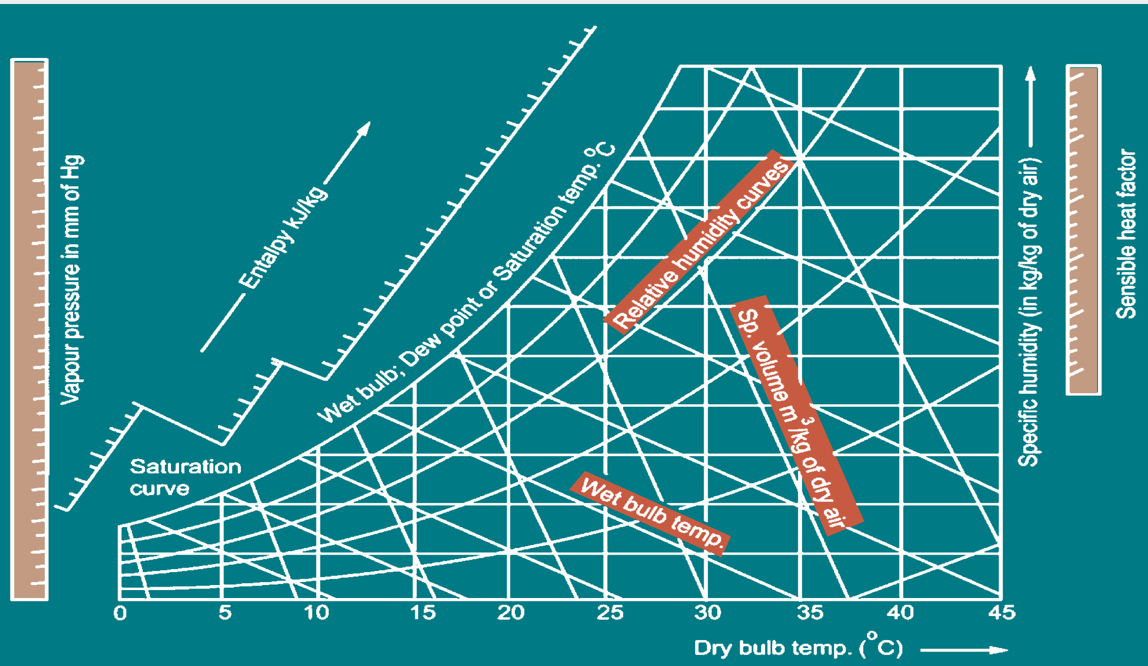
Part 2



Understanding Psychrometrics

***By Ramesh Paranjpey,** Distinguished 50-Year Member, ASHRAE*
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Introduction

In Part I, we explored the behavior of moist air and various forms of air-vapor mixtures present in the atmosphere. In this part, we shall cover some basic laws that govern and influence the properties of moist air.

Understanding Psychrometrics

To understand air moisture behavior, it's essential to learn about psychrometrics. It is the science of moist air, encompassing its thermodynamic properties and processes. Psychrometrics uses thermodynamic properties to analyze conditions and processes involving moist air. The term "psychro" refers to cold/hot air, and "metrics" means the measure of, indicating that it measures all properties of moist air, which is a mixture of dry air and water vapor.

The main purpose of using psychrometrics is to translate calculated heating and cooling loads into the mass (kg) of air that needs to be circulated to offset these loads.

Willis Haviland Carrier

was an engineer and inventor of Psychrometrics in (1911), and is known as the father of air conditioning technology.

Figure 1: Willis Haviland Carrier

About the Authors

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Standard Atmosphere, NTP, and STP

Standard Atmosphere

The standard atmosphere (symbol: atm) is a unit of pressure defined as 101.325 Pa (760 mm of Hg). It is sometimes used as a reference or standard pressure and is approximately equal to Earth's average atmospheric pressure at sea level.

Normal Temperature and Pressure (NTP) vs. Standard Temperature and Pressure (STP)

NTP and STP are both reference conditions used in science and engineering, primarily for gas behavior.

NTP

NTP refers to normal temperature and vapor pressure present in the atmosphere. NTP uses a temperature of 20°C (293.15 K) and a pressure of 1 atm (101.325 kPa).

NTP is used for:

Calibration of instruments
Data comparison
Thermodynamic calculations
Predicting behavior

Using NTP allows for the direct comparison of data from different experiments and the prediction of a substance's behavior under various conditions. In thermodynamics, a substance's properties are often described in terms of its internal energy, enthalpy, and entropy, which can be measured at NTP to provide a baseline for comparison. In instrument calibration, NTP is commonly used as a reference point.

Psychrometric calculations typically use NTP as 20°C (293.15 K) and 1 atm (101.325 kPa).

Standard Temperature and Pressure (STP)

The International Union of Pure and Applied Chemistry (IUPAC) defines STP as follows:

- **Until 1982:** STP was defined as a temperature of 273.15 K (0°C) and an absolute pressure of exactly 1 atm (101.325 kPa).
- **Since 1982:** STP has been defined as a temperature of 273.15 K (0°C) and an absolute pressure of exactly 1 bar (100 kPa, 105 Pa).

The ISO 13443 standard reference conditions for natural gas and similar fluids are 288.15 K (15.00°C) and 101.325 kPa. The US standard, as defined in ASHRAE Fundamental Volume Chapter-1, specifies 15°C dry air at a barometric pressure of 760 mm Hg (101.325 kPa).

As you can see, the reference conditions for STP differ among various organizations. STP provides a standard reference for estimating properties at various altitudes. Standard air is not an arbitrary condition.

Uses of STP:

1. Fluid mechanics
2. Acoustics
3. Astrophysics

STP is used in many areas of chemistry, including thermodynamics, gas laws, and phase changes. For example, the ideal gas law, PV = nRT, uses STP as a reference point for the number of moles of gas present (n) and the gas constant (R). Under STP conditions, 1 mole of any gas occupies a volume of 22.4 liters. Similarly, the density of a substance is often reported at STP, allowing for more accurate comparisons between different materials.

Psychrometric is founded on following important parameters

1. The ideal gas equation
2. Dalton's law of partial pressure
3. Avogadro's hypothesis
4. Conservation of energy
5. Conservation of mass

Ideal Gas Equation

The ideal gas law, also known as the general gas equation, is the equation of state for a hypothetical ideal gas. It is a good approximation of the behavior of many gases under many conditions, although it has several limitations. It was first stated by Benoît Paul Émile Clapeyron in 1834 as a combination of the empirical Boyle's law, Charles's law, Avogadro's law, and Gay-Lussac's law.

The Ideal Gas Law is simply expressed as: PV = nRT

Where:

- n is the number of moles of the gas
- R is the universal gas constant, 8.3143 joules per kelvin per mole
- V is Volume in m^3
- P is Pressure in Pascals (Pa)
- T is Temperature in Kelvin (K)

Barometric Pressure

Barometric pressure is the force per unit area exerted by the weight of a column of air above a specific location. This pressure is measured with a mercury barometer.

Barometric pressure is one of three psychrometric properties required to define a psychrometric state point. Dry bulb

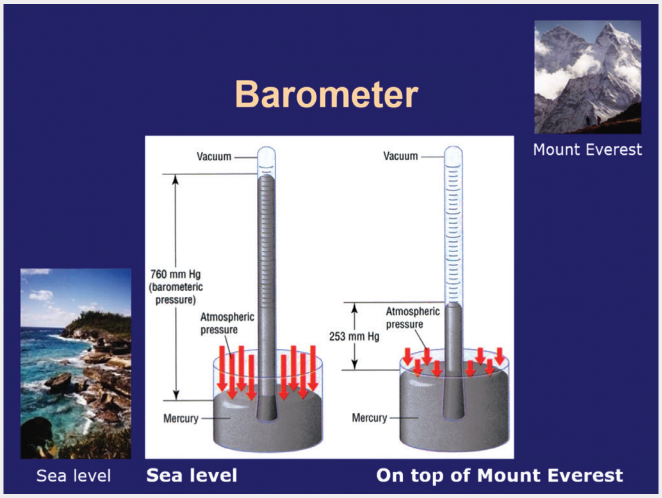


Figure 2: Barometer pressure

temperature is usually the second property. A humidity property, such as dew-point temperature, relative humidity, or wet-bulb temperature, is normally the third property used to determine a psychrometric state point.

The temperature and barometric pressure of atmospheric air vary considerably with altitude, as well as with local geographic and weather conditions. The standard atmosphere provides a reference for estimating properties at various altitudes. At sea level, standard temperature is 15°C, and 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.

Pressure and temperature values can be calculated from:

$P = 101.325\ (1\text{-}2.25577 \times 10^{-5}\ Z)^{5.255\,9}$

Where:

- Z = Altitude, m
- P = Barometric Pressure, kPa
- T = Temperature °C

The Universal Gas Constant

The universal gas constant is 8.3143 kJ/kg $_{\text{mole}}$·K (1545.32 Btu/lb·°F). Since the molecular weight of dry air is 28.9645, the gas constant for dry air is 8.3143/28.9645 = 0.287 kJ/kg$_{\text{da}}$·K

Similarly, gas constant for water vapor is 8.3143/18.015=0.461 kJ/kg$_{\text{da}}$·K

Dalton's Law of Partial Pressure

Dalton's Law of Partial Pressure states that in a mixture of non-reacting gases, the total pressure exerted is equal to the sum of the partial pressures of the individual gases. This empirical law was published in 1802.

$$p_{\text{total}} = \sum_{i=1}^{n} p_i = p_1 + p_2 + p_3 + \cdots + p_n$$

Partial pressure of a gas in the mixture of gases at certain temperature is equal to pressure that each gas alone would exert in the same volume of mixture at the mixture temperature.

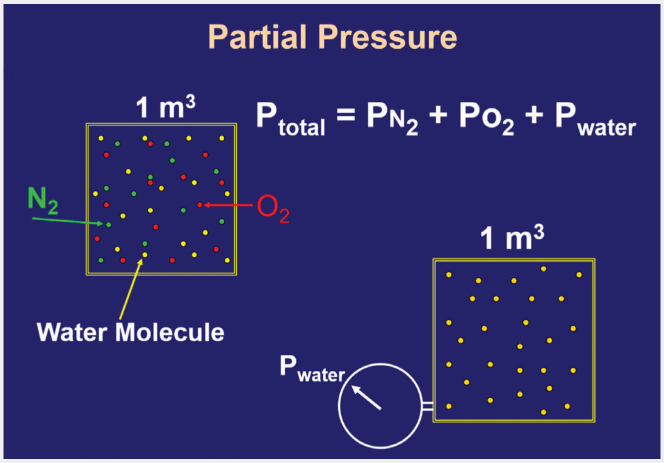


Figure 3: Dalton's law of partial pressure

Thus, according to Dalton's law of partial pressure

$P_b = P_a + P_v$ at 30°C, at 30°C saturation $P_v = P_s = 4.2460$

Therefore, $P_a = P_b - P_s = 101.325 - 4.2460 = 97.079\text{kP}_a$

Where

P_b = Barometric pressure of the mixture

P_a = Partial pressure of dry air

P_v = Partial pressure of water vapor

P_s = Saturation vapor pressure

At saturation $P_b = P_a + P_s$

Or $97.079\ P_a + 4.2460 P_{v/s} = 101.325(P_b)$

Where P_s is the pressure at saturation.

The total pressure is constant and is called as barometric pressure at a location, which is being considered. Therefore, if the partial pressure of water vapor decreases during a process, it follows that the partial pressure of the dry air would increase.

Conservation Laws and Avogadro's Law

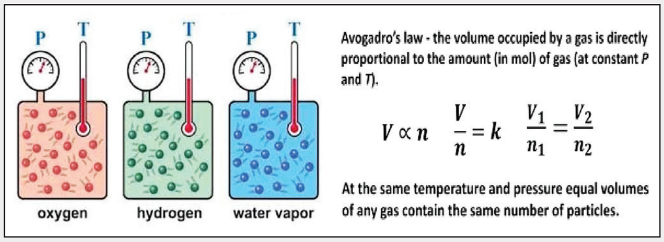
The law of conservation of energy states that the total energy of an isolated system remains constant; it is conserved over time. In a closed system, the principle states that the total amount of energy within the system can only be changed by energy entering or leaving the system. Energy can neither be created nor destroyed; rather, it can only be transformed or transferred from one form to another.

The law of conservation of mass states that "the mass in an isolated system can neither be created nor destroyed but can be transformed from one form to another."

Avogadro's Law (or Hypothesis), in simple terms, means that equal volumes of different gases, at the same temperature and pressure, contain the same number of molecules. For example, if you have two balloons filled with different gases (like helium and nitrogen) that are the same size and at the same temperature and pressure, Avogadro's Hypothesis states they'll both contain the same number of gas particles (molecules).

The volume of all ideal gases at normal temperature and pressure is same (22.4dm^3) and contain the same number of molecules (6.023x10^{23}).

The volume occupied by one gram-mole of gas is about 22.4 liters (0.791 cubic foot) at standard temperature and pressure (0°C, 1 atmosphere) and is the same for all gases, according to Avogadro's law. The specific number of molecules in one gram-mole of a substance defined as the molecular weight in grams, is



Avogadro's law - the volume occupied by a gas is directly proportional to the amount (in mol) of gas (at constant *P* and *T*).

$$V \propto n \quad \frac{V}{n} = k \quad \frac{V_1}{n_1} = \frac{V_2}{n_2}$$

At the same temperature and pressure equal volumes of any gas contain the same number of particles.

Figure 4: Avogadro's Law

6.02214076 × 10^{23}, a quantity called Avogadro's number, or the Avogadro constant.

For example, the molecular weight of oxygen is 32.00, so that one gram-mole of oxygen has a mass of 32.00 grams and contains 6.02214076 × 10^{23} molecules.

The volume occupied by one gram-mole of gas is about 22.4 liters (0.791 cubic foot) at standard temperature and pressure (0°C, 1 atmosphere) and is the same for all gases, according to Avogadro's law.

Avogadro's Law is important in psychrometric calculations because it helps determine the amount of gas, specifically water vapor, present in a given volume of air. This is crucial for accurate psychrometric calculations, as it establishes a relationship between the volume of air and the number of water vapor molecules within it. Doubling the number of molecules doubles the pressure.

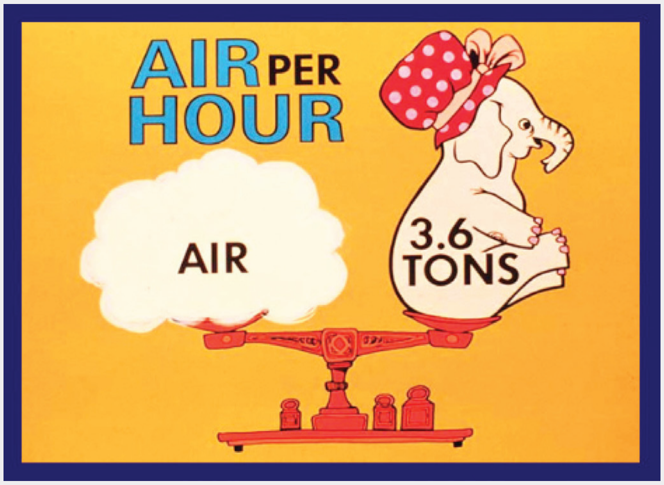


Figure 5: Air per hour

Charles's & Boyle's Law

The gas law, which dry air follows, states that if air were heated and maintained at constant pressure, the air would expand and weigh less per cubic volume. In other words, the density of air decreases.

The air exerts pressure and the barometric pressure at sea level is, (1.01325 bar or 101.325 kN/m^2 or kPa) or 29.92 inches (760 mm) of mercury and the pressure is 14.696 lb/sq.in. A rise in barometric pressure indicates good weather ahead, whereas a decrease forecasts bad weather. When the clouds appear in the atmosphere and is likely to rain, the vapor pressure drops.

Density and Specific Volume

Density of dry air is 0.075 lb/ft^3 = (1.2 kg/m^3).

Table 1: Chart from ASHRAE Software giving density and specific volume

Altitude (m)	Barometric Pressure (mm Hg)	Atmospheric Pressure (kPa)	Dry Bulb (°C)	Wet Bulb (°C)	Relative Humidity (%)	Humidity Ratio (g/kg)	Specific Volume (m^3/kg)	Density (kg/m^3)
0	760.001	101.325	30	25	66.979	18.04097	0.883337	1.152869

Table 2: Psychrometric data for air inlet and outlet conditions

Description	Altitude (m) sea level	Dry Bulb (°C)	Wet Bulb (°C)	Relative Humidity (%)	Humidity Ratio (g/kg)	Enthalpy (kJ/kg)	Dew Point (°C)
Air Inlet	0	30	25	66.98	18.04	76.270	23.20
Air Outlet	0	24	16.25	45	8.39	45.476	11.35

Dry air weighs more than wet air for same volume, since molecular weight of dry air is 28.9645 and water vapor is 18.016.

When we circulate the air, we do not realize how much weight of air we are passing over the coil. For example, if we are circulating 1600 cfm of dry air in an air handling unit, the weight of this air per hour being handled by the coil is

1600 cfm × 0.075 lb/ft^3 × 60 = 7238 lb/h or 3.6 Tons

It is 1/.075 = 13.33 ft^3/lb (0.833m^3/kg)

ASHRAE defines specific volume as volume of moist air per kg of dry air. ASHRAE defines density of moist air as mass of moist air per m^3 of moist air. *Table 1* is the chart from ASHRAE software that gives density and specific volume and you will note they are not exactly reciprocals.

In Part-I of this series, we mentioned how moisture in the air plays an important role cooling load calculation and in learning air conditioning.

Let us take an example to make this point clearer.

Assume the duty points as

1. Air inlet conditions: 30°C DB and 25°C WB
2. Air Outlet conditions: 24°C DB and 45% RH
3. Dry Air flow quantity: 1 kg/s

Solution:

1. Psychrometric data for air inlet and outlet conditions are mentioned in *Table 2*.
2. Dew point of inlet air 23.20
3. Dew point at outlet air 11.35
4. Average dew point - 17.3
5. Specific heat of Dry air = 1.0066 kJ/kg-Deg. C,
6. Specific heat of water vapor = 1.9 kJ/kg-Deg. C,
7. Specific heat of liquid water = 4.18 kJ/kg-Deg.
8. Latent heat of water at average dew point = 2460 kJ/kg
9. Mass flow of dry air = 1 kg/sec
   - **A.** Sensible heat removed from dry air = m × Cp × ΔT
     = 1kg/s × 1.0066 kJ/kg-Deg. C × (30-24)
     = 6.04 kJ/sec or 6.04 kW
   - **B.** Latent heat removed = Mass of dry air × latent heat x (Difference in kg of moisture)
     = 1 × 2460 × (18.04-8.39)/1000
     = 23.74kW
   - **C.** Sensible heat loss of moisture that did not condense and remained in the air
     = 8.39/1000 × 1.9 × (30-24) = 0.096 kW
   - **D.** Heat loss of outgoing water that was lost from inlet air
     = (18.04-8.39)/1000 × 4.18 × 23
     = 0.93 kW

   Total heat lost from inlet air
   = 6.04 + 23.74 + 0.096 + 0.93 = 30.806 kW

A simpler way is to calculate total heat by using enthalpy difference formula:

Total heat lost by air = 1 × (76.27 - 45.476) = 30.794 kW

The above calculations indicate that both the values of heat load match, i.e. one can calculating each component of enthalpy independently or calculating total heat directly based on enthalpy difference.

From the above calculations, one can notice latent heat percentage is (23.74/30.79) × 100 =77.1%.

The above calculations indicate clearly why latent heat plays very important role in cooling load calculations.

The standard formulae for load calculations in SI units are as under

1. Sensible heat:
W = J/s = m × c_p × ΔT
W = 1.204 kg/m^3 × L/s x 1.0216 kJ/kg.k × ΔT-k
W = 1.23 × L/s × ΔT
(Air density = 1.204kg/m^3)
(Specific heat = 1.0216 kJ/kg.K)

2. Latent heat
W = J/s = 3.010 × L/s × ΔW or 3 × L/s × ΔWg/kg_{da}
1.204 kg/m^3 × 2500 kJ/kg (=3) × L/s ΔW g/kg_{da}
Enthalpy of saturated water vapor at 0°C in kJ/kg is 2500.77, say 2500 kJ/kg
Ref: Carrier Psychrometrics T330-20-page 5)

3. Total Heat
= W = 1.2 × L/s × ΔH
W = J/s = 1.204 kg/m^3 × L/s × ΔH kJ/kg

In Part - III of this series, we shall deal in detail with dry bulb/wet bulb/dew point temperatures, relative humidity, absolute humidity, degree of saturation, etc.