

## PSYCHROMETRICS & MOISTURE

**MOISTURE** measurements involve different terms and units. Moisture terms and units all fall under the area of psychrometrics, the study of water vapor concentration in air as a function of temperature and pressure. Selecting a moisture term depends on the application at hand.

Dew points and frost points are often used when the dryness of the gas is important, (moisture condensation from gas at low process temperatures must be avoided). Dew point is also used as an indicator of water vapor in high temperature processes, such as industrial drying.

Mixing ratios, volume percent, and specific humidity are usually used when water vapor is either an impurity or a defined component of a process gas mixture used in manufacturing. Mixing ratios are also used, like dew point, in industrial drying.

Relative humidity is most commonly used in HVAC applications where it directly impacts human comfort and indoor air quality issues. Relative humidity is also of interest to process control personnel as low RH can cause brittleness and static electricity problems, while high RH can cause swelling and clumping regardless of temperature.

### MOISTURE TERMS, DEFINITIONS AND UNITS

Term	Definition	Unit
Absolute Humidity, (Vapor concentration)	$\frac{\text{Mass, Vapor}}{\text{Volume}}$	Grains/ft <sup>3</sup> Grams/m <sup>3</sup>
Mixing Ratio	$\frac{\text{Mass, Vapor}}{\text{Mass, dry gas}}$	lb/lb, grains/lb, kg/kg, grams/kg
Relative Humidity	$\frac{\text{Mass, actual vapor}}{\text{Mass saturated vapor}}$ $\frac{\text{Actual vapor pressure}}{\text{Saturation vapor pressure}}$ $\frac{\text{Partial pressure, vapor}}{\text{Vapor pressure water}}$	%
Dew Point	Temperature of saturation (condensation)	°F or °C
Volume Ratio	$\frac{\text{Partial pressure, vapor}}{\text{Partial pressure, dry gas}}$	% by volume
Mass Ratio	Same as Mixing Ratio	PPM by weight, PPM <sub>w</sub>
PPM by volume	$\frac{\text{Volume, vapor} \times 10^6}{\text{Volume, dry gas}}$	PPM by volume, PPM <sub>v</sub>
PPM by weight	PPM <sub>v</sub> × $\frac{\text{Mole weight of water}}{\text{Mole weight of carrier gas}}$	PPM by weight, PPM <sub>w</sub>
Hygrometer	Instrument for measuring moisture in gas (from Greek hygros – wet, moist)	
Psychrometer	Instrument using wet/dry bulbs to measure moisture in gas (from Greek psychros – cold)	

**PSYCHROMETRICS** deals with the thermodynamic properties of moist gases while the term **Humidity** simply refers to the presence of water vapor in air or other carrier gas.

Psychrometrics concerns mixtures of water vapor and dry air. Much of it also applies to other carrier gases since the thermodynamic characteristics of water vapor are fairly independent of the carrier gas. In addition, as the composition of atmospheric air is fairly constant, dry air is treated as a homogeneous gas with a molecular weight of 28.9645. The molecular weight of water is 18.01528.

**PARTIAL PRESSURE:** The gas laws say that the total pressure of a gas mixture is the sum of the partial pressures of the constituent gases. Also the volume ratios of constituent gases are equal to the ratios of their partial pressures. For example, atmospheric pressure is the sum of the partial pressures of dry air and water vapor ( $\rho_{\text{atm}} = \rho = \rho_a + \rho_w$ ).

**WATER VAPOR PRESSURE:** When a mixture of air and water vapor is in equilibrium with liquid water or with ice, it is considered to be saturated (RH = 100%). The water vapor saturation pressure over ice for the temperature range of -148 to 32°F is given by:

$$\ln(\rho_{ws}) = \frac{C_1}{T} + C_2 + C_3T + C_4T^2 + C_5T^3 + C_6T^4 + C_7 \ln(T)$$

where  $C_1 = -1.0214165E + 04$   $C_5 = 3.5575832E - 10$   
 $C_2 = -4.8932428E + 00$   $C_6 = -9.0344688E - 14$   
 $C_3 = -5.3765794E - 03$   $C_7 = 4.1635019E + 00$   
 $C_4 = 1.9202377E - 07$

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

$$\ln(\rho_{ws}) = \frac{C_8}{T} + C_9 + C_{10}T + C_{11}T^2 + C_{12}T^3 + C_{13} \ln(T)$$

where  $C_8 = -1.0440397E + 04$   $C_{11} = 1.2890360E - 05$   
 $C_9 = -1.1294650E + 01$   $C_{12} = -2.4780681E - 09$   
 $C_{10} = -2.7022355E - 02$   $C_{13} = 6.5459673$

In both of the above equations,

$\rho_{ws}$  = saturation pressure, psia  
 T = absolute temperature, °R = °F + 459.67

**SIMPLIFIED FORMULATIONS:** The preceding equations are very accurate, but may be overly cumbersome for real time calculation. The following equations are less accurate, but are generally suitable for mid-range calculations as used in HVAC applications, for example.

For dew points higher than ice point:

$$e = [1.0007 + P \times 3.46E-6] \times 6.1121 \times \exp\left[\frac{17.502 \times T}{240.9 + T}\right]$$

For dew points at or below ice point:

$$e = [1.0003 + P \times 4.18E-6] \times 6.1115 \times \exp\left[\frac{22.452 \times T}{272.55 + T}\right]$$

- e » p<sub>w</sub> vapor pressure in millibars  
(one psi = 68.94745 millibars)
- P = total pressure in millibars (1 atm = 1013.25 millibars, 14.696 psia)
- T = temperature in °C (°F = °C × 1.8 + 32)

**RELATIVE HUMIDITY:** the ratio of the partial vapor pressure to saturation vapor pressure at the dry bulb temperature:

$$RH = \frac{\rho_w}{\rho_{ws}} = \frac{\rho_{ws}(T_d)}{\rho_{ws}(T)}$$

where ρ<sub>ws</sub>(T<sub>d</sub>) is saturation pressure at the dew point temperature and ρ<sub>ws</sub>(T) is saturation pressure at the dry bulb temperature. Relative humidity is moisture and temperature dependent but independent of total pressure. If dew point and dry bulb temperatures are known, then RH can be derived by calculating saturation vapor pressure for dew point and for dry bulb, then applying the RH definition above.

**DEW POINT** is the temperature at which a given sample of moist air is saturated. If the sample is cooled below dew point, then water vapor begins to condense. This phenomenon is the basis for various chilled sensor type dew point meters.

**Frost Point:** If measurements are made below the freezing point of water – that is if the indicated dew point is below the freezing point of water, then the equilibrium occurs at the vapor pressure of ice (not water), which is less than that of water. That is, the frost point is a bit higher than dew point.

If RH and dry bulb temperature are known, dew point can be derived by first calculating saturation pressure at the dry bulb temperature and then multiplying by the RH ratio to obtain ρ<sub>w</sub>, the partial water vapor pressure. Now apply the following:

For the dew points in the range of 32 to 200°F:

$$T_d = C_{14} + C_{15}\alpha + C_{16}\alpha^2 + C_{17}\alpha^3 + C_{18}\rho_w^{0.1984}$$

And for dew points below 32°F:

$$T_d = 90.12 + 26.412\alpha + 0.8927\alpha^2$$

Where for both expressions:

- T<sub>d</sub> = dew point, °F
- C<sub>14</sub> = 100.45
- C<sub>16</sub> = 2.319
- C<sub>18</sub> = 1.2063
- α = ln(ρ<sub>w</sub>), ρ<sub>w</sub> in psia
- C<sub>15</sub> = 33.193
- C<sub>17</sub> = 0.17074

**VOLUME RATIO** (also called mixing ratio by volume, or ppmv) is the ratio of water vapor volume to dry air volume (V<sub>w</sub>/V<sub>a</sub>). Because the volume ratios of mixed gases are the same as their partial pressures, volume ratio can be expressed as:

$$VR = \frac{\rho_w}{\rho_a}; \rho = \rho_w + \rho_a$$

Because total pressure is the sum of partial pressures, the partial pressure of dry air can be readily derived (once vapor pressure is known), by measuring total pressure directly or by assuming one atmosphere (14.696 psia) total pressure. Multiply the ratio by one million to obtain ppmv (parts per million by volume).

**HUMIDITY RATIO** (also called mixing ratio by weight, or ppmw) is the ratio of the mass of water vapor to the mass of dry air. To calculate this, multiply the volume ratio by the ratio of the molecular weights:

$$W \equiv \frac{M_w}{M_a} = \frac{18.01528}{28.9645} \frac{\rho_w}{\rho_a} = 0.62198 \frac{\rho_w}{\rho_a}$$

The humidity ratio, in common use, is expressed in lb/lb, grains/lb, kg/kg, or g/kg. (There are 7000 grains in one pound.) Multiply the ratio by one million to obtain ppmw (parts per million by weight). An engineer may, for example, combine a humidity ratio value with the reading from a mass flow meter to calculate the mass of water vapor flowing through a dryer exhaust duct per unit time.

# Humidity Sensors

**VOLUME PERCENT:** equivalent to 100 times the mole fraction; the ratio of water vapor volume to total volume,  $V_w/V$  or  $V_w/(V_w + V_a)$  expressed as a percentage. Like the volume ratio, it can be calculated in terms of partial pressures:

$$V\% = \frac{\rho_w}{\rho}; \rho = \rho_w + \rho_a$$

**SPECIFIC HUMIDITY:** normally expressed as a percentage, is the ratio of the mass of water vapor to the total mass, and can also be calculated in terms of the humidity ratio:

$$q = \frac{M_w}{M_w + M_a} = \frac{W}{1 + W}$$

**ABSOLUTE HUMIDITY:** (or water vapor density) is the ratio of the mass of water vapor to the total volume:

$$d_v = \frac{M_v}{V} = \frac{217.6 \times e}{T_{db} + 273.16}$$

$d_v$  = absolute humidity expressed in grams H<sub>2</sub>O per cubic meter of dry air and vapor mix (divide by 16,018.46 for lb/cu ft; divide by 2.28835 for grains/cu ft)

$e$  =  $\rho_w$  vapor pressure in millibars (1 psi = 68.94745 millibars)

$T_{db}$  = dry bulb temperature in °C (°F = °C × 1.8 + 32)

**ENTHALPY:** the measure of the energy content per unit mass. The enthalpy of a gas mixture equals the sum of the individual partial enthalpies of the components, (dry air and water vapor). In the English system, the specific enthalpy of dry air is assigned a value of zero at 0°F and standard atmospheric pressure. To calculate moist air enthalpy in Btu/lb dry air:

$$h = 0.240T + W(1061 + 0.444T)$$

where

$T$  = dry bulb temperature, °F

$W$  = humidity ratio of the moist air

**STANDARD ATMOSPHERIC DATA:** Normal atmospheric pressure variations have small effects on calculations that require a value for total pressure. However, at higher altitudes (Denver, for example), atmospheric pressure variations become significant. The following standard data is adapted from NASA. At sea level, standard temperature is 59°F and standard barometric pressure is 29.921 in. Hg.

## STANDARD ATMOSPHERIC PRESSURE DATA

Altitude ft	Temp. °F	Pressure	
		in Hg.	psia
0	59.0	29.921	14.696
500	57.2	29.38	14.430
1000	55.4	28.86	14.175
2000	51.9	27.82	13.664
3000	48.3	26.82	13.173
4000	44.7	25.82	12.682
5000	41.2	24.90	12.230

Reference: 1993 ASHRAE Handbook of Fundamentals, published by American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., 1791 Tullie Circle, N.E., Atlanta, GA 30329. Telephone 404-636-8400.

**NOTE:** Most of the ASHRAE formulations are based on the thermodynamic temperature scale, which differs very slightly from practical scales (ITS-90) used for physical measurements. The boiling point of water is 211.95°F on this scale rather than the traditional 212°F. The slight difference is negligible for any practical application.

## SATURATION VAPOR PRESSURES OF WATER P<sub>w</sub>

Temperature (°C)	Saturation Vapor Pressure (mm Hg)	Temperature (°C)	Saturation Vapor Pressure (mm Hg)
-20	0.8	60	149.5
-10	1.9	70	233.8
0	4.6		
10	9.2		
20	17.5		
30	31.8	80	355.3
40	55.4	90	525.9
50	92.6	100	760.0