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A guide to designing Transcritical Refrigeration System with Carbon Dioxide (CO_2)

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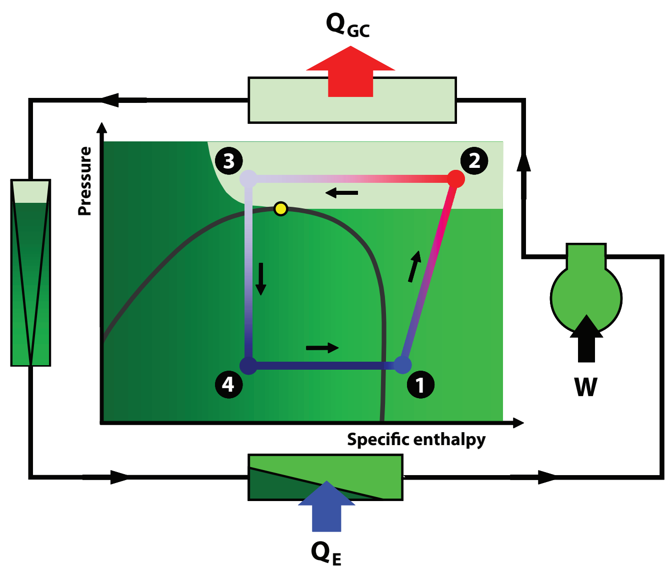
Introduction

The purpose of this guide is to provide the background for understanding how to design and operate a small-capacity (<10 kW) transcritical carbon dioxide (CO_2) system.



Carbon dioxide - System basics

Properties of carbon dioxide

Carbon dioxide (CO_2) is a natural substance that plays an important role in many natural and industrial processes. In nature, carbon dioxide plays a role in photosynthesis in plants and is one of the most important contributors to the global warming effect. In industry, carbon dioxide is used as dry ice for transport cooling, to generate the sparkling effect in some beverages, and as a protection.

It is odourless, non-flammable, and non-toxic, but if the concentration of carbon dioxide rises above the natural level in atmospheric air, it will cause the human breathing rate to increase. It is heavier than air, so if large quantities escape in a closed room the highest concentrations will typically be found close to the floor.

When carbon dioxide is used as a refrigerant it is often referred to by its refrigerant number - which is R744.

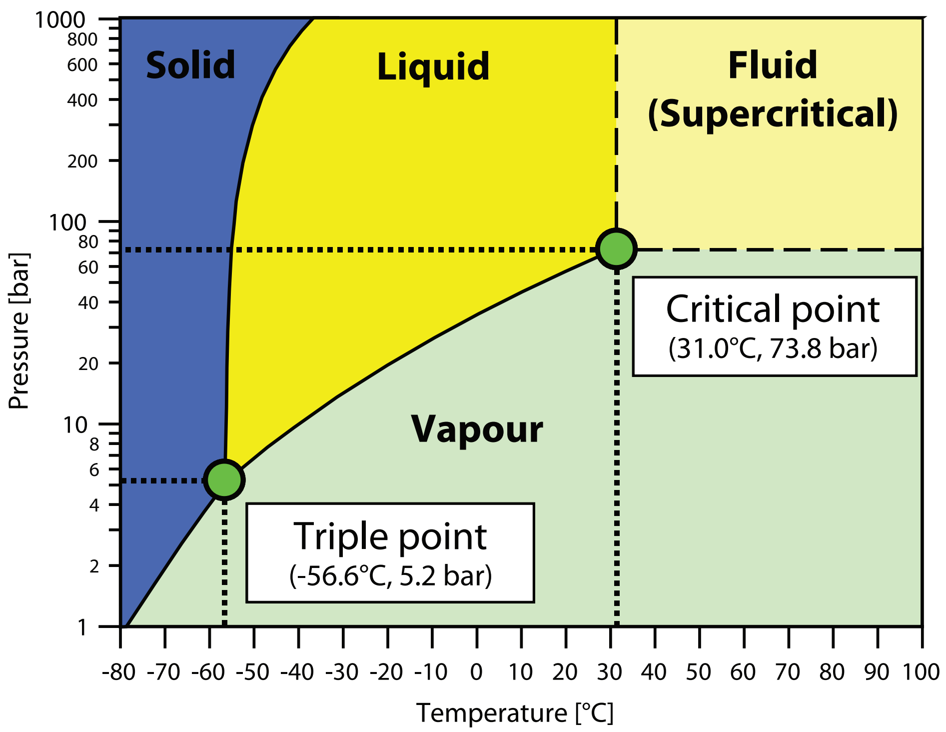


Figure 1: Phase diagram for R-744

Figure 1 shows a phase diagram of R744. The three well-known phases: solid, liquid and vapour are shown as coloured areas. A phase change occurs when a process crosses a boundary between areas - like evaporation or condensation for a process crossing the boundary between liquid and vapour phases. At the boundaries, the two phases exist in equilibrium, and properties, such as temperature and pressure, become dependent. The boundary line between liquid and vapour are often referred to as the vapour pressure curve.

Two important state points are marked in the figure: the triple point and the critical point. The triple point represents the condition where all three phases can co-exist in equilibrium. At temperatures below the triple point temperature, liquid can not exist - in other words the triple point temperature sets the lower temperature limit for any heat transfer process based on evaporation or condensation. At the other end of the vapour pressure curve, the critical point marks the upper limit for heat transfer processes based on evaporation or condensation.

At temperatures and pressures higher than those at the critical point, no clear distinction can be drawn between what is called liquid and what is called vapour. Thus there is a region extending indefinitely upward from, and indefinitely to the right of, the critical point –and this region is called the fluid region. The fluid region is bounded by dashed lines that do not represent phase changes, but which conform to arbitrary definitions of what is considered a liquid and what is considered vapour [1]. A condition in the fluid region is referred to as a supercritical condition – or very often also as a gas condition.

All substances have a triple point and a critical point - but for most of the substances used as refrigerants, the triple point and critical point are found for conditions that lie outside the region where they are normally used.

The term "critical point" has been the cause of misunderstandings as the word "critical" today often is used in the sense of "dangerous" or "serious". Its use to describe a specific state point of a substance can therefore incorrectly associate the use of this substance (e.g. as refrigerant) at conditions close to this state point with specific danger. Instead, the term "critical" should be interpreted as "difficult" - describing e.g. practical problems related to distinguishing between liquid and vapour at conditions close to - or at - this state point.

Refrigerant	Critical pressure [bar]	Critical temperature [°C]
R22	49.9	96.1
R134a	40.6	101.1
R404A	37.3	72.0
R410A	49.0	71.4
R600a (Isobutane)	36.4	134.7
R717 (Ammonia)	113.3	132.3
R744 (Carbon dioxide)	73.8	31.0

Table 1: Critical properties of selected refrigerants

Table 1 compares the critical pressure and temperature of a number of refrigerants. Typically, refrigerants have critical temperatures above 90°C but some of the refrigerants often used today (e.g. R404A, R410A and R744) have critical temperatures below that.

For R134a the critical temperature is found to be 101.1°C. This means that for R134a heat rejection processes by condensation can be established at temperatures up to 101.1°C. This temperature is higher than necessary for rejecting heat to the atmosphere for almost all refrigeration applications.

For R744 the critical temperature is only 31.0°C. This means that for R744 heat rejection process by condensation can only be established at temperatures up to 31°C. This temperature is much lower than necessary for rejecting heat to the atmosphere for many refrigeration applications. Considering the temperature difference needed in the heat exchanger, a practical upper limit for a heat rejection process based on condensation is reached at temperatures 5 to 10 K below the critical temperature.

For many refrigeration applications, the ambient temperature will exceed a level of 25°C, making it practically impossible to reject heat by condensing carbon dioxide. However, this doesn't mean that carbon dioxide cannot be used as a refrigerant in these applications. Carbon dioxide can indeed be used as a refrigerant for these applications - but the heat rejection process from these applications must be based on a different process than condensation.

Transcritical cycle process

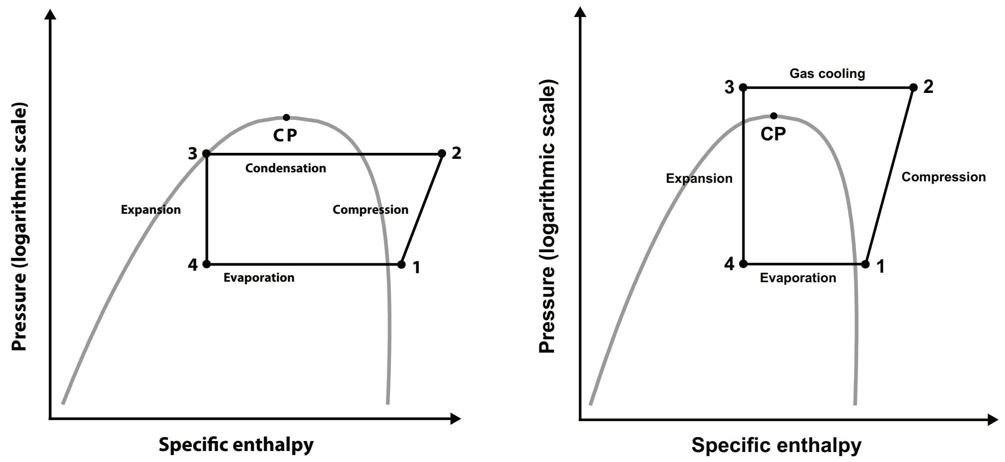


Figure 2: Subcritical and transcritical refrigeration cycle processes

Figure 2 shows two refrigeration cycle processes: one where the pressure in all parts of the process is kept below the critical pressure and one where the pressure during the heat rejection process is kept above the critical pressure.

Since the pressure in all parts of the first cycle process is below the critical pressure, such a process is referred to as a subcritical cycle process. The subcritical cycle process is the well-known traditional refrigeration cycle process. When parts of the cycle process take place at pressures above the critical point and other parts below the critical pressure the cycle process is referred to as transcritical cycle process.

Transcritical cycle process
(continued)

The terminology used for describing the processes and components are almost the same for the two cycle processes except for the heat rejection parts. In the transcritical cycle process, the heat rejection takes place at pressures and temperatures above the critical point – that is, in the fluid region. A condition in the fluid region is often referred to as a gas condition. For the transcritical cycle process, the heat rejection is therefore called gas cooling and subsequently the heat exchanger used is called a gas cooler.

Figure 3 shows a more detailed pressure-enthalpy diagram with a simple one-stage transcritical cycle process. The critical point is marked in the figure with a yellow dot. Colour (green and dark green) is used to indicate phases and transitions between them. The supercritical fluid region (gas) is coloured light green. System components have been included, and coloured according to the change of state for the refrigerant as it passes through them.

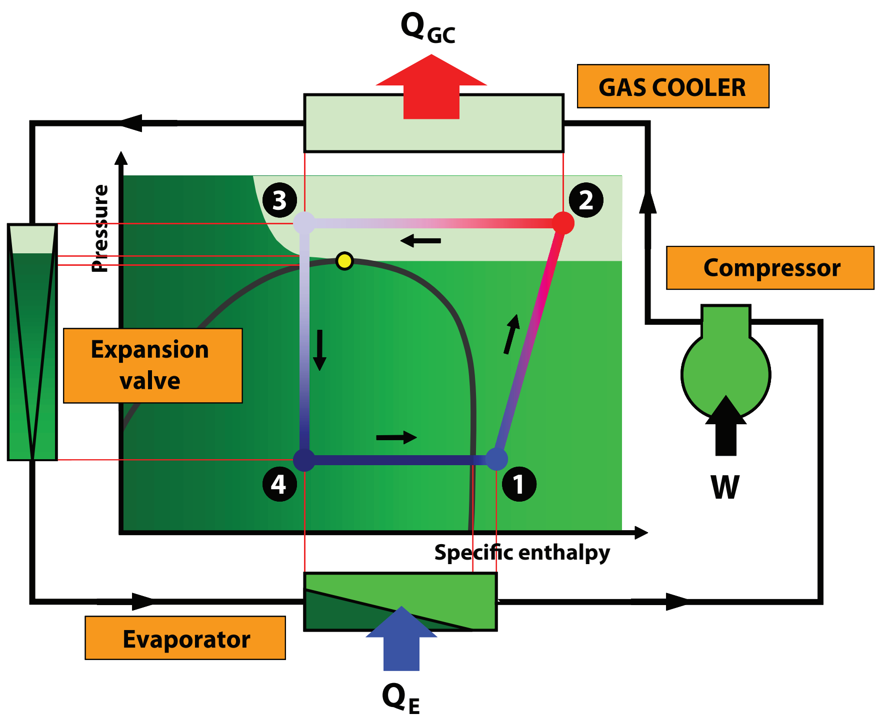


Figure 3: Transcritical cycle process & main system components

The transcritical cycle process begins with a one-stage compression from state point 1 to 2. During this process, the temperature rises significantly – and, for carbon dioxide, can reach a level of 130°C.

The heat rejection process from state point 2 to 3 occurs at constant pressure above the critical point. The temperature during this process varies continuously from the inlet temperature (at state point 2) to the outlet temperature (at state point 3).

The expansion process from state point 3 to 4 occurs at constant specific enthalpy. The inlet condition is supercritical (above the critical point) and the outlet is two-phase (mixture of liquid and vapour).

The heat absorption process (evaporation) from state point 4 to 1 occurs at constant pressure, and the evaporation part also at constant temperature. The outlet condition (compressor inlet condition) is slightly superheated.

The flow of heat and work is marked in the figure with arrows. The evaporator heat transfer rate is Q_E and the compressor power consumption is W. The heat transfer rate in the gas cooler is Q_{GC} - and ideally the energy balance gives $Q_{GC} = Q_E + W$.

Specifying the operating conditions of a transcritical refrigeration cycle is different than for subcritical cycle processes. For subcritical processes, it is normally only necessary to specify evaporating and condensing temperatures – and if more details are needed – also superheat and subcooling.

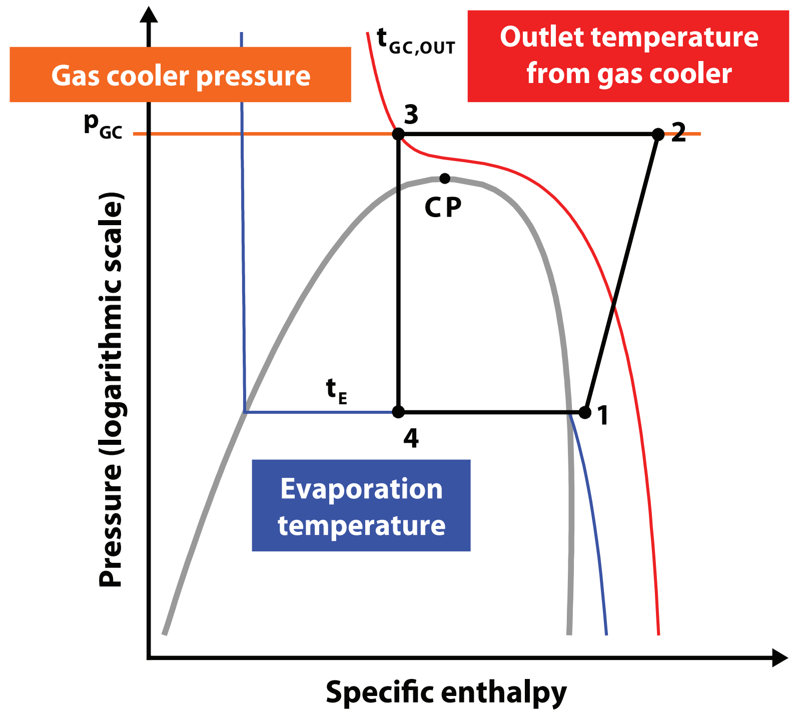


Figure 4: Pressure-Enthalpy Diagram for a transcritical refrigeration cycle process

Figure 4 shows a pressure-enthalpy diagram with a simple transcritical cycle process. Specifying the evaporating process is done the same way as for subcritical processes, using the evaporating temperature and superheat. In figure 4, the isotherm labelled t_E represents the evaporating temperature.

For the transcritical cycle process, there is no condensing process and consequently the terms condensing temperature and subcooling do not apply. Instead, the outlet condition of the gas cooler (state point 3) must be specified directly using temperature and pressure. In figure 4 the isotherm labelled $t_{GC,OUT}$ represents the temperature of the refrigerant after the heat rejection. In addition to specifying $t_{GC,OUT}$ the gas cooler pressure p_{GC} must also be specified. The intersection between the isotherm $t_{GC,OUT}$ and the isobar p_{GC} identifies the outlet condition (state point 3).

Effect of gas cooler pressure on system performance

The operation of a transcritical refrigeration system using R744 is, in many respects, different from the operation of a subcritical refrigeration system using a traditional refrigerant such as R134a.

In the subcritical refrigeration cycle process, the heat rejection process involves condensing of the refrigerant. A large part of the condenser volume on the refrigerant side will therefore be occupied by a two-phase mixture of liquid and vapour. For a two-phase mixture in thermal equilibrium, the pressure will be the saturation pressure at the temperature of the mixture.

For a transcritical process, the heat rejection process does not involve condensing but only cooling of a gas in the fluid region. Consequently, the temperature of the refrigerant will change continuously throughout the entire heat rejection process. Because this is not a phase change process, the temperature and pressure become independent. So what then determines the pressure in the gas cooler?

In a simple system without receiver the answer is: the refrigerant charge. In a system with a fixed restriction expansion device (e.g. capillary tube), the pressure in the gas cooler will depend on how much refrigerant the system is charged with and its distribution between the components. Having concluded that it is the charge of refrigerant that determine the gas cooler pressure, the obvious next question must be: Does the gas cooler pressure have an influence on capacity and energy efficiency of the system?

Figure 5 illustrates how the gas cooler pressure influences the cycle process. In the figure three different cycle processes are represented. They all have the same evaporating temperature, same evaporator outlet/compressor inlet condition and the same gas cooler outlet temperature. The compression process for all three cycle processes is assumed to be reversible and adiabatic (ideal = isentropic efficiency equal to 1).

The main difference between the three cycle processes is the gas cooler pressure.

Effect of gas cooler pressure on system performance
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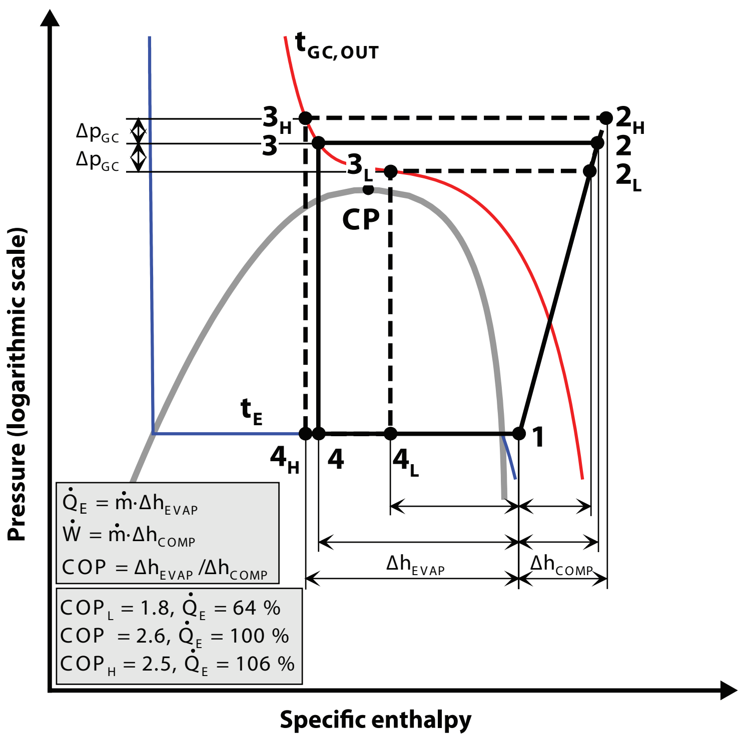

Figure 5: Influence of gas cooler pressure on cycle process

Figure 5 illustrates the changes in state point locations and cycle performance as the gas cooler pressure is either increased or decreased from a nominal value. The cycle process with the nominal gas cooler pressure is referred to as the nominal cycle process. The state points with index L represent the cycle with a lower pressure, state points with index H represent the cycle with a higher pressure.

The numbers in the figure show the consequences of a change of app. ±5 bars in the gas cooler pressure. The influence on cycle refrigerating capacity can be observed by comparing the changes in specific enthalpy in the evaporator Δh_{EVAP}. For the cycle process with a lower pressure, the refrigerating capacity is only 64% of that of the nominal cycle process. For the cycle process with a higher pressure, the capacity is 106% of that of the nominal cycle process. This shows that the gas cooler pressure has a significant influence on the refrigerating capacity.

The influence of gas cooler pressure on compressor power consumption can be observed by comparing the changes in specific enthalpy in the compressor Δh_{COMP}. The pressure change of ±5 bars causes changes in the compressor power consumption of app. ±10%.

Together the changes in refrigerating capacity and compressor power consumption cause changes in the Coefficient of Performance (COP). The figure shows that the gas cooler pressure has a significant influence on the COP. For the nominal cycle process, the COP is 2.6, but for both the processes with higher and lower gas cooler pressures, the values for COP are lower, indicating that an optimum gas cooler pressure exists.

Figure 6 shows the variations in refrigerating capacity and COP for a system operating with constant evaporating temperature, superheat and gas cooler outlet temperature. The figure is based on simulation using mathematical models of the components. The model of the compressor reflects "true" compressor behaviour – meaning isentropic and volumetric efficiencies vary with the operating conditions.

It can be seen that the optimum condition for refrigerating capacity is found for a higher gas cooler pressure than for the optimum condition for COP. For a system operating at conditions close to the optimum COP, the extra refrigerating capacity that can be obtained by increasing the gas cooler pressure is relatively small - normally only a few percent.

In almost all practical applications the operating conditions (evaporating temperature, superheat and ambient temperature) will vary. Consequently the optimum gas cooler pressure also varies. Depending on the application, and also magnitude and duration of the variations in operating conditions, different types of high pressure control must be used to ensure efficient and economical operation.

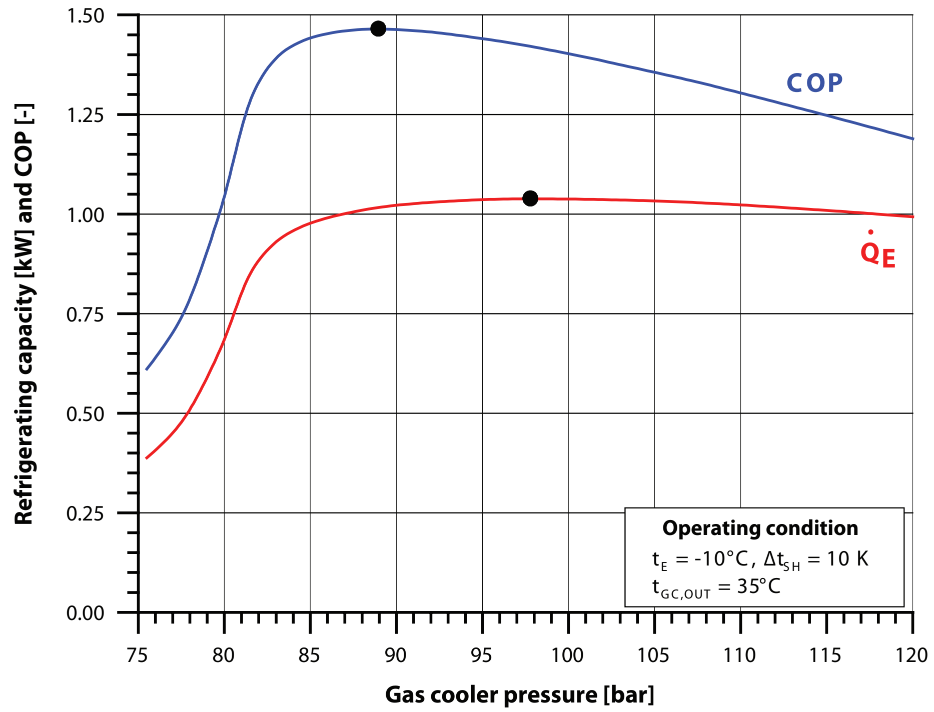

Figure 6: Effect of gas cooler pressure on refrigerating capacity and COP

System design

Figure 7 shows a pipe diagram for a very simple transcritical system. The system consists of a compressor, a gas cooler, an evaporator, and an expansion device.

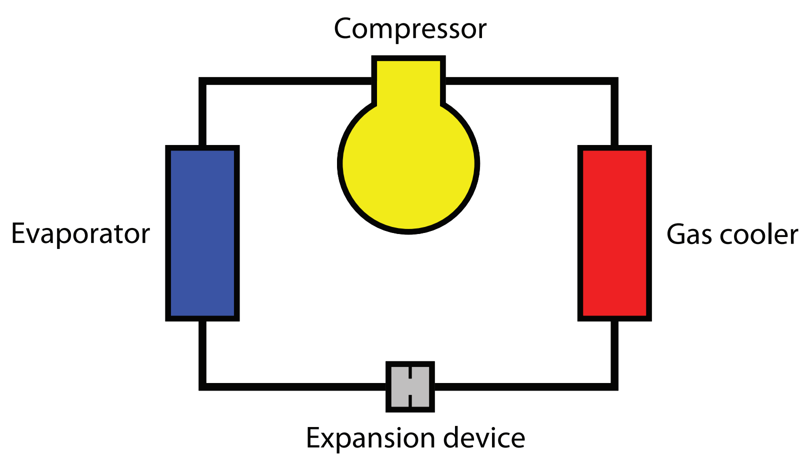

Figure 7: Layout of simple refrigeration system for transcritical operation

The most simple expansion device that can be used is a fixed flow restriction (e.g. an orifice or a capillary tube). In such a system, the high pressure is not controlled and the system will consequently only be operating with the optimum high pressure - and maximum efficiency (or capacity) - at one single operating condition.

Use of an internal heat exchanger between the suction line and the gas cooler discharge line can enhance the performance of the system (figure 8). If the expansion device is a capillary tube, the internal heat exchange can be established by soldering the capillary tube, or parts of it, to the suction line.

System design
(continued)

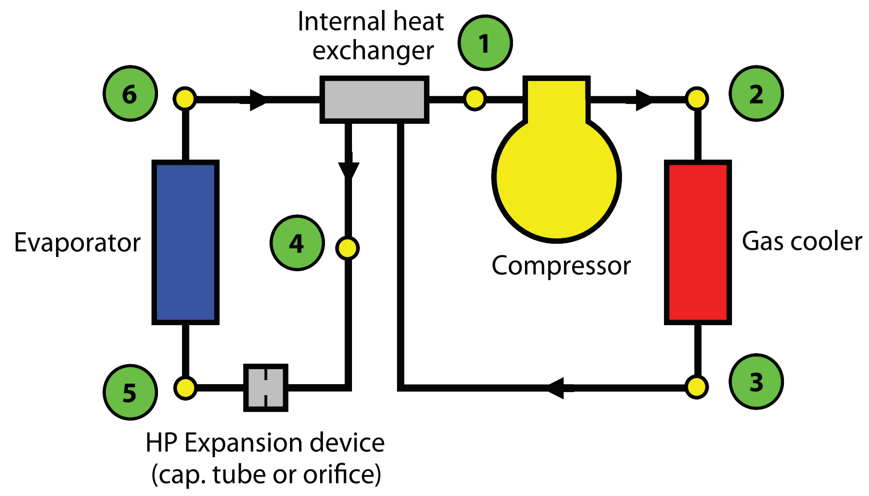

Figure 8: Layout of a transcritical refrigeration system with internal heat exchanger and fixed flow restriction as expansion device

The layout shown in figure 8 can be used for systems that operate with medium variations in ambient temperature but with requirements for capacity or efficiency at only one fixed rating point.

When the operating conditions change (e.g. ambient temperature, or evaporating temperature during a pull-down of refrigerated cabinet), the distribution of the refrigerant between the components will change thus the gas cooler pressure also changes. For uses requiring high variability in operating conditions and that must satisfy capacity and efficiency requirements under varying operating conditions, and meet capacity and efficiency requirements at varying operating conditions, high pressure control devices must be used. In addition, it may be necessary to install a low-pressure receiver to compensate for the charge variations on the high-pressure side.

For simple systems, it is possible to use the expansion device as the high pressure control device, and omit control of refrigerant flow into the evaporator.

Full control flexibility can be obtained with a system using an electronic expansion valve and an electronic system controller receiving information about one or more temperatures and pressures in the system. The figures show a controller receiving information about gas cooler outlet pressure and temperature, but much more advanced controllers could be envisioned. The complexity of the controller and the number of sensors/transducers can be selected according to the specific purpose of the system.

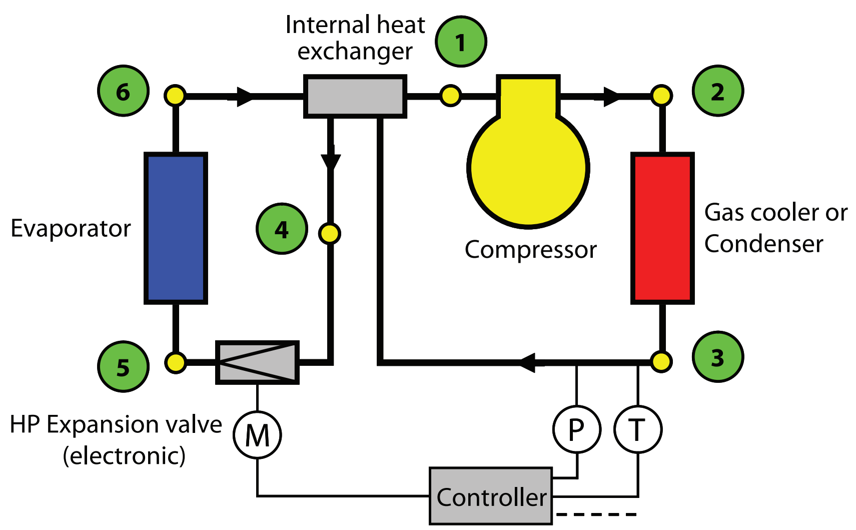

Figure 12: Layout of a transcritical refrigeration system with internal heat exchanger and an electronically controlled valve as expansion device

The layout shown in figure 12 can be used for systems that operate with large variations in ambient conditions and with extreme requirements for capacity or efficiency at all operating conditions. Often it is only for systems that are to be analysed experimentally in a laboratory that such control flexibility is necessary.

Other system configurations than the ones shown in this document are possible. The choice of system configuration depends on the requirements for performance under a given set of design conditions – or maybe even within a given application design envelope.

The design and use of receivers and pressure control devices for transcritical systems are covered by a number of patents. References to a few of these patents can be found later in this document [2], [3], and [4]. It is strongly advised to conduct a thorough patent search and analysis before making a specific transcritical refrigeration or air conditioning system commercially available.

System components

Expansion device

Depending on the location and type of system, variation in ambient conditions as well as variations in load, a specific type of expansion device can be recommended.

A general description of the mechanisms that can be employed for expansion is given in the System Design section of this guide.

Gas cooler

The gas cooler design has to be adapted to the application of CO_2 as refrigerant. Aside from the high pressures of up to 137 bars, there are two further issues that must be addressed:
a) The gas cooler outlet temperature of the CO_2.
b) The temperature change of the CO_2 during the cooling.

The gas cooler outlet temperature of the CO_2 has to be as low as possible in order to obtain the highest capacity and the best COP. This effect has been described in section "Effect of gas cooler pressure on system performance". The complete heat exchange between the gas cooler and the air has to be counter-current flow or cross-counter-current. The last tubes with the refrigerant before leaving the gas cooler should be located where the coldest air is entering.

Unlike condensers where most of the heat exchange takes place at a constant temperature, the temperature of the CO_2 steadily drops while the refrigerant flows through the gas cooler. This also means that the part of the gas cooler where the CO_2 enters into the gas cooler has a higher temperature than any other part while the lowest temperature occurs at the exit. With a standard design, heat would flow from the warmer parts to the colder parts of the gas cooler. This would not only lower the ability to reject heat to the ambient but also result in an increased temperature of the CO_2 leaving the gas cooler. To minimize this heat flow, the thermal contact between the gas cooler sections has to be minimized as shown in figure 13.

To get the air-flow as cold as possible to the gas cooler, the compressor should be located in the air flow behind the gas cooler. For optimum efficiency, the temperature of the CO_2 when leaving the gas cooler should not be more than 2-3 K above the temperature of the ambient air before entering the gas cooler.

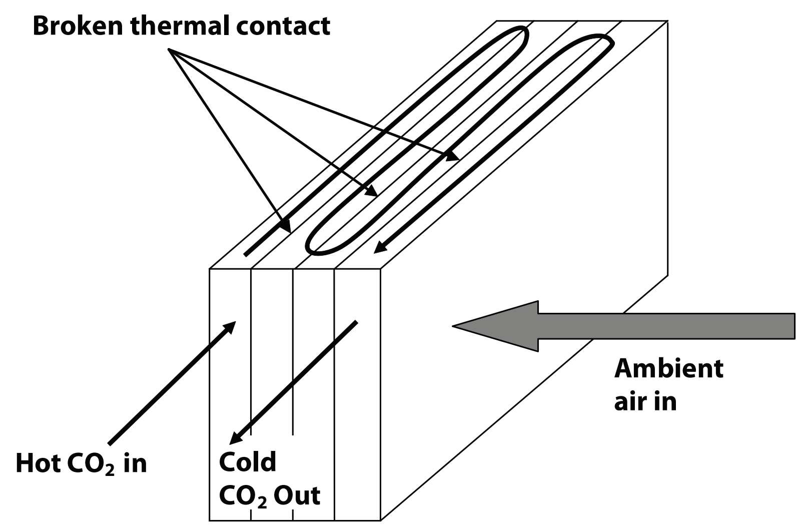

Figure 13: Principle of gas cooler design to avoid internal heat flow and to minimize the refrigerant exit temperature

Filter drier

In fluorinated refrigeration systems, filter driers are commonly used to remove water, usually the type with a zeolite core. The zeolite has extremely small pores, and acts like a molecular sieve. Water molecules are small enough to penetrate the sieve, and being very polar, they are adsorbed inside the zeolite molecules. R134a molecules are too large to penetrate the sieve. When the replaceable core is removed, the water goes with it.

CO_2 is a non-polar molecule, so the removal process is different. Like water molecules, CO_2 molecules are small enough to penetrate the molecular sieve. However, the water molecules adsorbed onto the molecular sieve, act in such a way as to "kick out" the CO_2 molecule, due to the difference in polarity. Even though the driers function differently in this respect in CO_2 systems, the efficiency is fairly good.

Activated alumina is often used in filter driers to remove acids produced in the reaction between oil and water. However, many of the reactions that produce acids will not take place in a well-maintained CO_2 system, where the water content is below the maximum solubility limit. Therefore, Danfoss recommends 100% MS for use with CO_2 to maximize water removal. For more information about filter driers available for CO_2 systems please contact Danfoss.

Piping

Due to the high volumetric capacity of CO_2 tubes with a smaller diameter than in conventional systems of similar capacity can be used.

Smaller diameters should be preferred as they decrease the refrigerant charge and withstand higher pressures. For the existing range of TN compressors, in most cases a tube of 6 x 1 mm will be sufficient. The maximum working pressure of the tubes must be observed (table 2).

Diameter [mm]	Max. allowable working pressure [bar]	Diameter [inch]	Max. allowable working pressure [psig]
6 x 1	200	1/4	775
8 x 1	143	3/8	662
10 x 1	111	1/2	613
12 x 1	91	5/8	537
15 x 1	71	3/4	495

Table 2: Maximum allowable working pressure for standard copper tubes as used in refrigeration

Safety components

A burst disc may be integrated into the discharge of the compressor opens if the pressure of the system exceeds the maximum working pressure. It is strongly recommended to additionally integrate a pressure switch, such as Danfoss Saginomiya CCB that cuts off the compressor before the burst disc would open to release the refrigerant and make the system operational.

It is strongly recommended to install a safety device like a burst disc or a pressure relief valve in each section of the refrigeration system that can be separated from the existing safety device, e.g. by closing a valve.

System handling

Refrigerant grades

To avoid problems caused by too high water content in the CO_2, it is recommended to keep the concentration below the max. solubility limit. CO_2 with maximum 10 ppm water is suitable for common used CO_2 systems.

Evacuation

Due to the low acceptable water concentration, the evacuation process of the system is very important.

The same vacuum pump and procedure can be used for all refrigerants if it is charged with ester oil.

Charging

It is important to start up with CO_2 in the vapour phase and continue until the pressure has reached approximately 5 bars. One must be aware when charging a refrigerant system that, until the pressure reaches the triple point, the CO_2 can only exist as a solid or vapour inside the refrigeration system. Also, the system will exhibit very low temperatures until the pressure is sufficiently raised. For example, at 1 bar, the sublimation temperature will be –78.4°C.

Material compatibility

CO_2 is compatible with almost all common metallic materials, like the fluorinated refrigerants. There are no restrictions in terms of compatibility, when using copper or brass.

The compatibility of CO_2 and polymers is much more complex. Because CO_2 is a very inert and stable substance, the chemical reaction with polymers is not critical. The main concern with CO_2 is the physiochemical effects, such as permeation, swelling and the generation of cavities and internal fractures. These effects are associated with the solubility and diffusivity of CO_2 in the actual material.

Danfoss has carried out a number of tests to ensure that components released for use with CO_2 can withstand the impact of CO_2 in all aspects.

Tests have shown that CO_2 is different, in particular when it is used in transcritical application, where a large amount of CO_2 can dissolve in polymers, has to be taken into consideration.

Only a few specific types of polymers are suitable for use as sealing materials in transcritical CO_2 components.

Water in CO_2 systems

In figure 14, the water solubility in the vapour phase of different refrigerants is shown. The acceptable level of water in CO_2 systems is much lower than with other common refrigerants. The diagram in figure 15 is shows the solubility of water in both liquid and vapour phases of the CO_2 as a function of temperature. The solubility in the liquid phase is much higher than in the vapour phase. Below these levels, water remains dissolved in the refrigerant and does not harm the system. Water (H_2O) molecules are dissolved if the concentration is lower than the maximum solubility limit, but if the water concentration is higher than the maximum solubility limit, the H_2O molecules precipitate out of the solution into droplets.

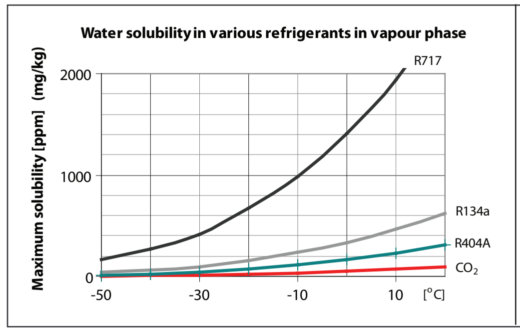

Figure 14: Water solubility of various refrigerants

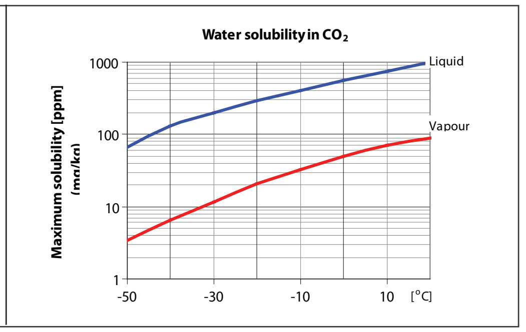

Figure 15: Water solubility of CO_2

If the water is allowed to exceed the maximum solubility limit in a CO_2 system, problems may occur, especially if the temperature is below 0°C. In this case, the water will freeze, and the ice crystals may affect the operation of e.g. control valves.

In small hermetic transcritical CO_2 systems, water is generally not a major problem. These systems do not normally operate at very low temperature, and do not have sensitive control equipment.

To avoid unforseen problems with water in CO_2 systems, a molecular sieve filter drier can be used.

Safety and design

Safety

CO_2 is a non-flammable and non-toxic fluid. However, if the concentration of CO_2 exceeds a certain level, the amount of oxygen in the atmosphere for breathing is reduced. In extreme cases this can be fatal. The CO_2 cannot be noticed as it does not have an odour that can be detected by humans.

CO_2 is heavier than air, so highest concentration levels will be found close to the bottom. Especially for systems installed below ground level, there is a risk of a high CO_2 concentration in the event of a leakage. The installation of a CO_2 sensor with an alarm is recommended.

The second safety issue with CO_2 involves the higher pressures by comparison with the traditional refrigerants. In the transcritical cycle, the discharge pressure will be between 80 and 120 bars. The pressure at the low-pressure side depends on the evaporation temperature but during off-conditions, the standstill pressure can be significantly higher.

All components must be designed for the adequate pressures. For this, all relevant national and international laws, regulations, and standards must be followed. Safety devices such as burst discs and pressure relief valves or pressure cut-outs are recommended to cover unintended operational conditions.

After assembling the system, it is necessary to conduct a pressure test to ensure that all soldered connections are tight. The use of a pressure switch will avoid exceeding the pressure limit, which may lead to an accident. In the discharge muffler, a burst disc that opens if the pressure exceeds 130 bars +/- 5% has been integrated. This pressure is the maximum allowable pressure (PS). The test pressure must be 1.43 x PS.

Safety standards

When this paper was prepared, no international standard had been established explicitly covering hermetic or semi-hermetic type motor compressors for CO_2 or appliances for household and similar applications with a CO_2 transcritical cycle.

There are some standards such as EN378 covering also systems with CO_2 as refrigerant. It may be necessary to comply with other national or safety regulations such as PED when setting up, operating, servicing or in another way working with a CO_2 system.

Danfoss has tested its components to its best knowledge. But as safety conditions for the products are not definitive, the user must ensure that the system is safe.

References

[1] "Theory and ", M.M. Abbott & H.C. van Ness, Schaum's outline series, McGraw-Hill, Second edition, 1989.
[2] "Control of high-pressure in transcritical vapour compression cycle", EP 0 604 417 B1
[3] "Method of operating a vapour compression cycle under trans- or supercritical conditions", EP 0 424 472 B2.
[4] "Refrigerating system with pressure control valve", WO 5890370

Article Transcritical Refrigeration Systems with Carbon Dioxide (CO_2)

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HFC-free cooling fluids are becoming increasingly popular as companies are looking for ways to reduce their carbon footprint. With Danfoss by your side you are perfectly capable of accommodating every customer specification. Our range of refrigeration solutions comprises components specially developed for the handling of CO_2 and hydrocarbons.

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