ENERGY CONVERSION

Notes on compression refrigeration

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Coolpack

Coolpack is a software for refrigeration design developed by the Technical University of Denmark DTU. It is available as a free download at: http://www.et.dtu.dk/coolpack/UK/index.html.
The software is quite complex and includes a number of sub-routines. The most important tools are those dealing with:

Refrigerant properties:

Cycle analysis:

Refrigerant properties contains some tools useful for diagrams and cycle drawing, marked as 1,2,3 in the following Figure. “Saturation table” 4 returns the saturation properties, i.e. the values along the saturation curve. Note that inside the saturation curve each pressure corresponds to only one temperature (and vice versa!). So given the evaporating and condensing temperatures it is possible to obtain their relative pressures. Then “Table” 5 can be used to display the properties (e.g. the enthalpy or the specific heat) of superheated gas or subcooled liquid at given temperature and pressure (note that in this case you need both!).

So, use “4” to get the saturation properties and “5” to get the enthalpies of give points.
Cycle analysis is very useful for refrigeration design and evaluation, but will not return accurate values for the lab analysis. In fact several unknown parameters (e.g. in such a small rig, the isentropic efficiency would be varying considerably with the working conditions) are needed to set up the calculation.
Therefore a step by step calculation with the refrigerant properties is suggested for the lab analysis.
Notes on compression refrigeration

Compression refrigeration is achieved using a working fluid called refrigerant. A refrigerant is typically a fluid that evaporates at very low pressure (and therefore temperature). As an example:

<table>
<thead>
<tr>
<th>Heat transfer fluid</th>
<th>Pressure (bar)</th>
<th>Approx evaporation temp (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water</td>
<td>1</td>
<td>100</td>
</tr>
<tr>
<td>R134A</td>
<td>1</td>
<td>-26</td>
</tr>
</tbody>
</table>

Which shows that at ambient pressure (1 bar) refrigerants are already in the gas region. This allows the extraction of the latent heat of vapourisation at low temperatures (and pressures). Once it has absorbed some heat, the refrigerant is compressed (to a higher pressure) this way it can condense releasing the latent heat of vapourisation at a higher temperature. In other words, the higher the pressure the higher the phase change (evaporation/condensation) temperature.

Being expanded and compressed the refrigerant can absorb heat at conveniently low temperatures and reject it at higher temperatures (it has to be hotter than ambient to reject it into air). Figure 1 shows the schematic diagram of a typical compression refrigeration plant and a typical set of temperatures of the refrigerant.

Compressor 1 compresses cold and low pressure vapour to higher pressure and temperature (like a bicycle pump). Condenser 2 cools hot (high pressure) refrigerant discharging heat into air or process water and producing liquid refrigerant. Expansion valve 3 expands the warm liquid refrigerant and turns it into a cold low pressure liquid (part of the refrigerant evaporates during the expansion). In the Evaporator 4 the cold low pressure liquid evaporates absorbing heat from the cooling load. Cold low pressure vapour is then returned to the compressor.

Figure 1
The processes and components of Figure 1 are reproduced in Figure 2 which shows pressures and enthalpies of the working refrigerant related to its quality (see Figure 13 in the Appendix).

![Figure 2](image)

Please note that the refrigerant swings between the two pressures P1 and P2. At lower pressure P1 the heat is absorbed whereas at higher pressure P2 heat is rejected.

**Suction Gas Heat Exchangers SGHX**

Volumetric reciprocating compressors are designed in order to have the least possible clearance volume i.e. the space between the top of the cylinder and the cylinder head at Top Dead Centre TDC (because it badly affects the compression efficiency). Therefore very little quantities of liquid entering the suction port could have drastic effects damaging permanently the compressor. Suction traps or liquid accumulators are usually fitted between the evaporator (which returns a “wet” vapour) and the inlet of the compressor (which requires “dry” vapour). Generally suction traps mechanically separate and accumulate any incoming droplets of refrigerant. Figure 3 shows the position in the circuit and the schematic principle of the trap.
The liquid sitting in the trap is very cold and can be evaporated to subcool the liquid refrigerant coming from 2 and going into 3. In other words the trap works as a heat exchanger between line 2-3 and line 4-1 and is called Suction Gas Heat exchanger SGHX. The effect of the SGHX can be seen in Figure 4.

Note that suction gas heat exchange should not be pushed too far as it would make the duty of the compressor more and more difficult.

**Compressor**

The compressor is processing vapour (not liquid!) and compressing from lower pressure (e.g. 3 bar) and temperature (e.g. –15°C) to higher pressure (e.g. 14 bar) and temperature (e.g. 50°C). A typical compression ratio ranges between 3 and 9.

\[
\therefore \frac{P_2}{P_1} = 3 \div 9
\]

The higher the ratio the lower the compression efficiency (due among other things to clearance volume and discharge temperature, think about it!).
The ideal compression is adiabatic (i.e. Q=0) or isentropic (i.e. dS=0) because the process should be fast enough not to exchange heat with the surroundings.
NB: adiabatic does not mean isothermal, in fact the temperature changes drastically during the compression (together with p and V).

Figure 5 shows the ideal compression in T-S and P-H diagrams.

The following formula expresses the ideal work of compression:

\[ W = \dot{m}(h_2 - h_1) = \dot{m}(C_p(T_2 - T_1)) = \frac{J}{S} = W \]

Note that both enthalpies and specific heats in the previous formula are referred to gaseous refrigerant (see Figure 13) because compressors are normally working in the superheated area. Real compression is not adiabatic/isentropic and some heat is picked up both from heat exchange with the compressor walls and from fluid friction. As a result the real work of compression is higher than the ideal work.

Figure 6 shows the real work compared with the ideal work and the isentropic efficiency is defined as their ratio:

\[ \eta_{is} = \frac{W_{ideal}}{W_{real}} = \frac{h_2 - h_1}{h_{2'} - h_1} \]
Heat exchangers (condenser and evaporator)

In a heat exchanger refrigerant exchanges heat with an external medium which typically is ambient air or process water. Heat is exchanged due to a finite temperature difference between the two working fluids. Typical values of temperature difference are:
- 10°C for refrigerant – air
- 5°C for refrigerant – water

In the refrigerant – air case, for example in the condenser this means that the refrigerant can be condensed or cooled down to the temperature of air plus 10°C:

\[ T_{\text{ref}} = T_{\text{air}} + 10^\circ C \]

In fact heat exchangers are built in copper and are quite expensive, therefore reaching smaller temperature differences is possible but usually not cost effective.

Figure 7 shows a typical layout of the temperatures inside a heat exchanger in the case of counter flow and parallel flow (both fluids being single phase!).

The heat exchanged is dependent on a heat transfer coefficient \( U \) (itself depending on working fluids and their conditions), on the area \( A \) and on the temperature difference \( \Delta T \):

\[ Q = U \cdot A \cdot \Delta T \]

Figure 8 shows the case of a condensing/evaporating fluid and the temperature trend due to phase change (according to Gibbs law, while the two phases are coexisting the temperature keeps constant).
As shown in Figure 9 the heat exchange process is ideally considered to be isobaric.

The heat exchanged can still be expressed as an enthalpy difference, but enthalpies are differently calculated for each phase! Further, the heat is conventionally positive when absorbed by the system and negative when rejected accordingly to the following formulae (see also the Appendix-Enthalpies):

$$Q_{rejected} = Q_2 = \dot{m}(h_3 - h_2) < 0$$

$$Q_{picked} = Q_1 = \dot{m}(h_1 - h_4) > 0$$

In real processes heat exchange is not isobaric as fluid friction in the pipes produces a pressure drop. On the other hand a certain pressure drop is necessary to drag the refrigerant throughout the heat exchanger. Pressure drops are almost nil in "shell and tube" heat exchangers (used for liquid to refrigerant exchange) whereas they are highly dependent on the geometry of “finned tubes” type heat exchangers. A typical value of pressure drop for a supermarket finned type heat exchanger is 0.3 bar which has a corresponding temperature difference (dependent on the type of refrigerant and on the working temperature!!).
Figure 10 shows both a shell-and-tube and a finned tube heat exchangers.

**Expansion valve**

In the expansion valve the pressure of the refrigerant is reduced from the condensing to the evaporating level. This is usually achieved with an obstruction in the refrigerant flow that causes the required pressure drop (while the velocity increases!).

The expansion valve also has the role of regulating the mass flow rate to match the required refrigeration duty.

Most common types of expansion valves are the capillary tube (used in small domestic applications), the thermostatic expansion valve and the electronic pulsing valve.

An example of thermostatic expansion valve is drawn in Figure 11. In it the flow and the pressure drop are regulated via a jet-needle similar to that of a car carburettor. A balancing temperature sensor inserted in the evaporator (or in the suction line) leads the opening of the orifice to match the cooling load. Note that the evaporating pressure varies with the evaporating temperature (Gibbs phase rule: two phases → pressure and temperature are interlinked).
The energy available in the refrigerant as pressure is simply wasted in the expansion valve. No work (which would be theoretically available!) is recovered during the expansion process. As shown in Figure 12 the expansion process is ideally isenthalpic:

\[ Q_{\text{expansion}} = L_{\text{expansion}} = h_3 - h_4 = 0 \quad \Rightarrow \quad h_3 = h_4 \]

In real application the expansion is not isenthalpic and some extra energy is wasted during the expansion and \( h_4' > h_3 \). This reduces significantly the refrigerating effect \( Q_1 \).

\[ h_4' < h_3 \quad \Rightarrow \quad Q_1' = h_1 - h_4' < Q_1 \]

In other words part of the refrigerant evaporates during the expansion (flash gas) increasing the quality of the resulting liquid and with it the refrigerating effect.
**Cycle efficiency**

The refrigerators and heat pumps are classified depending on their efficiency or on their benefit/cost ratio. This is achieved defining the Coefficient Of Performance (COP) which is the ratio of the cooling/heating effect versus the work spent to obtain it.

In a refrigerator:

$$COP = \frac{Q_1}{W} = \frac{\dot{m}(h_1 - h_x)}{\dot{m}(h_2 - h_t)} = \frac{h_1 - h_x}{h_2 - h_t}$$

In a heat pump:

$$COP = \frac{Q_2}{W} = \frac{h_2 - h_x}{h_2 - h_t} = \frac{Q_1 + W}{W}$$

Note that in refrigeration systems the primary product of the cycle is $Q_1$ (i.e. the heat absorbed from the low temperature source) whereas in heat pumps it is $Q_2$ (i.e. the heat rejected to the high temperature source)!

$Q_2$ is the sum of the heat picked at low temperature and the work done to extract it. In other words the work done by the compressor is usually entirely absorbed by the refrigerant and has to be rejected in the condenser (see Figure 14).

Note that the COP is not depending on the mass flow rate (which being the same in numerator and denominator can be simplified) but only on the working conditions of the system (i.e. evaporating temperature, condensing temperature, efficiency of the components and type of refrigerant!). In other words the COP does not depend directly on the system size.

Where a more precise system efficiency measurement is needed the Coefficient Of System Performance COSP is defined. This includes in the work $W$ also any eventual energy used by the auxiliaries, such as the condenser motor fans and any pump.
Appendix, and useful stuff

Energy and power

Energy is also defined as work (or heat) and in the S.I has dimension of \([N \ m]=[J]\) or Joules. As expressed by the first law of the thermodynamics heat and mechanical energy are equivalent and can be expressed in the same units. Think of a motor which friction and shear could all be transformed into heat (unfortunately we have not yet found a way to transform all the heat into work!). The equivalence between heat (traditionally expressed in calories \([\text{cal}]\)) and mechanical energy (expressed in joules \([J]\)) is of great use:

\[1 \text{ kcal} = 4186 \text{ J}\]

Power is the ratio at which work is done and is therefore expressed in Watts \([W]=[J/s]\). The difference between energy (or work) and power is substantial! As an example think of a caravan that needs to be trailed from Exeter to London. One could do the job either with a Ferrari or with a Morris Minor ideally spending the same amount of work (the force needed to trail the caravan is the same in both cases as it is the distance). Nevertheless the duty might take a few hours with the Ferrari whereas weeks with the Morris Minor! In other words with a more powerful device the same work duty can be achieved in a shorter time (or more work could be done in the same time).

Energy = work or heat = \([\text{Joules}]\)

\[\text{Power} = \text{Watts} = \text{Joules/s}\]

In a refrigeration system enthalpies have dimensions of specific energy (because referred to unit of mass) e.g. \(h=[J/kg]\) whereas heat and work are usually expressed with power units in Watts. Beware that heat and work could also be expressed as specific energy:

\[Q = W = h_a - h_b = [J/kg] \Rightarrow \text{Energy!}\]

\[\dot{Q} = \dot{W} = \dot{m}(h_a - h_b) = [W] \Rightarrow \text{Power!}\]

where:

\[\dot{m} = [\text{kg/s}]\]

To distinguish the two units, power measures are usually dotted (but not always!).

Did you know that…?

- The density of water is 1?! In fact one litre of water (which is also a cubic decimetre or \(10^{-3} \text{m}^3\)) weighs 1kg.
- The specific heat of water at ambient temperature is roughly 1?!

\[C_{p,\text{water}} = 1 \left[ \frac{\text{kcal}}{\text{kg \ K}} \right] \Rightarrow C_{p,\text{water}} = 4.186 \left[ \frac{\text{kJ}}{\text{kg \ K}} \right]\]
**Tips and figures**

Figure 13 shows a typical state P-h diagram for a refrigerant. In it the saturation curve together with the critical point (which is the highest value of the saturation curve) divides the three phases: gas, vapour and liquid.

![Figure 13](image)

Figure 14 shows a hermetically sealed compressor. In this widespread case, the refrigerant absorbs all the work done by the compressor. In other words, the heat produced by the electric motor is chilled by the worked refrigerant.

![Figure 14](image)

The work spent for the compression of a gas increases with the pressure ratio ($P_2/P_1$) as the discharge temperature increases (and the clearance volume gives worse and worse effect).
At higher pressure ratios it becomes convenient to split the compression into to stages in order to get advantage from an interstage cooling (usually achieved via liquid refrigerant injection between the two stages). The concept is graphically described by Figure 15.

![Figure 15](image)

**Enthalpies**

Generally, given the temperature and/or the pressure of the refrigerant it is possible to obtain the enthalpy directly from tables, diagrams or software such as Coolpack. In some other cases the following formulas can be of help.

In the gas region:

$$h_{\text{gas}} = C_{p,\text{gas}}T$$

In the vapour region:

$$h_{\text{vapour}} = (1-x)h_f + x h_g = h_f - x h_{fg}$$

where $h_{fg}$ is the latent heat of evaporation/condensation ($f$=sat liquid; $g$=sat gas).

In the liquid region:

$$h_{\text{liquid}} = C_{p,\text{liquid}}T$$

Note that Cp’s of gas and liquid are expressed in the same units (e.g. [kJ/kg K]) but have substantially different values.