

Trends and Perspectives in Supermarket Refrigeration

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Abstract

This paper describes the latest trends and perspectives in supermarket refrigeration. Focus is on improving energy efficiency, reducing refrigerant charge and using natural refrigerants. Several alternative systems such as indirect, distributed, cascade and two-stage are described. Measures for refrigerant charge reduction and energy consumption are presented.

1. Introduction

Refrigeration used to be very straightforward: Our forefathers simply used natural ice to cool their foodstuff. Starting in the mid 19th century, mechanical equipment was used to produce the ice needed for cooling food. Soon the cooling was performed directly on the food without the intermediate matter ice. Until the 1930s all refrigerants used in refrigeration systems were naturally occurring substances such as ammonia, carbon dioxide, propane and sulphur dioxide. Due to the safety concerns related to these fluids, refrigeration was mainly limited to large refrigeration plants. It was thanks to the benefits of the so called “safety refrigerants” CFCs introduced in the 1930s that refrigeration systems became very popular. Supermarket refrigeration was very simple with these fluids. Most central systems operated on R22 or for medium temperature also R12. Plug-in units and many condensing units were running on R12. Due to their ozone depleting potential, these refrigerants are now being replaced by a new class of synthetic fluids: the HFCs. For commercial refrigeration systems R134a and R404A are the most popular HFC fluids. Although safe to the local environment (nonflammable and nontoxic) they do have one big drawback: They have global warming potentials (GWP) up to several thousand times higher than carbon dioxide and are therefore included in the Kyoto Protocol, i.e. their emissions are to be reduced as far as possible.

Man made global warming is the big challenge for our society today. Refrigeration systems usually contribute by two ways:

- direct emissions of potent greenhouse gases such as CFCs, HCFCs and HFCs
- indirect emissions due to energy consumption

The contribution of commercial refrigeration to global warming can therefore be reduced by:

- reducing direct emissions of greenhouse gases; this can be achieved by
 - extremely tight refrigeration systems
 - reduced refrigerant charge
 - refrigerants without or with very low GWP
- reducing energy consumption
- using renewable energy

This paper will describe different ways of implementing these measures.

2. Reducing direct emissions of greenhouse gases

2.1 Extremely tight refrigeration systems

Typical German supermarket refrigeration systems have leakage rates between 5 and 10 %, i.e. 5 to 10 % of the total system charge is emitted to the atmosphere every year. Over 30 % of all leaks stem from mechanical joints. One attempt to reduce leakage rates is therefore to avoid mechanical joints as far as possible and use welding or brazing instead especially in hidden or inaccessible pipes. Another major leak source is failures of pipes due to vibration. Decoupling of compressors from the rest of the plant is therefore very important.

Many larger leaks start as very small leaks which grow over time. Regular maintenance with leak testing is therefore of key importance for tight systems. The European Regulation (EC) No. 842/2006 on certain F-Gases (e. g. HFCs) requires stationary refrigeration and air conditioning systems to be checked regularly depending on the systems amount of refrigerant:

- At least annually for applications with 3 kg or more of F-gases (unless the equipment is hermetically sealed, in which case this goes up to 6kg)
- At least once every six months for applications with 30 kg or more of F-gases
- At least once every three months for applications with 300 kg or more of F-gases
- Leakage detection systems must be installed on applications with 300 kg or more of F-gases, and when these are in place, checking requirements are halved
- If a leak is detected and repaired, a further check must be carried out within one month to ensure that the repair has been effective

Time will show whether this F-Gas Regulation will have an impact on leakage of stationary refrigeration systems.

Another approach is used by the Danish and Norwegian Governments: They impose a high greenhouse gas tax on all refrigerants. This tax is for R404A in Denmark approximately 50 €/kg and in Norway approximately 80 €/kg! Consequently these high prices encourage every user to keep his system tight, especially if the charge is in the order of several hundred kg as for multiplex systems in a larger supermarket.

2.2 Reduced refrigerant charge

In many refrigeration systems, most of the refrigerant is contained in the heat exchangers, especially in the condenser. Most central multiplex supermarket refrigeration systems use round tube and fin heat exchangers as evaporators and condensers. The typical tube diameter is 15 mm. The refrigerant charge inside the heat exchangers can be reduced by up to 80 % using minichannel heat exchangers well known within the automotive air conditioning industry. The automotive air conditioning industry has developed from large round tube condensers (ø 12 mm) in the 1970s over small round tubes (ø 7 mm) to Multi-Port-Extruded (MPE) all aluminum brazed heat exchangers with a fourfold increase in heat transfer coefficient on the refrigerant side together with a tremendous decrease in refrigerant charge. This development is yet to take place in stationary refrigeration and air conditioning equipment. One major American air conditioning manufacturer already offers its chillers with minichannel condensers with noticeably reduced refrigerant charge. It is just a matter of time until the commercial refrigeration market will follow.

Another possibility to reduce refrigerant charge is the application of indirect refrigeration systems, which is very common in Sweden where refrigerant charge per system has been limited to some 30 or 40 kg for many years. Typically, propylene glycol is used as liquid secondary refrigerant in the medium temperature (MT) loop. Glycol becomes too viscous for the low temperature (LT) loop. Attempts have been made using different potassium formate and Potassium acetate solutions for LT applications. Where MT secondary loop systems can achieve energy efficiencies quite similar to direct expansion systems, using a liquid secondary fluid in a low temperature application usually increases the energy consumption. Therefore systems were developed using carbon dioxide as a volatile secondary refrigerant. These systems show good energetic performance. Lately attempts have been made to establish the carbon dioxide loop as a fully integrated refrigeration system, i.e. build it as a cascade underneath the MT system, see figure 1. Although the MT primary refrigeration system is confined to the machinery room the LT system uses conventional direct expansion technology. Due to the potentially high system pressure of the carbon dioxide loop during stand still, special precautions have to be taken to avoid excessive pressures. In a typical supermarket system which operates 24 hours a day, seven days a week CO₂ is simply blown off to the atmosphere if pressures exceed the maximum allowable pressure during stand still.

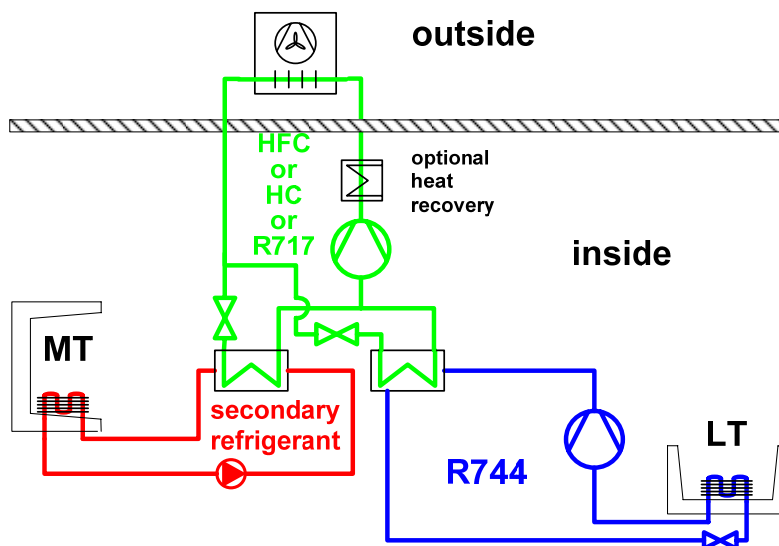


Figure 1: Secondary loop MT refrigeration system also called indirect refrigeration system. The low temperature loop is build as a cascade system to the MT system.

Employing a propylene glycol system for the MT cooling has a few advantages as compared to direct expansion systems:

- First of all reduced primary refrigerant charge; reductions up to 80 to 90 % are possible.
- Factory assembly of the primary refrigeration system with higher quality and lower risk for leaks.
- Reduction in oil charge of the much smaller internal volume primary refrigeration system.
- Possibility for using flammable or toxic refrigerants as primary refrigerant well confined to the machinery room. Air cooled roof top condensers are legally feasible in some countries, e.g. Denmark even with flammable or toxic refrigerants.

- Easy utilization of heat recovery when using a water cooling loop for the condenser, as is often the case in Denmark or Sweden in order to reduce the primary refrigerant charge as much as possible.
- More stable air temperature and air humidity in display cases due to lower temperature fluctuations of the glycol loop and higher surface temperatures of the heat exchangers inside the cabinets. Higher air humidity results in less shrinkage of the food stuff.
- Fewer defrost cycles.
- Possibility of constructing the secondary loop in plastic piping and fittings which can be cheaper than copper piping traditionally used with direct expansion systems.

Especially in the USA the use of distributed systems is gaining a considerable market share, see figure 2. In 2006 15 % of all new supermarket refrigeration systems in the USA were of the distributed type [Garry2007]. Losses in suction pipes can be greatly reduced due to the compact design of the individual compressor racks which are encased in noise reducing boxes and placed inside the store. Experience from American supermarkets therefore shows 5 to 8 % lower energy consumption [Walker1999] and about 30 to 50 % lower refrigerant charge [Baxter2007] than for comparable R404A direct expansion systems.

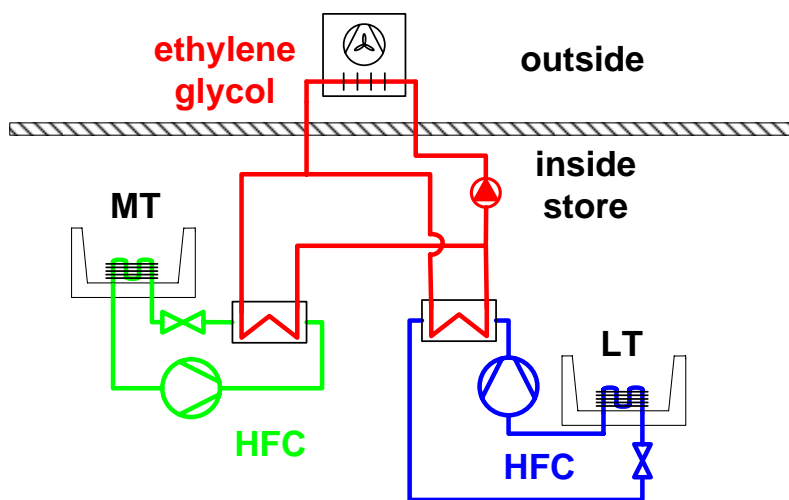


Figure 2: Distributed System – compact multiple compressor arrangements are housed in noise reducing boxes and placed close to the refrigerated cabinet inside the store. Condenser heat is rejected to a water loop which again rejects its heat via a cooler to the outside air unless used for heating the building.

2.3 Refrigerants without or with very low GWP

Another possibility to reduce direct emissions of greenhouse gases is to use refrigerants with negligible GWP. But GWP is not the only criterion when selecting a suitable refrigerant. Among others the following items are of interest:

- Zero ODP
- Good thermodynamic properties, among others
- Good heat transfer
- Low pressure ratio

- High volumetric refrigeration capacity
- Non-corrosive
- Oil compatibility
- Stable
- Non-toxic
- Non-flammable
- Available
- Cheap

Table 1 shows the properties of several refrigerant candidates suitable for commercial refrigeration systems.

Table 1: Properties of various refrigerants for commercial refrigeration systems.

	GWP	Flam- mability	Toxicity	Price of Refrigerant	Price of System	Theoretica l system efficiency
HFCs	high	No	no	moderate	low	good
Hydrocarbons	low	Yes	no	low	low to medium	good
Carbon Dioxide	low	No	only at high concentr.	low	medium	medium
Ammonia	low	can be ignited	yes	low	medium to high	good

From a technical point of view the vapour pressure curve is a rather important characteristic. Figure 3 shows the vapour pressure curves for several refrigerants for commercial refrigeration systems. It can easily be seen that one refrigerant is quite different from all the others: R744 – carbon dioxide. System pressures are much higher with R744 than with any other refrigerant shown. In addition, the critical temperature of R744 is only 31 °C. An air cooled R744 system will therefore during hot summer days not be able to condense the refrigerant in the condenser. The system COP of such a system without system modifications will be lower than that of a conventional system with condensation at all times.

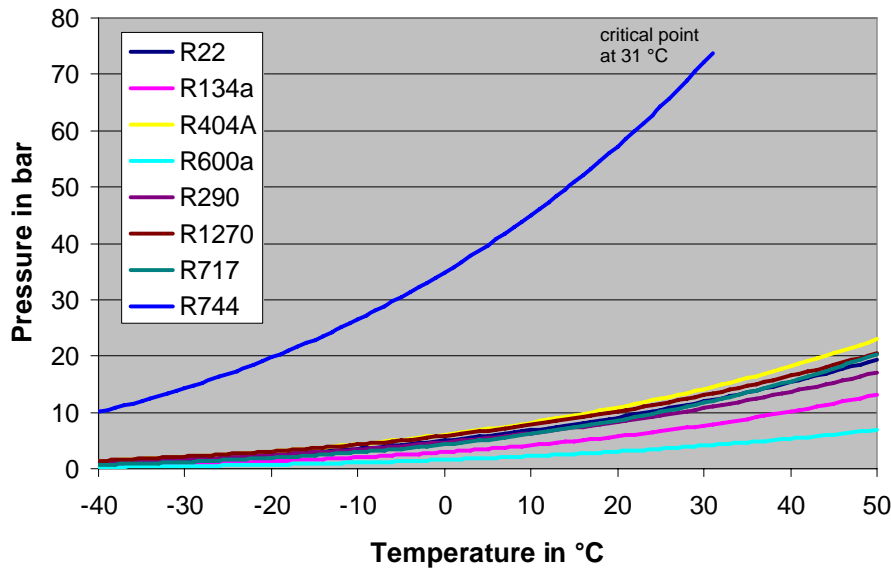


Figure 3: Vapour pressure curve of some common commercial refrigerants. The graph shows the corresponding vapour pressure for any given temperature, e.g. R744 (carbon dioxide) boils (evaporates) at $-20\text{ }^{\circ}\text{C}$ at a pressure of 20 bar or condenses at a pressure of 60 bar at a temperature of $22\text{ }^{\circ}\text{C}$.

A possibility for using carbon dioxide whilst ensuring it always operates well below its critical temperature is its application within a cascade system, as described above. The maximum operating pressure of such systems is typically limited to 40 bar. Throughout the last couple of years many components have been developed suitable for that pressure range e.g. expansion valves, control valves, filter/driers, heat exchangers and compressors. Such R744 cascade systems are now seen as state of the art by many European supermarket refrigeration equipment manufacturers [Sienel2007].

But also systems condensing CO_2 at ambient air temperatures are gaining popularity in Europe and slowly in the rest of the world. The typical direct expansion system for MT and LT applications uses a two stage compression for the LT side as shown in figure 4. Pressure inside the store is usually limited to 40 bar and the higher pressures (up to 120 bar during summer time) are kept in the machinery room and the outside heat exchanger. Up to now over 70 such stores have been built in Europe by several companies. Energy efficiency is usually better than for a comparable R404A system during outdoor temperatures below approximately $12\text{ }^{\circ}\text{C}$, equal to R404A between 12 and $26\text{ }^{\circ}\text{C}$ and slightly lower at higher ambient temperatures [Sienel2007].

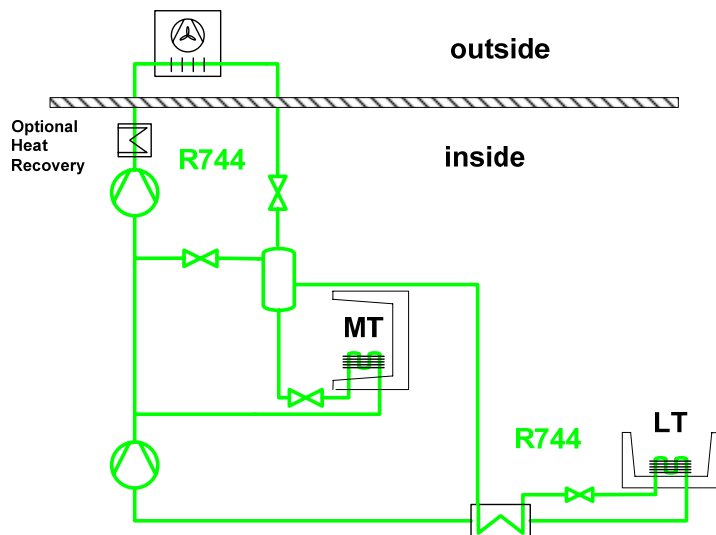


Figure 4: Central multiplex system with carbon dioxide as refrigerant.

Flammable (hydrocarbons) and toxic (ammonia) refrigerants can be used as primary refrigerant in indirect systems – see above. But hydrocarbons can also be applied direct in the store if certain safety precautions are taken. The usual standard considered is IEC 60335-2-89 which calls for a maximum charge of a flammable refrigerant of 150 g. Taking the systems internal volume and the volume-pressure product for the hermetic compressor into account, hermetic refrigeration systems up to about 1 kW refrigeration capacity are being build using propane (R290). Such systems have approximately 10 to 15 % lower energy consumption as comparable HFC-products [Jürgensen2004]. New developments also include variable speed compressors for these plug-in units which save an additional 10 to 15 % [Jürgensen2004]. Some countries try to force charge reduction in refrigeration systems. In Denmark, it is prohibited to use HFC in quantities larger than 10 kg in a single system since 1. January 2007. Sweden even has a longer record of prohibiting HFC in large quantities. As a result most Swedish supermarket refrigeration systems tend to be indirect systems.

Reducing energy consumption

Between 40 and 60 % of the electricity consumption of a typical supermarket is related to the refrigeration equipment.

The following can be done during the design and construction phase of a supermarket refrigeration system in order to reduce energy consumption:

- Glass door or lid instead of open cabinets
- Improved insulation by increased thickness or higher heat resistance
- Fan motor outside cabinet in order to avoid the heat of the motor as cooling load
- Improved evaporator fan and/or fan motor, e.g. higher efficiency fan blades or high efficiency electric motor
- Improved air flow in open multidecks such that air loss to the sales room is minimized and air infiltration from the sales room is minimized
- Infrared reflecting shades or baldachins in order to prevent heat load from shop lights and/or sun light
- Improved antisweat heaters / dew point control in order to run at lowest possible temperature

- Siphon in defrost drain rather than straight lines prone to air infiltration
- Hot gas defrost instead of electric defrost
- Speed control of compressors, pumps, fans instead of on/off operation
- Improved expansion valve, e.g. electronic expansion valves
- Expansion machine, e.g. a turbine which recovers expansion work and supplies it to the compressor
- Improved evaporator, e.g. enhanced air side or enhanced refrigerant side or minichannels – every degree centigrade higher evaporation temperature reduces energy consumption by approximately 3 %
- Flooded evaporator instead of using between 20 and 30 % of the refrigerant side surface for superheat
- Defrost on demand by for example monitoring the fan current and starting to defrost when fan current increases
- Improved lights, e.g. LEDs or high efficiency neon tubes in combination with sensors which turn off the light whenever there are no costumers
- Reduced condensation temperature – every degree centigrade reduction in condensation temperature saves approximately 3 % energy
 - Outside air temperature adjusted condensing temperature rather than constant high condensation temperature year round
 - Evaporative cooling of condenser
 - Condenser heat to ground
- Free cooling – outdoor temperatures are lower than the medium temperature in a supermarket, i.e. +5 °C, during certain times of the year and/or day in many countries
- Heat recovery and utilisation of this “waste” heat for heating purposes
- Cold storage, i.e. cooling a reservoir during night hours while the outdoor temperature is low and the condensing temperature can therefore be low too and energy consumption is reduced; the cold storage medium can be a separate tank with chilled water, an ice storage tank or simply the frozen food in the supermarket

The following can be done during operation of a supermarket refrigeration system:

- Correct loading of products in order not to disturb the air flow in the cabinet
- Air humidity in shop area should be at the lower end of the comfort range, i.e. approximately 40 % relative humidity
- Regular evaporator and condenser cleaning

Figure 5 shows the potential of some of these measures. Many of them can be combined in order to improve energy efficiency well above 50 % as compared to current design.

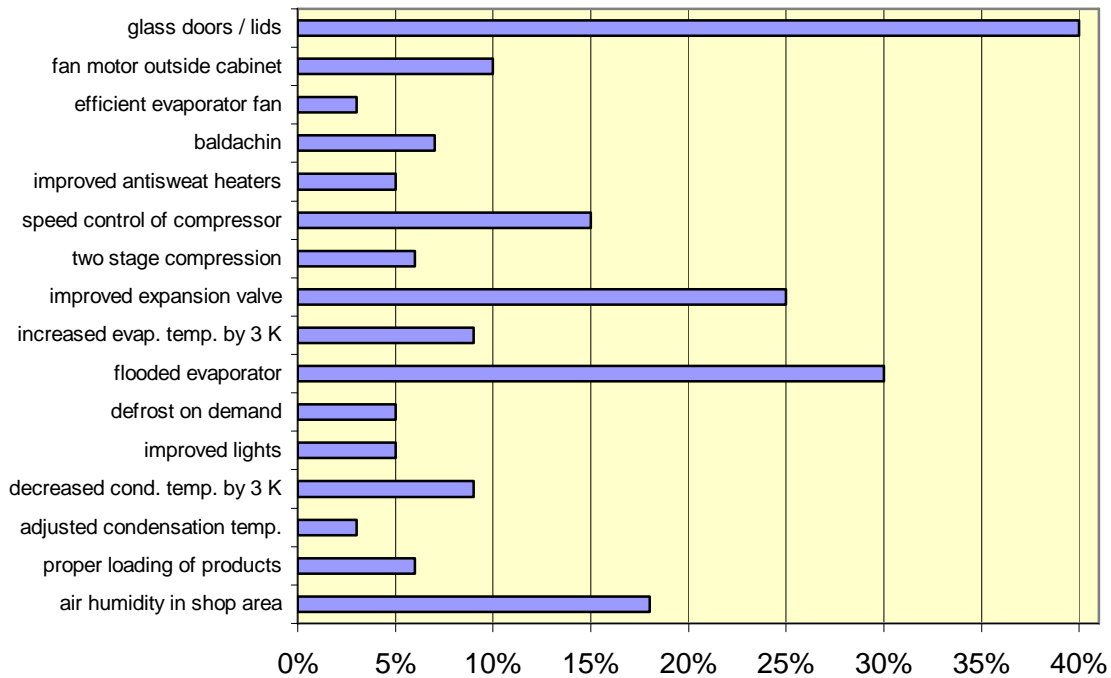


Figure 5: Energy savings by applying different measures. Many of the measures can be combined. The resulting energy savings can be estimated by multiplying individual values – NOT adding them! E.g. if speed control of compressors gives 15 % and fan motor outside cabinet gives 10 %, the resulting total would be 0.9 times 0.85 equal to 0.765 or 23.5 % total energy reduction.

Reduction of energy consumption is important because it:

- **reduces the contribution to global warming** through indirect emissions depending on refrigerant, leakage rate and refrigeration system, energy related global warming contribution varies from 50 % for a R404A multiplex system with 300 kg refrigerant charge, 10 % leakage rate and almost 100 % for a R290 plug-in freezer or a R744 central system.
- reduces the running cost and thereby **increases the profit** refrigeration accounts for 40 to 60 % of a supermarkets energy consumption; energy costs are some times in the same order of magnitude as the profit (1 to 2 % of turnover).

Using renewable energy

Supermarkets have rather large roof areas. It is therefore quite easy to establish photo voltaic systems on the roof top of a supermarket. This is done by several supermarket chains. Some install in some experimental stores also wind turbines and/or utilize ground source heat. Another possibility for the supermarket chain is to switch to a supplier of renewable energy as a few supermarket chains in Germany and the UK have done. The use of daylight by north facing windows is a simple way of reducing the need for electric lights.

Discussion

It is technically and economically feasible to build and operate supermarket refrigeration systems with reduced climate impact. This can be done in several ways as described above.

Which way is selected depends on personal preferences, the availability of components and skills as well as on the willingness to maybe pay a slightly higher system price to begin with. In many cases the higher investment can be recovered by lower operating and/or maintenance costs of improved systems.

Conclusion

- HFC can be replaced or their charge greatly reduced at acceptable cost in all applications
- Energy efficiency of such alternative supermarket refrigeration systems is at least as good as the state of the art HFC technology
- Supermarket refrigeration systems have an energy savings potential up to 50 % and more at moderate costs
- In countries with adequate laws, e.g. Denmark, Norway and Sweden, many HFC-free or HFC-reduced systems are built with good energy efficiency
- Some supermarket chains have environmental protection as their strategy and build low carbon emission supermarkets
- HFC-free plug-in units with better energy efficiency using hydrocarbon refrigerants are available up to approximately 1 kW capacity

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Nomenclature

CO ₂	Carbon Dioxide – as refrigerant also called R744
COP	Coefficient of Performance
GWP	Global Warming Potential
HC	Hydrocarbon
HFC	Hydro Fluoro Carbon
LED	Light Emitting Diode
LT	Low Temperature, i.e. cooling of frozen food usually at product temperatures around – 18 °C
MT	Medium Temperature, i.e. cooling of milk, meat and vegetables usually at product temperatures around +5 °C
NH ₃	Ammonia – as refrigerant also called R717
ODP	Ozone Depleting Potential

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