THE USE OF CARBON DIOXIDE IN REFRIGERATION and HEAT PUMP SYSTEMS

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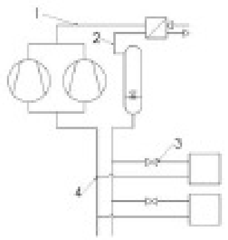
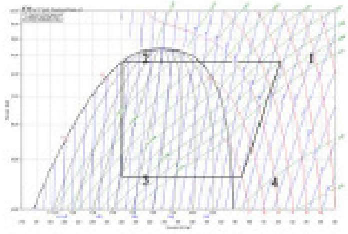
INTRODUCTION

Carbon dioxide has been deeply used as primary refrigerant until Forties due to its non toxicity and non flammability. However the high pressures involved made it easy to abandon this natural fluid preferring the use synthetic refrigerants characterized by extremely lower pressure levels. After several years the progressive restriction in matter of the use of ozone depleting (Montreal, 1987) and earth warming (Kyoto, 1999) refrigerants together with the development of components suitable for high pressures made CO_2 to gain renewed interest.

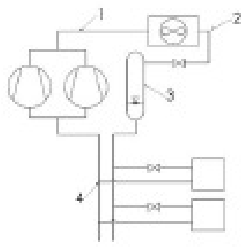
VAPOUR COMPRESSION REFRIGERATION SYSTEMS IN DIRECT EXPANSION

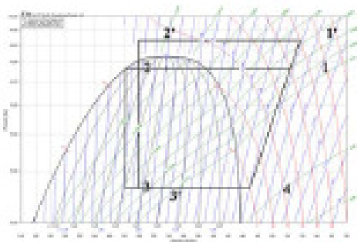
When high pressure refrigeration media (air or water) is available at temperature lower than 20°C, carbon dioxide can be used as a standard refrigerant, that's to say in a subcritical cycle. Of course the different pressures levels will make it mandatory to evaluate different systems solutions from the ones used with HFCs plants.





If the refrigeration media is available at a temperature higher than 20°C it will be most likely that the system will work in transcritical way.





In this second case the cycle ran by the refrigerant will be 4 – 1' – 2' – 3'; in the first case 4 – 1 – 2 – 3 will happen.

The transcritical way of operation will require a specific high pressure control due to the fact that in the high pressure heat exchanger the two refrigerant phases will no more be present and therefore no condensation will happen: it's no more possible to regulate the pressure simply controlling the temperature at which the heat exchange happens; it is mandatory to use an additional control that could be done basically in three ways:

- back pressure system regulation with a liquid receiver placed in intermediate pressure
- COP optimisation with pressure control enslaved to the refrigeration media inlet temperature
- Passive control with differential pressure valve and intermediate liquid receiver

The way this control is performed represents one of the key issues of every system; some of the regulation systems listed later on could be patented and who intends to realize such a systems should better personally check on that.

DESIGN FEATURES

Several aspects have to be considered when approaching the design of CO_2 systems; aspects that are extremely different from the ones that need to be faced while working with HFCs, both for subcritcal and transcritical CO_2 systems. For instance following points are described; of course they are not to be considered exhaustive regarding all the features by which a CO_2 plant differs from a HFCs one.

- **Discharge temperature**

  Semi-hermetic CO_2 compressors need to have a very strict control related to the suction return temperature inside their crankcase. It's rather easy to have end of compression temperature very close to 200°C even with evaporating temperature of –10°C; those values are of course not tolerable by the compressor. It's therefore recommended to evaluate the effective necessity of installing eventual regenerative heat exchangers in the suction line and is also recommended that a good control of the superheat is managed.
- **Low temperature systems**

In accordance to what aforesaid in relation with the high discharge temperature it is recommended the use of double stage compressors when evaporating temperature becomes lower than –25°C. The most practical solution is to use double stage “internal compound” compressors, belonging to TCDH DORIN 300 range compressors; in fact those compressors manage to divide the overall pressure ratio between two stages inside the same compressor body. It is recommended the use of a de-superheater between the first stage discharge and second stage suction; this solution allows for containment of second stage discharge temperatures and for overall compression work decrease.

- **Subcritical operating conditions**
  A system designed for working in transcritical conditions can work very efficiently also in subcritical operations; of course a good commutation logic and a high pressure heat exchanger specifically designed have to be in place. This opportunity leads to extremely high COP seasonal values.

- **Subcooling**
  Carbon dioxide thermophisical properties suggest it to design a high side pressure heat exchanger able to lead to the presence of subcooling while working subcritical; at the same time, while working transcritical, the system should be able to provide an evaporative cooling (by water spraying for instance) in the final part of the heat exchanger. Software [1] are already available on the market in order to evaluate these phenomena. It’s also important to highlight that, keeping the same subcooling value, the performance increase that happens in a CO_2 systems are much more important that the ones happening in a HFCs plant.

COMPRESSOR DESIGN

As it is for standard refrigerants, also with carbon dioxide the role of heart of the plant is acted by the compressor. The design and the development of such compressors lead to a lot of difficulties, mainly due to:

- ✓ high working pressures
- ✓ high discharge temperature
- ✓ high solubility of poliester oil
- ✓ volumetric specific refrigerating capacity from 5 to 10 times higher than the one of standard refrigerants
- ✓ reduction of pulsation phenomena and of noise level.

During last ten years there have been several attempts to realize open drive carbon dioxide compressors, capable to work in accordance to what described ed before, but the high pressure fields makes the shaft seal extremely critical.

Therefore the most suitable designs seems to be the hermetic and semi-hermetic ones.

So let’s deeper analyze which are the most critical issues related to the design of carbon dioxide compressors.

➢ **Mechanical stresses:**

As stated before carbon dioxide has a volumetric specific refrigerating capacity from 5 to 10 times higher than the one of standard refrigerants. This leads both to minor swept volumes of the same magnitude and to higher differential pressures across the piston of the same magnitude. Small bores can lead to small stresses on the connecting rods but, at the same time, they allow less space available, with consequent high specific loads on the moving parts. Very critical it has shown to be the dimensioning of the small end connecting rod bearing.

➢ **Thermal load:**

Having started with the design of single stage carbon dioxide compressors, one of the most challenging issue has revealed to be linked to the high discharge temperatures occurring with modest pressure ratio. This led to the choice of a valve plate assembly material capable to get to high temperature and to the choice of lubricants with flash temperature higher than 200°C and to

➢ **Lubrication:**

Poliester oils are extremely miscible with carbon dioxide, especially at the thermodynamic conditions occurring in the crankcase while the compressor is operating in transcrtical conditions; therefore the lubricating power of the mixture composed by oil and refrigerant decrease sensibly. This of course is an additional strong challenge to the design of such compressors.

➢ **Rotating speed:**

Nowadays the most part of semi-hermetic piston compressors for refrigeration and air conditioning works @ 1450 (1750) rpm (50 or 60hz), therefore using four poles motor. Having consistently reduced pressure pulsation phenomena it has been possible to validate the design of CO_2 compressors with two poles motors using the same compressor platform; this led to a ratio - price over refrigeration duty - extremely favourable. Of course, switching to two poles motor with the same compressor platform led to slightly lower volumetric efficiencies [Neksa et al., 2000].

➢ **Head and valve plate:**

Even though CO_2 compressors work with low pressure ratio it’s very simple to get extremely high pressure differences. Consequently another key issue has been the design of valve plate capable to get proper seal.

Two compressor ranges have been designed, into two different bodies. 300 range has now become reliable thanks to extremely severe life test; performances are also very encouraging, for both single and double stage models. As a matter of fact carbon dioxide allows evaporating temperatures down to –55°C therefore calling for two stage solutions [Rekstad et al.];

- **Single stage compressors:**
  All compressors model have two cylinders, build with the same crankcase. Different swept volumes are obtained varying the stroke and keeping the same bore. Compressors are equipped with an oil pump in order to grant a correct lubrication; the use of an oil cooler is recommended in order to keep a correct lubricating power.

- **Double stage compressors:**

As stated previously extreme refrigeration applications (evaporating temperatures lower than –30°C) calls for two stage solutions. Those model are build using the same crankcase, increasing the dimensions of the low pressure cylinder in order to keep it working in subcritical conditions.

- **Possible future developments: compressors suitable for multiple level compression**

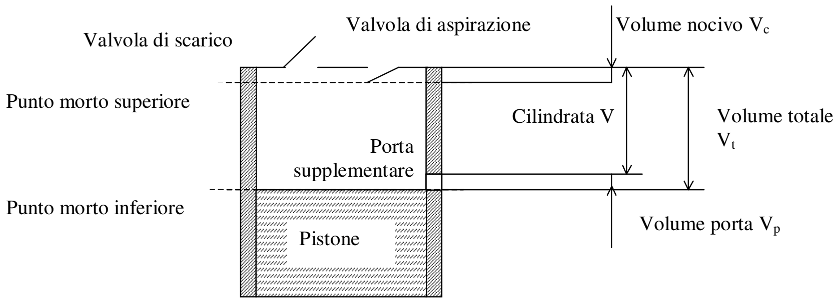
Issues related to:

- refrigeration capacity reduction with increasing heat sink temperature
- high discharge temperature with increasing pressure ration

were mentioned.

One possible common solution to both problems is represented by multiple compression cycles; the thermodynamic cycle will be analyzed in the next paragraphs. For the moment it is relevant to mention that this solution has deeply been used at the beginning of the XX century in ships refrigeration installations when water temperature was approaching somewhat higher values. This solution was ideated by G.T. Vorhees who actually gives its name to this specific cycle.

Actual reciprocating compressors are well suited to be used for such kind of application; it will be necessary to realize appropriate holes in correspondence of the bottom dead centre and to connect those to an intermediate pressure level.



Compressor layout for multiple compression adaptation

CO_2 REFRIGERATION SYSTEM EFFICIENCY: COMPARISON WITH R404A SYSTEMS

In order to correctly compare the efficiencies of R404A and CO_2 systems it is better to take a step backward a quickly describe which are the main systems designs for both typologies.

POSSIBLE SYSTEM LAYOUTS

Here follows five different refrigeration systems; figure 1 represents a standard R404A system.

SCHEMA 1

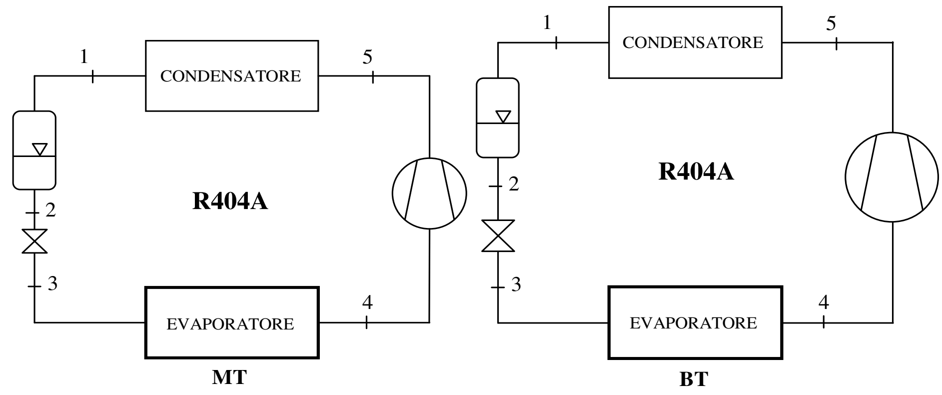


Figure 2 represents an indirect medium temperature system that both cools the condenser of a cascade low temperature system and the cabinet as well.

SCHEMA 2

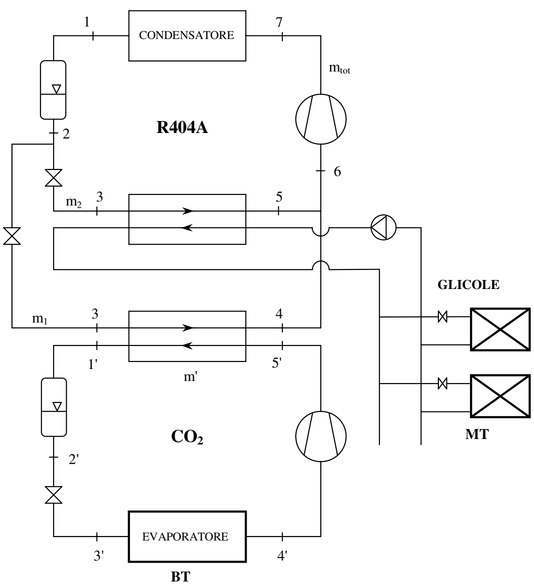


Figure 3 shows a cascade low temperature system; the medium low temperature is handled with condensing CO_2.

SCHEMA 3

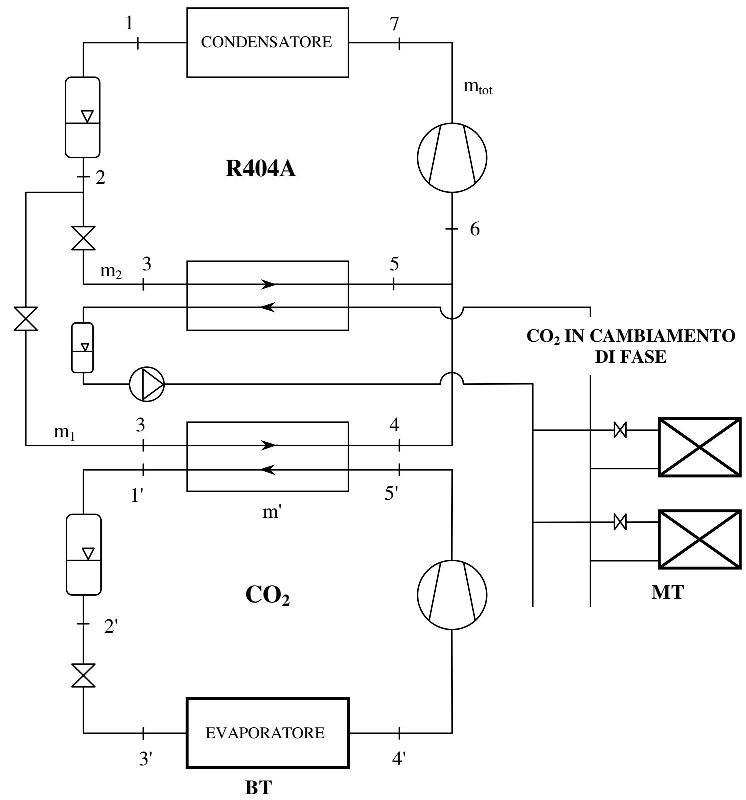


Figure 4 shows a medium low temperature system and a very low temperature systems both working with CO_2 as only refrigerant. This solution is surely the easiest and innovative; it can be worked out with DORIN CO_2 compressors thanks to single and double stage compressors availability. Additionally these system layouts are the ones that more reflects the HFCs ones.

SCHEMA 4

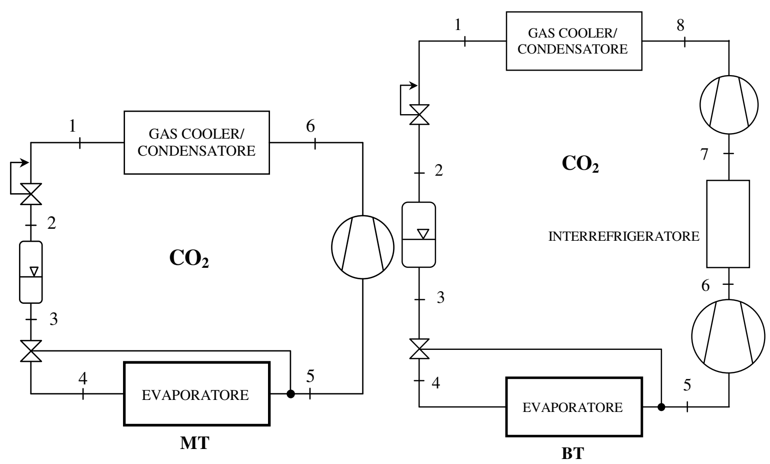
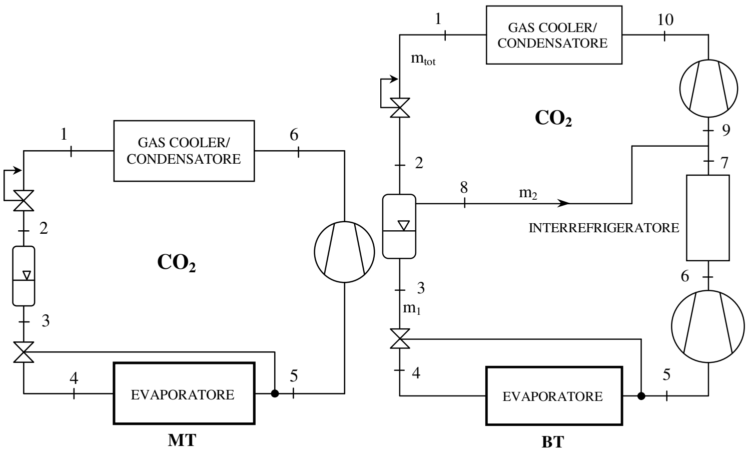


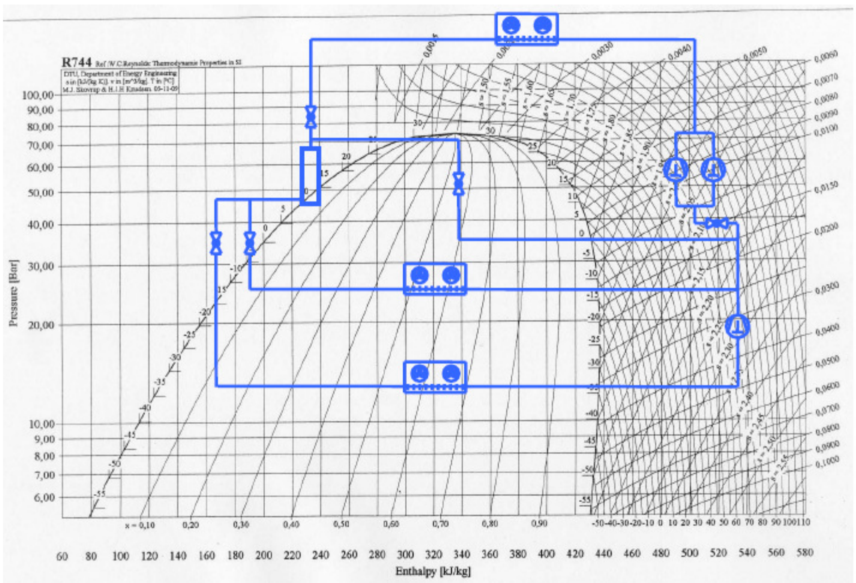
Figure 5 differs from figure 4 due to the fact that in the double stage system flash gas suction is used.

SCHEMA 5



SCHEMA 6

Figure 6 (please refer to following figure) shows a recent solution used in commercial refrigeration installations, generally known as “booster” system. [5].



In this installation the LT load is given by a compressor whose discharge flows direclty at the same pressare level of the MT load. In this way no additional load is required at the MT level (like it happens in the standard cascade applications). This type of system has already been commissioned with extremely encouraging results in terms of efficiency gains [5].

<u>SYSTEM COMPARISON</u>

All the system that have been listed can already be realized and tens of systems according figure 4 (medium low temperature and very low temperature working only with CO_2 in transcritical conditions) are working reliably and efficiently from several years woth DORIN CO_2 compressors.

The systems listed before presents of course different technologic contents, different installation costs and different efficiencies. It cannot be stated that one is better than another in a generic way. The choice between one or the other depends from several requirements, for instance:

- national laws that restrict the use if HFCs
- costs contraints
- energy consumption

A mere and purely theoretical comparison between CO_2 and R404A refrigeration systems could lead, for certain applications, to prefer the second one with the respect to the first one.

However, in order to conduct a more consistent comparison, it will have to be distinguished between HFCs systems with direct and indirect expansion (nowadays the only legally admitted in several northern European countries).

Anyhow, in the first case also, (direct expansions HFCs systems) sometimes the efficiency comparison turns favourably toward CO_2 systems if we include the use of an evaporative cooler during the hottest hours and the condenser fan consumption.

If we then include in the comparison R404A indirect expansion systems, CO2 applications often provide lower seasonal power consumptions kept the size of the refrigeration equipment the same.

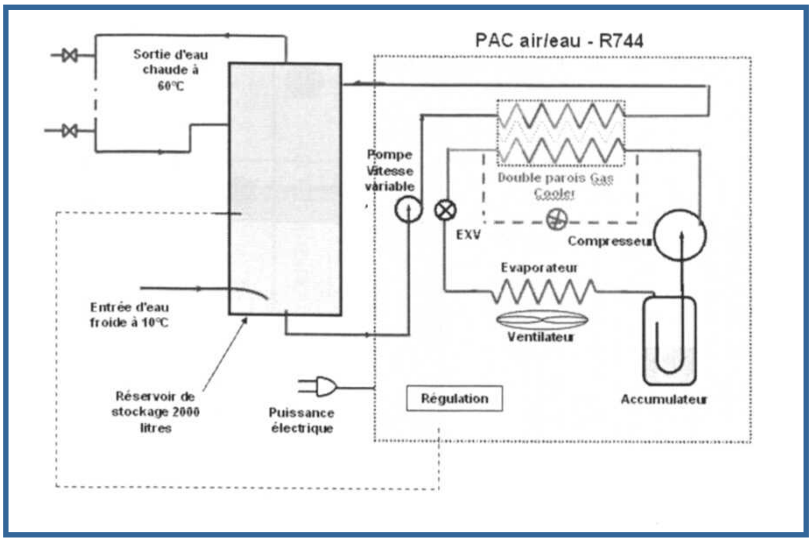
In order to correctly and exhaustively compare the power consumption of the two systems is anyhow necessary to evaluate how the two systems behave with all the different ambient temperature conditions during one year.

CO_2 heat pump systems

Actually the use of carbon dioxide has one of its preferred applications in heat pump, both used for water and space heating.

As a matter of fact these systems are extremely efficient and are leading the market in far east countries like Japan and Korea.

A possible system layout is shown below:



A very simple refrigeration loop is used; it made of:

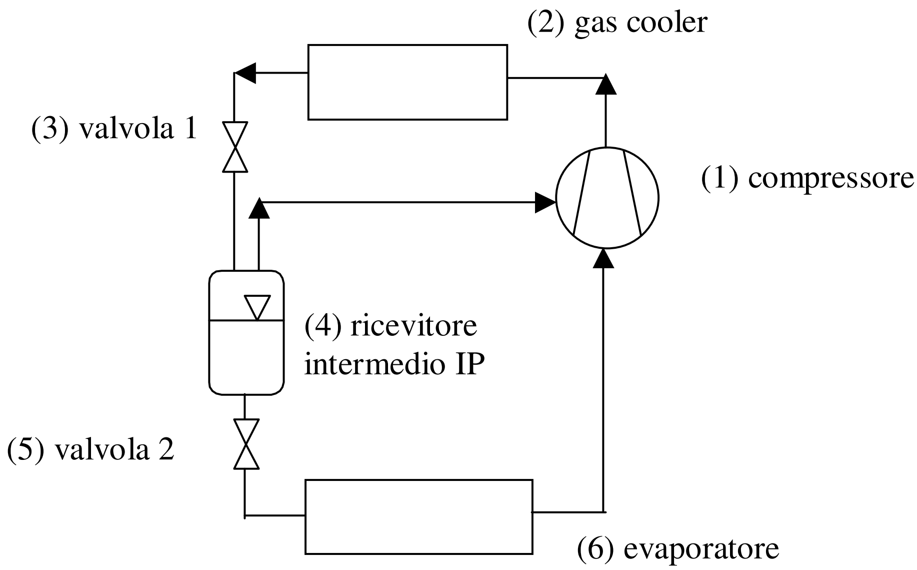
- compressor
- gas cooler
- expansion valve
- evaporator
- suction accumulator

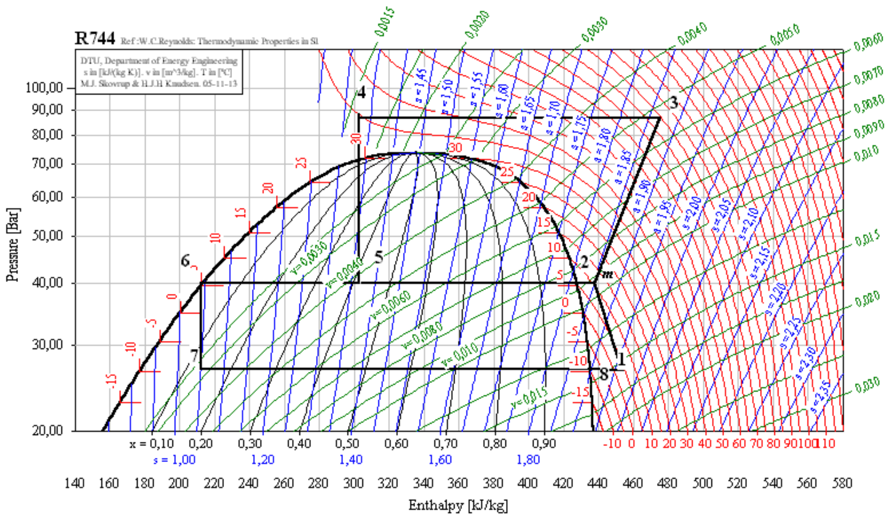
In the high pressure side heat exchanger water is heated up to the desired temperature. Since the maximum allowed discharge temperature for the compressor is 160°C, in theory even 100°C could be reached on the water side, thus giving some problems for vapour formation.

There are now about 2500 Dorin CO_2 compressors already successfully installed in such kind of application, leading to COP of 4.00 while heating water from 20°C to 65°C; this is of course could be one of the greatest application of carbon dioxide as primary refrigerant, also because much lower COP levels can be achieved with standard HFC refrigerant in this kind of applications.

MULTIPLE COMPRESSION SYSTEMS: VORHEES CYCLE

As it was previously mentioned, G.T. Vorhees introduced this kind of solution; here follow two pictures that are able to understand the cycle principles.





The intermediate pressure accumulator flash gas is injected inside the compressor, through the holes placed at the piston bottom dead point.

When the piston overcomes those holes, the middle pressure gas flows into the compression chamber, so that the compression beginning occurs in the point indicated with “m” and no more in “1”. In this way several benefits could be obtained, such as:

- refrigeration duty increase for increasing heat sink temperature
- discharge temperature decrease
- heating duty increase in heat pumps installation with decreasing cold sink temperature

It is anyhow mandatory to recall that this solution may lead to certain unknowns and complications for both system and compressor. Some experimental campaigns are in the way to be performed.

It’s necessary also to underline that the system layouts displayed before are simply indicative and absolutely not exhaustive. No liability is assumed with regard to the execution of the systems according to the figures shown.

The mentioned safety requirements are merely indicative as well and could not be the only necessary to assure a safe system design. The system design has therefore to be performed from qualified personnel only.

References:

[1] *Ever_Est srl,* Padova : Software REF-BOX
[2] *S.Girotto* : Anidride Carbonica come refrigerante, Convegno Milano, 27/11/2004
[3] *S.Sawalha, B.Palm* : CO_2 senza rischi, Il Freddo, Ottobre 2004
[4] *H.Rekstad, P.Neksa, G.Pisano:* Measurements on a 2 stage CO_2-compressor. [Proceedings from 6th Gustav Lorentzen Natural Working Fluids Conference 2004, Glasgow, UK]
[5] *J.A.Davies, S.da Ros:* Transcritical CO2 system, a case study into the latest evolution [Cooling with CO2 II, London, March, 2007]