Transcritical CO₂ system in a small supermarket
**Article**

Transcritical CO\(_2\) system in a small supermarket

**Abstract**

This paper will cover the design of a 10 kW (\(-30^\circ\)C) and 24 kW (\(-10^\circ\)C) refrigeration system for a small discount supermarket.

The main objective has been to design and build a system that is just as reliable and energy effective as a conventional HFC system.

The system is designed and built as a transcritical CO\(_2\) booster system with gas bypass from the intermediate pressure receiver to the suction side of the high pressure compressors.

Measurements have been carried out in the laboratory as well as in the field where the energy consumption is compared with other similar size systems working under similar conditions.

The system has been in operation since 1 of March 2007.

**Introduction**

In Denmark the use of synthetic refrigerants has been banned since 1st January 2007. In reality this means that there are only 2 or 3 alternatives: ammonia and hydrocarbons. However due to toxicity and flammability, ammonia is not considered an alternative. Hydrocarbons, being highly flammable, are not authorised for use under ground level and are also expensive to handle inside buildings. Transcritical CO\(_2\) is thus the only option possible to install at all sites.

Energy consumption is an issue that has been discussed a lot in other articles and the project group. Preliminary simulations showed that in Denmark the system would be running transcritical for less than 1 % of the year and would be able to condense at very low temperatures during winter. The annual energy consumption would be the equivalent of HFC refrigerants.

From an environmental point of view, the energy consumption is not as important, contributing with approximately only 50% of the TEWI for the system and the remaining 50% from the refrigerant.

The project has been subsidised by the EU life program and has been running from September 2005 to September 2007.

**System Design**

After an evaluation of different systems of energy consumption and availability of components, the booster system with gas bypass was chosen.

The system is divided into 3 pressure sections. The high pressure section begins at the high pressure compressor (1) and continues through the gas cooler (2) and suction line heat exchanger (3) to the high pressure control valve (4 – Danfoss ICMT motor valve). The design pressure in this section is usually between 90 and 120 bar.

The intermediate pressure section begins at the high pressure expansion valve (4) where the flow is divided into gas and liquid at the receiver (5). The gas phase is sent to the suction line of the high pressure compressors through a bypass valve (6 – Danfoss ICS+CVP-XP servo valves or ETS motor valves).

The liquid flows to the expansion valves (7 and 8 – Danfoss AKV pulse modulating valves) where it is expanded prior to continuing to the MT (9) and LT (10) evaporators. The gas from the LT evaporator is compressed in the LT compressor (11) mixing with the gas from the MT evaporator and forming the gas bypass. From here the gas enters the suction line heat exchanger and completes the circuit to the HP compressor.

The design pressure is 40 bar for the MT section and 25 bar for the LT section.

*Figure 1: PI diagram of the transcritical booster system with gas bypass*
The design conditions are: 32°C ambient, –10 ºC evaporation for MT and –30°C for LT. With the present gas cooler design, the 32°C ambient is equivalent to approximately 35°C CO₂ temperature leaving the gas cooler. The pressure is optimised for optimum COP - the pressure in the gas cooler is approximately 90 bar at 32°C gas cooler exit temperature.

The pressure in the receiver is controlled by the constant back pressure valve (6). The pressure in the receiver must be higher than the evaporation pressure in the MT evaporators to ensure differential pressure over the MT expansion valve (7). However, the pressure must be lower than the design pressure.

Figure 2: Cycle in log P-h diagram at 3 different intermediate pressures (30, 35 and 40 bar)

A simple investigation of the intermediate pressure shows that the pressure must be as low as possible to reduce the amount of liquid in the gas bypass line.

The liquid decreases the COP of the system and is therefore not wanted. Since the liquid fraction in the gas bypass is approximately 1%, 30 bar is chosen. This is not considered a practical problem and there is still a pressure difference of 4 bar which is sufficient.

The pressure in the receiver is constant regardless the ambient temperature, but the flow ratio between the gas bypass and liquid line varies with the pressure in the gas cooler and the gas cooler exit temperature.

Figure 3.1: Liquid vapour fraction at 10°C and 35°C outlet gas cooler
**System Design (continued)**

The decoupling of the ambient temperature and receiver pressure makes the flow in the evaporators only a function of the cooling capacity. In traditional transcritical systems, the ambient temperature causes the mass flow to vary by a factor of 2 which makes design of suction lines and oil return difficult.

**Controls**

Controls for a transcritical system can be divided into four groups:
- Gas cooler controls
- Injection controls
- Receiver controls
- Compressor capacity controls

The gas cooler control is relatively new in refrigeration systems and has therefore been subject to a lot of research the last few years. In this system the gas cooler controls have been divided into three sections:

- At low temperatures, the system is controlled as a conventional refrigeration system where subcooling is the control parameter.
- At higher temperatures, the algorithm changes when subcooling is increasing at higher temperatures.
- At transcritical conditions the pressure is a function of the temperature out of the gas cooler. The goal is to obtain as high COP as possible at the given temperature.

The gas cooler fans are controlled by the temperature out of the gas cooler. If the temperature is lower than the set point (0°C), the fans slow down. Subsequently when no compressors are running, the fans stop.
Controls
(continued)

On conventional systems the pressure is often used, but on transcritical systems, during cold periods, this can increase the subcooling resulting in too low a pressure in the receiver and therefore no differential pressure for the expansion valves.

Danfoss EKC 326 controller has the required functionality.

Injection control for the evaporators is regulated by a standard electronic controller with pulse modulating valves. The valves used are also standard valves for HFC refrigerants. Typically AK-CC 550 or AK-CC 750 controllers are used for this purpose.

Receiver control is not normally found in refrigeration systems and has therefore been investigated in the project. As described earlier, the pressure was chosen to be 30 bar, which is 4 bar higher than the evaporation pressure.

Two different strategies were investigated: constant back pressure valve and constant differential pressure.

The constant pressure valve was chosen due to its incorporated safety measure that is activated when suction pressure is too high. Hence the pressure difference is reduced by stopping the flow through the expansion valves until the pressure is low again.

This prevents the safety valves opening, thus minimising the loss of charge.

The last control group in the system is compressor capacity controls. The compressor controls are no different from conventional systems, yet have still instigated the largest problems.

The main issue being the system only having two high pressure compressors and one low pressure compressor. This makes night load an obstacle without getting too much start/stopping. The problem cannot be solved on a system this size, but has been reduced by fitting a frequency converter on one of the high pressure compressors. This makes the match between the low pressure and high pressure compressors better, but far from perfect.

Coordination between the low pressure and high pressure compressors was also implemented due to the system running on the edge of the compressor envelope - so the high pressure compressors have to be started before the low pressure compressor is released.

Danfoss pack controller AK-PC 750 is a good solution for compressor control, and it supports frequency converters as well. All controls, with the exception of the gas cooler controller, are standard controls used on conventional systems.

Energy consumption and experience

The energy consumption of the system has been monitored and will be compared with that of other systems. All systems are of similar size (cooling capacity and square metres) and have been selected because the load profile is comparable.

The reference R404A system has been chosen since such systems are already running in Denmark and other countries in very big numbers.

It has been the most common system in supermarkets, for a long period. Since 1st January 2007, R404A has been banned in Denmark. Cascade systems with small HFC charges are one solution but seem to have been taken over by transcritical systems.
## Article

### Transcritical CO\(_2\) system in a small supermarket

<table>
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<th>System</th>
<th>Description</th>
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<tr>
<td><strong>Reference System</strong></td>
<td>The reference system is using R404A as a refrigerant and is a standard parallel system for both medium and low temperature. The two-year-old system has been running without problems both prior to the test period and during the test period and is placed in Randers close to the east cost of Jutland.</td>
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<tr>
<td><strong>Cascade System</strong></td>
<td>The cascade system is using R410A as a refrigerant for high temperatures. The condenser is a plate heat exchanger fitted with a drying cooler. The low and medium temperature is served by two parallel systems with a common condenser. Both CO(_2) systems use CO(_2) compressors from LG converted from R410A. The system has been in operation for approximately 1 year prior to the test period and has been running without problems. During the test period, that took place in week 40, the energy consumption went up by approximately 50%. The explanation for this was found in a small leak in the drying cooler circuit resulting in too high condensation temperature. Therefore, this data has been removed from the comparison. After the test period the leak was repaired and the energy consumption returned to the same level as before the leak. This system is installed in Tranbjerg 10 km south of Århus on the east cost of Jutland.</td>
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<td><strong>Transcritical System</strong></td>
<td>The transcritical system is designed as a booster system with a gas bypass between the intermediate pressure receiver and the suction side of the high pressure compressor. More information can be found elsewhere in the report. The system was installed and started on the 1st March 2007. The project partners have been conducting tests and optimisations on these systems and the period, where measurements have been conducted, has been reduced but spread out over a period from May to December. This system is placed in Esbjerg on the west cost of Jutland approximately 150 km from the other systems. When entering the store which means that the load from the goods is relatively low. Weather conditions and geographic siting also have some influence on the results even though the stores are only placed 150 km apart. Nevertheless this is of small consequence. The fact that we only looked at one store of each type, makes it impossible to say anything about the validity of the data but this can still be used as an indication.</td>
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<td><strong>Uncertainties</strong></td>
<td>The measurements are considered to be better than 1% and are therefore not the biggest contributor to uncertainties. The majority of uncertainties are circumstances outside our influence such as behaviour around the system, turnover in the store and weather. We know from prior studies that energy consumption is closely tied to the store manager. If the manager moves to another store, the energy consumption follows. Therefore, part of energy consumption can be concluded to be tied to human behaviour connected with the use of these systems. The turnover varies form store to store and finding stores with matching turnovers was a priority in this store selection. However, this influence is relatively low since goods are cooled down</td>
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Data

**Figure 6: Energy consumption over time**

The energy consumption of the three systems is almost identical.

**Figure 7: Accumulated energy consumption over 37 weeks**

The energy consumption of the cascade is approximately 99% of that of the R404A system and the transcritical is approximately 96% of the R404A system.

With the data available, it is not possible to conclude that a transcritical system uses less energy. However, this seems to be the case for this system, since results from other studies conducted by Linde back up the results from this project.

Experience

The system has been in operation for more than one year without experiencing major problems. The problems encountered were related to noise/vibrations and oil handling. All problems have been solved along the way and approximately 50 systems were installed the first year.
Conclusion

The concept with booster and gas bypass has proven to be very efficient and reliable. The system has been built with standard components available from normal suppliers of refrigeration equipment.

From the above study on energy we can conclude that the energy consumption for this system is lower than that of a comparable R404A system. This conclusion is backed up by other studies.