

CO₂ AS REFRIGERANT, A WAY TO REDUCE GREENHOUSE GAS EMISSIONS

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Abstract: The potential of CO₂ as refrigerant in several applications are presented. CO₂ systems have already been commercialised in some applications, while systems for others have been developed from an R&D point of view, yet others are under development. The paper concentrates on the great possibilities CO₂ systems give for reducing greenhouse gas emissions from heat pumps, air conditioning and refrigeration systems. Direct emissions due to refrigerant leakage and indirect emissions due to reduced power consumption are discussed. Results from the applications heat pumps and air conditioning, commercial refrigeration and mobile air conditioning are focused. Influence of climatic differences and boundary conditions when comparing different alternatives are discussed. Ongoing developments for introducing further system efficiency improvements are also presented.

Key Words: CO₂, refrigerant, GHG emissions, heat pumping systems

1 INTRODUCTION

It is important to find alternatives to the halogenated refrigerants. Emissions of these refrigerants represent a major challenge for the environment both due to ozone depletion and greenhouse warming. On a global basis, in year 2000, the refrigerant emissions represented greenhouse gas (GHG) emissions equivalent to about 10% of CO₂ emissions resulting from fossil fuel burning (IPCC/TEAP, 2005).

Emissions can be reduced through improved containment. However, even with strong focus and incentives introduced by governments, it has proved to be difficult to reduce emissions to acceptable levels, especially for some applications and certain areas of the world. Use of alternative refrigerants with a lower or zero global warming potential will represent a more sustainable long term strategy.

CO₂ (R-744) is a substance occurring naturally in the biosphere. Thus, it is a long term alternative, known not to have adverse effects on the environment if emitted to the atmosphere. CO₂ is also a non-toxic and non-flammable alternative, properties which are advantageous in many applications. The CO₂ used as refrigerant is waste CO₂ from industrial processes, the same CO₂ as used for carbonizing beverages. Its excellent availability world-wide already today is also important to ease the introduction.

Many developing countries still extensively use ozone depleting substances. The Montreal Protocol allows use for many years to come, but for the environment it is important to convert to alternatives as soon as possible. These countries are however in the unique situation that they may convert directly to natural refrigerants, being long term alternatives, thus, avoiding interim use of HFCs.

Refrigeration, air conditioning and heat pump systems generally also generate indirect GHG emissions through their power consumption, either through electricity production based on

fossil fuels or in fossil fuel powered engines for transport and mobile applications. When evaluating alternative refrigerants and systems, it is important also to address this contribution given by the systems energy efficiency. One way to address this is through life cycle climate performance (LCCP) evaluations. This enables comparison of total emissions during the lifetime for different alternatives, also taking climatic and local differences into account.

CO₂ has become a viable alternative refrigerant for several different applications. It may serve as an alternative in replacing ozone depleting and global warming refrigerants. A review of some important aspects of CO₂ as refrigerant and the importance it may play as an alternative refrigerant are given here. LCCP calculations for different climates and applications are presented in order to substantiate CO₂ as a viable alternative. Focus will be given to systems using CO₂ as the only refrigerant. Thus, use of CO₂ in cascade systems or as brine is not covered.

2 INFLUENCE OF CLIMATIC DIFFERENCES AND BOUNDARY CONDITIONS

The thermophysical properties of CO₂ are different from those of HFC refrigerants and the other alternatives. These are described in detail in various references, such as Neksa (2002). Here we will concentrate on some specific characteristics. Typical efficiency curves (COP, Coefficient of Performance: cooling capacity divided by power input) shows different trends with the ambient temperature. CO₂ tends to be more efficient at lower ambient temperatures, while HFC systems may be slightly more efficient at the highest ambient temperatures. This tendency has been verified for various applications, such as vehicle air conditioning and supermarket refrigeration. Figure 1, from Hafner et al. (2004) illustrates this. For heat pumps there will be equivalence to incoming temperature of the heat sink. As a consequence, the system design must be adapted to obtain the return temperature from the heat distribution system as low as possible.

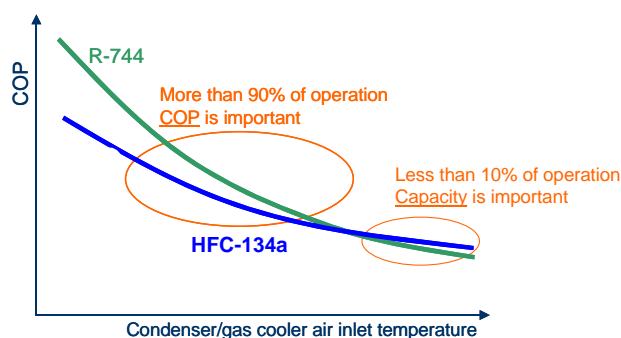


Figure 1: Typical efficiency (COP) curves at varying condenser/gas cooler air inlet temperature for CO₂ (R-744) and HFC-134a (Hafner et al. 2004)

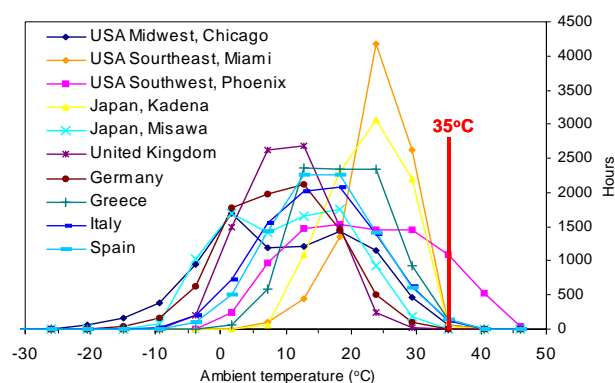


Figure 2: Temperature bin data for selected cities in USA, Japan and selected countries in Europe. Two extreme climates shown are Miami and Phoenix (Hafner et al. 2004)

The crossover temperature, given by the intersection of the two curves, will vary depending on various factors, such as component efficiency and system design. Results comparing CO₂ and HFC options reported in Hafner et al. (2004) for mobile air conditioning systems showed a crossover temperature above 30°C. Component or cycle improvements may of course move this temperature up, for instance by replacing the normal throttling valve with work recovery.

When comparing energy efficiency for CO₂ systems and alternative technologies it is of utmost importance to make a seasonal comparison based on the operating conditions the systems will experience during the year. A comparison only at rating conditions, typically 32 or 40°C, will not give comparability with respect to energy consumption. Usually the rating point is given for the most severe condition the equipment is likely to experience. It is very important to ensure the required cooling or heating capacity at these conditions, but operation at this condition will most often not be important for the annual energy consumption of the equipment. This is illustrated by Figure 2, showing temperature bin data for different climates around the world. Number of hours at the highest ambient temperatures is few. Results show that CO₂ systems satisfy capacity requirements at the highest ambient conditions very well.

In order to compare different systems and technologies it has now for several applications become a common procedure to work out seasonal energy consumption data based on the seasonal variation of the climate. This holds for example for HVAC units in USA, hot-cold vending machines in Japan and mobile air conditioning systems. Based on this data it is possible to calculate the indirect GHG emissions given by the power generation mix where the system is placed. When adding GHG emissions due to refrigerant leakage and other factors during the lifetime, it is possible to calculate the Life Cycle Climate Performance (LCCP) of the system, representing a measure of the GHG emission from the system during its lifetime. LCCP calculation comparisons for some applications are presented below.

3 CO₂ AS ALTERNATIVE IN DIFFERENT APPLICATIONS

After CO₂ was reintroduced as refrigerant around 1990, it has moved from being an outsider alternative for heat pump water heaters and maybe mobile air conditioning systems to become a viable alternative for several applications. CO₂ systems have been commercialised in some applications, are development from an R&D point of view for others. Systems for yet other applications are still under development.

3.1 Heat Pumps and Air Conditioning

Heat pump water heaters, heat pumps for tap water heating, were commercialised in Japan in 2001 for both residential and commercial applications. 1,000,000 units, primarily for residential applications, were sold at the end of year 2007. With a seasonal efficiency higher than 4, these systems make significant reductions in GHG emissions compared to use of gas fired heating or direct resistance heating. Characteristics of such systems are described in Nekså et al (1999). Systems adapted to European conditions are under development. An important advantage when using CO₂ as refrigerant is the ability of the systems to heat water to higher temperatures than systems with HFC refrigerants.

Low energy houses and passive houses are terms used for houses which are very well insulated and utilising balanced ventilation systems with heat recovery. For these houses tap water heating represents 50-85% of the yearly heating demand. They will typically also require some cooling in the warm season. In Europe today it is a clear trend to move towards buildings with such a balance between different demands. This opens up for a very interesting application for CO₂ heat pumps which may heat tap water very efficiently, and at the same time satisfy the modest need for heating and cooling during certain periods. Stene (2008) describes different integrated CO₂ heat pump systems for this application.

Stene et al. (2006) presents CO₂ systems for combined heating and cooling of non-residential buildings. The theoretical evaluation demonstrates that CO₂ systems can achieve equal or higher seasonal performance factor than heat pumps using HFC refrigerants.

Air-to-air reversible residential heat pumps represent another important application with a very high number of units produced each year. Jakobsen et al (2007) presented experimental results of a prototype CO₂ system compared to some of the best HFC-410A systems on the market. Seasonal performance for Oslo and Athens climates were calculated based on the experimental data and manufacturer data. The seasonal performance of the CO₂ unit and the top liner R-410A unit in heating mode were more or less identical, as well as in cooling mode for the Oslo climate. However, in cooling mode in the Athens climate, the seasonal performance of the CO₂ unit was about 17% lower than that of the top liner R410A unit, but higher than reference unit 2 (see Table 1). The CO₂ system has potential for further improvement to fully compete with the top liner R-410A systems in cooling mode for very high ambient temperatures. There are several ways to improve the performance; calculations shows that improved compressor performance will cause the CO₂ system to match the best reference system. Improved heat exchangers or the introduction of an expansion recovery device, such as an ejector or expander, will also make the CO₂ system fully compete with the top liner reference system. Table 1 sums up the results from the investigation.

Table 1: Results from comparison of CO₂ and R-410A reversible heat pumps (Jakobsen et al, 2007)

Seasonal cooling performance	Athens	Oslo
CO2 baseline, experimental data	4.1	6.4
CO2 intercooling, experimental data	4.4	6.7
CO2 intercooling, experimental data recalculated with 65 % Isentropic efficiency	5.3	8.0
R-410A reference unit 1, Manufacturer data with experimental validated rating-point	5.3	6.7
R-410A reference unit 2, Manufacturer data with experimental validated rating-point	3.9	4.9
Seasonal heating performance, including peak-load		
CO2 Baseline	4.3	2.7
CO2 Baseline, experimental data recalculated with 65 % isentropic efficiency	4.9	2.8
R-410A reference unit 1, Manufacturer data	4.0	2.6
R-410A reference unit 2, Manufacturer data	3.4	2.2

3.2 Commercial Refrigeration

Refrigerant emissions from the commercial refrigeration sector represent the largest GHG emissions within the refrigeration industry, more than 40% of the CO₂-eq emissions.

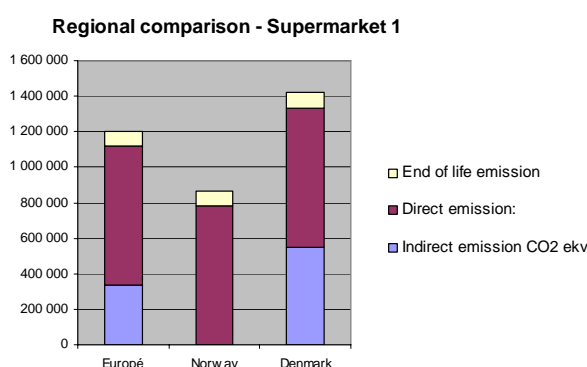


Figure 3: Direct, indirect and end of life emissions from a supermarket with refrigerant emissions representative for the world average, kg CO₂-eq

containment and reduced charge, it illustrates the great need for non-HFC alternatives.

Figure 3 shows total yearly CO₂-eq emission for a supermarket in kg CO₂-eq, including both indirect and direct emissions. Assumptions; charge 600 kg HFC-404A, yearly leakage 30% (world average), end of life recovery 50%, seasonal COP of refrigeration machinery 2.5 and a yearly operation time of 75 % with a nominal capacity of 250 kW. Power production is illustrated for an average European power system (0.51 kg CO₂/kWh), Norway (0 kg CO₂/kWh) and Denmark (0.84 kg CO₂/kWh). World average is 0.57 kg CO₂/kWh. The figure is taken from Neksa and Lundqvist (2005). A major part of the emissions is direct emissions from refrigerant leakage. Even though leakage may be reduced by better

CO₂ is an important refrigerant alternative to HFCs in commercial refrigeration systems. Some of the major manufacturers have introduced direct systems using only CO₂ as refrigerant in a transcritical/subcritical cycle, depending on ambient temperature, for both low- and medium-temperature refrigeration. So far about 100 supermarkets have been built in Europe with this kind of system design, from Italy in south to Norway in north. Energy consumption and cost is reported to be within the range of today's direct expansion R-404A systems and indirect system designs, Girotto et al. (2004). Reduced cost and increased energy efficiency is expected due to ongoing development. The CO₂ systems are also very well suited for making heat recovery from the refrigeration units. This is important since supermarkets require heating large parts of the year due to the refrigeration loads in the shopping area. Further LCCP figures and mitigation cost data may be found in Harnish et. al (2003) and IPCC/TEAP (2005).

Also in the light commercial sector, i.e. stand alone equipment such as bottle coolers and vending machines, some of the major manufacturers have introduced CO₂ technology (RefNat 2004). Jacob et al. (2006) reported 4.000 units installed in a pre-commercial deployment test. Efficiency comparison with comparable HFC systems shows that CO₂ units compete well for even most of the hot climates around the world. 100,000 units are expected to be installed within the period of 2008-2010 (R744.com 2008). Zimmermann and Maciel (2006) showed very promising energy efficiency for both medium temperature and low temperature cabinets.

3.3 Mobile Air Conditioning

Mobile air conditioning is the application with the largest HFC emissions and the second largest GHG emissions (in CO₂-eq) resulting from refrigerant emissions. This is also one of the reasons why EU will ban use of HFC-134a in mobile air condition systems for all new car models from 2011.

Hafner et al (2004) gives an in-depth LCCP comparison between CO₂ mobile air conditioning systems and HFC-134a and HFC-152a systems based on experimental data and climate data for different cities around the world. Compared to HFC-134a the investigations showed 18-48 % reduced LCCP, and thereby reduced emissions, for the CO₂ systems - smallest reductions for the very hot climate of Phoenix, USA, and highest for a more moderate German climate. Figure 4, from Hafner and Neksa (2006), shows calculated LCCP figures for CO₂ and HFC-134a for the hot climates of New Delhi, India, and Rome, Italy. Leakage rates of 120 g/a for the HFC-134a system represents today's global average system emission rate from these systems, while 30 g/a is expected to be best case future emission scenario. As shown, significantly reduced emissions can be achieved by changing to CO₂ as refrigerant.

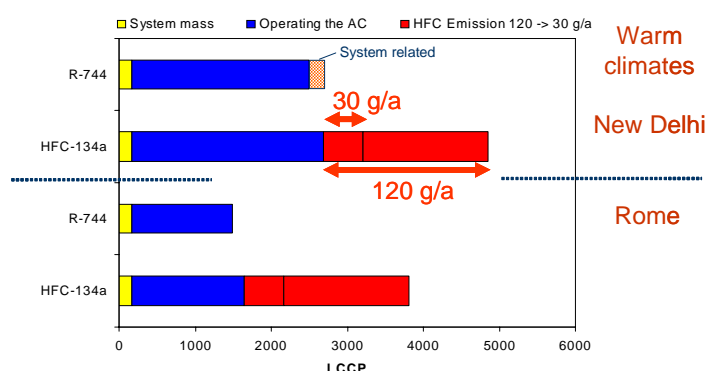


Figure 4: Life Cycle Climate Performance (LCCP, kg CO₂-eq) comparison between CO₂ (R-744) and HFC-134a for the relatively hot climates New Delhi in India and Rome in Italy (from Hafner and Neksa 2006)

Another very interesting feature of CO₂ as refrigerant is that it is very well suited for reversing the systems and use as heat pumps in the cold season. This may give the systems

increased features which are very interesting especially in colder areas and it may also contribute to reduced GHG emissions.

3.4 Other Applications

R&D on CO₂ systems for several other applications is being performed. Transport refrigeration, reefer containers and bus air conditioning are all applications with large emissions, where development of alternative systems is important. Development of water chillers and CO₂ systems for larger capacity refrigeration is also ongoing.

4 ONGOING DEVELOPMENTS FOR FURTHER EFFICIENCY IMPROVEMENTS

There is an ongoing development for improved components for CO₂. For compressors, focus is on developing more efficient, compact and reliable units. The properties of CO₂ make very efficient compression possible. For heat exchangers the focus is on developing more compact and efficient heat exchanger with microchannel tubes and enhanced fins. These developments have contributed in efficient systems for a variety of applications, some of them already mentioned.

In order to improve system efficiency further it may be a very interesting option to recover some of the throttling losses of the process. Both potential and importance are highest at operation with high heat sink temperatures, such as for air conditioning at high ambient temperatures and for heat pumps with high temperature heat distribution systems.

Wolf et al (2007) discusses the potential of replacing the throttling valve with a compressor-expander unit. 27% increased efficiency at an ambient of 38°C for a mobile air conditioning application was found to be feasible.

Another possibility would be to replace the expansion valve with an ejector. Drescher et al (2007) presents experimental results from an ongoing development. Figure 5 shows a drawing of the ejector presented. The ejector is used to increase the suction pressure to the compressor. In this way the compression work will be lower and the system efficiency increased.

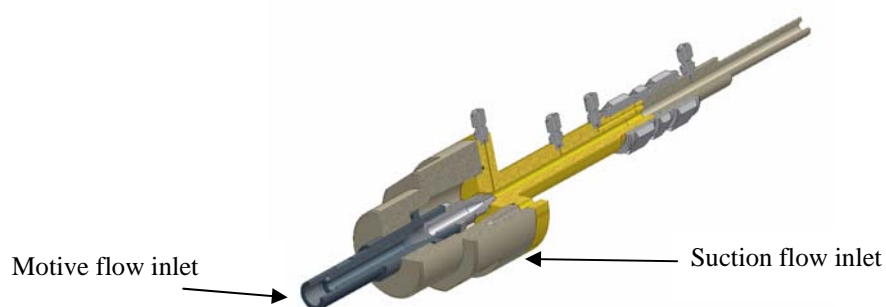


Figure 5: Ejector with associated pressure connections (from Drescher et al 2007)

Development of ejectors and expanders are ongoing at several institutions around the world. A challenge is to develop cost efficient concepts which will be economically feasible to implement in future systems.

Important developments are also ongoing in order to obtain improved system and component integration. This is especially important for CO₂ as refrigerant due to the difference in thermophysical properties and cycle behaviour compared to many other refrigerants. These are often differences that give CO₂ advantages in many applications.

5 CONCLUSIONS

- CO₂ (R744) has become an important alternative refrigerant
- CO₂ systems have been commercialised in many applications and are being commercialised in many others
- CO₂ systems will contribute to reduction in GHG emissions both by eliminating direct emissions and through reduced indirect emissions due to better energy efficiency
- CO₂ is a natural substance known not to be harmful to the environment, thus a long-term alternative
- Important work is ongoing in order to increase energy efficiency especially for the most challenging applications

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