Photo 1 (left): A 2500 kW chiller being installed. Photo 2 (right): Free chillers that use thermosyphon to provide highly efficient cooling.

Ammonia's Future

By Andy Pearson, Ph.D., CEng, Member ASHRAE

Ammonia has been the refrigerant of choice for industrial systems in many parts of the world for more than 100 years. It is cheap and readily available, provides high efficiency from relatively inexpensive equipment and is easy to use. It is also resistant to sloppy maintenance practices in many ways, as will be demonstrated in this article.

In recent years ammonia has been applied in many applications where traditionally it was not common. This article reviews the progress that has been made in bringing ammonia systems to a wider market and explores other possible applications that might be seen in the near future.

The move away from ozone depleting and global warming refrigerants has given a boost to system designs using ammonia. Recently, the environmental focus has shifted to energy efficiency, sustainability and carbon footprint. This has further reinforced ammonia's reputation as an eco-friendly choice for industrial systems, and has even sparked interest in ammonia from some unlikely quarters.

The interaction between ammonia and the environment is well understood, and it is unlikely to be subject to restrictive legislation beyond the extent of the constraints that are already in place. In this sense it can be considered to be future proof.

Making Ammonia More Acceptable

Two significant safety issues need to be addressed when contemplating using ammonia as a refrigerant. The gas is acutely toxic if inhaled in moderate quantities, and has an unpleasant smell even at much lower concentrations, which could lead to complaints from operating staff or members of the public if a system leaks regularly. Also, mixtures of ammonia and air are flammable under certain circumstances, and while an ammonia deflagration does not have the destructive power of hydrogen or petroleum, it is capable of causing burns and minor structural damage.

The first step in making ammonia more acceptable is educating the professionals

About the Author

Andy Pearson, Ph.D., CEng, is managing director at Star Refrigeration Ltd., Glasgow, U.K.

Polyalfaolefine (PAO) lubricant provides excellent long life stability and has a high viscosity index, so it remains relatively viscous at high temperature but still flows freely at low temperature. The pour point for the most common grades is –70ºC (–94ºF). When used on its own PAO can cause slight shrinkage of O-rings and other elastomers, so it is often supplied with a seal additive, or in a 50/50 mix with alkylbenzene lubricant. It is not miscible in ammonia, so some form of oil management system is required if it is to be returned automatically to the compressor.
Polyalkyleneglycol (PAG) lubricant is miscible in ammonia and so enables simpler systems of the type commonly associated with fluorocarbon refrigerants to be used. PAG has a strong affinity for water so it must be used carefully. It is also relatively expensive (about three times the price of PAO), so there is a temptation to keep oil that is left in a drum and not required for top up. This is bad practice. Once a container has been exposed to atmosphere, the oil should be used or sent for disposal.

Table 1: Modern lubricants for ammonia.

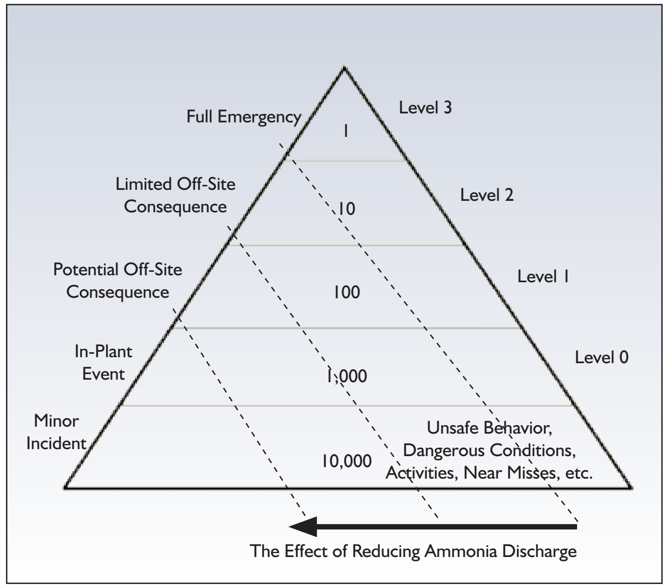

Figure 1: The ammonia risk triangle (courtesy of General Mills Inc.).

who work with it. The majority of industrial accidents involving ammonia in refrigeration systems affect those in the immediate vicinity of the leak, such as production workers on a refrigerated process or maintenance workers servicing the ammonia system. No known fatalities or serious injuries are associated with refrigeration systems where people were further than 20 m (66 ft) from the source of leakage. The injuries sustained in these incidents were all preventable, so it is clear that the most important factor in improving ammonia safety is education and training of workers who come into contact with ammonia occasionally. A correct understanding of the refrigerant properties also ensures money is not wasted on unnecessary safety measures.

It surprises many people to learn that the gas detection and ventilation systems required for ammonia installations are not significantly different and not any more expensive than the equipment that should be installed for a large fluorocarbon installation where a major leak would cause an asphyxiation hazard.

The system needs to be user friendly. Ammonia systems are already tolerant of poor maintenance practice. For example, ammonia systems have been reported in operation with several percent water in the refrigerant—even up to 26% in one case.[1] Of course, the influence of water on the evaporating temperature has an adverse effect on plant efficiency. If similar abuse were attempted with R-22, the plant would stop working long before these levels of contamination were reached. This is because either the expansion valve froze up or because the evaporator fouled up with sludge from the water/oil combination.

Many modern ammonia systems run fully automatically and require virtually no operator intervention, including automatic oil management, air purging and, where necessary, water treatment. The success of oil return systems is due to the use of modern long-life lubricants such as PAO or PAG (*Table 1*). Routine oil changes are no longer the norm, and plants can run for many years without a change of oil, provided the oil stays clean and dry. Allowing water to return from the low-pressure side of the system to the compressor may cause expensive bearing damage. If automatic oil return is used, the condition of the oil should be monitored on a regular basis to check for water buildup because there may not be any other sign of water contamination.

Reducing the quantity of ammonia required to achieve the cooling load has been a key part of the rehabilitation of ammonia as a refrigerant in public and corporate buildings. It is now relatively common to need no more than 100 g per kW of cooling capacity (0.75 lbs per ton) in packaged chillers, and some designs achieve even lower figures, down to 25 g per kW (0.2 lbs per ton). Equally important is the distribution of ammonia within the chiller. Designs that do not require liquid receivers in the high pressure part of the system are much less likely to cause problems. The benefits of charge minimization have been pursued in Europe since the early 1990s. A growing awareness exists in the North American market that these advantages are relevant there, too.

Following a detailed survey of accident statistics for industrial systems completed in 2007, General Mills introduced a reporting and tracking system incorporating incident investigation. The system is used to identify root causes of incidents. The company then shares the outcomes from issues common to multiple plants, and addressing those issues across all company facilities. The survey used the Heinrich Principle, as shown in *Figure 1*, to characterize safety-related incidents according to severity. By reducing the base of the Heinrich triangle, the likelihood of accidents can be reduced and, in some cases, they can be eliminated, using charge reduction. In a short course at the International Congress of Refrigeration in Beijing in August 2007 Jeff Welch, current chair of IIAR, identified the goal of charge reduction as being critical to the future of ammonia refrigeration.

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Current Applications

In recent years ammonia chillers have been applied to many projects that previously would have used R-11, R-12 or R-22. The city center offices of a major merchant bank in London were equipped with roof-mounted ammonia chillers in 2000. These replaced the existing packaged plant that had proved to be unreliable in hot weather. The investment in equipment paid dividends a few years later in 2003 when record temperatures exceeding 38°C (100°F) were experienced in the city. A similar installation for the International Maritime Organization (part of the United Nations) in 2001 replaced two R-11 chillers with an equivalent-sized ammonia plant. The building manager reported a significant reduction in energy use once the new system was commissioned.

Similar chillers are used for several ice rinks, with ethylene glycol under the floor. This technology has great scope for further development with the emergence in Europe and Scandinavia of rinks using carbon dioxide as the secondary. Larger chillers, in the range 2000 kW to 4000 kW (570 ton to 1,140 ton) were deployed for factory cooling, for example by Motorola in Swindon, Roche in Welwyn and Nestlé in York, all in England. These machines use large screw compressors, plate heat exchanger evaporators and plate condensers. The design refrigerant content of 100 g per kW means the total charge of each of these packages is typically five or six bottles of refrigerant.

High-efficiency chillers using free-cooling features have been used for water chilling in computer data centers during the last 10 years. These systems give an annual average coefficient of system performance (kW/kW) of 10 for air-cooled chillers and 13 for evaporative cooled. This suggests one-third of the energy consumption of a typical air-cooled chiller where the heat load is constant all year-round. As the free-cooling effect is achieved by bypassing the compressor in cold weather, no interruption occurs to the chilled water flow and there is only one set of heat rejection exchangers, so the system is highly reliable and compact compared with many other free-cooling solutions.

Large chillers are also used in more densely populated applications without any safety compromises. Four units, each with a cooling capacity of 6.6 MW (1,875 ton) are installed in the new Terminal 5 at Heathrow, the world's busiest international airport. One of the chillers installed is shown in *Photo 3*. Ammonia was selected by the airport authority because it was recognized as a future proof solution which offered excellent efficiency but the design choice was only confirmed after a comprehensive risk analysis and safety review had been conducted, which satisfied the design team that there was no greater risk to the public or the airport staff than with a conventional large chiller solution.

Future Applications

The wide acceptance of ammonia chillers in this diverse range of applications has created opportunities for new uses of ammonia equipment in unexpected places. Compared with R-134a, the best of the usual fluorocarbons for heat pump applications, ammonia offers more efficient heat recovery at higher temperatures as a result of its high latent heat

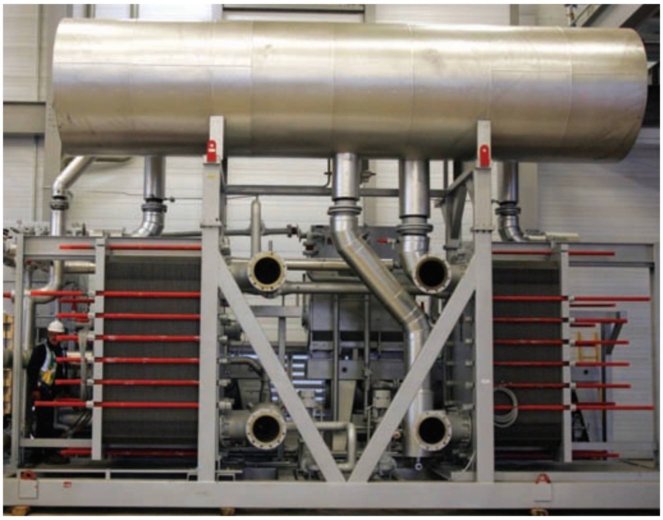


Photo 3: Ammonia chiller at Heathrow Airport (picture courtesy of JCI/Sabroe).

and high critical temperature (the maximum temperature at which liquid can condense). This means that heat pump efficiencies with ammonia are significantly better than with fluorocarbons, providing economically feasible opportunities for equipment that would not otherwise be considered. The number of ammonia chillers installed on the roofs of public and office buildings has shown that this technology is safe and reliable, so there is no reason why air-source ammonia heat pumps for water heating could not also be deployed provided the right compressors were available.

Traditional ammonia heat pumps in industrial applications tend to use reciprocating compressors rated for 40 bar (580 psig) discharge pressure. Reciprocating compressors are favored because they run with higher discharge temperatures than screw compressors, but they are less suited to installation on the roof of a modern building, so care would be required in vibration elimination. Both reciprocating and screw compressors have recently been developed for 50 bar (725 psig) operation in carbon dioxide applications. These machines would be an ideal platform for high-pressure ammonia heat pumps, configured as air-source water heaters.

The excellent performance of ammonia heat pumps has also attracted attention for the domestic heat pump market. Several research projects in Europe using ammonia or a mixture of ammonia and dimethyl ether have proved the concept of low charge systems for domestic heating; the major impediment being a lack of suitable components, particularly compressors and control valves.[2]

Ammonia has been widely applied in Europe to supermarket installations using a secondary refrigerant to distribute to the display cases. The secondary in some cases has been propylene glycol, but low viscosity potassium salts have also been used and, of course, carbon dioxide has become the preferred choice for supermarket secondary systems although often with fluorocarbon or hydrocarbon refrigerant in the high temperature side of the cascade.

Development Requirements

There is no doubt that compressor developments will offer new possibilities for ammonia systems. Hermetic and semihermetic compressors greatly reduce the risk of leakage and increase system reliability. Although obvious problems exist with copper windings in an ammonia system, several compressor concepts have been tested in recent years. One arrangement is the use of a canned motor, similar to those used in hermetic refrigerant pumps. This has been used for many years, but the efficiency reduction is relatively large and tends to inhibit development of the concept. This is perhaps a mistake, as a canned ammonia compressor still will be significantly more efficient than a traditional semihermetic R-404A compressor across the full range of operation. Another concept is the use of aluminium windings instead of copper. This also brings a slight efficiency penalty. A magnetic drive, similar to those used in some sealless pumps could also be used, although it might be difficult to overcome the starting torque for positive displacement compressors.

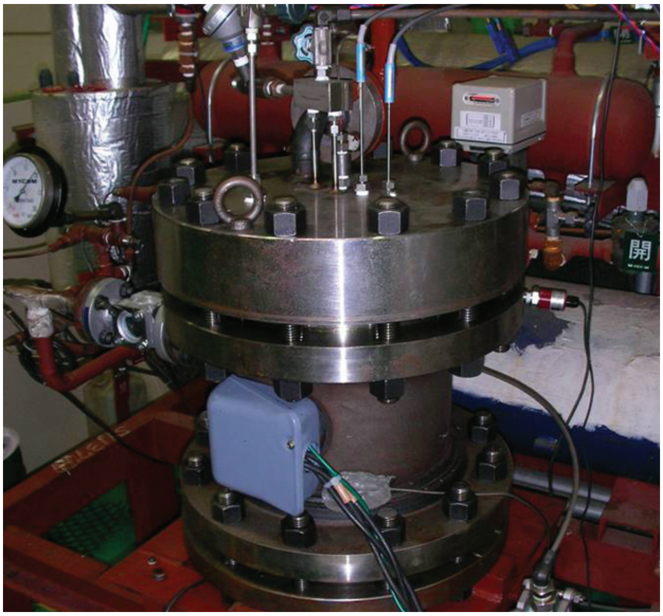
At least one manufacturer is already producing hermetic scroll compressors for ammonia. This was incorporated into a prototype water chiller with a cooling capacity of approximately 30 kW (8.5 ton) using a semihermetic can-less motor.[3] A second generation ammonia scroll is under development, and is expected on the market in the second half of 2008. Further details of the new compressor are given in *Table 3*.

	Ammonia	R-134a
Critical Temperature	133°C	102°C
Latent Heat at 80°C	892 kJ/kg	106.4 kJ/kg
Latent Heat at 5°C	1243 kJ/kg	193.4 kJ/kg
Pressure at 80°C	41.4 bar abs	26.3 bar abs
Pressure at 5°C	5.16 bar abs	3.50 bar abs
Pressure ratio	8.0	7.5
Vapor Quality after EV*	29.5%	60%
Isentropic Discharge T*	179.8°C	92.3°C
COP*	2.84	2.43

*These values are for single-stage compression. In a practical cycle the high discharge temperature for ammonia needs to be controlled, either by using two-stage compression or by some form of external cooling, such as oil injection for a rotary compressor or water-cooling of cylinder heads for a reciprocating compressor. These cooling methods need not detract from the overall heating COP, as the heat extracted by the cooling process may also be usefully recovered. The COP quoted is for heat pump operation, and is the ratio of the heat recovered to the work input.

Table 2: Comparison of heat pump properties.

Another attractive development in compressors would be a variable-speed oil-free compressor similar to those now available for R-134a. Many advantages exist in such a design—no oil management issues in the evaporator, no filter changes or shaft seal, low starting current and low noise/vibration levels. However, this is a large step from the existing technology, and while it is probably technically feasible, a substantial market is



1	Design Pressure	2.6 MPa (Gauge)
2	Design Temperature	120ºC
3	Cooling Capacity	30 kW as water chiller
4	Operation Range	
	Condensing Temp.	30°C to 55°C
	Evaporating Temp.	–35°C to 10°C (subject to operating limits)
	Shaft Speed	1,800 to 3,600 rpm
5	Driver	Hermetic Motor
6	Lubrication Oil	Synthetic Oil PAG
	Oil Supply	Integrated Pump
7	Temperature Control	Liquid Injection
8	Bearing	Antifriction Bearing for Shaft Support
		Hydrodynamic Bearing for Orbiting Scroll
9	Scroll Wrap	Asymmetric

Photo 4 (left): Prototype ammonia scroll compressor (courtesy Mayekawa Mfg. Co.). Table 3 (right): Ammonia scroll compressor.

needed for these compressors to justify the development cost. Additional factors are the risk of damage by entrained dirt and the proximity of the control electronics to the ammonia system, including the large capacitors in the drive system. This type of compressor is unlikely to receive much funding unless there is a significant move away from fluorinated gases in large chiller systems. In that case, it probably represents the best available technology for providing efficient chillers in the 100 kW to 1500 kW range (30 ton to 430 ton).

Apart from compressors, a need exists for further development in heat exchanger design for ammonia chillers. Microchannel air-cooled condensers offer a significant reduction in refrigerant charge, and it might also be possible to produce a direct expansion evaporator for water chilling based upon a shell-and-tube arrangement but with microchannel material for the tubes.

In parallel with these technical developments, a need exists for a comprehensive review of the structure of safety standards to ensure that ammonia equipment is not misapplied, but also that it is not excluded from appropriate, beneficial applications. The high efficiency of ammonia in domestic heat pumps, implemented across the domestic sector in reasonable numbers would produce significant savings in carbon emissions, even when compared to the use of mains gas as the primary fuel, and in the case of replacement of electric heating, the reduction would be more than 75% provided a suitable heat source was available. The charge limits for ammonia systems are based upon industrial IDLH values that assume 30 minutes is required to effect an escape from the affected area. This is reasonable for equipment installed in a large industrial complex, but it seems excessive in the domestic context, given the self-alarming smell associated with an ammonia leak.

It is important to recognize that ammonia is different than many other refrigerants in this respect because it is not possible to be exposed to a damaging concentration of ammonia and not be aware of its presence. Even for people with no sense of smell, they will experience characteristic signs of eye and throat irritation at levels far lower than the toxic limit, prompting the affected person to leave the area to seek relief in fresh air.

It seems reasonable to allow larger quantities of ammonia to be used in systems for domestic and commercial heat pumps and other appliances provided the unit is not installed in an area where people are restricted in their movements, for example, certain areas within hospitals, schools or prisons. Other types of water heaters are not installed in these areas either. They are located in a utility room. Therefore, this limitation would not significantly restrict the market potential for the new equipment.

Conclusions

Ammonia has been accepted in many new applications without significant overall additional cost, and without any compromise in occupant safety. This has been achieved by the adoption of a range of new technologies, materials and techniques. Further development in these areas present many opportunities to gain energy savings, and these opportunities should not be ignored. A coordinated approach to technical, commercial and legislative development is necessary. It is correct to include a detailed review of legislation and standards in the development exercise because the principles on which the codes and standards are based were laid down more than 50 years ago, and technology has changed beyond recognition since then.

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