MOIST AIR (Psychrometry)

“ENERGY MANAGEMENT HANDBOOK” sixth edition, Chapter 6, 10 and 17

Psychrometry is the science of studying the thermodynamic properties of moist air and the use of these properties to analyze conditions and processes involving moist air, for example

• Air conditioning
• Drying processes
• Flue gas condensation
## Composition of Air

<table>
<thead>
<tr>
<th>Gas</th>
<th>Ratio compared to Dry Air (%)</th>
<th>Molecular Mass - $M$ (kg/kmol)</th>
<th>Chemical Symbol</th>
<th>Boiling Point (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>By volume</td>
<td>By weight</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Oxygen</td>
<td>20.95</td>
<td>23.20</td>
<td>32.00</td>
<td>O$_2$</td>
</tr>
<tr>
<td>Nitrogen</td>
<td>78.09</td>
<td>75.47</td>
<td>28.02</td>
<td>N$_2$</td>
</tr>
<tr>
<td>Carbon Dioxide</td>
<td>0.03</td>
<td>0.046</td>
<td>44.01</td>
<td>CO$_2$</td>
</tr>
<tr>
<td>Hydrogen</td>
<td>0.00005</td>
<td>~ 0</td>
<td>2.02</td>
<td>H$_2$</td>
</tr>
<tr>
<td>Argon</td>
<td>0.933</td>
<td>1.28</td>
<td>39.94</td>
<td>Ar</td>
</tr>
<tr>
<td>Neon</td>
<td>0.0018</td>
<td>0.0012</td>
<td>20.18</td>
<td>Ne</td>
</tr>
<tr>
<td>Helium</td>
<td>0.0005</td>
<td>0.00007</td>
<td>4.00</td>
<td>He</td>
</tr>
<tr>
<td>Krypton</td>
<td>0.0001</td>
<td>0.0003</td>
<td>83.8</td>
<td>Kr</td>
</tr>
<tr>
<td>Xenon</td>
<td>9 $10^{-6}$</td>
<td>0.00004</td>
<td>131.29</td>
<td>Xe</td>
</tr>
</tbody>
</table>
The Ideal Gas Law

• \( p \ V = m \ R \ T \) \hspace{1cm} (1)

• where

• \( p \) = absolute pressure (Pa)

• \( V \) = volume of gas (m³)

• \( m \) = mass (kg)

• \( R \) = individual gas constant (J/kg,K)

• \( T \) = absolute temperature (K)

• This equation (1) can be modified to:

• \( p = \rho \ R \ T \) \hspace{1cm} (2)

• where the density

• \( \rho = m / V \) \hspace{1cm} (3)
The individual gas constant can be expressed with the universal gas constant and the molecular weight of the air as:

\[
R = \frac{Ru}{M_{gas}} \quad (2)
\]

where

\[
M_{gas} = \text{molecular weight of the gas}
\]

\[
Ru = 8314.51 = \text{universal gas constant (J/(kmol.K))}
\]

Dry air is more dense than moist air.

<table>
<thead>
<tr>
<th>Gas</th>
<th>Individual Gas Constant - ( R )</th>
<th>Molecular Weight (kg/kmol)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dry Air</td>
<td>286.9</td>
<td>28.97</td>
</tr>
<tr>
<td>Water vapor</td>
<td>455</td>
<td>18.02</td>
</tr>
</tbody>
</table>
Pressure in Moist Air - Daltons Law

Daltons Law for moist air can be expressed as:

\[ p = p_a + p_w \]  \hspace{1cm} (1)

where

\( p \) = total pressure of air (Pa)
\( p_a \) = partial pressure dry air (Pa)
\( p_w \) = partial pressure water vapor (Pa)
The maximum pressure possible before vapor start to condensate at an actual temperature is called the saturation pressure - $p_{ws}$.

*can be expressed as:*

$$p_{ws} = e(77.3450 + 0.0057T - 7235/T) / T^{8.2} \quad (1)$$

*where*

$p_{ws} =$ *water vapor saturation pressure (Pa)*

$e = $ *the constant 2.718.......*

$T = $ *temperature of the moist air (K)*
Example - The Saturation Pressure of Water Vapor

The Saturation pressure of water vapor in moist air at 25°C can be calculated as:

\[
p_{\text{ws}} = e \left( 77.3450 + 0.0057 \left( 273.15 + 25 \right) - \frac{7235}{273.15 + 25} \right) / \left( 273.15 + 25 \right)^{8.2} = 3160 \text{ Pa}
\]

<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>Water Vapor Saturation Pressure (Pa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>609.9</td>
</tr>
<tr>
<td>5</td>
<td>870</td>
</tr>
<tr>
<td>10</td>
<td>1225</td>
</tr>
<tr>
<td>15</td>
<td>1701</td>
</tr>
<tr>
<td>20</td>
<td>2333</td>
</tr>
<tr>
<td>25</td>
<td>3160</td>
</tr>
<tr>
<td>30</td>
<td>4234</td>
</tr>
</tbody>
</table>
Relative Humidity ($\varphi$)

Relative humidity is the ratio of the water vapor pressure - $p_w$, to the vapor pressure of saturated air at the same temperature - $p_{ws}$, expressed as a percentage.

- Relative humidity by partial pressure:
  - $\varphi = \frac{p_w}{p_{ws}} \times 100\%$

where
- $\varphi =$ relative humidity (%)
- $p_w =$ vapor pressure (Pa)
- $p_{ws} =$ saturation vapor pressure at the actual dry bulb temperature (Pa)
Example - Relative Humidity and Vapor Pressure

From table the saturation pressure at 20°C is 2337 Pa. If the vapor pressure in the actual air is 1636 Pa, the relative humidity can be calculated as:

\[ \phi = \frac{1636}{2337} \cdot 100 = 70\% \text{ RH} \]
Humidity Ratio \((x)\)

• Humidity ratio is the actual mass of water vapor present in moist air - to the mass of the dry air. Humidity ratio is normally expressed in kilogram water vapor per kilogram dry air (SI-units).

• The specific humidity or humidity ratio can be expressed as:

\[
x = \frac{m_w}{m_a} \quad (1)
\]

where

• \(x\) = specific humidity or humidity ratio (kg water/kg air)
• \(m_w\) = mass of water vapor (kg)
• \(m_a\) = mass of the dry air (kg)
The humidity ratio can also be expressed with the partial pressure of water vapor and air:

- \[ x = 0.622 \frac{p_w}{(p_t - p_w)} \]
- where
- \( p_w \) = partial pressure of water vapor in the moist air (Pa)
- \( p_a \) = partial pressure of the moist air (Pa) total pressure
- \( (p_t - p_w) \) is the partial pressure of dry air
- The maximum amount of water vapor in the air is achieved when \( p_w = p_{ws} \) the saturation pressure of water vapor at the actual temperature. (2) can be modified to:

- \[ x_s = 0.622 \frac{p_{ws}}{(p_t - p_{ws})} \]
- where
- \( x_s \) = humidity ratio at saturation (kgwater/kgair)
- \( p_{ws} \) = saturation pressure of water vapor

**Note!** The water vapor capacity increases dramatically with temperature. This is important especially in drying processes.
Example - Specific Humidity of Moist Air

The specific humidity for saturated humid air at 20ºC with water vapor partial pressure 2337 Pa at atmospheric pressure of 101.325 kPa can be calculated as:

\[ x = \frac{0.622 \times 2337}{101325 - 2337} \]
\[ = 0.0147 \text{ (kg/kg)} \]
\[ = 14.7 \text{ g/kg} \]
Example – Density of Moist Air

What density have the air in the earlier example.

1 kg of dry air “have” also 0.0147 kg water vapor. For the water vapor the ideal gas gives

\[
p_w = \frac{m_w \cdot R_u \cdot T}{M_w} \cdot \frac{V}{V}
\]

\[
V = \frac{0.0147 \cdot 8314.5 \cdot 293.15}{18.02 \cdot 2337} = 0.853 \ m^3
\]

The moist air density

\[
\rho = \frac{m_{\text{dry air}} + m_{\text{water vapor}}}{V} = \frac{1.000 + 0.0147}{0.853} = 1.190 \ \text{kg} / \ m^3
\]
Enthalpy \((h)\)

Enthalpy - \(h\) - (kJ/kg) of moist air is defined as the total enthalpy of the dry air and the water vapor mixture per kg of moist air, includes the

- enthalpy of the dry air - the **sensible** heat - and
- the enthalpy of the evaporated water - the **latent** heat
Enthalpy of moist air can be expressed as:

\[ h = h_a + x \, h_w \]

where

- \( h \) = specific enthalpy of moist air (kJ/kg)
- \( h_a \) = specific enthalpy of dry air (kJ/kg)
- \( x \) = humidity ratio (kg/kg)
- \( h_w \) = specific enthalpy of water vapor (kJ/kg)

\[ h = C_{p_a} \cdot t + x \, [h_w + C_{p_w} \cdot t] \quad \text{kJ/kg} \]

\[ h = 1.01 \cdot t + x \, [2502 + 1.84 \cdot t] \quad \text{kJ/kg} \]
Example - Enthalpy in Moist Air

The enthalpy of humid air at 25°C with specific moisture content $x = 0.0203$ kg/kg, can be calculated as:

- $h = 1.01 \times 25 + 0.0203 \times [2502 + 1.84 \times 25]$
- $= 25.25 + 51.72$
- $= 76.97$ (kJ/kg of dry air)

**Note!** The latent heat due to evaporation of water is the major part of the enthalpy.
Moist air

\[
\varphi = \frac{p_w}{p_{ws}} \cdot 100 \quad (\% \text{ RH})
\]

\[
x = 0.622 \frac{p_w}{p_a - p_w} = 0.622 \frac{p_w}{101325 - p_w} \quad (\text{kg/kg})
\]

\[
h = 1.01 \cdot t + x \ [2502 + 1.84 \cdot t] \quad (\text{kJ/kg})
\]