Environmental consciousness

Refrigerant options now and in the future
Danfoss helps define your refrigerant choice

A paper on the global trends within refrigeration and air conditioning. Guiding you through today’s and tomorrow’s refrigerants and technologies, with emphasis on Global Warming Potential, energy consumption, system efficiency and other information that will help you stay on top of the game.

Climate

Responsibility means new challenges.

Read how Danfoss enables you to obtain energy savings, contribute to a cleaner environment and build a cleaner image.

Energy

Efficiency and refrigerant choice.

Your refrigerant choice influence energy efficiency in your application. Read how our customers have cooperated with us to design solutions that meet their own customers’ challenges.
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Executive summary

The refrigeration and air conditioning industry has made tremendous progress over the past two decades in reducing the use of ozone-depleting refrigerants. The original targets of the Montreal Protocol, established in 1987 to reduce emissions of ozone-depleting substances, are being met and exceeded. Another consequence of these initiatives is that during the 1990s and the early part of the present century, there was considerable uncertainty regarding future refrigerant options. Now a path has started to appear, defined by the global agenda on climate change and global warming.

Seen from a global perspective, the tendency is that the industry is moving more and more toward natural refrigerants where this is technologically feasible. Synthetic refrigerants are still likely to play a large role in the refrigeration and air conditioning industry, but this will be in minimal charge systems and with new low GWP substances. Parameters such as efficiency, safety, environmental impact, relatively short atmospheric lifetimes, chemical properties and economy all influence the choice of future refrigerant options.

This paper is an effort to create an overview of the key global trends in refrigerants (including environmental aspects, developments and tendencies) and the regulatory incentives that impact the future. It also aims to introduce some of Danfoss’s visions and provide insight into some key Danfoss products that support these visions.
Policy Statement

Danfoss encourages the further development and use of low-GWP refrigerants to help slow – and ultimately reverse – the process of global warming while helping to ensure continued global wellbeing and economic development along with the future viability of our industry. We will enable our customers to achieve these refrigerant goals while continuing to enhance the energy efficiency of refrigeration and air conditioning equipment.

Danfoss will proactively develop products for low-GWP refrigerants, both natural and synthetic, to fulfil customers’ needs for practical and safe solutions without compromising energy efficiency. Danfoss will lead and be recognized in the development of natural refrigerant solutions. In the case of hydrocarbons, ammonia and carbon dioxide, we will focus on solving the challenging application difficulties related to flammability, toxicity, corrosiveness and extreme pressures, while enabling cost competitive and highly energy-efficient systems. Danfoss will also develop and support products for low-GWP synthetic refrigerants, particularly for those applications where natural refrigerant solutions are not yet practical or economically feasible.

Furthermore, Danfoss supports the establishment of a global regimen (such as the Montreal Protocol) to phase down emissions of high-GWP refrigerants. In recognition of the fact that HFC refrigerants enable safe, energy efficient products with positive societal benefits, HFCs should be controlled separately from undesired waste by-products of power plants, factories, automobiles, etc., by means of a knowledgeable global governance system and infrastructure. A practical cap and phase down schedule must be established to facilitate product transitions, to avoid severe market disruption or volatile prices during the transition period, and to provide for long-term production of very small quantities of HFCs for critical needs.
Background

Refrigerants and their properties
All compounds that can be used in a thermodynamic cycle with a phase change from gas to liquid and back can be used as refrigerants. Some of these refrigerants, such as ammonia, hydrocarbons and carbon dioxide, are natural substances, while others can only be produced artificially. Typical synthetic refrigerants are CFCs, HCFCs and HFCs. Synthetic refrigerants were introduced because they have a number of advantageous properties for refrigeration cycles, including good thermodynamic efficiency and relatively low pressure. Unfortunately, most of these synthetic refrigerants have adverse effects as well.

Influence of refrigerants on the environment
Most refrigerants have an influence on the atmosphere when they are released. It varies from not substantial (e.g. CO\textsubscript{2}) to very significant (CFCs). The two main influences on the environment are ozone depletion and the greenhouse effect.

After the adoption of the Montreal Protocol, HFCs were introduced as a replacement for ozone depleting refrigerants. In general HFCs are replacing HCFCs, which have been used as an intermediate solution after the phase-out of CFCs. Therefore the consumption and emissions of HFCs will increase substantially over the next decades.

Although HFCs help reduce the problem of ozone depletion, they are greenhouse gases with high global warming potential (see Figure 1). Common HFC refrigerants have GWPs ranging from 1,300 to almost 4,000.

This means in the worst case that 1 kg of R404A released to the atmosphere corresponds to 3.9 metric tons of CO\textsubscript{2} emission. This causes HFCs to receive close attention from environmental advocates, regulatory agencies, and of course the refrigeration and air conditioning industry. HFCs have been designated ‘potent greenhouse gases’ and are increasingly subject to legislation and regulation.

![Figure 1. Refrigerant options](image)

**Figure 1. Refrigerant options**
Emissions from refrigeration systems are a major contributor to global warming

Emissions occur during the entire life-cycle of refrigerants: production, use, and recycling or destruction. In total, estimated annual emissions of F-gases from refrigeration systems alone amount to the equivalent of more than 1,000 million metric tons of CO₂, which is augmented by emissions from mobile and stationary air conditioning units. The total contribution of emissions of fluorinated gases to global warming is comparable to that of the aviation or computer industries. Although the absolute figures and the projections from various sources are subject to debate, the scale of the problem cannot be underestimated.

There are two dimensions to the global warming issue for air conditioning and refrigeration: direct impact due to the emission of refrigerants and indirect impact due to energy consumption. The sum of these two factors is called the ‘total equivalent warming impact’ (TEWI) – see Figure 2. In accordance with its definition, the TEWI depends on a number of factors: direct leakage including leakage during production, annual leakage rates and recovery losses, and indirect factors including the efficiency of the installation and the carbon intensity of electricity production. For example, if the source of electricity is wind power or hydropower, direct leakage is more important than when electricity is produced by coal.

Figure 2. Direct and indirect emissions from refrigeration installations

TEWI = direct emissions (leakage and recovery loss, CO₂ equivalent) plus indirect emissions (CO₂ from power plants)

No ideal solution

The bottom line is that there is no universal solution among refrigerants. Every refrigerant should be assessed for each specific application and geographical area in order to achieve the goal of the lowest possible TEWI. Danfoss’s ambition is to provide the refrigeration components and solutions that can make environmentally friendly systems with minimal TEWI feasible.

Industry initiatives takes the lead

A number of initiatives aimed at reducing leakage rates and minimising system charges have already been taken up by the refrigeration industry. Supported by Danfoss, the industry has also begun to increase the use of natural refrigerants with very low GWPs. Danfoss produces components for use with hydrocarbons (HCS), carbon dioxide (CO₂), and ammonia (NH₃). Refrigerant producers are also working to develop low-GWP synthetics. Although none of these substances is regarded as a universal replacement for HFCs, the industry has made significant progress in the transition to low-GWP alternatives.
Trends

The ratio of the direct and indirect emissions differs between applications. As can be seen from Figure 3, the direct impact of the refrigerant can vary from insignificant as in chillers to major as in mobile applications.

![Figure 3. Direct and indirect emissions in various applications](image)

To a large extent, this shapes the drivers for refrigerant change in various applications.

**Domestic refrigeration**

Today about 63% of newly produced domestic refrigeration systems are charged with R134a and about 36% are charged with iso-butane. It is predicted that at least 75% of globally produced domestic refrigeration will use hydrocarbons in 10 years. The isobutane charge is less than the R134a charge, and in addition isobutane offers higher efficiency or comparable to R134a in refrigerators. Isobutane is already the main refrigerant in domestic refrigerators in Europe. Migration from R134a to R600a on new production refrigerators is completed in Japan and initiated in countries such as US, China and Latin American countries.

**Light commercial refrigeration**

Light commercial refrigeration systems (e.g. bottle coolers and ice cream chest freezers) presently use a variety of HFCs, but hydrocarbons are rapidly gaining popularity in Europe and some other parts of the world.

**Commercial refrigeration**

Commercial refrigeration is the refrigeration subsector with the highest equivalent CO₂ emissions. The main contributors are supermarket systems, which typically use an HFC refrigerant with a high-GWP (R404A).

Possible alternatives to HFCs are HCs and CO₂, while charge limitation with secondary cooling is a third option. CO₂ (both transcritical and subcritical) has become the standard solution in Northern Europe in the supermarket sector and is growing in a number of other countries. In the USA there is a preference for secondary cooling solutions, while in other parts of the world various technologies are being evaluated.

**Industrial refrigeration**

The predominant refrigerant in industrial refrigeration is ammonia. In some countries R22 and R507 are popular as well. As ammonia is a traditional refrigerant for industrial refrigeration, it is likely that it will increase in market share, in some cases in combination with CO₂ cascade systems or with secondary cooling. The main limitation on ammonia is safety concerns, which exert pressure on charge volumes. A possible solution to this problem is secondary cooling systems with CO₂, since they provide very high efficiency.

**Air conditioning**

Only a few alternatives to existing technologies are available for air conditioning. There are a few systems that operate on CO₂ and hydrocarbons, but they are still prototypes. Various options are being assessed, such as secondary systems and low-charge propane systems, improved CO₂ cycles, and systems with new synthetic low-GWP refrigerants. Most likely all of those options will be used in the future.
Heat pumps use mainly HCFC and HFC refrigerants today. However, natural refrigerants can be used successfully in this application. Propane is a good alternative for traditional space heating heat pumps, since it provides high efficiency in the required temperature range. Propane is especially good for air to water applications. Legislation in Europe already supports such applications, allowing charges up to nearly 5 kg. CO$_2$ is another attractive option for heat pumps where space heating can be combined with high temperature sanitary water production. It can also be used in district heating applications where high temperature water is also required. Japan is at the forefront of such applications with a range of ‘Eco-cute’ heat pumps. The first heat pumps of this kind have already appeared in Europe.

A summary of the trends is presented in the table below. The applications are divided into two main groups (refrigeration and air conditioning or heat pumps), and refrigeration applications are further classified by capacity. The trends are also noted in various regions for each of the refrigerants, since the drivers vary from region to region. The summary below is only an overall picture, as exceptions can be found in every application and every region.
Refrigerants

Although refrigerant emissions are taken seriously by the industry, they cannot be avoided entirely. As described above, this creates a need for new refrigerants that will have only a limited impact on the environment, if any.

To understand the implications of refrigerant transition, it is necessary to consider the system design and the use risks. Even if alternative refrigerants are viable in thermodynamic terms, they cannot always be used in existing systems.

The following aspects must be considered when selecting a future refrigerant (in no specific order):

- Efficiency (theoretical, volumetric, potential for optimisation of the working process);
- Safety (including toxicity, flammability, and extreme pressure);
- Environmental impact: refrigerants should have zero ODP and low GWP; relatively short atmospheric lifetime;
- Thermophysical properties:
  - Critical point and triple point
  - Low pressure level
  - Pressure ratio of the refrigerant in the application and climate scenario
- Chemical properties, such as material compatibility, miscibility with oil, chemical stability, and miscibility with water;
- Economic viability (including the initial cost of the system and the life cycle cost);
- Availability of the refrigerant.

Four main groups of refrigerants are reviewed below, with the focus on the above-mentioned factors. These refrigerants are HFCs, HCs, CO₂, and NH₃. CFC/HFC refrigerants are not included in the overview because they have already been phased out or are in the process of being phased out. New low-GWP refrigerants such as HFO 1234yf are also omitted because they are not yet produced and used commercially. This paper will be updated to include new refrigerants after they start to be used in refrigeration and air conditioning applications.

General properties

HFCs (hydrofluorocarbons) are synthetic refrigerants and comprise a wide range of individual compounds and mixtures. The main single-compound refrigerant is R134a, while the main HFC mixtures are R404A (R125 / R143a / R134a), R507 (R125 / R143a), R407C (R32 / R125 / R134a), and R410A (R32 / R125). Mixtures of HFCs can be designed to suit all types of applications.

Efficiency

The theoretical Carnot efficiency of HFCs varies greatly, depending on the specific refrigerant and the application area. As a rule, HFCs offer good efficiency in their application range.

Safety

The HFCs mentioned here are all classified as non-toxic and non-flammable. Some HFC blends contain a mildly flammable component such as R143a or R32. Although the resulting blend will not be flammable, entry of air into the system should be avoided. In Europe, HFCs must be handled according to the F-Gas Regulation. Contact of HFCs with flames or hot surfaces (greater than 250 °C) can cause decomposition and the release of toxic gases, consisting of hydrogen fluoride (HF) and carbonyl halides (phosgene).
Gaseous HFCs are heavier than air and will displace air in the lungs. At relatively low concentrations, they can cause dizziness, headaches, nausea, and loss of coordination. Excessive inhalation of the gas (oxygen concentration as low as 12 to 14%) causes asphyxiation.

Environmental impact
As HFCs have significantly GWP values (124 to 14,800), they are under pressure from regulators and environmental agencies. The latest TEAP proposal classifies GWP from 1000 to 3000 as “high” and from 3000 to 10000 as “very high”. HFCs will continue to be used, but in fewer applications with increased attention to leaks and in systems with reduced refrigerant charges.

Pressure and temperature
The specific properties of commonly used refrigerants are described below.

R134a
R134a is used in medium temperature refrigeration, chillers, and automotive air conditioning. The application range is approximately +20 °C to –20 °C. R134a was introduced as the most suitable replacement for R12.

The HFC blends are designed as replacements for R22 and R502, since no single-compound synthetic refrigerant has comparable properties. R502 is an azeotropic blend with properties similar to those of a single-compound refrigerant. It is mainly being replaced by zeotropic HFC blends.

R404A and R507
These are HFC blends intended to replace R22, primarily for medium- and low-temperature refrigeration. The application range is approximately –5 °C to –45 °C. R404A is a zeotropic ternary blend, while R507 is a binary azeotropic blend.

R407C
This a ternary zeotropic blend intended to replace R22, primarily in air conditioning and heat pump equipment. The application range is approximately +10 °C to –15 °C. It is popular due to its good match with the pressure and refrigeration capacity characteristics of R22.

R410A
This is a binary HFC blend that at present is primarily used as a replacement for R22 in new air conditioning and heat pump systems. The application range is approximately +10 °C to –45 °C. Additionally R410A has been used successfully in industrial applications down to -60°C.

This refrigerant offers significant cooling capacity, but at the price of high system pressure, so the cooling system and the various components must be designed for high pressure. As a consequence, R410A cannot be used for retrofits. The use of R410A for air conditioning is growing rapidly. R410A is also now being considered for refrigeration use. R32 is becoming a moderate GWP alternative to R410A. It is less expensive than R410A and production capacities are high. R32 is a mildly flammable refrigerant and must be handled according to this.

Chemical properties
HFCs are much more polar than CFCs and HCFCs due to their different molecular structures. As a result, they are not miscible with non-polar oils such as mineral oils and alkyl benzene. In applications using an HFC and the appropriate refrigeration oil, issues related to compatibility should be taken very seriously. This involves the polarity of the HFC refrigerant and the refrigeration oil, their ability to affect the characteristics of materials, and the inability to hold impurities in solution.
Refrigeration oils

• HFCs are miscible with the following oils:
  • POE (polyol ester)
  • PAG (polyalkylene glycol)
  • PVE (polyvinyl ether)

POE is the most commonly used refrigeration oil for HFCs, with PAG being used primarily in mobile air conditioning systems. PVE is receiving increasing interest for applications involving scroll compressors.

• If additives are needed, commonly known types of additives, such as antioxidants and wear inhibitors developed for other industries, are used. Many of these additives work best in combination with nonpolar or low-polarity base oils such as mineral oils, alkyl benzene, and PVE. Some additives also work well with POE.

Materials

If systems are operated properly and moisture content is kept low, the formation of organic acids can be avoided. Consequently, most metallic materials can be used without problems. Plastic materials, elastomers, and permissible process fluid residues should be chosen carefully. The most commonly observed compatibility problems are related to corrosion protection oils, drawing lubricants, release agents, and components released by elastomers or plastics.

Economic aspects

The price of HFCs is presently low in most countries because it does not reflect their environmental impact (GWP). A number of countries are considering or have already implemented a tax on HFCs that reflects their GWP.

HFCs presently offer the lowest initial cost in most applications, due to relatively low pressures and the absence of flammability issues.

Applications

HFCs are presently used in all refrigeration and air conditioning applications. With the increased focus on leaks (especially in large distributed systems), chiller applications with HFCs are becoming more and more popular, especially in Europe and the USA. HFC chillers are typically used in:

• Food/retail sector
• Industrial refrigeration (high temperature and medium temperature applications)
• Air conditioning

In certain applications such as supermarket refrigeration, secondary systems with HFCs can significantly reduce the direct impact on the environment. The drawback of the secondary system is lower efficiency due to lower suction pressure and the power required to run the pumps.

General properties

The following types of hydrocarbons are commonly used as refrigerants:

- R290 Propane
- R600a Isobutane
- R1270 Propylene

A number of other hydrocarbons, such as blends containing ethane, propane or butane, are also used as refrigerants.
Propane has been discussed since the late 1980s as a replacement for CFCs and HCFCs. It has a long history in refrigeration and is thus an interesting candidate. However, its flammability has limited its use. While isobutane (R600a) was introduced in household appliances in Western Europe from the start of CFC phase-out, R290 was introduced later and replaced R134a, R22 or R404A in some appliances.

**Efficiency**
Hydrocarbons have excellent thermodynamic properties, and in this respect they are as good as or better than HCF or HCFC refrigerants in most applications.

**Safety**
Hydrocarbons are highly flammable and must be handled with care. If they are used responsibly, hydrocarbons can be employed in a variety of refrigeration and air conditioning applications. In order to ensure safety, hydrocarbon applications are governed by various international, regional and national standards and legislation. Hydrocarbons can only pose an explosion risk if the concentration is between the lower and upper explosion limits (LEL andUEL). As a rule, in the event of leakage in domestic appliances (refrigerators and freezers) with a charge less than 150 g, the concentration never rises above 20% of the LEL.

<table>
<thead>
<tr>
<th></th>
<th>R 600a</th>
<th>R 290</th>
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</thead>
<tbody>
<tr>
<td>Lower explosion limit</td>
<td>(LEL) 1.80%</td>
<td>1.70%</td>
</tr>
<tr>
<td></td>
<td>approx. 38 g/m³</td>
<td>approx. 37 g/m³</td>
</tr>
<tr>
<td>Upper explosion limit</td>
<td>(UEL) 8.50%</td>
<td>9.50%</td>
</tr>
<tr>
<td></td>
<td>approx. 203 g/m³</td>
<td>approx. 177 g/m³</td>
</tr>
<tr>
<td>Minimum ignition</td>
<td>494 °C</td>
<td>470 °C</td>
</tr>
</tbody>
</table>

The necessary safety precautions and system design depend on the refrigerant charge. Most hydrocarbons are non-toxic, with the main safety risk coming from their flammability, although gaseous hydrocarbons are heavier than air and will displace air in lungs. Only authorised persons certified for the installation and maintenance of refrigeration systems containing flammable refrigerants are allowed to carry out installation and maintenance.

**Environmental impact**
Hydrocarbons belong to the group of natural refrigerants and have zero ODP and negligible GWP. As a rule, hydrocarbons are by-products from the petrochemical industry.

**Pressure and temperature**
The refrigeration properties of hydrocarbons, such as pressures, pressure ratios and discharge temperatures, are quite similar to those of HCFCs or HFCs in many respects.

**Chemical properties**
The most commonly used hydrocarbons (propane and isobutane) are compatible with standard refrigeration materials and oils. One exception is propene (propylene), which is not compatible with neoprene. Consequently, special O-rings must be used with this refrigerant.
Economic aspects
The relative cost of a system using hydrocarbons largely depends on the application. In domestic and light commercial applications, the cost of the system is similar to that of systems with HFCs. In commercial and industrial refrigeration applications, systems with HCs tend to be relatively expensive due to the need for explosion-proof enclosures for electrical equipment, though for chillers placed outdoors the added cost for safety is more modest.

Typical applications
Typical applications for hydrocarbons are:
• Domestic refrigerators and freezers
• Bottle coolers
• Ice cream freezers and commercial freezers
• Commercial refrigerators
• Beer coolers
• Beverage dispensers
• Dehumidifiers
• Heat pumps
• Supermarket refrigeration (in combination with secondary cooling or as a high temperature stage in a cascade CO₂ system)

General properties
Carbon dioxide (CO₂, R744) is chemically inert and environmentally benign, but it does present some challenges in the design of a refrigeration system. As shown in Table 1, CO₂ has several unique properties that must be taken into account when designing a CO₂ system.

Efficiency
Although the theoretical efficiency of CO₂ is relatively low, in practice many CO₂ systems deliver very good performance. The main reasons for this are better heat exchange (lower temperature differences in evaporators and condensers), the possibility of operating with a very low condensing pressure in the winter (in case of transcritical systems), and very low pumping power when CO₂ is used as a secondary fluid. In certain cases, CO₂ systems must be more complex in order to achieve the same efficiency as HFC systems. The efficiency of systems with CO₂ depends more on the application and the climate than with other refrigerants.

Safety
Safety with CO₂ can be divided into two aspects: the safety of CO₂ as a gas and the safety of CO₂ systems due to high pressure.
CO₂ is classified as a non-toxic and non-flammable fluid. Its atmospheric concentration is approximately 0.04% by volume, and it has a relative density of 1.55. Although CO₂ is not toxic and is directly involved in respiration processes, it can be dangerous at high concentrations. Adverse effects may be experienced with atmospheric CO₂ concentrations above 3%, starting with hyperventilation. Consequently, precautions must also be taken with CO₂, and it is important to install gas detectors in at least the machine room and the cold room.
The high pressure of CO₂ must be taken into account in the system design (standstill systems, safety valves, and components rated for high working pressures).
As CO₂ has only recently come back into use as a refrigerant, it is important for service technicians and site personnel to be trained to handle it properly.

Environmental impact
From an environmental perspective, CO₂ is a very attractive refrigerant. It is a natural material with zero ODP and a GWP of 1. It is a naturally occurring substance and abundant in the atmosphere.
Pressure and temperature

CO₂ is a high pressure refrigerant. The operating pressure of CO₂ is high and typically lies between 30 and 50 bar (between 90 and 140 bar for transcritical systems). 1 bar of pressure drop in the CO₂ working range corresponds to 1 degree K, which means that line losses are very low.

At the same time CO₂ has a low compression pressure ratio (20 to 50% less than HFCs and NH₃), which improves volumetric efficiency.

The triple point and critical point of CO₂ are very close to the working range. The critical point may be reached during normal system operation. During system service, the triple point may be reached, as indicated by the formation of dry ice when liquid containing parts of the systems are exposed to atmospheric pressure.

Special procedures are necessary to prevent the formation of dry ice during service venting.

CO₂ has a high volumetric capacity. With evaporation temperatures in the range of –55 ºC to 0 ºC, the volumetric performance of CO₂ is, for example, four to twelve times better than that of NH₃, which allows compressors with smaller swept volumes to be used.

Chemical properties

Material interactions: R744 does not react with common metals or with Teflon®, PEEK, or neoprene components. However, it reacts with elastomers and can cause swelling with butyl rubber (IIR), nitrile rubber (NBR), and ethylene–propylene materials (EPDM).

The density of liquid CO₂ is about 1.5 times that of NH₃, resulting in higher mass charge in evaporators (such as large plate chillers) in large industrial systems. Higher density means higher oil circulation as well, which in turn requires effective oil separators.

Economic aspects

CO₂ is a by-product in a number of industries, so the price of CO₂ is very low. CO₂ systems tend to be more expensive than traditional systems due to higher pressures (in transcritical systems) or increased complexity (in both transcritical and subcritical systems). As the number of CO₂ installations increases, the cost approaches the cost of the reference systems (using HFCs).

Secondary CO₂ systems, especially in industrial refrigeration, may be less expensive to build than their glycol counterparts and thus offer lower initial and life-cycle costs.

Applications

Unlike most other refrigerants, CO₂ is used in practice in three different refrigeration cycles:

- Subcritical (cascade systems)
- Transcritical (CO₂-only systems)
- Secondary fluid (CO₂ used as a volatile brine)

The technology used depends on the application and the intended location of the system.

There are several applications where CO₂ may be attractive and is already used today:

- Industrial refrigeration. CO₂ is generally used in combination with ammonia, either in cascade systems or as a volatile brine.
- Food/retail sector.
- Heat pumps.
- Transport refrigeration
**General properties**
Ammonia (NH₃) is a well known refrigerant. It is especially popular in large industrial plants, where its advantages can be fully utilised without compromising the safety of the personnel working with the refrigeration installation. Ammonia has very favourable thermodynamic properties. In a wide range of applications, it outperforms synthetic refrigerants such as R22, which is one of the most efficient HCFCs. However, it has a number of drawbacks that prevent it from being used in commercial refrigeration. These drawbacks include material compatibility, toxicity, and flammability.

**Efficiency**
Ammonia is a highly efficient refrigerant, with a theoretical efficiency slightly higher than that of R134a or propane. Ammonia systems perform even better in practice due to better heat transfer properties.

**Safety**
Due to the toxicity and flammability of ammonia, installations using ammonia are governed by national regulations to ensure that safety is not compromised. Even so, there is pressure on ammonia installations to reduce charge levels, especially in case of systems in populated areas. One way to do this is to use ammonia as a refrigerant in combination with CO₂ as a volatile brine (for medium or high temperatures) or in cascade applications (for low temperatures). Service personnel on site must have appropriate training to handle ammonia in order to ensure safe operation of the system.

**Environment**
Ammonia is a natural refrigerant. It has zero ODP and zero GWP. In combination with its efficiency, it is one of the most environmentally friendly refrigerants.

**Pressure and temperature**
The operating pressures of ammonia are comparable to those of other common refrigerants (HFCs and HCAs). Ammonia has a relatively high normal boiling point (–33.3 °C). Ammonia has high volumetric capacity, so ammonia lines are smaller than HFC lines, although suction lines are larger than that of CO₂.

**Chemical properties**
Ammonia is compatible with all common materials except copper and brass. This imposes certain limitations on system design. First, only welded steel lines can be used. Second, it is necessary to use either open compressors or compressors with special motor coatings. Ammonia is not miscible with common oils. In addition, ammonia is lighter than oil, which makes oil return systems fairly simple.

**Economic aspects**
Ammonia is a very inexpensive and abundantly available refrigerant. Ammonia installations tend to be relatively expensive due to the requirement for steel tubing, open compressors, and the installation of a number of safety devices, such as gas detectors.
Applications

There are ongoing efforts to develop low-charge ammonia systems in order to utilise the beneficial thermodynamic and environmental properties of ammonia.

These efforts include:
- Development of low-charge systems and associated control algorithms
- Optimisation of heat exchangers
- DX systems
- Cascade systems or combination with secondary systems with CO₂ as a brine

Today ammonia is primarily used in industrial refrigeration applications:
- Distribution cold stores
- Freezing tunnels
- Breweries
- Food processing plants (slaughterhouses, ice cream factories, etc.)
- Fish trawlers

Technologies

It is clear that there is no ideal refrigerant. Some refrigerants have adverse effects on the environment, while others pose safety risks. Other requirements for refrigerants include economic acceptability and energy efficiency. Danfoss assesses refrigerant options for various applications and develops technologies that can address the challenges of the best alternative. Some of the proposed solutions are already commercially available, so the more environmentally friendly systems can already be built now.

- **Micro channel heat exchangers.** Danfoss formed a joint venture with Sanhua in order to develop a range of micro channel heat exchangers for the refrigeration industry. Micro channel heat exchangers made from aluminium need only a small refrigerant charge (thus reducing environmental impact and improving cost effectiveness), and they are very compact and light compared with conventional fin and tube heat exchangers. MCHX technology was developed by the automotive industry in the 1980s. It has been used more and more in air conditioning systems since 2004, and it is now starting to be used in the refrigeration industry as well. Micro channel heat exchangers can be used with conventional refrigerants such as HFCs and with natural refrigerants, including ammonia, hydrocarbons, and even CO₂ in transcritical systems.

- **Direct weld components and valve stations for industrial refrigeration systems.** Danfoss has developed a range of direct weld control valves and valves stations (ICV and ICF types) for industrial refrigeration applications. These products won innovation awards in 2005 and 2007, and they have revolutionised the traditionally conservative industrial refrigeration segment. The valves reduce the number of flanged and welded connections in the system, which dramatically reduces the chance of leaks. In addition, the components are designed for higher pressures, so they can be used in subcritical CO₂ systems.

- **Danfoss solution for DX ammonia applications.** A combination of a motorised valve (ICM) and an electronic controller (EKC 315A) together with a pressure sensor and a temperature probe helps meet the challenge of using ammonia in compact DX chillers. The system has a very short response time, and it maintains a very stable, low superheat level under all load conditions, thereby minimising the risk of liquid flow back to the compressor and maximising energy efficiency.
Compact ammonia chillers with plate evaporators in combination with a secondary circuit can be used in a wide range of traditional industrial refrigeration applications, as well as in other segments such as commercial air conditioning and supermarket cooling. DX ammonia chillers can also be used as high temperature stages in a cascade systems with CO₂.

**B. Improving efficiency and meeting special control challenges**

- **Gas cooler control systems.** The biggest challenge in transcritical CO₂ systems is high pressure control. Danfoss can provide an integrated solution for gas coolers, including a set of valves, sensors, and an electronic controller. This solution optimises the efficiency of CO₂-only systems by maintaining the high pressure at the optimum level under all ambient conditions. This system can handle pressures as high as 140 bar, making it suitable for heat pump applications as well. The second function of the system is to regulate the pressure in display cabinets, since they are typically designed for pressures not exceeding those used with R410A (40 to 45 bar). This system is the first of its kind on the market and a major step toward adopting CO₂ in supermarket applications.

- **ADAP-KOOL® control system and variable-speed drives.** Danfoss has developed fully integrated electronic control systems that manage, monitor and optimise the performance of commercial refrigeration systems for supermarkets and/or industrial refrigerated processing installations. ADAP-KOOL® combines specially designed refrigeration controllers and valve combinations and utilises adaptive control algorithms for liquid injection to evaporators, while compressor and condenser pack controllers are used to ensure an efficient and effective energy optimisation strategy and handle overall system management. Extension functions enable continuous monitoring and status reports on refrigerant gas leak detection (to facilitate end user compliance, such as with the F-Gas Regulation), energy consumption and efficiency, product temperature status summaries to support compliance with food hygiene (HACCP) requirements, and overall system supervision and maintenance.

- **Compressors for hydrocarbons.** Danfoss is one of the market leaders in producing light commercial compressors for hydrocarbons. In addition to a product line of household compressors that work with R600a, Danfoss has introduced compressors for light commercial applications, such as integral ice-cream cabinets, using propane as a refrigerant.

- **Components for subcritical CO₂ applications.** Danfoss has a full range of valves and controls for commercial and industrial CO₂ cascade systems. Although the products for commercial refrigeration applications are the same as for R410A, a separate industrial refrigeration product line has been developed specifically to meet CO₂ requirements.

- **Components for transcritical CO₂ applications.** The challenge with transcritical CO₂ systems is even higher than with subcritical systems because the high pressure level is around three times as high as the pressure level of any other refrigerant used in commercial applications. Danfoss has already developed a high pressure controlled valve (ICMTS) and is working on expanding its range of products.

**C. High pressure. High pressure is primarily an issue with CO₂ systems, both transcritical and subcritical**
Case stories

A. CO₂: CO₂-only supermarket cooling system

In cooperation with several partners, Danfoss collaborated with a discount supermarket chain in Denmark to design a CO₂ transcritical refrigeration system with efficiency equal to or better than that of existing HFC systems. The main objective was to design and build a reliable and energy efficient system. This system has been in operation since the 1st of March 2007, and approximately 50 systems were installed in the first year. The system is designed and built as a transcritical CO₂ booster system with gas bypass from the intermediate pressure receiver to the suction side of the high pressure compressors.

Measurements have been made in the laboratory as well as in the field in order to compare the energy consumption with the energy consumption of other, similar sized systems operating under similar conditions. The design with a booster and gas bypass has proven to be very efficient and reliable. The system was built using standard components. The energy consumption of the system has been monitored and compared with that of other comparable systems. The conclusion of the energy study is that the energy consumption of this system is lower than that of a similar R404A system. This conclusion has been confirmed by similar studies carried out for moderate climates. The project was sponsored by the EU within the scope of the LIFE projects, and it was selected as one of the five best projects in 2008 and 2009.

B. Hydrocarbon: SolarChill

The overall objective of the SolarChill project is to help deliver vaccines and refrigeration to the rural poor. To achieve this objective, the SolarChill project has developed – and intends to make freely available – a versatile refrigeration technology that is environmentally sound, technologically reliable, affordable, and able to use various power sources. In addition to the public power grid, it can operate on solar power, wind power, biomass power, or diesel power. SolarChill uses hydrocarbon Greenfreeze technology, which utilises hydrocarbons for the insulation foam and the refrigerant cycle and thus avoids reliance on fluorocarbon compounds, which deplete the ozone layer and have high global warming potentials. Danfoss supplied direct-current isobutane compressors for the project.

C. Ammonia: NH₃/CO₂ chilled coldstore in Canada

Flanagan Foodservice is one of the leading distribution service companies in Kitchener, Ontario (Canada). For over 30 years, Flanagan Foodservice has provided a ‘customized approach to distribution’, enabling sound growth and expansion of their business. The company decided to construct a 5,000 m² cold storage facility featuring state of the art CO₂ refrigeration technology.

A dual-temperature ammonia / CO₂ brine packaged system refrigerates a 4,200 m² freezer area at –15 °C with 360 kW of cooling capacity and a 500 m² ice cream freezer (supplied by Mayekawa Canada) at –29 °C with 130 kW of cooling capacity. Danfoss supplied its well known ICF valve stations, which feed CO₂ to the evaporators and the flooded shell and tube NH₃/CO₂ heat exchangers, as well as the variable-frequency drives and pressure transmitters for the NH₃ screw compressors and CO₂ pumps. The ICM motorised valves in the ICF assembly play a key role in maintaining a stable liquid supply.

The Danfoss VLT variable-frequency drive enables a harmonious balance in load control of the NH₃/CO₂ system, thereby meeting the challenges of CO₂ flow and thermodynamics.
Annex 1. Refrigeration properties

<table>
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<tr>
<th>Refrigerant</th>
<th>R22</th>
<th>R134a</th>
<th>R404A</th>
<th>R410A</th>
<th>R717 (NH₃)</th>
<th>R744 (CO₂)</th>
<th>R290 (propane)</th>
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</tr>
</tbody>
</table>

* Some refrigeration applications  
** Heat pumps, secondary media, and some refrigeration applications  
*** Higher taxes (Nordic countries)

Table 1. Properties of various refrigerants

Annex 2. Legislation

**Montreal Protocol (global)**
Developed (non-Article 5) countries committed to reducing the production and consumption of HCFCs by 75% by 2010 and by 90% before 2015, with final phase-out in 2020. 
Developing (Article 5) countries committed to reducing the production and consumption of HCFCs by 1% by 2010, by 35% before 2020, and by 67.5% by 2025, with final phase-out in 2030. In addition, a small percentage (2.5%) of the original baseline amount will be permitted in developing countries until 2040.

**MAC Directive (EU)**
This directive bans the use of any refrigerant with a GWP above 150 in air conditioning systems in motor vehicles starting from:
- 1 January 2011 for new models of existing vehicles;
- 1 January 2017 for all new vehicles.
R134a, currently the most common refrigerant in MACs, has a GWP of 1410 and is thus affected by the ban as well. The directive does not cover other applications.

**F-Gas Regulation (EU)**
The F-Gas Regulation entered into force in June 2006. Its main objective is to contain, prevent and reduce emissions of fluorinated greenhouse gases (F-gases) with high global warming potential. More specifically, the regulation addresses the containment, use, recovery and destruction of F-gases; the labelling and disposal of products and equipment containing those gases; the reporting of information on and the control of uses of those gases; prohibitions on placing products and equipment on the market; and the training and certification of service personnel and operators involved. The primary impact of the regulation is on systems containing 3 kg or more refrigerant. The F-Gas regulation will be reviewed in 2011.

**Other local initiatives**
A number of countries and regions have already taken steps to promote low-GWP alternatives. Such steps include a cap on the refrigerant charge (Denmark), taxation of high-GWP refrigerants (Nordic countries), and subsidies for systems that use natural refrigerants (Germany and Quebec (Canada)).
Annex 3. Impact of direct leakage as a function of the leakage rate

Example:
The following example can serve to illustrate the relationship between direct and indirect impacts.

Typical refrigerant plant in a medium sized supermarket:
• Store size: 1000 to 1500 m²
• Refrigerant: R404A
• Refrigerant charge: 250 kg
• Cooling capacity: 100 kW
• Energy consumption: 252,000 kWh/year
• Service life: 10 years
• GWP: 3922
• Operating time: 19 hours per day
• Recovery/recycling: 90%

CO₂ emissions from electricity production
Country A (fossil fuels): 0.8 kg CO₂ per kWh
Country B (hydro and wind power): 0.04 kg CO₂ per kWh

Figure 6: Relationship between the direct and indirect impacts of the refrigeration plant
The Danfoss product range for the refrigeration and air conditioning industry

Danfoss Refrigeration & Air Conditioning is a worldwide manufacturer with a leading position in industrial, commercial and supermarket refrigeration as well as air conditioning and climate solutions.

We focus on our core business of making quality products, components and systems that enhance performance and reduce total life cycle costs – the key to major savings.

Controls for Commercial Refrigeration  Controls for Industrial Refrigeration  Electronic Controls & Sensors

Industrial Automation  Household Compressors  Commercial Compressors

Sub-Assemblies  Thermostats  Brazed plate heat exchanger

We are offering a single source for one of the widest ranges of innovative refrigeration and air conditioning components and systems in the world. And, we back technical solutions with business solution to help your company reduce costs, streamline processes and achieve your business goals.