

1. The pressure-enthalpy diagram

For refrigeration cycles, a convenient chart for calculations is the p-h diagram because it efficiently yields information about the enthalpy changes in the evaporator and condenser – which is the primary point of interest since the heat pump is responsible for transferring thermal energy from one place to another. The chart in the adjacent figure shows the following features which need to be identified:

- the vapour dome, which leans slightly to the right and has a maximum pressure of 13 bar at critical point
- constant temperature lines, which are vertical in the liquid region, horizontal in the mixture region and curve steeply downwards in the superheated region
- a typical refrigeration cycle is shown –

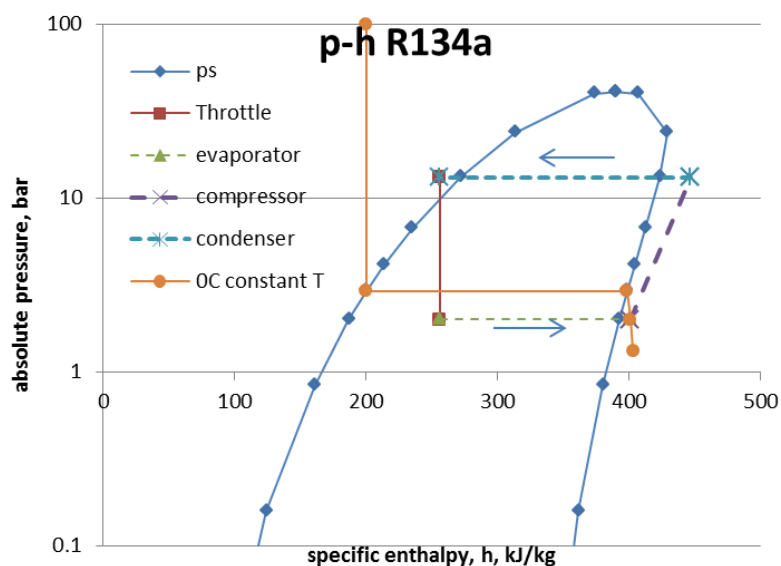


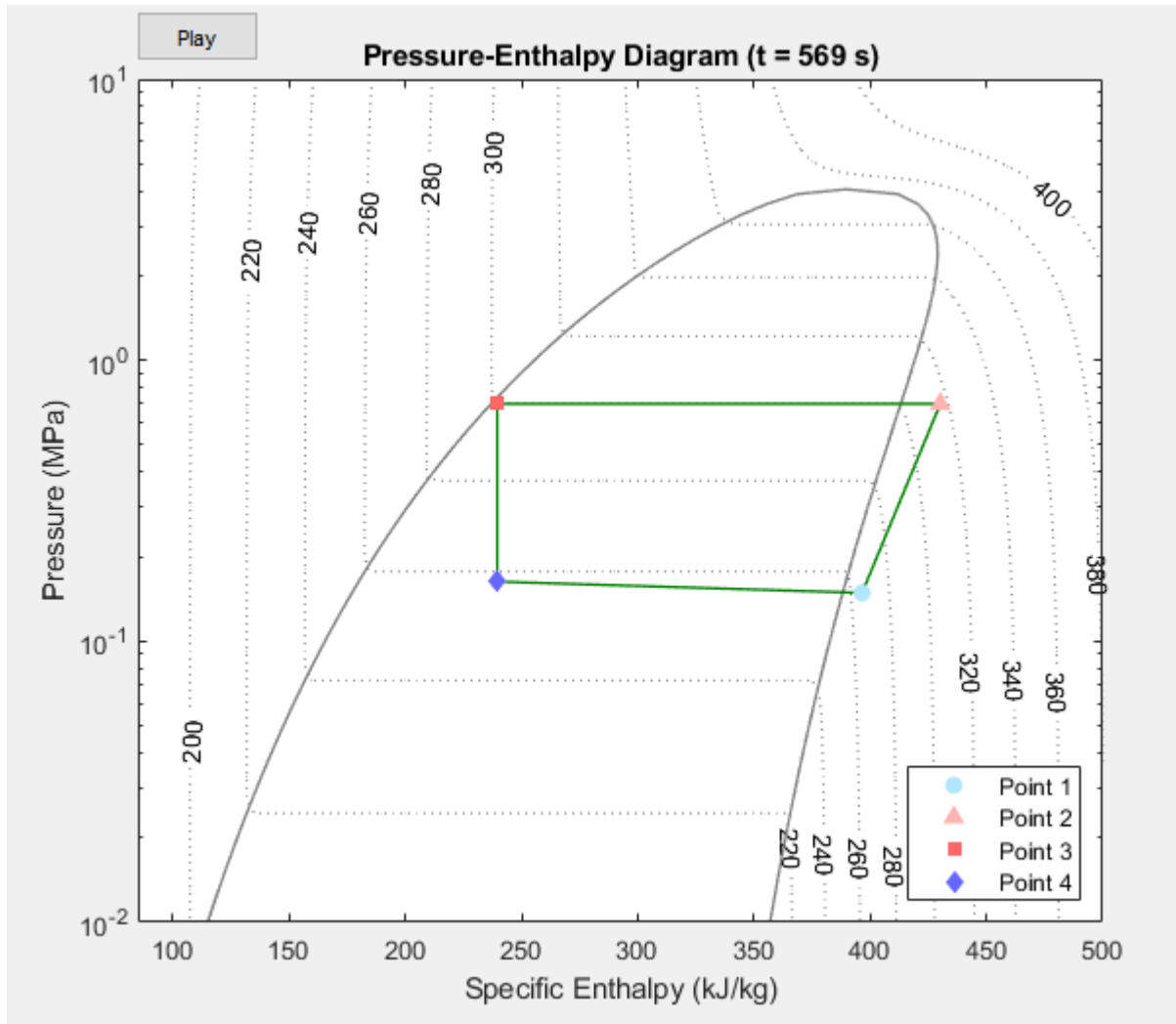
Figure 1 showing excel plot of absolute pressure versus specific enthalpy for refrigerant R134a; the vapour dome contains the mixture region of vapour and liquid underneath it; a constant temperature plot at zero degree C is shown which descends vertically in the liquid region and horizontally through the mixture region and descends sharply to the right in the superheat region. A refrigeration cycle is shown, going anti-clockwise, with the compressor on the right raising the pressure from approximately 2 bar up to approximately 13 bar; a condenser heat exchanger then cools the refrigerant making it condense across the mixture region; a throttle then decreases the pressure at constant enthalpy and finally the evaporator heat exchanger returns the flow into the compressor after it has evaporated and become slightly superheated.

- compressor raising the pressure from 2 bar up to 13 bar with corresponding enthalpy increase of 401 to 447 kJ/kg
- condenser at 13 bar and T_{sat} of 50°C, entering with 20K of superheat, i.e. at 70°C, and leaving super-cooled by 10K at 40°C, with enthalpy 256 kJ/kg
- throttle from 13 bar to 2 bar at constant enthalpy
- evaporator at 2 bar and T_{sat} of -10°C in the mixture region, starting with dryness of 0.34, and evaporating to the saturated vapour line and beyond that superheating by 10K to 0°C, with an enthalpy of 401 kJ/kg.

Example: confirm that the dryness after the throttle in the process described above is 0.34.

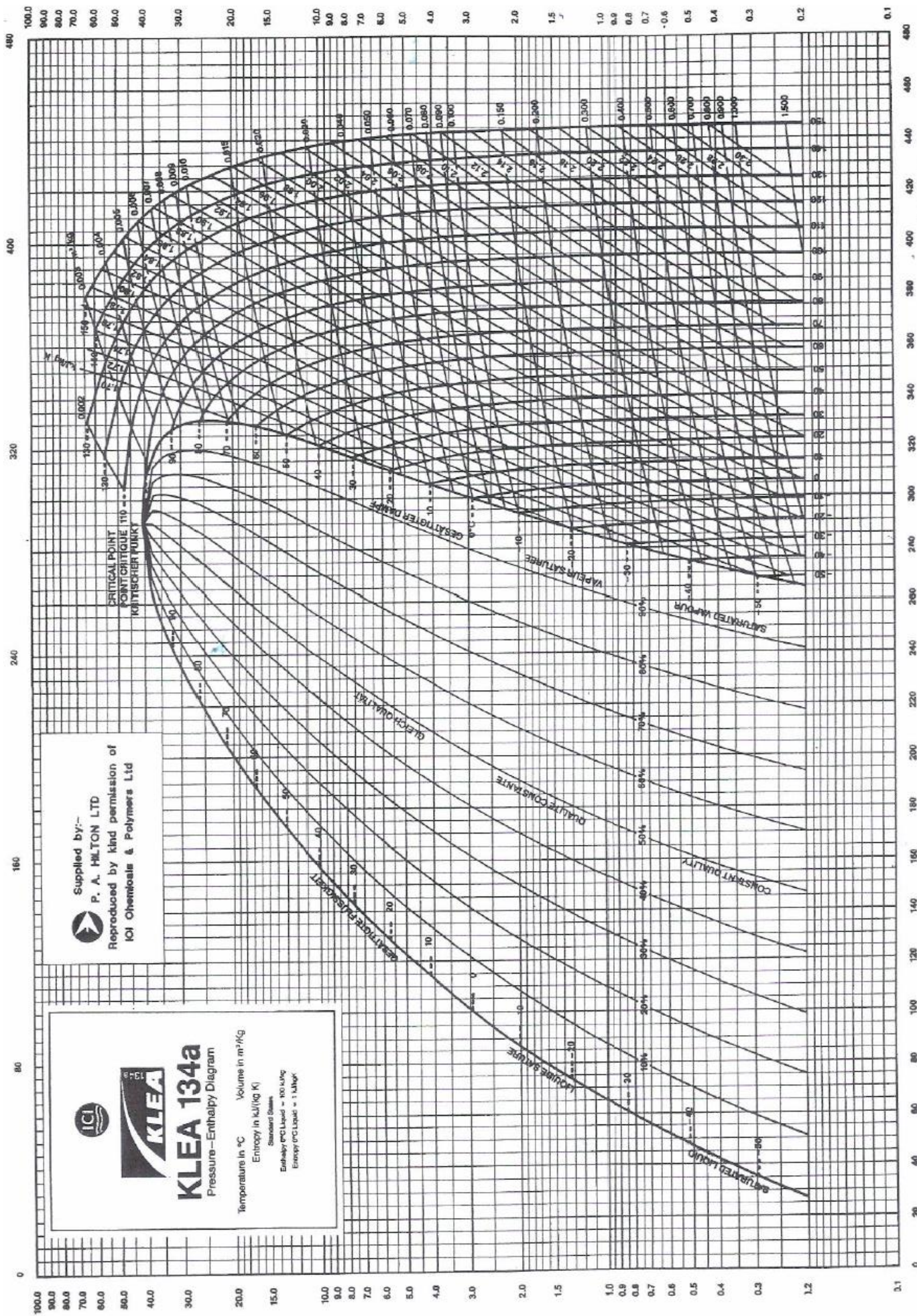
Example: the enthalpy change in the various components gives the energy transfer as W or Q depending on the component. What flow rate of R134a is required to produce 2kW of cooling at the evaporator and what is the work by the compressor in that case?

http://www.coolprop.org/fluid_properties/fluids/R134a.html#fluid-r134a



p-h diagram from Matlab's Simuscope simulation of a domestic refrigeration unit.

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5. Performance measurement – the coefficient of performance.

The performance of a heat pump is determined by the amount of useful heat transfer it does for a given amount of work from the compressor. This is often greater than 1, and so referring to it as efficiency is awkward. The measure used is called the coefficient of performance or CoP.

$$CoP_R = \frac{Q_{EVAP}}{W_C}$$

$$CoP_{HP} = \frac{Q_{COND}}{W_C}$$

$$CoP_{HP} = CoP_R + 1$$

Example: calculate the CoP_{HP} for the refrigerator cycle in the previous example.

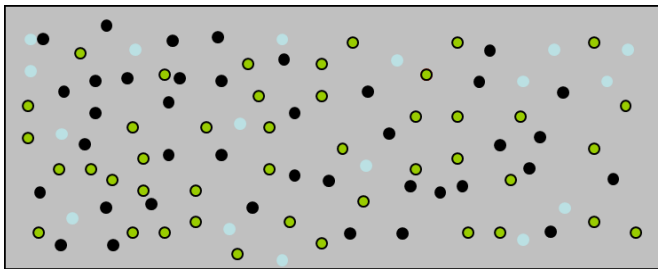


Figure 2 schematic of particles of nitrogen, oxygen and water vapour mixed in the atmosphere.

Air conditioning – motivation and basis

Schematic of nitrogen and oxygen molecules (black and green dots) are mixed with water vapour molecules (blue dots) – number of molecules is not representative

Air conditioning is needed for two main purposes. The first is called comfort air conditioning, and it is for making air in buildings suitable for people to breathe and work in. We have a limited comfort range due to requirement for steady core body temperature of 37°C. We produce heat and moisture into atmosphere as we live, breathe and work, producing thermal energy as heat loss to surroundings at approximately 80W resting, 120W office work, and up to 400W physical working. We also produce water vapour due to sweat production at varying rates depending on how much heat we need to lose in order to work comfortably (related to the principle of the 2nd Law – we must lose heat to do work) and we produce 100% humid air during respiration. Therefore it is a complex thing to create comfortable conditions for happy humans.



Figure 3 The water cycle of evaporation and then condensation, is captured by early morning dew – the condition of air is vital for life on earth.

The second is called control conditioning, and it is for maintaining appropriate conditions for machines and electronics, such as large computer processor bank rooms, which have no people in, but contain hundreds of processors producing in the order of 100s of Watts each, and having a preference for colder conditions, e.g. 16°C, with a need to maintain low humidity in the closed room so that no condensation can occur onto complex electronics.

There are two types of air – **dry air** and **atmospheric air** – and the difference between them is water vapour. Dry air is composed mainly of nitrogen, N₂ and oxygen, O₂ in approximate proportions by mass: 76.7% N₂ and 23.3% O₂; by volume, 79% N₂ and 21% O₂ as seen in the tables for approximate atmosphere. Humid or **atmospheric air** depends on the basis of partial pressure of water vapour in the air, and is limited by the saturation pressure of water vapour corresponding to the temperature of the air. Water boils at 100°C (b.p.) at a pressure of 1 atmosphere (1.01325 bar), and for lower pressures, **saturation** temperature is correspondingly lower. Water can evaporate into the air until its **partial pressure** equals its **saturation pressure**. The graph of p_{sat} vs. T_{sat} shows that the pressure rises sharply after 60°C – and that is related to how the world is such a good environment for life supported by water, being for the most part at temperatures below 50°C, where p_{sat} is low, and evaporation is limited so we have extensive pools of liquid water in the form of seas and lakes.

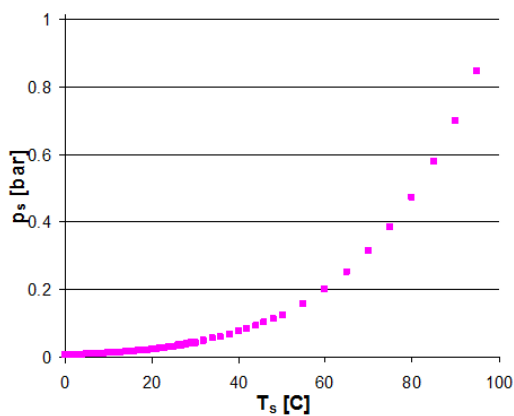


Figure 4 Saturation pressure of water vapour versus temperature

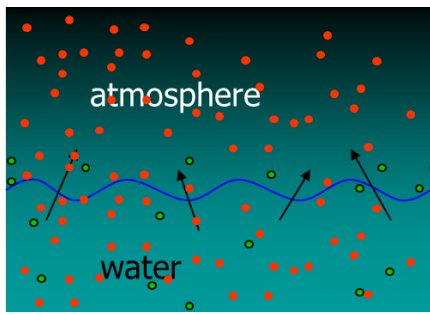


Figure 5 Water surface (blue line) allows transport of water molecules into and out of the air.

Water from a free surface can have water condensation into the liquid water, or evaporation from the water surface. When the partial pressure of the water vapour in the atmosphere is less than p_{sat} there is a net positive evaporation into the atmosphere.

This topic looks at the measures of humidity, and the energy alterations on atmospheric air to control humidity and temperature for comfort and control air conditioning.

1. Water vapour and partial pressure.

From the Gibbs-Dalton Law of partial pressure the pressure of a mixture of gases, p , is equal to the sum of pressures of individual constituents, their **partial pressure**, when each occupies a volume equal to that of the mixture at the temperature of the mixture. The figure shows how molecules of different gases mingle in the mixture. At lower temperatures, p_s is correspondingly lower. At the lower temperatures, free surface water can evaporate until the partial pressure in the atmosphere is p_s . After this point, only equal exchange of vapour between atmosphere and free liquid water surface occurs. The figure shows that water molecules can evaporate from the water surface and condense back into it.

The saturation pressure of water is reasonably flat at terrestrial temperatures, but then rises sharply at 60°C. This means that the higher the air temperature is, the greater the amount of water the atmosphere can carry as water vapour. This is the humidity of the air.

2. Psychrometry and Hygrometry

The study of atmospheric air, i.e. air and water vapour mixtures is called psychrometry or hygrometry. This is relevant to air conditioning plant, and cooling tower analysis, because the humidity affects on the one hand the amount of moisture needs to be removed from the air for comfort at a particular temperature, and on the other hand it affects how much cooling of warm water in the condenser heat exchanger of a power station can be done.

Relative humidity

Relative humidity, symbol ϕ (Greek letter *phi*), is the ratio of the partial pressure of water vapour actually in the atmosphere, p_s , and the saturation pressure of water vapour at the temperature of the atmosphere, previously indicated by p_{sat} in the tables, but for the purposes of air conditioning only this is represented as p_g .

$$\phi = \frac{p_s}{p_g}$$

Example: for 20°C air, if the value of p_s is 0.01 bar, what is the relative humidity?

Specific humidity

Specific humidity, symbol ω (Greek letter *omega*), is the ratio of masses of water vapour to dry air in a given volume, V . The previous example is exactly the point, but expressed as an equation it is:

$$\omega = \frac{m_s}{m_{dry-air}}$$

and since each of vapour and dry air occupy the same volume at their partial pressures, by the law of partial pressures, then it is useful to express this also as:

$$\omega = \frac{m_s/V}{m_{dry-air}/V} = \frac{v_{dry-air}}{v_{vap}}$$

where lower case v means specific volume.

It is useful to define specific humidity in terms of partial pressure. Water vapour can be regarded as an ideal gas when the partial pressure is below about 20 kPa (corresponding to p_s for 60°C). If both are treated as perfect gases, then:

$$p_s V = m_s R_s T \rightarrow \frac{m_s}{V} = \frac{p_s}{R_s T}$$

where R_s is the specific gas constant for water vapour and:

$$\frac{m_a}{V} = \frac{p_a}{R_a T}$$

where R_a is the specific gas constant for air and:

$$\omega = \frac{R_a p_s}{R_s p_a} = \frac{287 p_s}{461 (p_{atm} - p_s)} = \frac{0.622 p_s}{p_{atm} - p_s}$$

This is a useful formula for calculating the absolute amount of water vapour in atmospheric air. Note subscript s is for vapour here – in the tables it is *saturation* pressure – *different and not to be confused*.

Example: Calculate the maximum mass of water that can be supported in air at 20°C and 1 bar.

3. Dew point

If the temperature of the air falls until the saturation point or 100% relative humidity occurs, the air is at the DEWPOINT temp.

$$T_{dp} = T_{sat,ps} = T_g$$

it is the temperature at which air becomes saturated when cooled at constant pressure. Since the moisture will not condense out of the air until the dew point is reached, $\omega = \text{constant}$ and p_s is constant during cooling down to the dew point.

The saturation point is when:

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$$p_s = p_g = p_{\text{sat}}$$

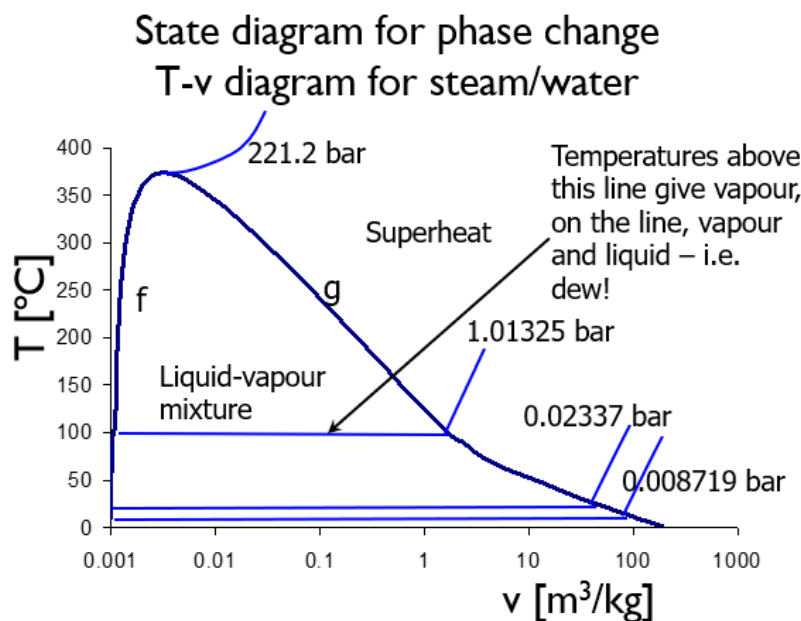
where p_s is the partial pressure of water vapour in the atmosphere, p_g is the saturation pressure of the water corresponding to the current temperature of the air, and p_{sat} is saturation pressure of water which is found from thermodynamic properties tables at the temperature of interest.

Conversely if we know p_s , partial pressure of water vapour in the air we can find the temperature at which:

$$p_s = p_{\text{sat}}$$

to give the dew point temperature corresponding to that vapour pressure.

It may be useful to see what is happening on a p-v diagram of the water behaviour:



In the figure we see that temperatures above the horizontal lines of constant pressure in the mixture region must mean that the water is superheated, and therefore in vapour phase. When the temperature is at the horizontal line, there must be some liquid present, and that is dew.

Example: For the previous example, find the dew point temperature.

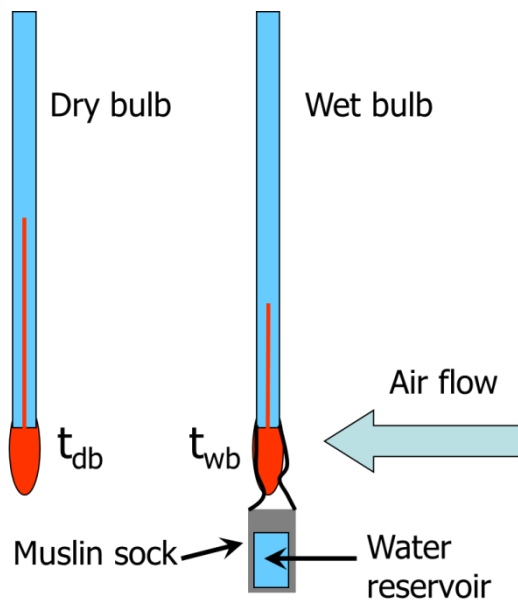


Figure 6 showing dry bulb thermometer on the left and wet bulb thermometer on the right; wet bulb thermometer has a muslin sock dipped in a water reservoir to keep the bulb wet.

4. Wet and dry bulb thermometers for hygrometry

Having equations to represent humidity is useful, but not much good without a method to measure the partial pressures or the mass of vapour in the air. This can be done by using the characteristic of water liquid evaporating faster in dryer air, and a method was devised from the known cooling effect of using porous jugs to store water – from which water would permeate the porous clay to the surface of the jug at a slow rate and then evaporate from the surface causing cooling down to the dew point. This observation was used on the **wet bulb thermometer** in order to represent how dry the air is. The dryer the air is, the greater the difference between the wet bulb thermometer temperature and the dry bulb.

The arrangement for measuring humidity is shown in the figure. If humidity is less than 100%, water will evaporate from the sock and cause the temperature of the bulb to drop and the thermometer to register a lower temperature than the dry bulb. This temperature relates to the relative humidity. There is a cloth sock around the bulb of the wet thermometer that is soaked in water from a reservoir that it draws water up from. A calculation can be done to determine the exact relationship – see Cengel and Boles book on Thermodynamics. A spreadsheet can be calculated based on this theory to determine the relative and specific humidity from the wet and dry bulb temperatures (see Moodle).

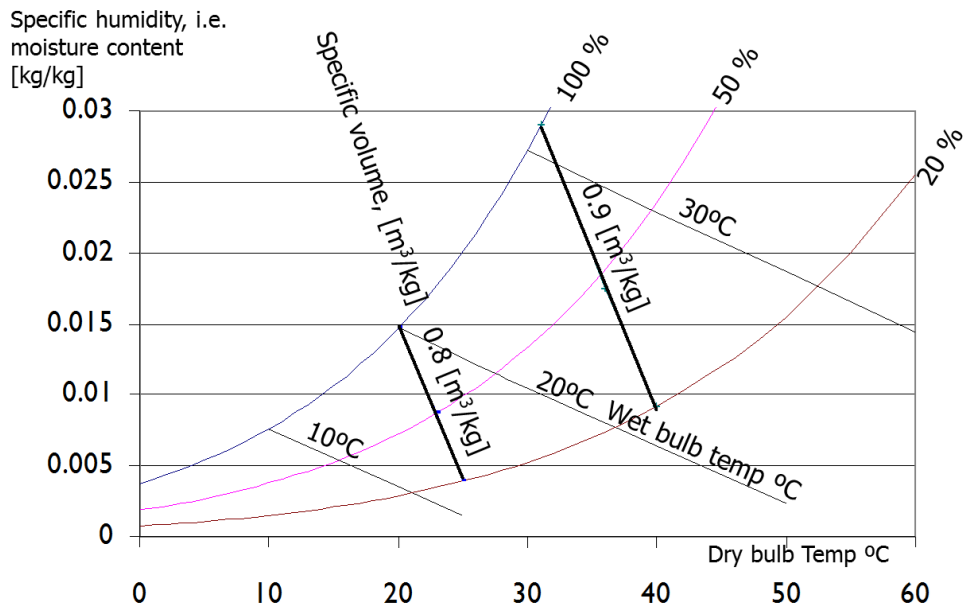


Figure 7 Excel plot of the psychrometric chart showing vertical axis of specific humidity, horizontal axis of dry bulb temperature, curves of constant relative humidity, inclined lines of wet bulb temperature 10, 20, 30 degree C, inclined lines of constant specific volume 0.8 and 0.9 meters cubed per kilogramme.

Psychrometric chart

Using the spreadsheet for the calculation of wet bulb/dry bulb relationship to humidity, a detailed chart can be plotted, the arrangement for which is plotted in the figure, and a separate copy on A4 is provided.

The figure is an accurately drawn schematic of the psychrometric chart showing the various measurements that can be made from knowing any two properties on the chart. Usually wet and dry bulb temperature are known. The full chart (A4 copy of the CIBSE psychrometric chart is shown on the following page with notes) shows the condition of the air for a given pair of wet and dry bulb temperatures with a fuller set of information including enthalpy of the mixture.

Example: what is the rh if the db is 30C and the wb is 20C?

What is the specific humidity if it is 100% humid at 30C?

What does this tell you about the relative masses of air and water at 30C?

What is the enthalpy for a 50% rh at 20C db?