

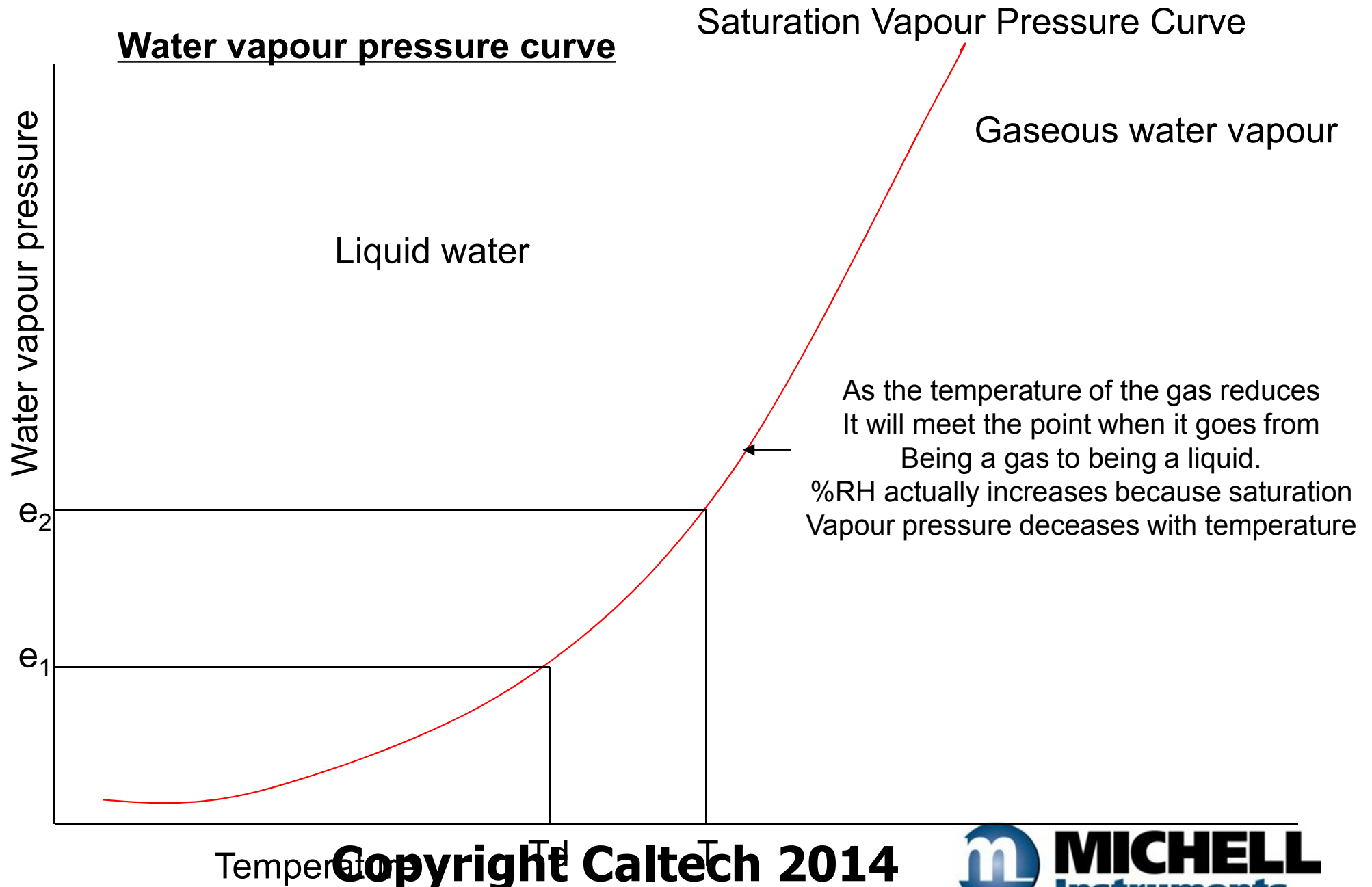
HYGROMETRIC DEFINITIONS AND RELATIONSHIPS



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- Humidity is the measure of water vapour present in air or other gases.
- The measurement of humidity is called hygrometry derived from the Greek term 'hygros' meaning moist.
- Earth is a very wet planet - Over 70% of the its surface is covered by water.
- Water vapour is present in atmospheric air -
 - Approximately 1% by volume in colder/drier climates
Up to 2% in warmer/wetter regions.
- All industrial gases contain moisture -
 - From trace levels for high purity special gases,
 - Up to high percentages >50% by volume for some product drying processes and humidity conditioning environments.



Water Vapour Pressure (e)

That part of the total gas pressure which is contributed by water vapour. Also referred to as the partial pressure of water vapour. This is the fundamental measure of humidity.

Saturation Water Vapour Pressure (e_s)

The maximum attainable water vapour pressure of a gas at a given temperature and pressure.

Water vapour in a gas can be considered as a gas itself in accordance with **Dalton's law** for a mixture of gases. The total pressure (P_{TOTAL}) of a gas is composed of the partial pressure of the dry gas ($P_{DRY\ GAS}$) plus the partial pressure of water vapour (P_{WATER}).

$$P_T = P_{DRY\ GAS} + P_{WATER}$$

For air,

$$P_{TOTAL} = P_{NITROGEN} + P_{OXYGEN} + P_{ARGON} + P_{WATER} + P_{TRACE\ ELEMENTS}$$

Typically, for atmospheric air, the partial pressures of the component gases can be expressed as follows:

$$P_{NITROGEN} = 78 \text{ KPa}$$

$$P_{OXYGEN} = 21 \text{ KPa}$$

$$P_{ARGON} = 1 \text{ KPa}$$

$$P_{WATER} = 1 \text{ KPa}$$

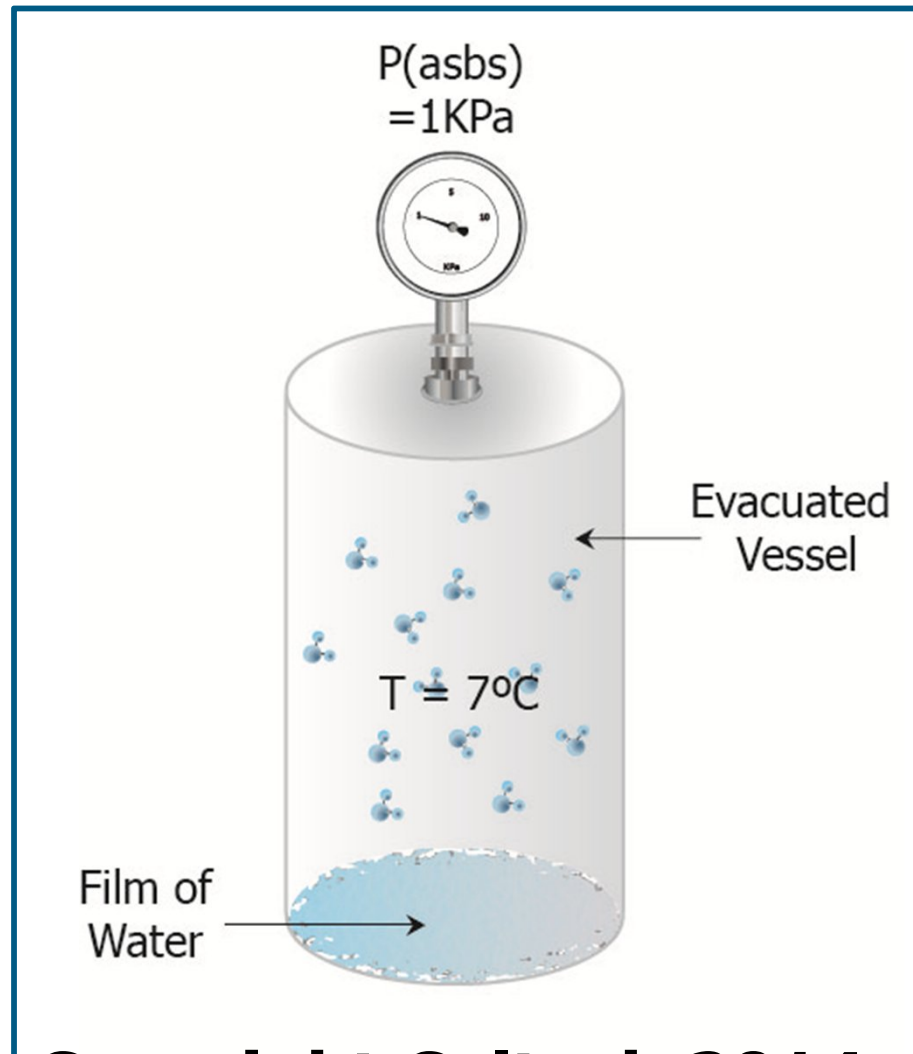
$$P_{TRACE} = 0.3 \text{ KPa}$$

$$P_{TOTAL} = 101.3 \text{ KPa}$$

Saturation Water Vapour Pressure Tables

-1	531.822	535.760	539.724	543.714	547.730	551.771
0	572.384	576.587	580.818	585.076	589.362	593.677
	0.0	0.1	0.2	0.3	0.4	0.5
°C	Pa	Pa	Pa	Pa	Pa	Pa
0	611.213	615.668	620.152	624.665	629.207	633.777
1	657.080	661.830	666.611	671.423	676.265	681.137
2	705.972	711.034	716.129	721.255	726.414	731.604
3	758.060	763.451	768.876	774.335	779.829	785.351
4	813.520	819.259	825.033	830.843	836.690	842.574
5	872.540	878.645	884.788	890.968	897.187	903.444
6	935.313	941.804	948.335	954.907	961.518	968.169
7	1002.04	1008.94	1015.88	1022.86	1029.89	1036.95
8	1072.94	1080.27	1087.64	1095.05	1102.52	1110.03
9	1148.23	1156.01	1163.83	1171.70	1179.62	1187.59
10	1228.13	1236.39	1244.69	1253.04	1261.44	1269.88

How are saturated water vapour pressure values derived?



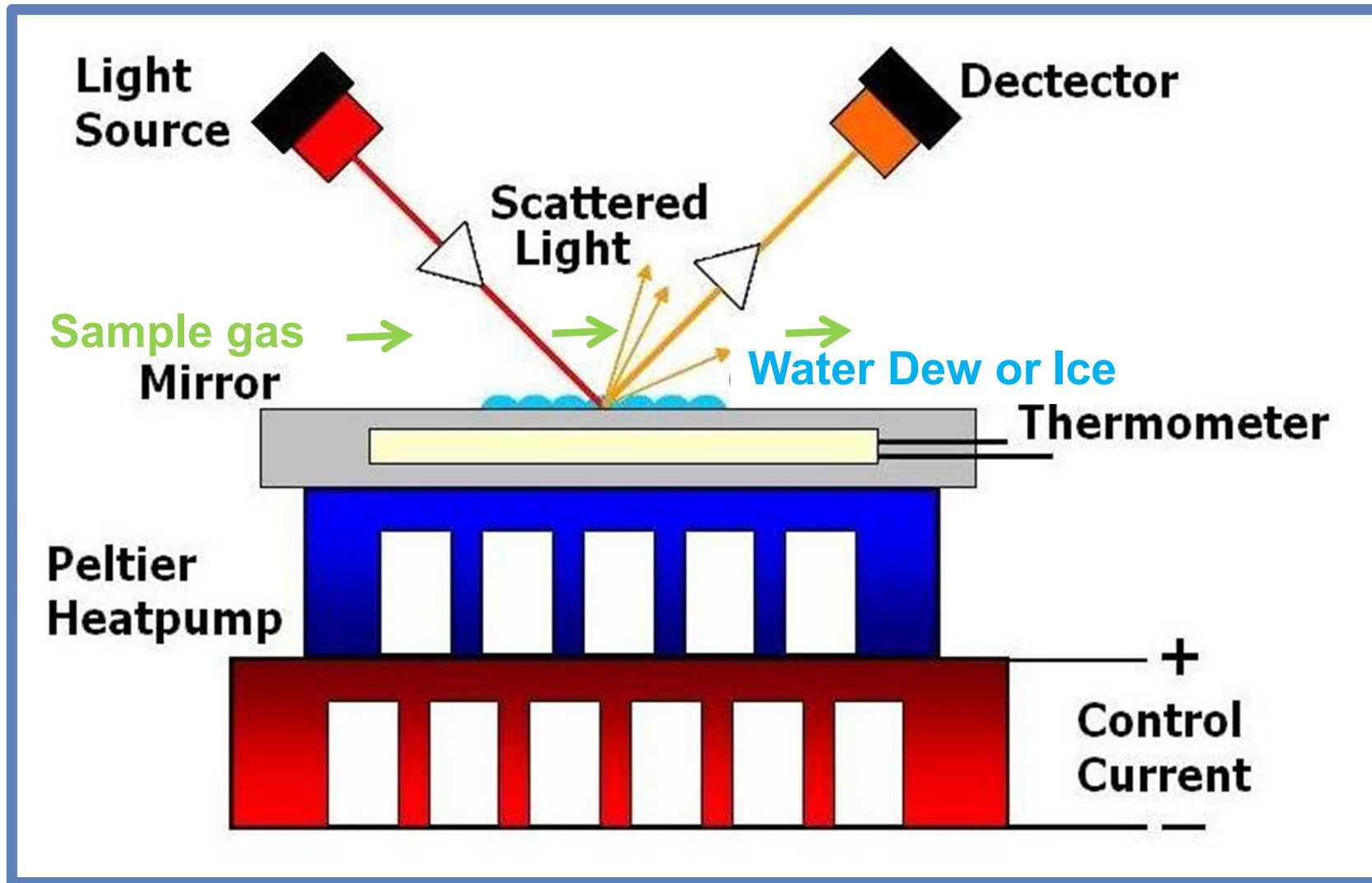
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Dew Point ($^{\circ}\text{C}_{dp}$, $^{\circ}\text{F}_{dp}$)

- The dew point is the temperature at which condensation occurs if a gas is cooled (at constant pressure). At the dew-point temperature a gas is saturated in equilibrium with water vapour.
- The dew point is therefore the temperature at which saturation water vapour pressure would occur if a gas were to be cooled (at constant pressure).
- In the operation of a cooled mirror dew-point hygrometer, a mirror surface is cooled to the temperature at which condensation occurs - *By definition this is the dew-point temperature.*
- The temperature measured under these localised saturation conditions, by reference to tables, gives the saturated water vapour pressure. This 'saturated' water vapour pressure is equal to the unsaturated water vapour pressure for the sample gas at process conditions.
- For any given partial pressure of water vapour there is one dew-point temperature.

For our example of atmospheric air, with a partial pressure of water vapour of 1 KPa, reference to tables shows the dew point measured would be +7°C.

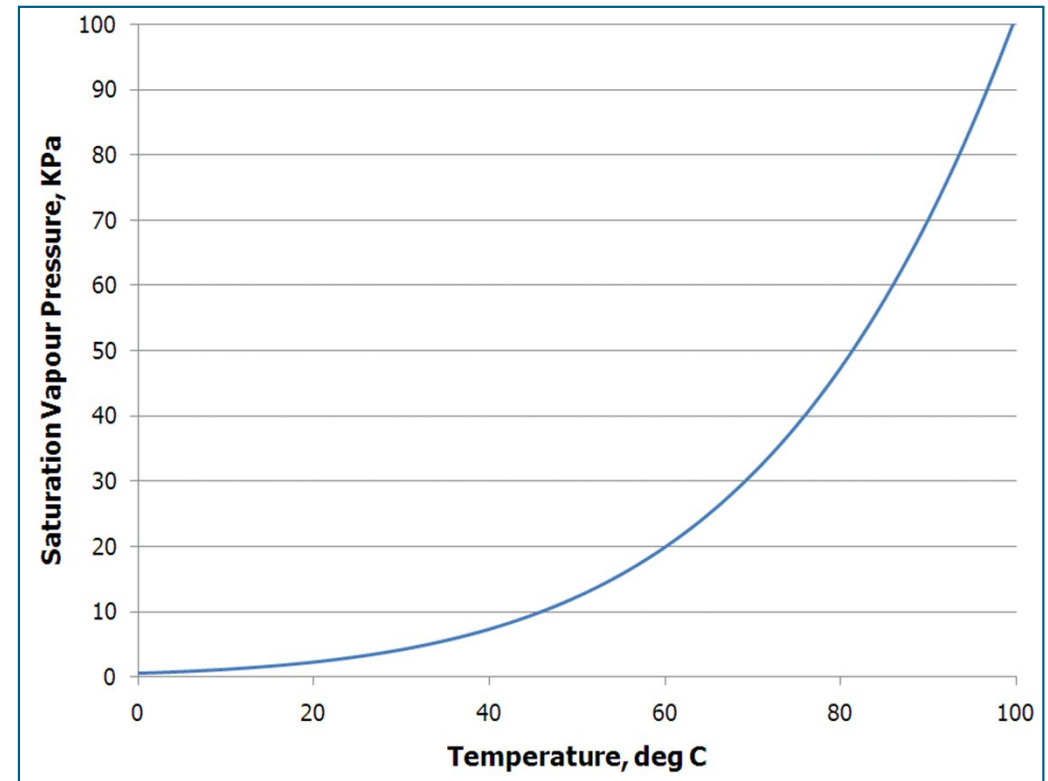
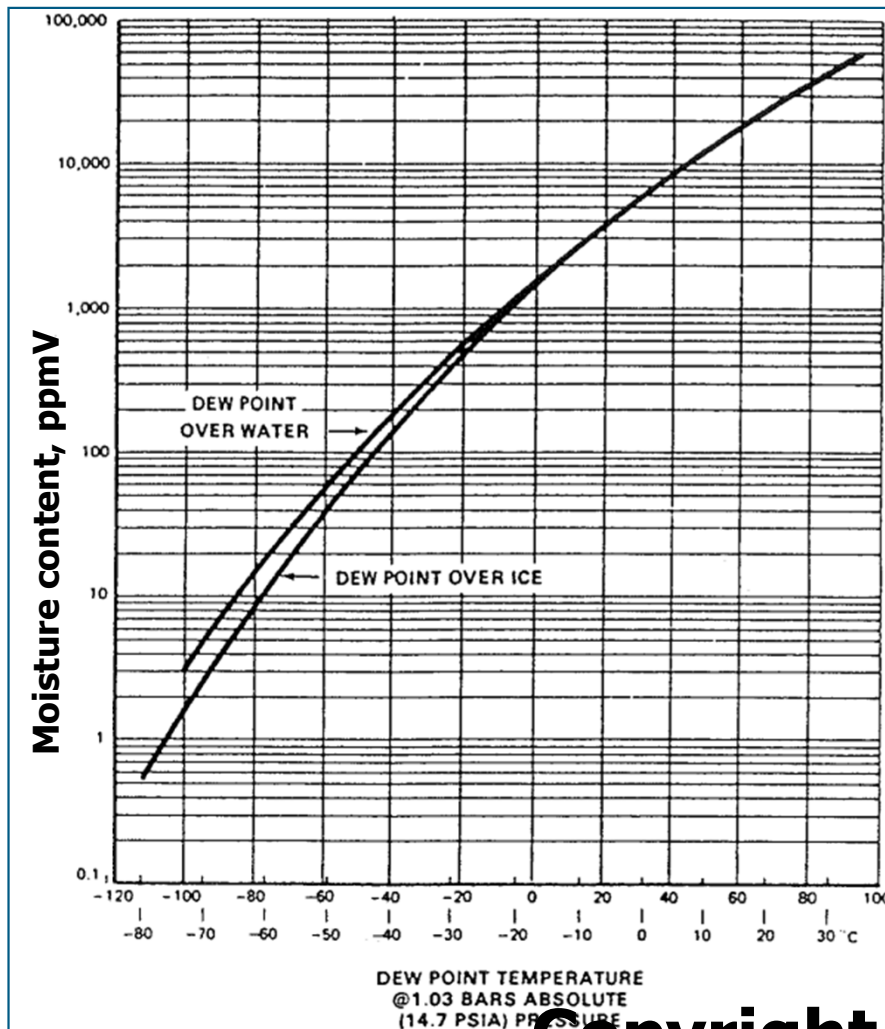
Cooled Mirror Principle of Operation



Frost-Point

- When a gas is saturated with respect to ice the appropriate term is 'frost point' although the convention has developed of using the term 'dew point' irrespective of temperature.
- However, confusion can arise from the fact that condensation formed below zero Celsius is not necessarily ice. At temperatures down to -30°C there is a high likelihood of liquid phase condensation, at least initially, in the form of super-cooled water.
- For a gas of fixed moisture concentration and thus partial pressure of water vapour, the temperature of saturation with respect to liquid water is around 10% lower than with respect to ice. Separate tables are available stating saturation water vapour pressures over ice and water in the region below 0°C .
- Care must therefore be taken when interpreting the measurements of condensation dew-point hygrometers, such as cooled mirror types. The convention employed by the manufacturers of non-condensing dew-point hygrometers is to calibrate with respect to ice, *frost-point*, but to refer to the measurements as *dew point* over the whole measurement range both above and below zero Celsius.
- For any given partial pressure of water vapour there is one frost-point temperature.
- The unit of dew-point temperature is a convenient expression over the whole humidity range from trace moisture concentrations (-100°Cdp @ atmos. pressure = 13 parts of moisture in a **billion** parts of dry gas) up to extreme high moisture concentrations ($+82^{\circ}\text{Cdp}$ @ atmos. pressure = 50/50 mix by volume of moisture in gas on dry basis).

Charts showing Dew Point to Moisture Content & Saturation Vapour Pressure



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Relative Humidity (%RH)

The ratio of actual water vapour pressure (e) to saturation water vapour pressure (e_s) at a given temperature and expressed as a percentage.

$$rh = \frac{e}{e_s} \times 100 \%$$

Relative humidity is the humidity present relative to the highest possible humidity at the same temperature.

rh is therefore an expression of degree of saturation expressed as a percentage.

As such, this unit is most commonly used where this factor is of significance: Air conditioning systems, food processing and storage environments (warehouses, museums).

For our example of atmospheric air, if we assume normal ambient temperature of 21°C then,

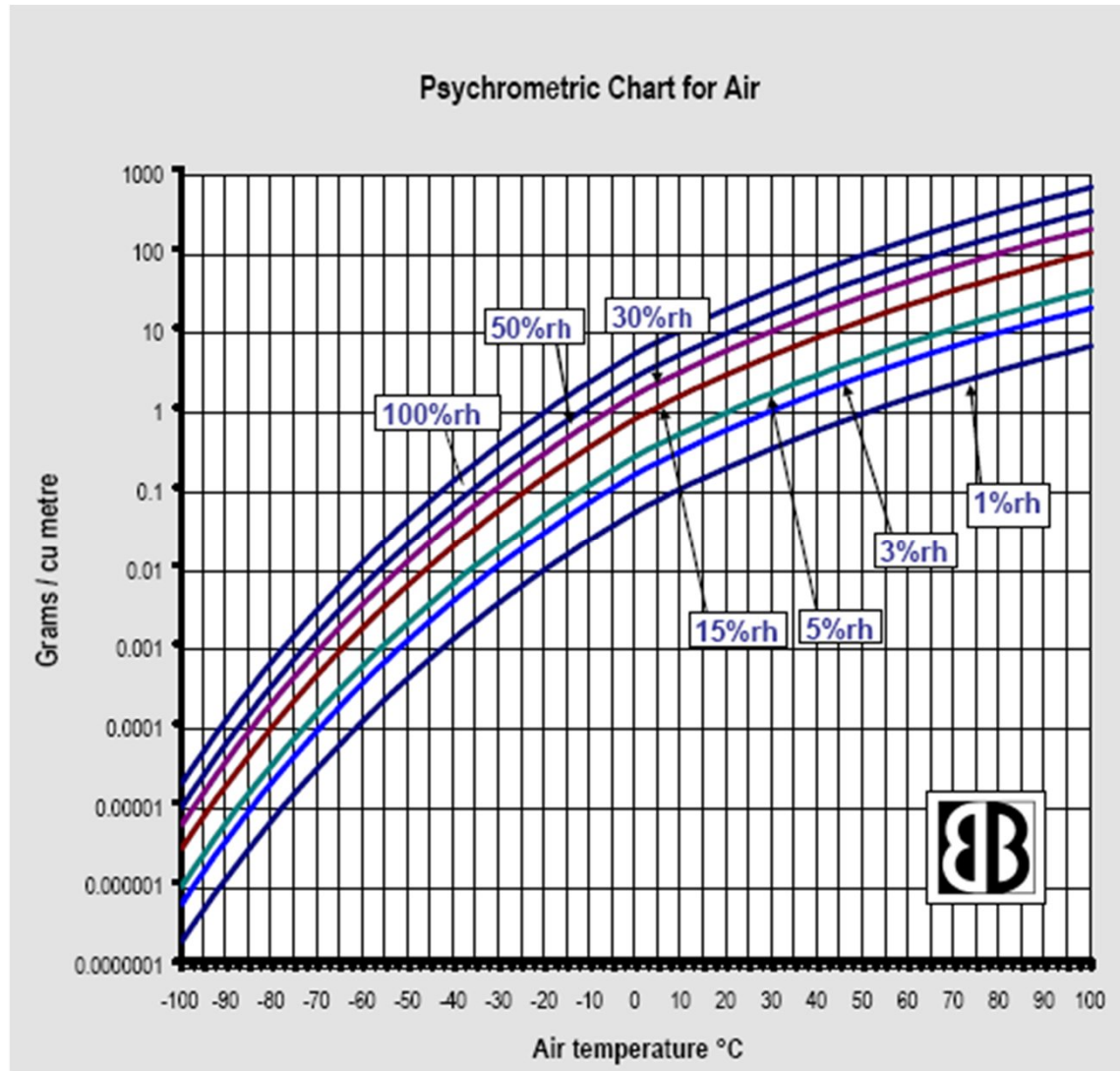
$$\begin{aligned} rh &= \frac{1}{2.5} \times 100\% \\ &= 40\% \end{aligned}$$

If the ambient temperature is decreased, say to 15°C, then the saturation water vapour pressure will fall and thus the relative humidity will rise,

$$\begin{aligned} rh &= \frac{1}{1.7} \times 100\% \\ &= 59\% \end{aligned}$$

It is therefore essential, in order to define a measured humidity level in rh, that the prevailing temperature is also stated.

%Rh variation with dew point and temperature



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Moisture Content

Units of moisture content are expressions of absolute humidity which will therefore remain constant for a gas of fixed composition irrespective of variations in gas temperature and pressure.

A number of different units are in common usage which are derived as a ratio of volume, mass or as a density.

Care must be taken as some units are expressed as a mixing ratio of moisture to dry gas whilst others are expressed as a specific humidity of moisture to humid gas. The difference between the two is almost negligible for trace moisture concentrations but is of significance at higher moisture concentrations.

Parts per million

For low humidity levels, the unit of moisture content in most common usage is **parts per million**: The number of parts of water vapour to one million parts of wet gas expressed either by volume (**ppmV**) or weight (**ppmW**).

$$\text{ppmV} = \frac{e}{P_{\text{TOTAL}}} \times 10^6$$

$$\text{ppmW} = \frac{\text{grams of water vapour}}{\text{grams of gas}} \times 10^6$$

or simply derived from ppm(V) as follows,

$$\text{ppmW} = \text{ppmV} \times \frac{\text{molecular weight of water}}{\text{molecular weight of gas}}$$

For our example of atmospheric air,

$$\begin{aligned} \text{ppmV} &= \frac{1}{101.3} \times 10^6 \\ &= 10,000 \end{aligned}$$

$$\text{ppmW} = 10,000 \times \frac{18}{29}$$

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Absolute Humidity (wet basis)

When moisture content is expressed as a **density**, the most common unit is **mg/m³** which can be calculated from ppmW as follows,

For an ideal gas, 1 mole (grams molecular weight) has a volume of 22.4 litres at s.t.p.

For air, 29 grams has a volume of 22.4 litres at s.t.p. therefore,

$$\begin{aligned}
 10^6 \text{ grams of air has a volume} &= \frac{10^6 \times 22.4}{29} \\
 &= 772,414 \text{ litres} \\
 &= 772.4 \text{ m}^3
 \end{aligned}$$

From above,

$$\text{ppmW} = \frac{\text{grams of water vapour} \times 10^6}{\text{grams of wet gas}}$$

Therefore,

$$\text{mg/m}^3 = \frac{\text{ppmW}}{772.4}$$

For the example of atmospheric air,

$$\begin{aligned}
 \text{mg/m}^3 &= \frac{6,207}{772.4} \\
 &= 8.04
 \end{aligned}$$

Influence of varying pressure and temperature on dew point, moisture content and relative humidity.

Dew Point:

The effect of increasing gas pressure on dew point is best illustrated through a worked example,

Taking our example of typical atmospheric air, if a sample of this air is taken in a vessel which is subsequently halved in volume then, as a result of this compression, the gas pressure is doubled to 202.6 KPa.

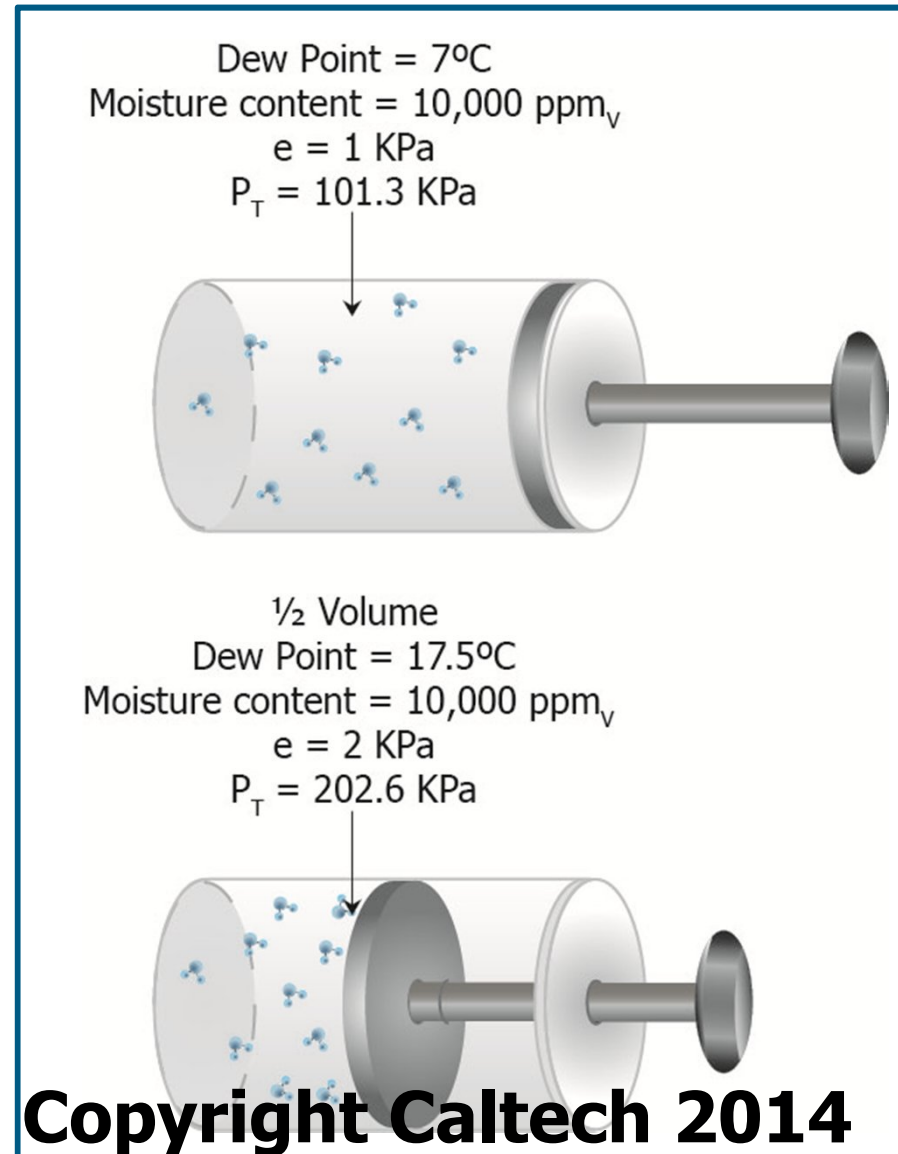
Under Dalton's law, a change in total gas pressure will effect each component partial pressure by the same proportion, so, in this case the partial pressure of water vapour will also be doubled from 1KPa to 2 KPa.

Referring to tables, this equates to a dew point temperature of 17.5°C. As such it can be seen that an increase in gas pressure results in an increase in dew point.

Reference to saturation vapour pressure tables

0	572.384	576.587	580.818	585.076	589.362	593.676	598.018	602.
	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.
°C	Pa	Pa	Pa	Pa	Pa	Pa	Pa	Pa
0	611.213	615.668	620.152	624.665	629.207	633.779	638.380	643.
1	657.080	661.830	666.611	671.423	676.265	681.138	686.042	690.
2	705.972	711.034	716.129	721.255	726.414	731.606	736.830	742.
3	758.060	763.451	768.876	774.335	779.829	785.357	790.919	796.
4	813.520	819.259	825.033	830.843	836.690	842.573	848.492	854.
5	872.540	878.645	884.788	890.968	897.187	903.444	909.740	916.
6	935.313	941.804	948.335	954.907	961.518	968.170	974.862	981.
7	1002.04	1008.94	1015.88	1022.86	1029.89	1036.96	1044.07	1051.
8	1072.94	1080.27	1087.64	1095.05	1102.52	1110.02	1117.57	1125.
9	1148.23	1156.01	1163.83	1171.70	1179.62	1187.59	1195.60	1203.
10	1228.13	1236.39	1244.69	1253.04	1261.44	1269.89	1278.39	1286.
11	1312.90	1321.65	1330.46	1339.31	1348.22	1357.18	1366.19	1375.
12	1402.77	1412.05	1421.39	1430.77	1440.21	1449.71	1459.26	1468.
13	1498.02	1507.85	1517.74	1527.68	1537.68	1547.74	1557.86	1568.
14	1598.91	1609.31	1619.78	1630.31	1640.90	1651.55	1662.26	1673.
15	1705.71	1716.73	1727.81	1738.95	1750.16	1761.43	1772.76	1784.
16	1818.74	1830.39	1842.11	1853.90	1865.75	1877.67	1889.66	1901.
17	1938.28	1950.60	1963.00	1975.46	1987.99	2000.59	2013.27	2026.
18	2064.66	2077.69	2090.78	2103.95	2117.20	2130.54	2143.96	2157.

Effect of increasing gas pressure on dew point and moisture content



Moisture content:

Again, looking to the effects of doubling the pressure of our typical atmospheric air, as the proportion of moisture to carrier gas remains constant, then the moisture content remains constant irrespective of pressure variations:

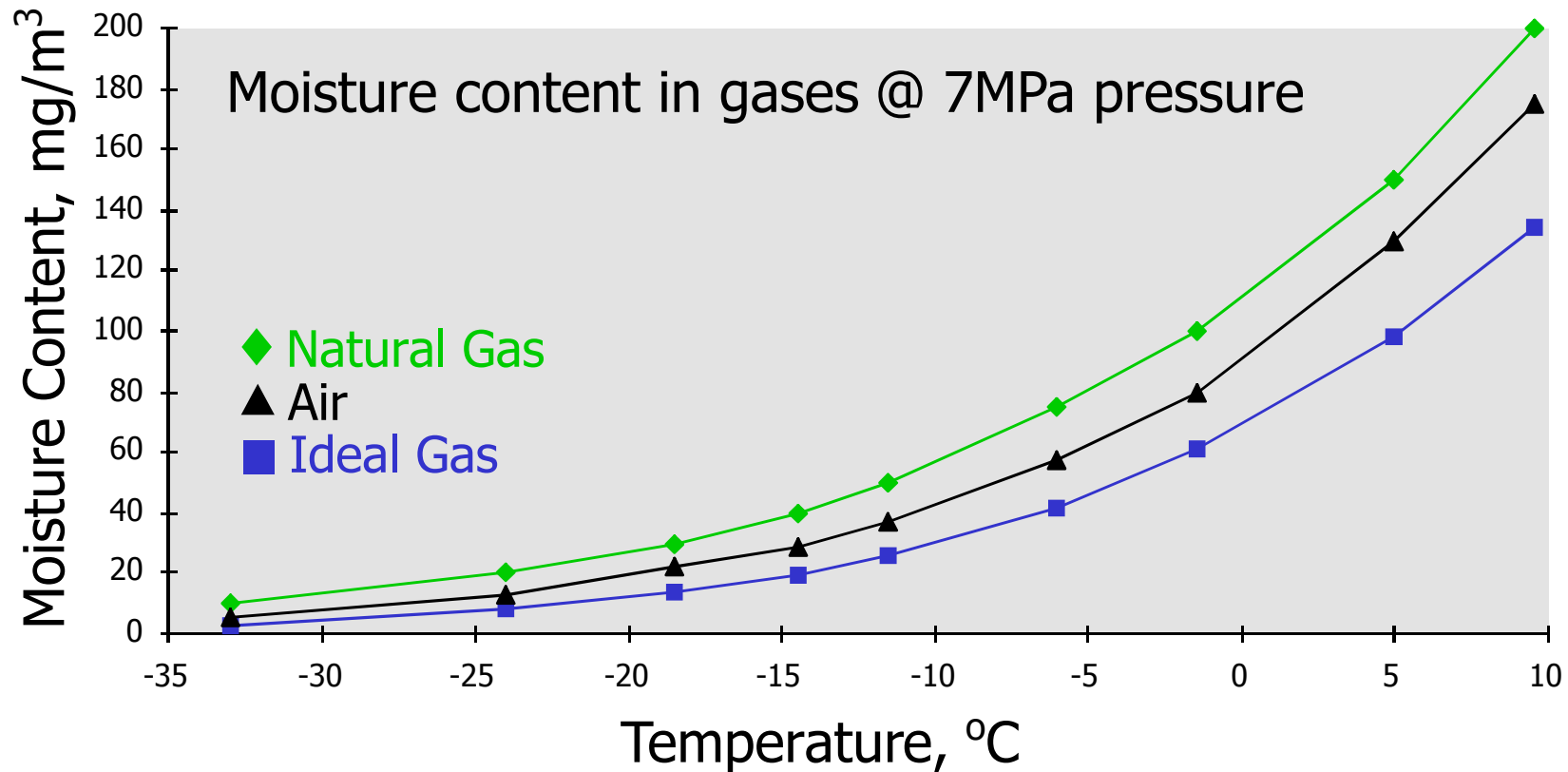
$$\begin{aligned} ppm(V) &= \frac{2}{202.6} \times 10^6 \\ &= 10,000 \end{aligned}$$

Relative Humidity:

Note that the parameter of relative humidity is influenced by both pressure variations, which changes the partial pressure of water vapour (e), and temperature fluctuations, which alters the saturation vapour pressure (e_s). Therefore, strictly speaking, for a statement of relative humidity to have validity in absolute terms then both the prevailing pressure and temperature should be given when stating %rh.

Summary:	Dew point	Moisture content	Relative humidity
Increase pressure	↑	0	↑
Decrease pressure	↓	0	↓
Increase temperature	0	0	↓
Decrease temperature	0	0	↑

Conversion from Measured Dew Point to Moisture Content



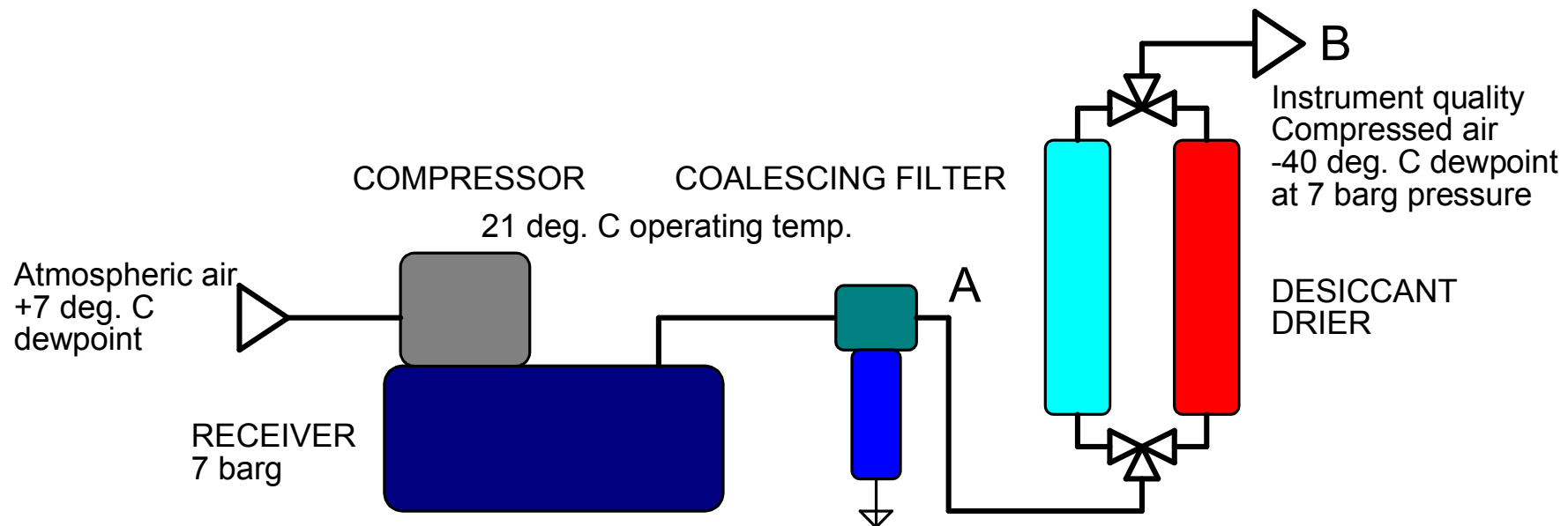
HYGROMETRIC CALCULATIONS

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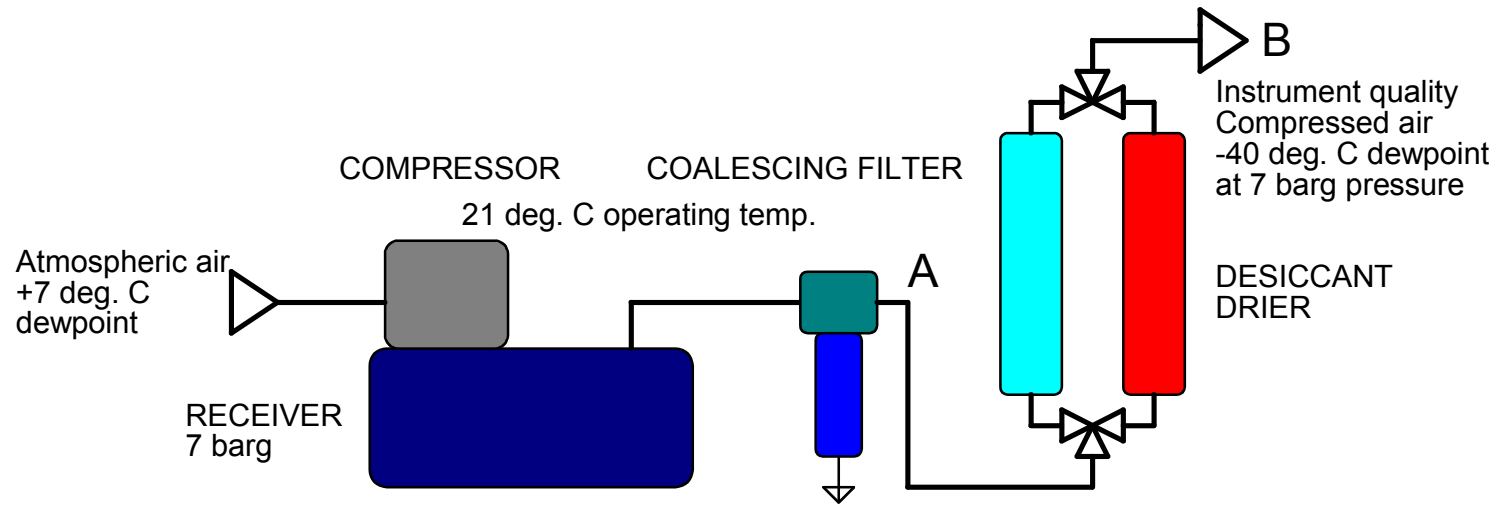


To illustrate the relationship between hygrometric units let us consider the changes in humidity which occur in two industrial applications: A compressed air system producing instrument quality air and a product drying process:

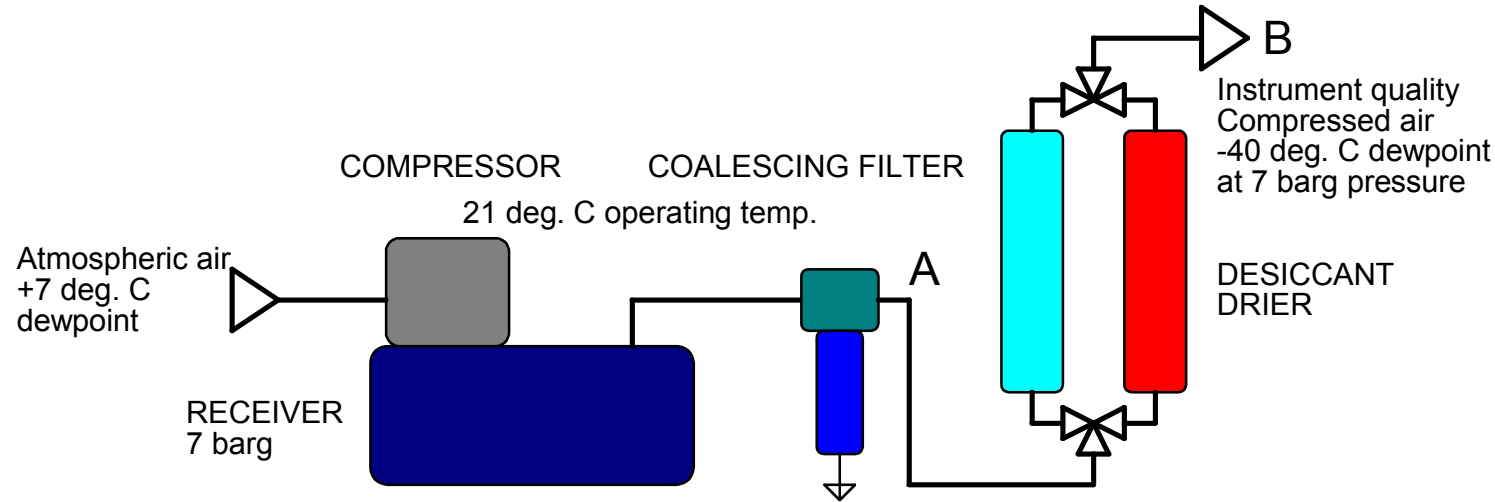
1. Atmospheric air with a dew point of $+7^{\circ}\text{C}$ is being sucked into a compressor which pressurises the air into a receiver at 7 barg. The air feeds from the receiver through a coalescing filter operating at an ambient temperature of 21°C into a twin column desiccant dryer which delivers instrument quality compressed air at -40°C dew point at pressure.



What is the dew point at point A after the coalescing filter?



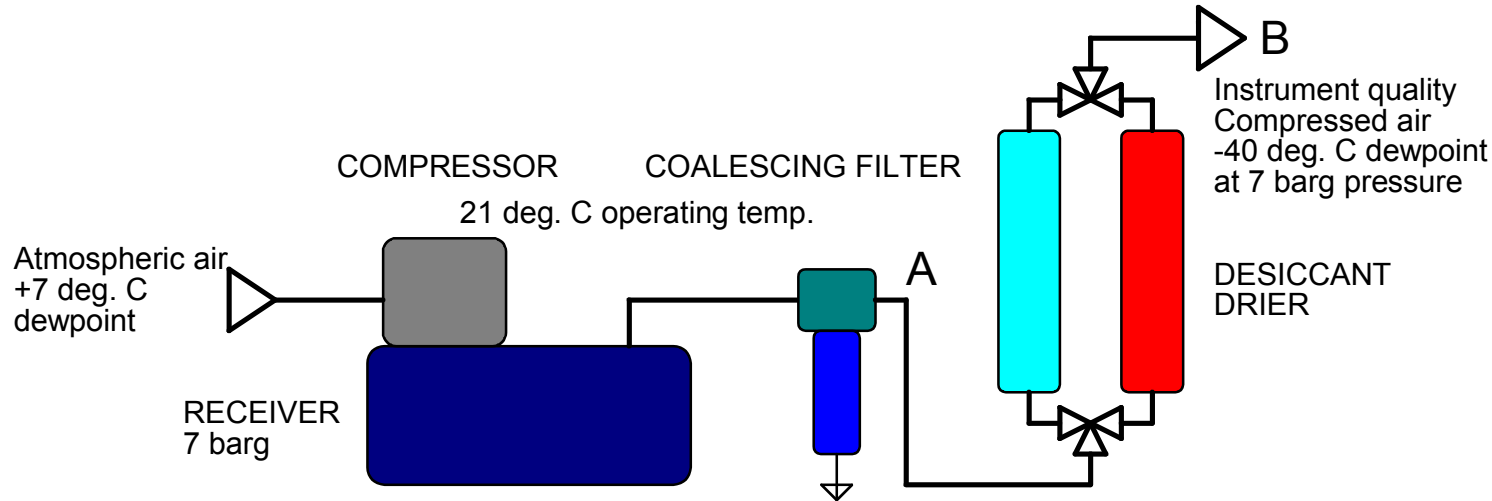
- In this example, the ambient air has a dew point of +7°C, and so becomes saturated with respect to water vapour at +7°C, therefore using tables of saturation water vapour pressures we obtain a partial pressure of water vapour of 1000 Pa.
- The pressure of the air at point A is increased to 8 bara (800 KPa). Applying the gas laws, an eight fold increase in the total gas pressure will also result in an equal rise in partial pressures so the water vapour pressure rises to 8,000 Pa.
- Looking back at the tables, this equates to a saturation temperature and therefore a dew point of +41.5°C.
- As the operating temperature of the receiver and filter is only +21°C we can assume that condensation is occurring within the receiver and filter vessels and air at point A is saturated at +21°C and therefore has a dew point of +21°C.



What is the moisture content in ppmV at point A?

From tables, the partial pressure of water vapour for a gas of +21°C dew point is 2,500 Pa. The total pressure at point A is 800 KPa. So using the formula:

$$\begin{aligned}
 \text{ppmV} &= \frac{e}{P_{\text{TOTAL}}} \times 10^6 \\
 &= \frac{2500}{800 \times 10^3} \times 10^6 \\
 &= 3,125 \text{ ppmV}
 \end{aligned}$$



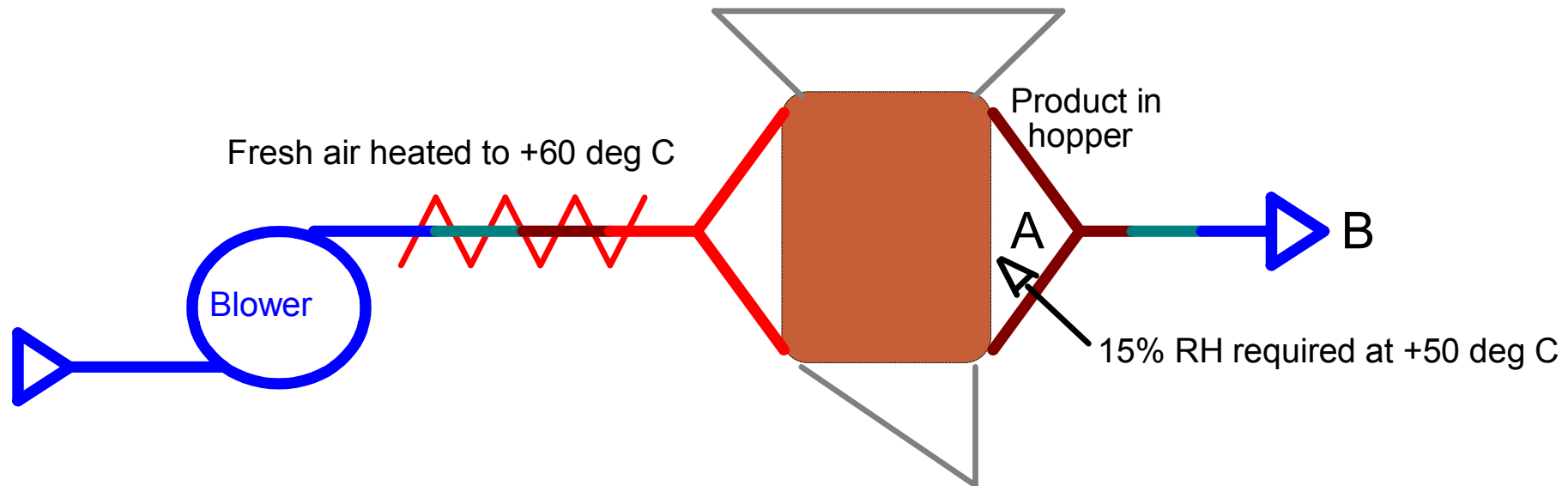
If the pressure of the air at point B is reduced to atmospheric, what is the effect on the dew point temperature and the moisture content?

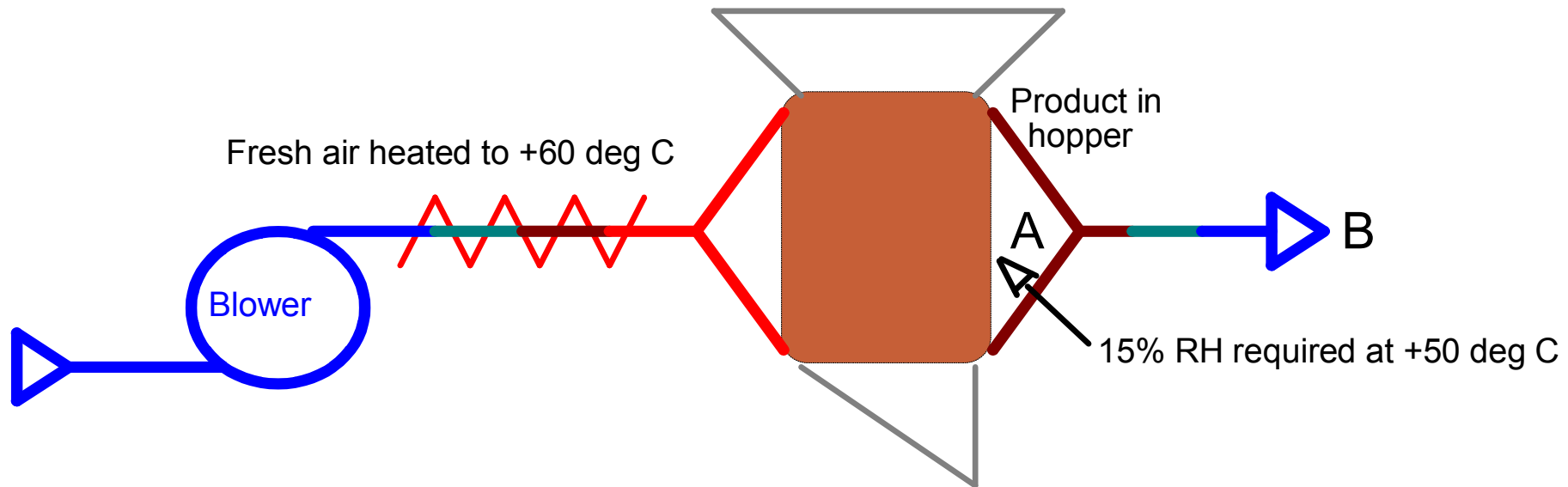
Applying the gas law's, an eight fold decrease in total pressure will result in an equal decrease in partial pressures so the water vapour pressure is reduced from 13 Pa to 1.6 Pa. Referring to saturation water vapour pressure tables we see that the dew point has reduced to -57°C.

Calculating the moisture content, we find that the ppmV remains the same irrespective of changes in pressure:

$$\begin{aligned} \text{ppmV} &= \frac{1.6}{101 \times 10^3} \times 10^6 \\ &= 16 \text{ ppmV} \end{aligned}$$

2. A hopper load of a food product is being dried prior to packaging by blowing through fresh air which is heated to $+60^{\circ}\text{C}$. The dew point of the exhaust air is being measured. During the drying process moisture is carried out of the product and at the same time the product temperature gradually increases. To ensure good storage life of the product when packaged, the requirement is to dry the product until the exhaust air is less than 15% relative humidity at the product temperature which measures $+50^{\circ}\text{C}$ towards the end of a drying cycle.

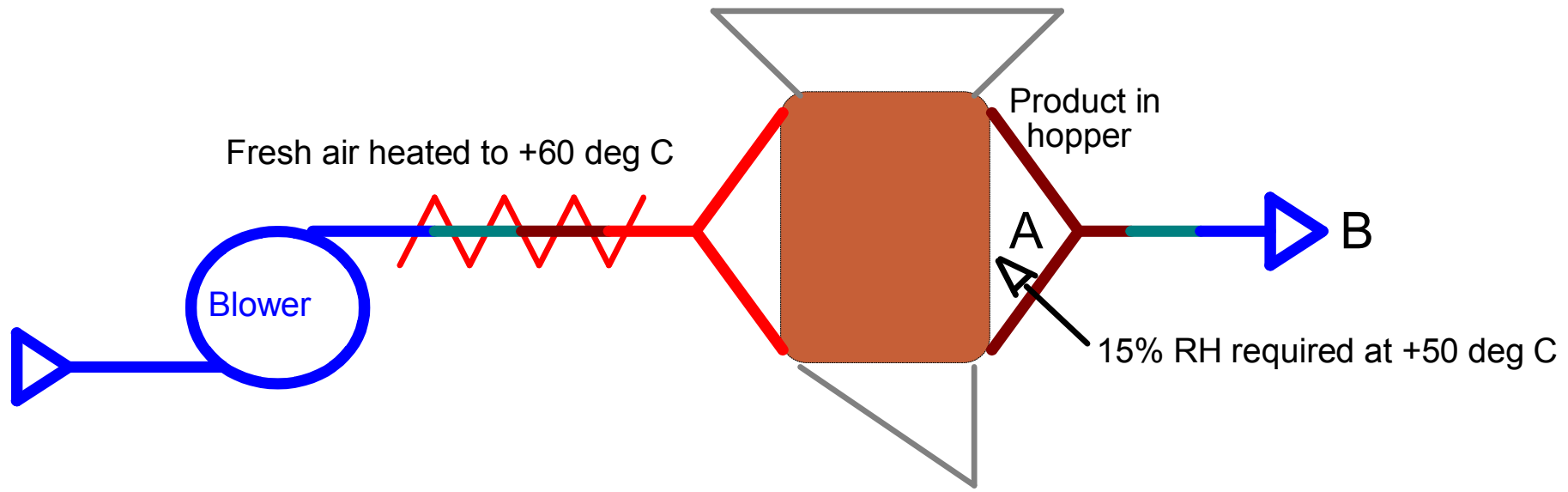




What is the equivalent dew point measured at point A at the end of a drying cycle?

rh is the ratio, expressed as a percentage, of actual water vapour pressure (e) at the measured dew point to saturation water vapour pressure (e_s) at the gas temperature. Rearranging the formula for calculating RH we obtain:

$$e = \frac{e_s \times RH}{100}$$



The saturation water vapour pressure at 50°C is 12,345 Pa so,

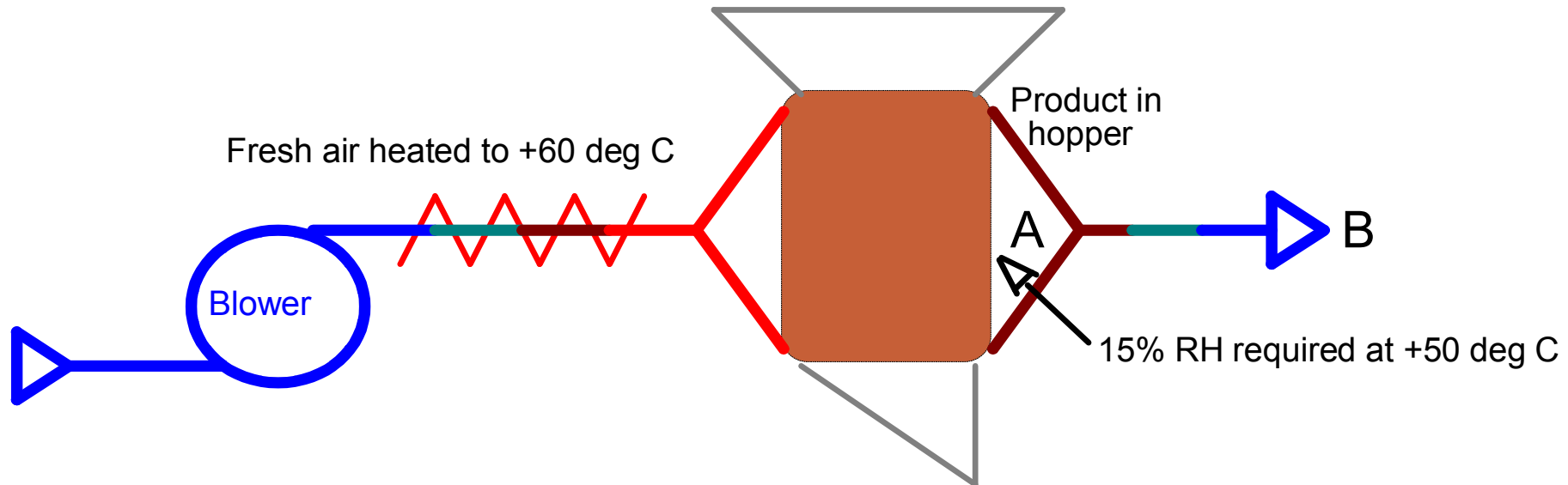
$$= \frac{12,345 \times 15}{100}$$

$$= 1,852 \text{ Pa}$$

From tables we see that a water vapour pressure of 1,852 Pa equates to a dew point of +16.3°C.

At the end of a drying cycle, what is the RH and dew point of the exhaust air at point B where the temperature cools to ambient at 21°C?

$$\begin{aligned} \text{rh} &= \frac{e}{e_s} \times 100\% \\ &= \frac{1,852}{2,487} \times 100\% \\ &= 74\% \end{aligned}$$



At the mid point in a drying cycle, the relative humidity approaches 100%RH at a temperature of +40°C. Why would it be impossible to measure this condition using a humidity sensor installed at point B?

As the air passing through the hopper at this stage is totally saturated at the operating temperature of +40°C, the dew point is +40°C.

However, the temperature at the exhaust vent point B is only 21°C and as a result the air flow will no longer be wholly gaseous as water vapour will condense to form mist droplets so a measurement at this point would not be valid.

Hygrometry

Terms and Definitions

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Absolute Humidity

A measure of the amount of water vapor present in the system



Dew-Point
Temperature



Frost-Point
Temperature



Parts Per
Million/Billion

DEW-POINT TEMPERATURE



The temperature to which a gas must be cooled to be saturated with water vapor.

- or -

The temperature to which a gas must be cooled where the first molecule of water vapor changes to the liquid phase.

For a given partial pressure of water, there is only one corresponding dew point.

FROST-POINT TEMPERATURE

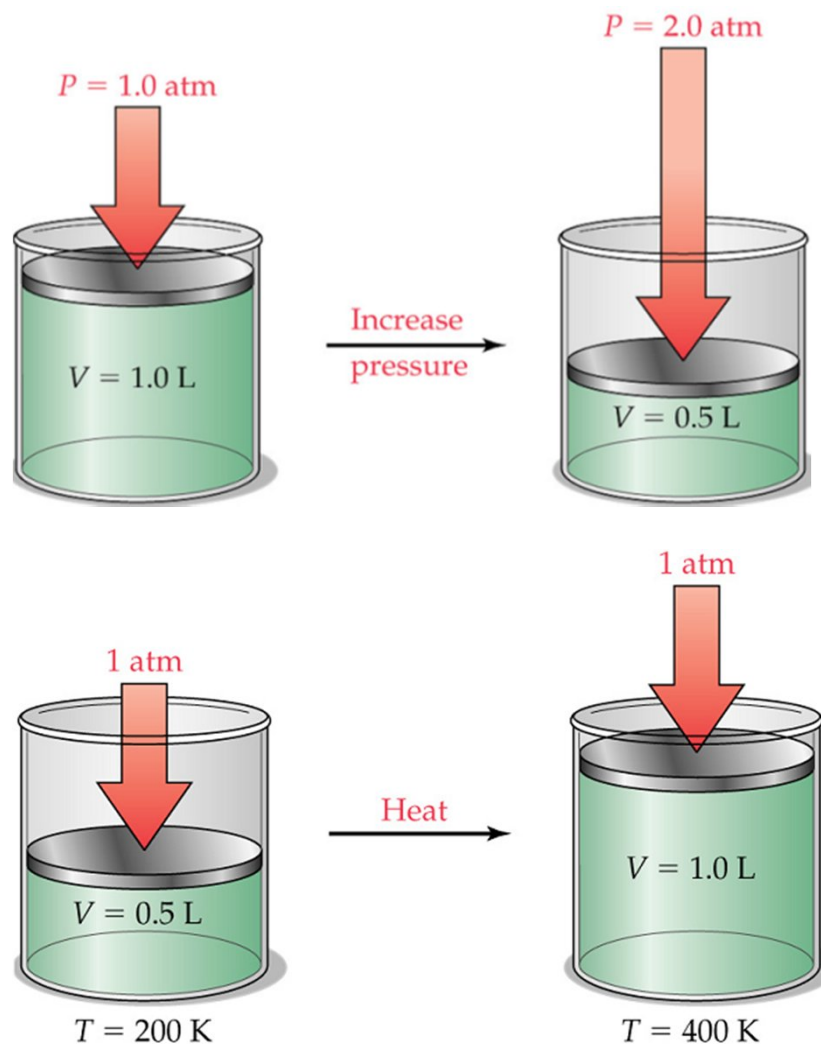


The temperature to which a gas must be cooled to be saturated with respect to ice (solid water).

- or -

The temperature to which a gas must be cooled where the first molecule of water vapor changes to the solid phase.

For a given partial pressure of water, there is only one corresponding frost point.



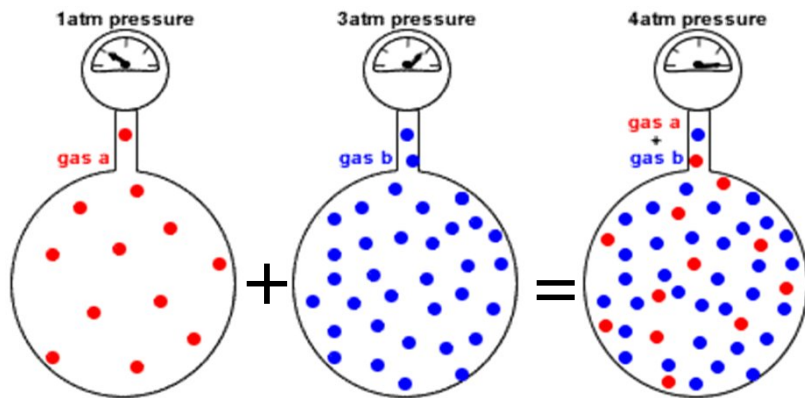
IDEAL GAS LAW

$$PV = nRT$$

- P = Total Pressure of the System
- V = Total Volume of the System
- n = Total Number of Moles in the System
- T = Absolute Temperature of the System
- R = Ideal Gas Law Constant (in the units of the above components)

DALTON'S LAW

$$P_a + P_b = P_{a+b} = P_T$$



$$\text{Gas a} + \text{Gas b} = \text{Gas a+b}$$

$$P_T = P_1 + P_2 + \dots + P_i$$

P_T = Total Pressure of the System

P_1 = Partial Pressure of the First Component

P_2 = Partial Pressure of the Second Component

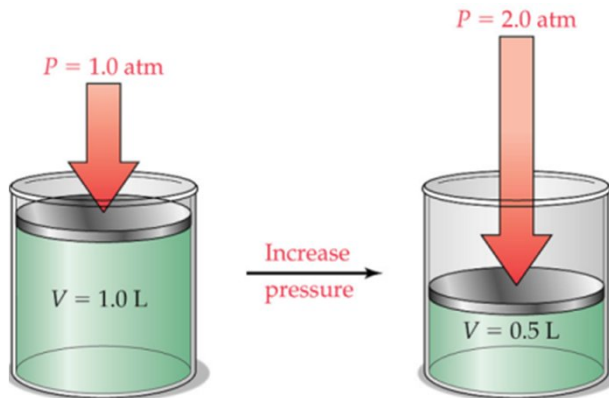
P_i = Partial Pressure of the i^{th} Component

Dew-Point Pressure Relationship

$$P_{T1} = 1277 \text{ mm Hg (10 psig)} \quad P_{T2} = 5930 \text{ mm Hg (100 psig)}$$

$$P_{W1} = 0.0966 \text{ mm Hg} \quad P_{W2} = 0.4486 \text{ mm Hg}$$

$$\underline{DP_1 = -40^\circ\text{C}} \quad \underline{DP_2 = -25.6^\circ\text{C}}$$



Dalton's Law

$$P_T = P_1 + P_2 + \dots P_i$$

$$P_T (\uparrow) = P_1 (\uparrow) + P_2 (\uparrow) + \dots P_i (\uparrow)$$

Pressure Increases (\uparrow) \Rightarrow Water Partial Pressure Increases (\uparrow)

Water Partial Pressure Increases (\uparrow) \Rightarrow Dew Point Increases (\uparrow)

PARTS PER MILLION BY VOLUME (PPM_V)



1 minute in 1.9
years = one PPM

$$PPM_V = (P_W / P_T) \times (10^6)$$

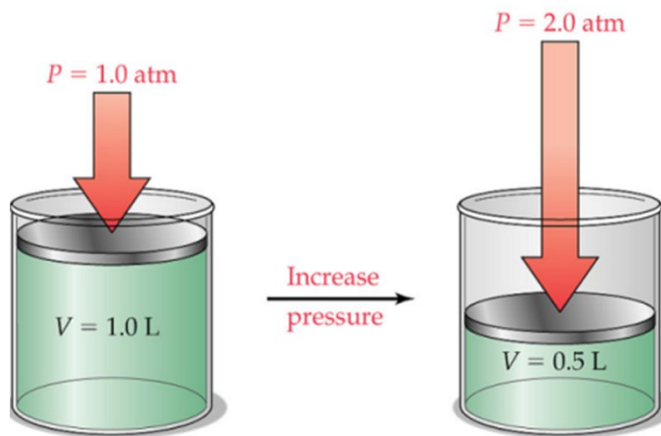
P_W = Partial Pressure of Water

P_T = Total Pressure of the System

PPM_V is most commonly used when measuring moisture in gases.

PPM_v/Pressure Relationship

$$P_1 V_1 = P_2 V_2$$



$$P_1 = 1277 \text{ mm Hg (10 psig)} \quad P_2 = 5930 \text{ mm Hg (100 psig)}$$

$$P_{W_1} = 0.0966 \text{ mm Hg}$$

$$P_{W_2} = 0.4486 \text{ mm Hg}$$

$$\underline{PPM_{v_1} = 75.6}$$

$$\underline{PPM_{v_2} = 75.6}$$

Dalton's Law $P_T (\uparrow) = P_1 (\uparrow) + P_2 (\uparrow) + \dots P_i (\uparrow)$

$$PPM_V = (P_{W_1} / P_{T_1}) \times (10^6) = (P_{W_2} / P_{T_2}) \times (10^6)$$

$$(P_{W_1} / P_{T_1}) = (P_{W_2} / P_{T_2})$$

The ratio of water partial pressure to total pressure doesn't change because every component changes proportionally, so $\underline{PPM_{v_1} = PPM_{v_2}}$

Parts Per Million By Weight (PPM_W) In Liquids

Application of Henry's Law

The mass of gas dissolved by a given volume of solvent, at a constant temperature, is directly proportional to the pressure of gas with which it is in equilibrium

$$C = KP$$

C = concentration of the gas

K = Henry's Law constant

P = pressure of the gas



Parts Per Million By Weight (PPM_W) In Liquids

Application of Henry's Law

The concentration of water in an organic liquid is equal to the vapor pressure of the water in the liquid multiplied by a constant.

$$C_W = K P_W$$

C_W = concentration of water in the liquid

K = Henry's Law constant

P_W = vapor pressure of water in the
liquid



Application of Henry's Law

...and $C_s = K P_s$

C_s = saturation concentration of water in the liquid

K = Henry's Law constant

P_s = saturation water vapor pressure

...eliminating K reveals that percent saturation is simply equal to the ratio of the actual vapor pressure of water (dew point) to its saturation vapor pressure at the same temperature.

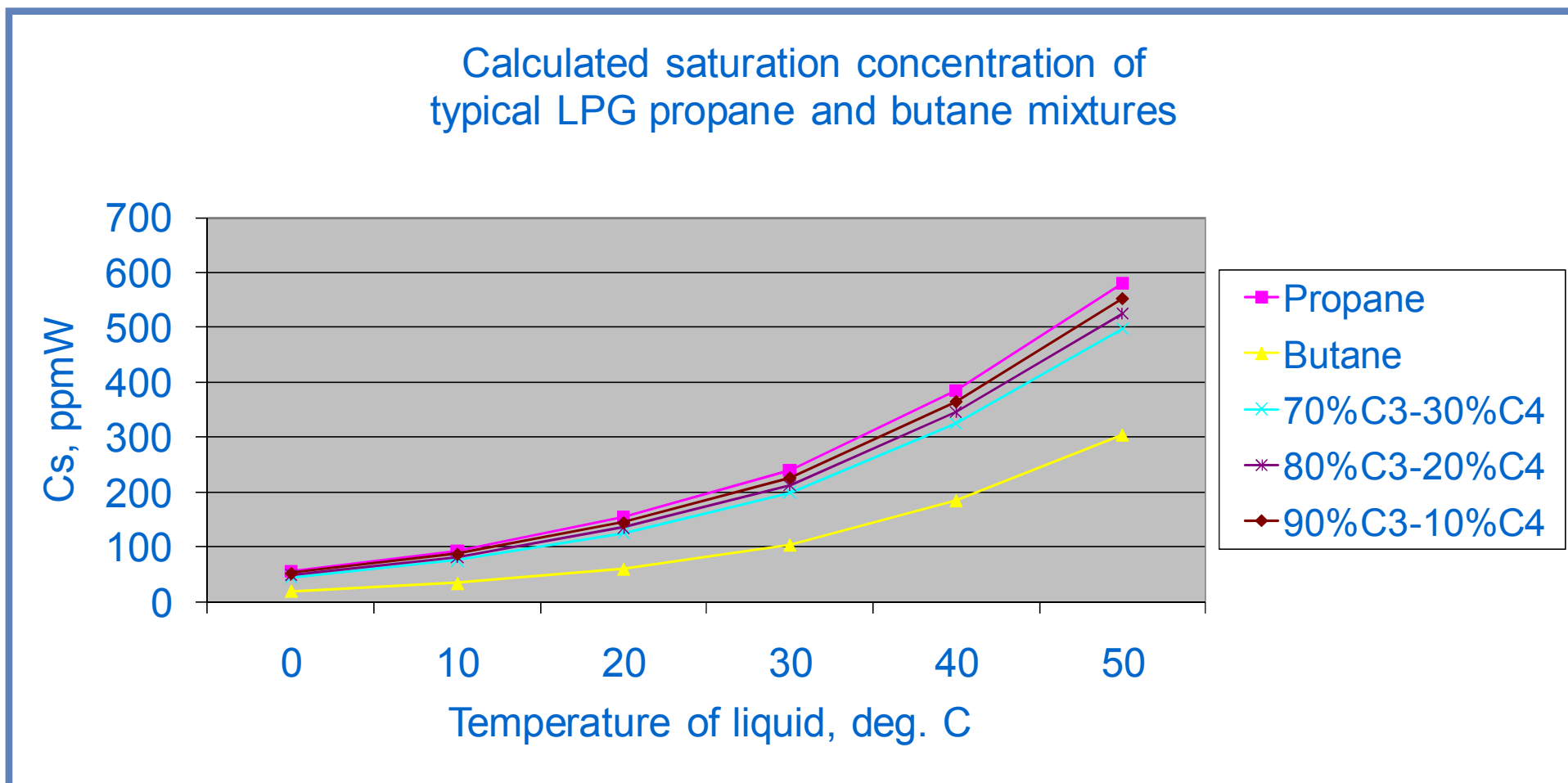
$$C_w/C_s = P_w/P_s$$

...and finally determining moisture content

$$C_w = (C_s/P_s) P_w$$



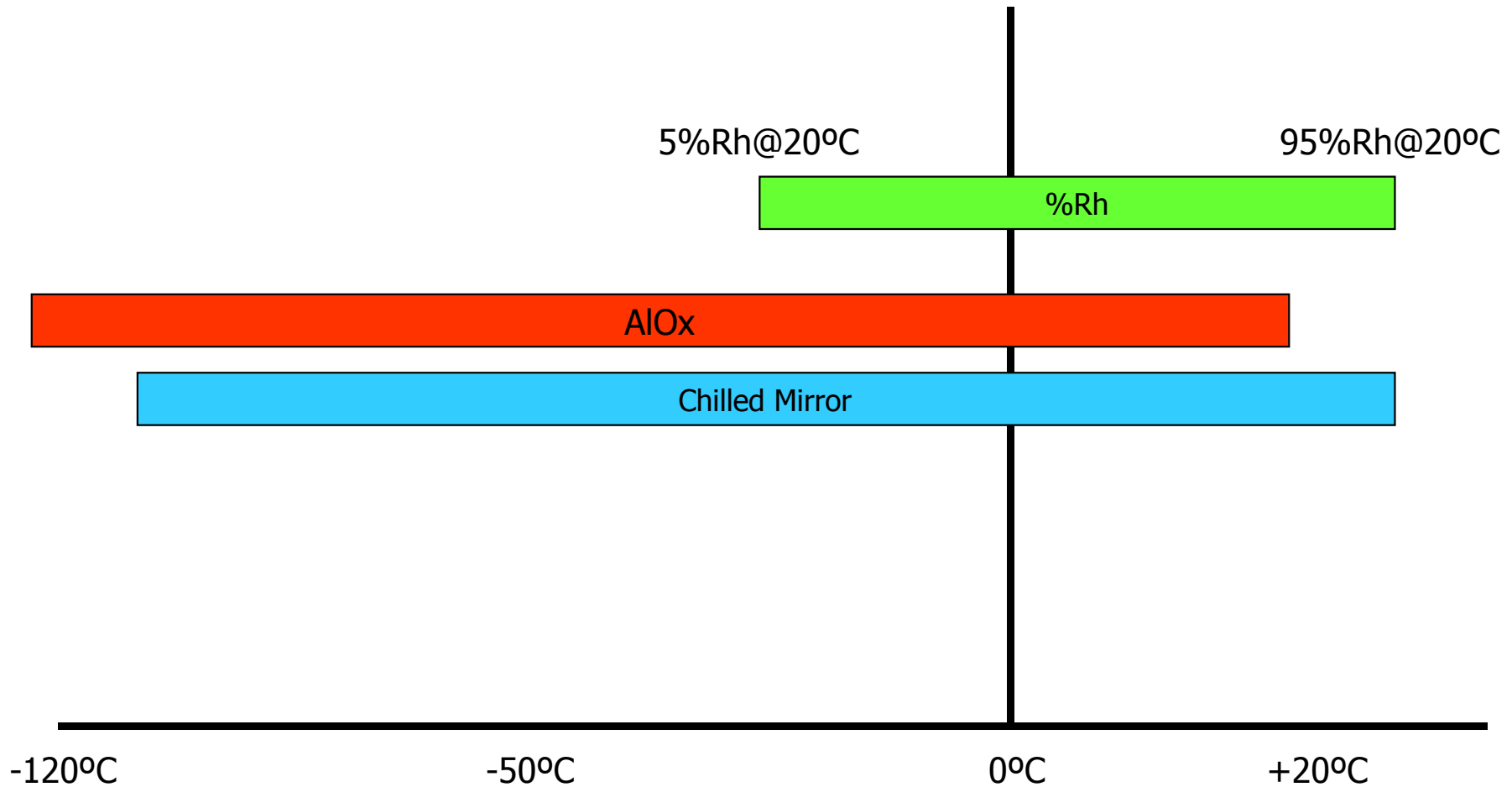
Water Solubility Data for Mixtures



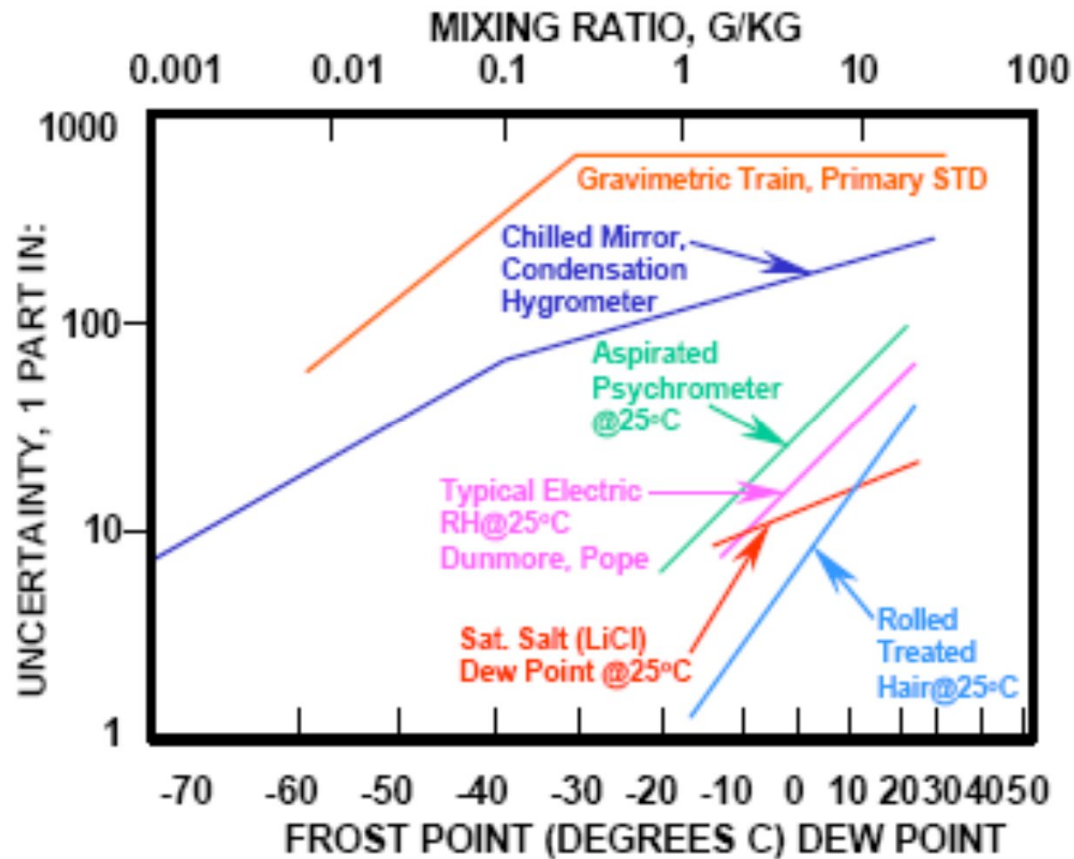
- Dewpoint is affected by pressure in a system
- Relative humidity is affected by both temperature and pressure
- Moisture content remains the same for changes in temperature and pressure

	Dew point	Moisture content	Relative Humidity
Increase Pressure	↑	○	↑
Decrease pressure	↓	○	↓
Increase temperature	○	○	↓
Decrease temperature	○	○	↑

Range coverage



Comparison of accuracies and ranges for hygrometers



Considerations

What is the range of measurement?

What is the media? Gas, liquid?

What are the ambient conditions?

At pressure or at atmospheric?

Sample system?