RECENT DEVELOMMENTS IN AMMONIA REFRIGERATION

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INTRODUCTION

Ammonia is the most trusted refrigerant right from the 19th century. All those who are involved in food preservation and industrial process plants know Ammonia as refrigerant of choice due to its unmatched thermodynamic properties. This article is written due to renewed interest ammonia has generated in not only in refrigeration but air conditioning community as well. The reason being banning of CFC refrigerants and GWP concerns for HFC substitutes, and other associated unforeseen problems those may reveal subsequently.

Environmental concerns are therefore making Scientists / technicians to take a serious look at natural refrigerants like air, water, ammonia and carbon dioxide and others as a long-term alternative which would be looked at as **'NO REGRETS SOLUTION'**.

Ammonia refrigerant having withstood the test of time over more than a century as one of the best choices, is receiving attention in the areas of application where it was unthinkable earlier.

This article discusses such areas of new applications, while restating some of the unbeatable excellent characteristics of Ammonia refrigerant.

BACKGROUND

Ammonia was used for refrigeration in 1876, for the first time in vapour compression machine by Carl Von Linde. Other refrigerants like CO_2, SO_2 also were commonly used till 1920's. Every refrigerant had its own advantages / drawbacks such as CO_2 was preferred as being less dangerous, although it operated at a much higher pressure than Ammonia.

Development of CFC's (Chlorofluorocarbons) in USA, in 1920's swung the pendulum in favour of these refrigerants, as compared to all other refrigerants used in those days, CFCs were harmless and extremely stable chemicals.
The consequences to the outer environment of massive releases of refrigerant could not be foreseen in those days. "CFC" refrigerants were promoted as safety refrigerants, resulting in an accelerating demand and CFC's success. These refrigerants became known as God sent & man-made chemicals.

Due to success of CFC's, Ammonia came under heavy pressure, but held its position, especially in large industrial installations and food preservation.

In 1980's the harmful effects of CFC refrigerants became apparent and it was generally accepted that the CFC refrigerants are contributing to depletion of ozone layer and to global warming, resulting in Montreal protocol (1989) where almost all countries agreed to phase out CFC's in a time bound program.

In view of seriousness of damage to atmosphere and resulting dangers due to CFC/ HCFC emissions as also due to global warming effects, the revisions in Montreal protocol (1990), 1992(Copenhagen) & 1998 Kyoto Japan demanded accelerated phase out schedule. Even HCFC's are also to be phased out and Europe has taken the lead. Many countries in Europe have stopped use of HCFC refrigerants, and new refrigerants as well as well tried and trusted refrigerants like Ammonia/ Carbon Dioxide are being considered for various new applications as well.

During 70's organizations like ASHRAE were not even entertaining articles on ammonia refrigeration, however as ammonia started generating renewed interest, ASHRAE issued a position statement in 1991 which is reproduced as under

"ASHRAE considers that the continued use of Ammonia is necessary for food preservation and air conditioning. ASHRAE would promote a variety of programs to preserve the economic benefits of Ammonia refrigeration while providing for management of risks.

ASHRAE will

1. Promote authoritative information on Ammonia by seminars and publications.

2. Continue research on Ammonia topics such as handling application, operation and control of emissions.

3. Maintain and develop standards and guidelines for practical and safe application of Ammonia.

4. Provide programs and publications of innovative designs and applications using Ammonia

5. Advise govt. and officials with information regarding Ammonia.

ADVANTAGES OF AMMONIA

Before we proceed further, it would not be out of place to re-look at various excellent qualities of ammonia as a refrigerant compared with HCFC 22, since ammonia is making rapid in roads in the areas so far exclusively reserved for HCFC 22 refrigerant.

1. PERFORMANCE

The COP is highest for ammonia (4.84) compared to other regularly used refrigerants, next only to CFC 11(5.09), which is already banned refrigerant.

2. EFFICIENCY

Ammonia systems mostly operate on flooded designs. The artificial head pressure control to ensure proper operation of expansion valve is therefore not necessary in ammonia plants. The condensing temperatures can be as low as possible, and this increases cycle efficiency and reduces energy consumption if yearly energy consumption is established, in comparison with HCFC/HFC direct expansion systems.

3. HEAT TRANSFER

Most of the thermal properties influencing heat transfer are favourable to ammonia compared to HCF 22 refrigerant

a. Specific heat of liquid is 4 times - 4 to 1
b. Latent heat of vaporization is- 6 to 1
c. Liquid thermal conductivity is -5.5 to 1
d. Viscosity is less- 0.8 to1
e. Liquid density is less as mentioned above- 0.5 to 1

All these properties help in improving heat transfer correlation between ammonia relative to HCFC 22 for condensing and evaporating heat transfer processes.

The table below will illustrate this	Ammonia	HCFC 22
Condensation outside tubes(W/m^2K)	7500-11000	1700-2800
Condensation inside tubes	4200-8500	1400-2000
Boiling outside tubes	2300-4500	1400-2000
Boiling inside tubes	3100-5000	1500-2800

The higher heat transfer coefficients help in use of smaller evaporators & condensers or retain same heat transfer areas & operate at higher evaporating temperatures & lower condensing temperatures, thus improving the cycle efficiency.

4. DENSITY

Density of ammonia is half of HCFC 22. (582 m^3/kg for Ammonia compared to 1128.4 m^3/kg for HCFC 22). Thus refrigerant floats on oil layer even if it goes in the crankcase & possibility of oil getting diluted with refrigerant and thereby affecting lubrication is much less compared to HCFC 22.

5. MASS FLOW RATE

Ammonia is more efficient. Its mass flow rate for a given refrigeration capacity is 1/7 times that of HCFC 22, (0.00091 kg/s for ammonia compared to 0.00616kg/s for R-22 at 250K evaporation and 303K condensation temperatures) which means only 1/7 liquid needs to be pumped for given refrigeration capacity. Thus, mechanical pumping power will be much less in ammonia system.

6. NATURAL REFRIGERANT

Ammonia is present in the atmosphere and available in nature in abundance. In nature it is produced by biological processes and is naturally decomposed & does not add to GWP(0 compared to 1500 for HCFC 22)or ODP(0 Vs 0.05 for HCFC 22). Each human being produces approx. 17 g of ammonia per day. Human liver has capacity to convert 130 gms of ammonia into urea each day.

7. LEAK DETECTION

Ammonia has a pungent odour and even small leaks less than 5 PPM are detectable by smell so that maintenance staff can correct them. The odourless refrigerants like HCFC- 22 or HFC 134a, even from the system if it leaks in large quantity, it won't be noticed till cooling performance drops.

8. LIGHTER THAN AIR

Since ammonia in vapour form is 1.7 times lighter than air, it quickly rises up in the air in case of leaks and does not stagnate in the plant room. Density of ammonia is 0.644, for air is 1.21 and for HCFC 22 is 3.2. In case of HCFC leaks, due to its odourless character, it settles down in plant room when leaks develop without anyone noticing it and deaths have been reported due to suffocation since required quantity of oxygen has been displaced by refrigerant.

9. LEAKAGE LOSSES

The molecular weight of ammonia is 17.03, whereas HCFC 22 has 86.48. This means if plant develops leak of equal size on both plants, loss of higher density refrigerant HCFC 22 would be greater than ammonia.

10. WATER CONTAMINATION

Ammonia systems are more tolerant to water contamination than HCFC/HFC systems. A little leak of moisture in the system which does not exceed concentration beyond 100 PPM stays in the solution & does not freeze out. Hence modest contamination with water does not usually interfere with ammonia system operation.

11. BEHAVIOUR WITH OIL

HCFC 22 & other HFC refrigerant liquids and commonly used lubricating oils are mutually soluble in varying degrees depending upon type of oil, operating temperature and pressure, while ammonia & oil are virtually insoluble. Hence recovering oil from various parts of system is easier & requires different approach to oil management. Oil recovery problems are non existent with ammonia at partial loads unlike HCFC 22 systems.

12. PIPE SIZES

Ammonia pipe line sizes are smaller or on other words same size would carry 2 to 3 times more refrigeration capacity than HCFC 22. The cost of piping is therefore less. For example a 10 cm diameter Pipe has 280 kW suction line capacity with HCFC 22 at pressure drop equivalent to $1^{0}C$ per 30 m length, where as for ammonia the same line would be suitable for 728 kW capacity.

13. CRITICAL TEPMERATURE

Critical temperature for ammonia is $132.4^{0}C$ and for HCFC22 is 96. 00C.hence ammonia is better suited for heat pump applications.

14. SAFETY GROUP

Earlier gases were grouped only in two categories, group I and group II.

ANSI standard and ASHRAE regrouped these to differentiate them as Group A1, A2, A3 and B1, B2, and B3. Ammonia is in B2 category. The BS standard 4434-1995 permits use of ammonia for air conditioning plants in public areas directly, if the refrigerant charge is restricted to less than 50 kg.

15. COSTS

Ammonia costs are 20 times lower than HCFC 22 or HFC 134a in India. Not only ammonia is cheaper but is available in any part of the country and is produced indigenously. The HFC refrigerants which have been introduced recently as CFC substitutes need to be imported still.

LIMITATIONS & DRAWBACKS

Having covered most of the advantages and positive points of ammonia as refrigerant, we need to also look at its drawbacks/limitations for its use in some of the major applications like air conditioning.

1. FLAMABILITY

General public perception is ammonia is flammable and toxic and therefore it is not permitted in direct cooling air conditioning plants for public areas.

Ammonia is extremely hard (above 650^{0}C) to ignite and breaks down above 450^{0}C. The leaks are detectable above 5PPM by most. It is therefore extremely rare to encounter such high temperatures in normal air conditioning and refrigeration applications. There is no reason for any concern that exposure to ammonia is a health hazard.

2. TOXICITY

Laboratory trials have proved that continuous exposure levels for 10 to 15 years up to and exceeding 24 PPM has no adverse effect on human beings. Exposure to 100 PPM causes irritation but no health hazard. Exposure for ½ an hour above 5000 PPM may be fatal. Since the pungent smell of ammonia above 5 PPM is detectable, and serves as early warning, no one in its right senses would remain in the vicinity of ammonia leaks and would run away if the leaks are not controllable.

3. HIGH DISCHARGE TEMPERATURES

Since index of compression for ammonia being 1.31 compared to 1.18 for HCFC 22 refrigerant, for the same pressure ratio, discharge temperatures in ammonia plants are substantially higher. For example, at 60^{0}C condensing and -15^0 C evaporating temperatures, for ammonia it is around 180^{0}C, whereas for R-22 it is 115^{0}C.

Above 120^{0}C, mineral lubricating oil properties start deteriorating and for ammonia refrigerant applications, one has to therefore go in for two staging system design beyond 50K temperature difference between saturated condensing and evaporating temperatures. These applications can normally be met with single stage system design, if R-22 refrigerant is used. The recommended limit for single stage operation for R-22 is 70K.(beyond which two stage designs are preferred)
In heat pump application this can be looked at as an advantage. The available heat at discharge is much higher for ammonia compared to R-22 systems.

4. INCOMPATIBILITY WITH CERTAIN MATERIALS

Ammonia is not compatible with copper and copper bearing alloys. It is fully compatible with iron, steel and aluminum.
Since chlorofluorocarbons are compatible with all materials, any material can be chosen and thus provides greater flexibility. Technicians are more comfortable with simple soldering or brazing copper than welding steel. This is however not an issue with those who are used to work on ammonia plants and therefore cannot be considered as an area of concern.

From the foregoing advantages and disadvantages of ammonia refrigerant, one can easily see that the advantages overwhelmingly outweigh disadvantages.

The question then has to be addressed as to why ammonia refrigerant is not used across the board?

We shall now look at some of the application limitations for ammonia refrigerant in more details.

1. As discussed earlier, while using reciprocating compressors, for evaporating temperatures below -15^{0}C up to -30^{0}C, R-22 is preferred since a single stage system design is possible which is much simpler, although uni-build two stage compressors using single motor are available. In R-22 plants, discharge gas temperature limitation is rarely a consideration, whereas in ammonia plant system design, it is one of the primary considerations designers should ensure that discharge gas temperature at the compressor out let does not exceed 120^{0}C.
2. Ammonia air cooled condensers are rare due to the limitations mentioned, especially for tropical countries like India where ambient temperatures are high throughout the year. Smaller plants or appliances using ammonia are not available using air cooled condensing units and all systems are water cooled which requires water circulation system with pumps, piping and cooling tower. Another reason being, as ammonia is having large latent heat, and low mass flow, the smaller size compressor designs are not easy to design & would be expensive as well as regulation of the refrigerant injection becomes more difficult for smaller capacities for applications like domestic refrigerators or room air conditioners, use of electronic expansion valves would solve this problem. In some countries like Germany/Denmark efforts are being made to make units using ammonia for capacities below 50 kW(10 Ton)
3. Due to insolubility of oil and ammonia, high efficiency and expensive oil separators are required and flooded evaporators with gravity or pump circulation are usually employed requiring larger quantity of refrigerant.
4. Because of danger to the public in case of major ammonia leaks, with the current technology used for ammonia plants, the evaporators often cannot be installed directly and indirect secondary refrigerant circuit is needed.

This can make the plant more expensive and consume more power as one more intermediate cooling medium is introduced.

As mentioned earlier, since Ammonia refrigerant has now generated renewed interest, we shall look at the opportunities available for use of Ammonia Refrigerant.

RECENT TRENDS AND FUTURE TECHNOLOGY

1. Heat pump applications are on increase. Ammonia refrigerant is better suited for this duty. High speed ammonia compressors also need to be developed. Earlier ammonia reciprocating compressors were slow speed in the range from 300 to750 RPM. Current compressor designs are available up to 1500 RPM. Screw compressors running at 3000 RPM are also available.
2. In order to make air cooled condensing units, compressors have to be redesigned to withstand at least 40 bar pressures so that condensing temperatures of 60^0C are possible.
3. Montreal protocol prohibits release of refrigerants to the atmosphere, because of this there is already a general trend to shift to indirect cooling systems, so that refrigerant charge in the system is reduced, system becomes more compact & potential leaks through longer pipe lengths are drastically cut down.
4. Factory build, compact ammonia liquid cooling packages (with refrigerant charge limited to less than 50 kg) mounted in air tight containers, with leak detector actuated automatic safety ventilation would avoid any risk of accidental leaks of ammonia entering public places. The containers would also be built with integrated water reservoirs to absorb ammonia in case of leaks. (One liter of water is capable of absorbing 0.517 kg of ammonia liquid or 650 liter of ammonia vapour).
5. Hermetically sealed compressor/motors units are currently not available for ammonia, although canned designs are widely used for ammonia liquid circulation pumps. If similar design is employed for compressors, it reduces motor efficiencies drastically due to air gap, especially for larger sizes, and semi hermetic compressors are currently therefore not popular.
   Lot of research is under way in Germany & other parts to design hermetic compressors with aluminum windings and some manufacturers have already started marketing such compressors.
6. Many companies are working on use of aluminum heat exchanger technology since aluminum is compatible with ammonia refrigerant. Using aluminum improves heat transfer efficiency compared to steel up to 17% depending on operating conditions. Aluminum heat exchangers, if widely made available, would enable use of direct expansion cooling coils and accelerate development of air-cooled condensers with ammonia, similar to HCFC/HFC refrigerants. Also finned tube compact heat exchangers, similar to R-22 can be manufactured. (Manufacturer-Lewis Cimco)

7. Welded plate heat exchangers introduced in the last decade has changed the entire scene with ammonia refrigerant applications. Earlier, or even today many designers use shell and tube plain tube heat exchangers which are large. The plate heat exchangers have made factory assembled packages possible. It has also reduced quantity of refrigerant drastically, making use of small capacity air conditioning applications possible. Sabroe Denmark is marketing such packages using Welded plate heat exchangers for both evaporator and condenser side.

   Some of the advantages of PHE's over conventional shell and tube heat exchangers are as under

   a. Smaller refrigerant wolumes-90% savings
   b. Very compact construction/ Factory built packages-2 to 5 times less space
   c. Minimum temperature differences/improve efficiency- 1.5^{0}C compared to 5^{0}C
   d. Easy access for capacity addition
   e. No risk of bursting due to freezing
   f. Less maintenance time-15 minutes compared to 60/90 minutes.
   g. Direct cooling due to highly resistant Plate Material (beer, milk, wine)
   h. Higher heat transfer coefficients – 3.5 times
   i. Lowe operating weight – 3 to 10 times
   j. Not sensitive to vibrations
   k. Easy to detect leaks- on exterior
   l. Repairs- Easy to replace plates-requires tube plugging for S&T design

It would therefore be not out of place to mention that in the years to come, PHE's would replace use of S&T heat exchangers for ammonia plants in majority of applications once the costs start coming down.

8. Since ammonia evaporators are not allowed to be used where they are exposed to public areas, a recent development of using ammonia and CO_2 cascade systems are becoming popular for super markets. Ammonia is used in high stage system and CO_2 is used for low stage. Thus, direct exposure of ammonia containing parts is thus avoided.
9. Systems using melt ice slurry for chilling is also being used, which reduces energy consumption by 10% compared to most HCFC or HFC direct expansion systems. Since ice slurry is used as secondary coolant and works on phase change, latent cooling capacity is available & smaller volumes need to be pumped.
10. Thermal storages with ice build up during night time and using this capacity during day time for air conditioning is becoming popular in developed countries. This is due to large differential electrical tariff rates for day time and night time (4/5 times more during day compared to night tariff). It therefore works out economical to produce ice/or chilled brine at night and use this stored capacity during working hours during day time.

11. As discussed earlier, since oil is immiscible with ammonia, transportation of ammonia for direct expansion systems is an issue. An azeotropic mixture of 60% ammonia and 40% DME has been tried successfully to improve oil miscibility characteristics. A German research Institute has developed system using this mixture.

We have covered some of the areas where active research/optimization efforts are globally on, to make ammonia refrigeration more popular.

We shall now look at what published literature and some of the experts have to say on use of Ammonia as a refrigerant.

PROBLEM OF PUBLIC PERCEPTION

ASHRAE Journal –May 99

William McCloskey, Executive vice President of Baltimore Air Coil said "IIAR & its members must dedicate themselves to countering the negative perception about ammonia, not with the industry peers but with general public. This includes the faulty perception that city code prohibits use of ammonia in installations in metropolitan areas".

He sited an example that in several cities including Chicago which has restrictive codes, more than 140 urban ammonia installations are operating.

The air conditioning installations using ammonia include McCormick Place & W.W. Grainger office building. The 40 storey Blue Cross Blue Shield building that also has ammonia chillers for air conditioning.

OSLO AIRPORT AIR CONDITIONED WITH AMMONIA

The most recent example is installation of Ammonia system for air conditioning of Oslo Airport Finland, which was commissioned in October 1998.

This is one of the largest and most advanced airports having a capacity to handle 16 to 18 million passengers / year with 64 check-in counters and handling 80 aircrafts per hour. The total operational building area is 18, 000sq.mtr and commercial area 2.7 sq.km. The total area is 13 sq.km.

Plant uses Ammonia refrigerant in indirect cooling chilled water system, using 3 number reciprocating 16-cylinder compressors in one area & 2 number reciprocating compressors of 8 cylinders in another area.

Total refrigeration capacity		6300 KW
Electrical Motors	5 x 280 + 2 x 160 =	1720 KW
Condenser Capacity		8000 KW
Cooling Tower		4000 KW

Quantity of Ammonia	2500 Kg

The above example makes the point in favour of Ammonia as refrigerant for Air conditioning & dispels all myths about safety and fire hazard issues.

POST & TELEGRAPH BUILDING AIR CONDITIONING - COPENHAGEN

This plant uses reciprocating compressors with Plate Heat .Exchangers for Evaporator as well as on Condenser side.

The particular mention of this plant is made in this article to stress the point that with use of plate Heat Exchangers, the quantity of refrigerant required to be circulated reduces to nearly 20% and thus handling of refrigerant and dangers due to possible leaks are minimized substantially. A factory assembled water chiller using PHE heat exchanger of 2700 kW capacity uses only 165 kg of Ammonia (0.22 kg/Ton)

The point worth mentioning from above examples is most of the large plants use indirect cooling systems. These plants were using R-11 refrigerant till recently. After banning of this refrigerant, manufacturers started producing machines with R-123, which was also discontinued by most and presently R-134a or R-22 water chillers are being promoted. In comparison ammonia screw chiller packages or reciprocating packages becomes a more attractive alternative for in direct cooling applications as it saves substantial power.

ASHRAE Journal May 2000

An article describing use of ammonia for ice storage application for air cooling using 700 HP screw compressors, by Byron H Bakenhus won the best engineering excellence award.

EURAMMON- This is a German organization promoting use of Ammonia- It states that use of PHE has reduced ammonia charge per kW to 0.06 kg/kW for dry expansion & 0.04 to 0.1 kg/kW for flooded evaporation. This permits liquid chillers with less than 50 kg ammonia charge to be used in publicly accessible rooms without a separate machine room.

RAC NEWS 2001

Mycom has developed an ammonia compatible compressor oil(patented world wide) which means there is no decreasing heat transfer I evaporator or condenser and does not require oil separator to be installed in the plant. The oil

will return back to compressor automatically the easiest way with refrigerant suction gas & thus the plant becomes maintenance free.
Miscible PAG oils up to minus 20^0C have also been tried by other manufacturers.

ASHRAE JOURNAL OCTOBER 2001

This journal has excellent article giving a case study of ammonia installation for super market instead conventional R-22 refrigerant. The article gives comparison with use of both refrigerants. The installation is in Brazil.

ASHRAE JOURNAL 2001 MAY

William Duffy, President of P & O cold logistics, said 15 of his company's cold storage facilities use ammonia. He also plans to convert remaining two of his R-22 plants to ammonia.

RAC –January 2000

Increased use of adhesives is being tried for pressure containing parts for joining. Use of aluminum and associated joining techniques such as brazing of stainless steel or aluminum is being experimented. Use of resin bonded printed circuit heat exchangers is being explored. All these will help in popularizing ammonia refrigerant use in direct use of ammonia in small cold/chill rooms and packaged air cooled chillers suitable for roof top installations for offices, supermarkets and factories.

WEILAND GEMANY

This company is leading tube manufacturer. It has developed steel tubing with Enhanced heat transfer surfaces for use in ammonia shell and tube heat exchangers. This Geva B tubing for use in evaporators has double enhanced tubing with ridged inside surface as well the heat exchangers using this tubing have been manufactured by one of the Indian companies successfully.

STAR COOLERS

This UK based company with its manufacturing facility in India promotes use of Stainless-steel coolers for ammonia applications and have installed many such units successfully in India and abroad.

CONCLUSION
The author has tried to cover most of the information on current use of ammonia with various applications and the recent trends in research activities for promoting use of ammonia. Author firmly believes that Ammonia is the refrigerant fr the future and efforts should be made to overcome its limitations for some

applications. With the current level of technology available in the world and safety standards in place, if the design and execution is done properly, there is hardly any danger of using Ammonia as refrigerant. In India, in fact, most of the cold storages and ice plants use Ammonia and the plants are manned by uneducated and untrained technicians. To the best of Author's knowledge, no major accidents or mishaps have been reported or recorded so far.

The article can be summed up by no better comments than made by Nestle, one of the most popular brands known world over.

Mr. Bent Weincke, Nestle USA said, Nestle believes HFC. are a transient refrigerant & we don't know if they will be around in another 10 years. We strongly believe in advantages of ammonia and ammonia is therefore Nestle's preferred choice.

Ramesh Paranjpey **December 26, 2003**

Comparative Refrigerant Performance per kW of Refrigeration
Standard cycle 258 K evaporation/303 K condensation
ASHRAE Hand book Fundamentals 2005 Page 19.8Table 7

Refrigerant	Evap.Pr. MPa	Con.Pr MPa	Comp. Ratio	Ref. Effect kJ/kg	Comp.Disp. L/s	Power consm kW	COP	Disc. Temp. K
R-22	0.295	1.187	4.02	162.67	0.478	0.214	4.66	326
R134a	0.163	0.767	4.71	148.03	0.814	0.216	4.60	310
R404A	0.365	1.42	3.89	114.15	0.470	0.237	4.21	309
R407C	0.288	1.26	4.38	163.27	0.492	0.222	4.50	321
R410A	0.478	1.872	3.92	167.89	0.318	0.222	4.41	324
Ammonia	0.235	1.162	4.94	1103.14	0.463	0.210	4.76	372

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