator http://www.greenheck.com/content/view/software_psychrometric?ref=software

8.2.7.4 Spreadsheet-Based Calculators

The author has created an Excel add-in that performs all the major psychrometric calculations (http://go.uvm.edu/psychrocalc).
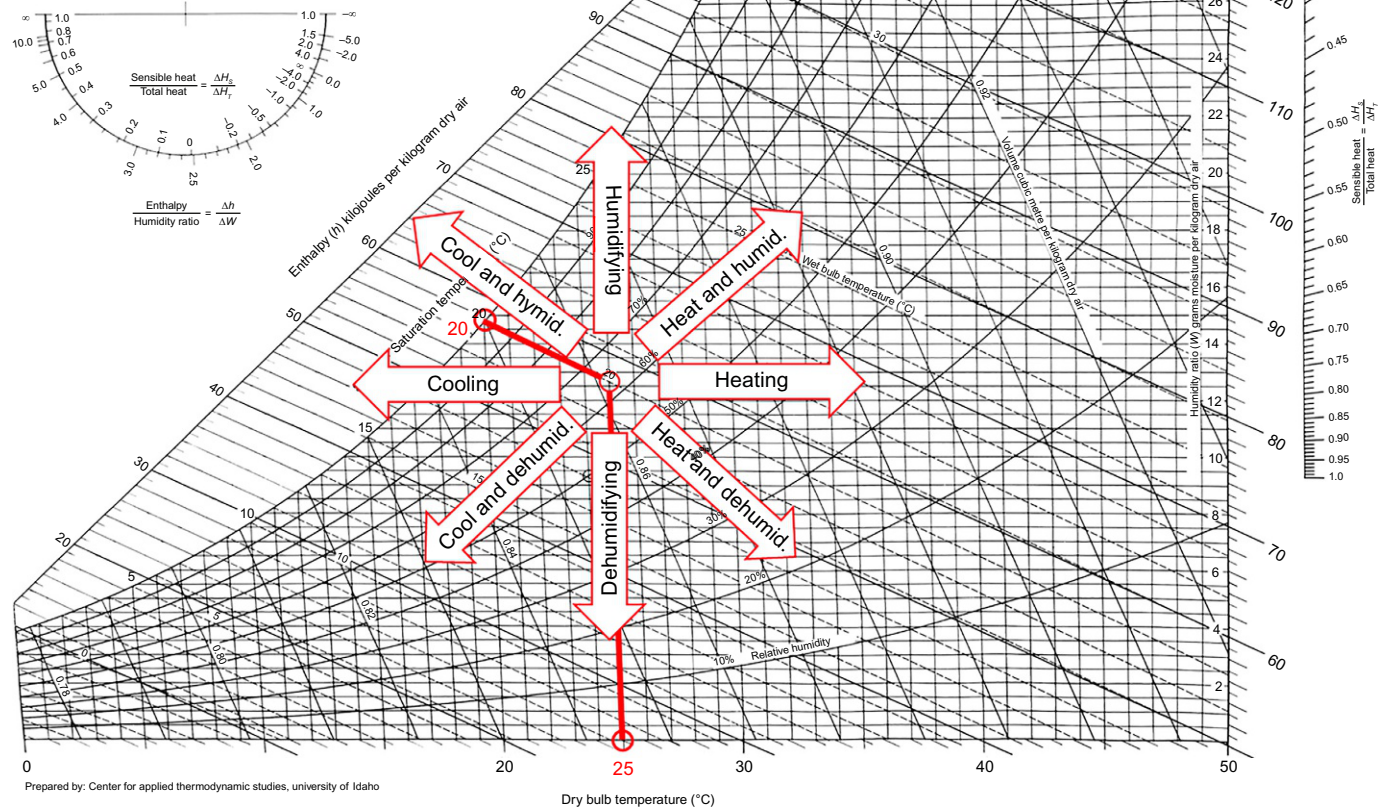
FIG. 8.11   Moving around a psychrometric chart with a "compass."

8.3 POSTHARVEST APPLICATIONS

8.3.1 Refrigeration and Associated Drying of Air

The use of mechanical refrigeration in the postharvest handling of horticultural crops is ubiquitous. As noted above and in other chapters, the reduction of temperature is critical to the preservation of quality among many crops, and a very common way to do this is through the use of refrigeration. In this process, a refrigerant is compressed in one part of the system and then expanded to reduce its boiling temperature. As this fluid enters the "evaporator," it is boiled at a low temperature across the evaporator. The evaporator is typically a heat exchanger with a large surface area provided by many fins attached to the refrigerant pathway. Air flows past this heat exchanger, generally induced by fans.

The transfer of heat from the air to the refrigerant reduces the air temperature and thereby provides cooling of the space. But another thing also happens: The cold surface of the evaporator can be thought of as a glass of ice water on a humid summer day. Water will condense from the air surrounding the glass on the outside surface of the glass. In the same way the cold surface of the evaporator in the cold room will condense water from the air, removing moisture from the air, dropping it into the condensate pan and reducing relative humidity (Fig. 8.12). The temperature of the refrigerant in the evaporator is typically the lowest in
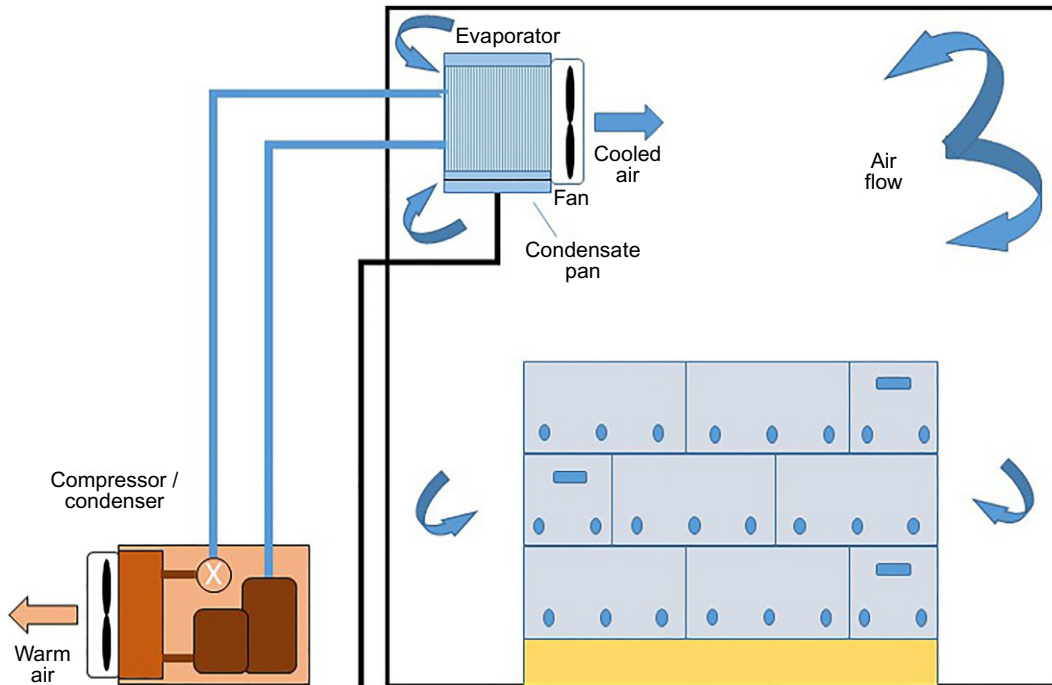
FIG. 8.12   Schematic of a typical room cooling refrigeration system showing the evaporator (the coldest surface in the room) and the condensate pan (where water removed from the air exits the room).

the room. This can be thought of as the lowest dew point temperature in the room and the point in the room at which the minimum relative humidity is set.

This may be important when considering the evaporator sizing for cold rooms that need a high level of relative humidity. In order to remove heat from the room (i.e., to cool) the evaporator temperature must be lower than the target room temperature (dry-bulb air temperature). The heat transfer rate is partially determined by the temperature difference between the hot and cold sides of the heat exchanger. Therefore as evaporator refrigerant temperature is increased the surface area of the evaporator (and its overall size) must be increased to provide the same cooling capacity. This approach is sometimes referred to as a "low delta T" or "high humidity" evaporator. While others have highlighted the importance of this design factor in postharvest refrigeration applications (Bartsch and Blanpied, 1990), it remains overlooked in many system designs and leads to unnecessary loss of product quality as a result of water loss. The impact of the evaporator refrigerant temperature on the minimum relative humidity in a cold room is shown in Table 8.3, which was developed using the psychrometric relationships between dew point temperature and dry-bulb temperature.

TABLE 8.3   Equilibrium, Minimum Relative Humidity (RH) in a Cold Room Based on the Target Air Temperature (Dry-Bulb Temperature), and the Evaporator Refrigerant Inlet Temperature (Dew Point Temperature)

		Target Room Temperature (Dry-Bulb Temperature, °C)							
		0.0	0.5	1.0	1.5	2.0	2.5	3.0	3.5
Refrigerant inlet temperature (dew point temperature, °C)	−2.0	65%	58%	51%	44%	38%	32%	27%	22%
	−1.5	74%	66%	59%	52%	45%	39%	34%	28%
	−1.0	82%	74%	67%	60%	53%	47%	41%	35%
	−0.5	91%	83%	75%	67%	60%	54%	48%	42%
	0.0		91%	83%	75%	68%	61%	55%	49%
	0.5			91%	83%	76%	69%	62%	56%
	1.0				92%	84%	76%	69%	63%
	1.5					92%	84%	77%	70%
	2.0						92%	85%	77%
	2.5							92%	85%
	3.0								92%
	3.5								
	4.0								

The *gray* area represents cases where cooling would not happen because the evaporator temperature must be below the target room temperature to result in cooling.

8.3.2 Drying and Curing

Another postharvest application of psychrometrics is the controlled drying or "curing" of certain storage crops, such as white/Irish potatoes, sweet potatoes, onions, and garlic. This postharvest process involves the slow and controlled drying of an outside layer of the product to provide a protective coating that can extend storage life and reduce damage from handling in the value chain. This process therefore intentionally removes moisture from the crop and uses the moisture carrying capacity of air to do so.

Facilities designed for the curing process typically require both heating and ventilation. Heating is used to maintain the air temperature so that it can carry moisture away from the product at the proper rate. Ventilation is used to exchange the humidified inside air with fresh (and drier) outside air (Abd-el Rahman and Ebeaid, 2009; Boyhan and Kelley, 2014). Circulation is often also used to "mix" the inside air and provide relatively uniform conditions to each unit of product.

The heater must be sized to heat the room and product against a lower outside temperature (i.e., sensible load). But it must also be sized to heat the incoming ventilation air and to account for the evaporation of water into the air as part of the curing process (evaporative cooling). Additionally the ventilation rate must be determined based on the curing rate and period (e.g., how much water is to be removed or how much weight is to be lost over a certain amount of time) and also based on the relative humidity of the incoming air.

EXAMPLE 8.1

An onion grower wishes to cure onions for long-term storage after harvest using a facility shown in Fig. 8.13. The outside conditions are 30°C (dry-bulb) and 50% RH during the curing period. The grower wishes to limit the room conditions to 38°C (dry-bulb) and 65% RH to provide optimal curing conditions. The batch being cured is 10 tons, and the measure of completion for curing is a weight loss of 8% over 4 days. Assume the room is well mixed and the exhaust conditions are the same as the limited room conditions. Neglect the heat and water vapor release due to respiration
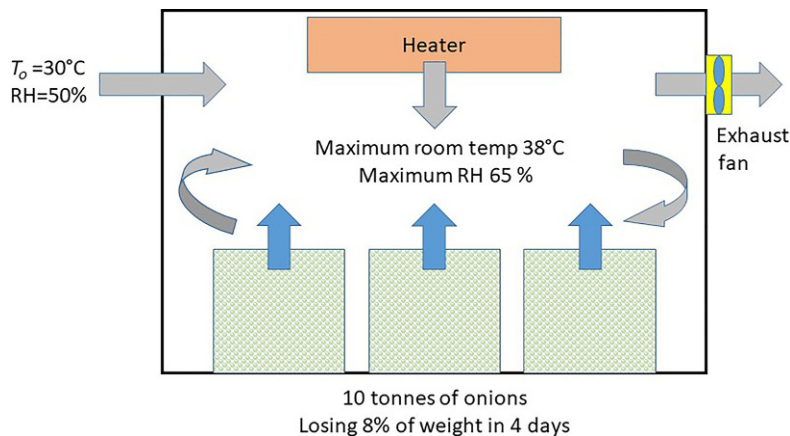

FIG. 8.13 Example of controlled drying or "curing" of onions.

from the product. Determine (1) outside air conditions; T_{db}, RH, T_{wb}, w, and h, (2) inside room (and exhaust) conditions; T_{db}, RH, T_{wb}, w, and h; (3) amount of water vapor added to the air from the drying/curing of the onions (kg); (4) rate of water removal from onions/addition of vapor to air (kg/h); (5) air flow rate required to carry the water vapor out of the room (m^3/h) and the heater output to support this process (kJ/h).

(1) Conditions of outside air, assuming $T_{db_1} = T_o = 30°C$ and $RH_1 = 50\%$. Using a psychrometric chart or calculator:

Wet-bulb temperature:	$T_{wb_1} = 21.9°C$
Humidity ratio:	$w_1 = 0.013 kg_v/kg_a$
Enthalpy:	$h_1 = 64.2 kJ/kg$
Specific volume:	$v_1 = 0.87 m^3/kg$

(2) Conditions of room air, assuming limiting conditions of $T_{db} = 38°C$ and $RH = 65\%$. Using a psychrometric chart or calculator:

Wet-bulb temperature:	$T_{wb_2} = 31.8°C$
Humidity ratio:	$w_2 = 0.028 kg_v/kg_a$
Enthalpy:	$h_2 = 109.2 kJ/kg$
Specific volume:	$v_2 = 0.92 m^3/kg$

(3) Amount of water removed as vapor from the onions:

$$10 \text{ tons of onions} = 10,000 \text{ kg}$$

$$\text{Mass loss} = \triangle m_v = 8\% \text{loss} = 0.08 \times 10,000 \text{ kg} = 800 \text{ kg}$$

(4) Rate of water removal from onions:

$$\text{Rate of mass loss} = \dot{m}_v = \frac{\triangle m_v}{\triangle t}$$

$$= 800 \text{ kg}/(4 \text{ days} \times 24 \text{ h/day})$$

$$= 8.3 \text{ kg/h}$$

(5) Air flow required to carry water vapor out of room:

$$\text{Air flow rate} = \dot{v}_a = \frac{\dot{m}_a}{\rho_2} = \dot{m}_a v_2$$

(assuming conditions at exit where the exhaust fan is located)
With:

$$\dot{m}_a = \frac{\dot{m}_v}{(w_2 - w_1)}$$

$$= 8.3\,\text{kg}_v/\text{h}/(0.028 - 0.013\,\text{kg}_v/\text{kg}_a)$$

$$= 296.4\,\text{kg}_a/\text{h}$$

With substitution:

$$\dot{v}_a = 296.4\,\text{kg}_a/\text{h} \times 0.92\,\text{m}^3/\text{kg}_a$$

$$= 272.7\,\text{m}^3/\text{h}$$

(6) Heat addition required:

$$\text{Heat addition rate} = \dot{Q} = \dot{m}_a(h_2 - h_1)$$

$$= 296.4\,\text{kg}_a/\text{h} \times (109.2 - 64.2\,\text{kJ}/\text{kg}_a)$$

$$= 32,303\,\text{kJ}/\text{h}$$

8.3.3 Humidification at Low Temperatures

Humidification of postharvest handling and storage facilities can be challenging due to the generally low temperature required to promote postharvest quality. As we learned when constructing the psychrometric chart above, these low temperatures translate to a narrower range of absolute humidity (moisture ratio).

As noted above the most passive method of controlling humidity in a cold storage room is to size the evaporator to allow a higher evaporator temperature yet still provide cooling. This will inherently limit the minimum relative humidity in the room by limiting the lowest dew point temperature in the room at the evaporator and therefore limit the rate of water condensation and removal from the room.

Common humidification practices include watering the product directly, watering or "flooding" concrete floors, misting the air, and using water vaporizers to inject moisture into the air. When using water for humidification, it is important to remember that this may be a

food contact application, and so appropriate produce safety measures should be taken. Standing or pooling water and/or significant condensation in a cold storage environment, for example, has been identified as a risk factor that could contribute to the growth and spread of Listeria monocytogenes, which can be pathogenic (US FDA, 2015). For this reason, it is important to ensure careful attention to the design and operation of a cold storage space and the performance of the humidification systems in place.

EXAMPLE 8.2

In the refrigerated cooler shown in Fig. 8.14, carrots are stored in packed cartons. Condensate is formed on the evaporator, which is used to cool the room. This condensate is routed outside the room to prevent pooling of water in the room. The storage conditions desired by the operator are $T = T_{db} = 2°C$ and $RH = 98\%$. Assume the room is sealed, aside from the condensate drain shown, and that there are well-mixed conditions in the room. Neglect the heat and water vapor produced from respiration. Determine: (1) the equilibrium (steady state) RH if the evaporator temperature is $-2°C$ and (2) $0°C$. (3) What would be the ideal evaporator temperature to meet the target conditions (assuming there is unlimited space and no cost penalty for a larger evaporator)?
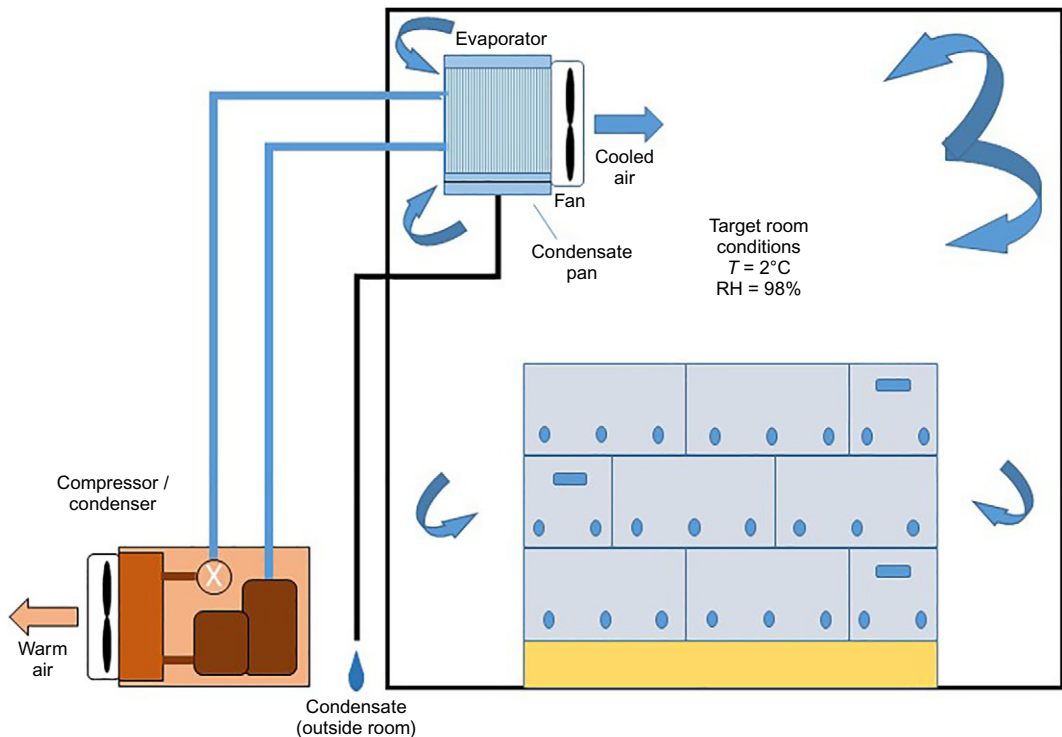

FIG. 8.14   Example of evaporator temperature impact on relative humidity.

(1) Steady-state RH for $T_{evap} = -2°C$

$$\text{Room conditions} : T_{db} = 2°C$$

$$\text{RH} = 98\%$$

Using psychrometric chart or calculator:

$$\text{Wet} - \text{bulb}, T_{wb} = 1.88°C$$

$$\text{Dew point}, T_{dp} = 1.71°C$$

Condensation at the evaporator happens at 100% RH, with the air temperature equal to the evaporator temperature. This is right at the saturation line of the psychrometric, using the dry-bulb temperature equal to the evaporator temperature. In other words:

$$T_{db} = T_{dp} = T_{wb} = -2°C$$

But when mixed back in with the warmer room air until the target room temperature is 2°C:

$$\text{Dry} - \text{bulb}, T_{db} = 2°C$$

$$\text{Dew point}, T_{dp} = -2°C$$

Using a psychrometric chart or calculator with $T_{db} = 2°C$ and $T_{dp} = -2°C$, we determine:

$$\text{Humidity ratio}, w = 0.0017 \, \text{kg}_v / \text{kg}_a$$

We are not adding or removing more moisture from the air as it is heated by the rest of the room air, so we just follow the line of constant humidity to the right until we intersect with the dry-bulb temperature of the room (i.e., we hold moisture level constant at the 0.0017 kg/kg level and set T_{db} back to 2°C.

$$\text{RH} = 38\%$$

(2) Steady-state RH for $T_{evap} = 0°C$
Using the same method as (1) above:

$$\text{RH} = 68\%$$

(3) Ideal T_{evap} for room to be $T = 2°C$ and RH $= 98\%$

We know from the above that T_{wb} needs to be 1.9°C at T_{db} of 2°C in order to reach 98% RH. Therefore the evaporator temperature would ideally be 1.9°C, if space and cost were not limiting.

8.4 CONCLUSION

The ability to know and manage the level of moisture in air is crucial to preserving the quality of many crops as they are distributed to consumers. This chapter was intended to provide an overview of psychrometrics and its importance relative to the postharvest handling and

storage of horticultural crops. Although not comprehensive the chapter should provide the reader with a working knowledge of the topic. Despite a long history the field of psychrometrics remains active, especially as it relates to postharvest applications; further reading and study is encouraged.

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