

5. Steam wetness

If the pressure is further dropped to 0.1MPa (1 bar), at the same entropy value, then the steam enters the saturated state, and there will be a mixture of dry steam and microscopic droplets, which is referred to as **wetness**. The key to finding how much liquid there is in the system, is the value of specific entropy. The steam started at a much higher pressure and temperature, but when those both reduce using a perfectly insulated and friction free process, no further transformation to chaotic energy is occurs in the steam, and so the entropy is constant.

To further explain this complicated idea, this is a well controlled **expansion**, i.e. to reducing pressure implies increasing volume, and expansion is standard thermodynamic language for lowering pressure processes. The prevention of heat transfer (by insulation) and prevention of friction (reducing drag against mechanical devices in the flow and reducing fluid turbulence generation to such a level they are negligible) in the limit of perfection causes entropy to be the same at the end of the process as at the beginning. Of course practically perfection is impossible, but it is a limiting condition and we can approach it; therefore it is of significant interest and a good benchmark for power processes. In this case the starting point entropy at the high pressure and temperature was $7.359 \text{ kJkg}^{-1}\text{K}^{-1}$.

At this condition of the same entropy, but much lower pressure, how do we know the steam is wet?

Look at the entropy value for saturated vapour at 1 bar: it is $7.359 \text{ kJkg}^{-1}\text{K}^{-1}$, which is higher than the value we are looking for ($7.159 \text{ kJkg}^{-1}\text{K}^{-1}$);

look at the value for entropy at saturated liquid condition at 1 bar, it is $1.303 \text{ kJkg}^{-1}\text{K}^{-1}$, which is lower than the value we are looking for.

Therefore the steam at this state is somewhere between saturated liquid (water) and saturated vapour (dry steam), which has some vapour and some liquid dispersed as droplets so that the mean value of the sample is the value between. And that requires a particular proportion of droplets, called the wetness.

Droplets of course are familiar as rain, but also consider the boiling of a pan of water – the mist that forms above the boiling water (seen below) consists of very many microscopic droplets, and in the picture we see the wet steam, but what you don't see is the dry steam which still hasn't condensed after being boiled out of the pan of water.

The entropy of the droplets in the mixture is s_f and the entropy of the dry steam in the mixture is s_g . But the entropy of the mixture on average is the mass weighted average of both of them.



Figure 1 showing simmering water in a pan, with large bubbles on the base, and convection currents in the water.

When the system has only steam and no air in it, then there is a mixture of only steam vapour and water droplets like this.

It is important to be able to determine how wet the steam is, and this is done by referring to its dryness, i.e. the proportion (by decimal value) of steam which is dry. This is given the symbol 'x' by standard practice. In the example here, the wetness can be worked out by putting x into an equation for entropy.

We know the actual entropy ($7.159 \text{ kJkg}^{-1}\text{K}^{-1}$); we know the liquid entropy, s_f ; we know the vapour entropy, s_g , as found above. The actual specific entropy (i.e. entropy per kg of the steam) is the combination of the of dry $x \text{ kg}_{\text{vapour}}\text{kg}^{-1}_{\text{liquid_and_vapour}}$ of the entropy of saturated vapour $\text{kJ}\times\text{kg}^{-1}\text{K}^{-1}$, and the wet, or liquid, $(1-x) \text{ kg}_{\text{liquid}}\text{kg}^{-1}_{\text{liquid_and_vapour}}$ of the entropy of saturated liquid $\text{kJ}\times\text{kg}^{-1}\text{K}^{-1}$; i.e.

here, the wetness can be worked out by putting x into an equation for entropy.

$$ms = m_{\text{vapour}}s_g + m_{\text{liquid}}s_f \text{ and } m = m_{\text{vapour}} + m_{\text{liquid}}$$

$$ms = m_{\text{vapour}}s_g + (1 - m_{\text{vapour}})s_f$$

$$\text{divide by } m \text{ for per kg, specific entropy: } s = xs_g + (1 - x)s_f = s_f + xs_{fg}$$

From which you get x, the dryness fraction or amount of vapour by mass out of the total sample of liquid and vapour.

6. Graphical representation of properties

Graphs representing the state of water and steam are useful for assisting thinking about work-cycles involving steam as a source of power generation. It is natural to consider the pressure of the steam, since pressure acting on an area produces a force, and where there is significant pressure differential over a machine, then it will produce more force. In the course of this module the main graphs to be considered are those relating:

temperature and entropy of steam:

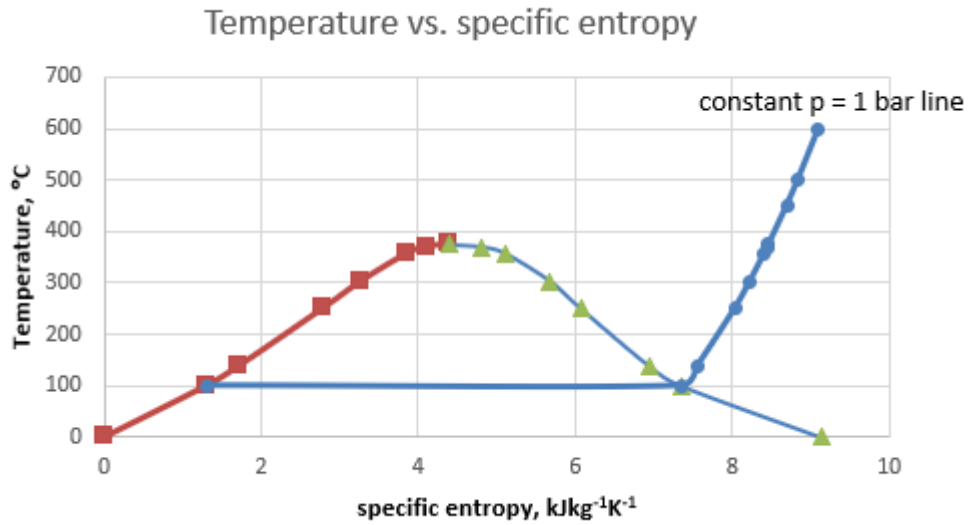


Figure 2 showing plot of temperature versus specific entropy for water and steam; it shows the vapour dome across the mixture region, and a plot of constant pressure equals 1 bar is drawn, which is horizontal across the mixture region and rises on the right in the superheat region.

The plot has also the constant pressure line of 1 bar on it - we can plot as many pressure lines as we like depending on the operating condition - usually there are 3 or 4 pressure lines in a cycle.

enthalpy and entropy of steam:

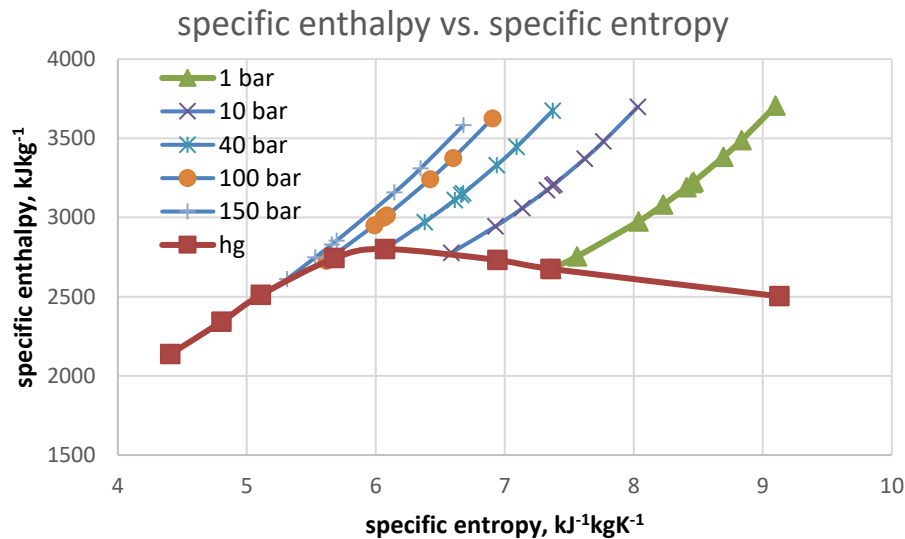


Figure 3 plot of specific enthalpy versus specific entropy for steam; showing the mixture region underneath the left to right curve, and superheat lines of constant pressure above for 1, 10, 40, 100 and 150 bar.

The lines of constant pressure are shown here, but lines of constant temperature are also put on this chart which cross the pressure lines in the direction of the saturated steam line 'hg'. This chart is useful for steam power calculations.

pressure and enthalpy of refrigerant R134a:

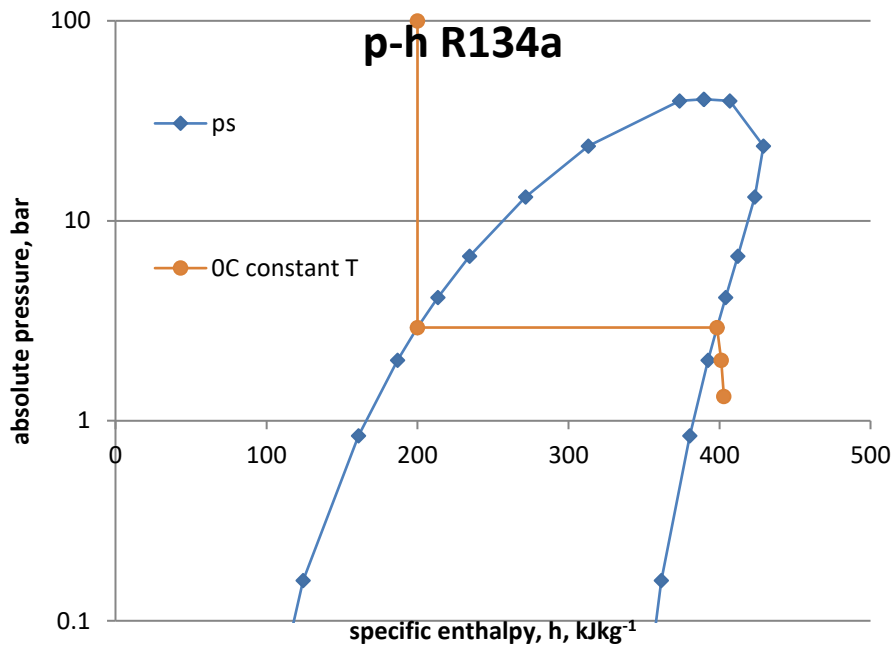


Figure 4 showing plot of absolute pressure versus specific enthalpy for refrigerant R134a; the vapour dome contains the mixture region of vapour and liquid combined underneath it. A line of constant temperature is plotted, which descends vertically in the liquid region (on the left) is horizontal across the mixture region, and then descends sharply to the right in the superheat region.

The chart has a plot of constant temperature zero degrees centigrade - we can plot more, and there are more on the plots available. This chart is useful for working out heat transfer in refrigeration cycles. These will be presented as they are met, but are dependent on the derived data as seen from the data sources. We'll meet these more as we go along, but for now, just be aware that these are

7. Transport property

The molecular characteristics of the fluid also affect how it moves, since a fluid in motion has to do so in relation to the surrounding fluid and bounding walls. Three fundamental transport properties are density [$\text{kg}\cdot\text{m}^{-3}$], viscosity [dynamic, $\text{kg}\cdot\text{m}^{-1}\cdot\text{s}^{-1}$ or kinematic, $\text{m}^2\cdot\text{s}^{-1}$] and thermal conductivity [$\text{W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$] and it is worth considering how they change with temperature and pressure.

Density

Density for steam and non-perfect gases can be found as specific volume. Some gases are very dense - see the YouTube video link with carbon-hexafluoride - surprisingly dense.

<https://www.youtube.com/watch?v=DzLX96VWTKc&feature=youtu.be>

Viscosity

Viscosity, which in all fluids varies significantly with temperature. For example, modern multigrade car oil is described by its viscosity at different temperatures (multi-viscosity values dependent on temperature), i.e. 5W30 means specific viscosity at a low (the 'winter' grade 5W) and high (the viscosity at 100°C) temperature). The actual viscosity does not bare a relation to the number indicated by the grade. This can be seen at the website of Kew Engineering:

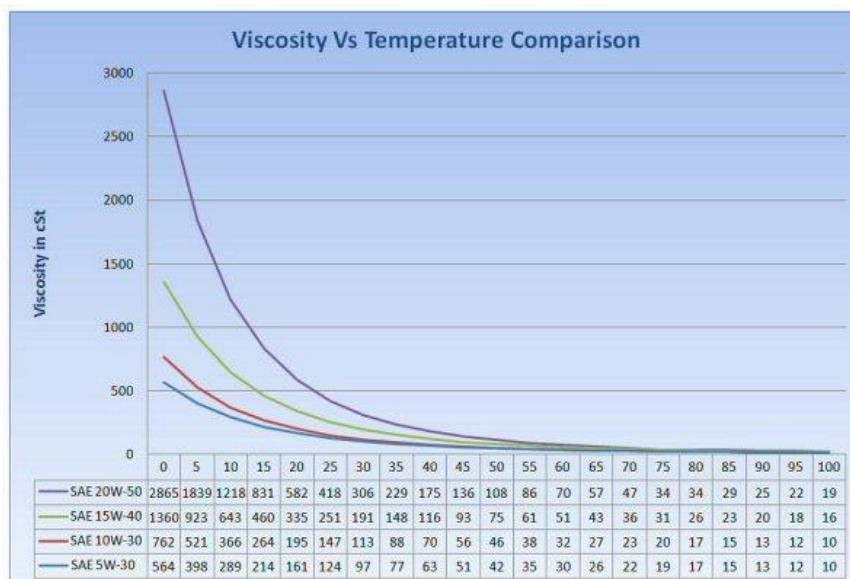


Figure 5 Viscosity changing with temperature for various grades of multigrade motor oil from http://www.kewengineering.co.uk/Auto_oils/oil_viscosity_explained.htm

The effect of temperature on the viscosity of oil is illustrated nicely in the YouTube video:

<https://www.youtube.com/watch?v=V5a4kP-5Jiw>

The units of viscosity here are cSt, which is centi-Stokes. $1 \text{ St} = 10^{-4} \text{ m}^2\cdot\text{s}^{-1}$ and therefore 1 cSt is $1/100^{\text{th}}$ of this, i.e. $10^{-6} \text{ m}^2\cdot\text{s}^{-1}$. The units are those of **kinematic viscosity**, ν , i.e. viscosity independent of density.

Commonly viscosity is expressed as **dynamic viscosity**, μ , i.e. viscosity with the density included:

$$\mu = \rho \nu \text{ [kg}\cdot\text{m}^{-1}\text{s}^{-1}\text{]}$$

The viscosity of water is in the order of $10^{-3} \text{ kg}\cdot\text{m}^{-1}\text{s}^{-1}$, and air is in the order of $10^{-5} \text{ kg}\cdot\text{m}^{-1}\text{s}^{-1}$. Viscosity and transport properties are interesting from the point of view of heat transfer as distinct from thermodynamics. Heat transfer is a process which is important to thermodynamics, but it can be treated as a separate subject at this stage.

Thermal Conductivity

Conductivity of a fluid determines how well it dissipates high temperature regions to cooler surrounding areas.

Thermal conductivity, $k \text{ [W}\cdot\text{m}^{-1}\text{K}^{-1}\text{]}$ is given for water (subscript f) and steam (subscript g) on p.10 and values are stated in the order of $10^{-6} \text{ kW}\cdot\text{m}^{-1}\text{K}^{-1}$ (i.e. multiply by 1000 to get $\text{W}\cdot\text{m}^{-1}\text{K}^{-1}$) in order to show that water vapour has a conductivity 3 orders of magnitude less than liquid. On p.16 conductivity of dry air is given, this time in the order of $10^{-5} \text{ kW}\cdot\text{m}^{-1}\text{K}^{-1}$ (i.e. multiply by 1000 for $\text{W}\cdot\text{m}^{-1}\text{K}^{-1}$), and the magnitude is about twice that of water vapour. On p.23 conductivity of various liquids is given including some liquid metals, and finally on p.24 the conductivity of the atmosphere at various heights is given.

What is the conductivity of water liquid and vapour at 75 °C in $\text{W}\cdot\text{m}^{-1}\text{K}^{-1}$?

What is the conductivity of dry air at 350K in $\text{W}\cdot\text{m}^{-1}\text{K}^{-1}$?

What is the conductivity of hydrogen at 400K in $\text{W}\cdot\text{m}^{-1}\text{K}^{-1}$?

What is the conductivity of atmospheric air at a height of 10000m in W/mK ?

The effect of combining thermal conductivity and viscosity are seen in the dimensionless Prandtl number, which characterises the relationship between momentum and thermal conduction for transporting thermal energy from one place to another:

<https://www.youtube.com/watch?v=NKflnQjJ8ys&feature=youtu.be>

and the effect of conduction in a beam as the beam warms up in time is simulated in the video below, where the graph at the start shows how an initial temperature gradient along the length settles down in time, the rate of which is due to thermal conductivity and specific heat capacity.

<https://www.youtube.com/watch?v=UBcZsWJ5TNA&feature=youtu.be>

MM2TF2 THERMOFLUIDS

Topic 2. Refrigeration and air conditioning

Aim of this section

Keeping cool is desirable in many situations of interest to the human race and essential in others. Refrigeration has history stretching back to ancient China and other ancient civilizations. Early attempts involved simply fetching ice from snow peaked mountains, keeping it as insulated as possible during transit, until it could be placed in an underground storage room to keep food cold. Food stuff, potable liquids require refrigeration to enhance flavour and to preserve against bacteria action to prolong the 'use-by' date. Beer is served at 8°C; lager at 5°C; ice cream and other frozen foods are kept at -20°C until used. In addition to our desire to prolong food usefulness and enhance its flavour, refrigeration is used to keep vaccines sufficiently cool to preserve their life and to preserve corpses before funeral services can be conducted. Refrigeration is used in industrial processes also. Refrigeration also enables control of the local atmosphere in confined spaces, and this can be useful for humans in hot environments and for computers, which require their diodes to be cooled just as humans need their cells to be maintained at 37°C. In tropical countries it is soon obvious on arrival that air conditioning is as needed there as central heating in colder climates. Therefore the engineer needs to understand and apply refrigeration techniques in a large variety of situations and the use of refrigerant fluids to produce the refrigerant effect and of the properties of air to determine the amount of cooling required to control the atmosphere are essential for this.

Aim: learn to calculate and describe the processes of refrigeration and air conditioning.

Objectives: describe the refrigeration circuit as a reversed Carnot cycle and as a heat pump; understand the importance of selecting an appropriate refrigerant; find the properties of the refrigerant R134a from the tables and use them to make refrigerant effect calculations; interpret the data from a p-h diagram for a particular refrigerant; calculate coefficient of performance; describe the meaning of air conditioning in terms of controlling temperature and humidity; describe and calculate relative and absolute humidity in terms of saturation pressure of water vapour; describe the meaning of hygrometry/psychrometry and of the psychrometric chart; calculate dew point; describe the purpose and action of wet bulb and dry bulb thermometers; calculate the refrigeration load required to cool a continuous mass flux of atmospheric air for humidity control.



Figure 6 showing photo of footprints in the snow.

Relying on cold produced by weather conditions is unreliable – snow falls in some places at certain times. Therefore to produce reliable cold spaces, thermodynamic methods make a source of cold available to everyone – converting work into cold.

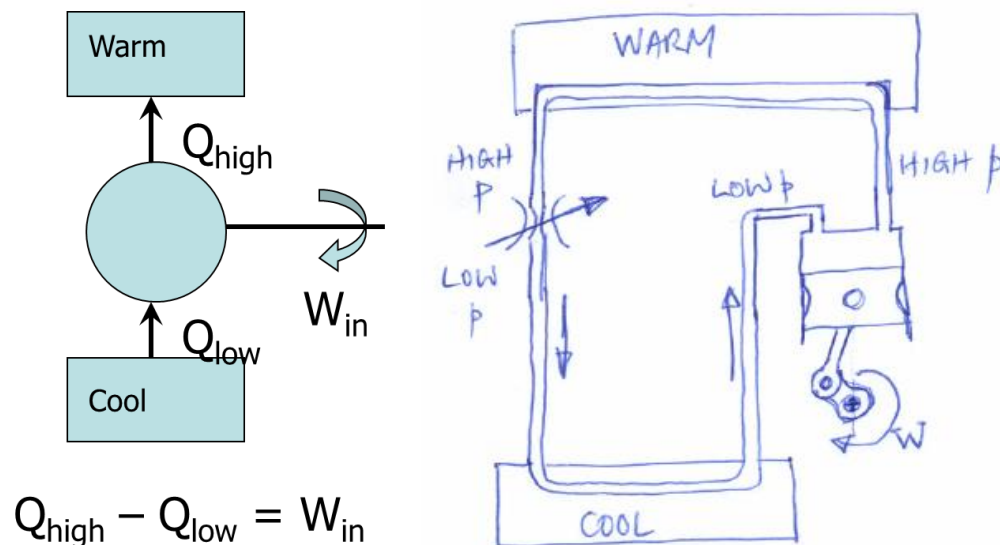


Figure 7 showing on the left a schematic of a heat engine running in reverse, using work input to drive heat from cold to hot and on the right a hand drawn schematic of a refrigeration cycle demonstrating how the heat engine can be run in reverse – compressor drives the cool vapour up to a hot and high temperature above that of the warm reservoir, where heat is rejected as the vapour cools and condenses; after the condenser heat exchanger a throttle reduces the pressure so the saturation temperature drops to that of the refrigerant in the tubes inside the heat exchanger which is colder than the cool reservoir that it extracts heat from.

1. Refrigeration effect

The Carnot cycle was derived to produce power – as demonstrated in the vapour power section. If the cycle is reversed, and power is delivered to the cycle, then the effect is to transfer heat in the reverse direction – from cold to hot (as illustrated in the schematic diagram of a reversed heat engine)!

In practice this is done using a positive displacement compressor (which raises the pressure of a superheated vapour and drives it against the pressure gradient) as shown in the sketch. The vapour arrives at a WARM reservoir, at a greater temperature than that reservoir and can therefore exchange heat with it. As it loses thermal energy the vapour converts to a liquid with the production of heat transfer at a constant temperature – the saturation temperature of the refrigerant fluid at that pressure – this is **condensation** and the section of pipe in which it happens is called the **condenser heat exchanger**. From this point, the subcooled liquid at the high pressure can be expanded (i.e. its pressure is reduced so that it can get bigger), and this is done by allowing it to pass through a constriction, or **throttle**. Its pressure immediately is reduced and the saturation temperature correspondingly reduces. This results in some instantaneous boiling in the fluid as it converts some of its thermal energy level above the saturation level to latent heat of boiling. At this point a level of equilibrium is established until the two phase flow, mostly liquid with a small amount of vapour, arrives at the COOL reservoir. The temperature of the reservoir is greater than the

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saturation temperature of the fluid at this low pressure. Therefore heat transfer can once again occur as the liquid content of the refrigerant boils off to vapour. This is **evaporation** and the section of pipe in which it happens is called the **evaporator heat exchanger**. By the end of the heating process in this cold heat exchanger, the refrigerant is still at a lower temperature than the reservoir, but is at a superheated state.

It is important to remember that this all depends on saturation pressure and temperature of the refrigerant contained in the tubes of the machine in this cycle. And temperature is a relative scale – a low temperature does not appear cold necessarily to the refrigerant depending on its saturation temperature at the pressure it is held at.

This device is called a **heat pump**, because it uses work to extract heat from a cold source and deliver it to a hot sink.

2. The nature of the cycle

The compressor.

The whole cycle is driven by a small amount of work – the work is much smaller than the heat transferred by a factor of between 2 and 5 usually because of the Second Law and for reasons which will become clear. Superheated refrigerant vapour leaving the evaporator is drawn into the compressor, which is a reciprocating device – like the air compressor in previous notes – which compresses the vapour from superheated cold, low pressure vapour to superheated hot high pressure vapour.

The condenser.

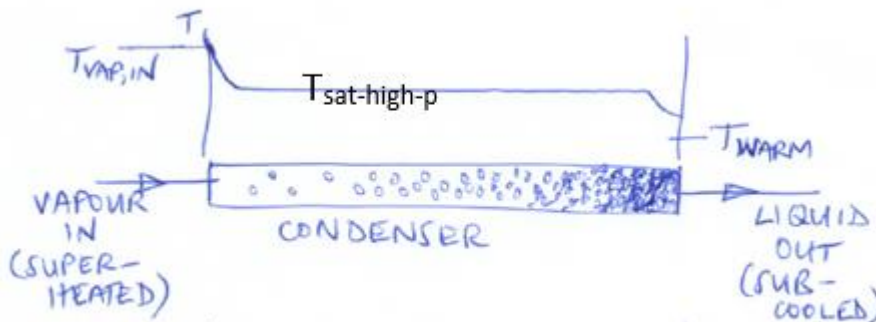


Figure 8 showing a schematic of a condenser heat exchanger tube, with refrigerant going from left as vapour, losing heat to the surroundings and cooling to saturation temperature, condensing to liquid and then subcooling.

Vapour enters condenser at temperature above ' T_{warm} ' and exchanges heat, Q_{out} out of condenser to cool the vapour. The vapour condenses when it reaches T_{sat} until all is condensed. T_{sat} needs to be a few degrees above the T of the hot reservoir, T_{warm} , to work properly.

The throttle.

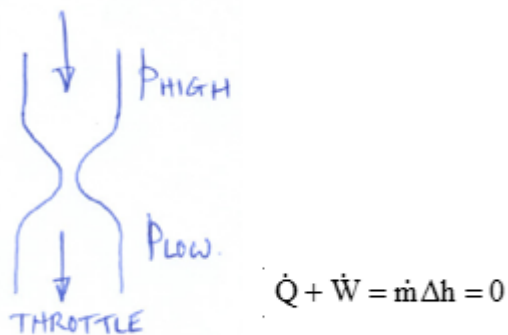


Figure 9 of schematic of a throttle flow restrictor, which reduces pressure; with a refrigerant the pressure drop is sufficiently high to make the fluid boil at the lower pressure. Enthalpy is constant by the First Law since there is no heat or work on this system.

The condensed and slightly sub cooled liquid passes through the throttle. This reduces the pressure of the fluid and therefore the T_{sat} reduces to a point below the cool reservoir (which contains the evaporator) temperature T_{cool} . We know that the throttle is short and should be well insulated (it often is NOT at all well insulated!!), and so Q is zero. There is obviously no work – no paddles, pistons, hands etc. Use the SFEE, where Q and W are rates of heating and power input and m is the mass flow rate. It is easy to see that if Q and W are zero, then the enthalpy entering is the same as that leaving. Physically this is a LOT harder to understand because of the complex fluid dynamics going on. Further, because the temperature of the ingoing liquid was higher than the new saturated vapour pressure, the liquid must cool itself down. There is no Q from the outside, so the cooling comes from the liquid – it boils until the temperature is the new saturation temperature at the lower pressure. The refrigerant is now in the mixture region and has a low dryness fraction.

Example: R134a liquid having enthalpy $h=100$ kJ/kg pressure drops from 7 bara, 27°C to 1.3bara (as on chart p.49 throttle process), -20°C. What is dryness fraction, x ?

The evaporator.

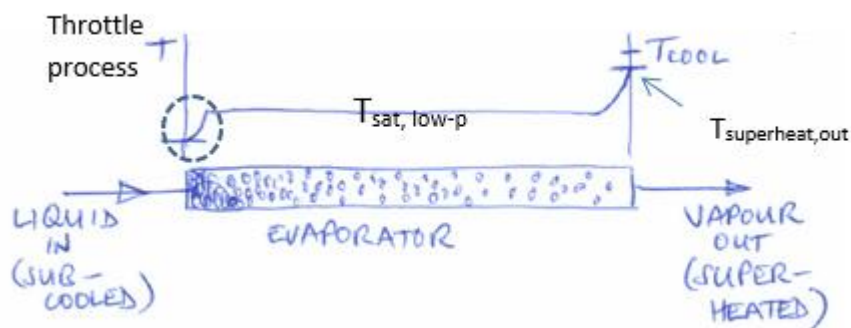


Figure 10 showing schematic of the evaporator heat exchanger, with liquid entering at the left and boiling as it receives heat transfer from the surroundings until it is a superheated vapour.

As it enters the evaporator, liquid is at T_{sat} and with the temperature of the surrounding being higher than T_{sat} the liquid boils at constant temperature until the saturated vapour state. By the time it reaches the end of the evaporator, all is evaporated and the vapour gains a little superheat.

3. Refrigerant fluids

Any thermodynamic fluid can potentially be used as a refrigerant fluid; but there is a caveat. Refrigerants are appropriate only over limited ranges of temperature and pressure. So water might be used as a refrigerant, but it would be at temperatures in the order of hundreds of degrees centigrade. Carbon dioxide, CO_2 is used as a refrigerant; butane has been used as a refrigerant but obviously has disadvantage of being potentially explosive – the effect is well known to those who camp with a butane camping stove, when the fuel canister becomes cold as the cooking proceeds.

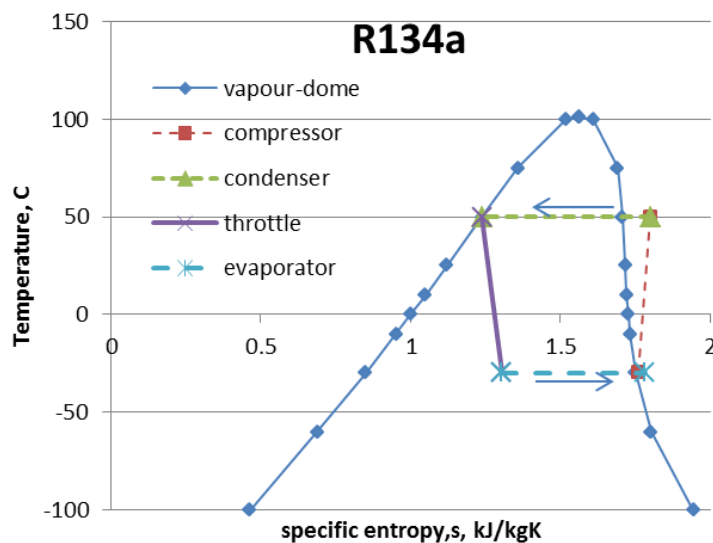


Figure 11 showing Excel chart of temperature versus specific entropy of refrigerant 134a

Refrigerants in practical refrigerators are selected from fluids which have low saturation temperatures over a reasonable pressure range. The pressure range is usually in the range 0 to 20 bar, and the boiling temperature can vary usually between $-30^{\circ}C$ and $10^{\circ}C$, and the condensing temperature can vary between $50^{\circ}C$ and $100^{\circ}C$.

The tables of thermodynamic data contain three potential refrigerants – ammonia (R717), dichloro-difluoro-methane, CF_2Cl_2 (R12) and tetra-fluoro-ethane, CH_2F-CF_3 (R134a). R22 is now not permitted as a refrigerant in new installations as of January 2015 because of its destructive effect on the atmosphere. Ammonia is not commonly used. R134a is a common refrigerant.

The figure shows the T-s diagram for R134a with a refrigerant cycle plotted onto it. Notice how similar the cycle is to the Carnot cycle for vapour power, but that the arrows show it cycles in the opposite direction. Where there was a turbine in vapour power, there is no a compressor for raising the pressure of the superheated vapour on the right hand side; on the left, a throttle, which has a constant enthalpy value shows a slight increase in entropy – the irreversibility.

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Example: Refrigerant leaves the condenser heat exchanger as a saturated liquid at 50°C . Find the enthalpy of the refrigerant at this point. It expands through an expansion valve (or throttle) to a lower pressure where the saturation temperature is -30°C , and receives heat transfer in an evaporator heat exchanger until it is superheated by 10K above its saturation temperature at the same pressure. What is the enthalpy at this point? What is the heat exchange rate in the evaporator if the mass flow rate of refrigerant is 5 g/s ?