Selection of refrigerants on a per-application basis: trends

Summary

There is no general rule governing the selection of refrigerants. There are, of course, the five classic criteria: thermophysical properties, technological and economic aspects, safety and environmental factors; however, in addition to these criteria, others have to be considered: local regulations and standards and “cultural” criteria associated with professions, applications, customs and user training levels. The best approach when presenting evolution and trends is certainly the per-application approach.

The 8 following applications are analysed: domestic refrigeration, commercial refrigeration, industrial refrigeration (storage, the food industry, other industrial applications), land refrigerated transport, marine refrigerated transport, unitary air conditioning and heat pumps, water chillers, and mobile air conditioning. For each of these applications, national and global figures are displayed in order to provide an insight into the economic importance of the sector, trends in the selection of refrigerants (HFCs, ammonia, hydrocarbons, CO₂, etc.) are analysed, and finally some long-term orientations are outlined.

Introduction

There is no general rule governing the selection of refrigerants. The best approach when presenting trends is certainly the per-application approach. Eight applications are examined: domestic refrigeration, commercial refrigeration, industrial refrigeration, land refrigerated transport, marine refrigerated transport, unitary air conditioning and heat pumps, water chillers, and mobile air conditioning.

Only refrigerants which are not covered by the Montreal Protocol and European Regulation 2037/2000 will be presented.

1. Domestic refrigeration

Global production of appliances reached 83 million in 1996, including 33 million in developing countries.¹ The number of refrigeration appliances in the world is estimated at 1 billion, which represents 1 for 6 inhabitants. In France, the total is estimated at 37 million,² which represents 1.7 appliances (refrigerator and/or freezer) per household, given that there are 21.9 million households in France.³

The most widespread technology is that employing a vapour-compression cycle and reciprocating compressors. Over the years, manufacturers have designed extremely reliable systems using technologies developed specifically for refrigerators: capillary expansion devices, wire-and-tube condensers, roll-bond evaporators, etc. A refrigerator's compressor works for 100 000 hours without any problems, whereas a car engine's lifespan is approximately 2500 hours.

Absorption refrigerators (ammonia-water pair) were developed for hotels and camper vans. Kerosene refrigerators are found in areas with no power supply. Thermoelectricity is used for ice boxes in cars or camper vans. Nowadays, a refrigerating capacity of 300 W can be achieved using such appliances. This is therefore quite close to the capacity required for household refrigerators, which have refrigerating capacities of 400-500 W and electrical power input within the 100-150 W range. However, energy efficiency is far from that achieved using vapour-compression systems.

Since 1992-1994, the refrigerants used are R134a and isobutane. Experts agree that these 2 refrigerants have similar performances in terms of refrigerating capacity and energy efficiency.⁴ After being used for a
few years, the propane/isobutane mixture was abandoned, in particular because these systems proved to be noisy. Refrigerators using isobutane represent 50% of sales in Europe. In the US, all refrigerators use R134a. As leaks are very small and direct emissions represent only about 1-2% of the TEWI (Total Equivalent Warming Impact), in fact, the refrigerant has very little impact on the greenhouse effect. On the other hand, power consumption represents 98-99% of the TEWI and is therefore the dominant factor in terms of climate change. It is important to bear in mind that refrigerators consume approximately 5% of all electricity consumed in developed countries.

Insulation that reduces power consumption is particularly important. It must be noted that the mass of blowing agent in insulation represents approximately 4 times the mass of the refrigerant. Although the importance of the blowing agent is preponderant in terms of greenhouse effect, strangely, it is the refrigerant that gives rise to the most debate. Foams use mostly 2 types of blowing agents: R141b and pentanes (cyclopentanes and cyclopentane and isopentane or isobutane mixtures). In Europe, the latter dominate, whereas in the US, it is R141b. In the future, it is likely there will be two main families: pentane foams and those using blowing agents such as R245fa, R365mfc and R134a. Logically, the foam with the lowest overall heat transmission coefficient should dominate.

In order to reduce the energy consumption of refrigerators, several approaches are being explored, including the linear motor, which should consume 50% less energy than current motors, and vacuum insulating panels. In reality, these technological leaps could take decades to achieve. Energy labelling which is now compulsory in France and on a European level has proved to be effective. Consumer purchasing criteria have changed: there is now a move towards appliances that consume less.

2. Commercial refrigeration

In France, there are 8000-9000 supermarkets and hypermarkets with a total length of refrigerated display cabinets estimated as being 775 km. When one considers the 160 000 or so French retail outlets, the total length of refrigerated display cabinets is estimated as being 400-500 km. In terms of value, fresh and frozen products purchased by households represents over half of all food products purchased. It must be underlined that in France, the area devoted to refrigerated (chilled and frozen) food represents only 22% of the overall retail surface area of large and medium-sized stores, and that cabinets used for frozen food represent 25% of the total length of display cabinets.

There are two categories of equipment: self-contained display cabinets and central systems.

Self-contained display cabinets are mainly used in local shops and can also be found as back-up equipment in supermarkets and hypermarkets. They have the advantage of presenting a relatively low charge of refrigerant and of having very tight circuits. They usually use R134a for chilled products and R404A for frozen food. In some countries, there are a few cabinets running on R600a, with charges of up to 800 g.

In supermarkets, the concept used for decades has been that of a direct-expansion refrigerating installation supplying the store’s cabinets. Nowadays, new concepts abound. However, it is difficult to say what solutions will be adopted in the future.

The guiding principles of these new concepts are: a low refrigerant charge, improved containment of the refrigerant, enhanced flexibility (achieved for instance during periodic refitting of the stores).

The most frequent designs and refrigerants used are:

- Centralized direct-expansion systems using R404A (sometimes R507) both for low and medium temperatures. CO₂ is sometimes used as a low-pressure stage refrigerant in cascade systems.
- Distributed systems comprising several small plants. This concept allows the refrigerant charge to be halved and is more widespread in the US as it requires more space.
- Indirect systems are attracting a lot of interest. The refrigerant is usually R404A (or R507). However, in Europe, there are over 50 plants using ammonia and 10 using hydrocarbons.
- There are many developments in terms of secondary refrigerants with classic alcohol solutions, and brines (calcium chloride, potassium formate) which have made a comeback, two-phase liquid-vapour CO₂ and liquid-solid ice slurries.
This is an area where the TEWI and LCCP (Life Cycle Climate Performance) concepts are not really taken into consideration as indirect systems are very popular despite the fact that overall they have a higher TEWI, especially in low-temperature applications. Considerable research and development is conducted in this domain because of the relatively high GWP of R404A (3260), the large amount of refrigerants used and the leakage rates which are still too high in direct-expansion plants.

3. Industrial refrigeration: refrigerated storage, agri-food and other industries

Being so diversified, this is a field which is difficult to describe using figures. Trends in the field are as follows:

- Increasing use of ammonia in medium- and high-capacity plants (there are no compressors with capacities of less than 50 kW).
- Development of the capacity of dry-expansion evaporators to replace flooded evaporators (up to 300 kW) in order to reduce the charge.\(^4\)
- Use of R404A (or R507) for dry-expansion evaporators in medium-capacity plants (< 300 kW). R404A is rarely used in recirculating systems, despite its low glide and the fact that it has shown that there is no significant change in the composition of the mixture.
- Distinct interest in R410A for low-temperature applications because of its high specific refrigerating capacity (1 kg of R410A supplies 50% more refrigerating capacity than 1 kg of ammonia). However, high- and medium-capacity components remain to be developed.
- R134a is used in small-capacity plants for temperatures above 0°C.
- Interest in CO\(_2\), in particular for low temperature applications (frozen food, ice cream). The ammonia (high-pressure stage)/CO\(_2\) (low-pressure stage) pair should have a promising future. It tends to replace ammonia used alone.\(^4\)
- Distinct interest in secondary refrigerants. Indirect systems have always been used in the food industry (fruit stations, offal conservation, dairy plants…) for precise temperature regulation. Nowadays, such systems offer an additional benefit: a reduction in the refrigerant charge. There is a great diversity of secondary refrigerants. Recently, CO\(_2\) has been widely used as a secondary refrigerant in the French food industry.
- There have also been developments in the field of hydrocarbons. In fact, hydrocarbons have always been used in some industrial plants where risk control was guaranteed.
- Energy-saving measures. In a warehouse, energy consumption represents 10-15% of total running expenses.\(^1\) High-rise warehouses enable energy consumption to be reduced substantially (from an average of 30-50 kWh/(m\(^3\).year) to 16 kWh/(m\(^3\).year)).

4. Land refrigerated transport

Worldwide, there are approximately 1 000 000 road vehicles and 80 000 railway wagons used for refrigerated transport.\(^1\) In France, the number of refrigerated vehicles is estimated as being 60 000,\(^2\) and the number of insulated refrigerated vehicles as being 10 000.

Vehicles comprise carriers, semitrailers or trailers with self-contained refrigerating units (with their own engine-driven motor). Vans and small trucks often use compressors running on the engine of the vehicle, which means that the vehicle’s engine, using a belt, drives the compressor.

Despite its breakthrough in the 1990s, intermodal rail-road transport using swap bodies has not gained much ground because of higher costs and the lack of flexibility of the process compared with road transport. In France, there have not been many developments in “piggy-back” (rail transport of whole vehicles) either.

Nowadays, the most commonly used refrigerant is R404A because it enables good energy efficiency to be achieved when transporting chilled as well as frozen products, and it is a well-known fact that ATP class C multipurpose vehicles represent the majority (63%) of refrigerated vehicles.\(^1\) The problem with R404A is that it has a GWP of 3260 and that the transport application leads to significant leakage. R134a is sometimes used for transporting of chilled products only. R410A is another refrigerant used. The high temperature at the end of the compression process requires the injecting of liquid refrigerant into the suction line, thus lowering the system’s COP. Trials on hydrocarbons and CO\(_2\) have also been conducted.
Solid absorption technology using ammonia as the refrigerant has not reached breakthrough status so far, despite considerable research and development. Laboratories are working on defining energy labelling.

Most insulants use blowing agents of the R141b type, which will be banned in Europe as of January 1, 2004 for new refrigerated-transport equipment. Again, the future in this field is uncertain. Will R245fa, R365mfc, pentanes or other blowing agents be used? The choice will depend on the availability of suitable HFCs, their cost, conduction and mechanical resistance properties, surface adhesion properties, inflammability and ageing properties.

5. Marine refrigerated transport

There are currently 715 000 TEUs (Twenty-foot Equivalent Units) worldwide. In 1998, sales of TEUs reached a level of 96 500 (500 insulated containers and 96 000 refrigerated containers). The trend is therefore clearly towards self-contained refrigerated containers. They are technological wonders which can transport perishable products for weeks, or even months, under very stable temperature, humidity and controlled-atmosphere conditions.

In this sector, R134a dominates. This is understandable for chilled products, which are the most commonly transported products. For frozen products, either R134a is used, which is surprising considering its very poor energy efficiency at low temperatures, or R404A can be employed.

On refrigerated ships (reefers), besides R22, the main refrigerants used are R410A, R407C and R404A. In 1993, five refrigerated ships using ammonia were built. Since then, ammonia has no longer been used, except on fishing boats. Indirect systems using brines such as calcium chloride, and plate exchangers, are the most commonly used. However, refrigerated ships have been on the decline since the breakthrough of self-contained containers (in 1999, only 861 refrigerated ships with a capacity of over 100 000 cubic feet remained). On the other hand, the fleet of container ships is increasing proportionally, and nowadays there are more than 4000 such vessels.

6. Unitary air conditioning and heat pumps (air cooling systems)

The refrigerating-capacity range of air conditioners or heat pumps is typically 2-420 kW. Sales of these systems have increased considerably, in particular sales of individual air conditioners for a single room or several rooms. Global sales in 2000 reached 29.9 million for non-packaged equipment and 9.8 million for packaged equipment. That is a quarter of the estimated number of air conditioners and heat pumps in use in 1996 (168 million).

In terms of refrigerants, R22 is still used a lot in the US. Europe has moved towards R407C, probably because European regulations allowed insufficient time to develop drop-in equipment operating on R410A. In Japan, the policy is to use R410A. It is likely that R410A will dominate this sector in the future, especially for small capacities where energy efficiency is good, and because R410A is an almost azeotropic mixture. For medium capacities and capacities over 100 kW, R407C and R134a are undoubtedly used the most. Propane is used for portable equipment, but sales of portable equipment are decreasing in favour of benefit sales of split systems. CO$_2$ is used in some heat pumps. Unitary air conditioning systems is an area in which HFCs are essential.

7. Water chillers

In terms of capacities, the range of equipment is very wide, varying from 7 to 35 000 kW. The refrigerant used depends mainly on the compressor and the capacity. Various types of compressors used are summarized according to capacity in Table 1.
Table 1. Types of compressors used in water chillers depending on refrigerating capacities

<table>
<thead>
<tr>
<th>Type of compressor</th>
<th>Range of refrigerating capacity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scroll and reciprocating</td>
<td>7-1600 kW</td>
</tr>
<tr>
<td>Screw</td>
<td>140-1600 kW</td>
</tr>
<tr>
<td>Centrifugal</td>
<td>350-35 000 kW</td>
</tr>
</tbody>
</table>

For high capacities, centrifugal compressors are used, preferably with R134a as it is a pure refrigerant. Furthermore, high-capacity chillers (over 700 kW) are equipped with flooded evaporators which only work well with pure or azeotropic fluids. R134a has valuable heat-transfer properties. Besides, it is a known fact that ammonia cannot be used with centrifugal compressors, unless the number of stages is increased.

For medium-capacity chillers working in dry expansion with positive-displacement compressors, R407C is a popular choice. The high glide of R407C means that it cannot be used with flooded evaporators. In this capacity range, there are many plants using ammonia in France’s neighbouring countries. Refrigerant charges are approximately 0.15 kg/kW with ammonia (with variations from 0.04 to 0.25 kg/kW) and 0.35 kg/kW with R134a.¹

Research is being carried out on water chilled chillers using CO₂ and there is an air-conditioning plant in Germany which uses water vapour as the working fluid, but this is a technological feat rather than a common application.¹

There are few absorption water chillers in France because of the favourable price of electricity in summer. Policies promoting the use of gas have been implemented in several countries in the Far East (China, Japan and Korea), leading to widespread use of this technology.

Nevertheless, in France, the surface area of gas air-conditioned premises has risen from 1% of total of air-conditioned surface areas in 1998 to 8% (550 000 m²) in 2000.¹⁵

8. Mobile air conditioning

This is the field which is developing the fastest. It is also the field which requires the most attention to be paid to environmental issues. In fact, it is thought that refrigerant emissions by car air-conditioning systems in Europe will represent approximately 50% of all HFC emissions in 2010. At this same date, there will also be approximately the same quantity of HFCs in mobile air-conditioning circuits as in all other refrigeration and air-conditioning plants.¹⁶

Since the end of 1994, the refrigerant universally used in all new equipment is R134a. Research is being conducted on the use of propane in indirect cooling systems. The volumetric refrigerating capacity of propane is 15% higher than that of R134a, but the indirect system increases energy consumption by about 20%.³ Globally, these two designs have similar energy efficiencies.

CO₂ requires a longer developmental period due to various factors to be addressed: the reliability of components, the development of tubes capable of resisting high pressures, the increased weight of systems and the poor energy efficiency of compressors. However, a group of German automobile manufacturers has announced that it will be using CO₂ air-conditioning systems as of 2006.

But, in the meantime, mass production of appliances using R134a and constant developments mean that the performance of R134a has also been improved.

Hybrid systems using hermetic compressors operating on R134a and electricity also constitute a new innovative trend.

In this field, it is very difficult to predict which will be the most widespread refrigerant in the future. The optimal refrigerant that will emerge will probably be the working fluid enabling the best energy efficiency to be achieved.
Conclusion

In conclusion, trends in refrigerant selection early in 2002 are as follows:

- R134a is the main refrigerant used either pure in applications such as domestic refrigeration, mobile air conditioning, high-capacity water chillers, self-contained display cabinets, etc. or as part of a mixture with R404A, R507 or R407C.
- Isobutane has had a breakthrough in domestic refrigeration where it competes on an equal footing with R134a, except in the US and in Japan where R134a still dominates.
- R404A dominates in refrigerated transport and commercial refrigeration.
- R410A seems very promising for unitary air conditioning.
- R407C used in air conditioning seems more likely to be used on a short-term than on a long-term basis.
- Ammonia is increasing its market share in industrial refrigeration but has a small share of the water-chiller market.
- CO₂ is the refrigerant which is attracting the most interest in almost every application field. However, a much longer developmental process is required in order to deal with its specific properties.

Of course, beyond the scope of this short summary, there are many other refrigerants and many other applications.

References