CO_2 Refrigeration, Air Conditioning and Heat Pump Technology Development in Europe

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CO_2 20세기 초 천연 냉매 CO_2는 광범위하게 사용되었지만 프레온계 냉매의 출연으로 1940년경부터 CO_2 냉매는 사용이 제한되었다. 그러나 반 세기 동안 사라졌던 CO_2 냉매는 1980년 후반에 노르웨이 과학 기술대학(NTNU)과 북구 최대 인간연구소 (SINTEF)의 Lorentzen 교수에 의해 CO_2 천연 냉매 사용을 재고하게 되었다. 프레온계 냉매의 환경적 논쟁이 쟁점이 되면서 천연 냉매를 사용하는 시스템에 관심이 집중되었으며, 특히 비가연성과 비유독성으로 인한 CO_2 냉매가 주목을 받고 있다.

초월임계 사이클에서의 고압 제어에 대한 새로운 개념은 Lorentzen 교수와 동료 연구원에 의해 특허로 제안되었다. 이에 대한 상업적 권리를 Norsk Hydro사는 1990년에 얻었고, 1990년대 초반에 NTNU/SINTEF의 공동 연구개발 프로그램을 통해 기술 경쟁력과 실현 가능성이 검증되었다.

현재 연구소에서는 최초로 초월임계 CO_2 사이클을 이용한 상업용 온수 열펌프 시스템, 2003년 시작할 연료전지 전기 자동차에 대한 연구를 수행하고 있다. SINTEF/NTNU에서 개발된 CO_2 기술은 Hydro-SINTEF 공동 벤처 기업인 Shecco 기술회사를 통해 제조업자에게 허가된다.

본 고에서는 SINTEF/NTNU에서 수행했거나 수행중인 과제들을 중심으로 유럽의 CO_2 시스템의 결과와 주요 개발 범위를 정리하였으며, 특히 작동유체로서의 CO_2 냉매의 특징을 간단히 설명하고, 온수 열 펌프, 자동차용 공조기 및 열 펌프, 상업 냉동기 등이 기술되었다. 그 외 압축기 위주의 요소기술 개발에 관한 내용도 기술되었고, 차세대 기술 경향과 전망에 대해서도 제시되었다.

CO_2 – THE REDISCOVERED NATURAL REFRIGERANT

Although CO_2 (R-744) was widely used as refrigerant in the early 20^{th} century, its use disappeared from around 1940 with the advent of the fluorocarbon chemicals. Thus, when professor Gustav Lorentzen at NTNU/SINTEF in the late 1980s proposed to reconsider the use of CO_2, it had been absent for almost half a century. Increasing focus on environmental issues of fluorocarbon chemicals created a strong interest in systems using natural fluids in general, and CO_2 in particular (Lorentzen and Pettersen, 1992) due to its non-flammability and non-toxicity.

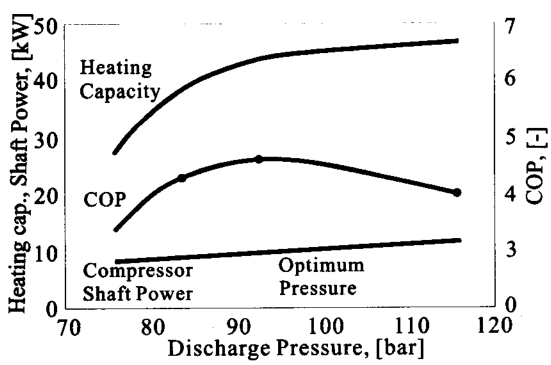
New concepts of high-side pressure control in what came to be called a "transcritical" cycle were devised in early patent applications by Lorentzen and his co-workers. The industrial group Norsk Hydro acquired all commercial rights to this technology in 1990, and through a joint R&D program at SINTEF/NTNU in the early 1990s the feasibility and competitiveness of the technology was demonstrated. We are now seeing the first commercial use of transcritical CO_2 systems, in hot water heat pumps starting from 1999, and in fuel cell electric vehicles starting from 2003. In both cases, the CO_2 technology developed at SINTEF/NTNU has been licensed to the system manufacturer through the Hydro-SINTEF joint venture Shecco Technology (www.shecco.com).

The present article outlines key development areas and results for CO_2 systems in Europe, mainly focusing on projects where SINTEF/NTNU has been or is involved. Initially, a brief introduction to the peculiarities of CO_2 as a refrigerant is given, before the status and trends within selected areas of technology is discussed, including heat pump water heaters, mobile air conditioning and heat pumps, commercial refrigeration, and heat pumps for space conditioning. Some comments are given regarding component development, mainly focusing on compressors. Finally, some concluding remarks are given on general trends and outlook for the next years.

CARBON DIOXIDE AS WORKING FLUID

Compared to conventional refrigerants, the most remarkable property of CO_2 is the low critical temperature of 31.1oC. Vapour compression systems with CO_2 operating at normal ambient temperatures thus work close to and even above the critical pressure of 73.8 bar. This leads to three distinct features of CO_2 systems :

- Heat is rejected at supercritical pressure in many situations. The system will then use a transcritical cycle that operates partly below and partly above the critical pressure. High-side pressure in a transcritical system is determined by refrigerant charge and not by saturation pressure. The system design thus has to consider the need for controlling high-side pressure to ensure sufficient COP and capacity. An example of the measured effect of varying high-side pressure (compressor discharge) on heating capacity and COP in a heat pump water heater system is shown in **Figure 1**.
- The pressure level in the system will be quite high (around 30-100 bar). Components therefore have to be redesigned to fit the properties of CO_2. Due to smaller volumes of piping and components, the stored explosion energy in a CO_2 system is not much different from a conventional system. A benefit of high



[Fig.1] Variation of heating capacity, heating-COP and compressor shaft power with the discharge pressure for a CO_2 heat pump water heater pressure is the 80~90 % smaller compressor displacement needed for a given capacity. Compressor pressure ratios are low, thus giving favourable conditions for high compressor efficiency.

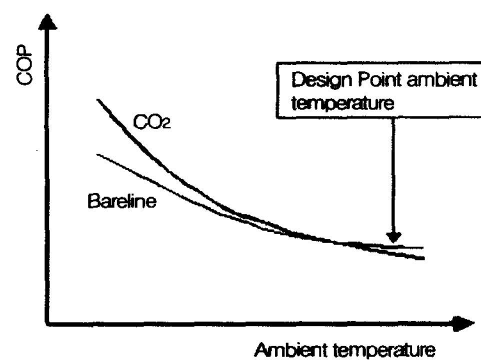
- Large refrigerant temperature glide during heat rejection. At supercritical or near-critical pressure, all or most of the heat transfer from the refrigerant takes place by cooling the compressed gas. The heat rejecting heat exchanger is then called gas cooler instead of condenser. Gliding temperature can be useful in heat pumps for heating water or air. With proper heat exchanger design the refrigerant can be cooled to a few degrees above the entering coolant (air, water) temperature, and this contributes to high COP of the system.

Experience from testing and modelling of CO_2 refrigeration and air conditioning systems shows that cooling COP is more sensitive to ambient temperature variation than with conventional refrigerants. This typically leads to the situation shown in **Figure 2**, where the CO_2 system is superior at moderate and low ambient temperature, and slightly inferior at very high temperature. In this situation, it would be misleading to base the comparison on design-point conditions, which typically are at an extreme ambient temperature. A more sensible basis for comparison is to use mean/average conditions, or to apply a seasonal analysis based on climatic variation.

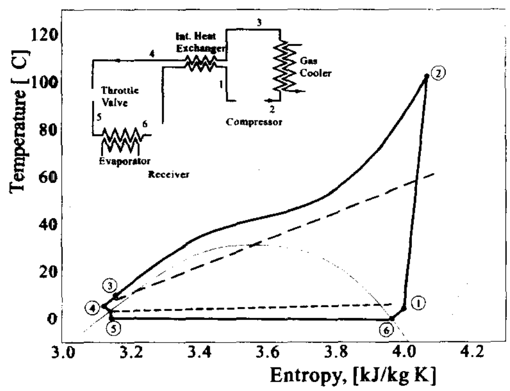
EFFICIENT HEAT PUMP WATER HEATERS

The first application of CO_2 systems on the market is heat pump water heaters, where the thermodynamic properties are very favourable. **Figure 3** shows, in a temperature-entropy diagram, how the temperature characteristics of the transcritical cycle matches the temperature profiles of the heat source and heat sink, giving small heat transfer losses and high efficiency.

Studies on CO_2 heat pump water heaters were initiated at SINTEF/NTNU from the late



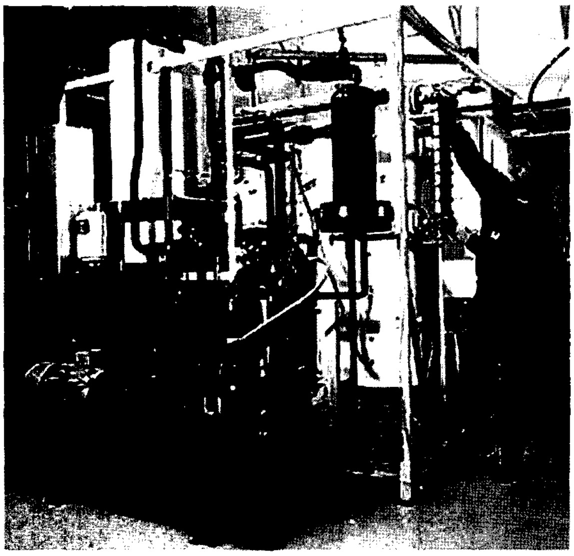
[Fig.2] Principal COP behaviour of CO_2 system and conventional (baseline) system at varying ambient temperature.



[Fig.3] T-s-diagram showing the transcritical CO_2 cycle used for water heating.

eighties, and a full-scale lab.prototype system of 50 kW heating capacity was completed in 1996, **Figure 4**. Results from extensive measurements on this prototype showed that a COP above 4 was achievable even for a hot water temperature of 60℃, **Figure 5** (Neksa, Rekstad et al., 1998). The high process efficiency is partly due to good adaptation of the process to the application, but also due to efficient compression and the good heat transfer characteristics for CO_2. A CO_2 heat pump water heater may produce hot water with temperatures up to 90℃ without operational

problems and with only a small loss in efficiency. Increasing the required hot water temperature from 60℃ to 80℃ reduces the heating COP only slightly (from 4.3 to 3.6 at an evaporating temperature of 0℃), and one of the big advantages of this technology is the

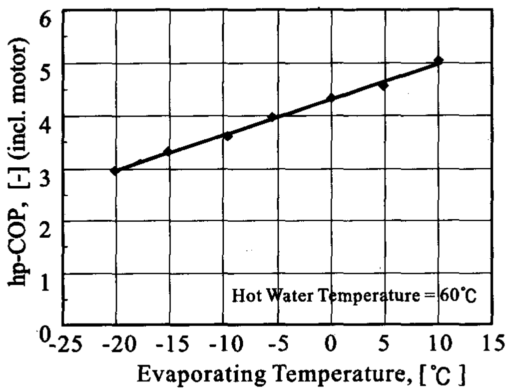


[Fig.4] 50kW prototype heat pump water heater in SINTE/NTNU laboratory

ability to supply water at high temperature with good COP. Important application areas for commercial-size systems are in hotels, apartment houses, hospitals, and food industries.

The above heat pump water heater system was included in the European Union (EU) cooperative project "COHEPS" from 1996 to 1998, where research groups in Norway (SINTEF/NTNU), Germany (University of Hannover, Essen University) and Belgium (Catholic University of Leuven) together with their industrial partners studied various aspects of heat pumping applications for CO_2, including commercial-scale heat pumps, residential heat pumps, systems for hydronic heating circuits, and drying heat pumps.

A 25 kW pilot plant was installed in a food-processing factory in Larvik, Norway in 1999, using waste heat from an industrial NH_3 refrigerating system as a heat source. Performance has exceeded the initial expectations, and the system has proven to be a very profitable investment for the company.



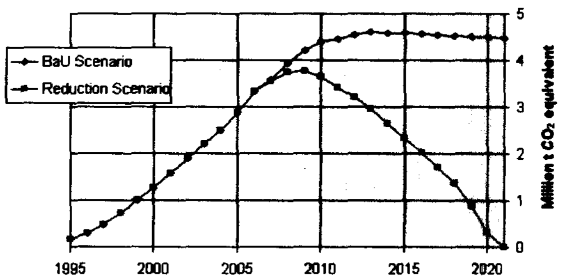
[Fig.5] Measured heating COP of lab. prototype system, at water inlet temp 10℃

A new pilot plant is now under erection in Oslo, Norway.

MOBILE AIR CONDITIONING

Mobile air conditioning systems have been and still are a dominating source of refrigerant emissions to the atmosphere, and the growing production volume of HFC-134a for this purpose is raising concern. As a result, government bodies and environmental organizations are focusing on the need for reducing the emissions. A recent study made for the German environmental agency shows that a full replacement of HFC-134a by CO_2 in mobile AC systems from 2007 would cut the greenhouse gas emissions of Germany by 1 million tonnes CO_2-equivalents in 2010 and completely eliminate the emissions by 2021 (Schwartz, 2000), **Figure 6**. A comprehensive study using statistical data from German automobile workshops showed that the average annual emission rate from HFC-134a mobile AC systems was 10.2% (Schwartz, 2002).

Lorentzen and Pettersen (1992) published the first experimental data on CO_2 in a mobile air conditioning lab.prototype system, demonstrating COP data that were competitive to baseline CFC-12 system performance. Based on these positive test results, the automobile industry initiated several development projects and further studies on CO_2 systems. The European RACE project from 1994 to 1997 included development and testing of car-installed prototype systems, with results confirming the potential for CO_2-based car air conditioning. Members in the RACE project included car manufacturers (BMW, Daimler-Benz, Rover, Volvo, Volkswagen), system suppliers (Behr, Valeo), and a compressor manufacturer (Danfoss).



[Fig.6] Equivalent emissions (in million tonnes CO_2-equivalents) from mobile AC systems in Germany, using a Business-as-Usual scenario (BaU) and a reduction scenario with phase-in of CO_2-based AC systems from 2007. From (Scwartz, 2000).

City bus air conditioning systems with CO_2 have also been developed, and the results from two years (1800 hours) of road testing are very positive.

Over the last years, the German Motor Vehicle Industry Association (VDA) has coordinated development and testing of CO_2 systems, and several car manufacturers have had test vehicles on the road since the late nineties. Presentations made by BMW, Audi and DaimlerChrysler at a recent industry meeting showed the following consistent results from independent studies by the three companies:

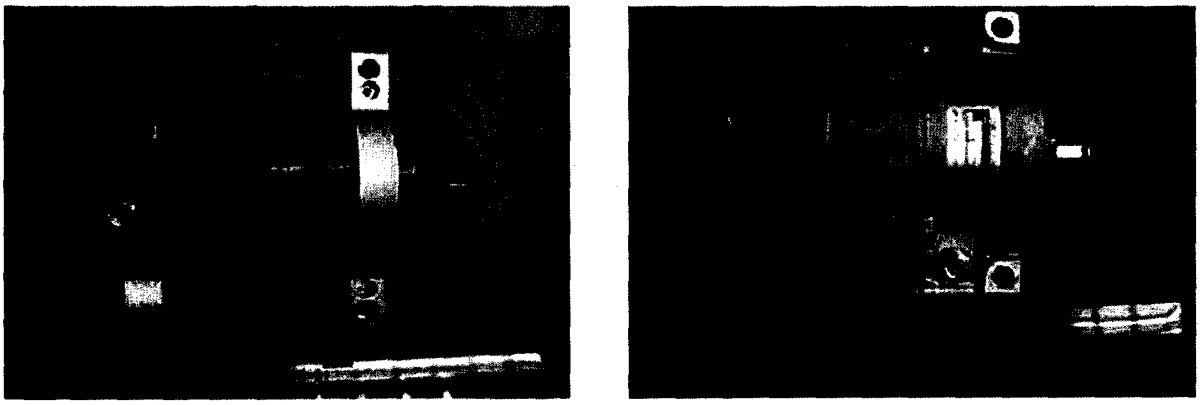
- higher performance in cool-down mode for R-744 (CO_2) than for R-134a
- lower compartment temperature and faster temperature pull-down with R-744
- reduced fuel consumption for R-744 system

The technology for CO_2-based mobile air conditioning systems has reached a very advanced level after years of development. One example is a recent compressor model shown by Parsch (2002), where the potential for a compact design with CO_2 has been exploited, **Figure 7**.

HEAT PUMPS IN AUTOMOBILES

Modern cars with fuel-injection engines often have insufficient waste heat for heating of the passenger compartment in the winter season. The long heating-up period and slow defroster action is unacceptable both in terms of safety and comfort. Supplementary heating is therefore necessary, and one attractive solution may be to operate the air conditioning system as a heat pump. Carbon dioxide systems have special benefits in heat pump mode, since high capacity and COP can be achieved also at low ambient temperature and with high air supply temperature to the passenger compartment.

Hafner et al. (1998) proposed an advanced circuit for reversible cooling and heating, but work is also progressing on simplified system concepts for internal-combustion engine cars and electric/hybrid vehicles. The heat pump feature may turn out to be an important factor for the introduction of CO_2 systems in motor vehicles. One of the key questions is the choice of heat source. The simplest solution is of course to use ambient air, but this may give problems related to frosting and defrosting. Other solutions being studied use engine coolant or exhaust as heat source. Hammer and Wertenbach (2000) showed test data for an Audi A4 car with 1.6 liter gasoline engine, comparing a standard heater and a CO_2 heat pump system based on engine coolant as heat source. **Figure 8** shows measured air temperatures at foot outlet nozzles and passenger compartment temperatures using standard heater core ("production"), and a heat pump system (without heater core). The more rapid heating up with heat pump is clear, with almost 50% reduction in the heating-up time from −20 to +20 ℃. Since the heat pump used engine coolant as heat source, the possible risk

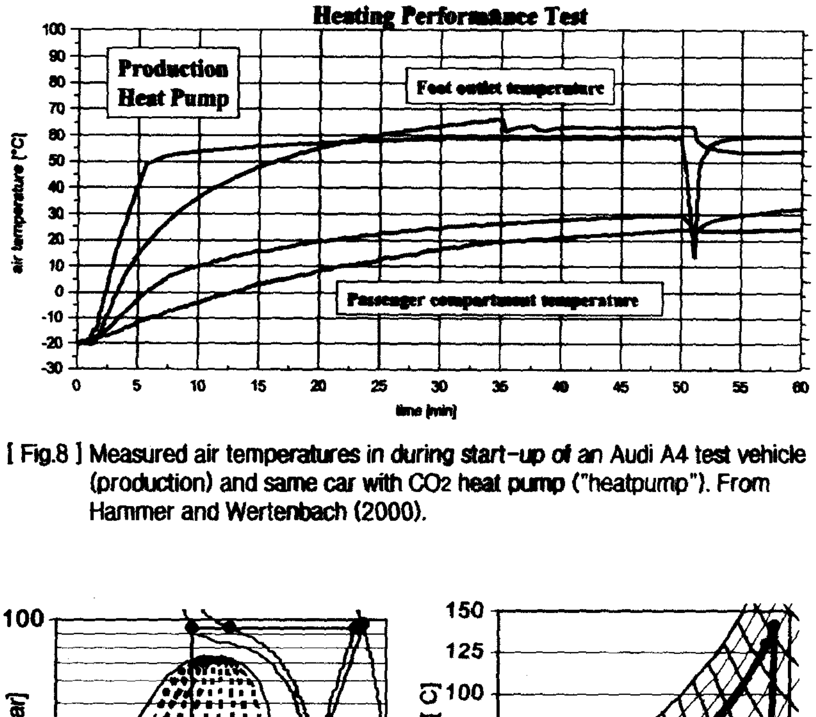


R744 compressor　　　　R134a compressor

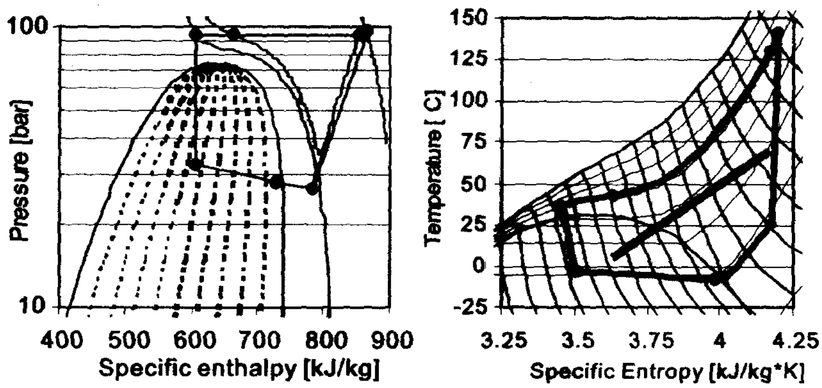
[Fig.7] Equivalent emissions (in million tonnes CO_2-equivalents) from mobile AC systems in Germany, using a Business-as-Usual scenario (BaU) and a reduction scenario with phase-in of CO_2-based AC systems from 2007. From (Scwartz, 2000).

of extended heating-up time for the engine was of some concern. Measurements showed that owing to the added load on the engine by the heat pump compressor, the heating-up time was in fact slightly reduced even when heat was absorbed from the coolant circuit.

Systems using air as heat source will be simpler and less costly, and there is quite some interest in clarifying the practical possibilities and limits of reversible air toair systems. Frost build up may in many situations be slow enough to allow heat pump operation until the heating system can take over, and solutions may be developed that control and delay frost build up. **Figure 9** shows experimental data from a test on a "reversed" AC system operated as a heat pump, with interior/exterior air temperature 5 ℃ (Hafner, 2000).



[Fig.8] Measured air temperatures in during start-up of an Audi A4 test vehicle (production) and same car with CO2 heat pump ("heatpump"). From Hammer and Wertenbach (2000).



[Fig.9] Process data for air-to-air mobile heat pump operated at +5℃ interior and exterior temperature, using components designed for AC operation. From Hafner (2000)

As may be observed, the heat pump delivers an air temperature of more than 60 ℃, i.e. a temperature rise of almost 60 K.

COMMERCIAL REFRIGERATION

Commercial refrigeration systems for shops, supermarkets, larger kitchens etc. have large refrigerant emissions, and the energy use is in many cases high. Thus, there is a need for efficient, safe and environmentally friendly refrigeration systems. New concepts based on CO_2 have been demonstrated for centralized systems using CO_2 as a secondary heat transfer fluid or in a low-temperature cascade stage, and recently decentralized concepts with heat recovery have been shown.

Some of these developments are outlined in the following text.

Eggen and Aflekt (1998) reviewed the possibilities for CO_2 : i) as secondary refrigerant, ii) as a primary refrigerant in a low temperature stage in a cascade system, and iii) in all-CO_2 centralised systems. They also presented a prototype CO_2/NH_3 cascade system built in Norway. Several secondary fluid systems are already operating in the Nordic countries using CO_2 as a volatile secondary refrigerant. The safety aspects and good thermophysical properties of CO_2, leading to small pipe dimensions and good heat transfer, make it a preferable fluid in indirect systems.

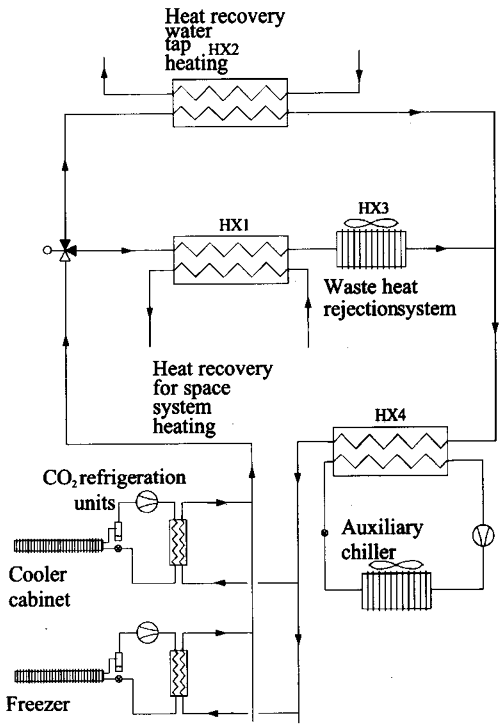
Further advantages of cascade systems include the greatly reduced low-temperature compressor sizes, the absence of a liquid pump, and fewer stages of heat transfer. With heat recovery, centralized all-CO_2 systems may also have an interesting potential

The decentralized supermarket system uses CO_2 as the only refrigerant in a system with heat recovery. Self-contained display cabinets each with CO_2 refrigeration units are connected to a hydronic heat recovery circuit that heats service water and buildings, **Figure 10.**

By utilizing the transcritical CO_2 process, it is possible to have a large temperature glide in the hydronic circuit, typically 50-60 K, and a correspondingly low volume flow rate and small pipe dimensions. Waste heat with high temperature (70-75℃) is available for tap water and/or space heating. Excess heat is rejected to the ambient air by direct heat exchange. The system offers a very easy installation and gives the owner of the store a great flexibility in arranging and rearranging the cabinets.

System simulations for a medium size supermarket have been carried out. Optimum hydronic supply and return temperatures to the cooling and freezing cabinets were identified. A comparison of the CO_2 system and a conventional R-22 system with respect to the overall energy consumption of the supermarket for one year of operation in a southern European climate was carried out. The CO_2 system was found to reduce the energy consumption by 32% compared to the R-22 system.

Each CO_2 unit can also be equipped with a condensing unit in order to reject heat directly to the shopping area when space heating is

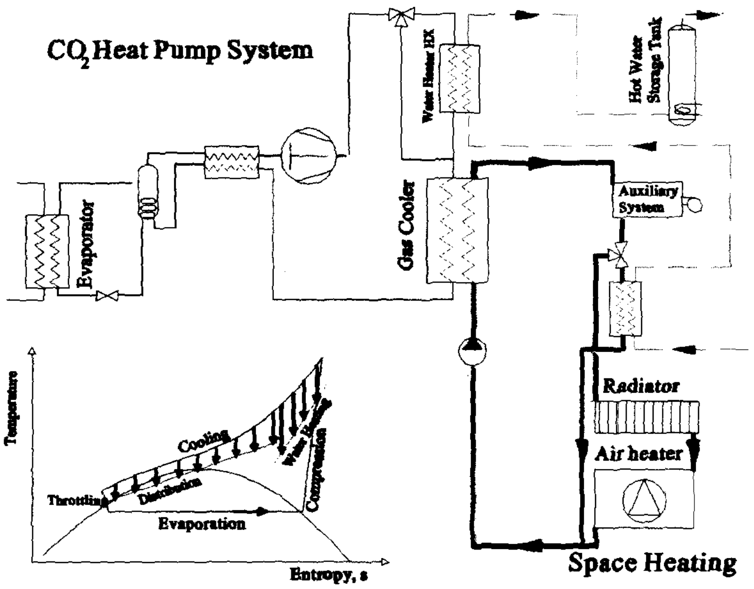


[Fig.10] Distributed CO_2 supermarket refrigeration system with central heat recovery required. In the warm season with a heat surplus, the waste heat recovery circuit remove the heat. This concept reduces the power demand for the refrigeration units to the same level as for the baseline R-22 system, and the resulting overall energy consumption of the supermarket will then be further reduced.

The company Costan has now installed CO_2 systems in supermarkets in Italy for field-testing.

HEAT PUMPS FOR SPACE HEATING

The market for CO_2 heat pumps would of course be extended significantly if the demand for space heating could be covered efficiently in addition to the demand for water heating. Schiefloe and Neksa (1999) investigated a system design as shown in **Figure 11**.



[Fig.11] System design for a combined space and water heating system. *The process is also illustrated in the T-s diagram.*

In order to achieve a lowest possible return temperature from the heating system, radiator and air heating are connected in series. Tap water is preheated in parallel with the space heating and heat exchange against hot discharge gas is used to achieve the required hot water temperature. In order to simplify the system design, the tap water heating part could also be imple-mented as a separate system or covered when space hea-ting is not required.

A comparison to using R-134a as working fluid showed favourable seasonal perf-ormance for CO_2 when more than 30 % of the power demand for space heating was covered by the air heating system. The rest is then covered by the radiator system. A 70/50 ℃ radiator system and heat recovery efficiency of the balanced ventilation system of 60 % was assumed. In larger buildings in Norway typically more than 50 % of the heat-ing demand is air heating and this percentage is increasing due to better insulation and increased air quality requirements. This indicates that CO_2 may be a promising candidate for this applicat-ion. (Rie-berer and Halozan 1998) and (Rieberer, Kasper et al. 1997) made detailed theoretical studies of controlled ventilation air heating systems with an integrated CO_2 heat pump. The results look very promising. The overall system seasonal per-formance factor for a Graz, Austria climate was calculated to be in the range 6.15 to 6.5. This corresponds to a seasonal performance factor of the heat pump of above 4 (author's remark).

HEAT PUMP DRYERS

Another interesting application is heat pump dryers. Based on theoretical considerations, Steimle (1997) reported that energy saving is possible due to better temperature adaptation in the heat exchangers, compared to subcritical processes. It is also possible to achieve higher air temperatures without loss in efficiency, thus increasing the moisture extraction rate.

Experimental results from Schmidt, Klocker et al. (1999) reports hp-COPs in the range 5.5 and 55 % reduction in the energy consumption, including fan power, compared to a traditional electrically heated clothes dryer. The results were achieved after a first optimising of the prototype system and it is hoped that further essential improvements still can be reached.

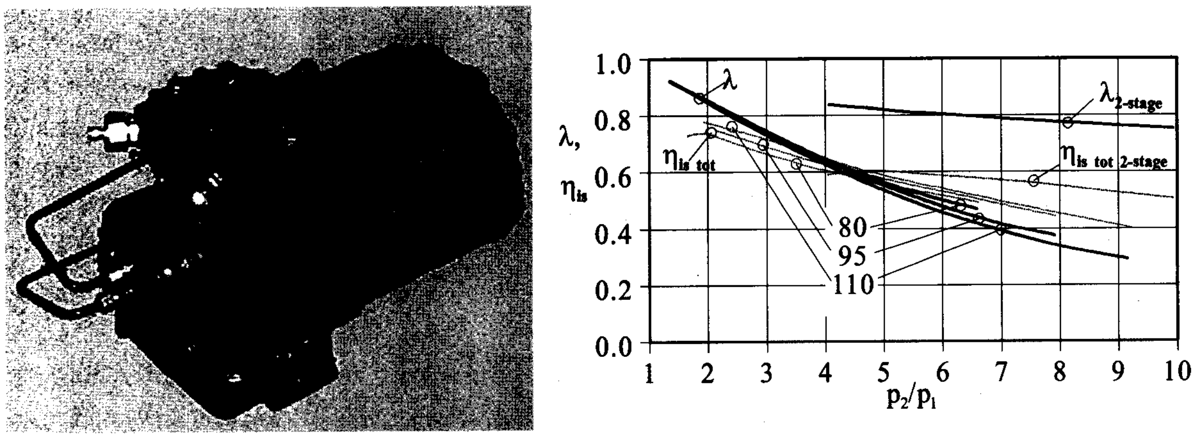
COMPRESSORS

The company Dorin, Italy, developed the first high-pressure semi-hermetic CO_2 compressor series in the range of 1.7-10.7 m³/h swept volume. The series comprises single- and two-stage compressors with two cylinders, running at nominal speeds of 1450 and 2900 rpm (50 Hz).

This corresponds to cooling capacities in the range of 3-25 kW at -10℃ evaporating temperature. **Figure 12** shows a picture of the compressor, and measured overall isentropic and volumetric efficiency figures for medium sized compressors at the current stage of development.

HEAT EXCHANGERS AND HEAT TRANSFER

Owing to the high operating pressure, CO_2 heat exchangers generally use small-diameter tubing. Studies on compact heat exchangers for mobile and unitary applications have demonstrated the

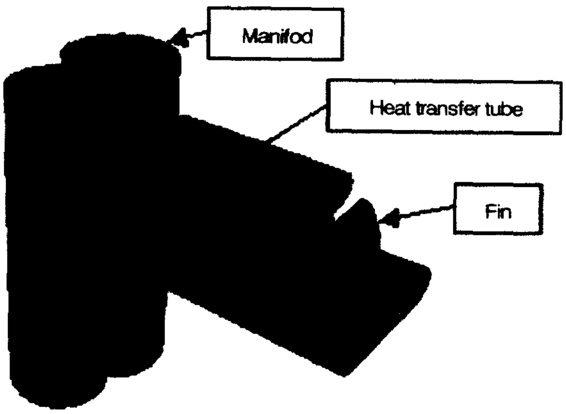


[Fig.12] Compressor design and measured volumetric and isentropic efficiency for a single-stage and a two-stage pre-series CO_2 compressor with a swept volume of 2.7℃/h, as function of the pressure ratio, for high-pressures of 80, 95 and 110 bar. A constant suction gas superheat of 10℃ was applied. For the two-stage compressor the intermediate pressure gas was cooled to 20℃.

potential for compact and lightweight designs with high performance, especially when using extruded microchannel tubing, **Figure 13** (Pettersen et al., 1998).

Extensive studies have been conducted on heat transfer and pressure drop in microchannels, both covering supercritical-pressure cooled flow, and flow vaporization. Supercritical-pressure microchannel heat transfer is correlated well with well-known single-phase correlations, while flow vaporization is greatly influenced by nucleate boiling, dryout and post-dryout heat transfer and thus need more advanced correlations.

Heat exchangers for heat pump water heaters have been built using double-tube concepts, thus creating the counter-current flow conditions required for large temperature glide.



[Fig.13] Principles of CO_2 heat exchanger geometry using "multi-port" extruded tubes with microchannels, folded fins, and a compact "double barrel" manifold. The heat exchanger is assembled by brazing in a furnace. From Pettersen et al., (1998).

CONCLUSION

The revival of CO_2 as a refrigerant started in Europe more than 10 years ago, and there has been a strong development of new technology using this refrigerant in several application areas since then. Developments which initially were driven primarily by environmental concerns has in many cases given many additional advantages by using CO_2 such as higher COP, higher cooling and heating capacity, better comfort, and added possibilities of heat recovery.

With increasing focus on climate gas emission reductions, strict regulations on the use of HFC chemicals may be expected, possibly followed by phase-out targets and dates as announced recently by Denmark and Austria. These trends will clearly drive the interest in the direction of natural refrigerants in general and CO_2 in particular.

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