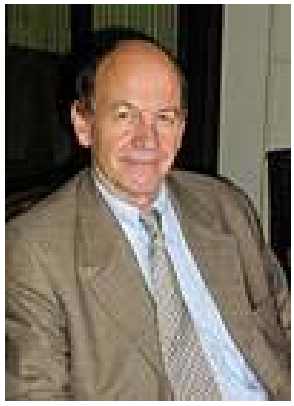

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Refrigerating Equipment, Energy Efficiency and Refrigerants

by

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INTRODUCTION

Regulations on ozone-depleting substances and on climate change are inducing modifications of the refrigerating equipment and refrigerants used, and this article focuses on these modifications.

This article provides an analysis of trends in 7 main applications in the refrigeration and air-conditioning fields. For each application, recent global figures are given, the main refrigerants used and new developments are detailed and comments on energy efficiency are provided.

The changes over the last few years are impressive and a broad range of options enabling use of non-ozone-depleting substances is now available.

Refrigerating equipment and refrigerants are rapidly evolving in order to comply with regulations on ozone-depleting substances (ODS) and regulations or draft regulations on climate change. Other driving forces underlie changes: consumers, purchasers, users, media, lobby groups, standards, etc. The main regulations addressing ODS are the Montreal Protocol and the European Regulation No. 2037/2000 of June 29, 2000.

The main texts on climate change are:

- the Kyoto Protocol adopted on December 10, 1997, will enter into force in February 2005;
- the proposal for a Regulation of the European Parliament and of the Council on certain fluorinated greenhouse gases of August 11, 2003 and successive versions of it;
- the Danish statutory order No. 522 of July 2, 2002 regulating certain industrial gases;
- the Austrian ordinance FLG No. II 447/2002: Management of bans and restrictions for partly and fully fluorinated hydrocarbons and sulphur hexafluoride;
- the Swiss ordinance on dangerous substances for the environment (adopted by the Swiss Federal Council on 29-30 April, 2003).

In order to provide up-to-date information the author collected information from recent documents particularly the TOC Report[1] which was issued early 2003 and is an excellent balanced document prepared by high-level experts in the refrigeration industry. The presentation of new trends is made at the level of each application.

I. DOMESTIC REFRIGERATION

I.1 Data

There are approximately 1 billion domestic refrigerators worldwide.[2] Most of them are in industrialized countries. In France, for instance, there are 1.7 refrigerators per household (1 refrigerator and 0.7 freezers on the average).[3] However, production in developing countries is rising steadily (30% of total production in 2000).

I.2 Refrigerants

HFC-134a and HC-600a continue to be the dominant alternative refrigerant candidates to replace CFC-12. The figures on production in Europe and worldwide in 2000 are shown in *Table 1*.

Table 1. Production of domestic refrigerators in 2000 (million units)[1]

	HFC-134a	HC-600a	Others	CFC-12	Total
Europe	8.3 (42%)	11.4 (58%)			19.7
Worldwide	44.0 (53%)	17.6 (21%)	1.8 (2%)	19.8 (24%)	83.2

In 2000, isobutane refrigerators represented 58% of total European production but only 21% of global production.

Both HC-600a and HFC-134a have been shown to be suitable for mass production of safe, efficient, reliable and economic use appliances. In practice, similar product efficiencies result from the use of either refrigerant. Other design parameters introduce more efficiency variation opportunities than those arising from refrigerant choice.

I.3 Energy

When you consider a LCCP (Life Cycle Climate Performance) approach, the emissions of refrigerant in a HFC-134a refrigerator represent only 1-2% of the total contribution to global warming and emissions due to energy consumption represent 98-99%. Therefore, energy consumption is the most significant issue with regards to global warming.

Labelling and purchase rebate incentives are 2 ways of shifting consumer purchase decisions towards high-efficiency models. Voluntary agreements involving manufacturers who place on the market high efficiency models are also effective approaches. Early disposal incentives are also efficient measures leading to reduced energy consumption, but only if a mandatory system for disposal of old appliances is in force.

There are several technological areas where improvements for efficiency enhancements are possible:

- forced convection for evaporators and compressors;
- lower viscosity oils;
- reduction of temperature level inside the compressor;
- variable speed motors;
- linear compressors;
- insulation.

I.4 Insulation

HCFC-141b, a very widely used blowing agent in insulating materials was phased out in 2003 in Europe, the US and Japan. Europe has mainly moved towards blowing agents belonging to the cyclopentane family. There are now 2 HFC-blowing agents on the market: HFC-245fa, which is produced in the US (Gieismar, Louisiana), and HFC-365mfc, which is produced in France (Tavaux).[4] *Table 2* shows the relative thermal conductivities of foams at a temperature of 23.9°C:

Table 2. Relative thermal conductivities of foams[1]

Blowing agent	Relative thermal conductivity
HCFC-141b	100
HFC-134a	120-123
HFC-245fa	108-109
HFC-365mfc	102
Cyclopentane	110-113

The relative thermal conductivity of cyclopentane compared with HFC-blowing agents seems to be a drawback for this component; however, the issue of aging, which is not the same for HFCs and cyclopentane, should also be considered. It needs additional studies.

Recovery of blowing agent during end-of-life disposal needs further research. It is interesting to note that some experts consider that much of the blowing agent in foam may be broken down by enzymes in the soil and that very little may ever be released into the atmosphere.[5] The European Parliament, at the first reading of the draft regulation on fluorinated greenhouse gases, on March 31, 2004, voted to remove the obligation to recover foams containing f-gases from old fridges.

II. COMMERCIAL REFRIGERATION

II.1 Data

Worldwide data[1]:

- 322 000 supermarkets

- 18 000 hypermarkets
- 32 500 000 condensing units
- 31 000 000 stand-alone units
- 14 700 000 vending machines.

II.2 Types of equipment

There are several types of equipment and systems:

II.2.1 Stand-alone equipment and condensing units: HFC-134a is mainly used for fresh food and beverages and HFC-404A (or HFC-507A) for frozen foods and ice creams. HFC-290 is used for medium- and low-temperature stand-alone display cabinets in certain countries.

II.2.2 Centralized systems: centralized systems are very commonly used in supermarkets and hypermarkets. There are two options:

a) *Direct systems*

A widespread refrigerant used both for medium- and low-temperature circuits is HFC-404A. It is a popular refrigerant because it can be used for fresh and frozen foods. An attractive refrigerant is R-422A, because it is a drop-in of R-502A which can use mineral based lubricants.[6] An interesting development is the cascade direct system using CO_2 as a refrigerant for the low-temperature circuit. Another development is a direct transcritical CO_2 system currently tested in a small Italian supermarket.[7] A Costan transcritical CO_2 system has been installed in the supermarket SuperBest in Bellinge near Odense, Denmark.[8]

b) *Indirect systems*

There is a growing interest for indirect systems in order:

- to lower the refrigerant charge by 50 to 75% compared with classic direct systems;[1]
- to be able to use flammable or toxic refrigerants located in a machinery room separated from the sales area;
- to easily modify the disposition of display cabinets in the sales area.

Initial costs are about 15% higher than usual direct systems.[1]

The Heat Transfer Fluid (HTF) which is mainly used is MPG (MonoPropyleneGlycol) for medium-temperature applications and potassium acetate or other brines for low-temperature applications.

There is growing interest in phase-change HTFs, either solid/liquid (also called ice slurries) or vapour/liquid such as CO_2. The IIR Working Party on ice slurries, which organized 5 workshops since 1999, is promoting the development of this technology. There are a few supermarkets equipped with ice-slurry systems in France and in Switzerland.

II.2.3 Distributed systems: these are used in large supermarkets and comprise several smaller plants which reduce refrigerant circuit length and charge. This concept launched in 1997 in the US has not secured a significant market share.

II.3 Energy

The energy consumption of the refrigeration equipment represents an average of 35-50% of the total energy consumption of an average supermarket.[1] Experts have not reached a consensus on the energy consumption of indirect systems. Some consider that energy consumption of indirect systems is 10-15% higher than in a comparable direct system, because of the double exchange; others consider that in some cases the energy consumption is the same or even lower, because of energy savings at defrosting level, for instance.[1] Unfortunately, there is no reference standard to measure the energy consumption of an entire supermarket. The standard only applies to stand-alone equipment.

Commercial refrigeration is an application characterized by long pipes, large pressure drops and high leakage rates which nevertheless have recently been reduced from 30% to 10-15% per year.[1]

III. INDUSTRIAL REFRIGERATION

III.1 Data

This domain is so wide that it is difficult to characterize it by detailed figures. Let's just mention that annual sales of chilled and frozen foods represent 1200 billion US dollars.[2] All these products have been stored in refrigerated outlets. In addition, about 80% of the food that we consume is processed food transformed in food processing industries which use refrigerating and heating processes.

The total volume of refrigerated stores is over 300 million m^3 capable of storing 350 million tonnes per year.[9]

III.2 Refrigerants

- Ammonia has reinforced its position as the leading refrigerant for cold stores and food processing, especially in the European Union where HCFCs are banned in new plants. Some examples of new developments in ammonia refrigeration are: better welding procedures, charge reduction thanks to plate-type heat exchangers, the use of direct-expansion tube-and-shell evaporators instead of flooded evaporators for medium-capacity plants (less than 300 kW refrigerating capacity) and aluminium-wiring engines.[10]

- HFCs are also utilized: HFC-404A is applicable; however it is not very commonly used because it is a near-azeotropic mixture and not a pure fluid (glide: 0.46°C). HFC-410A which has a high volumetric capacity, a good energy efficiency and small size compressor is an interesting option.
- HCs are historically used in large refrigeration plants in the oil and gas industry.
- CO_2 is attracting a lot of interest. The IIR has organized 6 Conferences on Natural Working Fluids, the latest one being held in Glasgow, U.K. (August 29-September 1, 2004). At the last 2 conferences about 40% of total papers dealt with CO_2. Applications concern the use of CO_2 as a refrigerant or a HTF in the low-temperature circuit in both cases. The high volumetric capacity (5 times as high as HFC-410A) and good environmental properties are attractive assets. The transcritical cycle is not yet being used in the field of industrial refrigeration because of the lack of large-size equipment.

IV. REFRIGERATED TRANSPORT

IV.1 Worldwide data

There are 1 200 000 refrigerated vehicles.

With 550 000 intermodal refrigerated containers in operation (both TEU [Twenty foot Equivalent Units] and 2TEU) this type of equipment is dominating marine refrigerated transport with a share of the total volume expected to reach 60% within the next few years. The fleet of reefer ships is stabilizing at an estimated level of 1100 units.[1]

Refrigerated transport is an important field if we consider that each product is transported 2.5 times on the average.[2] In addition, foods are transported over an average distance of 2100 km before arriving on the US consumer's plate.[11]

IV.2 Refrigerants

IV.2.1 Road: the main characteristics of road refrigerated transport equipment is that it operates under adverse conditions and encounters very large temperature ranges depending on the geographic locations.

- In this sector, the evolution has led to overall acceptance of HFC refrigerants. The main problem is refrigerant availability worldwide. Road transport has moved to HFC-404A because it can be used both for medium-temperature and low-temperature applications. HFC-134a is used in smaller units driven by the truck engine for fresh food applications. HFC-410A is also applied, even if its low critical temperature (70.2°C) and high pressure (24 bar at 40°C) are drawbacks in summer or in warm countries.
- Cryogenic systems using liquid nitrogen or Synthetic Liquid Air (SLA) have been developed.
- Cryogenic systems using liquid carbon dioxide that is vaporized in an evaporator have also been developed. These systems are markedly different from those using direct vaporization inside the vehicle, which raises safety issues. Engines using vapour carbon dioxide as a fuel have also been designed for air circulation.
- HC-290 has been tested and risk assessment conducted; HC units are marketed in a few countries.
- The adsorption technology studied for many years has not achieved complete commercial development.

IV.2.2 Marine: in reefer ships, HFC-410A is gaining importance. Recent ammonia indirect systems are now used both for reefer ships and fish boats. HFC-134a is dominating the intermodal refrigerated container market, because most products transported are fresh foods: fruit and vegetables and meat. Another reason: the critical temperature should be reasonably high due to the high condensation temperatures encountered in tropical regions and the use of air-cooled condensers. Transcritical CO_2 systems are also considered and tests are currently being implemented.[1] Ammonia and HCs are not allowed in containers with reference to IMO (International Maritime Organization).

V. UNITARY AIR CONDITIONING (AIR-COOLED EQUIPMENT)

V.1 Data

This category covers air conditioners and refrigerant-to-air reversible heat pumps whose cooling capacities range from 2 kW to 420 kW.

The main data in this field are summarized in *Table 3*.

Table 3. Data on air-cooled air conditioners and reversible heat pumps[1]

Equipment	Units manufactured in	Increase in 2001 cf 1998	Estimated unit population	Estimated HCFC-22 inventory

	2001 (million)		(million)	(tonnes)
Windows	13.6	12%	131	84 000
Duct-free split air conditioners	24.2	48.5%	158	199 000
Ducted split air conditioners	5.9	3.6%	60	164 000
Roof-tops	1.7	0%	19	101 000
Total			**368**	**548 000**

V.2 Refrigerants

We will explore only non-ODS developments keeping in mind that globally 85-90% of the air-cooled air conditioners produced in 2000 were still using HCFC-22 as the refrigerant.[1]

The shift over the last few years toward the use of duct-free residential air conditioners should be underlined. This trend is particularly visible in Asia. The 48.5% increase in sales between 1998 and 2001 is particularly significant. The development of reversible heat pumps in North America, Japan and Southern regions of Europe is also an interesting trend.

Today, there is a complete range of HFC-407C air-conditioning equipment. This is easily explained by the fact that HFC-407C and HCFC-22 have properties which are similar, even if the former is a 3-component zeotropic blend and the latter a pure component. It was, therefore, the easiest solution. However, HFC-410A is becoming dominant in many applications thanks to its high volumetric capacity, its good energy efficiency and the small compressor size. It took longer to develop new components designed for HFC-410A because of the pressure, which is approximately 50% higher than with HCFC-22. R-417A, a refrigerant launched in 1997, is interesting because it is a near drop-in which can work with mineral oil lubricants due to the small amount of HC-600 in the mixture.[6]

HCs have attractive thermophysical and environmental properties which were applied in some low-charge units. Current work at the level of standards should be underlined.

Tests with transcritical CO_2 air conditioners were carried out. Unless the transcritical cycle can be cost-effectively modified to the point where its energy penalty is smaller than the direct global warming impact of subcritical HFCs, then it will be unlikely to prevail in most cooling and air conditioning applications.[12]

VI. WATER CHILLERS

VI.1 Data

CFC chillers are still numerous all over the world. This is due to the fact that these units are very costly and have a long lifespan estimated at 30-40 years. ARI (Air conditioning and Refrigeration Institute) estimated recently the number of CFC chillers still operating in the US at the end of 2003 as 36 200 units in comparison with 80 000 CFC chillers in the early 1990s, and only 3000 new HFC-chillers are installed each year.[13]

There are 2 large families of chillers: vapour-compression-cycle chillers (*Table 4*) and absorption chillers. Large absorption chillers are mainly concentrated in Japan, Korea and China. This is the consequence of voluntary policies in these countries in order to encourage use of such equipment.

Table 4. Cooling capacity range depending on the type of compressor[1]

Type of compressor	Cooling capacity
Scroll and reciprocating compressors	7.0-1600 kW
Screw compressors	140-6000 kW
Centrifugal compressors	350-30 000 kW

VI.2 New trends

Trends in chiller technology are the following:

- the market share of air-cooled systems for small and middle-size chillers is increasing in comparison with that of water-cooled water chillers;
- the market share of scroll and screw compressors is growing in comparison with that of reciprocating compressors;
- the number of reversible heat pumps on the chiller market is rising;
- integrated units for space heating, delivering heat and cooling simultaneously for commercial buildings are becoming popular;
- heat pump water heaters are capturing a growing fraction of water heater sales;
- ground-source heat pumps have become more popular in recent years.

VI.3 Refrigerants

Options for non-ODS refrigerants are the following:

- In large chillers (above 700 kW) equipped with centrifugal compressors and flooded evaporators, HFC-134a is the main option so far.[1] The excellent heat transfer properties and pure fluid characteristics of this refrigerant are advantages.
- HFC-407C is used in direct-expansion systems with counter-flow heat exchangers so as to benefit from the refrigerant glide. However, when low-price components are developed for HFC-410A, the latter may compete with HFC-407C.
- CO_2 has no commercial applications to date. It does not seem to be competitive as a chiller refrigerant because of its low-cycle energy efficiency.
- Several manufacturers have designed ammonia chillers with positive displacement compressors. However, the market share of this refrigerant is still small.
- There are about 100 to 150 HC-units sold per year.[1] Refrigerants are HC-1270, HC-290 and propane/ethane mixtures. Typical HC chillers have cooling capacities in the range of 20 kW to 300 kW and refrigerant charge varies between 3 and 34 kg.[1]
- CO_2 heat pump water heaters, which entered the Japanese market in 2001, are interesting developments. They raise the temperature of tap water from 5-10°C to 70-80°C and their heating capacity is 4.5 kW. A CO_2 compressor developing a heating capacity of 22 kW is quoted in the literature.[1]

VII. VEHICLE AIR CONDITIONING

VII.1 Data

There are currently 740 million vehicles worldwide; 380 million (51.7%) of them are air conditioned.[2] This percentage is growing steadily.

VII.2 Refrigerants

Since 1995, all air-conditioned vehicles in industrialized countries use HFC-134a. Considerable progress has been achieved at the level of the initial charge, the leakage rate and servicing. There are constant improvements at the level of HFC-134a air conditioners.

In 2002, interest in CO_2 technology was officially announced by VDA (Verband der Automobilindustrie), a group of German manufacturers which declared their intention to market new cars equipped with CO_2 air conditioners as soon as 2006 and with CO_2 heat pumps in 2008.[14] The issue is that in new cars there is not enough lost heat to be recovered in order to sufficiently warm the habitacle; in that respect CO_2 heat pumps are a smart development, because they immediately warm the passenger cabin. In 2002, a Japanese manufacturer unveiled a fuel cell car with a CO_2 air conditioner.[15] The development of the transcritical technology in mobile air conditioning is extremely expensive. The training of technicians and the equipping of all garages will be very costly.

There is also research being conducted on HCs and HFC-152a (a flammable refrigerant) both in direct and indirect systems.

New developments in microchannel heat exchangers should be underlined.

Life Cycle Analysis is of paramount importance due to the fact that the energy consumption of mobile air conditioners is said to be between 12% and 30% of the total energy consumption of the vehicle, depending on the standard or test protocol used (urban or extra-urban cycle), on the internal and external temperatures adopted and on the type of the engine (diesel or gasoline).[16] In addition, in European countries, the air-conditioning system is only used 100 hours per years.[16] The European Commission in its 2nd

ECCP Report[17] mentioned that about one third of emissions are due to higher fuel consumption of vehicles and consequent CO_2 emissions and two thirds due to emissions of refrigerant HFC-134a and added that this would be equivalent to 16 to 28 grams of CO_2 equivalent per kilometre in 2010 depending on assumptions (9-16% of total greenhouse gas emissions).

VIII. CONCLUSION

The options for non-ODS refrigerants are very diversified today. HFCs are popular and dominant; however HCs and ammonia are gaining market shares, and CO_2, even if not very common yet at the level of the market, is attracting a lot of interest for a number of applications.

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