MAKING MODERN LIVING POSSIBLE

Food Retail CO_2 Refrigeration Systems

Designing subcritical and transcritical CO_2 systems and selecting suitable Danfoss components

REFRIGERATION &
AIR CONDITIONING DIVISION

Application Handbook

Contents **Page**

Introduction to this handbook

In recent years, CO_2 has become an increasingly important refrigerant in the food retail business area. Most important to this development, is that CO_2 is one of the few sustainable refrigerants for supermarket systems from an environmental and safety perspective.

The purpose of this handbook is to give an overview of typical CO_2 system designs for both subcritical and transcritical applications. Additionally, this document can be used as a reference guide to Danfoss components for CO_2. The target group for this handbook is engineers who are new to CO_2 systems. The first 7 chapters of the application handbook describe the building blocks of CO_2 systems while chapters 8 to 10 cover the design of the complete systems.

It also needs to be mentioned that this handbook is not an ultimate design guide for CO_2 systems. When creating an actual design, it is highly advantageous to use calculation software for components such as DIRcalc^{TM} and to use Danfoss technical leaflets as well as other relevant literature or software. Should you have any questions, please contact your local Danfoss sales office.

Additional information can also be found on the Danfoss web page www.danfoss.com/co2

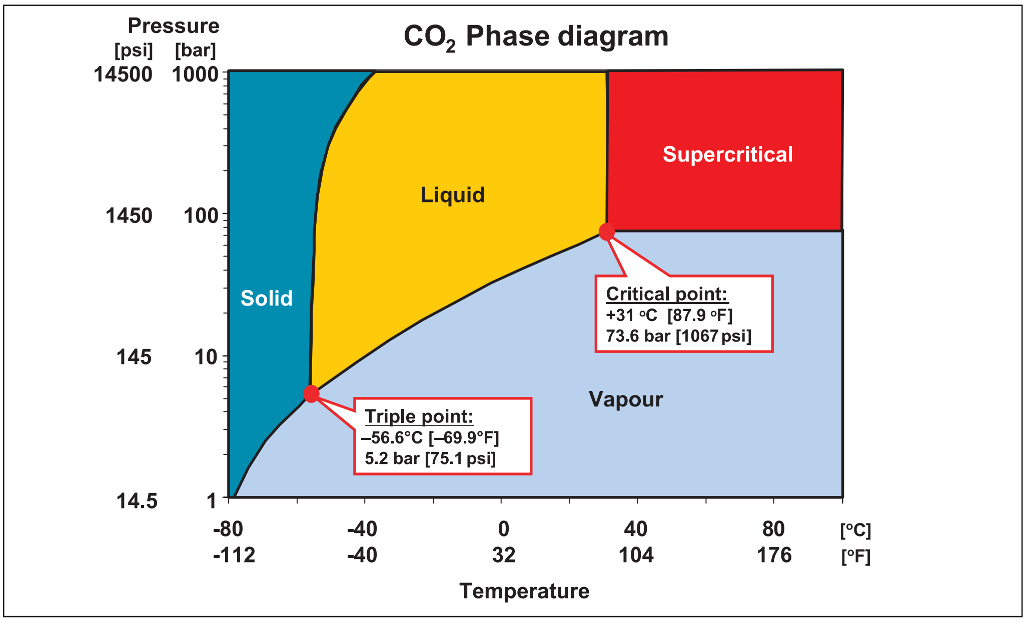
Characteristics of CO_2

The below figure shows the temperature pressure phase diagram of pure CO_2. The areas between the curves define the limits of temperature and pressure at which different phases can exist: solid, liquid, vapour and supercritical fluid.

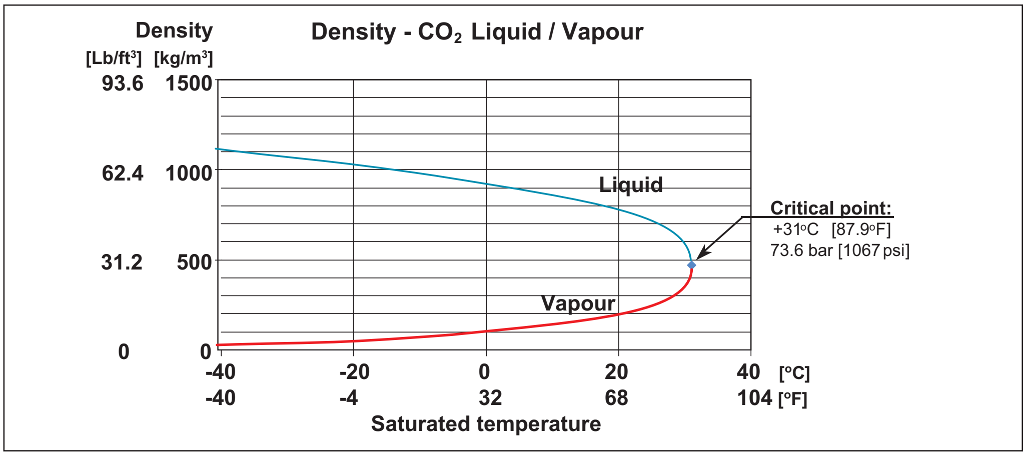
´The points on these curves indicate the pressure and corresponding temperatures under which two different phases can exist in equilibrium e.g. solid and vapour, liquid and vapour, solid and liquid. At atmospheric pressure CO_2 can exist only as a solid or a vapour.

At this pressure, it has no ability to form a liquid: below –78.4°C [–109.1°F], it is a solid “dry ice”; above this temperature, it sublimates directly to a vapour phase.

At 5.2 bar [75.1 psi] and –56.6°C [–69.9°F], CO_2 reaches a unique state called the triple point. At this point all 3 phases i.e. solid, liquid and vapour exist simultaneously in equilibrium.



CO$_2$ as a refrigerant



CO$_2$ reaches its critical point at 31.1°C [88.0°F]. At this temperature, the density of the liquid and vapour states is equal. Consequently, the distinction between the two phases disappears and this new phase, the *supercritical* phase, exists.

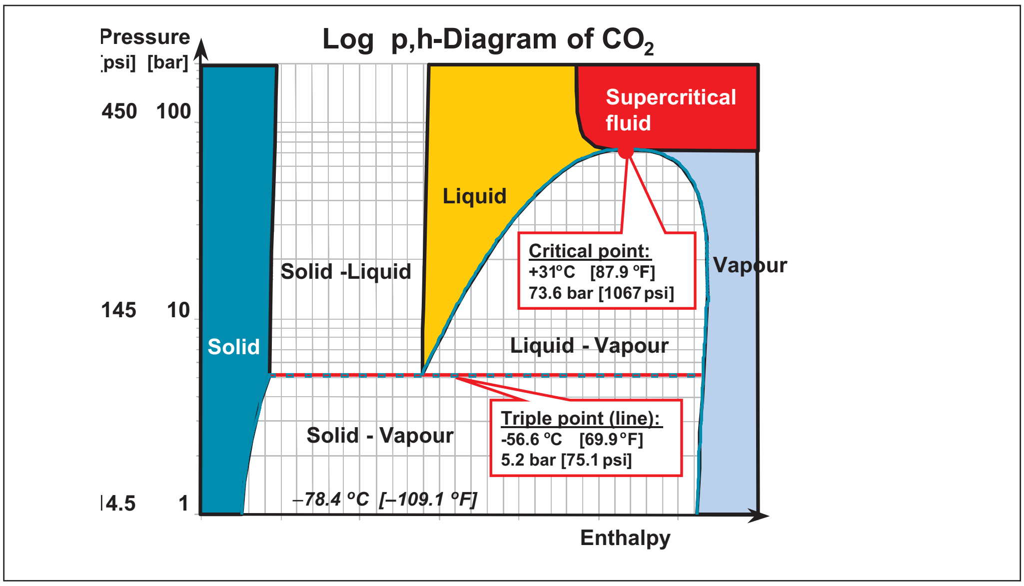
Pressure-enthalpy diagrams are commonly used for refrigeration purposes. The above diagram is extended to show the solid and supercritical phases.

CO$_2$ may be employed as a refrigerant in a number of different system types including both subcritical and transcritical. For any type of CO$_2$ system, both the critical point and the triple point must be considered.

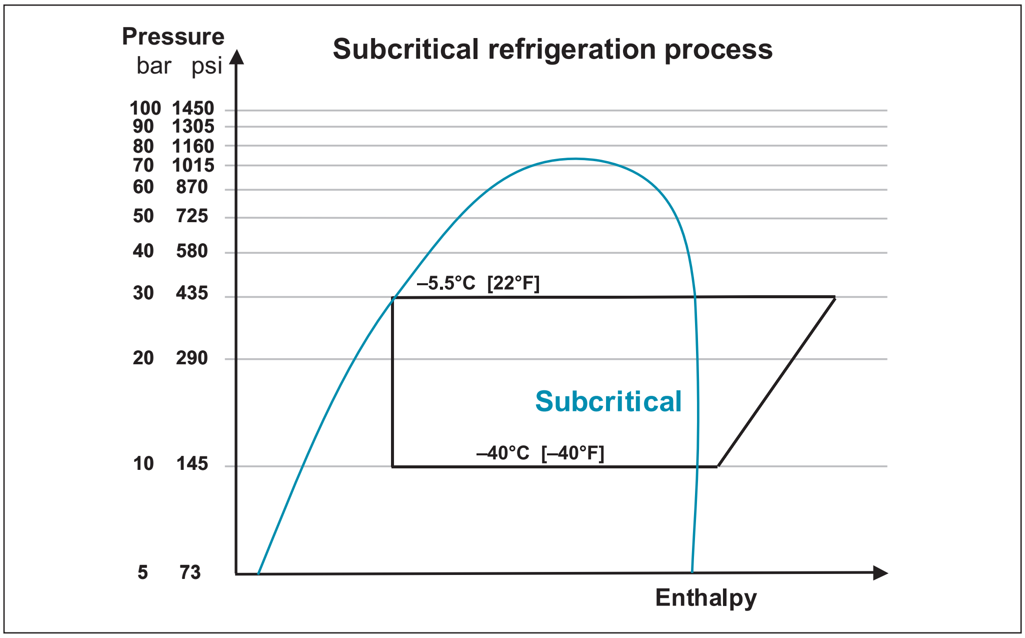
The classic refrigeration cycle, we are all familiar with, is subcritical i.e. the entire range of temperatures and pressures are below the critical point and above the triple point.
A single stage subcritical CO$_2$ system is simple but it also has some disadvantages because of its limited temperature range and high pressure.

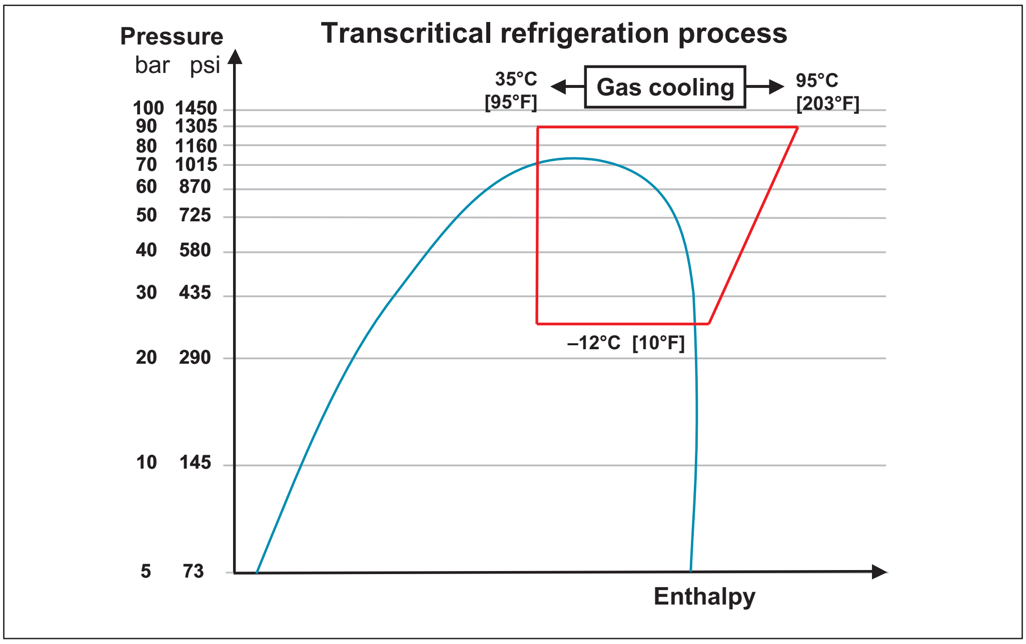
Transcritical CO$_2$ systems are, at present, only relevant for small and commercial applications e.g. mobile air conditioning, small heat pumps, and supermarket refrigeration and not suitable for industrial systems.

Operating pressures for subcritical cycles are usually in the range of 5.7 to 35 bar [83 to 507 psi] corresponding to –55 to 0°C [–67 to 32°F]. If the evaporators are defrosted using hot gas, then the operating pressure is approximately 10 bar [145 psi] higher.



CO_2 as a refrigerant (Continued)





CO_2 is most commonly applied in cascade system designs in industrial refrigeration because its pressure can be limited to such extent that commercially available components like compressors, controls and valves can be used.

CO_2 cascade systems can be designed in different ways e.g. direct expansion systems, pump circulating systems or CO_2 in volatile secondary "brine" systems or combinations of these.

1.
Gas cooler and intermediate pressure receiver

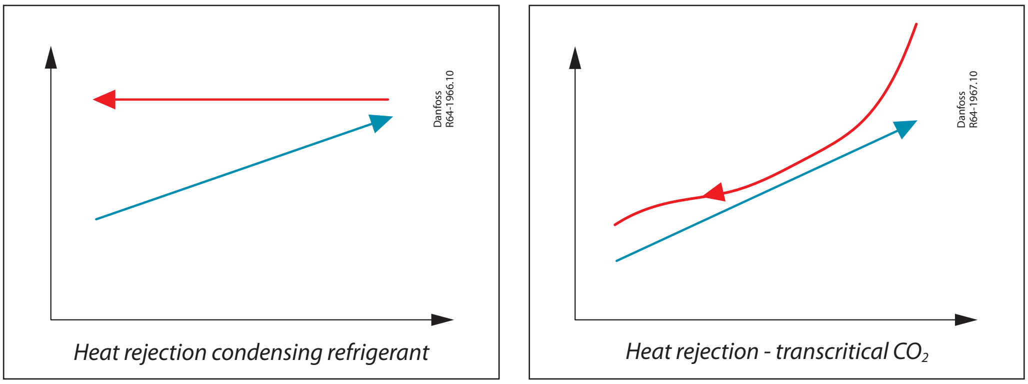
1.1 General description

The gas cooler is the component in a transcritical system that is the most different from a system with conventional refrigerants. It takes the place of the condenser in conventional refrigeration systems.

At temperatures higher than 31°C, CO_2 is not able to condense. Consequently pressure and temperature are no longer interdependent during the heat rejection process.

As CO_2 is not a changing phase, the temperature continues to decrease as CO_2 passes through the gas cooler.

The heat capacity of CO_2 also changes when CO_2 is cooled. This makes gas coolers different from both water-to-refrigerant heat exchangers, where the heat capacity is constant, and Condensers, where the heat capacity in the gas phase is relatively low and very high when gas starts to condense (fig. 1.1.1).



Heat rejection condensing refrigerant

Heat rejection - transcritical CO_2

Fig. 1.1.1

The heat rejection for condensing refrigerants happens at constant temperature and therefore the condensing temperature is determined by the exit temperature of the media used for cooling because the lowest temperature difference is at the media outlet.

For transcritical CO_2, the lowest temperature difference is not at the outlet but often at the media inlet or in between the gascooler inlet and outlet depending on the pressure and temperature set. Therefore it is possible to achieve very high temperatures using CO_2. To get the most out of the gas cooler, it is important to configure it as a counterflow heat exchanger.

The temperature difference between air and CO_2 cooling media in a gas cooler is typically half of what is normal for a condensing refrigerant.

Water, brine and air are the most commonly used media for cooling a gas cooler. In the next sections both types are described.

As the temperature of the cooling media typically is not constant in a gas cooler, the high side pressure can be optimised to maximise the COP (fig. 1.1.2). The pressure can thus be controlled dependent on the CO_2 outlet temperature from the gas cooler.

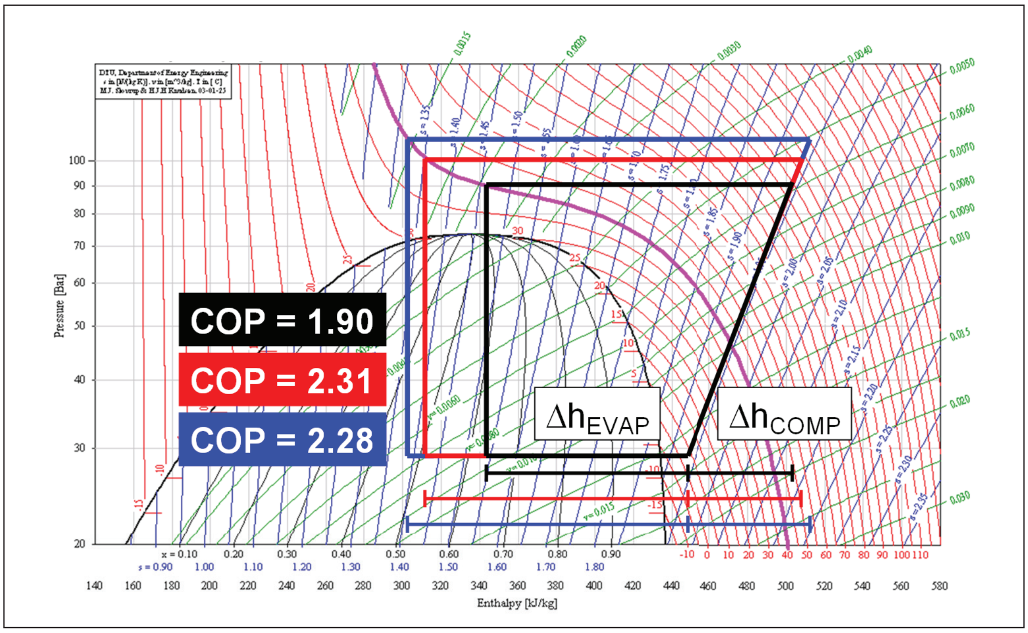


Fig. 1.1.2: Optimal COP in gas coolers

1.1 General description (Continued)

Pressure optimisation is done by the Danfoss EKC 326 controller and ICMT expansion valve that is installed on the outlet of the gas cooler. This design gives the possibility to optimise gas cooler pressure and intermediate receiver pressure independently.

The pressure in the receiver is one important parameter but the design of the receiver is also important because it typically acts as a liquid separator as well. In order to keep the intermediate pressure low, flash gas is expelled through a gas bypass valve to the suction side of the compressor. The 2 phase mixture from ICMT expansion valve has to be separated before gas enters the gas bypass. If the separation is incomplete, liquid will be carried through the gas bypass and into the high pressure compressor. Therefore the design of the receiver has to be considered very carefully.

A simple investigation of the intermediate pressure shows that the pressure has to be as low as possible to reduce the amount of liquid in the gas bypass line (fig. 1.1.3). Liquid may not only damage the compressor but also decrease the COP of the system and is therefore undesired. A pressure of 30-35 bar (-8°C/-10°C) is often chosen because the liquid fraction in the gas bypass is approx. 1-2 % which is not considered a practical problem and there is still a pressure difference of 4-10 bar which is sufficient for the AKV valves.

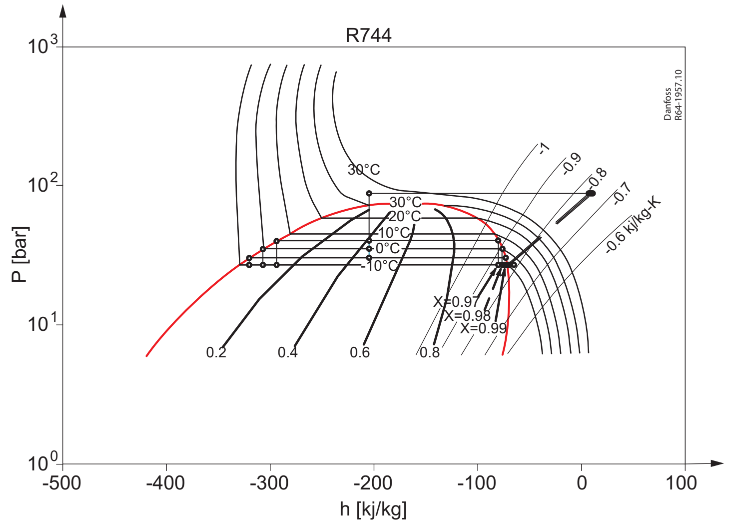
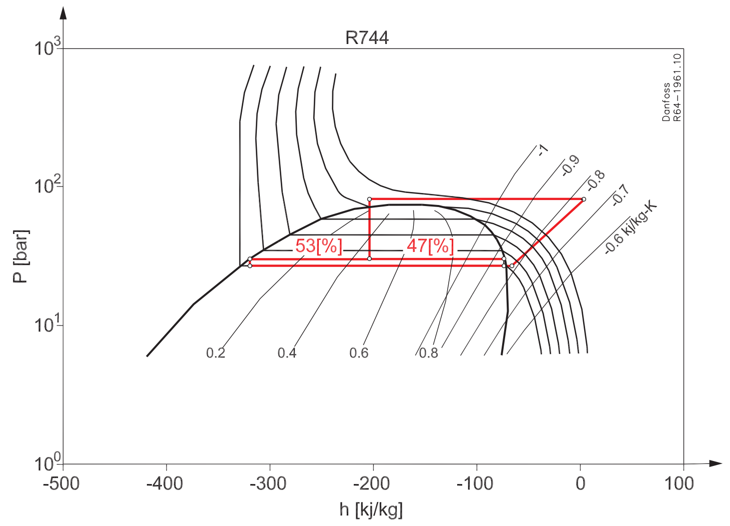


Figure 1.1.3: Cycle in log P-h diagram at 3 different intermediate pressures (30, 35 and 40 bar)

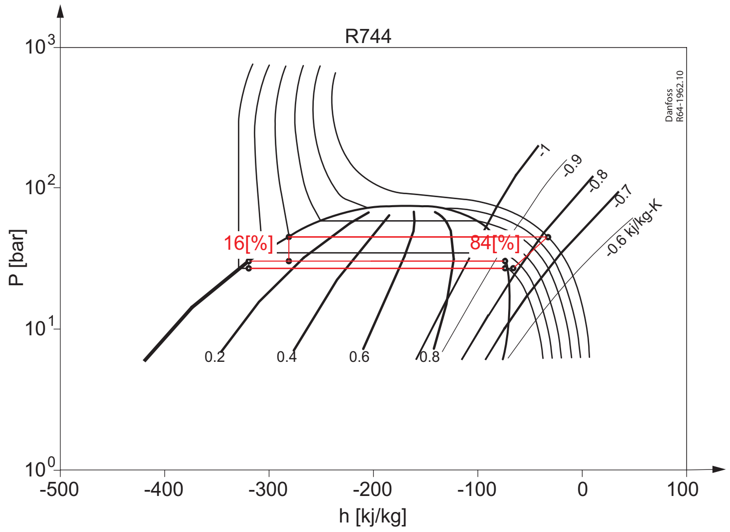
The pressure in the receiver is constant regardless of the ambient temperature but the flow ratio between the gas bypass and the liquid line varies with the pressure in the gas cooler and the gas cooler exit temperature (fig. 1.1.4 and fig. 1.1.5).



Transcritical operation

Figure 1.1.4: Liquid vapour fraction at 35°C outlet gas cooler/condenser

1.1 General description (Continued)



Subcritical operation

Figure 1.1.5: Liquid vapour fraction at 10°C outlet gas cooler/condenser

The decoupling of the ambient temperature and receiver pressure makes the flow in the evaporators only a function of the cooling capacity.

In transcritical systems without gas bypass, the mass flow varies by a factor of 2 due to the ambient temperature alone, which makes design of suction lines and oil return difficult.

1.2.1 Gas cooler control with EKC 326

The gas cooler control is relatively new in refrigeration systems and therefore has been subject to a lot of research during the past years. In this system the gas cooler controls had been divided into 3 sections.

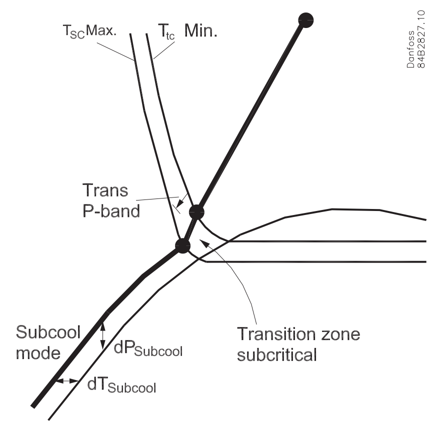


Figure 1.2.1: Gas Cooler controls in log P-h diagram

At low temperatures the system is controlled as a conventional refrigeration system where the subcooling is the control parameter (normally, control is not necessary with condensing refrigerants).

At temperatures approaching the critical point the algorithm changes, gradually increasing the subcooling to bridge the gap between conventional control and transcritical control.

At transcritical conditions, the pressure is a function of the temperature out of the gas cooler. The goal is to obtain as high a COP as possible at the given temperature.

The gas cooler fans are controlled by the CO_2 temperature out of the gas cooler. If the temperature is lower than the set point, the fans slow down. When no compressors are running, the fans stop as well.

In conventional systems the pressure is often used as a control parameter (as efficiency increases with the reduction of the condensing pressure) but on transcritical systems this can, during cold periods, increase the subcooling, resulting in too low pressure in the receiver and therefore no differential pressure for the expansion valves.

1.2.2 Water-cooled gas cooler

Water-cooled gas coolers are often used in heat pumps and supermarket systems where heat reclaim is a part of the system. Water-cooled gas coolers are characterised by high heat flux due to high heat transfer coefficients on both sides and are therefore very compact.

The high pressure is another thing that is different from conventional refrigerants. The requirement to withstand high pressures together with counter flow makes coaxial heat exchanges very well suited for gas coolers.

However, shell and tube and other similar types are closer to cross flow and therefore not suitable.

The internal volume of coaxial heat exchangers is very small compared to the capacity which, in turn, reduces the required receiver volume. This is especially important, since the change in refrigerant charge in the gas cooler varies greatly with pressure and temperature, magnifying the need for a heat exchanger with small internal volume.

High temperatures of CO_2 create a problem with limestone that needs attention. The discharge gas of some systems are as high as 160°C and together with the relatively high heat capacity and high heat transfer coefficient compared to other refrigerants, the wall temperature will be higher than that of other refrigerants.

Water flow in the system is controlled by an AVTA pressure operated water valve, which regulates according to the discharge temperature. CO_2 pressure is regulated by an ICMT valve and an EKC 326 controller taking an input from the AKS11 temperature sensor and the AKS32 pressure transmitter (Fig. 1.2.2).

🟥 HP vapour refrigerant
🟨 HP liquid refrigerant
🟦 LP vapour refrigerant
🟩 LP liquid refrigerant

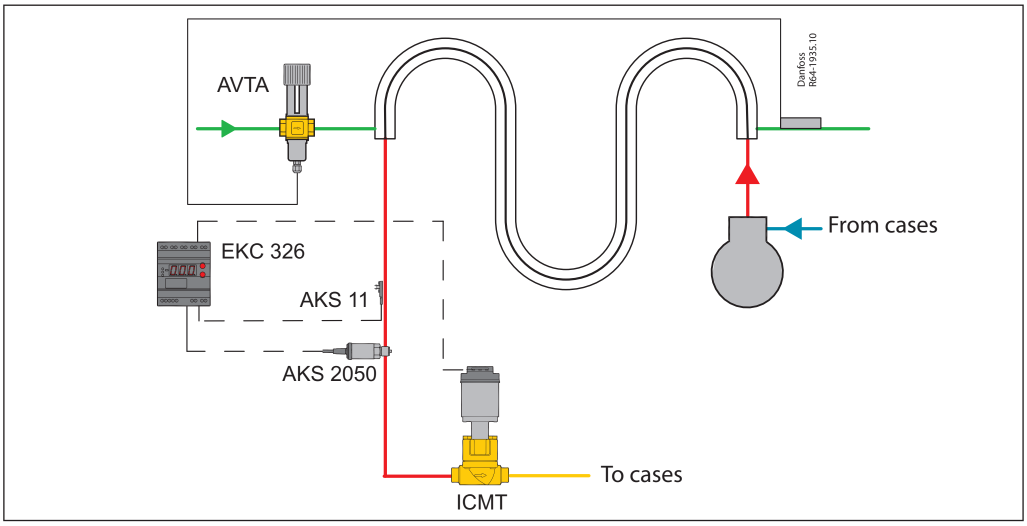


Figure 1.2.2: Water-cooled gas cooler

1.3 Air-cooled gas coolers

Air-cooled gas coolers are often used in refrigeration systems where there is no heat reclaim or only partial heat reclaim. Typically fin and tube gas coolers are used for CO_2. They have lower heat transfer coefficient on the air side and therefore the heat exchangers are often bigger and have a higher larger volume than water-cooled gas coolers.

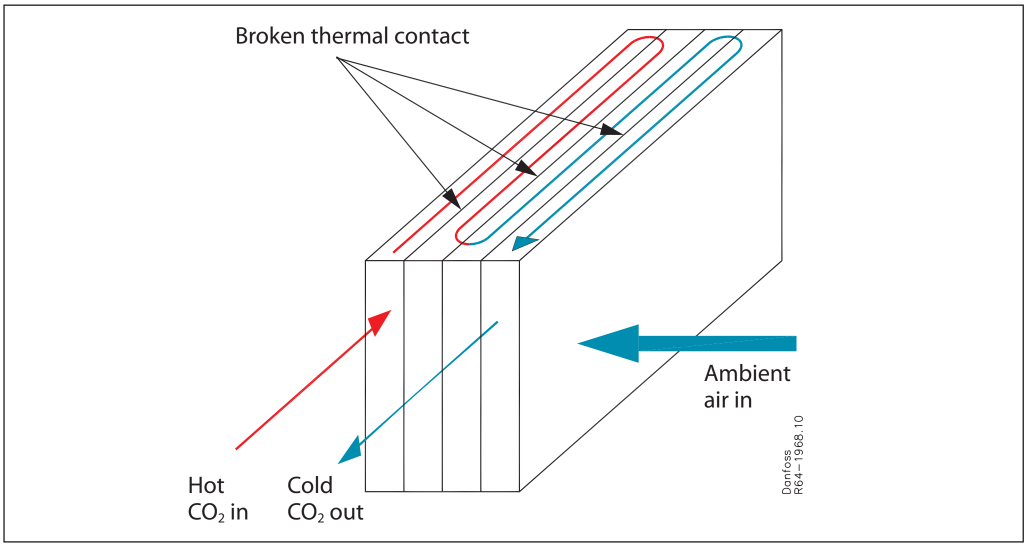


Figure 1.3.1

1.3 Air-cooled gas coolers (continued)

An interesting aspect with CO_2 is that the pressure drop does not influence the efficiency of the refrigeration cycle to the same extent as for conventional refrigerants and a pressure drop of 0.5-1 bar is normal. In practise, it is even more advantageous to have the high pressure drop as it can help boost the internal heat transfer coefficient and allows the use of smaller pipes in the gas cooler (namely, 5/16" or 3/8" pipe sizes are commonly used for this purpose).

Air-coolers do not have perfect counter flow and therefore heat conduction in the fins is a problem that needs to be addressed. Depending on pipe configuration there can be a 100K temperature difference between two pipes with only 20-25 mm distance.

The pipes are connected with fins of high heat conductivity and high fin efficiency to make the heat exchanger more efficient. However, this makes heat conduction from a hot pipe to a cold pipe possible and this needs to be avoided.

The capacity penalty of this heat bridge could be as high as 20-25%. It can be reduced or cancelled by dividing the fins.

The internal volume of the gas cooler is particularly important as it influences the size of the receiver.

The average density of CO_2 in the gas cooler changes drastically, going from transcritical to subcritical conditions and therefore affects the size of the receiver.

Special attention has to be given to systems where gas cooling is done in two parts where the first part is heating water with a compact heat exchanger and cooling the transcritical fluid down in the air-cooled gas cooler (please see Chapter 7 for more details).

The average density in this case is very high and therefore volume variations are very large.

Also, the subcooling can cause big variations in the charge in the gas cooler. Therefore the control of the subcooling is very important.

There a few different ways to control the medium pressure:

Option 1:
To reduce the pressure in distribution systems, the gas bypass is introduced.

After the high pressure expansion, the gas and liquid are separated and the gas is bypassed directly to the suction side of the compressor.

The liquid is distributed to the evaporators. This makes it possible to use standard pressure components (Fig. 1.3.2).

Intermediate pressure is controlled by the ETS stepper motor valve and EKC 326 controller, while high pressure is controlled by the ICMTS valve.

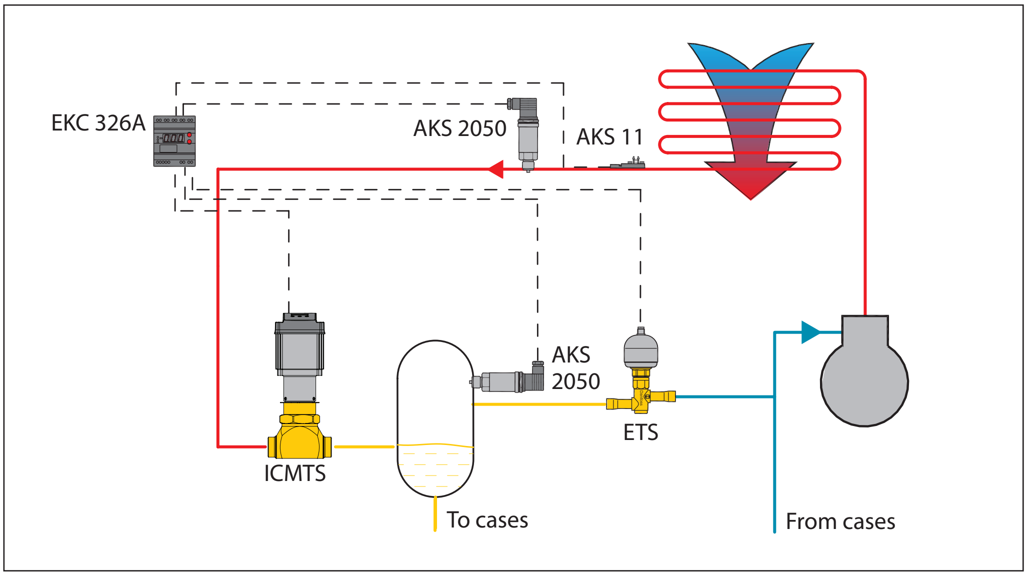
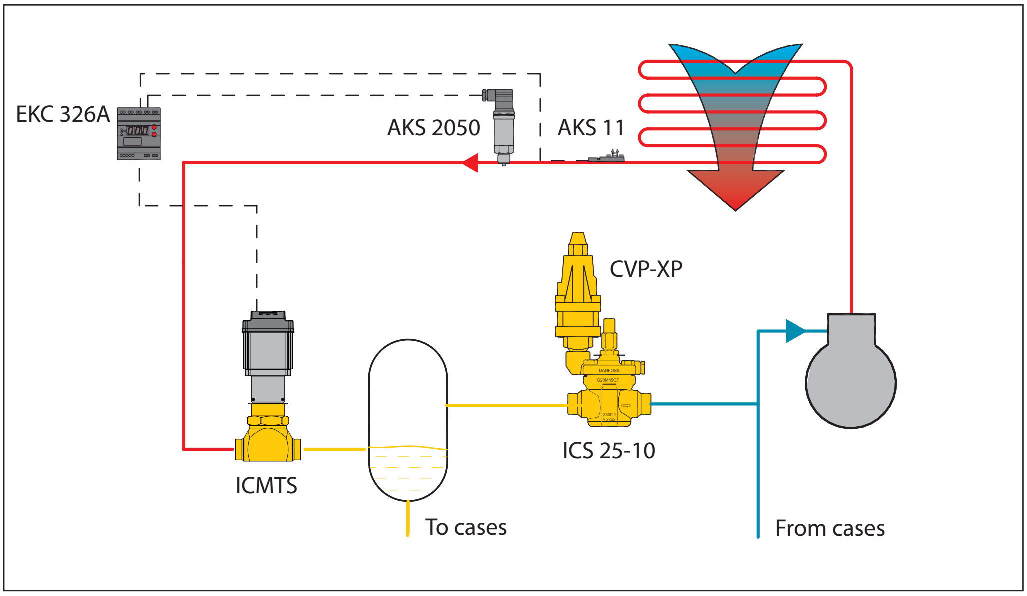


Figure 1.3.2: Intermediate pressure control by ETS stepper motor valve

🟥 HP vapour refrigerant
🟨 HP liquid refrigerant
🟦 LP vapour refrigerant

1.3 *Air-cooled gas coolers (continued)*

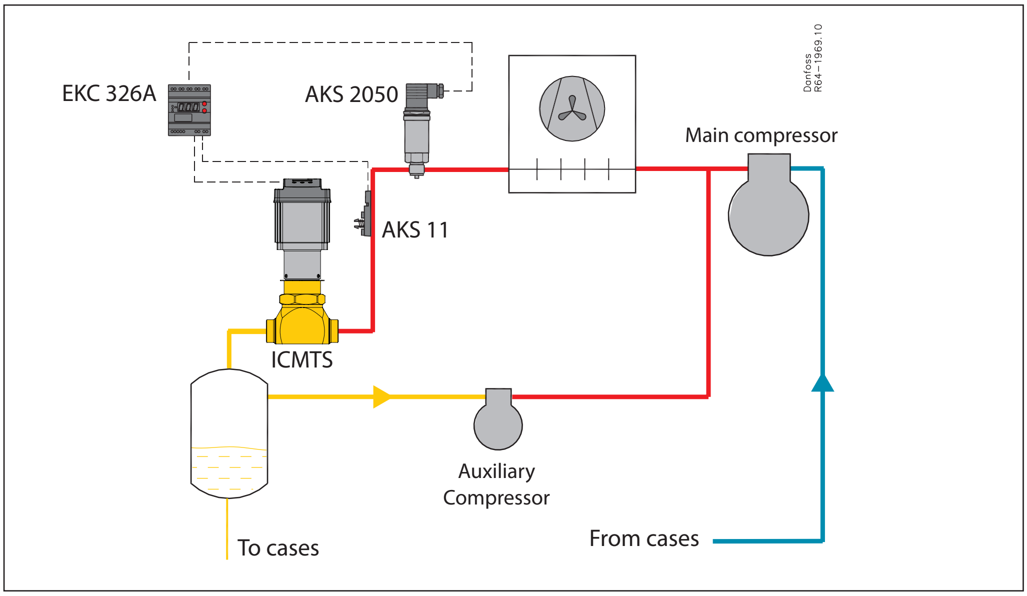
Option 2:
In some cases (typically in larger systems), an ETS valve can be replaced by an ICS+CVP-XP pilot valve, which maintains the pressure according to the setting of the specially designed CVP-XP pilot valve (Fig. 1.3.3).



🟥 HP vapour refrigerant
🟨 HP liquid refrigerant
🟦 LP vapour refrigerant

Figure 1.3.3: Intermediate pressure control by a CVP-XP pilot valve

Option 3:
To lower the energy consumption, parallel compression is one of the technologies that is available. In this case, instead of bypassing the gas from the receiver, the gas is compressed directly (Fig. 1.3.4).



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🟦 LP vapour refrigerant

Figure 1.3.4: Intermediate pressure control with an auxiliary compressor

1.4 Summary

System	**Air-cooled gas cooler with a motor valve**	**Air-cooled gas cooler with a mechanical control valve**	**Air-cooled gas cooler with additional compressor**
Advantages	Flexible system	Simple to use	High efficiency Reduced energy consumption
Limitations	Efficiency is lower than that of the system with parallel compression	Only one set point available	Cost and complexity
Danfoss components used	ICMT EKC 326A ETS AKS 2050 AKS11	ICMT EKC 326A ICS+CVP-XP AKS 2050 AKS11	ICMT EKC 326A ETS AKS 2050 AKS11

2.
Cascade heat exchanger

2.1 General description

In a cascade refrigeration system with CO_2 on the low temperature side, the CO_2 compressor discharge is piped to the cascade heat exchanger. Here, the heat from the low temperature stage is removed by the high temperature stage and the CO_2 discharge gas is condensed to high pressure liquid. The high stage system absorbs the heat of rejection from the low stage by evaporating the high stage refrigerant.

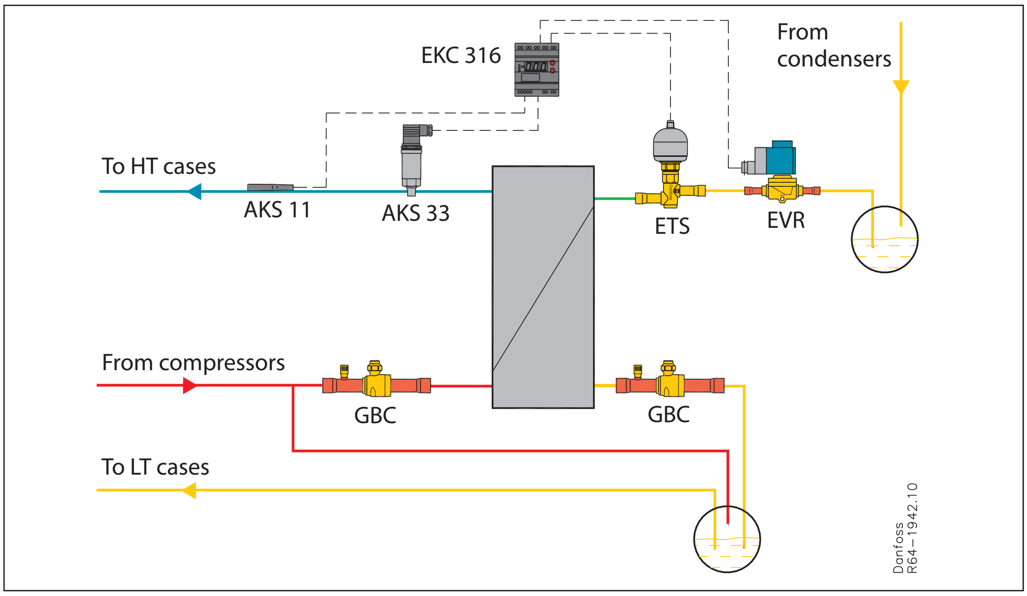
The design, manufacturing, testing and installation of such a heat exchanger is one of the most complicated issues in cascade refrigeration systems. It is very important to dimension a cascade heat exchanger correctly, so that it runs well at both low and high capacity conditions.

The design of a cascade heat exchanger is a challenge because it has phase changes from both sides. If it is oversized, then at part load conditions, it is almost impossible to get stable heat exchange and an optimal running operation of the system.

In commercial refrigeration systems, plate heat exchangers are commonly used for this function. For larger systems other types of cascade heat exchangers can be used as well.

Typically, 3 configurations of cascade heat exchangers are used.

2.2 Standard cascade heat exchanger



- 🟥 HP vapour refrigerant
- 🟨 HP liquid refrigerant
- 🟦 LP vapour refrigerant
- 🟩 LP liquid refrigerant

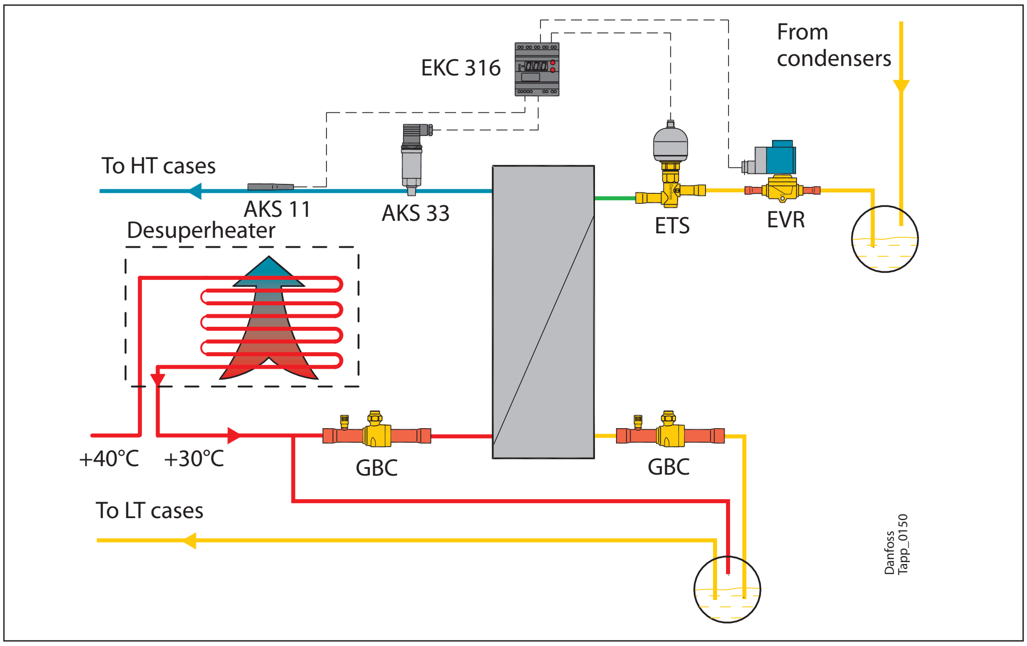
Fig. 2.2.1: Cascade heat exchanger with direct discharge from the compressor

Injection to the cascade heat exchanger is done by a motorised valve ETS, controlled by the EKC 316. The EKC 316 is enabled when compressor on the CO_2 side starts up. This is monitored by a pack controller running the system (e.g. AK-SC 255, AK-PC 730 or AK-PC 840), which in turn, initiates the EKC 316 and ETS motor valve.

Please be aware that ETS cannot be used for flammable refrigerants. For instance, in case propane is used on a high stage, a mechanical solution with a thermostatic expansion valve has to be used. The control algorithm remains the same.

Also, it is important that liquid from a cascade heat exchanger is properly drained. In order to ensure this, an equalisation line is recommended.

2.2 Standard cascade heat exchanger (continued)



🟥 HP vapour refrigerant
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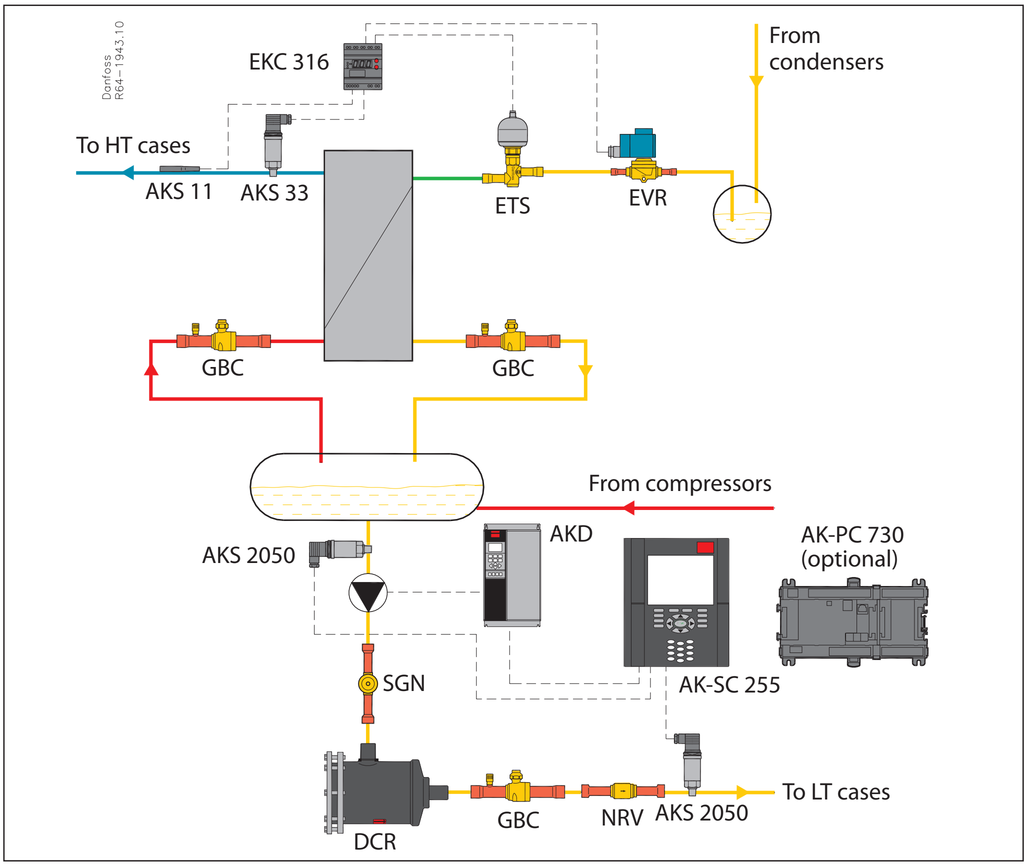
Fig. 2.2.2: Cascade heat exchanger with desuperheater

2.3 Cascade heat exchanger with an intermediate vessel



🟥 HP vapour refrigerant
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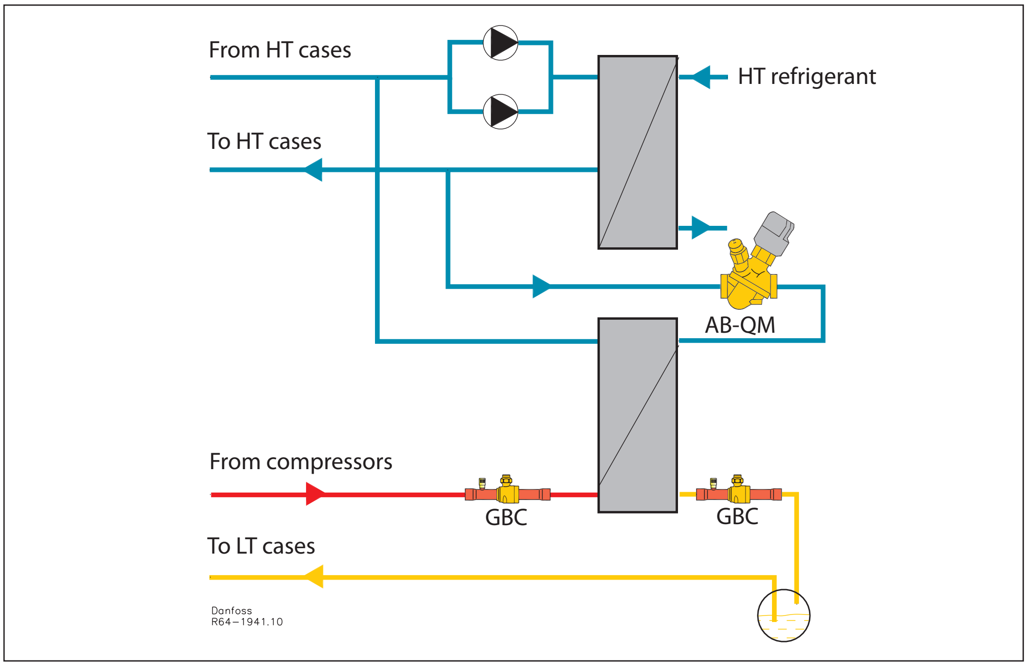
🟦 LP vapour refrigerant
🟩 LP liquid refrigerant

Fig. 2.3.1. Cascade heat exchanger with pumped circulation

Another configuration of a cascade CO_2 system does not require a separate equalisation line. A drawback of this system is that it is somehow more sensitive to CO_2 piping size and layout. High temperature side control is done by the same ETS + EKC 316 system. Liquid out of the vessel is pumped to medium or low temperature cases.

The flow is adjusted according to the pressure by varying the speed of the pump using for example an AKD 102 Variable Speed Drive or alternatively using fixed orifices.
Variable speed drive is a preferred option from an efficiency perspective.

2.4 Cascade heat exchanger with secondary cooling



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🟦 LP vapour refrigerant

Fig. 2.4.1: Brine cooled cascade heat exchanger

In the last described configuration, the cascade heat exchanger can be used in the systems where brine is used for HT cases. The same pumps can be used for cooling cascade heat exchanger as well.

A Danfoss AB-QM valve, designed for low temperature brine systems, is used to control the flow to the cascade heat exchanger. EV220 solenoid valves can also be used for brines. An advantage of this set up is that plate heat exchanger functions acts as a standard plate condenser which is much easier to dimension and to control. This allows a more simple mechanical control with AB-QM.

2.5 Summary

System	**DX**	**DX with CO_2 vessel**	**Secondary cooling**
Advantages	Simple piping	No need for equalisation line	Stable operation
Limitations	An equalisation line is required	Relatively complicated piping	Lower efficiency of the system
Danfoss components used	EKC 316 ETS AKS 11 AKS 33 GBC	EKC 316 ETS AKS 11 AKS 33 GBC AKD	GBC AB-QM

3.
Low pressure receiver/ pump separator

3.1 Types of cascade systems

The functions and duties of vessels and heat exchangers for CO_2 applications are basically the same as for other refrigerants. The vessels have to be designed to meet the physical properties of the refrigerant.

A liquid separator is a vessel that, by gravity, separates liquid and gas and also contains a managed level of liquid which goes to the evaporators.

CO_2 could be either pumped to evaporators or flow by pressure difference from compressors (DX system). A combination of the two is possible as well if two temperature levels are required.

Because CO_2 has much higher pressures than most refrigerants, for corresponding temperatures, considerable care has to be put into defining the design working pressure of the system and consequently the vessel.

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🟨 HP liquid refrigerant
🟦 LP vapour refrigerant
🟩 LP liquid refrigerant

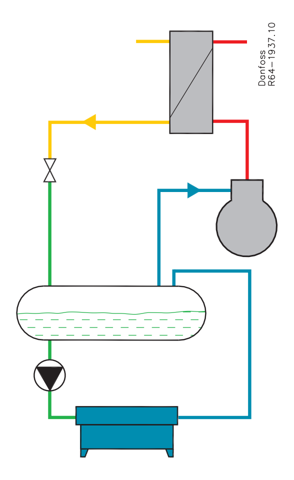


Fig. 3.1.1: Pumped system

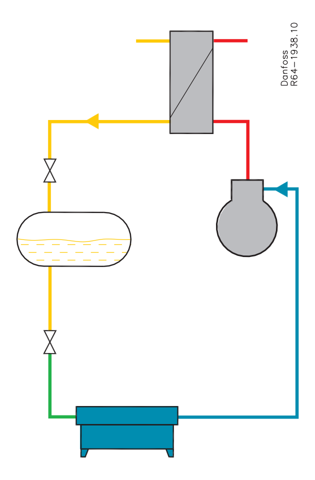


Fig. 3.1.2: DX system

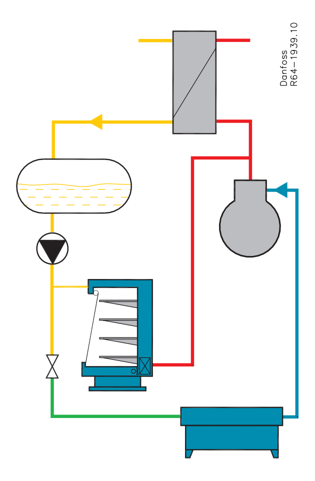


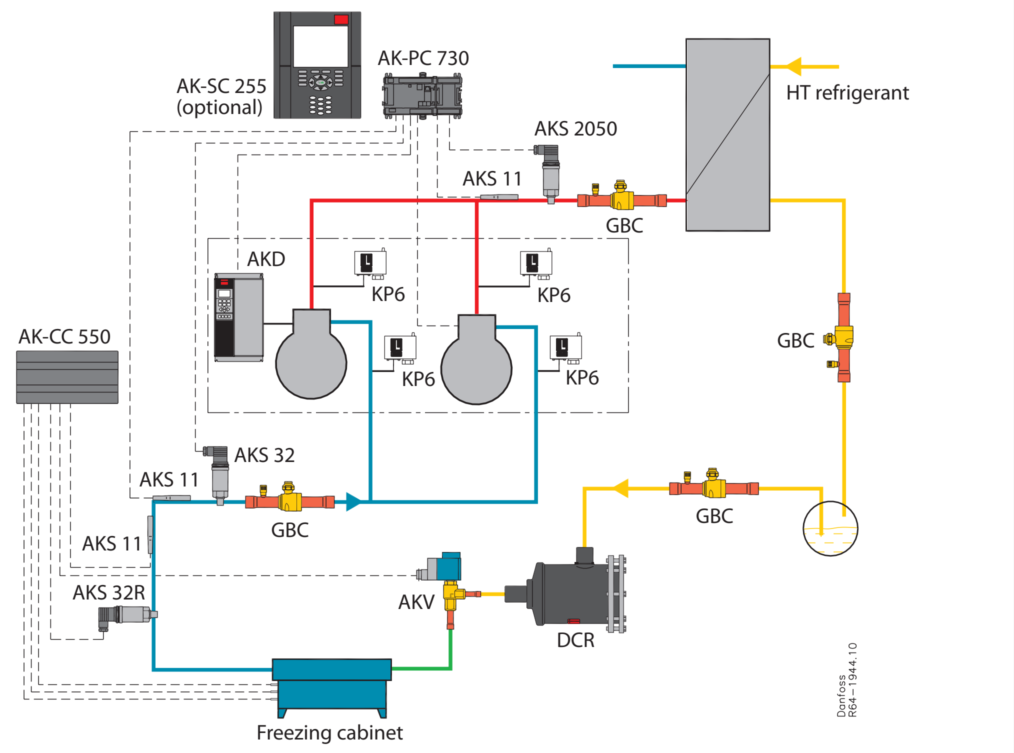
Fig. 3.1.3: Combined system

3.2 DX systems

Smaller charged DX systems are less complex, as they do not require pumps or liquid level controls systems. A downside of these systems is an efficiency penalty due to the higher superheat level. This is why they would be typically used for smaller systems (e.g. Discount stores or convenience store concepts).

It is also preferable to install AKV expansion valves close to the liquid receiver in order to avoid flash gas.

Pressure drop in the filter dryer also needs to be considered in this set up.



🟥 HP vapour refrigerant
🟨 HP liquid refrigerant
🟦 LP vapour refrigerant
🟩 LP liquid refrigerant

Fig. 3.2: CO_2 DX cascade system – low temperature cycle

3.3 Pump systems

In pump recirculated systems, refrigerant is pumped to the evaporators at a specific flow rate. A 1.5:1 to 2.5:1 recirculation ratio means about two units of liquid are pumped out and one unit evaporates. Lower circulation ratio than in traditional systems can be accepted due to higher efficiency of CO_2.

The three remaining units of liquid return to the vessel as two phase flow. The vessel then separates the two phase flow, collecting the liquid and allowing the dry gas to exit to the compressors.

Typically industrial refrigeration pumps can be used for larger systems. They are completely closed and require minimal maintenance if installed correctly.

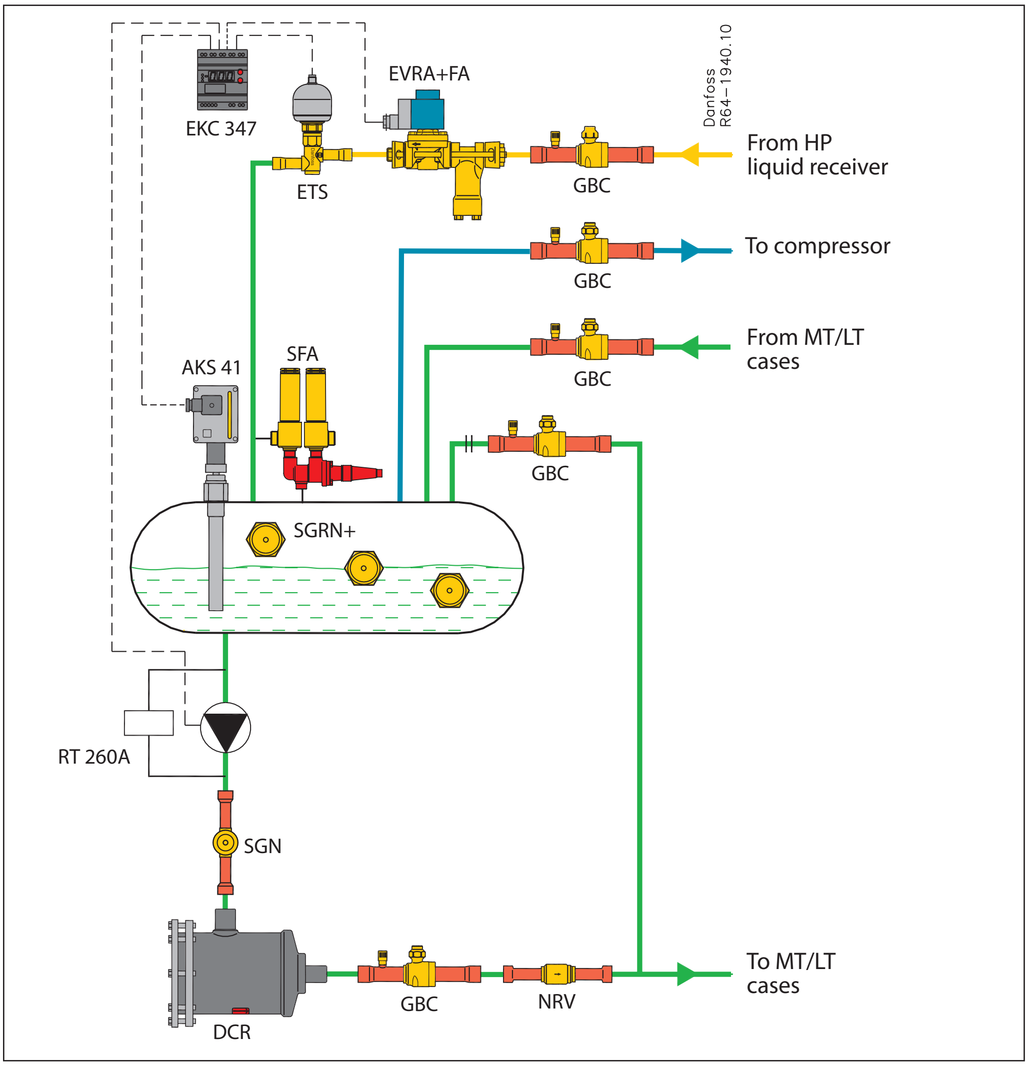
There are CO_2 pumps on the market with flow rates down to 0.5 m^3/h.

Liquid level control system design

Liquid level in pumped separators is controlled by an electronic expansion valve (AKV, ETS or ICM), taking a signal from an EKC 347 controller. Liquid level is measured by a capacity rod, type AKS 41.

Not all liquid recirculated pumped systems have some form of liquid level alarm indicator. It is quite common that the first sign of low liquid derives from low differential pressure trips of the liquid pump. Obviously low liquid level leads to low head pressure which in turn trips the pump on low differential pressure. A typical minimum differential pressure over CO_2 pump lies between 1 and 3 bar.

One example of this is when liquid is returned from the cabinets back into the vessel. After a delay period, the pump will attempt to restart until a desirable differential pressure is achieved. With horizontal receiver designs, there are usually several sights glass indicators as shown below.



🟥 HP vapour refrigerant
🟨 HP liquid refrigerant
🟦 LP vapour refrigerant
🟩 LP liquid refrigerant

Fig. 3.3.1: Low pressure receiver and pump arrangement

3.3 Pump systems (continued)

Pump design
When designing CO_2 applications with liquid pumps, careful considerations should be taken to sizing and design of the suction line to the pump. The "rule of thumb" for max. velocities should be 0.3 – 0.5 m/sec in order to achieve optimum performance.

Always ensure a minimum flow in order to cool the motor winding in the low flow range of the pump. This is done with the use of a "Q-min orifice". This is necessary particularly when refrigerated cabinets have reached their set points and all solenoid or AKV valves have cycled off.

Two pressure transducers, type AKS 2050 and a pack controller AK-PC 255, AK-PC 730 or AK-PC840 could be used for this purpose. This functionality needs to be programmed in Boolean logic.

As CO_2 pumps operate at high pressures, standard safety pressure controls cannot be used for differential pressure protection. However it is possible to do a safety trip by using pressure transducer and Boolean calculation in AK SC 255 or the free pressure switches in the AK-PC 730 and AK-PC840.

A "Q–max orifice" is used to maintain a maximum flow rate and suction head, maintain motor power rating and prevention of cavitation (which typically happens after defrost of the evaporators). Alternatively, a constant flow regulator may be utilised in lieu of the Q-max orifice when higher pump discharge pressures at higher flow rates are necessary to meet system designs.

Satisfactory operation of pumps in a CO_2 system depends on correct installation and operation.

🟨 HP liquid refrigerant

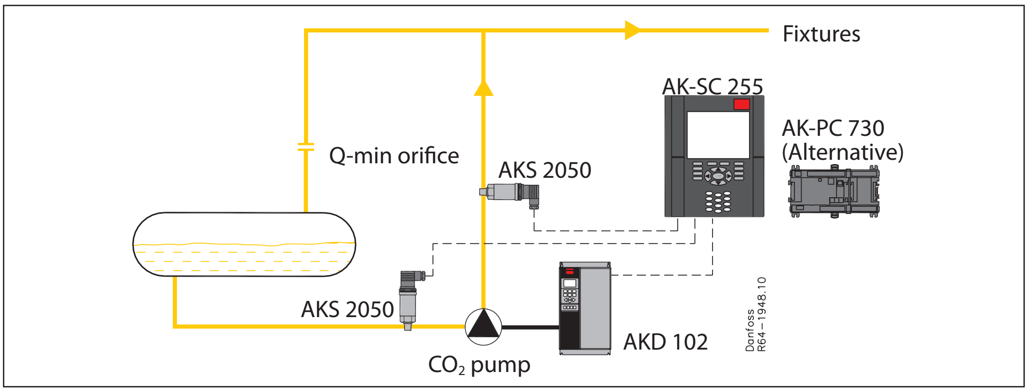


Fig. 3.3.2: Q-min orifice (minimum flow) arrangement

Four key points must be observed:

- Observe minimum suction head to avoid cavitation (even though it proved to be less of a problem than in Freon systems.
- Operation is within permissible range, between minimum and maximum capacity.
- Suitable automatic venting of the pump i.e. avoid trapped CO_2 liquid.
- Avoid sudden lowering of system pressure or temperature. Variable speed drives for compressors are recommended.

A variable speed drive type AKD102 could be successfully used for CO_2 pumps, as they are quite often oversized.

A check valve typically has to be installed in a discharge line of a pump in order to prevent backflow during standstill and parallel operation. NRV, CHV or SCA valves can be used for this purpose, depending on the pipe size etc..

🟥 HP vapour refrigerant
🟨 HP liquid refrigerant
🟦 LP vapour refrigerant
🟩 LP liquid refrigerant

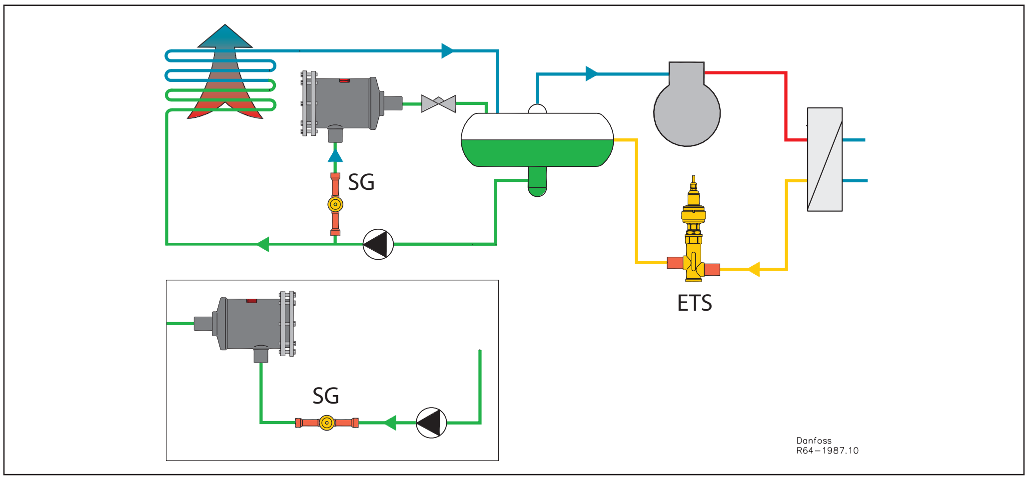


Fig. 3.3.3: Recommended installation of filter dryer in CO_2 systems

3.3 Pump systems (continued)

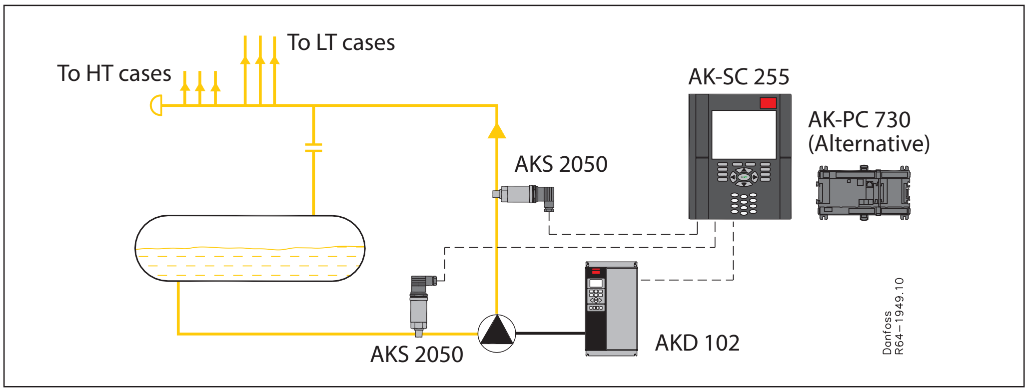
It is recommended to install a DCR filter dryer on a discharge line of the pump or on a parallel line. A parallel line could be a preferred option in some cases as it would reduce the pressure drop after the pump. Water concentration is highest in the liquid line and by installing a filter dryer, an optimal separation of water from CO_2 can be achieved.

A pure molecular sieve insert should be used. Please refer to the Danfoss technical leaflet for the filters capacity calculation and to the calculation software DIRcalc for pressure drop calculations.
Recommendations for Dryer installation are the same for cascade and transcritical systems.

3.4 Combined systems

Combined DX along with liquid recirculated CO_2 is quite common in order to accommodate two temperature levels (medium and low temperatures as a rule). It requires the discharge of the liquid pump to be piped to a multi circuited header assembly where it feeds both high temperature and low temperature cabinets.

This is to ensure that an appropriate head of liquid is present at all times and to eliminate the boiling off of refrigerant due to low flow rates before the AKV expansion valves on low temperature cabinets. In certain system applications where the distance from the plant room may be in excess of 100 metres away, it is best to select this type of method due to the higher flow rates required to satisfy the system design.



▬ HP liquid refrigerant

Fig. 3.4: Discharge header for multiple cabinets

3.5 Summary

System	**DX**	**Pump**	**Combined**
Advantages	Simple. Does not require pumps	High efficiency; CO_2 can be pumped relatively large distances	Efficiency provides 2 temperature levels
Limitations	Energy efficiency is not optimal	Relatively complex and expensive; Energy consumption from the pump is often very high for small systems	Relatively complex; The most expensive out of the three alternatives
Danfoss components used	GBC NRV or CHV DCR SGN	GBC NRV or CHV DCR SGRN+ AKS 41 EKC 347 AKV or ETS	GBC NRV or CHV DCR SGRN+ AKS 41 EKC 347 AKV or ETS

4.
Evaporators

Two types of Evaporators can be used for CO_2 systems, namely, one for DX and the other for pumped operation. There is a difference in coil design, as well as in the valves used and the control strategy applied.

The issue is that due to efficiency gains of the refrigerant, the room temperature can be reached with only half the use of the evaporator coil which results in additional defrosts to combat ice formation.

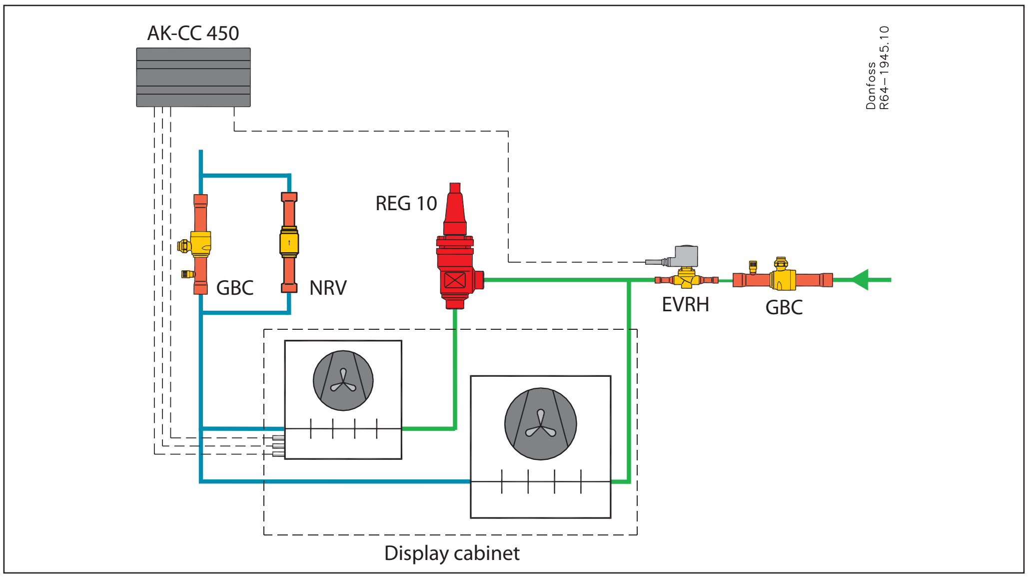
CO_2 optimised coils have been redesigned with reduced circuit and reduced tube sizing due to the volumetric efficiency of CO_2. As a result of these changes, less defrost period is required. The other benefit of CO_2 is the quick pull down time after defrost compared to conventional systems.

4.1 Flooded evaporators (pumped operation)

The two forms of evaporators are single with multi circuited evaporator coils. As a rule, pumped evaporators are medium temperature which have to be designed for condensing the temperature of CO_2 in cascade systems or intermediate temperature in transcritical booster systems.

The major benefits of using CO_2 is the reduction of refrigerant charge in the total system as well as pipe sizing and evaporator sizing which should still deliver optimum heat exchange and efficiency. Refrigeration capacity is increased for a given coil size and oil circulation within the system is also improved.

Single circuited evaporator



🟦 LP vapour refrigerant
🟩 LP liquid refrigerant

Fig. 4.1.1: Single circuited evaporator in a liquid pump circulated system

In Figure 4.1.1, it shows a typical liquid pump circulated system with different sized cabinet or cold room evaporators (smaller ones reach settings quicker). In order to control the liquid flow to both evaporators, an additional Danfoss mechanical regulating valve (REG-10) is fitted to the smaller evaporator in order to balance the liquid supply. This method of control stabilises the temperature between different evaporator sizes.

One of the most important commissioning tasks is the cleaning of the filter/strainers at the CO_2 rack/pack and solenoid valves at cabinets and cold rooms.

The main liquid strainer or filter must be cleaned along with all solenoids pulled down for inspection of foreign particles etc., 24hrs after plant start up.

Not complying with this will lead to solenoid vales not seating correctly which leads to iced up evaporators.

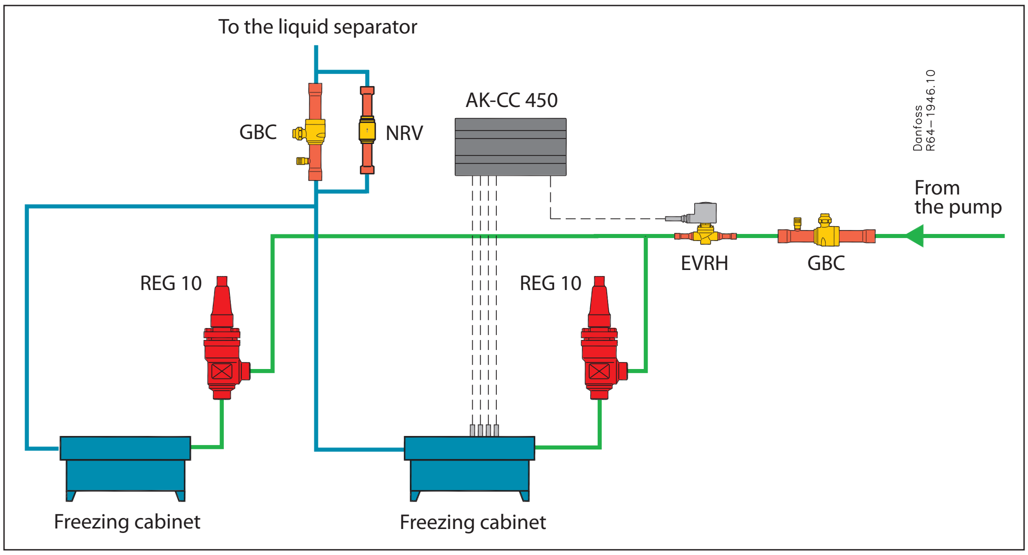
4.1 Flooded evaporators (pumped operation) (continued)

Multiple circuited evaporator

Figure 4.1.2 shows a typical set up for pump liquid circulation in cold rooms. The Danfoss regulating valves (REG-10) are fitted to each evaporator. Again this is done in order to equally distribute liquid to the evaporator.

The control set point parameters for CO_2 in cabinets and cold rooms are set a lot warmer than that of conventional HFC systems due to the flooded coil. Once the solenoid has cycled "off", there is a further 2-4K temperature gain in air "off" temperature depending on the internal volume and circulation ratio of the coil.

This happens due to the fact that CO_2 remaining in the coils still evaporates with the solenoid valve already closed.



🟦 LP vapour refrigerant
🟩 LP liquid refrigerant

Fig. 4.1.2: Multiple circuited evaporator in a liquid pump circulated system

Electronic controls

There are 3 possibilities to control pumped evaporators:

- Centrally from the AK-SC 255 system manager plus AK-XM I/O modules, purely solenoid to control temperature and defrost.
- Decentrally from AK-CC 750 or AK-CC450 electronic case and cold room controller
- Decentrally from EKC controllers

4.2 Direct expansion

DX (direct expansion) evaporators in CO_2 systems are typically used for low temperature evaporators (e.g. refrigerated merchandisers and cold rooms). Again, due to the efficiency and benefits of CO_2 there may be significant reduction in pipe sizing. Typical pipe sizes do not exceed 3/8" to 5/8" inch diameter and smaller evaporators are necessary to get the required capacity.

Defrost in CO_2 supermarket installations is typically done by brine or electrical heating elements. It is important to control the pressure during defrost, as it can easily exceed max. working pressure of the components (typically 46 bar ~ 10°C).

Suction heat exchanger in CO_2 cascade systems is recommended between the CO_2 suction line and high pressure liquid from a high temperature stage. This is necessary as suction superheat, required by compressor manufactures, cannot be provided by low temperature CO_2 liquid (i.e. it actually gets subcooled in the process).

4.2 Direct expansion (continued)

🟥 HP vapour refrigerant
🟨 HP liquid refrigerant
🟦 LP vapour refrigerant
🟩 LP liquid refrigerant

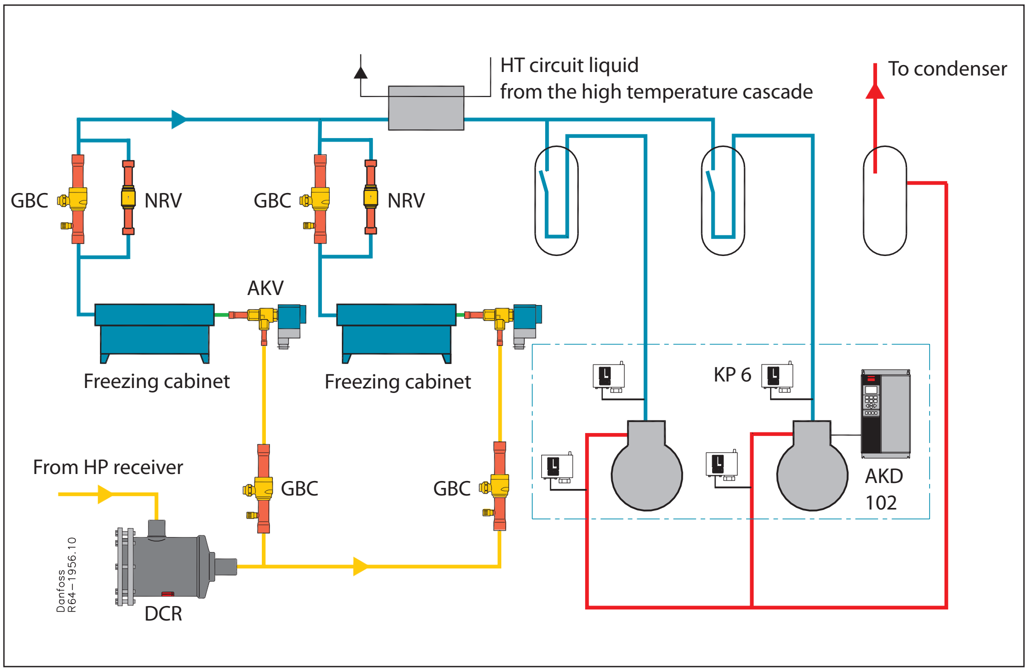


Fig. 4.2.1: Typical low stage CO_2 system

Electronic controls

It is extremely important to select the right electronic controller suitable to control CO_2 refrigerant due to high dynamics of the gas. In addition, with conventional refrigerants, the popular method of control was with inlet and outlet temperature probes to control the superheat of the evaporator.

When controlling the superheat of CO_2 system fixtures, it is imperative that precise true superheat control is used in order for the controllers algorithm to react to the fast changes in CO_2 pressures.

The Danfoss AK-CC550 or AK-CC750 evaporator case and cold room controllers were designed for this application and have proven to be extremely successful when applied.

It is not recommended to use standard coil for HFC/HCFC for CO_2 as it is almost impossible to control superheat.

🟥 HP vapour refrigerant
🟨 HP liquid refrigerant
🟦 LP vapour refrigerant
🟩 LP liquid refrigerant

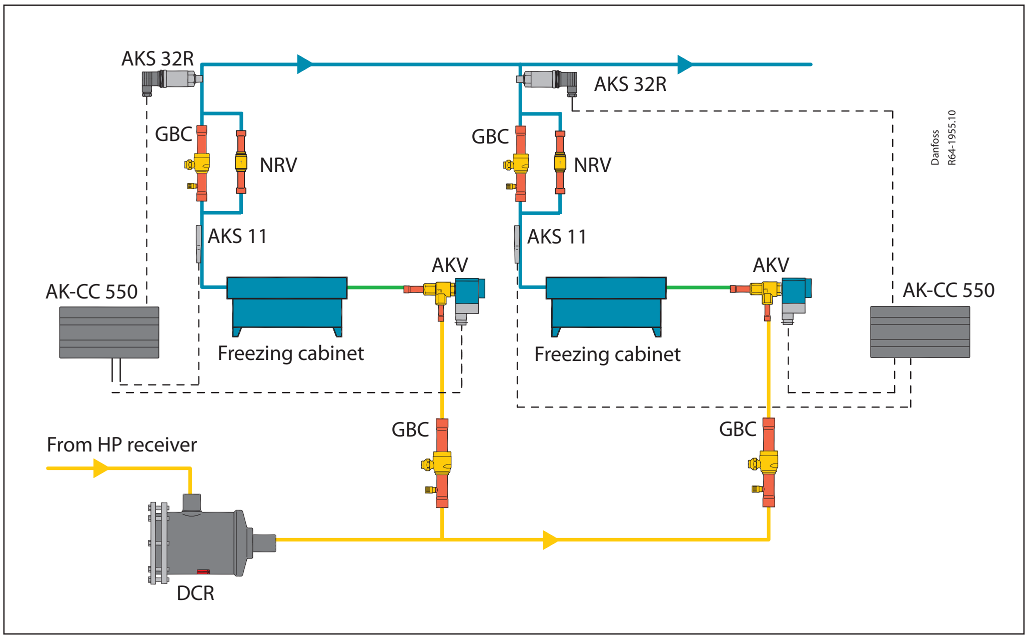
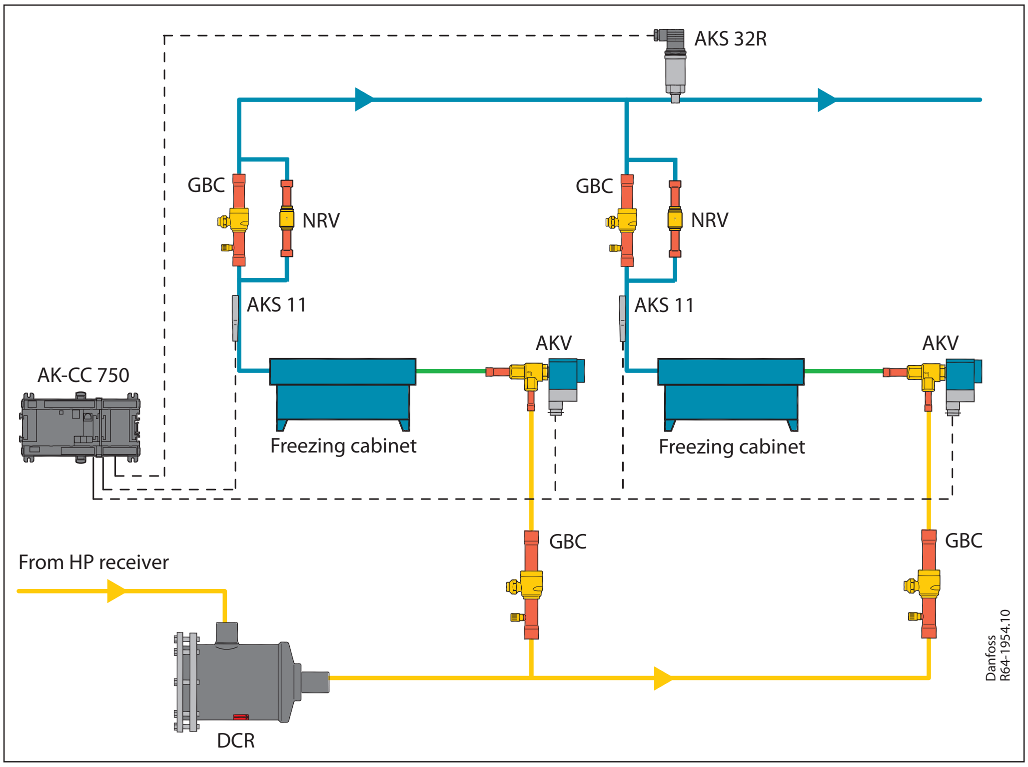


Figure 4.2.2: Superheat measurement with AKS temperature probes and an AKS32R pressure transducer (individual controllers)

4.2 Direct expansion (continued)



🟥 HP vapour refrigerant
🟨 HP liquid refrigerant
🟦 LP vapour refrigerant
🟩 LP liquid refrigerant

Fig. 4.2.3: Superheat measurement with AKS temperature probes and an AKS32R pressure transducer (1 controller for up to 4 evaporators).

It is important to use AKS11 (Pt1000) temperature sensors and AKS32R pressure transmitters for superheat measurement to ensure input sensing accuracy and response.

Note experience shows that only two temperature sensors to measure superheat is not enough as the system cannot follow or respond quickly enough to the CO_2 dynamics and there is a risk that some liquid would return to the compressors. Therefore such configuration cannot be used for CO_2 evaporators.

4.3 Summary

System	**DX**	**Pump (single circuit/multi circuit)**
Advantages	Optimal for low temperature applications	Allows operation with 0 superheat
Limitations	Energy efficiency is not optimal	Requires low pressure control system with pumps
Danfoss components used	AK-CC750 AK-CC550 AKV AKS11 AKS32R GBC	AK-CC750 AK-CC450 EKC 414 or EKC 514 REG valve EVR AKS 12 GBC

5.
Compressors

5.1 Compressor types and protection devices

Nowadays, several companies can offer compressors for R744. Some of the compressors are on prototype stage while some have several years experience behind them. There are hermetic, semi hermetic and open compressors for both subcritical and transcritical operations. Some of the transcritical compressors operate on one stage and some on two stages. Some of the transcritical compressors can also be equipped with intermediate cooling or economiser connection.

Danfoss transcritical CO_2 compressors, type TN, are tailored to MBP applications such as bottle coolers and wending machines. The displacements of the single stage reciprocating compressors operating at speed of 2950 rpm are from 1 to 2.5 cm^3.

For transcritical systems, Danfoss can offer Danfoss-saginomiya CCB cartridge pressure controls. In small hermetic systems, expansion devices, such as type MBR and type TBR, operate also as safety valves, releasing pressure from high pressure side to low pressure side.
(See also Chapter 9, Simple transcritical systems.)

In subcritical systems, Danfoss KP6 pressure controls with 46.5 bar maximum operating pressure can be used. Heavy duty MBC 5000 series of pressure switches are suitable for both subcritical and transcritical systems. Also, MBC 5080 and MBC 5180 pressure differential switches can be used for compressor oil pressure control. However, it needs to be mentioned that MBC devices do not have category 4 approval according to PED. Safety valves must always be installed as the last protection.

When using the pressure differential switches for control, an external time delay relay must be used.

5.2 Capacity control

R744 is a very efficient and dynamic refrigerant. With on/off control, the power pack cooling capacity is most of the time too low or too high compared to the actual cooling load. Also, the suction pressure will fluctuate and that has an adverse effect to compressor lubrication especially with CO_2.

When one compressor in power pack is controlled by AKD 102 (variable speed drive), the suction pressure will be quite stable. This will also reduce the number of compressor starts and stops.

The number of the compressors is selected according to the lowest desired capacity, reliability and total cost.

Fig 5.2.1 illustrates a power pack where one of the three compressors (i.e. typically the lead compressor) is driven by AKD102 according to the suction pressure measured by pressure transmitter sensor AKS 2050.

Figure 5.2.2. describes the capacity curves of power packs with 2, 3, 4 and 5 compressors when one of them is driven by AKD 102 within 30…60 Hz.

🟥 HP vapour refrigerant
🟦 LP vapour refrigerant

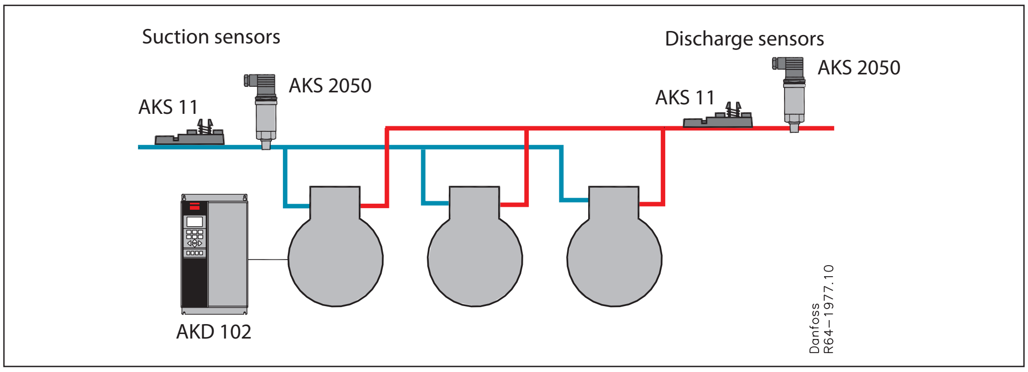


Fig. 5.2.1: One of the three compressors connected in parallel is controlled by AKD102

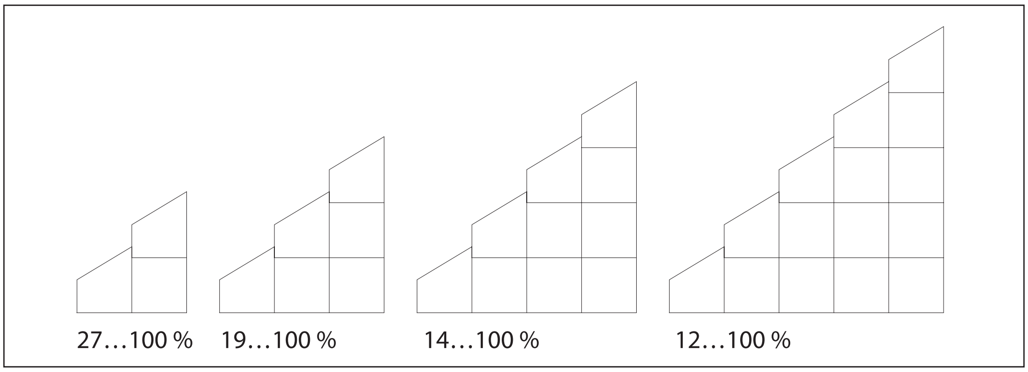


Fig. 5.2.2: Capacity control, when one compressor is running 30-60 Hz and others on/off 50 Hz

5.2 *Capacity control (continued)*

At night time and weekends, the cooling load may be so low that even the smallest capacity step is too much. Hence, to be able to change the starting order, another compressor with AKD102 is a good solution, see figure 5.2.3.

🟥 HP vapour refrigerant
🟦 LP vapour refrigerant

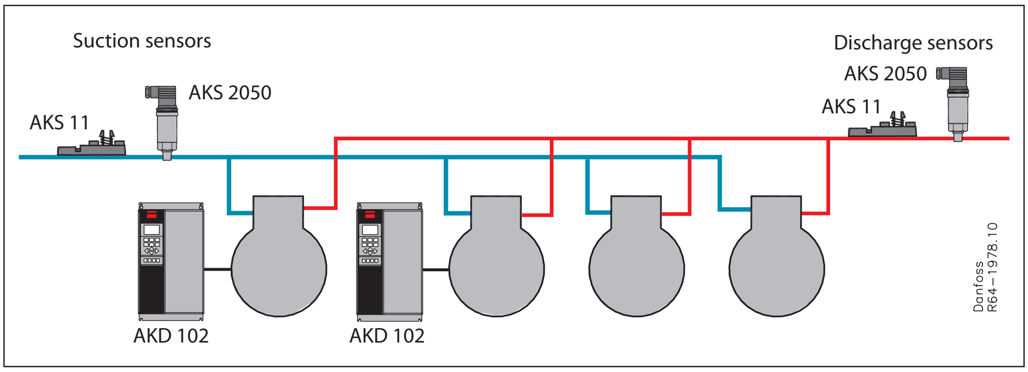


Fig. 5.2.3: Two of the four compressors connected in parallel are controlled by AKD102

Figure 5.2.4. describes the capacity curves of power packs with 2, 3, 4 and 5 compressors when two of them are driven by AKD within 30…60 Hz. This will provide stepless capacity control from minimum capacity to maximum capacity.

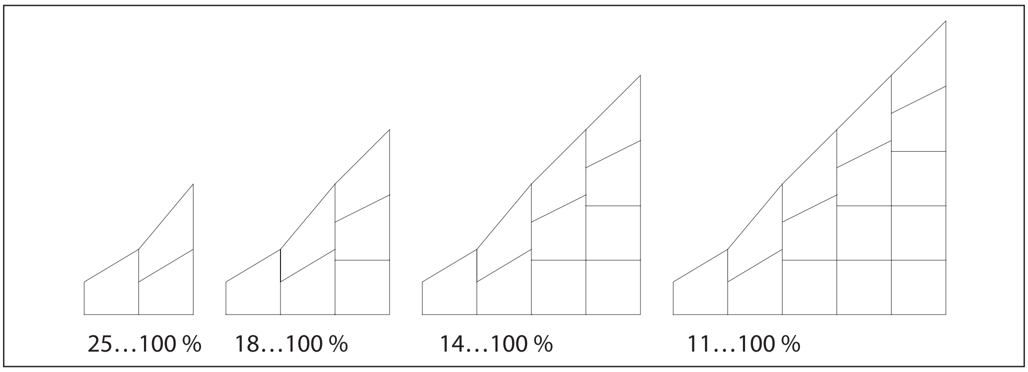


Fig. 5.2.4: Capacity control, when two compressors are running 30-60 Hz and others on/off 50 Hz

These examples use the same size of compressors. By using different sized compressors, it is also possible to achieve capacity control even without AKD. However, in such circumstances, one has to take into consideration what will happen if the biggest compressor fails.

When compressors are controlled by variable speed, the minimum and maximum speed must be selected according to the manufacturer's recommendation. The suction and discharge lines must be sized and installed so that oil circulation is ensured in all cooling load conditions.

5.3 Equipment required

A suction line accumulator (1) is highly recommended if the compressor is not located at a higher and warmer place than the evaporators. Even still, the suction line accumulator is recommended because most of the compressor failures have occurred while filling and starting the system. Although the compressor is normally stopped using pump down technique, there is a risk of liquid hammering in the case of power supply failure or if safety devices have stopped the compressor.

The system must be designed so that trapped liquid or vapour cannot cause too high pressure during use, service or reparation of the system. This also includes compressors (2) and an oil return system that consists of an oil separator (3), an oil reservoir (4), a differential pressure regulator (5), an oil filter (6) and oil level regulators (7).

With compressors that do not have an oil pump, it is recommended to use an oil level regulator that will stop the compressor, if the oil level is too low. It is also useful to equip the oil reservoir (4) and the liquid reservoir (8) with a level control (9) that gives an alarm if the level gets too low.

The cascade heat exchanger (10) must be placed and connected so that it drains the liquid reservoir. Conducting the condensate line to the bottom of the receiver or connecting it from the bottom of the receiver will help drain the cascade heat exchanger. Depending on the system, there is either refrigerant or brine on the cold side of the cascade heat exchanger.

When the discharge line is typically made of steel and especially if there is a risk of vibrations, then CHV check valves (11) are an ideal choice. There are steel and stainless steel versions available with maximum working pressure (MWP) of 52 bar. With copper pipes, NRV and NRVH check valves with MWP of 46 bar are used.

The suction line filter (12) DCHR with strainer protects the compressors against fine dirt particles within the system. The DCHR can be connected both to the copper and steel pipes. Those who prefer stainless steel pipes can use FIA filters.

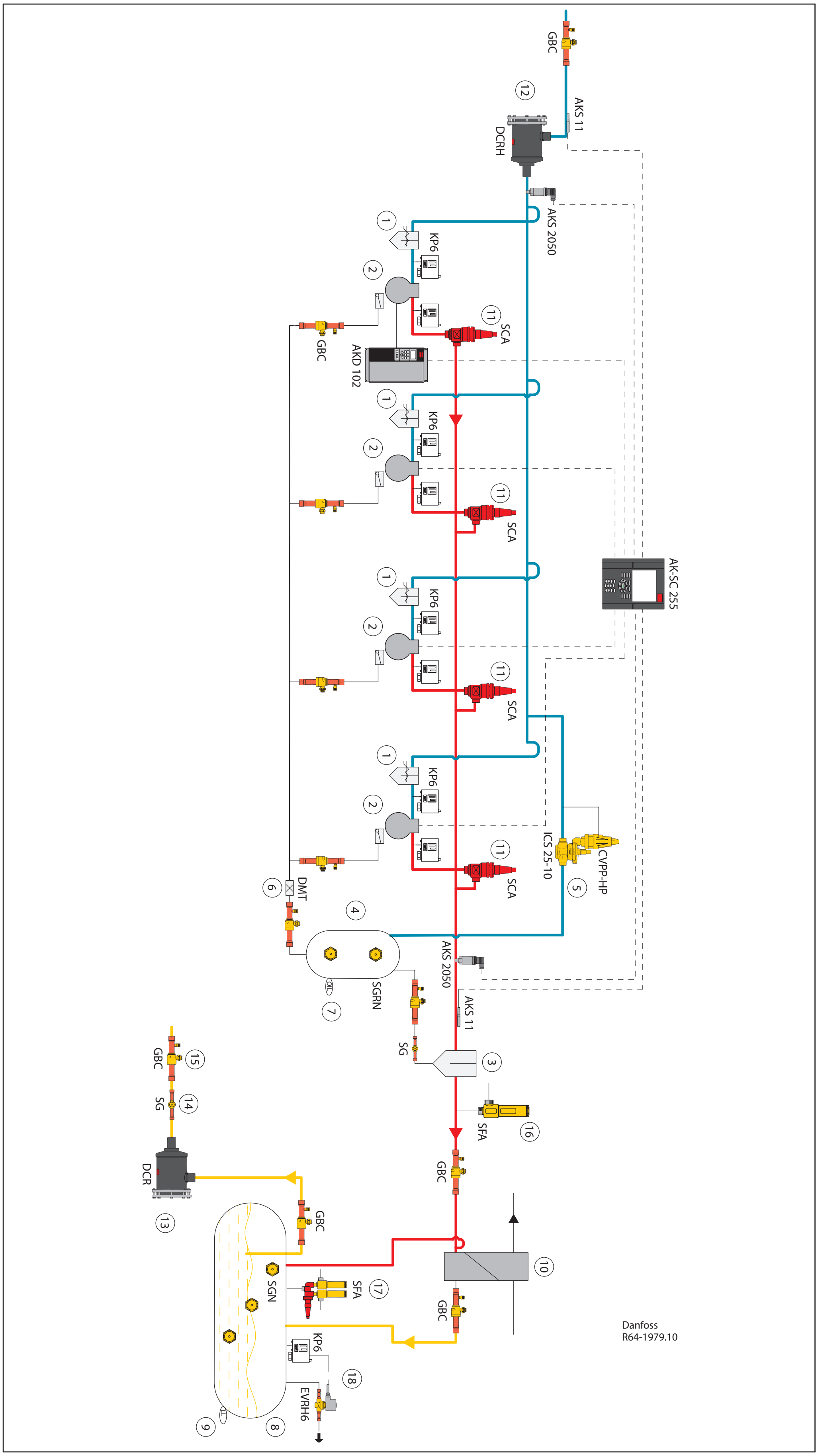
With CO_2, we recommend using pure molecular sieves cores in DCHR filter dryers (13). The sight glass (14) will indicate if the relative humidity in CO_2 is too high.

For copper pipes, GBC stop and isolation ball valves (15) are used. For steel and stainless steel pipe applications, Danfoss offers a wide range of SVA stop valves and SNV stop/needle valves to be used as a service valve.

SFA safety valves (16) protect the system against excessive pressures. In the liquid receiver, usually two safety valves are connected to the DSV double stop valve (17). Sometimes, the liquid receiver is equipped with pressure control (KP6 pressure switch or MBC) that will give an alarm and open the EVRH solenoid valve (18) when the pressure is near the opening of the safety valve. In this way, the CO_2 losses can be minimised in most cases.

Transcritical systems are described in Chapter 10.

5.3 *Equipment required (Continued)*



🟥 HP vapour refrigerant
🟨 HP liquid refrigerant
🟦 LP vapour refrigerant

Fig. 5.3.1: Schematic circuit diagram of subcritical CO_2 power pack.

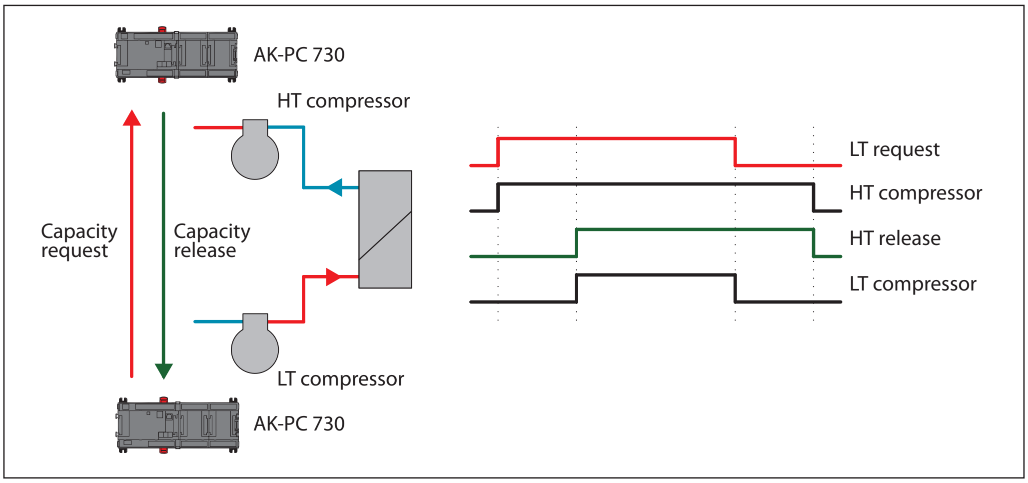
5.4 Full control

In cascade systems, it is essential that at least one compressor in the high temperature side is already running before the first compressor in the low temperature side starts. Otherwise, the compressor in the low temperature side may be cut out due to the high pressure.

It is also essential that the ETS valve starts the injection to the cascade heat exchanger at the same time as the first compressor in the low temperature side. It should also stop injection when the last compressor in the low temperature side has stopped.

Danfoss pack controllers like AK-SC 255, AK-PC 730 and AK-PC 840 are specially designed with built in control functions to coordinate these operations.

The switchover from transcritical operation to subcritical operation and the optimal pressure in gas cooler is controlled by EKC 326A, plus ICMT motorised valve



🟥 HP vapour refrigerant
🟦 LP vapour refrigerant
🟩 LP liquid refrigerant

Fig. 5.4.1: Controlling cascade systems

6. Standstill systems

6.1 General description

The first step in defining the design pressure is to determine the system parameters. Design pressure depends on:

- Pressure during operation
- Pressure during stand still
- Temperature requirements for defrosting
- Pressure tolerances for safety valves (10-15%)

As a rule, standstill pressure is the main limiting factor for design pressure of CO_2 systems. Most systems with traditional refrigerants can be stopped without any risk of pressure exceeding the MWP of the components.

For CO_2, standstill pressure can be as high as 65-80 bar (corresponding to 25-30ºC). This is above the MWP of most of the commercially available components today. If it is not possible to design a system that can withstand such high standstill pressures, then it is necessary to take measures to keep CO_2 pressure low – both transcritical and cascade installations.

There are two major factors defining CO_2 pressure during standstill:

- ambient temperature and
- the charge of the system.

As long as CO_2 is in liquid form, the pressure in the system is saturated and corresponds to the ambient pressure (e.g. ambient temperature 20ºC corresponding to approx. 57 bar).

By contrast, when CO_2 is in gas form, it is no longer saturated which means that the pressure increase is lower even though it is still higher than for other traditional refrigerants. For instance, if the total CO_2 charge turns into gas at 0ºC, then its pressure corresponds to approx. 34.8 bar. With a further temperature increase of up to 30ºC, the pressure only rises to 42.5 bar.

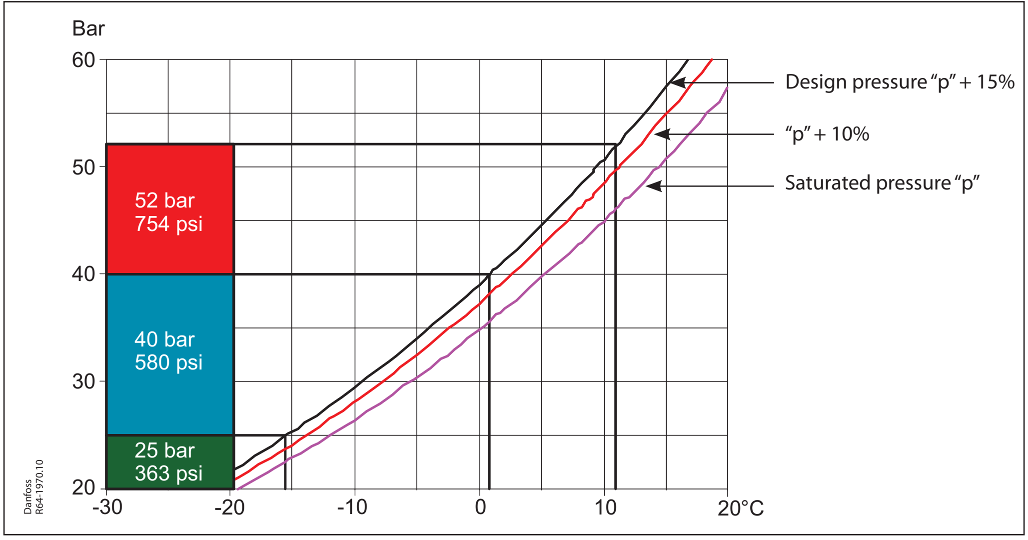


Fig. 6.1.1: Design pressure / temperature for CO_2

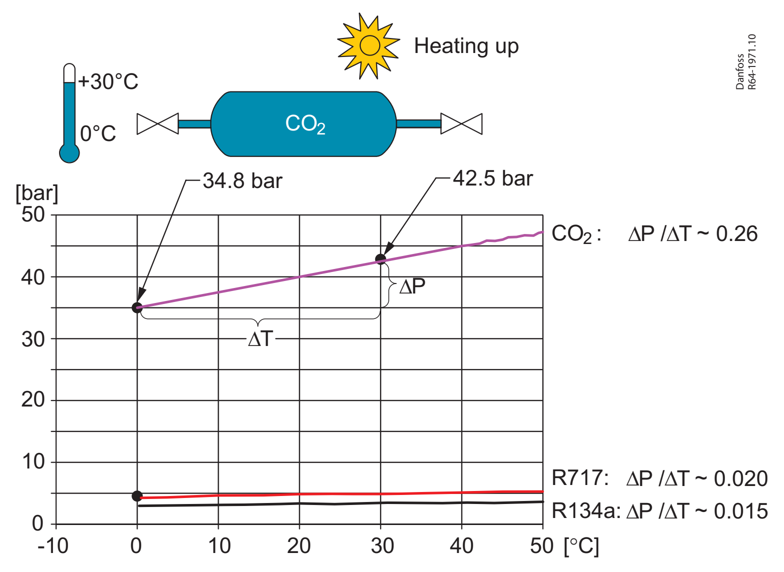


Fig. 6.1.2: CO_2 liquid expansion

6.1 General description (continued)

This principle can be used to limit pressure increase in the system. See 6.4.

The most typical ways of keeping the standstill pressure low are as follows:

6.2 Auxiliary refrigeration system

In the case of a pressure increase during standstill, an auxiliary refrigeration system starts and cools the CO$_2$ tank thus limiting the pressure to the maximum acceptable pressure. A generator receives a signal from the pressure switch on the receiver (KP or MBS 5000 type, depending on the pressure).

In both cases, a small condensing unit is used to cool down the CO$_2$ tank. This system is more typical for large commercial applications (e.g. big supermarkets and hypermarkets, distribution cold stores etc.). The Danfoss Optyma™ range of small condensing units can be ideally used for this application.

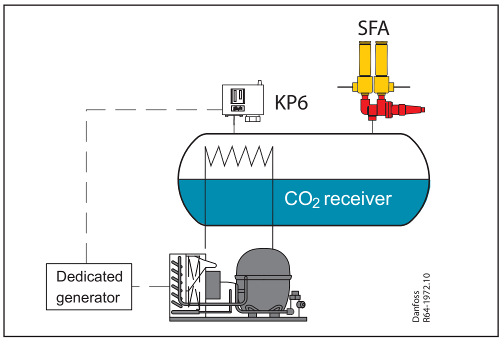


Fig. 6.2.1: Auxiliary refrigeration system

6.3 CO$_2$ venting

With the pressure increase, a small amount of CO$_2$ can be released into the atmosphere before it reaches the design pressure. The pressure will therefore be reduced due to:

- The release of some CO$_2$ into the atmosphere
- The cooling of the remaining liquid due to boiling CO$_2$

When the pressure in the receiver rises above set point on CVP-XP, a pressure regulating valve starts to release CO$_2$ into the atmosphere. As the CVP-XP is a proportional regulating valve, pressure release is slow and only a very limited amount of refrigerant escapes. An ICS pressure regulator can be used for this purpose. For smaller systems, a CVP-XP pilot valve can be used directly in the CVH valve body.
While the pressure in the receiver drops, the liquid CO$_2$ starts to boil off. This causes a temperature decrease and a further pressure drop.

If pressure increases to 10-15% above the CVP-XP set point, then a large amount of CO$_2$ is discharged into the atmosphere.

This system can be very cost effective as only a small amount of CO$_2$ needs to be relieved.

Another option is to install a solenoid valve EVRH6 on the outlet pipe of the receiver. The solenoid valve is controlled by means of boolean logic in an AK-PC 255 system manager, AK-PC730 or AK-PC840 pack controller which in turn receives a signal from the AKS 2050 pressure transducer. It is important to install EVRH6 on the outlet of this pipe in order to avoid dry ice formations. A more simple version of this system is achieved by using a EVR6 (NO) with a KP 6 pressure switch.

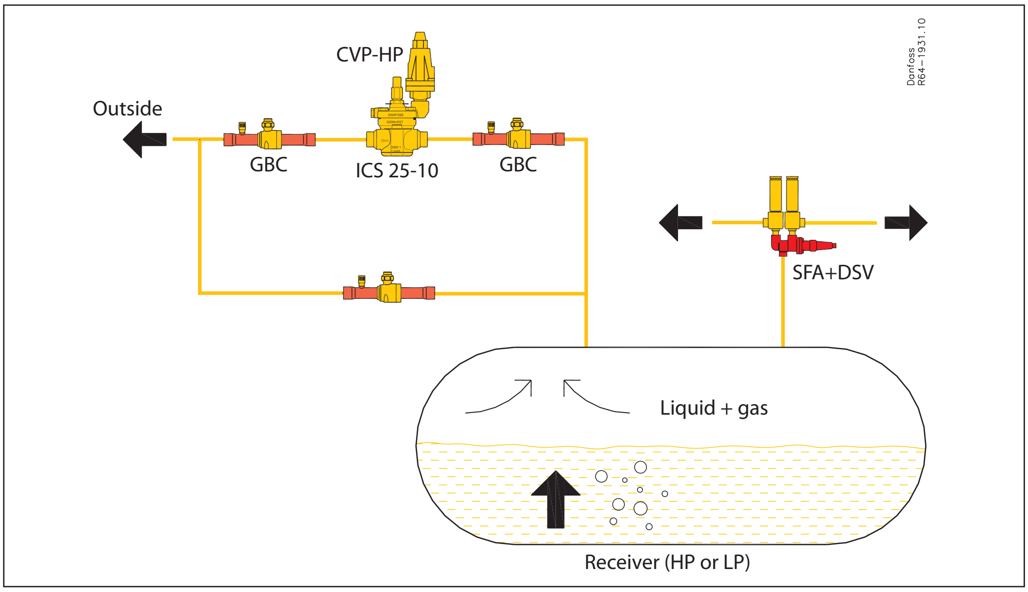
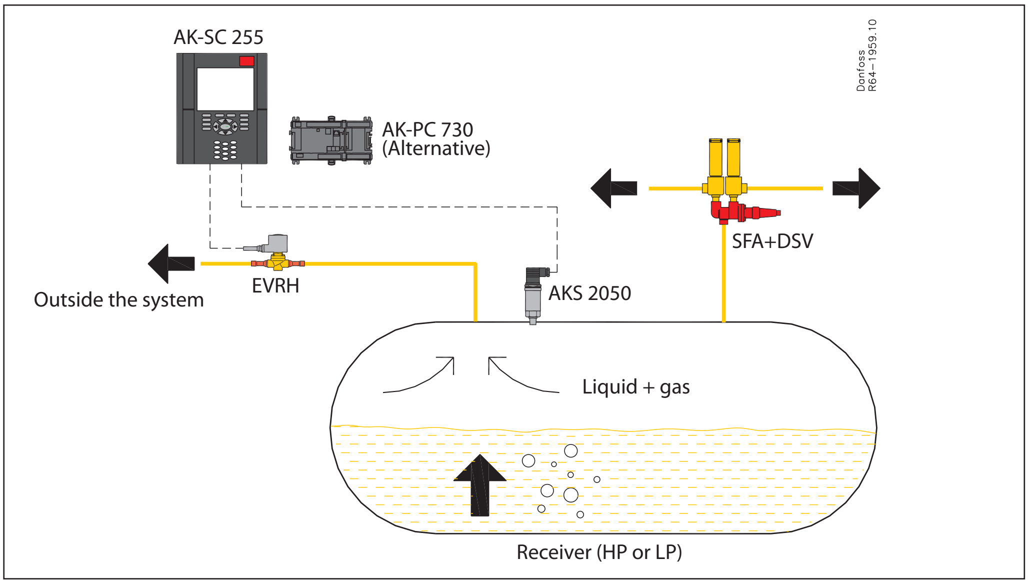


Fig. 6.3.1: CO$_2$ release system with pilot regulated valve

▬ HP liquid refrigerant

6.3 CO_2 venting (continued)



▬ HP liquid refrigerant

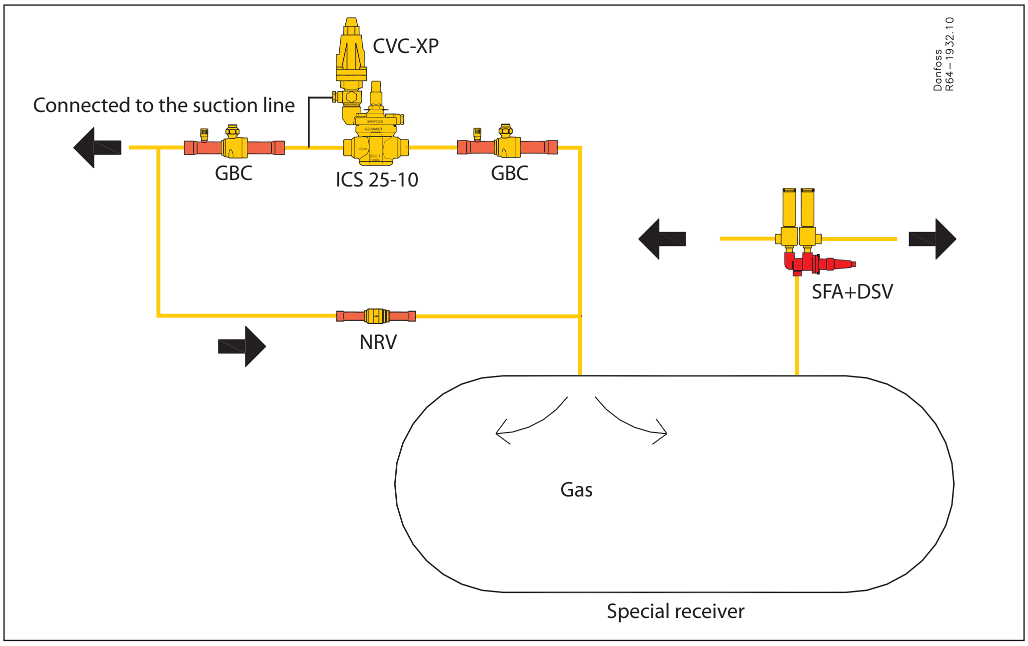
Fig. 6.3.2: CO_2 release system with pilot regulated valve

6.4 CO_2 expansion vessel

In systems with limited charge, a separate expansion receiver can be used to keep an acceptable pressure level.

When pressure increases in the system, CO_2 expands to the receiver through the NRV valve. This vessel needs to be quite large in order to accumulate enough CO_2 to keep the pressure in the remaining part of the system constant.

When the system starts up again, CO_2 gas is released back to the suction line via a back pressure regulator ICS with a CVC-HP pilot valve. For smaller systems, a CVC-HP valve can be directly used in a CVH body.



▬ HP liquid refrigerant

Fig. 6.4: CO_2 expansion vessel

6.5 Summary

System	**Auxiliary condensing unit**	**CO_2 release**	**Expansion vessel**
Advantages	- No CO_2 release into the atmosphere - No additional vessels required	- Simple system design - No additional or special vessels required - Additional power sources are not necessary - Can be relatively cheap	- No CO_2 release into the atmosphere - Additional power sources are not necessary
Limitations	- Special designed vessel - Uninterrupted power supply required - Auxiliary refrigerant needs to be used - Can be relatively expensive	- CO_2 is released into the atmosphere - Requires precise charge calculations	- Requires an extra vessel - Requires precise charge calculations - Can be relatively expensive
Danfoss components used	Optyma™ condensing unit MBS 5000 or KP pressure switch	ICS+CVP-XP or CVH+CVP-XP pressure regulator GBC ball valves SFA15 safety valve EVR NO KP	ICS+CVC-XP or CVH+CVC-XP pressure regulator GBC ball valves SFA15 safety valve NRV check valve

7.
Heat recovery for CO_2 systems

7.1 General description

Heat recovery systems for refrigeration have been described in many books and articles. When designing a refrigeration system with CO_2, heat recovery can be one of the customers' requirements.
This can be solved in different ways. Two principles will be described in the following passages:

- (a) partial and
- (b) full heat recovery

When designing these systems, some topics need particular consideration:

- The condensing of liquid in the recovery unit
- Avoiding boiling on the water side.
- Sufficient water quality, different levels of Calcium carbonate, bacteria etc.
- Temperature levels of operation preventing too low/high condensing temperature

It is commonly known that heat recovery with CO_2 works perfectly in transcritical mode. But even in subcritical mode, CO_2 heat recovery is still much more efficient than that of e.g. 134a and 404A. It is also possible to reach high temperatures in the subcritical mode due to the temperature distribution across the condenser. With a condensing temperature of +15°C, about 30% of the energy can be reclaimed at approx. +60°C.

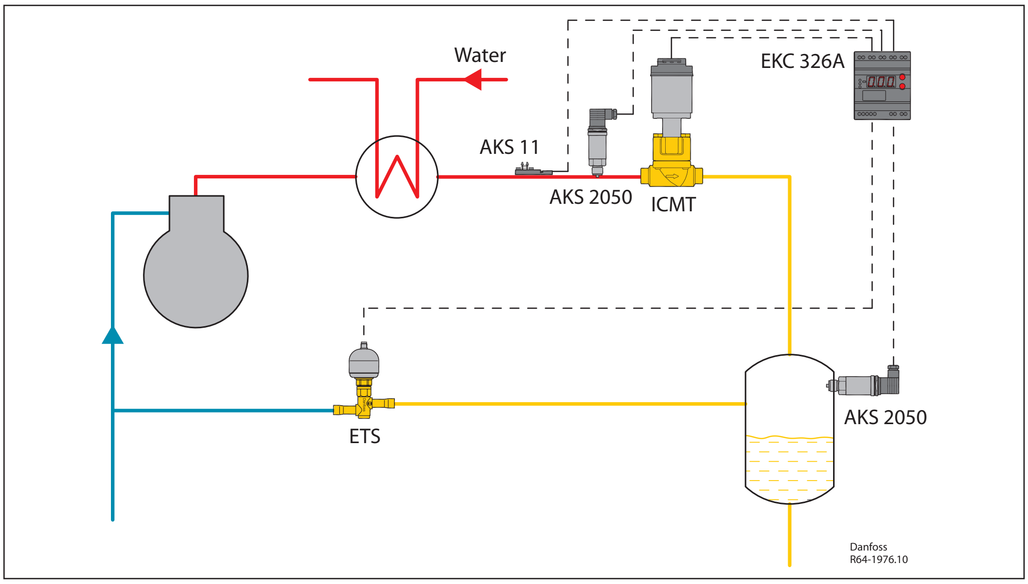
7.2 Heat recovery (Heat pump), simple system

The simplest system is shown in fig. 7.2.1 without a subcooler.

In this case, the water side determines the load of the system. The system is limited by the functionality on the water side since the heat on the water side must always be removed from the refrigeration cycle.

The disadvantage of this kind of system is that it is much more difficult to obtain the right pinch point of the gas cooler.

- *Compressor control*
  AK-PC 255, AK-PC730 or AK-PC840
- *Gas cooler control*
  EKC 326A plus ICMT
- *Bypass valve control*
  ETS + EKC 326A



🟥 HP vapour refrigerant
🟨 HP liquid refrigerant
🟦 LP vapour refrigerant

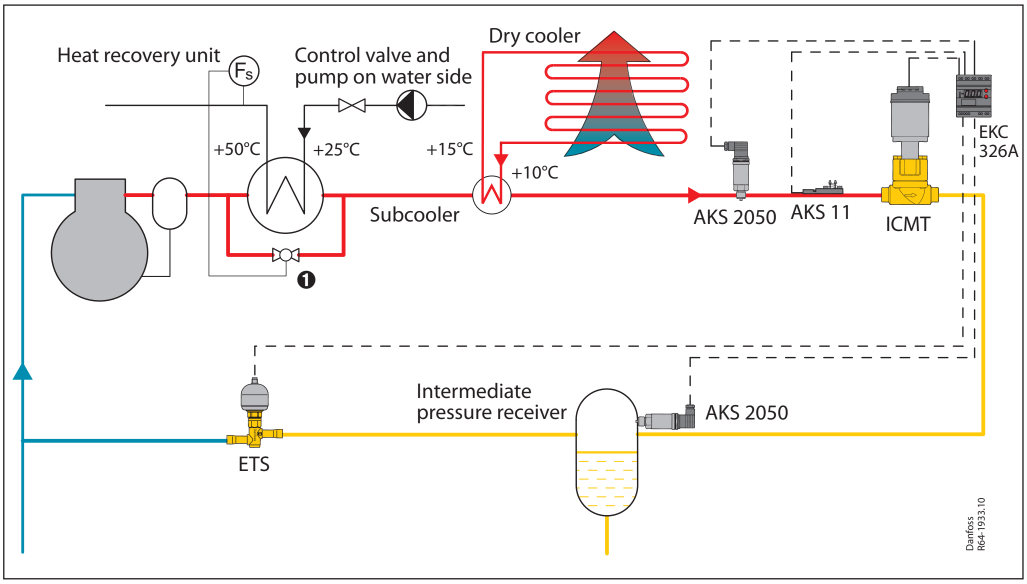
Fig. 7.2.1: Simple heat recovery system

In the case of a typical heat recovery system (fig. 7.2.2), the heat exchanger needs to be properly sized for continuous operation as a gas cooler and the water needs to be carefully controlled. The subcooler must be optimised according to the pinch point for the process.
The main reason for having two heat exchangers is to have two independent water flows thus achieving the best possible performance.
The valve is used when there is no water flow and operates in an on/off mode only. If the water pump is not running, the valve opens and bypasses CO_2. This is done in order to avoid overheating the water heat exchanger. An ICMT valve can be used for this purpose.

Controlling the high pressure valve can be done, as usual, by an EKC 326A which can be used for this application also. The EKC 326A can also control the ETS valve for the gas bypass while the ICMT valve is in operation.

- *Compressor control*
  AK-PC 255, AK-PC730 or AK-PC840
- *Gas cooler control*
  EKC 326 plus ICMT
- *Bypass valve control*
  ETS + EKC 326A
- *Dry cooler control*
  AK-PC420

7.2 Heat recovery (Heat pump), simple system (continued)



🟥 HP vapour refrigerant
🟨 HP liquid refrigerant
🟦 LP vapour refrigerant

Fig. 7.2.2: System for heat recovery (or heat pump)

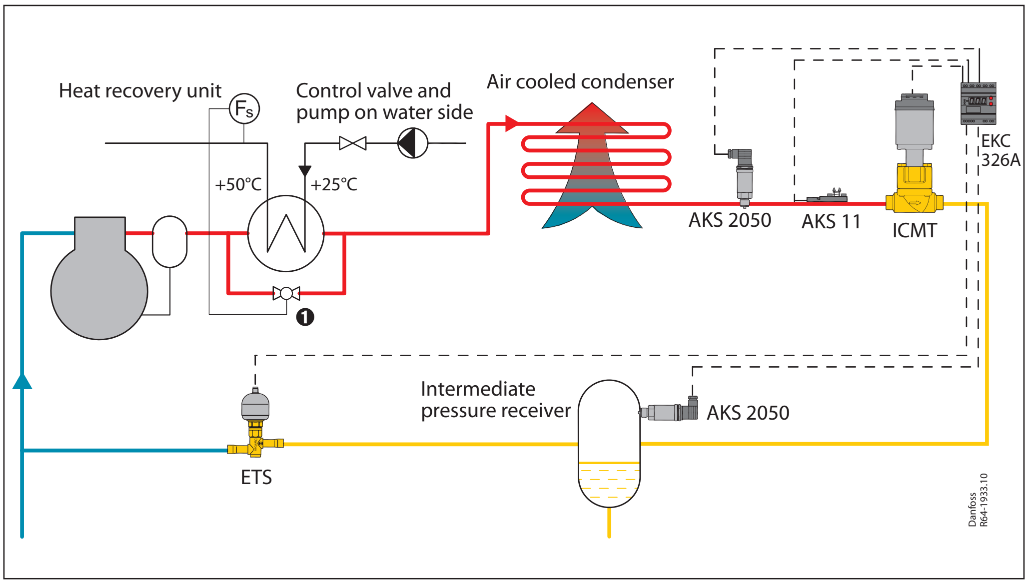
7.3 Heat Recovery, partial

This application is similar to the previous application except for the fact that it is possible to use a traditional gas cooler in conjunction with the heat recovery unit, making this a very flexible system.

The major advantage of this is the possibility to adapt the system to certain needs, ensuring sufficient cooling on the high pressure side of the refrigeration circuit.

- *Compressor control*
  AK-PC 255, AK-PC730 or AK-PC840
- *Gas cooler control*
  EKC 326A plus ICMT
- *Bypass valve control*
  ETS + EKC 326A
- *Dry cooler control*
  AK-PC420

In new designs of the EKC 326, it is possible to control the ICMT and the ETS simultaneously with the same controller.



🟥 HP vapour refrigerant
🟨 HP liquid refrigerant
🟦 LP vapour refrigerant

Fig. 7.3: Partial heat recovery system

7.4 Summary

System	Simple heat recovery system	Full heat recovery system (heat pump)	Partial heat recovery system
Advantages	Simple system	High performance	Flexible system
Limitations	Difficult to keep stable temperature	Complex system; 2 x heat exchangers required	Higher charge
Danfoss components used	ICMT EKC 326A ETS AKS 2050 AK-PC 730 (or AK-PC840) AK PC 420 AK-SC 255	ICMT EKC 326A ETS AKS 2050 AK PC 730 (or AK-PC840) AK PC 420 AK-SC 255	ICMT EKC 326A ETS AKS 2050 AK PC 730 (or AK-PC840) AK PC 420 AK-SC 255

8.
Cascade CO_2 systems

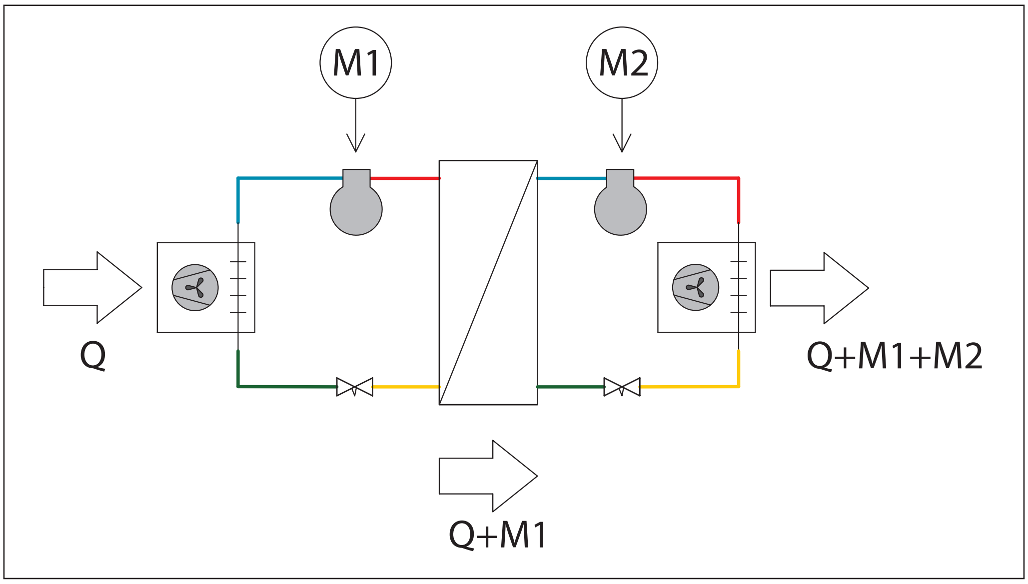
8.1 Introduction

Cascade systems are not used in FR applications with traditional refrigerants. There are a few reasons for this such as the need to maintain two different refrigerants in one system; system control strategy (especially that of a cascade heat exchanger) is more complex. At the same time using CO_2 in cascade systems gives a number of advantages:

- Working pressures of CO_2 in cascade systems are low (typically 40-45 bar)
- Efficiency of the system is high even in the hot climates
- Only a small amount of refrigerant is needed for high temperature stage
- Temperature difference for cascade heat exchanger is relatively low

Examples of typical cascade layouts can be found in Chapter 3 (fig. 3.1.1 to 3.1.3). On a high temperature side HC, HFC or NH_3 can be used. Please be note that the use of HC refrigerants depends on local legislation and is not covered in this manual. Ammonia/CO_2 cascade systems have the highest efficiency of all. If HFC is to be used at a high temperature stage, R134a is a preferable option due to its thermodynamical properties and lower (compared to R404A) GWP potential.

Heat rejection from the low to high temperature side is as shown in fig. 9.1 and it is important to dimension the high temperature condenser correctly.



🟥 HP vapour refrigerant
🟨 HP liquid refrigerant
🟦 LP vapour refrigerant
🟩 LP liquid refrigerant

Fig. 8.1: Energy transfer in a cascade system

8.2 Temperatures and pressures in cascade systems

Intermediate temperature in a cascade system is selected based on the required temperature for high temperature cases in a store which means they can be cooled by CO_2 directly. Intermediate temperature can also be optimised for the highest energy efficiency if the system is used for low temperature only.

Since a cascade system actually consists of two different refrigeration systems which are interfaced but isolated at the cascade heat exchanger, the design working pressure for each can be different. CO_2 design pressure is normally based on the availability of components and is equal to 40-45 bar (corresponding to +5 - +10°C).

In order to prevent pressure from increasing above the previously mentioned measurements, standstill systems are recommended. Safety valves should have the highest setting.

For example:
CO_2 side

- System design working pressure (saturated suction temperature): 40 bar (+5°C)
- Safety valve settings: 36 bar (-10% MWP)
- System emergency relief setting: 34 bar (-1°C)
- CO_2 discharge pressure setting: 30 bar (-5°C)

The higher the efficiency of the cascade heat exchanger, the lower the difference between the condensation temperature of CO_2 and the evaporating temperature of the refrigerant on the high temperature side. As the temperature difference on the cascade condenser increases, the overall efficiency of the refrigeration system decreases. The smaller the temperature difference, the more costly the cascade condenser is.

8.2 *Temperatures and pressures in cascade systems (continued)*

On systems with low temperatures of the discharge CO_2 gas (low superheat), the superheat of the expansion valve can be the dimensioning factor for the heat exchanger. If a CO_2 system has high superheat, then desuperheaters need to be used in order to reduce the load on the high temperature side.

Optimal intermediate pressure in CO_2 cascade systems depends on a number of parameters (high temperature refrigerant, load pattern etc.). Generally 2 cases need to be considered:

- Systems with load at the medium temperature. In this case intermediate pressure should be as high as possible in order to reduce the load at the high temperature stage. The limitations are therefore required temperature on the intermediate level and pressure rating of the system.
- Systems without load at medium temperature. In this case the intermediate temperature should be in the range of -10 - 0°C where lower limit is defined by efficiency and higher by system pressure rating.

8.3 *Operating sequence of cascade systems*

In Cascade Systems, it is essential that at least one compressor in the high temperature side is running before the first compressor in the low temperature side can start. Otherwise, the compressor in the low temperature side may be cut out due to high pressure.

The same sequence is also valid for filling up the system. First of all, the high temperature circuit needs to be filled with refrigerant and started up. When this is done, the CO_2 can be filled into the low temperature system.

The high temperature expansion valve (ETS) to the cascade heat exchanger should begin simultaneously with the high temperature compressors. After this, the valve controls the superheat of the high temperature gas. LT compressors are then started up by the CO_2 pressure increase on the suction line.

Danfoss pack controllers such as AK-SC 255, AK-PC 730 and AK-PC 840 are specially designed with built in control functions to coordinate these operations.

8.4 *Injection into cascade heat exchanger*

Injecting liquid into a plate heat exchanger is not a trivial matter. The heat exchanger is often compact and therefore the time constant is very low. AKV valves are therefore not recommended for this application.

It is recommended to use motor valves or other valves that give constant flow. Desuperheating of CO_2 gas entering the cascade heat exchanger can also be recommended for three reasons.

One reason is that the gas is often 60°C and therefore the heat can be rejected to the ambient or used for heat recovery without problems. The second reason is to reduce thermal stress in the heat exchanger. The third reason is that the CO_2 gas gives very high heat fluxes which therefore creates unstable conditions on the evaporation side. Therefore it is recommended to reduce the superheat on the CO_2 side.

Distribution on the CO_2 side is also a critical issue. Therefore the heat exchanger has to be designed for direct expansion to make sure the mixture of gas and liquid is evenly distributed to the heat exchanger.

When the heat exchanger is designed for reasonable pressure drop at part load, the oil transport and distribution will work under most conditions.

8.5 *Electronic control of cascade system*

A ETS valve combined with a EKC 316 provides typically the best regulation on cascade heat exchangers. EKC 316 uses both pressure and temperature, measured at the exit of the heat exchanger, to control the superheat.

The temperature sensor should be placed at 12 o'clock on the pipe and the pressure sensor should be placed so that there is no risk of oil or liquid pockets.

8.5.1 *Cascade systems with DX and pumped CO_2*

Cascade systems with pump circulation of CO_2 on MT were among the first CO_2 installations built after the use of CO_2 returned to the refrigeration industry and are still widely used today.

The efficiency of cascade systems is probably among the highest possible and is also unique regarding the small pipe dimensions for both LT and MT compared to those using brine.

Pumped circulation systems are best suited for installations with relatively high capacity. In small systems or systems with very high variations in load, pumps can be difficult to control.

🟥 HP vapour refrigerant
🟨 HP liquid refrigerant
🟦 LP vapour refrigerant

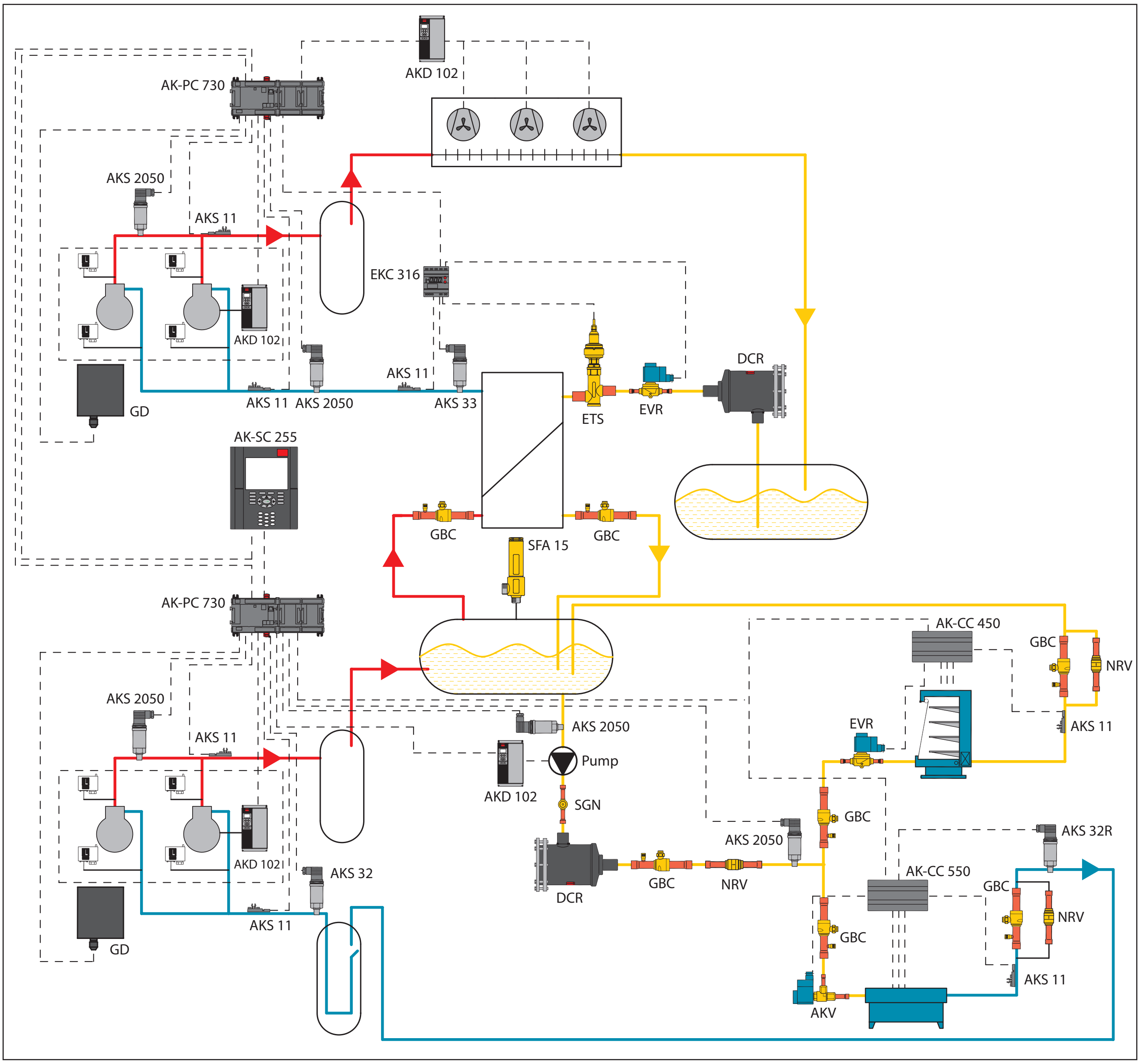


Fig. 8.2: Cascade system with pumped MT CO_2 and DX LT CO_2

8.5.2 Cascade system in combination with brine

System with brine on MT and CO_2 on LT have been built since 1998 and are still widely used in the Nordic countries. It seems that brine systems are slowly being phased out and taken over by cascade systems with CO_2 only or transcritical systems.

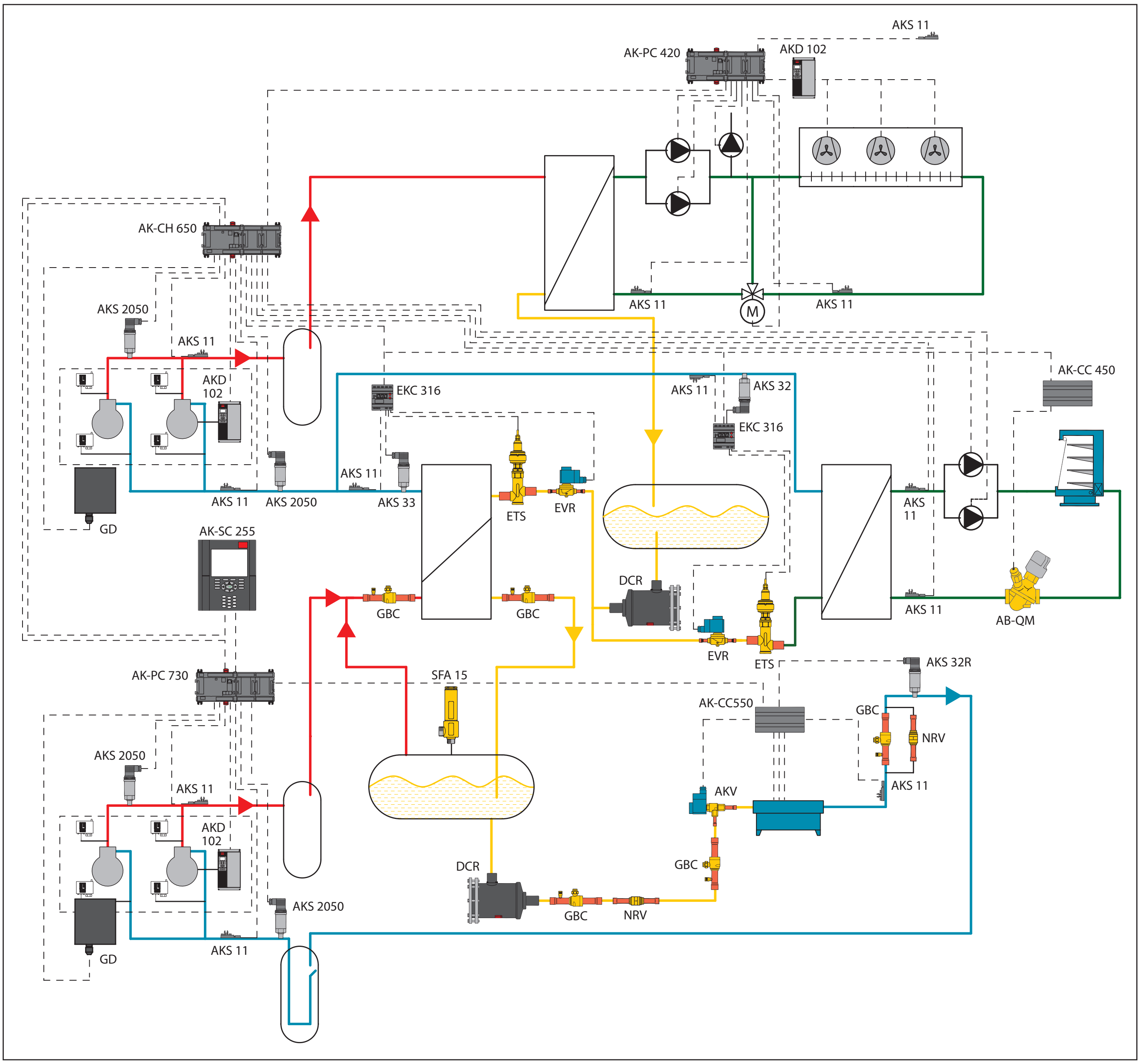


Fig. 8.3: Cascade system with MT brine and DX LT CO_2

🟥 HP vapour refrigerant
🟨 HP liquid refrigerant
🟦 LP vapour refrigerant
🟩 LP liquid refrigerant
🟩 Brine

8.5.2 Cascade system in combination with brine (continued)

The advantage of the brine system is that it has a relatively slow time constant making the compressor easier to control. To slow the system down even more, the brine circuit is used to condense the CO$_2$.

The advantage of this is that it is easier to control the cascade heat exchanger. The disadvantage is that there are two temperature differences instead of one. The maximum condensing temperature of CO$_2$ sets the limit for the brine temperature.

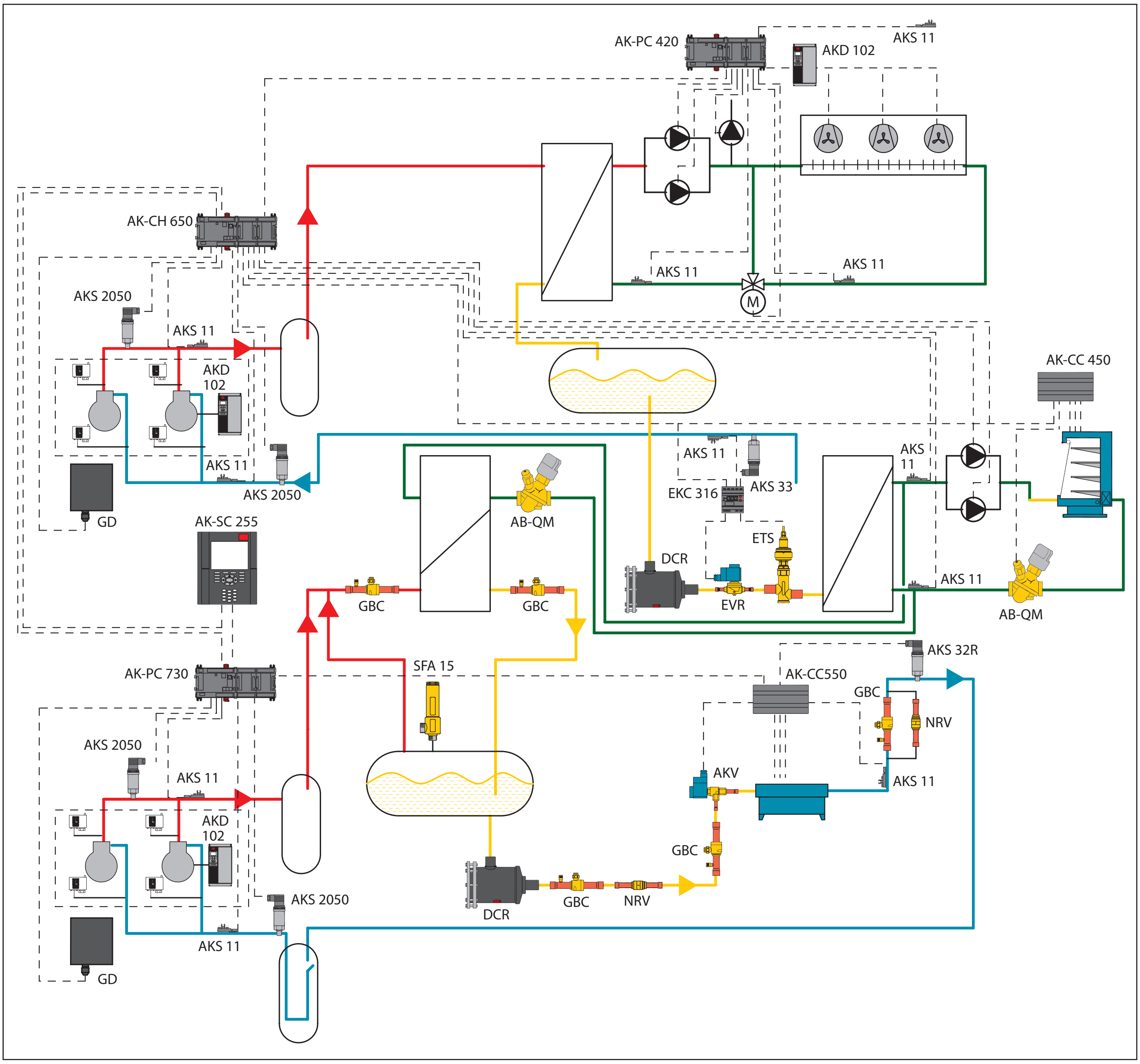


Fig. 8.4: Cascade system with DX LT CO$_2$, MT brine and brine cooled cascade heat exchanger

🟥 HP vapour refrigerant
🟨 HP liquid refrigerant
🟦 LP vapour refrigerant
🟩 Brine

9.
Simple transcritical system designs for food retail applications

9.1 *General description*

Transcritical system designs vary in complexity from simple designs used in unitary equipment, such as stand alone displays, to more advanced designs used in complete supermarket power pack systems.

The most simple transcritical system designs are used in unitary equipment installed inside or outside the retail area. These designs incorporate few electronic components with simple high pressure control such as an orifice or capillary tube which at the same time acts as the expansion device.

For applications where greater performance or efficiency is needed, an automatic back pressure regulator is incorporated in the design. (For more information on CO_2 properties and the theory of transcritical process, see Danfoss application article PZ.000.F1.02.).

Figure 10.1 shows a pipe diagram for a very simple transcritical system. The system consists of a compressor (TN type), a gas cooler, an evaporator, and an expansion device.

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. Another possibility is to use a thermostatic valve controlling the gas cooling temperature.

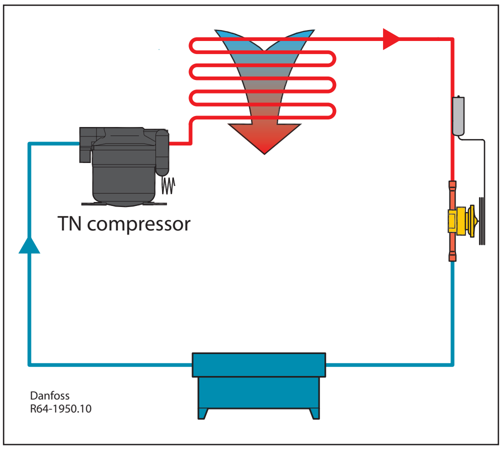


Figure 9.1.1: Layout of simple refrigeration system for transcritical operation

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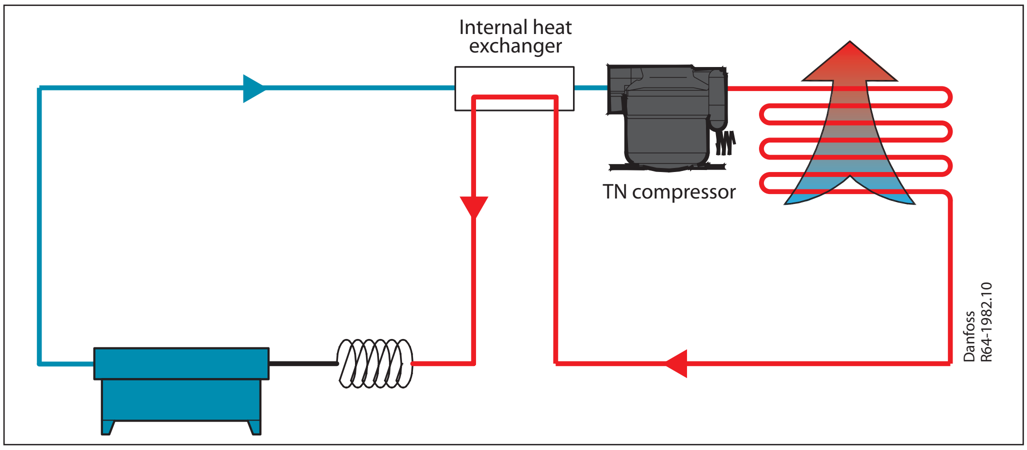
Using an internal heat exchanger between the suction line and the gas cooler discharge line can enhance the performance of the system (figure 8). If the expansion device is a capillary tube, the internal heat exchange can be established by soldering the capillary tube, or parts of it, to the suction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

The layout shown in figure 9.1.2 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 applications requiring high variability in operating conditions that must satisfy capacity and efficiency requirements under varying operating conditions and meet capacity and efficiency requirements at varying operating conditions, a high pressure control valve must be used. This can be either a mechanical or an electronic valve.

In addition, it may be necessary to install a low pressure receiver to compensate for the charge variations on the high pressure side.



🟥 HP vapour refrigerant
🟦 LP vapour refrigerant

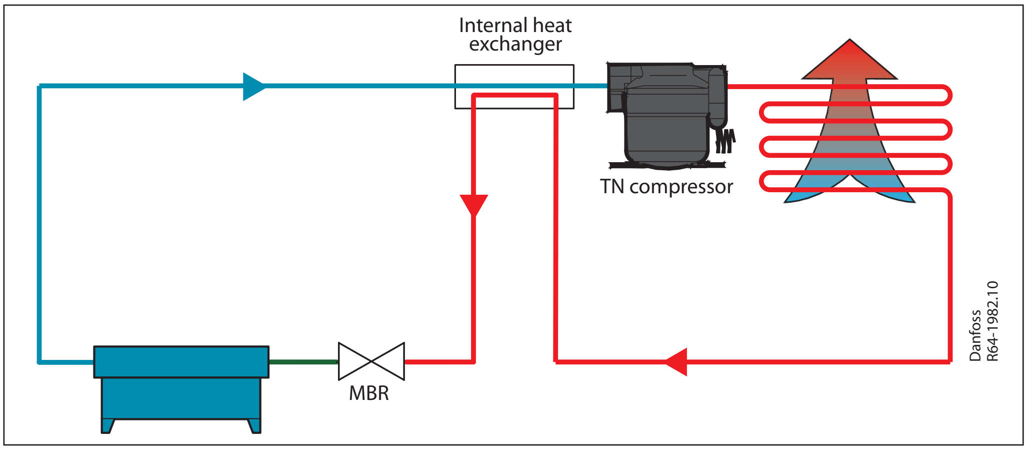
Figure 9.1.2: Layout of a transcritical refrigeration system with internal heat exchanger and fixed flow restriction as expansion device

9.2 System with an automatic valve

A system with an automatic valve is shown in figure 9.2. The valve senses the inlet pressure (the gas cooler pressure) and opens and closes according to a set point for inlet pressure.

The valve set point may be manually adjusted. The Danfoss MBR valve is designed and applied for this purpose.

The automatic expansion valve can be used for systems that operate with small variations in ambient temperature (e.g. for ambient temperatures above the critical temperature only) but with requirements for capacity or efficiency at two or more rating points.



🟥 HP vapour refrigerant
🟦 LP vapour refrigerant
🟩 LP liquid refrigerant

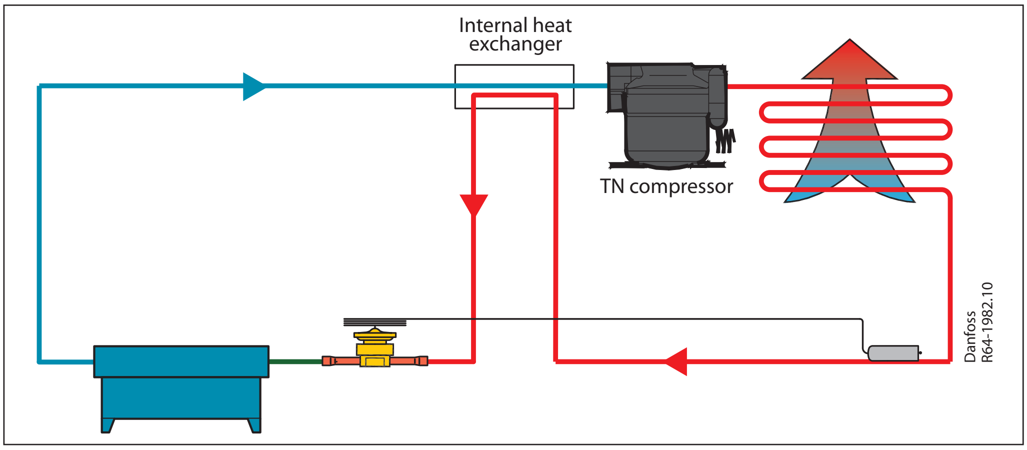
Figure 9.2: Layout of a transcritical refrigeration system with internal heat exchanger and an automatic valve as expansion device

9.3 System with a thermostatic expansion valve

A system with a thermostatic expansion valve is shown in figure 9.3.1 The valve uses a traditional bulb (filled with a liquid/vapour mixture of a substance) to sense the refrigerant outlet temperature of the gas cooler hereby controlling the inlet pressure (the gas cooler pressure).

Alternatively, the bulb can sense the air inlet temperature of an air cooled gas cooler.

The thermostatic expansion valve can be used for systems that operate with large variations in ambient conditions and with requirements for capacity or efficiency at two or more rating points.



🟥 HP vapour refrigerant
🟦 LP vapour refrigerant
🟩 LP liquid refrigerant

Figure 9.3.1: Layout of a transcritical refrigeration system with internal heat exchanger and a thermostatic expansion valve as expansion device

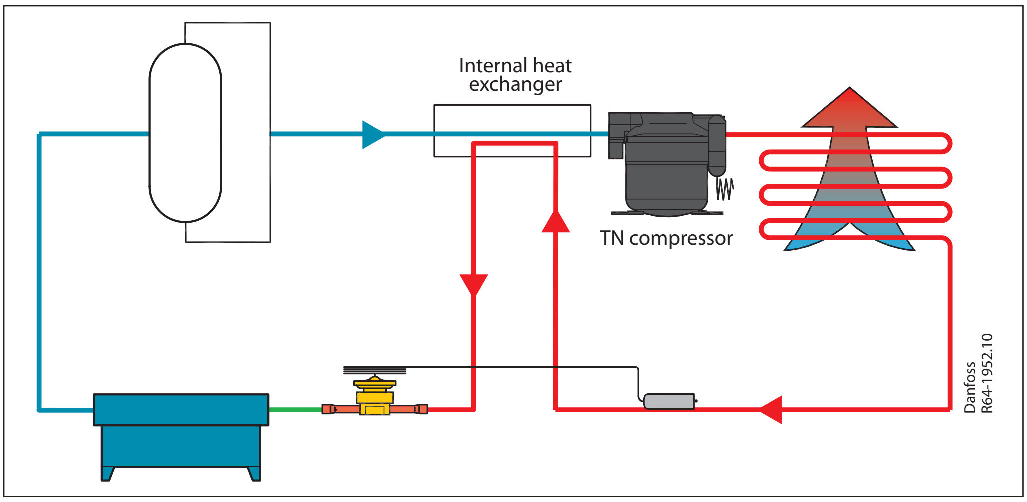
9.3 System with a thermostatic expansion valve (continued)

Improvements of performance for this type of system can be obtained by using a low pressure receiver as shown in figure 9.3.2.

As the temperature at the thermostatic expansion valve changes, the high pressure refrigerant is taken from or added to the low pressure receiver. Special care must be taken to avoid oil build up in the Receiver.

This can be avoided by an oil drain line allowing a small flow of liquid oil/refrigerant to exit the receiver and enter the internal heat exchanger.

A simple electronic controller (e.g. EKC 202 type) can be used to run the system.



🟥 HP vapour refrigerant
🟦 LP vapour refrigerant

Figure 9.3.2: Layout of a transcritical refrigeration system with internal heat exchanger, a thermostatic valve as expansion device and a low pressure receiver

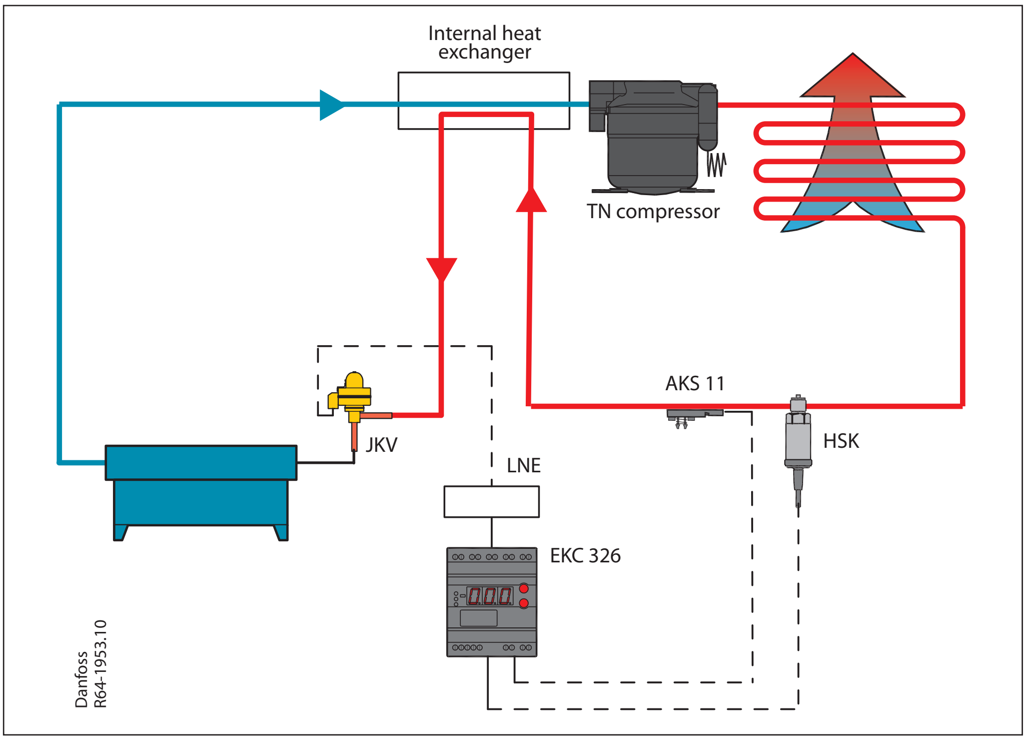
9.4 *System with electronic expansion valve*

Full control flexibility can be obtained with a system using an electronic expansion valve JKV and an electronic system controller EKC 326 receiving information about one or more temperatures and pressures in the system. It is also necessary to use a pulse converter for the stepper motor valve.

The layout shown in Figure 9.4 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.

Such control flexibility is often only necessary in systems that are to be analysed experimentally in a laboratory.

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.



🟥 HP vapour refrigerant
🟦 LP vapour refrigerant

Figure 9.4: Layout of a transcritical refrigeration system with internal heat exchanger and an electronically controlled valve as expansion device

9.5 *Summary*

System	**Capillary tube**	**Mechanical valve**	**Thermostatic expansion valve**	**Electronic expansion valve**
Advantages	Simple and reliable	Adjusts to variable capacity	Adjusts to variable ambient temperature	Gives full control and optimisation of the system
Limitations	Optimised for specific conditions only	Only one set point; does not react on changes in ambient temperature	No optimal for variable capacity	The most complex and expensive system
Danfoss components used	TN compressor	MBR TN compressor	TN compressor	JKV pulse converter EKC 326 AKS 2050 AKS11 TN compressor

10.

Transcritical booster system

10.1 General description

The transcritical system is one of the most promising systems in cold climate areas. The reason for this is that the energy consumption is on the same level as R404a systems or better and the design is relatively simple.

A typical CO_2 transcritical booster system is divided in to three pressure sections. The high pressure section begins at the high pressure compressor **(1)**, through the gas cooler **(2)** and the suction line heat exchanger **(3)**, to the high pressure control valve **(4)**.

The design pressure in this section is usually between 90 and 120 bar.
Controls for a transcritical system can be divided into four groups: gas cooler controls, injection controls, receiver controls and compressor capacity controls.

The intermediate pressure section begins at the high pressure expansion valve **(4)** where the flow is divided into gas and liquid in the receiver **(5)**.

The gas phase is sent to the suction line of the high pressure compressors through a bypass valve **(6)**. The liquid flows to the expansion valves **(7 and 8)** where it is expanded before the MT **(9)** and LT **(10)** evaporators.

The gas from the LT evaporator is compressed in the LT compressor **(11)** and mixed with the gas from the MT evaporator and from the gas bypass. From here the gas enters the suction line heat exchanger and completes the circuit to the HP compressor.

The design pressure for the MT section is often 40-45 bar and 25 bar for the LT section. There seems to be a tendency to design MT and LT sides for the same pressure.

The pressure in the receiver is controlled by the ETS stepper motor valve **(6)**. The pressure in the receiver has to be higher than the evaporation pressure in the MT evaporators to ensure differential pressure over the MT expansion valve **(7)**.

On the other side, the pressure has to be lower than the design pressure.

All controls illustrated, except the gas cooler controller, are standard Danfoss controls used on conventional systems and already applied throughout the industry.

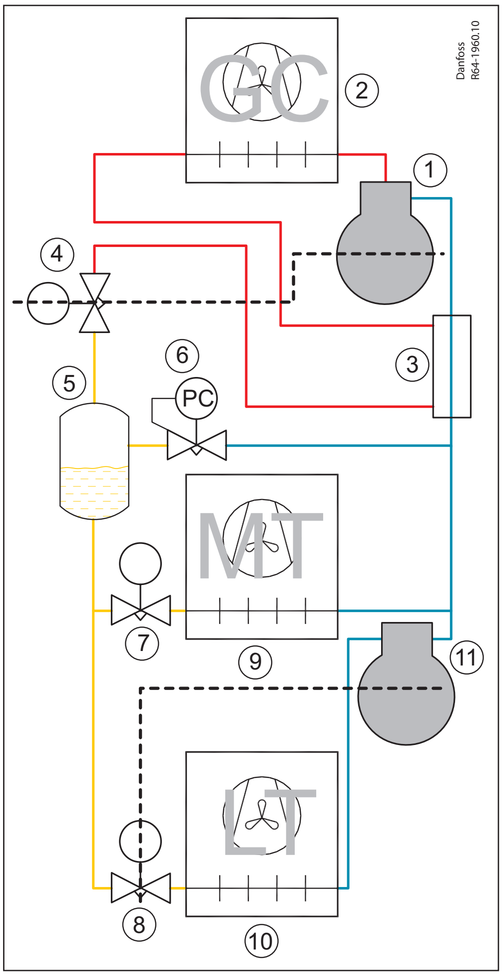


Figure 10.1: PI diagram of the transcritical booster system with gas bypass

🟥 HP vapour refrigerant
🟨 HP liquid refrigerant
🟦 LP vapour refrigerant

10.2 Transcritical cascade system

🟥 HP vapour refrigerant
🟨 HP liquid refrigerant
🟦 LP vapour refrigerant
🟩 LP liquid refrigerant

Pack Controller AK-PC 730, controls the condensing pressure and is a standard controller for controlling one suction group in any refrigeration system.

The controller is able to control the condensing pressure in the LT circuit and at the same time monitor the suction pressure. The AK-PC 730 is also able to coordinate the LT and HT start to ensure a smooth operation.

Injection control for the case and cold room evaporators is a standard electronic controller.

AK-CC 550 utilising pulse-width-modulating injection valves AKV and patented software algorithms to optimise system performance and operation. The AKV valves are also used as standard valves for HFC refrigerants.

The overall system management and interface is carried out through a choice of AK-SM 350 or AK-SC 255 or AK-SM 720 depending on application design preference.

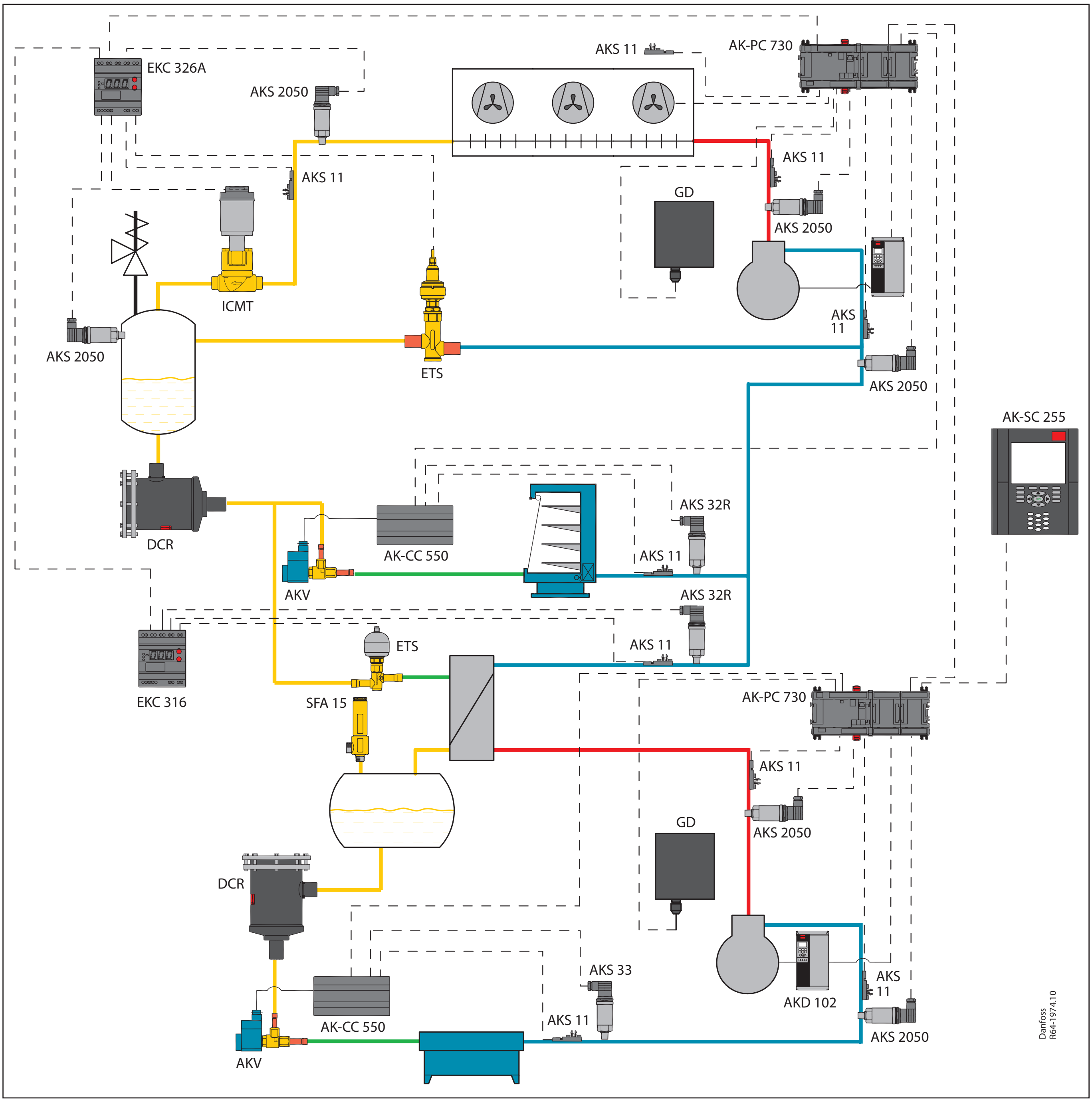


Figure 10.2: Transcritical cascade system

10.3 Transcritical booster system

🟥 HP vapour refrigerant
🟨 HP liquid refrigerant
🟦 LP vapour refrigerant
🟩 LP liquid refrigerant

Pack controller AK-PC 730 controls the suction pressure and is a standard controller for controlling one suction group in any refrigeration system.

The AK-PC 730 is also able to coordinate the LT and HT start to ensure a smooth operation. Injection control for the case and cold room evaporators is a standard electronic controller. AK-CC 550 utilising pulse-width-modulating injection valves AKV and patented software algorithms to optimise system performance and operation.

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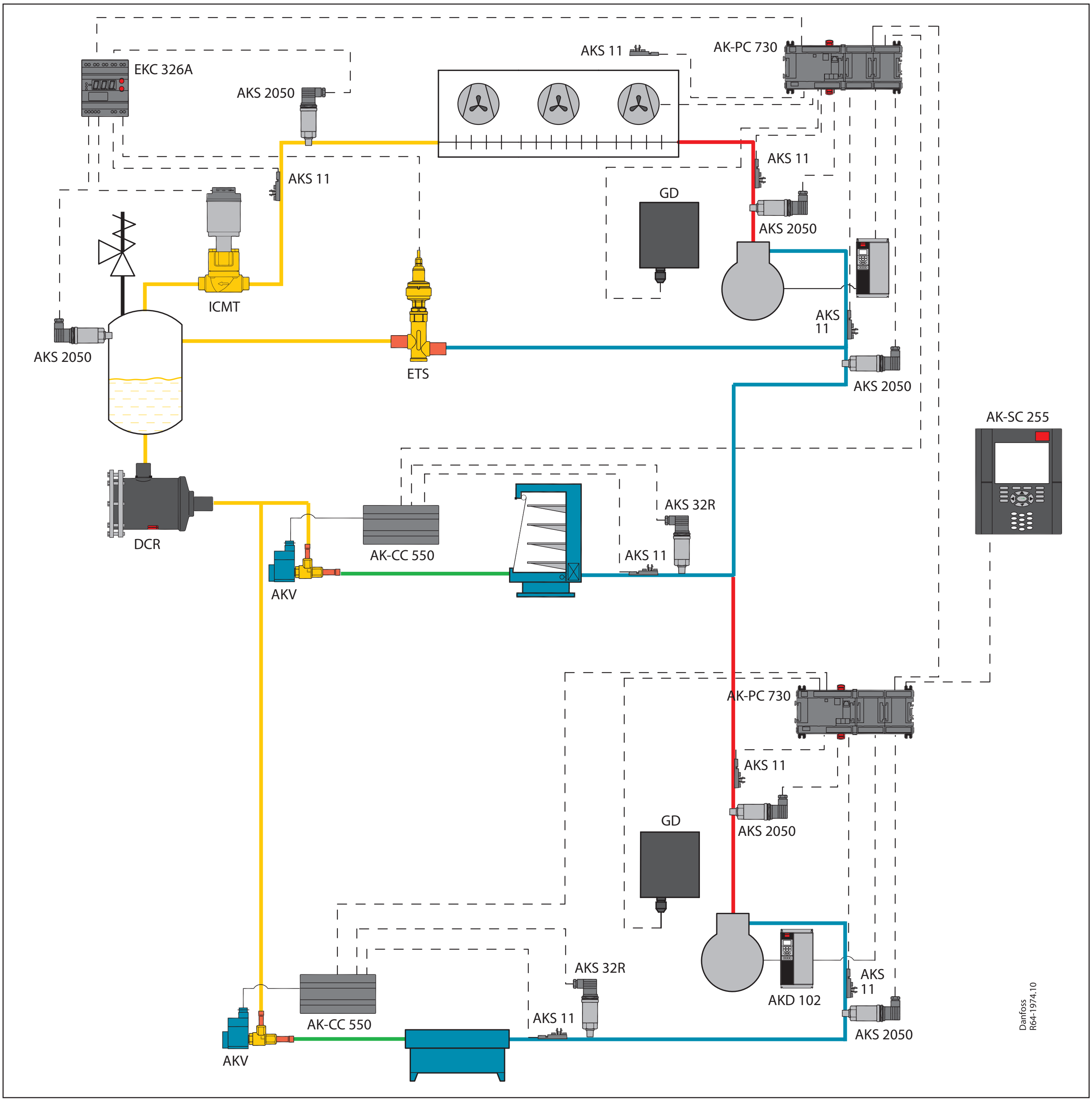

Figure 10.3: Transcritical booster system.

Danfoss – Your CO_2 Solution Provider

Danfoss offers a complete range of valves for cascade CO_2 systems

Complete ADAP-KOOL® system control solutions
Danfoss has more than 15 years of experience in developing subcritical and transcritical CO_2 systems
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.

Read more about Danfoss CO_2 products and solutions
– visit us at www.danfoss.com/CO2

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