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# Expanding the Use Of Ammonia

By Paul de Larminat, Ph.D.

Discussing new developments for ammonia sounds like a paradox, as ammonia is one of the oldest industrial refrigerants. As emphasized by J.W. Pillis,<sup>1</sup> it never stopped being a leading refrigerant for large systems used in food industry and for other industrial applications. After losing market share to R-22 in recent decades, it is making a strong comeback due to the pressure to phase out R-22. Some major food industry companies have a clear strategy of using only ammonia for their new investments, and to retrofit their existing plants worldwide.

A growing tendency is to use ammonia in large, centralized applications like district cooling and heating, including heat pump applications. The technology in these large systems is already well known and traditional, except for heat pump applications. These large systems often use direct cooling, and (or) evaporative condensers.

Besides the large systems using “conventional” technologies, the new concerns about the environment have promoted investigations for new applications for NH<sub>3</sub>. The potential growth of ammonia depends on the various market segments.

- For domestic refrigeration and unitary products, the pressure to seek alternatives to HFCs is coming from Northern Europe and Germany, where hydrocarbons are being considered as the alternative.
- For the automotive industry, flammable or toxic products cannot be used in direct cooling systems for safety reasons; CO<sub>2</sub> is being investigated as an alternative to HFCs.
- In commercial refrigeration, a potential definitely exists for increased use of ammonia.

- Ammonia has significant potential for growth in medium-size air-conditioning systems.
- With the increased emphasis on energy savings, market opportunities exist for NH<sub>3</sub> heat pumps.

Therefore, the newly identified market and products are primarily for small and medium capacity (~50 to ~2000 kW) liquid and water chillers for air-conditioning, industrial and commercial refrigeration applications, and occasionally including heat recovery. New ammonia products are packaged chillers because indirect cooling systems are safer for small systems. This tendency to indirect cooling is not limited to ammonia. This is a general trend to improve the charge containment with any refrigerant including HFCs. Once it is decided to get rid of direct cooling, the question comes naturally: “why not ammonia?”

## Safety and Environment Issues

The advantages and disadvantages of ammonia are well known:

- It has excellent thermodynamic and thermophysical properties.
- It is “natural” and environment-friendly.

- However, it is moderately toxic and flammable, which requires special care for implementation.

As seen earlier, the major incentive to use ammonia for new applications, is the pressure to phase out the HCFCs (including R-22). This phasing out has started in Europe. Since early 2000, the production of new equipment using R-22 is already prohibited if the motor power exceeds 150 kW. Further restrictions are coming. According to an EC project, HCFCs should not be sold in new equipment with a cooling capacity of more than 100 kW after Dec. 31, 2000.

The replacement of R-22 is shared between the HFCs on one hand, and the “natural” refrigerants (ammonia and hydrocarbons) on the other hand. The split depends on the environmental and safety regulations, which vary greatly according to the countries.

In Northern Europe (Germany, Benelux, Scandinavia, etc.), restrictions on the use of ammonia and hydrocarbons are minimal, while the phaseout of HCFCs is anticipated and there is pressure for the future elimination of HFCs. This situation strongly favors natural refrigerants. In Southern Europe, safety regulations severely limit the use of ammonia and most of the market goes to HFC-based equipment.

Within the “natural” refrigerants, hydrocarbons are taking a share of the market, but only in small capacity packages (below 150 kW), because of their higher flammability. Whatever the local regulations, ammonia safety features deal with

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minimizing the refrigerant charge; suitable ventilation; ammonia absorbing systems; restricting the use of ammonia in public locations; and promoting indirect cooling systems.

Incidentally, the use of air-cooled condensers with ammonia is particularly attractive from a safety standpoint. Ammonia is lighter than air and will rise quickly from the environment of a roof-top unit in case of a leak. Therefore, ventilation is not a problem, and safety issues are easier to solve. The same applies to evaporative condensers, which are widely used for large systems. Another safety reason to prefer air-cooled condensers, is to reduce the risk of "Legionella" disease, in situations where this is a concern.

### **Compressor Developments**

Ammonia compressors have been around for more than a century, but the new regulations and market trends have driven new developments, mostly related to the use of new types of oils, the tendency to go to higher pressures, and requirements for semi-hermetic compressors.

#### Oils

With ammonia, the traditional choice in the past was to use inexpensive mineral oils, and occasionally PAO oils when a very low pour point is required. These types of oils are not miscible with ammonia. The oil is significantly heavier than liquid ammonia and tends to separate and drop at low points of the circuits, where it can be collected for elimination or automatic oil return. This technology is proven in flooded evaporators or pump-fed in-tube recirculation systems, where the heat transfer surfaces are continuously flushed with liquid ammonia.

It is not so in shell-and-tube D-X ("dry-expansion") evaporators. Because of their basic principle, the refrigerant is boiling inside the heat transfer tubes, and is totally evaporated when reaching the tube outlet. As a result, no pool of liquid is available to wash the oil away, which tends to leave a thermally insulating oil coating that drastically reduces the efficiency of the exchangers.

The solution to these problems has been found within a new generation of PAG oils (Poly Alkylene Glycol) that are miscible with ammonia. These new brands of oils allow the use of shell-and-tube D-X evaporators, down to a temperature of about  $-20^{\circ}\text{C}$  ( $-4^{\circ}\text{C}$ ). The mutual miscibility of oil and ammonia is an advantage in the exchangers; but it also generates some oil dilution and occasional foaming in the compressors, which alters the conditions of lubrication. This phenomenon occurs with most combinations of oils and refrigerants. It is a well known pitfall that can cause an epidemic of compressor failures.

Any new combination of oil and refrigerant requires that the compressors be carefully validated, through endurance and field testing, with subsequent corrective actions when necessary. The introduction of the HFC refrigerants combined with polyolester oils required such validations. Similar procedures are an absolute must for ammonia with miscible oils.

#### High Pressure Compressors

The environmental-driven pressure to find alternative refrigerants is necessitating solutions with higher pressure refriger-

ants. Examples are the growing use of R-410A, and the questions being raised about the potential uses of  $\text{CO}_2$ . The need for energy savings also is boosting the market of heat pumps and heat recovery, which require higher operating pressures. This conjunction of incentives is driving the compressor manufacturers to develop new generations of compressors, suitable for operation at higher operating pressures (up to 40 bar discharge). This impacts many points of the compressor design, like casing resistance, bearing arrangement, shaft stiffness, etc. Taking advantage of this higher pressure opens the possibility to make ammonia heat pumps up to  $75^{\circ}\text{C}$  ( $167^{\circ}\text{F}$ ).

#### Motors

Open drive motors are commonly used with ammonia systems, to avoid problem with copper motor windings. New shaft seal technology can limit leakage to less than 0.01% of the refrigerant charge annually, eliminating concerns about shaft seal leakage. Flange-mounted open motors also address alignment issues. This is a cost effective approach, allowing the use of standard open motor technology.

Semi-hermetic motors also are being tested, as the motor technology is being developed now for ammonia, using either aluminium windings (expensive), or encapsulated copper windings. Open motors with magnetic couplings can also be used for medium-size units.

### **Heat Exchangers For Ammonia**

#### General

Ammonia has excellent thermodynamic properties, but part of this potential will be lost if the heat exchangers have a low efficiency. The liquid chillers using HCFCs or HFCs have shell-and-tube heat exchangers using high-efficiency copper tubes, with sophisticated enhanced surfaces. Spectacular improvements have been achieved with this technology in the past decade. However, copper is not compatible with ammonia, and the traditional carbon steel shell-and-tube ammonia heat exchangers tend to be significantly larger than those used with other refrigerants. They also have a large refrigerant charge, which is not desired with ammonia for safety reasons.

For new applications, this excludes the use of the traditional flooded evaporators or pump-fed in-tube recirculation systems. On the other hand, shell-and-tube D-X evaporators could not be used until recently because miscible oils were not available. This is why new solutions had to be found, implementing new combinations of materials, exchanger technologies (e.g., plate heat exchangers, or high efficiency tubes), new miscible oils, and expansion devices.

#### Materials

With ammonia, the most commonly used material is steel (carbon or stainless steel), but it has a lower thermal conductivity than copper or aluminum. Its toughness also makes it difficult to manufacture high-efficiency heat transfer surfaces required for high performance. Because of this combination of thermal and mechanical properties, steel is not a very good material to manufacture heat transfer surfaces. Carbon steel is also relatively sensitive to corrosion on the water side; there-

fore, its use is not recommended in water-cooled condensers connected to an open cooling tower. It is suitable in closed circuits, but it is penalized by higher fouling factor than copper tubes. Alternatives to carbon steel are:

- Stainless steel has the same qualities and defects as carbon steel, except that it is much more corrosion resistant; therefore, thinner tubes or plates can be used. Stainless steel also requires less fouling factor allowance than carbon steel.
- Titanium is also suitable for ammonia, but its cost is prohibitive for most applications. It is still practically the only solution for sea water-cooled ammonia condensers.
- Aluminum could be attractive because of its compatibility with ammonia, good thermal conductivity, and mechanical compliance for easy manufacturing of high performance tubes; but it is relatively sensitive to corrosion on the water or brine side; therefore, it is not a practical, realistic alternative.

From this, it appears that no really good substitute exists to carbon or stainless steel, to manufacture ammonia heat exchangers. Therefore, the challenge to improve these exchangers has been to optimize the implementation of these traditional materials for ammonia applications. The way it was done is detailed later.

### Exchanger Technologies

#### Shell-and-Tube Heat Exchangers

**Evaporators.** Traditionally, large ammonia systems used pump-fed exchangers with recirculation, or flooded evaporators, which are not acceptable for the new applications because of their high refrigerant charge. The alternatives are shell-and-tubes D-X evaporators, plate heat exchangers, and “hybrid” heat exchangers.

**D-X shell-and-tube evaporators** with ammonia were not used at all until recently because:

- The aforementioned oils problems were not solved.
- The technology of traditional thermo mechanical expansion valves was not well suited, because of the low mass flow required with ammonia. This refrigerant also is especially harmful to the compressors in case of liquid flooding, because of its unusually high specific enthalpy of evaporation. Actually, thermal expansion valves have made great progress, and the technology is now appropriate. For the most difficult cases, electronic expansion valves have also been developed, which provide an excellent control of D-X evaporation.

With these new features, D-X shell-and-tube evaporators are now perfectly suited for use with ammonia, provided the temperature is not too low, and the reliability of the compressors is carefully validated with the new miscible oils. Areas of further investigation are mostly new enhanced tube geometries, which are making progress in spite of the difficulties to manufacture them from a tough material.

**Spray evaporators** are sometimes considered as an alternative. The idea is to keep the geometry and advantages of a flooded evaporator, while reducing the refrigerant charge. Liquid refrigerant is “sprayed” above the tube bundle, to keep the

tubes wet without immersion within a pool of liquid. Tests have been made with this technology, but its cost-effectiveness is questionable.

**Condensers.** Exchange tubes for water-cooled condensers still need to make progress, like for evaporators. Carbon steel is not recommended for condensers with open cooling towers, because of fouling and corrosion on the water side. Stainless steel is preferred, but enhanced surfaces are still expensive to produce, and require relatively thick tubes. Although not very effective, plain stainless steel tubes are relatively inexpensive, and provide an acceptable compromise. Corugated tubes are also an interesting alternative.

### Air-Cooled Condensers

Air-cooled condensers have the disadvantage of generating higher condensing pressures, which result in poor system efficiency. Yet, the demand is growing for air-cooled condensers in general, because of the ease of installation and increasing scarcity of water. As seen earlier, the combination of ammonia with air-cooled condensers also is interesting from a safety standpoint. The state-of-the-art technology uses galvanized steel tubes with aluminium or stainless steel fins. Yet, this technology still makes the condensers significantly more expensive than the copper tubes/aluminium fin technology that is used with HFCs and HCFCs. All-aluminium condensers are also being investigated, and may be a good alternative for the future. The high cost of the air-cooled limits the economical feasibility of large capacity air-cooled ammonia chillers. For large systems, water-cooled condensers associated with cooling towers are normally more cost effective.

Air-cooled condensers are also difficult to implement in hot areas, because ammonia does not “like” high condensing temperatures: the pressure is substantially higher than R-134a, for instance. The use of new generation, higher pressure compressors will help to solve this problem in the future, at least with screw compressors. With reciprocating, the problem of higher discharge temperatures will remain rather than with other refrigerants. Special features must be included to cool the compressors properly, like water cooled cylinder heads or liquid injection.

### Plate Heat Exchangers (PHE)

The use of PHEs in refrigerant circuits requires them to be perfectly leak-tight. Traditionally, PHEs for refrigerants were brazed, but traditional brazing materials are not compatible with ammonia. Technical evolutions were necessary, and have been achieved in the past few years. Two technologies are now available with ammonia nickel brazed exchangers, all stainless steel welded cassettes.

It also has been necessary to improve the resistance to thermal stresses, because of the high discharge temperature into condensers with ammonia, especially with reciprocating compressors. These problems are now solved and good, reliable ammonia PHEs are available for condensers and evaporators as well. PHEs manufacturers are still working to optimize the plates profile for improved performance and pressure drop characteristics.

With PHE evaporators, several possible arrangements exist for expansion devices and feeding systems. The traditional way to implement them is to use gravity fed systems with a surge drum. This requires an extra vessel to be located above the evaporator, which takes more space, and requires a bit more refrigerant. With gravity fed NH<sub>3</sub> systems, miscible oils are not necessarily required, depending on the circuit arrangement.

The gravity fed system can be improved by using ejector recirculation. The idea is to boost the recirculation of liquid refrigerant from the surge drum, using an ejector driven by high pressure liquid from the condenser. The advantages are:

- The flash gas from the expansion takes up space in the evaporator, and reduces the charge of refrigerant.
- The refrigerant side heat transfer is boosted by higher velocity.
- This allows for a very simple expansion device.

Disadvantages of the ejector recirculation system are:

- The possibility of by-passing a limited amount of gas in capacity reduction.
- Less flexibility when large variations of operating conditions can be expected (evaporation and condensation pressures).

Another area of investigation is direct, dry expansion in a PHE evaporator. The use of the heat transfer surface is less efficient, but the surge drum is not needed. This technology requires carefully designed distribution systems to equalize the ammonia flow between the plates. It also requires high performance expansion valves, which usually are electronic for these kinds of applications.

**Plate and Shell Heat Exchangers.** Used for evaporators, this concept combines features of the PHE and flooded evaporator. They are made of cassettes with water inside, immersed in a pool of boiling liquid refrigerant.

## Comparing Shell-and-Tubes and PHEs

### Fouling and Cleaning

In general, a PHE requires less fouling factor allowance than a shell-and-tube heat exchanger, because of the high shear velocity on the water side. If carbon steel tubes are used in an evaporator, then, the fouling factor difference will be even larger between a stainless steel PHE and a carbon steel shell-and-tube.

Cleaning normally is not a problem on a chilled liquid circuit. It is an issue mostly for condensers, especially with open tower condensing water circuits. A significant advantage of shell-and-tube condensers is that they can be cleaned very easily without opening the ammonia circuit; whereas a nickel brazed PHE cannot be cleaned mechanically at all, and a cassette PHE requires complete dismantling, including opening the refrigerant side.

### Performance and Size

In shell-and-tube heat exchangers with “conventional” refrigerants (HCFCs and HFCs), copper tubes with high efficiency enhanced surfaces are systematically used. They cannot be used with ammonia because of material compatibility. Therefore, ammonia and R-22 give relatively similar performance in

shell-and-tube heat exchangers as shown by K.E. Starner,<sup>2</sup> shell-and-tube D-X evaporators can be as good with ammonia as they are with R-22. The situation is different with PHEs, because stainless steel is the usual material irrespective of the refrigerant. With any refrigerant, PHEs inherently have a good efficiency, because of their excellent combination of high shear velocity between plates, with moderate pressure drops.

Due to the excellent thermophysical properties of ammonia, the use of this refrigerant with PHEs gives an outstanding combination, and a PHE can be made quite smaller with ammonia than with other refrigerants. This is why, in practice, most of the PHEs used as evaporators or condensers in refrigeration plants operate with ammonia. Yet, this advantage is at its best only when the exchanger is flooded, with a recirculation drum. Part of the advantage will be lost for PHE used as D-X evaporators, because of the low heat transfer coefficient in the gas-superheating zone.

Therefore, the use of PHEs is a must when the highest possible COP is required. Yet, shell-and-tube exchangers will tend to be more cost-effective when a lower efficiency can be accepted, which still covers a number of applications.

PHEs have the reputation of being more compact, and of enabling a smaller “footprint” packaging. This may have been true, but is now quite questionable with new generation packages including shell-and-tube exchangers, which have substantially reduced in size. The combination of a shell-and-tube condenser with a PHE evaporators could be the most interesting for some applications; but is a little awkward to install, because a vertical PHE evaporator does not fit well within a compact packaging of horizontal cylinders.

### Refrigerant Charge

PHEs had the reputation of having the lowest refrigerant charge. This is also questionable. It may be true when used in direct expansion; but gravity fed systems will give a higher charge. Anyway, the difference between the technologies is not drastic. Other factors are of significant importance such as the piping arrangement, or the rating of the exchangers: an exchanger rated for large temperature differences will have lower size, refrigerant charge... and efficiency.

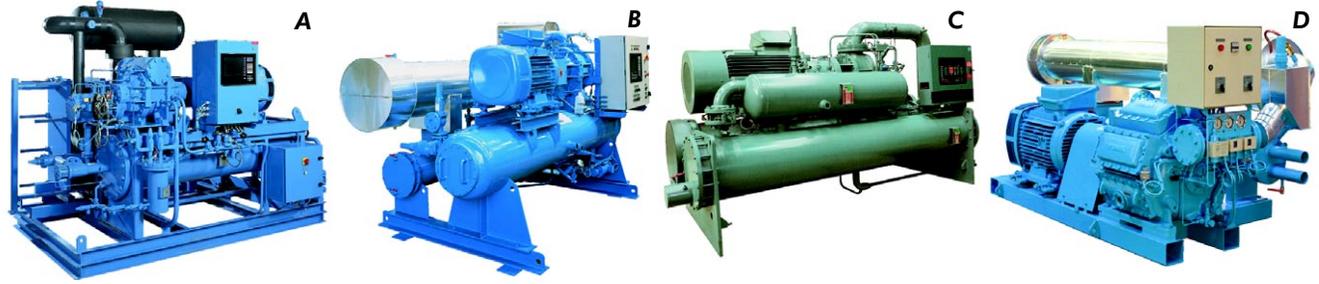
### Low Temperature Applications

As mentioned earlier, D-X evaporators are questionable below  $-20^{\circ}\text{C}$  ( $-4^{\circ}\text{F}$ ), and practically unsuitable below  $-30^{\circ}\text{C}$  ( $-22^{\circ}\text{F}$ ). At lower temperatures, PHEs or “hybrid” heat exchangers must be used, in combination with mineral oils and a carefully designed oil management system.

### Typical Combinations

As seen earlier, typical new generation ammonia products are packaged water and liquid chillers and these new products tend to go lower capacities; they can be air cooled or water cooled. Typical new products on the market mix-match exchanger technologies. When the lowest capital cost is required, a preferred combination is typically:

- Reciprocating compressor (or screw for high capacity).
- Shell-and-tube D-X evaporator.



Type of chiller	A	B	C	D
<b>Compressor</b>	Screw, Variable Vi		Screw, Fixed Vi	Reciprocating
<b>Oil</b>	Non Miscible	Miscible		
<b>Condenser</b>	PHE	Shell-and-Tube, stainless steel		
<b>Evaporator</b>	PHE	Shell-and-Tube D-X, carbon steel		
<b>Feeding System</b>	Recirculation Drum	D-X Expansion		
<b>Expansion</b>	Ejector	Thermomechanical Expansion Valve		
<b>Capacity range @ LWT = 6 C</b>	475/1990 kW	418/1727	470/1760	115/730
<b>@ LWT = 10 C</b>	250/1045 kW	226/842	235/870	53/336

**Table 1: Products implementing these technologies are now available on the market. The table and photos show typical ranges of products.**

- Shell-and-tube condenser if water cooled.
- Miscible oil, which is required with a D-X shell-and-tube evaporator.
- Thermo-mechanical thermal expansion valve.

When a high COP is critical, PHEs are often preferred. Then, miscible oils are not necessarily required. Different types of expansion devices are being proposed, from direct expansion with an electronic expansion valve, to gravity fed systems with a surge drum (with or without a recirculation ejector).

### Conclusions

The growing care for the environment has boosted the demand for ammonia as refrigerant even for air-conditioning applications. This demand was initially driven by the Northern Europe market. However, satisfying the absolute requirements of safety, compact size, low cost, reliability, reduced maintenance was quite challenging.

Only water or brine chillers used in indirect cooling could be considered, because this arrangement minimizes the refrigerant charge. Each of the individual components had to be optimized: exchangers, compressors, lubrication, expansion devices. Then, consistent combinations of all these improvements were implemented. The result is a new generation of standardized medium capacity NH<sub>3</sub> chillers. They can be used for water and brine cooling, for air-conditioning and industrial applications. Hun-

dreds are now in operation, with an excellent record of safety and reliability.

This confirms that ammonia is now a fully satisfactory alternative refrigerant. This in turn is inducing a growing market acceptance and demand. Already, signs of this “green” wave for refrigerants are visible from Northern Europe down to Southern Europe. Worldwide might be the next place to go...

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