Application guide to CO₂ secondary coolant systems

Fighting global warming with CO₂ may seem counter intuitive, but by replacing water-based brine systems you can both reduce your carbon footprint and reduce your energy consumption.

Energy savings
with CO₂ secondary systems
500 kW at 0°C room temperature

How much could you save?
Visit www.danfoss.com/COtoo to calculate your system’s CO₂ and energy savings, and see why you should be considering CO₂, too.

www.danfoss.com/COtoo
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General description of CO₂ systems

A typical schema of a low/medium temperature NH₃/CO₂ system (fig. 1) consisting of
- a Standard NH₃ refrigeration system with a cascade heat exchanger acting as evaporator
- CO₂ acts as a volatile fluid in the evaporators (flooded system (1-6))

CO₂ is circulated by gravity in the cascade heat exchanger, which gives good control of the CO₂ temperature in the receiver.

The CO₂ gas flows up (7) into the cascade heat exchanger, where it is cooled by NH₃ condenses and flows back down into the CO₂ receiver as liquid CO₂ (8). On the ammonia side the refrigeration cycle can be controlled using a high pressure float valve (HFI) or by direct expansion into the evaporator (e.g. with an electronic expansion valve type ICM, and a cascade controller type EKC 313).

Differences to traditional NH₃/brine systems.

System performance:
NH₃/CO₂ fluid systems have significantly lower energy consumption compared to traditional systems with NH₃ and water based brines. COP of the system is higher due to the following:

- Evaporation temperature and PHE efficiency
  Typically the high side NH₃ system evaporation temperature is a few degrees higher. The reason for this is the better CO₂ heat transfer coefficient in the air coolers and the PHE, resulting in a lower temperature difference in the heat exchangers. This directly reduces the energy consumption of the NH₃ compressors. Some figures indicate that the COP of NH₃/CO₂ systems is close to that of pure NH₃ systems.

- Pump energy
  The pump energy needed to circulate the CO₂ through the air coolers is significantly lower, due to the fact that less CO₂ needs to circulate, but also thanks to the lower density of CO₂. The pump recirculation rate for CO₂ is relatively low as well (typically between 1.1 and 2), and this also makes it possible to use a smaller pump.

Line and component sizes in a flooded system:
Due to the high specific heat content of CO₂ and its lower density, smaller components and line sizes can be used compared to a traditional brine system, for both the outward and the return lines.

The smaller volume of CO₂ to circulate means that smaller pumps can be used which yields lower energy consumption for the circulated cooling capacity.

The smaller CO₂ pipes have a smaller surface and therefore lower heat-loss compared to larger brine/glycol pipes.

Figure 1 - General diagram of CO₂ pumped system.

Figure 2 - Comparative pipe size
Optimising energy control:
Further reduction of energy consumption by NH3/CO2 systems is possible using smart control algorithms. A good way to improve the efficiency (COP) of the system is to reduce the pressure ratio in the NH3 compressor. The 2 ways of doing this are
- Keep the condenser at the lowest possible pressure.
- Keep evaporation at the highest possible pressure

The condenser control is similar to that of traditional systems, where fans can be controlled by an AKD102 variable frequency drive, and the condensing pressure can vary depending on the ambient temperature.

That can be done using Danfoss pack controller AK-PC 730/840.

The management of the suction pressure is another area where there are differences between CO2 cascade systems and brine/glycol systems.
Assuming a system design as shown in fig. 3. A pressure signal from the CO2 receiver can be used to control the capacity of the cascade compressors (the NH3-system).
If the pressure in the CO2 receiver decreases, then the speed of the cascade compressors also decreases, in order to keep up the CO2 pressure.
This function can be provided by the AK-PC 730 / 840 Pack Controller.

Figure 3 - Integrated control of pump-circulated CO2 systems
Frequency control of the CO₂ pumps

There are two ways to control the liquid CO₂ pumps; using a simple on/off step control or using a frequency converter (type AKD). Frequency converter operation is becoming increasingly popular for 2 good reasons: Energy savings and Better liquid distribution in the evaporator coils.

Energy savings
CO₂ pumps are typically controlled by a constant pressure difference. Under standard conditions the energy consumption is the same as or slightly higher than that of a fixed speed pump. When running under partial load conditions, a fixed speed pump would still consume the same energy due to the increased pressure difference. A liquid CO₂ pump using a frequency converter will run at a lower velocity and consume less energy.

The savings will vary depending on the running time and the actual running conditions. Savings can, however, be up to 50% compared to pumps operating on/off at full speed.

Better liquid distribution in the evaporators
A requirement for good performance of the evaporators / air coolers is a good distribution of the refrigerant liquid in the system.

A precondition for good distribution of refrigerant liquid is having a stable pressure differential across the evaporators.

Pumps controlled by frequency converters can ensure that the pressure is kept at a stable level under all load conditions. At low capacity the energy consumption will be low and at high capacity there will be sufficient flow of CO₂.

A typical piping layout with CO₂ pumps controlled by frequency drives (AKD 102 type) is shown in figure 4. Another benefit of pumps driven by frequency converters is that the Q-max orifices can be omitted.
Defrosting CO₂ systems

There are several ways to defrost pumped CO₂ systems:

- **Electrical defrosting.** This is the simplest and least energy efficient method of defrosting. The additional power consumption for defrosting can be quite significant in some cases.
- **Hot gas defrosting.** CO₂ hot gas defrosting can be used if a compressor is built into the system to support defrosting. That compressor will then only operate when defrosting is needed. This method is more economic than electrical defrosting.
- **Brine defrosting.** By using brine it is possible to utilize the heat from the cascade system to defrost CO₂ evaporators. This application is especially attractive if the ammonia condenser is water cooled.
- **Water defrosting.** In some cases (especially in rooms with temperatures above zero) evaporators can be defrosted using sprayed water.

The process is similar to a traditional NH₃ defrosting system.
Defrosting CO₂ systems

Traditional industrial refrigeration systems are flooded (pumped) systems. In a flooded system, the evaporators are injected with more liquid than needed for full evaporation. The amount of liquid supplied to the evaporators is defined by the “circulation rate”:

<table>
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<tr>
<th>Circulation rate</th>
<th>Gas mass flow created</th>
<th>Liquid mass flow supplied</th>
<th>Liquid mass flow out</th>
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<tbody>
<tr>
<td>1</td>
<td>x</td>
<td>x</td>
<td>0</td>
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The benefit of liquid overfeed is increased efficiency of the coolers, because of better use of the evaporator surface, and better heat transfer due to an increased heat transfer coefficient. In addition, flooded systems are relatively easy to control.

The injected liquid at the correct temperature is pumped from a separator to the evaporators.

When liquid is needed, a solenoid valve in front of the evaporator is opened. In order to be able to set the required circulation rate, and to hydraulically balance the system, a manual regulating valve is normally installed behind the solenoid valve.
Evaporator control (continued)
Temperature control in evaporators can be managed as follows:

- Regulating valve for distribution control + ON-OFF solenoid valve for temperature control
- Regulating valve for distribution control + pulse-width modulating solenoid valve for temperature control
- AKV valves for both distribution control (orifice size) and PWM temperature control

![Diagram of evaporator control](image)

Traditional injection valves
In a traditional flooded system, the liquid injection is controlled by a thermostat which constantly measures the air temperature. The solenoid valve is opened for several minutes or longer until the air temperature has reached the set point. During injection the mass of the refrigerant flow is constant.

This is a very simple way to control the air temperature, however, the temperature fluctuation caused by the differential of the thermostat may cause unwanted side effects in some applications, like dehumidification and inaccurate control.

The capacity of an air cooler
The capacity of an air cooler is described by the following equations:

Refrigerant side:
\[ Q_{\text{cooler}} = \text{massflow} \times \Delta h \]  
Massflow [kg/s evaporated liquid]  
\( \Delta h \) [kJ/K]

Refrigerant/Air side:
\[ Q_{\text{cooler}} = k \times A \times \Delta T \]  
\( k \) [W/(m².K): the total heat transfer coefficient, (depending on the heat transfer coefficient of the air and refrigerant, which depend on air/refrigerant flow) and the heat conductivity of the materials used in the coolers.  
A [m²]: cooler surface  
\( \Delta T \) [K]: the difference between the evaporation and air temperatures.

![Graph of temperature fluctuation](image)
Injecting an air cooler in a flooded system using pulse width modulation AKV(A) valve

Instead of injecting periodically, as described above, one can also constantly adapt the liquid injection to the actual need. This can be done by means of a pulsing AKV(A) valve.

The air temperature is constantly measured and compared to the reference temperature. When the air temperature has reached the set point, the opening of the AKV(A) valve will be reduced, giving it a smaller opening angle during a cycle, resulting in less capacity and vice versa. The duration of a cycle is normally between 3-6 seconds.

In a flooded system this means that the average refrigerant flow is constantly controlled and adapted to the needs. So when less refrigerant is injected, the circulation rate decreases.

The result of this is that more refrigerant will be evaporated, creating a certain amount of superheated gas in the air cooler. A direct effect of this is a cooler average surface temperature, resulting in a smaller ΔT between the refrigerant and the air.

Looking at the equations (1) and (2), it can be concluded that less injection results in:
- a decreasing ΔT (evaporating temperature comes nearer to ambient temperature)
- a decreasing k value
- a decreasing heat transfer surface on the air cooler (less “wetted” surface)

All resulting in smaller cooler capacity.

This approach to liquid injection in a flooded system generates a high degree of flexibility in terms of engineering. The amount of injected liquid can be controlled exactly, which increases the accuracy and the energy efficiency of the system.

Typical applications are cool stores for fruit/vegetables, where adaptation to the actual load is frequently needed. A chilling cycle (AKV valve fully open) needs much more capacity than a storage cycle (AKV valves in PWM mode).

Also these types of cool rooms are often used for different amounts and types of fruit, so load adaptation is a must.
How to select an AKV(A) valve in a flooded CO₂ application?

When selecting a valve in a flooded system, we need to know the maximum cooler capacity required, given the highest circulation rate, so basically what is the maximum amount of liquid to be injected. Secondly, we must define the net available fall in pressure across the AKV(A) valve. The selection can be made easily using CoolSelector.

Please be aware that the total pump pressure required depends on several factors, such as system pressure drop (distributors/nozzles of the air coolers, components, lines, bends, static height and so on).

Example:
- Refrigerant: CO₂
- \( N = 1.5 \)
- \( T_o = -8°C \)
- Available fall in pressure across valve: 1 bar
- Cooler capacity: 30 kW

CoolSelector calculates an AKVA 15-3, \((kV = 0.63 m^3/h)\) which yields 30 kW at a circulation rate of 1.5 and a pressure drop across the valve of 1 bar. If more capacity is needed, a bigger valve or higher fall in pressure across the valve should be provided.

The minimum fall in pressure needed in practice for an AKV(A) alone in a flooded system to operate satisfactorily has been shown to be 1 bar (or more if enough pump pressure is available).
Pumped systems with ICF

The example in fig. 6 is done using a standard AKVA valve. A multi-modular valve of type ICF could usefully be applied for this application as well.

If the coolers are defrosted using CO₂, a version with a check valve is needed.

Special care should be taken with the solenoid valve in the wet suction line. A commonly applied defrost temperature is around 9-10°C, meaning 44-45 bar (a) pressure upstream of this solenoid valve.

Depending on the separator pressure, the MOPD of this valve could be too small to open. It is good practice to use a small bypass valve like EVRST (PS = 50 bar) to equalise the pressure first, before opening the main valve. MOPD of ICM 20-32 is 52 bar, so always capable of opening after a defrost, even when the separator pressure is near the triple point of 5.2 bar a.

When using ICM, a benefit is that the defrost pressure can be equalised by slowly opening the valve. A cost-effective way to do this is using the on/off mode on the ICM and selecting a very low speed (I04), or it can be achieved by using the modulating mode, so the PLC totally controls the opening degree and speed.
# Application guide
## Pumped CO₂ in Industrial Refrigeration Systems

### Reference Literature - Alphabetical overview

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Application guide  Pumped CO₂ in Industrial Refrigeration Systems
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