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AMMONIA USAGE IN VAPOR COMPRESSION FOR REFRIGERATION AND AIR-CONDITIONING IN THE UNITED STATES

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KEY WORDS

ammonia, refrigerants, refrigeration systems, cooling systems, district cooling

ABSTRACT

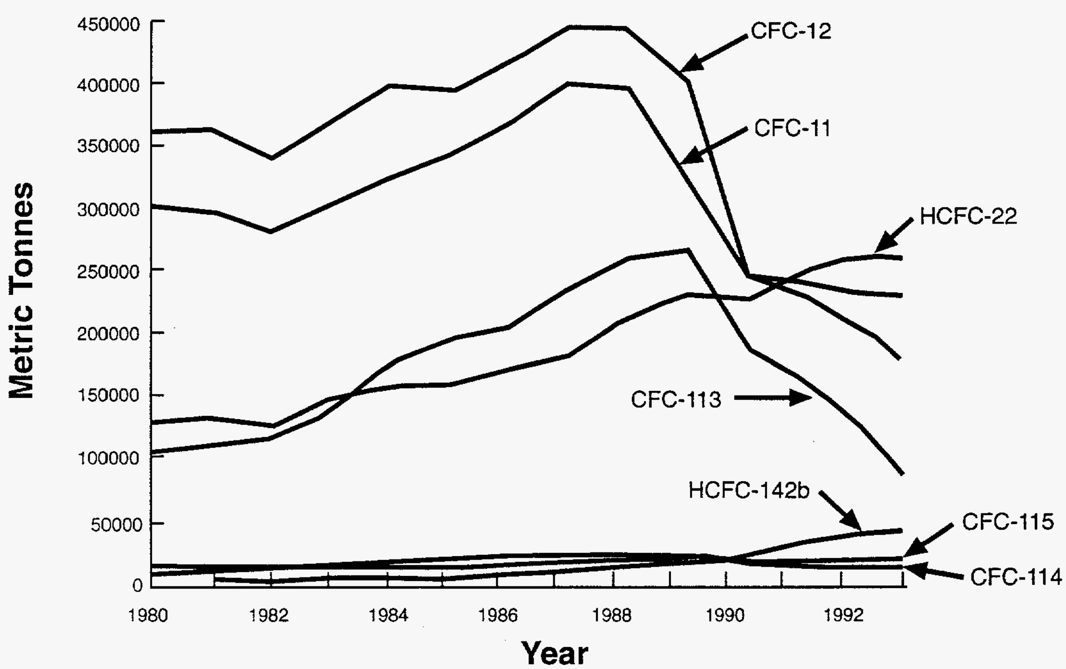
The impending phaseout of CFCs and HCFCs has led to a worldwide search for refrigerants that can provide equivalent performance while not damaging the environment. Long used as a working fluid in industrial and large-scale refrigeration, ammonia provides high efficiency, low initial cost, and no detrimental impact to the environment. However, its toxicity and flammability, along with technical considerations and increased operating costs, deter its use in many refrigeration and cooling applications. Utilization of ammonia in applications where its safety considerations and technical concerns can be addressed provides the best growth opportunity for adoption as a replacement refrigerant. Applications such as district or large-scale cooling, thermal storage, packaged systems, and combined systems hold promise for increased usage of ammonia. Ongoing research and development are providing solutions to technical considerations, and innovations in safety and containment of ammonia are addressing those particular concerns, but code restrictions and regulations present the greatest barrier to wider adoption of ammonia as an alternate refrigerant in the U.S. To encourage wider use, future efforts will need to continue on improved safety and more efficient design, along with an increased emphasis on educating and informing industry and the public about the advantages of ammonia and the factors restricting its use.

1. INTRODUCTION

The impending phaseout of Chlorofluorocarbon (CFC) and Hydrochlorofluorocarbon (HCFC) refrigerants in the early part of the next century poses both problems and opportunities for professionals in the Heating, Ventilation, and Air-Conditioning/Refrigeration (HVAC/R) industry. The problems arise from the need to identify replacement refrigerants, and design new HVAC/R systems and retrofit existing equipment to utilize these refrigerants. The opportunities lie in the new focus to design systems which use reduced amounts of refrigerant and energy, and in the growing interest in previously unused or underutilized working fluids such as ammonia. Used as a refrigerant as early as the turn of the century, ammonia saw its popularity as a refrigerant surpassed by the introduction of CFCs in the 1930s. Because of their relatively low toxicity and flammability, CFCs were seen as a safer alternative to ammonia. The discovery of the ozone depleting and global warming potential of CFCs spurred wider use of HCFCs, which are also slated to be phased out. To replace these classes of refrigerants, options such as blends, Hydrofluorocarbons (HFCs) and "natural" working fluids such as ammonia and propane are being tested for wide-scale usage as refrigerants. Ammonia and other natural refrigerants are called "natural" because they occur in nature, and pose a reduced or nonexistent threat of ozone depletion and global warming.

2. PRODUCTION AND USAGE TRENDS FOR CFCS AND HCFCS

The Montreal Protocol and the London and Copenhagen amendments have mandated that production and utilization of CFCs and HCFCs be phased out by 2030. As Figure 1 shows, production of several widely used CFC and HCFC refrigerants dramatically declined during the reporting period 1986 to 1993. According to production figures reported to AFEAS, production of CFC-11 decreased to 42% of the base year level and production of CFC-12 decreased to 54% of the base year level. Between 1992 and 1993, production of CFC-11 decreased 21% and production of CFC-113 decreased 55%. Production of HCFCs decreased

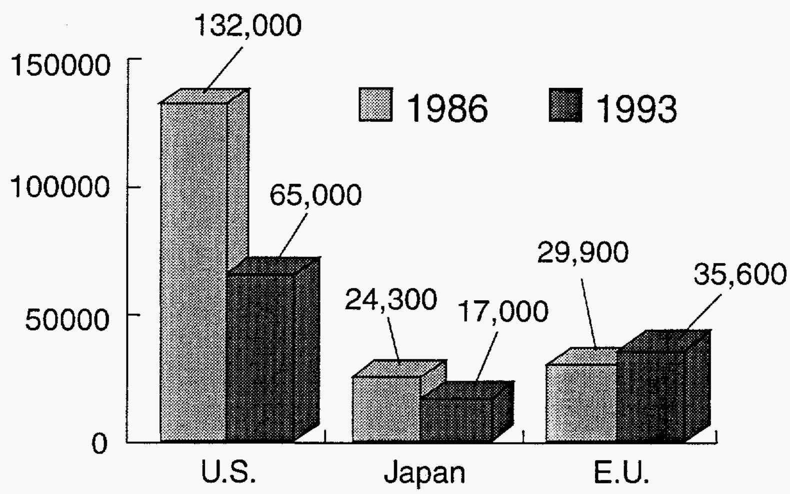


NOTE: "Production" (as defined in the Montreal Protocol) does not include feedstock uses.
Source: AFEAS 1995 Report, "Production, Sales, and Atmospheric Release of Fluorocarbons Through 1993"

Figure 1: Annual Production of Fluorocarbons Reported to AFEAS – 1980-1993

as well, with HCFC-22 production decreasing by 2% and HCFC-142b by 13%. It is anticipated that this trend will continue and increase, especially as the deadline for phasing out CFCs and HCFCs draws closer.

Usage of CFCs has seen a dramatic drop as the deadline for their phaseout approaches. The UNEP Refrigeration, Air-Conditioning, and Heat Pumps Technical Options Committee reported that U.S. usage of CFCs decreased from 132,000 metric tonnes in 1986 to 65,000 metric tonnes in 1993, a 50% decrease. Usage of CFCs in Japan decreased from 24,300 metric tonnes in 1986 to 17,000, a 33% drop. And finally, European Union usage of CFCs *increased* from 29,900 metric tonnes in 1986 to 35,600 metric tonnes in 1995. (See Figure 2) The committee attributed the reductions in the U.S. and Japan and the increase in the European Union to differences in governmental regulations and policies, especially the imposition of excise taxes and restrictions on venting and stockpiling of CFCs.



Source: UNEP 1995 Assessment, "Report of the Refrigeration, Air Conditioning and Heat Pumps Technical Options Committee"

Figure 2: CFC Refrigerant Use (Metric Tonnes)

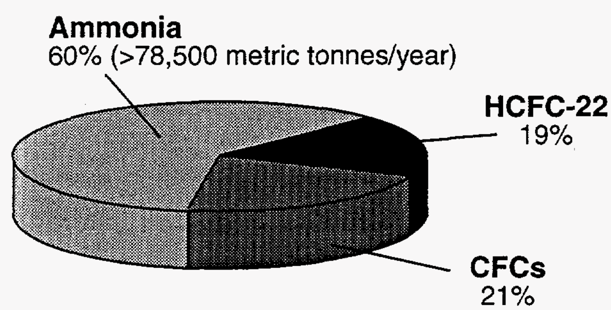
As these numbers indicate, compliance with the Montreal Protocol and its amendments is moving towards completion, accelerating the need to identify alternate refrigerants and focusing increased attention on design and engineering of technologies and applications to fully utilize those refrigerants. Work is progressing on study of the properties and potential usage of blends, HFCs and natural refrigerants, but the largest body of experience and knowledge exists for ammonia

3. WHERE AMMONIA IS BEING USED

Due to the toxic and flammable properties of ammonia (discussed later in this paper), ammonia is primarily used in large-scale and industrial applications where the compressor apparatus is located away from inhabited areas. Ammonia is the most widely used of the non-chlorofluorocarbon refrigerants, with a 60 percent usage level in cold storage and food processing applications (see Figure 3) and over 100,000 metric tonnes a year used, including industrial applications. Ammonia can be found in wide variety of applications, including:

- Chilling of meat, fish, poultry, perishable fruits and vegetables for storage and processing
- Refrigeration of dairy products and beverages such as beer and wine
- Freezing foods for storage, delivery, and distribution
- Freezing and hardening of ice cream
- Manufacture and storage of ice
- Freezing and chilling of surfaces of ice rinks

In addition, systems are now being designed for ammonia to be used as a replacement for CFCs and HCFCs. For instance, chiller and refrigeration units are being initially designed to use HCFC-22, with the option of using ammonia after the HCFC phaseout is implemented. Perhaps the largest growth area for ammonia usage is large-scale air-conditioning or cooling, where a separate contained ammonia compressor chills water or brine to provide comfort cooling for business, industry, or housing blocks.



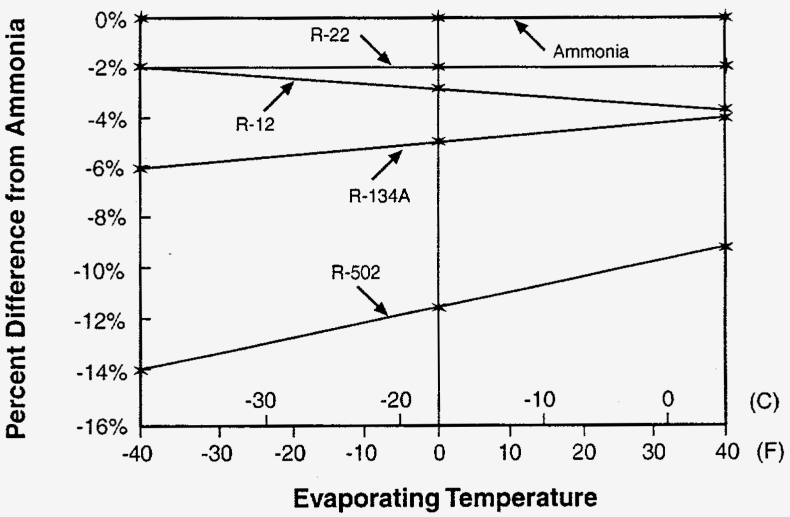
Source: UNEP 1995 Assessment, "Report of the Refrigeration, Air Conditioning and Heat Pumps Technical Options Committee"

Figure 3: Working Fluid Usage in Cold Storage and Food Processing Applications

Some research is underway to expand the use of ammonia in vapor compression heat pumping/ heat recovery applications. In addition, much research is being conducted on usage of ammonia-water solutions in absorption heat pumps - applications which could boost usage of ammonia in small-scale, unitary HVAC/R equipment. However, heat pumps remain a largely untapped and unexplored market for ammonia.

4. ADVANTAGES OF AMMONIA AS A REFRIGERANT

Ammonia offers many advantages as a refrigerant. Its cycle efficiency is very good, offering a favorable Coefficient of Performance compared to CFCs, HCFCs and other alternative refrigerants (see Figure 4). As Tables 1 and 2 show, ammonia's efficiency and thermophysical properties compare favorably to R-12 and R-22, two widely used refrigerants slated for phaseout. Its heat transfer capacity, coupled with low friction loss translates to lower pumping requirements and smaller pipe sizes and lengths - important considerations in cooling/ refrigeration system design.



Source: Pills, J.W. (1993). "Expanding ammonia use in air-conditioning."

Figure 4: COP of Refrigerants Based on Isentropic Compression

Table 1
Theoretical Cycle Coefficient of Performance for Four Refrigerants*

Refrigerant	Coefficient of Performance
Ammonia	4.84
R-12	4.69
R-22	4.75
R-502	4.43

**At -15°C evaporator and 30°C condenser*

Table 2
Thermophysical Properties of Three Refrigerants*

Refrigerant	Specific heat kJ (kg • K)	Thermal Conductivity W/(m² • K)	Viscosity mPA • s
Ammonia	4.57	1.82	0.204
R-22	1.16	0.341	0.248
R-12	0.92	0.265	0.284

**At -7°C*

Source: Cole, R.W. (1990). "Ammonia as a refrigerant in light of the CFC phase-out."

Ammonia has low miscibility in oil, which means separation and removal of compressor oil from the refrigerant is easily accomplished. Ammonia and water mix well, which reduces the likelihood of water collecting and freezing in expansion valves and other components.

Compared to other refrigerants, ammonia is inexpensive (approximately $0.35 US per pound). It is a by-product of the nitrogen cycle, produced in ongoing industrial processes for chemical and agricultural industries. This cost becomes most attractive in large-scale applications, where initial refrigerant charges and recharges involve hundreds or even thousands of pounds of refrigerant.

Ammonia offers excellent environmental benefits as a refrigerant - zero ozone depletion potential and zero global warming potential. It forms a fertilizer if released into the atmosphere and becomes a base when absorbed in water.

Lastly, ammonia has been used as a refrigerant for over 150 years. Much is known about its properties, its benefits and its disadvantages. This gives it an edge over emerging refrigerants, which are not yet full proven in the laboratory or field.

5. DISADVANTAGES OF AMMONIA AS A REFRIGERANT

Ammonia does have some strong disadvantages which have prevented it from becoming the refrigerant of choice after the phaseout of chlorofluorocarbon -based refrigerants. It is toxic to humans at low concentrations, although its strong odor serves as an effective alarm for leaks, and compels people in the vicinity to leave as soon as possible (See Table 3 for the effects of ammonia exposure). Ammonia has several other properties which help mitigate the toxicity question - it is lighter than air, so it rises away from the ground, and it mixes well with water, lending to the utilization of sprinkler systems or water dumps as control measures in the event of an ammonia leak. Lastly, its pungent odor serves as an effective warning indicator of a leak in progress.

Ammonia is also mildly flammable in high concentrations. It requires a strong ignition source and is less flammable than propane or other hydrocarbon-based refrigerants. Its high solubility in water identifies a strong fire control strategy and its low miscibility with compressor oil means that it is easy to isolate and safely remove oil from ammonia compression systems, reducing the risk of fire. Ammonia can be explosive in the presence of mineral oils, so for safety considerations, the low miscibility is a positive quality.

One of the biggest drawbacks to ammonia as a refrigerant is its high reactivity to copper in the presence of water. This reduces the probability of ammonia being used as a "drop-in" refrigerant, since most of the piping and metal components used in chlorofluorocarbon-refrigerant systems are made of copper. In addition, ammonia attacks the copper windings in compressor motors, meaning that the refrigerant cannot be used to cool the motor. Steel and

Table 3
Effects and Levels of Ammonia Exposure

Exposure, ppm	Effects
0-5	Smell hardly detectable
5-20	Human nose starts to detect
25	TLV-TWA (Threshold limit value - time weighted average, 8 h)
35	STEL (Short term exposure limit - 15 minutes)
150-200	Eyes affected to limited extent after about 1 minute exposure. Breathing not affected
500	IDLH (Immediately Dangerous to Life and Health) per NIOSH
600	Eyes streaming after about 30 seconds of exposure
700	Tears to eyes in seconds. Still breathable
1,000	Eyes streamed instantly and vision impaired, but not lost. Breathing intolerable to most individuals. Skin irritation to most individuals
1,500	Instant reaction is to get out

Source: Pills, J.W. (1993). "Expanding ammonia usage in air-conditioning."

some aluminum alloys can be used with ammonia - a trait which increases the costs of building ammonia-based systems, but results in increased durability of the system components.

6. DESIGN CONSIDERATIONS FOR AMMONIA AS A REFRIGERANT

Ammonia's properties and disadvantages mandate certain considerations when designing, installing, or operating systems using it as a refrigerant. First and foremost, in response to concerns about ammonia's toxicity and flammability, a wide variety of trade and engineering organizations have instituted codes and standards for systems using ammonia. These standards include the Uniform Mechanical Code, the Uniform Fire Code, U.S. Occupational Safety and Health Administration Process Safety Management, ASHRAE-15 Safety Code, and the ASME Piping and Safety Code. In addition, the U.S. Environmental Protection Agency has instituted exposure regulations for ammonia and the International Institute of Ammonia Refrigeration has guidelines for the safe usage of ammonia. These codes, standards, and guidelines have imposed numerous restrictions on the usage of ammonia in comfort cooling and refrigeration systems. Among the restrictions:

- Ammonia cannot be used directly with air in comfort cooling systems
- Maximum ammonia charges are limited for indirect systems
  - 225 kg for institutional applications
  - 450 kg for public area applications

- Many codes require operators on duty at all times that the system is in use
- Water dump/sprinkler systems are required in machinery rooms for pressure relief situations at some sites
- Some codes as well as state and local laws mandate extensive (and expensive) air monitoring and scrubber systems

These restrictions and others like them add to the complexity and cost of ammonia systems. In response to these obstacles, many users of ammonia systems abandoned the use of ammonia and numerous would-be users have opted to try other refrigerants, even though they may be less efficient or slated to be phased out.

Safety considerations and code and guideline restrictions have led to the widespread usage of ammonia in secondary loop cooling/refrigeration systems. These systems, where ammonia is used to cool a fluid such as water, glycol, or brine, offer additional isolation of the ammonia from the public, but thermal losses are incurred because of the inefficiencies brought on by the extra heat exchange process. In addition, the increased space requirements resulting from a more complex system limit areas where ammonia systems can be installed.

Ammonia's incompatibility with copper necessitates the usage of steel or aluminum alloys for all parts containing or contacting ammonia. While this does translate into increased durability of the system, these materials offer a poorer level of conductivity than copper. In addition, ammonia has a high discharge temperature when compressed at high compression ratios. In most systems, the refrigerant is used to cool the motor, but since ammonia reacts with the copper windings in the motor, other options have to be explored. Most ammonia systems utilize open compressor motors, which allow for better air-cooling, or utilize water or a secondary cooling fluid like glycol to cool the motor.

Ammonia's poor miscibility with oil offers several advantages - easier separation of the refrigerant from the oil and reduced risk of fire, but it does create an additional design requirement - a means of pumping oil back into the motor. In CFC and HCFC systems, oil mixes with the refrigerant and its transported into the motor with the refrigerant. Since ammonia and oil do not readily mix, a separate mechanism must be found to return oil to the compressor. Many ammonia systems use a pump to circulate the oil.

Despite these safety and technical considerations, ammonia remains an excellent choice as an alternate refrigerant when compared with other options. Unlike CFCs and HCFCs, ammonia has no negative impact on the environment, it is not as flammable or explosive as propane or other hydrocarbons, and unlike zeotropic and azeotropic blends which can separate back into their component refrigerants, ammonia has uniform, well-known properties. The bottom line is that while ammonia has some drawbacks as a refrigerant, its strengths and weaknesses are well known and understood, and efforts to harness those strengths and mitigate those weaknesses can be highly successful, especially as technology continues to evolve.

7. LEADING GROWTH MARKETS FOR AMMONIA IN THE UNITED STATES

As stated before, most of ammonia's market penetration as a refrigerant is in the area of industrial or large-scale refrigeration. Ammonia is the premier refrigerant for cold storage and food processing. Ammonia is also seeing some increasing use in comfort cooling. Virtually all of the applications of ammonia in refrigeration and cooling involve containment and isolation of the ammonia from people, and engineered safeguards to ensure containment and safe disposal in the event of an ammonia leak. In industrial refrigeration and cold storage applications to some extent, there is less emphasis on this containment since it is assumed that human contact with the system will be infrequent and usually only by trained and appropriately equipped personnel. However, the emphasis on safety and containment for comfort cooling has led to a industry-wide acceptance of secondary loop systems as the best way to use ammonia. Most of the emerging applications for ammonia involve secondary loop systems, custom engineered and manufactured designs, and industrial or large-scale applications. These applications consist of dual design systems, thermal storage/chilled water systems, district cooling, packaged systems, and retail refrigeration systems.

7.1. Dual Design Systems

As mentioned before, some manufacturers are producing refrigeration and cooling equipment which is initially designed to use refrigerants such as HCFC-22, and can be converted to ammonia after the CFC/HCFC phaseout. The big selling point with this application is the high capital cost of large-scale refrigeration and cooling equipment. Many customers are balking at spending thousands of dollars on equipment using a refrigerant which will be unavailable or price prohibitive in a few years. Buying a dual design system enables the customer to use a refrigerant such as HCFC-22 in the short term, then switch the system over to ammonia when HCFC-22 is no longer available. One manufacturer, Thermatech Ltd., is offering two lines of dual use chillers which are marketed to new customers and retrofit customers. The chillers are engineered to use HCFC-22 or ammonia and are sold as packaged systems for easy installation, customized applications, and ensured containment of ammonia leaks. Thermatech also promotes their equipment as using smaller refrigerant charges, which reduces the risk of large-scale exposure to ammonia. Dual design systems are likely to enjoy strong growth as the date for the CFC and HCFC phaseouts approaches.

7.2. Ice Thermal Storage/Chilled Water Systems

Some ammonia users are now employing a combination of ammonia refrigerated, chilled water comfort cooling systems with icemaking and storage for thermal recovery. Attractive because of its potential to reduce electrical demand during peak hours, this approach uses an ammonia screw compressor system to make and store ice at night, then melts the ice to provide chilled water during the day for comfort cooling or process refrigeration needs. Miller Electric

Manufacturing Company in Appleton, Wisconsin, installed such a system at their 46,450 m^2 plant. The system provides over 4900 kW of cooling capacity and has room for expansion as cooling or process needs grow. One of the incentives for Miller to try this approach was a rebate offered by the Wisconsin Electric Power Company for a peak demand reduction program. Many U.S. utilities are offering such rebates to manufacturers and other large-scale power users.

A food processing company in Southern California, Best Foods, installed a thermal storage refrigeration/cooling system as part of an overall plant retrofit. The system replaced an aging steam system and CFC-11 chilling/refrigeration system with an integrated package consisting of a dual-source gas-fired steam generator, a bank of five screw compressors supplying -9°C and -43°C ammonia for process refrigeration and comfort cooling needs, and a thermal storage air conditioning system that uses the -9°C ammonia to produce 90,800 kg of ice per day. Best Foods not only enjoyed better performance from its heating, cooling, and refrigeration system, but also realized significant savings thanks to a rebate from Southern California Edison. As is demonstrated here, ammonia can be used for process refrigeration and comfort cooling in an integrated approach with high-efficiency gas heating.

7.3. District Cooling

One of the most promising market segments for ammonia as a refrigerant is district cooling. District cooling takes the containment and isolation needs for ammonia usage to a greater level, where chilled water, glycol, or brine is transported from a machinery building to buildings located around the machinery building. Although district heating and cooling has not traditionally been strong in the United States, there is a growing interest in its efficiency and economic benefits, particularly for cooling public housing projects which have no cooling systems in place. A 1992 U.S. Department of Energy Study on district heating and cooling in the United States determined that nearly 5,800 district systems operate in the United States and collectively provide about 1.3 percent of all energy used in the country each year. An increasing number of utilities have entered or reentered the district heating and cooling business, largely on the cooling side. These utilities include Commonwealth Edison Company, Northern States Power Company, Atlantic Electric Company, and Peoples Energy Corporation. District cooling systems have been successfully utilized in several parts of the country:

- Montgomery College in Rockville, Maryland, installed a district cooling system in 1994 and is building one at its Germantown Campus.
- Two 7040 kW ammonia chillers with gas turbine driven compressors and steel tube heat exchangers were installed by Trigen Energy Corporation in Tulsa, Oklahoma and Oklahoma City, Oklahoma to provide district cooling. Interestingly enough the ammonia approach was selected because it provided better efficiency than a HCFC-22 unit of similar size and capacity.

- A district cooling approach is being used in conjunction with a steam and power generation system at McCormick Place, an exhibition center in Chicago, Illinois. Ammonia is being used to chill a sodium nitrite solution, which will supplement and eventually replace an existing CFC-12 glycol chilling system. The ammonia chiller is fitted with a thermal storage tank for storage of ice for peak period cooling, and the system is located in a separate building with gas-fired steam boilers and a motor/generator, which generates electricity.

Perhaps the most notable use of ammonia as a refrigerant for large-scale cooling is the Biosphere Project. Vilter Manufacturing Corporation built a 4365 kW ammonia chiller to provide comfort cooling and heating to the Biosphere 2 complex. The complex was fitted with two chillers, with one serving as backup. In addition to providing chilled water for cooling purposes, the screw compressor-driven system provided chilled water for heat recovery, where 4°C water was circulated to a storage tank containing eutectic salts in sealed containers. Heat was generated as the salt solution changed phase. This system performed efficiently during the Biosphere 2 project, helping to maintain varying temperatures in six biomes, or environments, in the complex. With the biomes representing areas of the earth, including a rain forest, ocean, marsh, desert, and farming area, a great deal of demand was placed on the HVAC/R system to maintain a variety of appropriate temperatures. The system's success underscored the usefulness of ammonia in both large-scale cooling and heating applications.

7.4. Packaged Systems

Perhaps one of the most exciting developments in ammonia technology is the advent of packaged systems. Using smaller charges of ammonia refrigerant in self-contained units, these systems have potential for wider usage in residential, commercial, and industrial applications. Sized to fit on a slab or on a rooftop, these units provide cooling capacities ranging from 107 kW to 704 kW, utilize air to cool the compressor motor, and offer a high level of safety and containment. Some models even have a water tank or water supply built into the unit to absorb ammonia in the event of a leak. In the U.S., these systems are being offered by two manufacturers - Thermatech Ltd. and York International. Thermatech is offering several of its product lines as dual use systems.

7.5. Retail Refrigeration

As with large-scale applications, efforts are underway to design and install ammonia cooling and refrigeration applications in supermarkets and convenience stores. Because of their multiple cooling and refrigeration needs both for process areas such as the meat department or deli, refrigerator and freezer storage, and comfort cooling, these retail operations could take maximum advantage of ammonia's properties as a large-scale refrigerant. On nearly all of the prototype designs observed so far, a central ammonia compressor uses an ammonia-to-glycol/

water/brine approach to provide cooling for storage and display refrigeration or freezing, as well as for comfort cooling. While this approach ensures greater safety, it does incur losses in efficiency because of the heat transfer between the ammonia and the secondary refrigerant. One ammonia-system prototype demonstrated a four to ten percent drop in efficiency from HCFC-22 systems. Also, the systems tend to be more complicated, which makes them less attractive to retailers.

One innovative prototype system was installed in a convenience store under construction near Jacksonville, Florida. A 7.5 kW variable-speed compressor was installed just outside the store and provided with an 8.6 kg charge of ammonia. An ammonia-flooded evaporator driven by the compressor chilled a walk in cooler for beverages, dairy products, and packaged ice to temperatures ranging from 0 to -1°C. The cooler provided access for bulk storage and swing out doors for customer access. In the event of an ammonia leak, the cooler doors would isolate the ammonia from the store interior and a high wall return would vent the lighter-than-air ammonia up into the atmosphere. For comfort cooling purposes, 1°C return air from the cooler was used to chill a 30% glycol/70% water brine mixture. Running through a air-liquid heat exchanger, the mixture is cooled to between 1°C and 10°C, yielding cooled air between 12°C and 15°C. This particular system is yielding lower operating and maintenance costs and better efficiency than standard CFC/HCFC applications.. While additional testing, research, and development needs to be performed before wider-scale adoption of ammonia as a retail market refrigerant, the success of this and other new prototype systems identifies a significant market opportunity for ammonia-based applications.

8. TECHNOLOGY AND DESIGN ADVANCES FOR EXPANDED AMMONIA USE

There are several challenges common to all of the emerging markets for ammonia applications. As the technology matures and the price of these systems decrease, ammonia usage should grow. However, the major roadblock to wider-scale adoption of ammonia are concerns about safety, and the code restrictions that have been enacted to ensure safety of the public. Not only do these codes prevent certain designs from being used, but they drive up the cost of using ammonia, offsetting ammonia's low basic cost and deterring many from considering it. Technology has evolved to increase the safe handling and containment of ammonia. In addition to designs involving smaller amounts of ammonia, numerous innovations have been developed and applied to make ammonia use safer and more cost-effective. These innovations have evolved into a 15-point safety list for ammonia applications. The list includes:

1. Mechanical ventilation for equipment rooms
2. Pump-out system to remove ammonia from all operating surfaces if repair is called for
3. Ammonia fume-sensing system
4. Automatic alarm and exhaust fan activation if ammonia concentration exceeds 50 PPM
5. Automatic shutdown of system if concentration exceeds 500 PPM

6. Rooftop scrubber/spray system on roof activates if ammonia exceeds 500 PPM
7. Evaporative condenser fans blow air from exhaust fans through evaporative condenser
8. Low pressure vessels are designed to take higher capacities
9. All vessels designed, tested, and inspected according to ASME code
10. Chiller room has dikes in the floor to prevent liquid ammonia from escaping
11. Sprinkler system to flood chiller room if ammonia concentration reaches 1,500 PPM
12. Redundant stand-alone and computer control systems
13. Emergency manual equipment stop outside the machinery building
14. Respirators and protective clothing located at machinery building
15. Computer notification of remotely located personnel in case of emergency

As can be seen, an increased emphasis is being placed on automated processes for ammonia refrigeration and cooling applications. Not only are equipment and facilities being modified to reduce exposure and increase containment of ammonia, but procedures are being developed and people are being trained to increase safe handling and usage of this refrigerant.

In addition to increased or new safety features, advances are being made in compressor technology which will allow increased use of ammonia. Screw compressors are heavily favored for ammonia applications and are continuously being redesigned and improved to harness ammonia's strengths and its weaknesses. The two major areas of concern in ammonia design technology are ammonia's poor miscibility with oil, which necessitates adding a cycle to pump oil back into the compressor, and ammonia's incompatibility with copper, which requires that copper windings in compressor motors be isolated from the ammonia if the refrigerant is used to cool motor. Increased research and development is proceeding on solutions for these concerns. Motors are appearing on the market which have coated windings, meaning that ammonia can cool these motors. In addition, a new generation of lubricating oils is appearing, which could address the miscibility question. A new polyalkylglycol (PAG) miscible oil offering heat transfer benefits has been developed for use with ammonia, which could be used in reciprocating compressor applications.

One of the greatest technical concerns for ammonia applications is heat exchangers. Heat exchangers traditionally are made of copper, but ammonia's reactivity to copper has mandated the use of steel in heat exchangers, a requirement which can result in a heat transfer penalty. In addition, the predominance of secondary loop systems in ammonia applications results in further heat transfer penalties for ammonia systems. A great deal of research has gone into identifying heat exchanger designs which can mitigate these heat losses. Adding to the requirements of lower heat losses and separation of ammonia from the secondary refrigerant, the heat exchangers must have readily accessible surfaces, since fouling of the exchanger surface is an increased concern with ammonia applications. Extensive testing has shown that plate-type heat exchangers offer increased thermal performance, compactness (and reduced refrigerant charge), adequate separation of the two refrigerants, and easy access to all surfaces. In addition to steel, aluminum alloys are being explored for use in heat exchangers.

These advances in technology and design should help provide increased opportunities of ammonia as a refrigerant. Continuing development and increased industry and public awareness of these advances is critical, not only for increased usage of ammonia, but changing perspectives and opinion of ammonia as well.

9. CONCLUSIONS

Ammonia has many excellent qualities which make it a strong candidate as a replacement refrigerant for CFC and HCFC applications. Its high cycle efficiency, low cost, zero ozone depletion and global warming properties, favorable thermophysical properties, and long history of usage as a refrigerant make it a good choice for many refrigeration and cooling applications. However, ammonia's toxicity and flammability serve as strong deterrents to wider usage. In addition, technical concerns such as its reactivity to copper, high discharge temperature, and poor miscibility with oil compel many engineers, manufacturers, and consumers of refrigeration and cooling equipment to ignore ammonia as an alternative to other refrigerants.

Steps can and are being taken to address ammonia's negative qualities and accentuate its positive ones. An increased emphasis on operator and public safety has led to designs using smaller amounts of ammonia; increased automation of operation, detection, and warning processes; adoption of contained, package designs; and usage of ammonia in large-scale applications where the ammonia compression process is contained in a separate room or building. In addition, ammonia is finding its way into dual design systems and absorption process heat pumps, which may be ammonia's best hope for entry into the residential and unitary equipment markets.

Ammonia's strong presence in chilled water and thermal storage systems indicates perhaps its strongest potential growth area. Applications in large-scale refrigeration and district cooling present an opportunity to use ammonia in ways that incorporate key safety features and spread the cost of compliance with codes and safety restrictions across a wider base.

This leads to the two foremost challenges to ammonia's increased use as a refrigerant - code restrictions and industry and public acceptance of ammonia as a refrigerant option. The technical issues arising from ammonia's incompatibility with copper, its discharge temperature, and its poor miscibility with oil can be addressed through good engineering and continued research. However, increased costs and design considerations brought on by code restrictions, and industry and public antipathy to ammonia are obstacles that can prove fatal to any effort to increase ammonia usage. The fundamental challenge to proponents of ammonia is to establish a building code that addresses safety concerns at a reasonable cost, and can be adopted across thousands of political jurisdictions. Ammonia is not suited to all refrigeration and cooling applications, but it can be used very well in many.

Education is as important a part of the ammonia adoption process as engineering and development. Simultaneous refinement of ammonia technology, as well as widespread efforts to revise codes and restrictions, will be necessary before this highly attractive and useful refrigerant can be employed to full advantage.

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