Mutigas: Basic thermodynamics (4 hrs)

Syllabus: Carnot cycle / engine cycle, Heat pump, Refrigeration basics
Components :
compressor, reciprocating piston type, swash plate type, vane type
metering device: expansion valve /condenser /evaporator
oil separator/ phase separator.
Accumulator down stream of evaporator.
Liquid receiver down stream of condenser for variable load metering devices

Thermodynamics is the study of Heat and Work.
The word thermo means heat and dynamics is the change so in reality we can think that thermodynamics is meaning just the changes in heat. But in reality, the study of just heat is typically called heat transfer, such as happens in a heat exchanger or as happens when sun warms up a building. In thermodynamics we study (and understand) the interaction between heat and work.

The need to understand heat and work (thermodynamics) is due to the need that came about in the industrial revolution that people wanted machines to run independently from wind, water or mule and started using fuels to power machinery. Hence the 'engines' that started being developed were using heat (from burning of fuel) that in turn were capable of generating some mechanical power (typically shaft rotation) which can be used to run machinery example mills lathes etc.

Different engines were capable of generating different amounts of work from the same quantity of fuel, that is efficiency. So let us introduce the term efficiency η in the way we need to use it in thermodynamics.

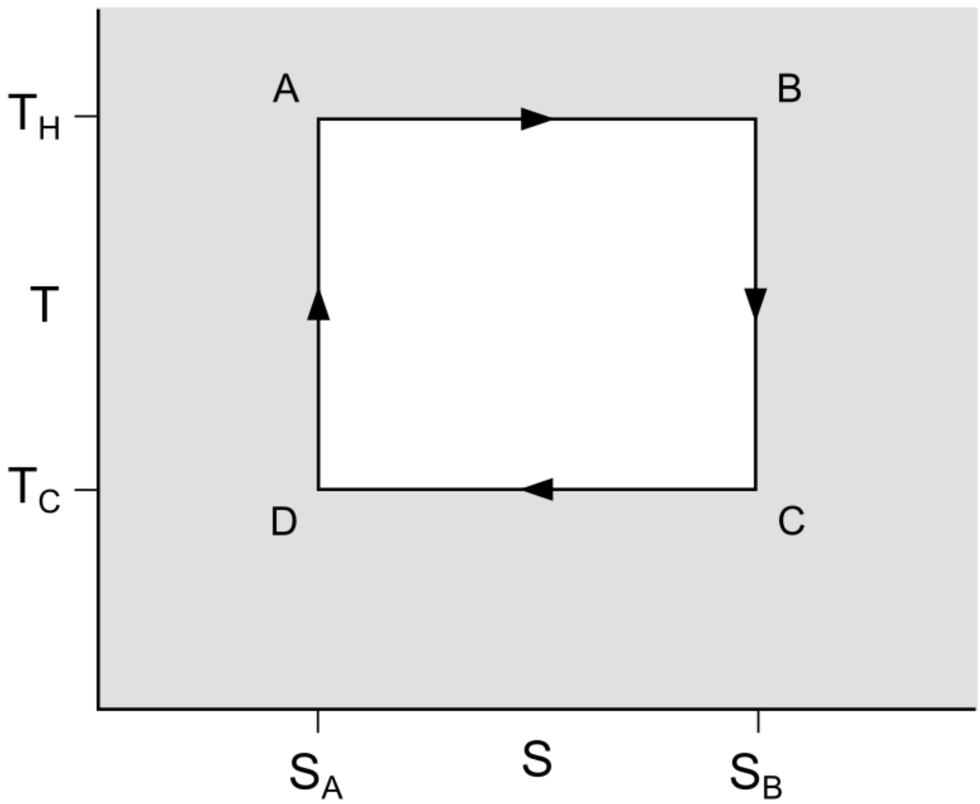
$$\eta = \frac{Net\ Work\ Out}{Gross\ Heat\ Input}$$

Net Work Out means, how much work output the engine generates minus what it uses itself, that is for example in an internal combustion engine (petrol or diesel) the net work out is what is available at the flywheel, while the gross is what is available on the top of the piston. It needs to be appreciated that what is available at the top of the piston, referred to as the gross, needs to counteract friction (and other losses such as pumping losses) so the net is smaller than gross.
Gross Heat Input means, how much heat energy is being supplied to the engine, typically by burning fuel. Gross Heat Input is different from Net Heat Input, because all heat engines have to reject heat. Example in an Internal combustion engine, heat is rejected in two main paths, the coolant and the exhaust.

So let us now define the Heat Engine.
The Heat Engine is the system by which heat energy is changed into work.
There are a number of different types of Heat Engines, example, petrol engine (more academically referred to as Otto cycle of Spark Ignition cycle), Diesel Engines, Gas Turbines also called Brayton cycle), Steam Cycles (also called Rankine cycle) and a few less important ones like Sterling Cycle and Ericsson Cycle. These are real and practical cycles but there is a fundamental cycle which is used to lay a foundation to understand the thermodynamics of Heat Engines and also acts as the best, most efficient cycle. This is called the Carnot Cycle.

The Carnot Cycle is given the name after the French scientist Carnot who after the Napoleonic wars wanted that France understand better the generation of mechanical energy.
The Carnot Cycle is made up of four simple and reversible processes.

The Carnot cycle can be drawn on a Ts (Temperature versus entropy s) diagram as a rectangle. These are isentropic compression DA, isothermal heat Input AB, isentropic expansion BC and isothermal heat rejection CD.



Entropy is a measure of irreversibility, but is a parameter, actually in thermodynamics we group it as property together with the more popular properties such as Pressure Temperature and Volume.   An isentropic process is one of constant entropy and is therefore a vertical line on a TS diagram. An isothermal line is process at constant temperature, so it is a horizontal line on a Ts diagram.

The niceness of entropy, s , is that the area under the Ts diagram is heat. Just like the area under the pv diagram is work. So, as in thermodynamics we are trying to understand and calculate how much heat goes to work, these two diagrams are very useful, the pv diagram and the Ts diagram. So in my opinion it is worth accepting and getting used to s even just to be able to draw Ts diagrams because they give a pictorial representation of quantity of heat.

The reason why the Carnot cycle is introduced is because it is the most efficient cycle. However, unfortunately, it is not practical to build and use. The reason being that isentropic compression and expansion are idealistic because they require adiabatic conditions (meaning no heat flow) but it is very difficult to make a compression or expansion completely adiabatic meaning perfect insulation from surroundings. Furthermore the isothermal heat input and isothermal heat rejection are very difficult to implement on a gas. Typically say if we heat a gas we expect it to warm up, but in an isothermal heat input we have to have the gas expand (while it is being supplied with heat) at an appropriate rate to that the cooling due to expansion counteracts the warming up due to heat supply and should result in a constant temperature. So now it should become a bit more understandable why the Carnot cycle is only an idealistic (not practical Cycle). Nonetheless, the importance of the Carnot cycle is that it introduced the concept that heat has to be rejected.

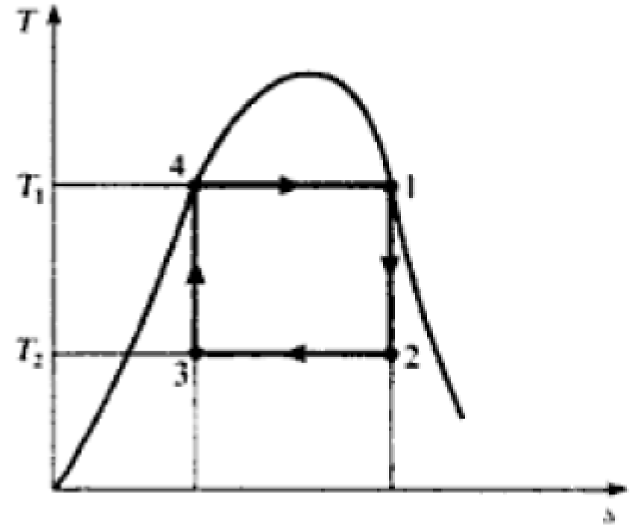
Heat Rejection: it is important to appreciate that the term is heat rejection not for example heat loss. Heat Loss would imply losing something without wanting to, say losing one's wallet. Heat rejection implies intentional heat being thrown away, eg rejecting one's wallet or rejection of inheritance for example.

So the Carnot Cycle introduces the fact that in Heat Engine we put in heat but also need to reject heat. This is a very important and fundamental concept that needs to be accepted. Of course the lower the quantity of heat rejection the better but we have to reject something. Analogy….

If we use the concept that heat under a Ts diagram is heat, then we come to the fact that Heat Rejection in the Carnot cycle can be quantified by the area under the lower horizontal line. This brings us to the conclusion that the lower the heat rejection temperature, the lower the heat rejection, thus the more efficient the engine. On the other hand the Heat input is the area under the upper horizontal line. Thus this means that for a certain amount of energy it is better to have it at the highest temperature possible for the better efficiency. Analogy with water, it is better to have water on top of a high mountain rather than on top of a small hill if one wants to generate hydroelectricity.
This leads us to the concept that heat does not only have quantity but also quality. Just like water say.

While the Carnot is difficult to implement on a gas, say air, it is more manageable to implement on a liquid/vapour because many liquids, example water boils (meaning heat input) at constant temperature if maintained at constant pressure. Example water boils at 100 Celsius in a kettle while heat is being continuously put in. Water also condenses at constant temperature if at constant pressure.

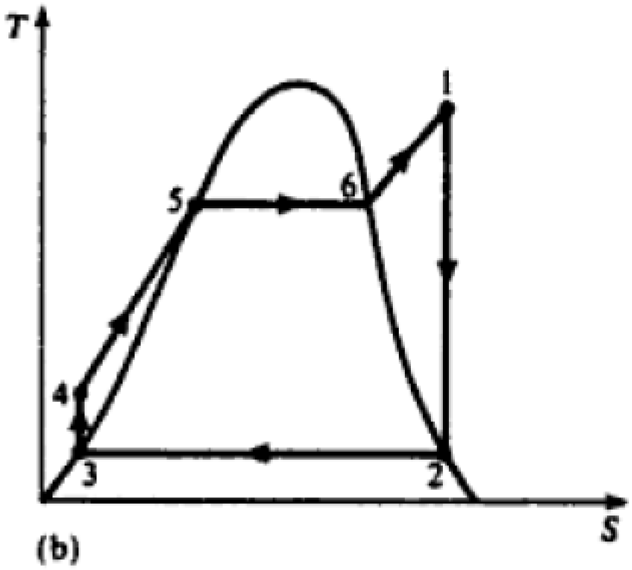
So we can introduce the Rankine or steam cycle which can be thought of as the implementation of the Carnot Cycle on water as the working fluid. That is a rectangular cycle as before drawn within the so called vapour dome.



The horizontal lines are doable because of the boiling at constant temperature is easy for liquids and also condensation at constant temperature. The main issue with the Carnot used for a liquid/vapour fluid is that lower horizontal line is problematic because the line does not reach the vapour dome neither on the left nor on the right. Hence The Carnot cycle for steam is modified by allowing the fluid to condense completely on the left hand side of the lower horizontal line. This means that the working fluid is fully condensed and become liquid. This implies that the pressurisation can be done by a liquid pump and hence consumes much less mechanical power than if a compressor had to be used if the fluid was a mix of liquid and vapour. Also in reality compressing a mix of liquid and vapiur is very problematic from a mechanical perspective. It should be noted that compression of liquid consumes mhux less power than pressurisation of gas. Note that is is used for example to fill the nitogen gas bottles, pressurisation is done on the liquid rather than on the gas.

The second modification is on the right hand side of the lower line which is also allowed to extend till the vapour dome. Consequently the vertical line becomes outside the dome. This means that the expansion is on a completely dry vapour, while in the Cranot it would have been on a wet vapour. Expansion of a wet vapour is problematic because it can neither be done in an expander intended for liquid neither an expander intended for vapour. The vertical line outside the dome then requires that the tip of the vertical line as shown in the below figure, point 1, is in the superheat region. Superheat means the vapour is at a higher temperature tha the saturation condition.

,



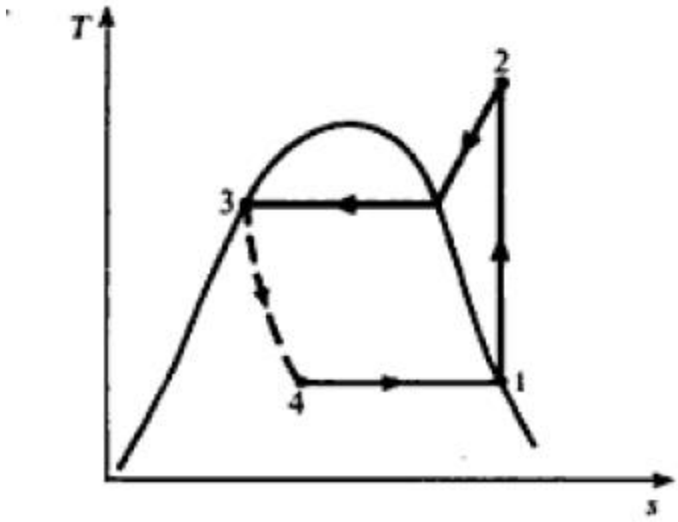
To conclude the main point of the steam cycle or Rankine cycle. It has a big advantage that pressurisation is on a liquid and hence very little mechanical work is required for pressurisation. So the so called Work Ratio is very good

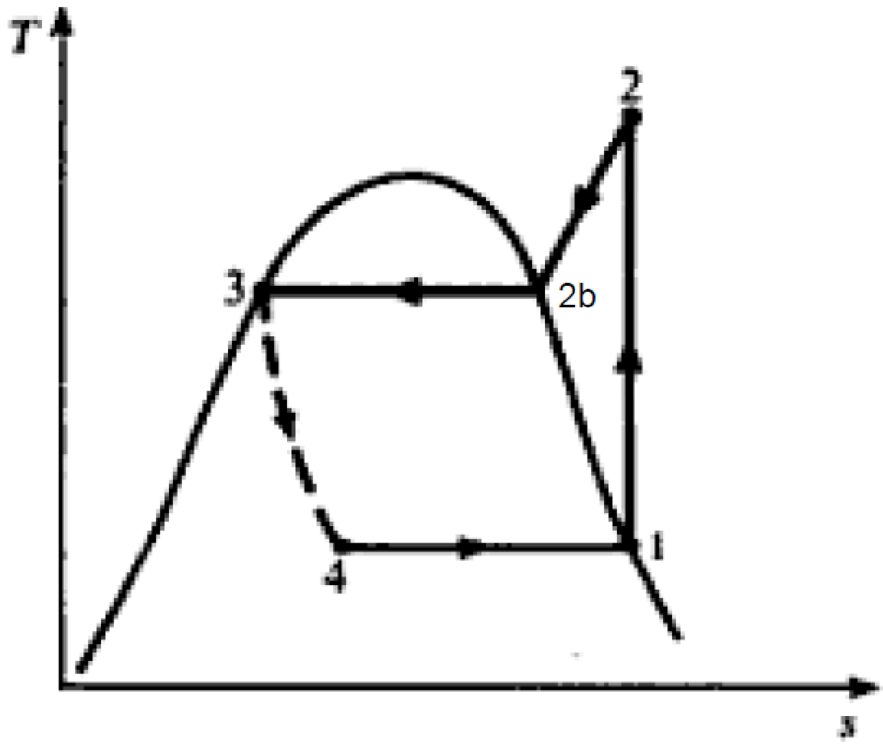
$$Work\ Ratio = \frac{Net\ Work\ Out}{Gross\ Work\ Output}$$

This is a very basic description of one of the most important heat engines, the Rankine cycle. This understanding leads to the introduction of the so called 'vapour compression refrigeration cycle'.

The refrigeration vapour compression Cycle
This cycle is similar in many ways to the Rankine cycle but the process arrows are in the opposite directions. The refrigeration cycle in thermodynamics is actually considered as a reverse heat engine. This is why from a thermodynamic perspective, it makes sense to understand the Heat Engine first (that is the engine that changes heat into work and then understand or accept the refrigeration as being the reverse of the Heat Engine. Refrigeration is the reverse of the heat engine because in refrigeration work is inputted (in the for of rotation driven by electric motor driving the compressor) and the output is the movement of heat against the natural tendency. The natural tendency of heat is to move from a high temperature to a low temperature. Refrigeration/airconditioning is capable of moving heat from low temperature to a higher temperature, thus this is movement of heat against the natural tendency. Once again maybe we can use water as the analogy, water moves naturally from high level to low level but if we want to move water from a low level to a high level we have to put energy, for example in the form of rotation of a water pump. Therefore we also can appreciate why, correctly so, refrigeration /airconditioning is sometimes called Heat Pump. In reality the terminology refrigeration / airconditioning is used when the desired heat movement is that of extraction of heat from the low temperature reservoir, while the terminology heat pump is used when the desired heat from is that

of movement of heat into the higher temperature reservoir. So we need to appreciate that the reverse Heat cycle is the same for refrigeration/airconditioning or heat pump, it is what is the desired output that is different.
The terminology reverse heat engine is correct because it also leads us to the fact that the processes are in reverse to those we have in the heat engine. That is the arrows are in the other direction, and overall the cycle has an anticlockwise rotation. Thus the upper horizontal line becomes the condenser while the lower horizontal line becomes the evaporator. The principles found from the Carnot process, i.e that the levels of the horizontal lower and upper lines effect the performance are carried over to the refrigeration cycle. However here the gap in height between the two horizontal lines shows the difficulty to transfer heat upwards against the natural tendency (while in the heat engine the gap between the horizontal lines shows the potential of doing work).





The above refrigeration/airconditioning or heat pump cycle is the most basic vapour compression cycle. Point 1 is the outlet of the evaporator, the working fluid is in vapour form at the saturation condition. The process 12 is the compression of the vapour that happens in the compressor that is typically driven by the lectrical motor. As a consequence of the compression process the pressure rises and so does the temperature. In refrigeration it is very important to always remember that pressure and temperature are related, if the pressure is increased the temperature increases and also vice versa, if pressure is dropped the temperature drops. Thus the fluid at state 1, when pressurised to 2 ends up with a higher temperature that will be (or needs to be) higher than the heat sink. The Fluid at temperature 2 then passes through the heat exchanger 23. The first portion of the heat exchanger drops the temperature of the fluid and brings the fluid down from the superheated condition to the dry saturated condition point 2b (i.e. the point where it hits the dome). The horizontal section 2b to 3 is the condenser where the fluid looses its latent heat, condenses and becomes completely liquid. So technically on the portion 2b to 3 is the condenser but in a real system the heat exchanger is a single part that offers the possibility to the working fluid to lose its heat to the sink and it is not possible (nor important) to actually see physically where point 2b is in the heat exchanger. Hence the whole heat exchanger from 2 to 3 is typically referred to as the condenser. The fluid in liquid form at point 3 is still at the higher pressure level. The condenser is not a restrictive path to the fluid it just offers the possibility to the fluid to reject heat to the sink. The fluid at point 3 is then made to expand down to the lower pressure and this expansion is what generates the drop in temperature. Hence if we consider refrigeration, the condenser will be hotter than the hot outside, while the evaporator will be colder than the cold inside. The evaporator is also a heat exchanger that provides the possibility to the working fluid to get the latent heat from the heat source. It is good to note that in the heat exchangers (condenser and evaporator) heat moves in the natural tendency. Thus in the condenser, the refrigerant has to be hotter than the heat sink for example the air outside of the building. On the other hand, in the evaporator, the refrigerant has to be colder than the cold inside air temperature.
The expansion process 34 is typically done using a capillary tube that acts as the restriction that results in a pressure drop. So it is good to appreciate that the drop in pressure happening across the capillary is 'fought' by the compressor. The term used in the expansion process that happens across the capillary is one that is practically adiabatic (because the capillary does not have much surface area) and no useful work is produced, thus it is referred to as constant enthalpy. Academically speaking, the expansion can happen in an expander that will be able to get some useful work from the expansion process. However, in refrigeration/airconditioning, since the refrigerant at point 3 is liquid, the expander will have to work with a liquid that is transitioning to vapour and hence is problematic and also since liquid does not require much work to pressure, conversely the drop in pressure of a liquid does not generate much work either. Hence it is not technically nor economically feasible to have an expander producing mechanical work. The expansion device is also referred to as a throttling device. Throttling is the verb from the noun throttle, and it is good to associate the throttle as that part that restricts air flow into a typical petrol engine.

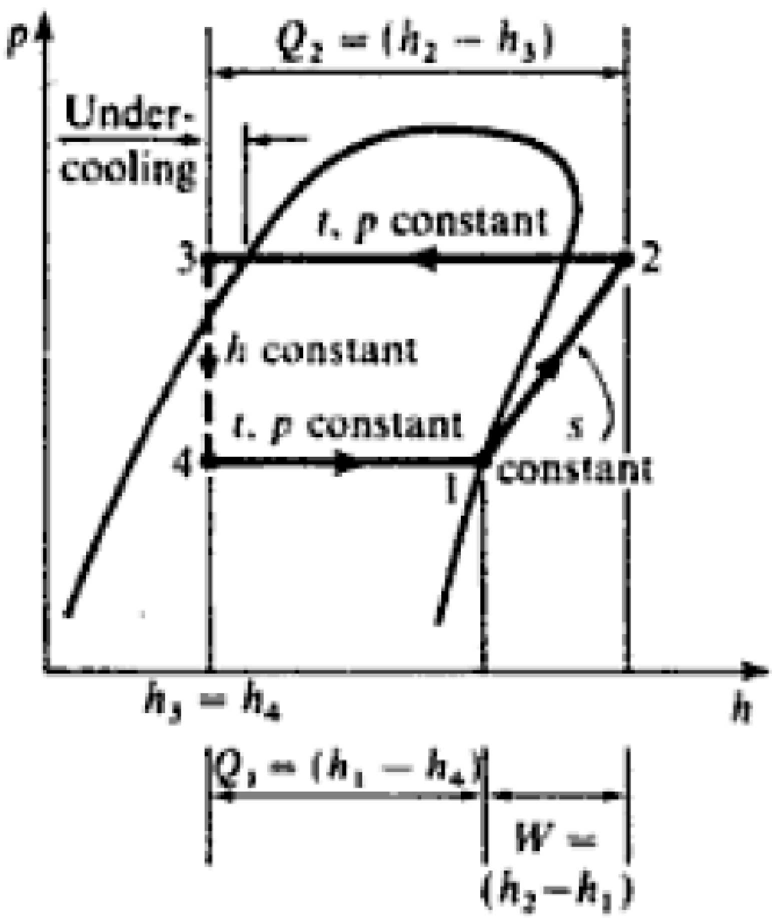
A more general or realistic diagram of the refrigeration will have a bit of superheat of the fluid upstream of the compressor and a little bit of subcooling downstream of the condenser. The superheat before the compressor is beneficial to make sure no liquid drops enter the compressor since liquid drops might damage the compressor as it has very low clearances and high compression ratio. While the subcooling in the condenser is beneficial because it lengthens the condensing line and the evaporation line. Once again it is good to remember that the area under a process on the Ts diagram is heat. Hence lengthening the condenser and evaporator lines means more heat flow.

The vapour compression cycle is also beneficially drawn on a Pressure enthalpy diagram, ph diagram. Enthalpy, h, is a property that is introduced in thermodynamics because it better quantifies the amount of energy of a fluid in a flow process. Enthaphy is not measurable by a meter but is calculated from thrre other properties, pressure p, internal energy u and specific volume v.

$$h = u + pv$$

However we do not really need to calculated h from u, p and v because typically we can find charts or programs that give us the value of h.

The ph diagram is in reality the one used far more often in analysing refrigeration than the Ts diagram. The reason is that it has three straight lines and just one sloped line! And the points at the end of the processes are easy to pinpoint by means of easy to measure pressure and temperature.



The refrigeration cycle is very 'efficient' so much so that it is more than 100% efficient and therefore for refrigeration the terminology Coefficient of Performance is used COP.
The COP is the desired output divided by the Work Input.

So for refrigeration it is

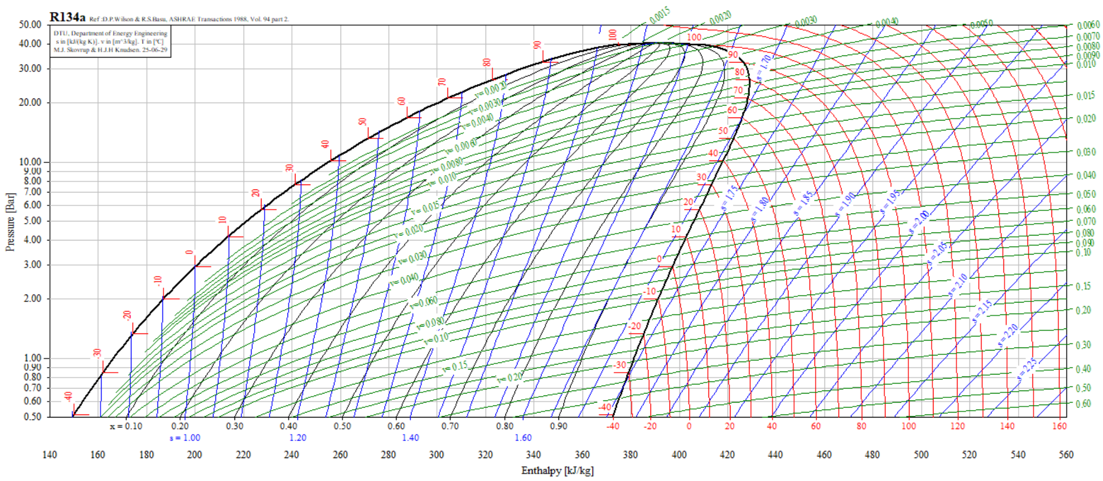
$$Coefficient\ of\ Performance_{refrigeration} = \frac{Heat\ Extracted\ From\ Cold\ Side_{evaporator}}{Compressor\ Work\ Input}$$

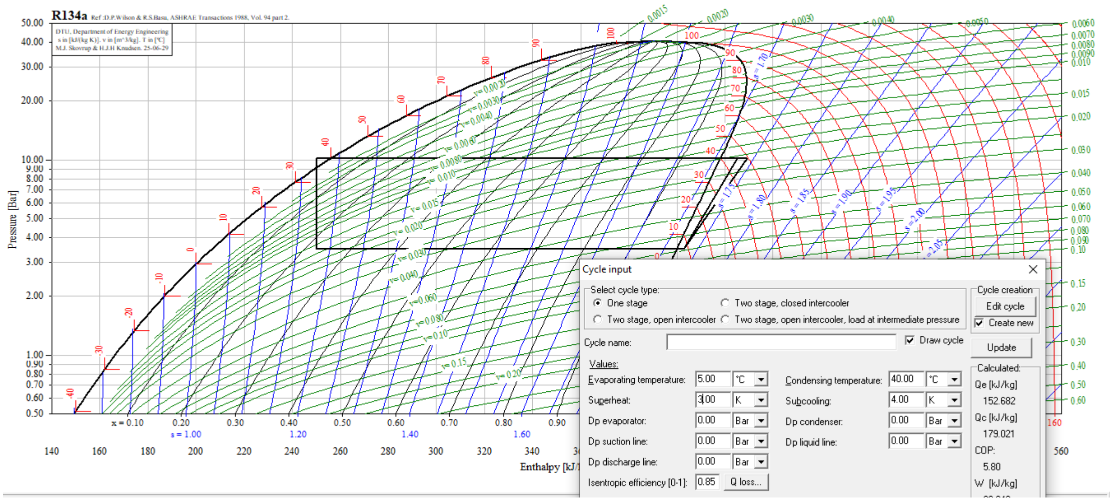
While for Heat Pump, i.e. when the desired is the heating effect

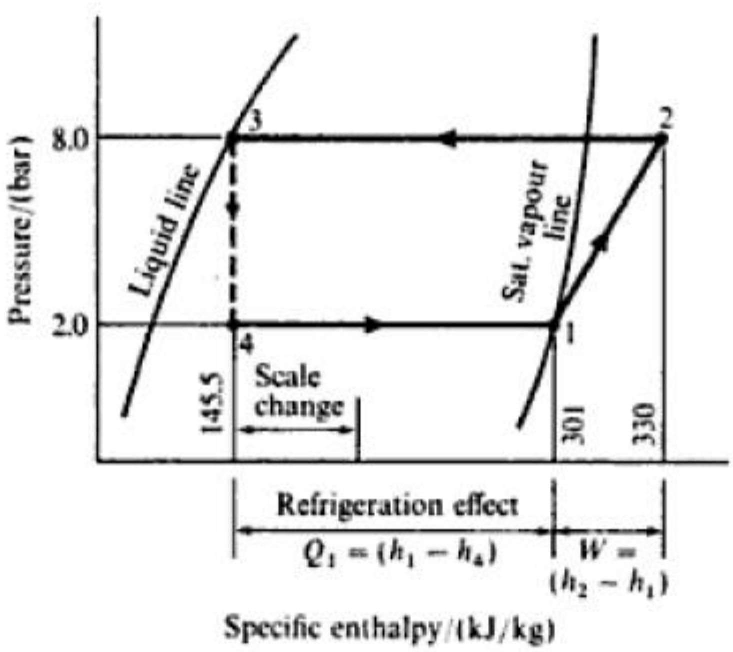
$$Coefficient\ of\ Performance_{heat\ pump} = \frac{Heat\ Rejected\ By\ Hot\ Side_{condeser}}{Compressor\ Work\ Input}$$

As can be seen from the ph diagram sketch, the compressor work is smaller than the evaporator line hence the COP refrigeration is bigger than 1, typically 3 or 4.
Also the condenser line is longer than the evaporator line, hence the COP heta pump mode is even bigger than the COP refrigeration mode.

The ph diagram for R134a, very common in cars and also in refrigeration is shown next and then the same diagram with superimposed cycle for condenser at 40 deg C, evaporator at 5 deg C, 4 deg C of Subcooling and 3 deg C of superheat. From the diagram we can see what the pressure in the condenser and evaporator should be. That is around 3.5 bar and just over 10 bar. In reality, when trouble shooting or filling a system, the pressures are the mostly widely measured/used and the lower pressure is by far the more important because it immediately shows if there is loss of gas and it does not vary much with outside temperature. The condenser temperature and hence pressure do vary with outside temperature.

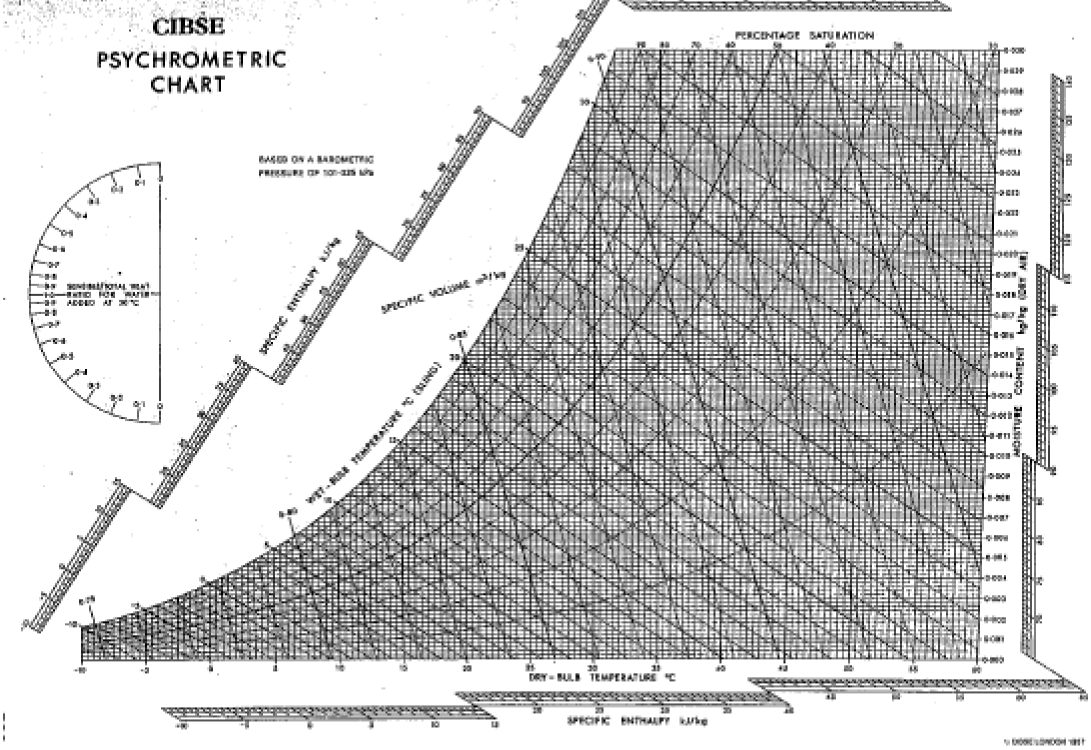


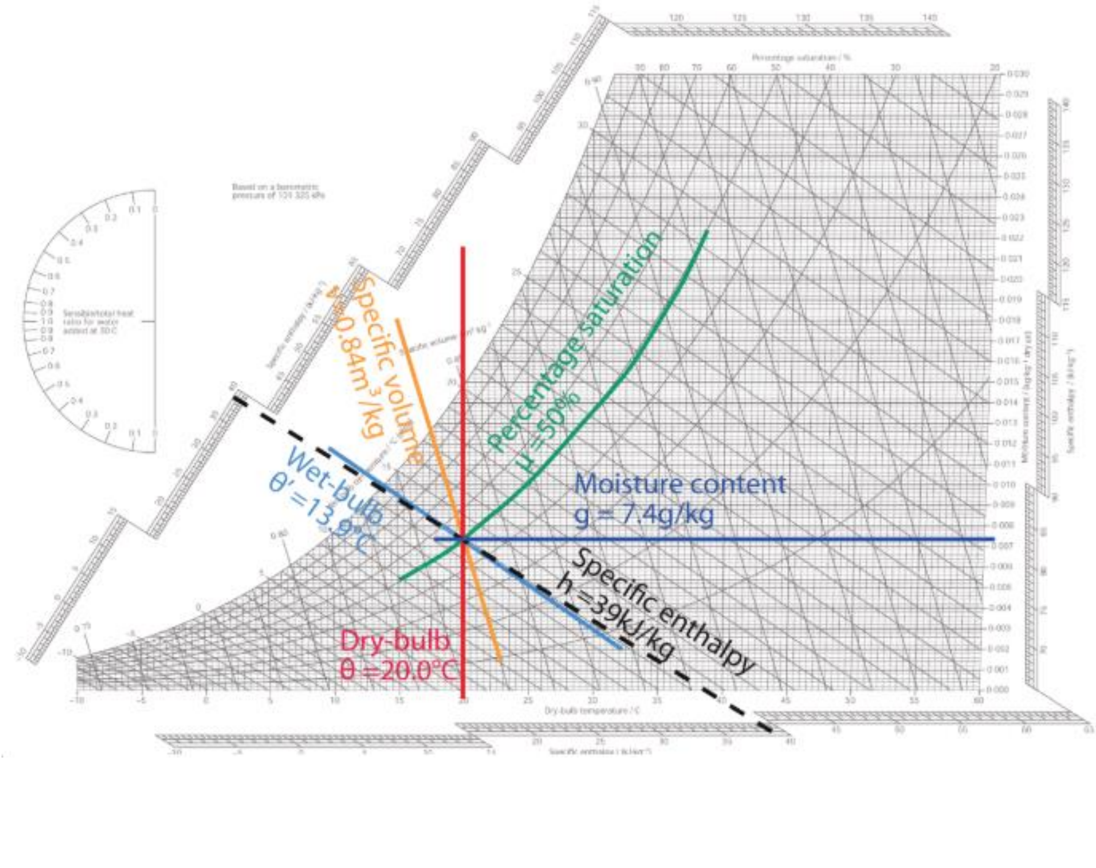


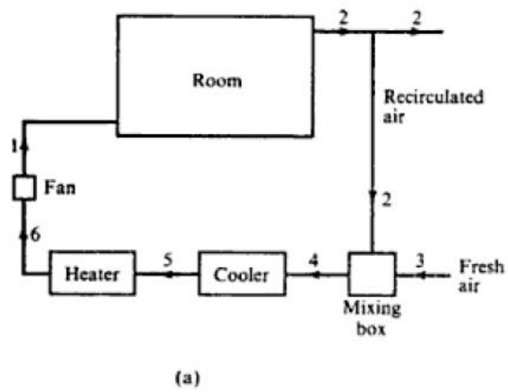


Psychrometric Chart

permission of CIBSE)







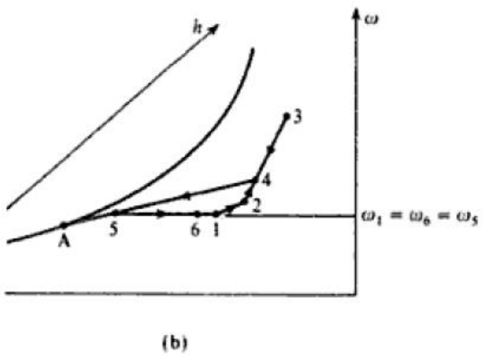


Fig. 15.6 Summer air-conditioning system (a) with the processes on a psychrometric chart (b)

A mass balance of the moisture gives

$$r\omega_2 + (1 - r)\omega_3 = \omega_4$$