Development Trends and Possibilities in Industrial Refrigeration

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Historical Perspective

Industrial refrigeration grew with development of improved transport in the 19^{th} century.

Deliberate use of low temperature to preserve food has a history that extends back for many thousands of years, perhaps to a time before emergence of Homo Sapiens, but it was not till the steam locomotive made possible the rapid transport of block ice over hundreds of miles that industrial use of lower temperatures became practicable.

The first industrial use of block ice was in brewing but block ice was also used for preservation of fresh fish and other foods.

The use of natural ice harvested in ponds in the North Eastern parts of USA continued for many years and was copied in other parts of the world including Norway.

Safe use of natural ice came to an end due to pollution arising from population growth and primitive sanitation that made use of flushing toilets without associated treatment of the resulting sewage.

A contributory factor in the replacement of natural ice by mechanical refrigeration was the American Civil War that cut off the Southern States from supplies of block ice to which they had become accustomed. One of the first refrigerating systems in North America was a Ferdinand Carre absorption system imported through Mexico and installed in San Antonio, Texas.

Absorption refrigeration systems are much less efficient than vapour compression systems but early vapour compression systems were very dangerous, due to use of substances like ethyl ether which are denser than air but highly flammable.

Early mechanical refrigerating systems used air cycle machines with compressors coupled to expansion engines to reduce power consumption to some degree. The inherent inefficiency of the air cycle led to its replacement by vapour compression systems using ammonia or carbon dioxide.

In general, ammonia came to dominate land based industrial refrigerating systems but carbon dioxide was used on ships because it is much less toxic.

Ammonia remained the dominant refrigerant in industry, though the introduction of halo-carbon refrigerants in the nineteen thirties resulted in its use being progressively restricted to large systems.

Carbon dioxide remained dominant in marine applications till the late forties but it was rapidly displaced by halo-carbons in the nineteen fifties. The most commonly used halo-carbon was R-22.

From 1974 onwards, continued use of halo-carbons was threatened by the hypothesis that they were responsible for damage to the stratospheric ozone layer that protected the earth from harmful ultra-violet radiation.

In 1987 it was laid down in the Montreal Protocol that use of chlorinated halocarbons as refrigerants should be progressively reduced. The Protocol was subsequently amended to require the complete abolition of chlorinated fluorocarbons (CFCs and HCFCs) as refrigerants.

As a consequence, the chlorinated refrigerants have been progressively replaced by halo-carbon refrigerants that do not contain chlorine and there has also been a return to the classical refrigerants ammonia and carbon dioxide for larger systems.

Factors Influencing Present Development Trends

Global warming

The industrial society depends to a great extent on combustion of fossil fuels to provide power and heat. Unfortunately this process liberates large quantities of carbon dioxide, that had been sequestered for millions of years, and returns them to the atmosphere, where they cause the earth to retain heat that would otherwise have been radiated to space.
Carbon dioxide is not the only anthropogenic release contributing to global warming.
Release of methane as a result of increased animal husbandry and increased production of rice also contributes, as do releases of synthesised chemicals produced for a variety of purposes including refrigeration.
Refrigeration is thus doubly affected, firstly by the need to minimise use, and release, of refrigerants of high Global Warming Potential (GWP) and secondly by the need to avoid un-necessary use of energy in the production of refrigeration.
The need to mitigate rate of global warming, influences Industrial Refrigeration by restricting the choice of refrigerant available and by making it important to improve efficiency of Industrial Refrigerating Systems.

Safety Legislation

Ammonia and carbon dioxide are typical industrial refrigerants and have had a good safety record over many years. However this good record is largely due to compliance with voluntary industry safety standards. Serious accidents in chemical and fertiliser plants have led to scrutiny of the way in which ammonia is used in all industrial systems including refrigerating systems.
Legislation is now in place that specifies precautions to be taken when using ammonia in refrigeration systems. The degree of precaution is related to the amount of ammonia in the system.
Conventional ammonia refrigeration systems, especially in USA, have not been designed with charge minimisation in mind. It is possible to design systems that will operate with much lower refrigerant charges than conventional systems.
Direct systems that will operate with less than one tenth of the charge of a conventional system have been in use for over twenty years.
Secondary systems have been designed and operated with less than one hundredth of the charge of a conventional US ammonia refrigerating system.

Electronic and Computer Advances

There have been unprecedented advances in electronics and computers within the last ten years.

It is now possible to control and indicate refrigerating systems remotely and in real time, thus making it possible to acquire data, that would previously have been prohibitively expensive, for control and diagnostic purposes. The data can be transmitted to any location, even across national boundaries.
Variable speed drives are now a practicable possibility for large units. Benefits of variable speed drive are particularly evident for rotary pumps and fans where power consumed varies as the cube of the rotational speed and where maximum rotational speed is rarely required.
Introduction of computer controlled variable speed drive of salient pole motors has opened the way for quiet and efficient high speed centrifugal compressors.
Intelligent and Versatile Control Valves are Now Available

Efficiency Legislation

Governments around the world have begun to realise that refrigeration of various sorts consumes over ten percent of electrical energy in their countries and that it would consume a lot less if it were more efficient.

Legislation will cause a trend to the use of more efficient refrigerating systems.

Legionnaires Disease

This pneumonia like disease, first described in 1976, is caused by inhalation of bacteria in very fine droplets of water. Cooling towers and evaporative condensers are one possible source of such droplets.
Legislation in many countries making it mandatory to declare the presence of cooling towers on a site and giving to Local Authority inspectors, power to shut down the cooling tower on suspicion that it might have been the source of a case of Legionnaires Disease, makes business increasingly reluctant to employ evaporative cooling.
There has therefore been a trend away from use of evaporative cooling for heat rejection from refrigerating systems. However such a trend will have to be reversed if system efficiency is to be increased.

Main-frame computer cooling

Computers have become hundreds of times more efficient over the past few years but, in the same period, they have become thousands of times more powerful. Power requirement for such computers, therefore, continues to increase.
Main frame computer centres have electrical requirements of several MW. The heat generated by electrical input to computer and ancillaries has to be rejected to the surroundings. This usually requires some form of refrigeration.
In view of the numbers of such installations and the large amounts of heat to be rejected it is obvious that this application will drive innovation to provide more efficient means of providing the refrigeration.

IT Systems

IT systems rely on computers of various types but the problem is not the sheer size of the load, as is the case with main-frame computers. The problem is the intensity of the load.
Typical blade-server cabinets, which have not increased in dimension, have increased in heat load from about 1.5kW to about 20kW in the past few years. There will be a trend towards new methods of carrying heat away from these cabinets whose heat loads are predicted to rise to about 30kW.
A similar problem arises in connection with stock market dealer floors. It is necessary for dealers to have access to two or more personal computers. Apparently, speed of reaction precludes their connection to a

central computer. As a consequence the dealer, in the confines of the floor, can be subjected to intolerable heating from his own computers.

Current trends in Industrial Refrigeration

There is a general trend towards larger systems. This results from ever larger business groupings whether in the food industry, the retail industry or the chemical and oil industries. Large installations favour use of screw compressors, evaporative condensers and ammonia refrigerant.

The most obvious trend in Industrial Refrigeration is a move away from halocarbon refrigerants of all types towards use of ammonia. This is, in part, due to the size of typical installations but is also a reaction to doubts about the long term future of synthetic refrigerants.

The move towards ammonia is accompanied by a move towards increasing use of screw compressors. There are several reasons for this;
Screw compressors do not suffer from the high discharge temperatures associated with use of ammonia in reciprocating compressors.
Screw compressors are more reliable than reciprocating compressors and require less frequent maintenance.
Screw compressors are more compact than reciprocating compressors with the result that fewer compressors are required to match large loads.
However, in general, screw compressor systems tend to be less efficient than reciprocating compressor systems. This is because of friction losses in the sealing oil film.

In conjunction with the return to ammonia, there has also been a return to use of carbon dioxide as a refrigerant. An important reason for this is that ammonia charge can be minimised by circulating a secondary refrigerant to evaporators rather than pumping ammonia to them. An efficiency penalty is associated with use of secondary refrigerants but liquefied carbon dioxide is by far the best secondary refrigerant available, whether used purely as a liquid or, even better, allowed to evaporate within the cooler. Pumping power for carbon dioxide used as a volatile secondary refrigerant is about 0.05% of the power required for a conventional secondary. In addition, heat transfer coefficients obtained with boiling carbon dioxide are particularly high.

Carbon dioxide is also now used in cascade systems in conjunction with ammonia. Pressures within the carbon dioxide system are moderate, though compressors are now available for pressures up to 50 Bar. Performance of ammonia refrigerating systems at low temperature is limited by the very high specific volume of saturated ammonia vapour at these temperatures. Penalties associated with suction line pressure drops are significant and very large compressors are required.
The ammonia/carbon dioxide cascade system avoids the weaknesses of each refrigerant and makes use of their strengths. The ammonia is used at high back pressure but still condenses well below the critical temperature of ammonia. The ammonia compressor is relatively compact and is efficient because of its low pressure ratio. The carbon dioxide compressor also operates at a moderate pressure ratio and remains at positive suction pressure. Heat transfer is particularly good in evaporator, inter-stage condenser/evaporator and high temperature condenser.
It has been found possible to design inter-stage heat exchangers to operate with overall temperature differences of the order of 3K.
A major benefit in the operation of pumped circulation freezers is that temperature drop in wet suction lines becomes insignificant when using carbon dioxide. It has been found that freezing time in vertical plate freezers using carbon dioxide is about half that which would be expected when using ammonia at

the same saturated suction temperature. This is largely due to reduced temperature drop in the flexible connections to the freezer plates.

Trans-critical compressors are now available for use on carbon dioxide. The main application, so far, has been to Supermarkets and to water heating. Compressors are available with absorbed powers of up to about 10kW. It is assumed that larger compressors will become available. The annual power consumption of supermarkets using trans-critical carbon dioxide in temperate regions has compared favourably with annual power consumption of conventional supermarkets using R-404A.

Site erection is so costly that even large installations are usually composed of packaged units taken to site in one piece, leaving only interconnecting piping and some isolating valves to be welded on site. This is in sharp distinction to the early days of Industrial Refrigeration when the expert erection teams of the various manufacturers waited with impatience for winter to end so that they could get out of the factory to the freedom of site erection.
Pumpless, low-pressure receiver systems can be arranged so that every valve in the system, including valves for defrosting, is on the packaged unit as is the electrical panel and the drive motors. As well as minimising charge, this makes for a very reliable system.

A recent trend has been increasing use of oil-free, high-speed centrifugal compressors using R-134a as refrigerant. Such compressors are now in regular use in systems for chilling water and also for condensation of carbon dioxide for circulation as a volatile secondary refrigerant. These compressors have many advantages including light weight, compactness, virtual silence and very low starting currents.

Future possibilities

Refrigerants

The future of R-134a is threatened because of its relatively high global warming potential of 1300. The immediate threat is to its use for car air-conditioning but its industrial use in centrifugal chillers might also be under threat.
A proposed substitute for car air-conditioning is R-1234yf ($C_3H_2F_4$) which has similar properties but much lower global warming potential.
Molecular weight of R-134a is 102. Molecular weight of R-1234yf is about 114.
It would therefore be possible to design high-speed centrifugal compressors to operate on R-1234yf which would produce much lower direct global warming than use of R-134a. It remains to be seen whether systems using R-1234yf would be as efficient as systems using R-134a. The latent heat would appear to be lower but the critical temperature is similar at 94C compared to 101C for R-134a. This is much higher than the critical temperatures of refrugerants R-404A and R-410A which are commonly used refrigerants of much higher global warming potential.
R-1234yf is probably slightly flammable but the disadvantages of refrigerant flammability in a sealed refrigerating system have been much exaggerated.
It would be possible to produce a blend duplicating the molecular weight of R-134a by mixing R-152a with R-1234yf in proportions including about 14% of R-152a. The blend would certainly be flammable.
It would be a serious blow to industry to be deprived of the convenience of using non flammable, non-toxic synthetic refrigerants where appropriate.
It may well be that the Chemical Industry will produce further fluorinated refrigerants of low global warming potential and low toxicity but the days of cheap mass market fluorocarbon refrigerants are almost certainly over.

It now appears that there may be a significant niche market for air cycle refrigeration in conjunction with continuous freezers. Air cycle refrigerators tend to be very inefficient compared to vapour compression refrigerating systems because the required mass flows are high compared to mass flows required when the refrigerant can be allowed to evaporate. Air cycle would only be efficient if the air could be allowed to refrigerate over a significant range of temperature. Continuous freezers extract heat from product being frozen through temperatures ranging from 40C to -40C. Use of air through such temperature ranges would appear to favour air cycle refrigeration. Calculations confirm this intuition.
Air cycle has become more practical because of the development of oil-free, high speed centrifugal compressors and expanders that could be arranged on opposite ends of high speed, salient pole motors.

Compressors

The most dramatic compressor development of recent years has been the high speed, oil-free centrifugal compressor. This compressor has been configured for R-134a and, within USA only, for R-22.
There is no reason why the compressor programs should not be arranged for other refrigerants, though the very low molecular weight of ammonia would indicate difficulties associated with number of stages required and rotational speed that is practicable before the device explodes under the action of centrifugal force.
Surprisingly, there is little problem anticipated from the corrosive effect of ammonia because the motor windings are not exposed to the refrigerant vapour.

Reciprocating and screw compressors have probably reached a plateau of development though there is a possibility that some form of oil-free single-screw compressor will successfully be developed. This would almost certainly require development of some type of self-lubricating material for the single screw. Special material is already used for the gate rotors.
There is potential for development of trans-critical screw compressors for use with carbon dioxide. Carbon dioxide refrigerating systems benefit greatly from the "economising" that can be obtained by two stage expansion from high pressure with attendant sub-cooling.
Such compressors would be constructed with short, stiff rotors and would probably have to have a special design of economiser port to ensure that intermediate pressure was below critical pressure.
Trans critical screw compressors for carbon dioxide can be expected to be efficient compared to screw compressors for other refrigerants because the very small rotors relative to refrigerating effect will produce less of the oil sealing friction which is a major cause of inefficiency in screw compressors.
The application of trans-critical screw compressors would be mainly to air conditioning and to heat pump systems but they could also be used as the high stage of a two stage carbon dioxide refrigerating system. This would give rise to the intriguing possibility of three stage expansion in the system and also to the possibility of running the system as a cascade with the low temperature stage oil-free. Such systems would compare favourably in terms of efficiency with single stage economised ammonia screw compressor systems.

Scroll compressors are still at a relatively early stage of development and can be expected to extend in range and in application. The most common refrigerant for scroll compressors at present appears to be R-410A. This provides a very compact compressor and could be described as "A compressor manufacturer's refrigerant ". In other words, "A lot of refrigeration from a very little compressor". However the situation is not quite so attractive from the standpoint of the end user. Critical temperature

of R-410A is very low at 72.4C. This makes it much less efficient under air-conditioning conditions than a similar refrigerant with a higher critical temperature would have been.
There is undoubtedly a future for a hermetic scroll compressor suitable for use with ammonia. Such compressors are being developed in Japan.
A major market for such compressors would be as components of heat pumps where relatively high temperature hot water could be produced as well as lower grade heat for buildings.
Such compressors could also be used for air conditioning, perhaps in conjunction with the circulation of liquefied carbon dioxide as a volatile secondary refrigerant.

Semi-hermetic compressors for use with ammonia have been developed in Europe. These are highly efficient machines but have not so far been released for general use.
Such machines will also find a use in air conditioning and in heat pumps.
The high latent heat and low mass flow of ammonia in refrigerating systems restricts the availability of suction gas cooling for the rotor. However such machines are released for use up to slightly over 50C condensing.

Low charge systems

There are several good reasons for minimising refrigerant charge.
Refrigerant can be expensive.
Refrigerant loss can be overlooked for a time in systems with massive charges.
Potential refrigerant loss is proportional to refrigerant charge and may have unfortunate local and global consequences. It is not generally realised that world- wide fatalities from refrigerant loss are more or less equally divided between those caused by asphyxiation due to leakage of non-toxic refrigerants and those caused by acute poisoning from toxic refrigerant leaks.
There are two proven methods of reducing refrigerant charge:-

1. By using a secondary refrigerant to distribute the refrigerating effect away from the engine room thus restricting the primary refrigerant to the sealed engine room.
   The secondary refrigerant can be a liquid, transporting heat in the form of sensible heat, or it can be a volatile liquid such as carbon dioxide making use of the latent heat of evaporation.
   It is obvious that pumping power for circulation of a volatile secondary refrigerant is low and that heat transfer coefficients are likely to be very high.
2. By using an overfeed system that does not require a pump and associated liquid storage vessels. One such system is the Star Refrigeration low pressure receiver which has been in the public domain for many years.
   In the Star system, high pressure liquid refrigerant is overfed to the cooler through an expansion valve. The returning wet refrigerant is evaporated to dryness in a heat exchanger associated with a vessel known as the low pressure receiver.
   Excess liquid is stored at low pressure in the low pressure receiver.
   The compressor is protected at all times from possibility of flooding.
   Very reliable and effective reversed cycle defrosting can be provided.
   The system cannot be applied to more than three or four similar evaporators at a time, because of the need to distribute refrigerant to them equally, but this limitation also has the effect of minimising charge of individual systems in the complete installation.

Low pressure receiver systems have still not been accepted by the majority of conservative refrigerating engineers, possibly because they do not understand how simple they are to operate in practice, though the mathematics of explaining how they work are slightly complicated.
There is some evidence that they are more efficient in operation than conventional pumped circulation systems. This is for a variety of reasons including reduced pressure drop in the wet suction line and more efficient operating conditions during defrosting.

Evaporators

Enhanced surface tubing is now readily available for evaporators of almost all types. Enhancement is more than just provision of increased surface. The effectiveness of the surface can also be increased, for example, by promoting boiling at low temperature difference and reducing hysteresis effects.
Many heat exchanger tubes are now available with enhancement on both sides.
Plate type evaporators have proved to produce surprisingly high coefficients of boiling heat transfer at relatively low Reynolds numbers. This is a function of the turbulence produced in the refrigerant channels and of the internal "corners" produced where plate meets plate at very acute angles.
In terms of size for refrigerating effect at small temperature differences, the plate and shell type of exchanger is unrivalled among industrial evaporators. It is also capable of withstanding pressures of the order of 500 BarA.
Prices of such heat exchangers appear to be high in relation to their material content.

Finned air coolers are a specialised form of refrigerant evaporator that are capable of further development, especially for ammonia refrigerant. The dominant resistance to heat flow is on the air side of the heat exchanger as evidenced by the large area ratios provided on most air coolers. However there are circumstances where the internal boiling coefficient can become important. This is especially the case where ammonia is being evaporated at low temperature and at low overfeed ratios or even to dryness. When the tube material is stainless steel, which is quite common in large ammonia air coolers, it will be found that, at very low evaporating temperature, as in an air-blast freezer, the ratio of volume of ammonia liquid to low density vapour is so low that the liquid tends to separate out and flows along the bottom of the tube. Conductivity of stainless steel is so low that it is difficult to get heat to flow round the circumference of the tube to evaporate the trickle of ammonia running along the bottom of the tube. The obvious solution would appear to be to use aluminium tubing and to enhance the inner surface to promote capillary flow up from the liquid in the bottom of the tube. I hope that evaporators of this type will make their way onto the market in the near future.

There are significant advantages in the use of micro-bore tubing in evaporators but development has mainly been aimed at small air conditioning systems. There are obvious possibilities for larger industrial systems.

Condensers

There is an obvious contradiction between the desire to use evaporative condensers to provide lower condensing temperatures and therefore higher efficiencies and the desire to avoid the costs and complications that are associated with protection against growth of Legionella bacteria. The bacteria are almost universally present but they grow to dangerous concentrations in dirty tanks and in other situations where nutrients are found.
There is an unusual situation in UK where some departments of the British Government are encouraging use of evaporative condensers and cooling towers to promote high efficiency while other departments are discouraging their use to reduce risk of Legionnaire's Disease.

The obvious answer would appear to be to remove the association between storage of water and evaporative cooling. This could be done by designing a "once through" evaporative cooler without provision for re-circulation of cooling water by means of a pump.
Such evaporative coolers have been proposed at several times in the past. It now seems that their time may have come.

Controls

The author's Company pioneered the introduction of robust computers to control and indicate refrigerating systems over twenty five years ago. Since that time computers have become ubiquitous and remarkably cheap.
There are two approaches to the problem. One is to have a computer, or at least a PLC associated with every piece of refrigerating equipment and to encourage these items to communicate with each other and, possibly, with a BMS system. The other is to provide standardised software that controls the complete refrigerating system in accordance with the expertise of the system designer and to have minimal interface with the BMS system.
The latter approach seems to provide more reliable and more rapidly commissioned systems than the full integration with BMS systems.
It is hoped that eventually true compatibility will be achieved between competing systems but the prospect always appears to be just on the horizon.

Standards

We live in an age of increasing standardisation. The adoption of de facto standards in many industries is one of the minor miracles of our time. Without such standards and standardisation, international trade would be much hampered.
Refrigeration is no exception but the process is not yet complete.
At present there are at least three significant sets of technical and safety standards existing in parallel. These are US Standards, European Standards and Japanese Standards. These sets of standards influence each other but they are by no means identical. In theory the International ISO Standards should be the preferred set of Standards with all others subsidiary to them.
Unfortunately we are a long way from producing an internationally acceptable set of ISO Standards for refrigeration. The task is not made easier by existence of National Legislation and Directives to which Standards must comply.
In addition, it appears that vested interests play a part in trying to promote methods acceptable, or preferred in certain areas or even trying to discriminate against methods that do not suit them.
This should not be so but it is an unfortunate fact of life. As a result the same battles have to be fought over and over again at National, International and ISO level.

Conclusion

We live in an interesting and challenging time. I very much hope that the present generation of young engineers will face up to the challenges.

Engineering is for young people. All the great advances of the past were made by young people.
Older engineers should be listened to because they must have learned something in their years of toil:- but don't let them get in the way.
The future will be shaped by young engineers and it starts now.