CO_2 as Refrigerant, an Option to Reduce GHG Emissions from Refrigeration, Air Conditioning and Heat Pump Systems

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Emissions of halogenated refrigerants represent a major challenge for the environment both due to ozone depletion and green house warming. On a global basis today, the refrigerant emissions represent GHG emissions equivalent to about 10% of CO_2 emissions resulting from fossil fuel burning (IPCC/TEAP, 2005).

In principle 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. A change to use of alternative refrigerants with a lower or zero global warming potential therefore represent a more sustainable long term strategy.

CO_2 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. CO_2 is also a non-toxic and non-flammable alternative, properties preferred in many applications. The CO_2 used as refrigerant is waste CO_2 from industrial processes, the same CO_2 as used for carbonizing beverages. It is also important that it has excellent availability world-wide already today.

Ozone depleting substances are controlled through the Montreal protocol and will be phased out. However, they are still extensively used in many countries, especially developing countries that potentially may use these ozone depleting substances for many years to come, even if this is undesirable from an environmental point of view. Unique is that these countries may use this opportunity to convert their technology directly to long term solutions using natural refrigerants.

Since refrigeration, air conditioning and heat pumps generally generate indirect CO_2 emissions through their power consumption, either through electricity production based on fossil fuels or in engines for transport and mobile applications, it is important to focus also on these emissions, and thereby on energy efficiency. One way to address this is through life cycle climate performance evaluations, LCCP, which takes the total emissions during the lifetime into account.

CO_2 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 CO_2 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 CO_2 as an alternative. Focus will be given to systems using CO_2 as the only refrigerant. Thus, use of CO_2 in cascade systems or as brine is not covered.

Energy Efficiency and Ambient Conditions

Due to the difference of CO_2 thermophysical properties and cycle characteristics compared to HFC refrigerants, typical efficiency curves (COP, Coefficient Of Performance: cooling capacity divided by power input) shows different trends with the ambient temperature. CO_2 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.

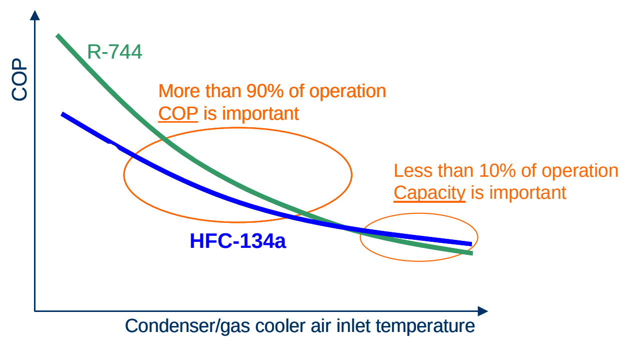

Figure 1. Typical efficiency (COP) curves at varying condenser/gas cooler air inlet temperature for CO_2 (R-744) and HFC-134a (Hafner et al. 2004)

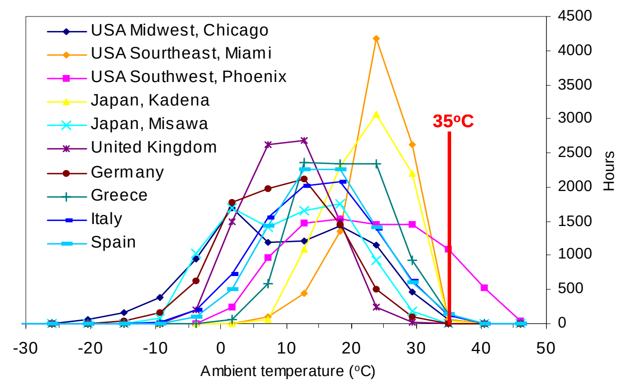

Figure 2. Temperature bin data for selected cities in USA, Japan and selected countries in Europe. Two extreme climates shown are Miami and Phoenix (Hafner et al. 2004)

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 CO_2 and HFC options reported in Hafner et al. (2004) for mobile air conditioning systems showed a crossover temperature above 30^oC.

When comparing energy efficiency for CO_2 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^oC, 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. Results show that CO_2 systems satisfy capacity requirements at the highest ambient conditions very well.

For several applications it has now become a common procedure to work out energy consumption based on a seasonal variation of the climate in order to compare different systems and technologies. This holds for example for HVAC units in USA, hot-cold vending machines in Japan and mobile air conditioning systems. LCCP calculation comparisons for some applications are presented below.

CO_2 as an Alternative in Different Applications

CO_2 systems have been commercialised in some applications, are readily developed from an R&D point of view for several different applications and systems for yet others applications are still under development.

Commercial Refrigeration

The commercial refrigeration sector represents the largest GHG emissions from refrigerant leakage within the refrigeration sector, more than 40% of the CO_2-eq emissions.

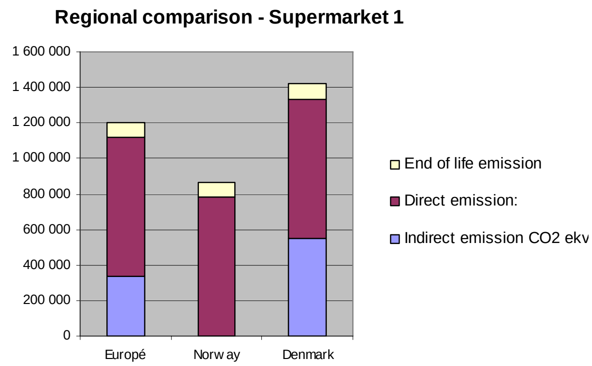

Figure 3. Direct, indirect and end of life emissions from a supermarket with refrigerant emissions representative for the world average, kg CO_2-eq

Figure 3 shows total yearly CO_2–eq emission for a supermarket in kg CO_2-eq. 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 are illustrated for an average European power system (0,51 kg CO_2/kWh), Norway (0 kg CO_2/kWh) and Denmark (0,84 kg CO_2/kWh). World average is 0.57 kg CO_2/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 containment and red. charge, it illustrates the great need for non-HFC alternatives.

CO_2 is an important refrigerant alternative to HFCs in commercial refrigeration systems. Some of the major companies have introduced direct systems using only CO_2 as a refrigerant with a transcritical/subcritical cycle, depending on ambient temperature, for both low- and medium-temperature refrigeration. So far, between 10 and 20 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. 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 companies have introduced CO_2 technology (RefNat 2004). Jacob et al. (2006) reported 4000 units installed in a pre-commercial deployment test. Efficiency comparison with comparable HFC systems shows that CO_2 competes well for even most of the hot climates around the world. Zimmermann and Maciel (2006) showed very promising energy efficiency for both medium temperature and low temperature cabinets.

Mobile Air Conditioning

Mobile air conditioning is the application with the largest HFC emissions and the second largest GHG emissions in CO_2-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 CO_2 mobile air conditioning systems and HFC-134a and HFC-152a systems based on experimental data and climate data fro different cities around the world. Compared to HFC-134a the investigations showed 18-48 % reduced LCCP, and thereby reduced emissions, for the CO_2 system. Least reductions for the very hot climate of Phoenix in USA and most for a more moderate German climate. Figure 4, from Hafner and Nekså (2006), shows calculated LCCP figures for CO_2 and HFC-134a for the hot climates of New Dehli in India and Rome in Italy. Leakage rates of 120 g/a for the HFC-134a system represents today's global average 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 CO_2 as refrigerant.

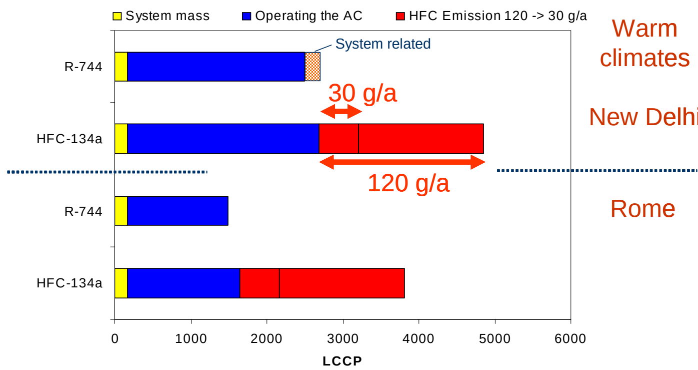

Figure 4. Life Cycle Climate Performance (LCCP, kg CO_2-eq) comparison between CO_2 (R-744) and HFC-134a for the relatively hot climates New Dehli in India and Rome in Italy

Heat Pumps and Air Conditioning

Heat pump water heaters, heat pumps for tap water heating, was commercialised in Japan in 2001 for both residential and commercial applications. About 210.000 units, primarily for residential applications, were sold in 2005 (a growth rate of 60% compared to 2004). With a seasonal efficiency higher than 4, these systems make significant reductions in GHG emissions compared to use of gas or electricity directly. Systems adapted to European conditions are under development. An important advantage is the ability of the systems to heat water to higher temperatures than systems with HFC as refrigerant.

Stene et al. (2006) presents CO_2 systems for combined heating and cooling of non-residential buildings. The theoretical evaluation demonstrates that CO_2 systems can achieve equal or higher seasonal performance factor than heat pumps using HFC refrigerants. Air-to-air reversible residential heat pumps are also under development.

Other Applications

R&D of CO_2 systems for several other applications are being performed. Transport refrigeration, reefer containers and bus air conditioning are all applications with large emissions, where development of alternative systems will be important.

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