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PSYCHROMETRICS

PSYCHROMETRICS uses thermodynamic and transport 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.

Hermann et al. (2020) prepared formulas for transport properties of moist air.

1. 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 kg_{da}/kmol, based on the carbon-12 scale. The gas constant for dry air using the 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). According to the Industrial Formulation IAPWS-IF97 (R7-97 2012), the relative molecular mass of water is 18.015 257. The gas constant for water is

$$R_w = 8314.472/18.015\,257 = 461.524 \text{ J/(kg}_w\cdot\text{K)} \qquad (2)$$

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

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

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

The equation for temperature as a function of altitude is

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

Table 1 Standard Atmospheric Data for Altitudes to 10 000 m

Altitude, m	Temperature, °C	Pressure, kPa
−500	18.2	107.478
0	15.0	101.325
500	11.8	95.461
1000	8.5	89.875
1500	5.2	84.556
2000	2.0	79.495
2500	−1.2	74.682
3000	−4.5	70.108
4000	−11.0	61.640
5000	−17.5	54.020
6000	−24.0	47.181
7000	−30.5	41.061
8000	−37.0	35.600
9000	−43.5	30.742
10 000	−50	26.436

Source: Adapted from NASA (1976).

3. THERMODYNAMIC PROPERTIES OF MOIST AIR

Table 2, calculated using ASHRAE's (2021) LibHuAirProp software (based on ASHRAE RP-1485; Hermann et al. 2009, 2020), shows values of thermodynamic properties of saturated moist air and dry air at101.325 kPa and temperatures from–60 to 90°C.

The following properties are shown in Table 2:

v_{da} = specific volume of dry air, m³/kg$_{da}$.
v_s = specific volume of moist air at saturation, m³/kg$_{da}$.
h_{da} = specific enthalpy of dry air, kJ/kg$_{da}$. In Table 2, h_{da} is assigned a value of 0 at 0°C and standard atmospheric pressure.
h_s = specific enthalpy of moist air at saturation, kJ/kg$_{da}$.
$c_{p,da}$ = specific heat capacity of dry air, kJ/(kg·K)
$c_{p,s}$ = specific heat capacity of moist air at saturation, kJ/(kg·K)
s_{da} = specific entropy of dry air, kJ/(kg$_{da}$·K). In Table 2, s_{da} is assigned a value of 0 at 0°C and standard atmospheric pressure.
s_s = specific entropy of moist air at saturation kJ/(kg$_{da}$·K).

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

Temp. t, °C	Humidity Ratio W_s, kg$_w$/kg$_{da}$	Specific Volume, m³/kg$_{da}$		Specific Enthalpy, kJ/kg$_{da}$		Specific Heat Capacity, kJ/(kg·K)		Specific Entropy, kJ/(kg$_{da}$·K)	
		v_{da}	v_s	h_{da}	h_s	$c_{p,da}$	$c_{p,s}$	s_{da}	s_s
–60	0.0000067	0.6027	0.6027	–60.341	–60.325	1.0062	1.0062	–0.2494	–0.2494
–59	0.0000076	0.6055	0.6055	–59.335	–59.317	1.0062	1.0062	–0.2447	–0.2446

Table 3 Thermodynamic Properties of Water at Saturation

Temp. *t*, °C	Absolute Pressure p_{ws}, kPa	Specific Volume, m³/kg: Sat. Solid/ Liquid v_i/v_f	Specific Volume, m³/kg: Sat. Vapor v_g	Specific Enthalpy, kJ/kg: Sat. Solid/ Liquid h_i/h_f	Specific Enthalpy, kJ/kg: Sat. Vapor h_g	Specific Heat Capacity, kJ/(kg·K): Sat. Solid/ Liquid $c_{p,i}/c_{p,f}$	Specific Heat Capacity, kJ/(kg·K): Sat. Vapor $c_{p,g}$	Specific Entropy, kJ/(kg·K): Sat. Solid/ Liquid s_i/s_f	Specific Entropy, kJ/(kg·K): Sat. Vapor s_g
–60	0.00108	0.001081	90972	–446.12	2390.14	1.6612	1.8522	–1.6842	11.622
–59	0.00124	0.001082	79885	–444.46	2391.99	1.6683	1.8523	–1.6764	11.569
–58	0.00141	0.001082	70236	–442.79	2393.85	1.6754	1.8524	–1.6687	11.516
–57	0.00161	0.001082	61826	–441.11	2395.70	1.6826	1.8525	–1.6609	11.463
–56	0.00184	0.001082	54488	–439.42	2397.55	1.6897	1.8526	–1.6531	11.411
–55	0.00209	0.001082	48078	–437.73	2399.40	1.6968	1.8527	–1.6453	11.360
–54	0.00238	0.001082	42470	–436.03	2401.25	1.7040	1.8528	–1.6375	11.309
–53	0.00271	0.001082	37559	–434.32	2403.10	1.7111	1.8530	–1.6298	11.259
–52	0.00307	0.001083	33254	–432.61	2404.95	1.7183	1.8531	–1.6220	11.209

Table 5 Transport Properties of Saturated Moist Air and Dry Air at Standard Atmospheric Pressure, 101.325 kPa

Temp., °C	Humidity Ratio, kg_w/kg_{da}	Density, kg/m^3		Viscosity, μPa·s		Kinematic Viscosity, 10^{-6} m^2/s		Thermal Cond., W/(m·K)		Prandtl Number (—)	
t	W_s	ρ_{da}	ρ_s	η_{da}	η_s	ν_{da}	ν_s	λ_{da}	λ_s	Pr_{da}	Pr_s
–60	0.0000067	1.659	1.659	14.07	14.07	8.478	8.478	0.01960	0.01960	0.7223	0.7223
–59	0.0000076	1.651	1.651	14.12	14.12	8.552	8.552	0.01968	0.01968	0.7220	0.7221
–58	0.0000087	1.644	1.644	14.18	14.18	8.625	8.625	0.01976	0.01976	0.7218	0.7218
–57	0.0000100	1.636	1.636	14.23	14.23	8.699	8.699	0.01984	0.01984	0.7216	0.7216
–56	0.0000114	1.628	1.628	14.29	14.29	8.773	8.773	0.01993	0.01993	0.7214	0.7214
–55	0.0000129	1.621	1.621	14.34	14.34	8.848	8.848	0.02001	0.02001	0.7211	0.7211

Table 6 Transport Properties of Water at Saturation

Temp. t, °C	Absolute Pressure p_{sat}, kPa	Density, kg/m³		Viscosity, µPa·s		Kinematic Visc., 10^{-6} m²/s		Thermal Cond., mW/(m·K)		Prandtl Number (—)	
		Sat. Liq.	Sat. Vap.	Sat. Liq.	Sat. Vap.	Sat. Liq.	Sat. Vap.	Sat. Liq.	Sat. Vap.	Sat. Liq.	Sat. Vap.
		ρ_f	ρ_g	η_f	η_g	ν_f	ν_g	λ_f	λ_g	Pr_f	Pr_g
0	0.61121	999.79	0.0048511	1792	8.945	1.792	1844	555.6	16.76	13.61	1.0078
1	0.65709	999.85	0.0051963	1731	8.974	1.731	1727	558.1	16.82	13.08	1.0075
2	0.70599	999.89	0.0055629	1674	9.003	1.674	1618	560.6	16.89	12.58	1.0073
3	0.75808	999.92	0.0059519	1619	9.032	1.619	1517	563.0	16.95	12.11	1.0070
4	0.81355	999.93	0.0063645	1567	9.061	1.568	1424	565.4	17.02	11.67	1.0068