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Refrigerating concept for small supermarkets using multiple modular cascade systems with carbon dioxide and propylene.

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Abstract

This paper presents a project that has been partly funded by the Danish Environmental Protection Agency (Heerup, 2004) in order to increase the number of available technical solutions as an alternative to fulfilling the requirements of Statutory Order no. 552 of 2 July 2002 Regulating Certain Industrial Greenhouse Gases, which implies limiting the size of HFC refrigerant charges to a maximum of 10 kilograms for refrigeration systems after January 1st, 2007.

The concept addresses the safety issues involved with hydrocarbons by minimizing the refrigerant charge and containing the hydrocarbon filled parts in a module comprising a closed cabinet. The modular concept has the following features:

In need of service, it will simply be exchanged with a new or manufacturer recon module, thereby eliminating the elevated risk involved with the servicing on site (Colbourne et al., 2003).

The refrigeration capacity can be satisfied by installing from 3 to 10 modules in parallel.
If one module fails the remaining will in most cases suffice as back up capacity until replacement.

The modules contain each a refrigerant charge of maximum one kilogram propylene serving as the upper stage of a cascade system. The condensers for the upper stages are cooled by a conventional dry cooler circuit. The upper stage is cooling the primary side of a plate heat exchanger, the secondary side acting as condenser for carbon dioxide as the secondary refrigerant.

The liquid carbon dioxide is pumped to the low temperature display cabinets via expansion valves and is returned to the condenser by multiple rolling piston compressors, thus completing the low stage of the cascade system. The medium temperature display cabinets are simply pump fed via solenoid valves with liquid carbon dioxide which partly or totally evaporates and then returns to the condenser.

The project involves: Identification and testing of components, Capacity measurements of compressors with mass flow meter, System configurations and performance, Risk assessment of electrical components, Oil control, Prototype modules and carbon dioxide pack, Performance calculations of evaporators, Cost compared to traditional pack, Comparison with other systems, Practical experiences.

Background.

DEPA (The Danish Environmental Protection Agency) proposed in 1999 a complete phase out of HFC refrigerants by January 2006. In July 2001 the HFC refrigerants got heavily taxed. This immediately accelerated the need for reducing HFC charges on new plants. Solutions with CO_2 on large installations became highly relevant.

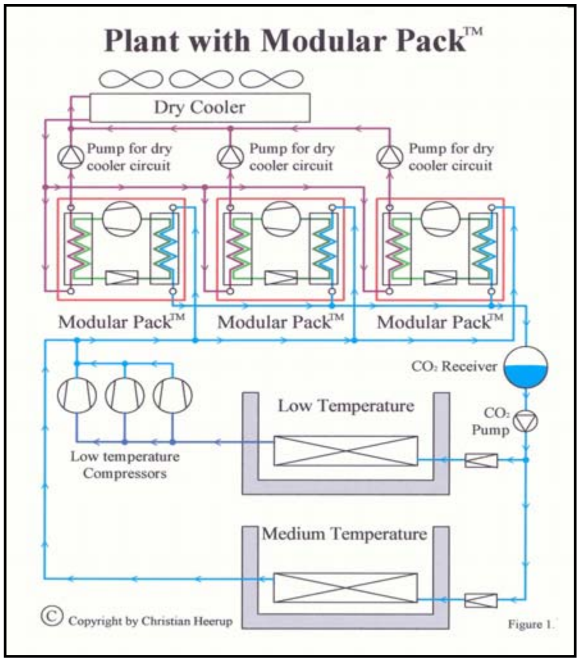
In 2002 the HFC phase out proposal was made statutory with the following major revisions: Charges between 150 g and 10 kg HFC per circuit are permitted, as well as factory assembled heat recovery units with less than 50 kg. All other new plants with charges above 10 kg are prohibited after January 1st, 2007.

As a wholesaler Tempcold A/S, with production of packs for small and medium sized supermarkets, based entirely on components for HFC's, had in 1999 no components for, or experience with natural refrigerants.

Inspired by earlier projects (Christensen, 1999) funded partly by the Danish government using subcritical carbon dioxide and hydrocarbon the idea was formed to develop a concept capable of replacing the traditional pack without compromising safety and energy consumption.
The project was commenced in 2001.

Introduction.

The use of CO_2 in subcritical state at saturated temperatures below 0 ºC, allows the use of standard components at slightly elevated pressures. This is facilitated by small bore piping and the improved availability of components for higher pressures thanks to the increased use of R410A. Thus CO_2 can be utilized as a safe and efficient medium for distributing the refrigerating capacity to the cabinets and cold rooms.



To maintain the low temperature for the CO_2 it is necessary to have a high temperature cooling stage. In order to use low cost components ((semi)hermetic compressors, copper tubing and brazed assembly) the only choice left among the natural refrigerants are hydrocarbons.

The small charge minimises the need for mechanical ventilation and special machine rooms and even makes it possible to install the modular pack below ground level (in agreement with the recommendations of EN378).

For a schematic of the concept see Fig 1.

Refrigerant for the high temperature stage.

The choice of propylene as refrigerant is based on the good thermodynamic characteristics, low pressure ratio and high volumetric capacity, as can be seen from Table 1.

As a very important intrinsic safety bonus it has a very sharp and characteristic foul odour of gas. Even if the smell is not as characteristic as mercaptan in small concentrations it will clearly reveal it self to a normal person before reaching the recommended safety limit at 20 % of LEL.

In the event of a leak even untrained people will associate the smell with a potential fire hazard and open doors and windows to reduce the risk. This will of course apply even if all other safety measures fail, such as the gas alarm and the mechanical ventilation.

Table 1. Comparing Refrigerants

	Natural			Synthetic		
Properties \ Designation	R600a	R290	**R1270**	R134a	R22	R404A
Specific capacity [W/m^3/h]	180	493	**604**	338	568	563
COP (see below) [kW/kW]	2.35	2.27	**2.26**	2.31	2.29	2.05
Pressure ratio Pc/Pe	5.9	4.7	**4.5**	6.2	5.2	5.0
Discharge temperature [ºC]	66	76	**86**	79	106	74
Lower explosion limit [g/m^3]	43	38	**43**	-	-	-
Characteristic smell of gas	No	No	**Yes**	No	No	No
Tax in Denmark [€/kg]	0	0	**0**	17.3	-	50.4
Density at 40 ºC [g/l]	535	469	**478**	1167	1136	885
COP at summer design conditions (at ambient 27 ºC) for modular pack: Compressor isentropic efficiency 0.65, Evaporation temperature -13 ºC, Superheat 5 K, Condensing temperature 43 ºC, Subcooling 2 K, Thermal efficiency of the internal heat exchanger 0.20.						

Components available for hydrocarbon.

Most components used for HFC refrigerants can also be used for HC's (ACRIB, 2001). But not all manufacturers allow this due to legal issues or e.g. lack of adequate testing of seals or the need of revising the relevant PED approvals.

The shell e.g. of a hermetic compressor is classified as a vessel according to the PED. Large manufacturers often threaten to suspend warranty for all compressors sold even if only a small fraction is used for HC. One of the reasons is that the use of HC may change the necessary safety category to one not supported by the manufacturers procedures and quality management system.

Even for components covered by Safe Engineering Practise (SEP), the PED requires documentation for the installation and approved fluids etc. If HC's are not covered in manufacturers documentation the responsibility shifts to the next in the supply chain.

This is not a main issue for prototypes, but when marketing the end product e.g. risc assessments add to the load of necessary paper work. The documentation is an important factor when using HC's ensuring that the marketing company is covered by the product liability insurance.

This ruled out the hermetic scroll compressors, which otherwise was thought to be well suited to the job. We did test some Asian produced scrolls, but as design conditions weren't suited to the fixed pressure ratio and the required flow for the discharge check valve we had to give it up.

The compressor finally chosen is a semi hermetic of conventional construction with 2 cylinders, reed valves and sling disc lubrication. It has a capacity of 12.5 kW at summer design conditions (Table 1). At this working point we calculated for the measured mass flow under steady state conditions an isentropic efficiency of 0.65.

In order to optimize the cooling capacity while limiting the charge to 1 kg (Fernando et al., 2001), several test modules was build (see Fig 2). One of the basic ideas was to keep the refrigerant circuit as simple as possible, the ideal being the household refrigerator, but the size of the module and the running conditions made it necessary to add a thermostatic expansion valve, an internal heat exchanger, high and low pressure switches as well as discharge temperature thermostat.

By placing the termistor relay in a remote electrical box and connecting the safety cut outs in series with the termistor leads, the enclosed volume of the module will comply with the requirements for zone 2 according to the Atex directive when the volume is connected to a separate mechanical ventilation system. (IEC 60079-10:2002, DS/EN 50021 Annex A).

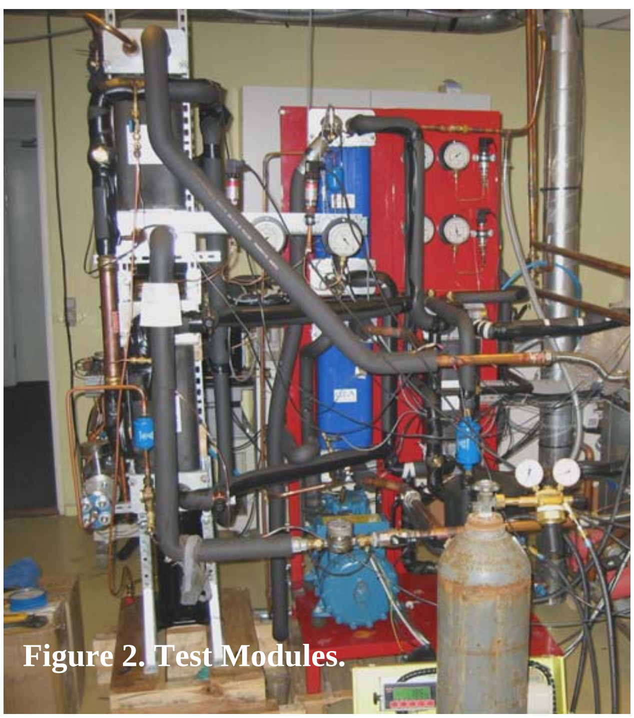


Figure 2. Test Modules.

Components available for CO_2.

Because of the small capacities needed, as the compressors for CO_2 currently available are much too large to ensure a convenient capacity control by staging, we acquired some test samples of rotating piston compressors which could match the pressure level.

The compressors have a swept volume of 2 to 3 m^3/h. They perform very well with a isentropic efficiency of 0.65 measured with the mass flow meter at design conditions -30 ºC evaporating temperature and -8 ºC condensing temperature.

Due to the geometry of the piston and a low torque motor it will however not start under load. It was necessary to device a configuration with a solenoid valve for start unloading.

The oil level in the compressor is maintained by an adequate oil level in the suction manifold by an optical oil level control fed from the oil separator. A surplus return of oil by the suction line (accumulated in the cabinets under low load conditions) will simply pass the compressor to the oil separator with a momentary decrease in capacity.

As expansion device for the evaporators is used electronically controlled pulse band modulated solenoid expansion valves which has turned out to work well with CO_2.

Means of circulating CO_2 in the medium temperature circuit.

Commencing the project we believed that it was possible to acquire a suitable CO_2 centrifugal pump. But it appeared that the available pumps was either to big for the required flow around 0.5 m^3/h, too expensive (several times the price for the R1270 compressor) or would simply not meet the pressure requirements of 35 to 40 bars working pressure with a pressure differential between 2 and 5 bars.

To overcome this we devised an alternative. The pump and receiver was substituted with the arrangement seen in Fig 3.

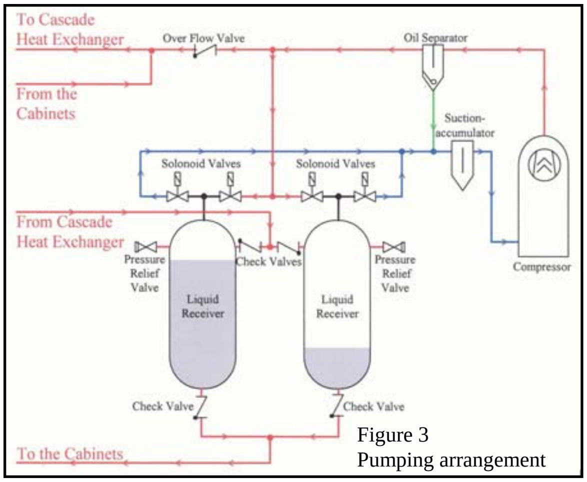


Figure 3
Pumping arrangement

The idea is that the pressure generated by a rolling piston compressor with oil separator is fed intermittently via solenoid valves to one of two receivers equipped with check valves on inlet and outlet, each in turn receiving CO_2 liquid from the cascade heat exchanger or delivering liquid to the cabinets. The disadvantage of this is the price of the extra receiver and assembly of valves even though it is cheaper than the pumps available.

Figure 4. Prototype.

This arrangement was presented with the modular pack as a prototype (See Fig 4) at the Exhibition, Danish Cooling Days. (Danske Køledage, 2003). The footprint of the pack is 1.5 m x 0.7 m.

A second alternative is an extra set of compressors for direct expansion on the medium temperature cabinets. The advantage of this system is that the evaporating temperature of the modular pack is elevated, as a minimum, corresponding to the necessary pumping pressure, which will say around 4 K.

As the efficiency for the gas pumping system is only 10 to 20 %, this second alternative will reduce the energy consumption because of the higher resulting suction pressure of the high temperature cascade stage. The resulting lower power consumption here more than compensates the power consumption of the extra compressors.

Sizing of heat exchangers.

To a key customer has been delivered packs, unit coolers and air cooled condensers for more than 100 plants as a concept with standardized components.

In order to be able to compare the calculations for the new concept with this well known concept based on R404A, the surface on the air side for all corresponding heat exchangers are the same.

On the condenser side this will lead to a 3 K higher condensing pressure in order to be able to dissipate the same heat capacity compared to direct condensing with R404A under full load, via plate heat exchanger and dry cooler by circulating a 6.5 K differential, 30 % Ethylene Glycol solution.

For the evaporators in cabinets and unit coolers the use of CO_2 will give the possibility to raise the evaporating temperature because of the higher heat transfer coefficient for this fluid. The only changes of the heat exchangers are the increased wall thickness of the pipe to cope with the increased pressure for CO_2 and the reduced number of circuits.

In general it is possible to reduce the number of circuits to the half of what is used for R404A. Small evaporators below 2 - 4 kW are most efficient with reduced diameter of the pipes, but as CO_2 coils are for the time being only produced on order in very small numbers it is often the cheapest to use standard diameter pipes.

This means that the capacity is only increased by about 15 %, whereas the larger evaporator's capacity increases up to 35 % for the same delta t compared to smooth pipe HFC evaporators. (Compared to inner grooved pipes the increase under the same conditions is 0 - 15 %).

When using pump circulation and circulation rates around 2 (= the mass flow through the heat exchanger is twice the evaporated mass flow; half of the supplied liquid is thus returned in the suction line) the capacity will increase by further 5 % due to the increased wet area obtained when not generating superheat.

As the capacity is increased by lowering the fin temperature on the air side, it is very important to recognise that this will lead to more dehumidification of the cooled space, i.e. that the percentage of sensible cooling decreases. To increase the efficiency of the plant while maintaining the sensible capacity the suction design temperature at the pack end of the suction line is chosen to -8 ºC compared to the standard of -10 ºC.

By using a step controller with adaptive setting of the suction pressure it will however be possible to raise the evaporating temperature to between -6 ºC and -4 at low load conditions.

Comparison with other systems.

The introduction of plate heat exchangers to limit the charge of R1270 will result in a higher pressure ratio. In Denmark, however, it should be noted that because of the future limiting of the charge of HFC plants it will also be necessary to introduce secondary heat exchangers to these as well.

The low temperature CO_2 stage is much more efficient than the R404A one stage compression because of the heat transfer capacity of CO_2 and the intrinsic two stage compression in the cascade systems. As for transcritical systems this is what determines the total energy efficiency for the plant.

For the small systems in question with 12 kW low and 23 kW medium cooling capacity it has been calculated from measured compressor efficiencies, that the reduction in power consumption in the low stage compensates for the higher consumption of the medium stage plus the refrigerant pump and the dry cooler pumps. This is yet to be proven in field test for the modular pack, but has been measured for a larger plant (Høgaard Knudsen, 2004).

Table 2. Comparing Pack Configurations

	Low temperature cabinets		Medium temp. cabinets		High temp Cascade	Condenser cooling	Power consumption	First cost
1	R404A	dx	R404A	dx	No	air	1	0
2	CO_2	cascade	R134a	dx	No	air	0.9 – 0.95	–
3	CO_2	cascade	CO_2	pump	R404A	water	0.95 – 1.0	+
4	CO_2	transcritical	CO_2	transcritical	No	water	1.1 – 1.2	+
5	CO_2	cascade	CO_2	pump	R1270	water	1.0 – 1.05	+
6	CO_2	cascade	CO_2	cascade	R1270	water	0.95 – 1.0	+
7	CO_2	cascade	CO_2	cascade	R407C	air	0.95 – 1.0	–
Power consumption and first cost is relative to the reference pack.								

Table 2 gives examples on different pack configurations that are or might be relevant in Denmark in the near future.

Number 1 is the reference pack and the most common of the existing installations.

There has been built several plants of Number 2 due to the lower tax on R134a and because the CO_2 substitutes a part of the refrigerant charge and raise the efficiency of the low temperature cooling.

Number 3 has been build by several contractors for larger supermarkets, some with air cooled condensers (Høgaard Knudsen, 2003).

Number 4 has been installed in Denmark in one case and its power consumption is being measured this year and is expected to be published in the spring 2005. The estimation here of lower COP is not the result of these measurements.

Number 5 is the type for this project (the proto type) and Number 6 is the alternative without pump and with separate compressors for the medium temperature side, none of which have yet been installed. Number 7 is similar to number 6 on the CO_2 side and has recently been commissioned.

It should be noted that the tax on the refrigerants has been included in evaluation of the first cost. It is not possible to give a more accurate evaluation as too many variables influence the results e.g. the ratio between low and medium temperature capacity and the size of the plants.

Compared to our reference R404A pack, including taxed refrigerant, compressors, oil management system, suction filters, filter dryers, receiver etc, completely assembled, pressure tested and insulated, the price of a Modular Pack will be 50 % higher.

This price estimate includes the extra cost for components such as special unit coolers, gas and CO_2 detection alarm systems and mechanical ventilation, but excluding the higher cost of the display cabinets and the lower cost of the piping.

The price will become competitive when rationalising the production as the sales increase and including the expenses to topping up the R404A system over 10 years due to the expected 5 % leak rate per year. This leak rate is the target value on the reference pack. The actual leak rate is 10 % (average value for 250 new and old plants).

Conclusion.

A concept for an all natural refrigerant plant has been evaluated, by testing of prototype and components. The proposed concept will be a safe alternative with a competitive price compared to a standard R404A pack thanks to the extensive use of standard components and the taxation of HFC's in Denmark.

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