Design and Operating Experience of Large Ammonia Systems with Small Refrigerant Charge

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Ammonia has been in use as a refrigerant since 1859 when the absorption process was developed by the Carré brothers in France. It was first used in the United States during the Civil War in 1863, when four absorption ice makers were smuggled through Union blockades via Mexico and installed in the Southern States; the first being a 200kg (440lb) per day machine constructed in Augusta, Georgia. Almost a decade later, David Boyle, born in Johnstone, Scotland, installed the world's first ammonia refrigeration compressor, in Jefferson, Texas. This pre-dates Carl von Linde, who at that time recognised the potential of vapour compression systems, but was experimenting with methyl ether. He switched to ammonia in 1876, applying a scientific rigour to the compressor and system design, and achieved new levels of success with his new design which was licensed to Augsbourg (Germany), Sulzer (Switzerland), Carels (Belgium), Morton & Burton (Great Britain) and Fred Wolf (USA). Within ten years, many more ammonia compressor manufacturers were active on both sides of the Atlantic, including De La Vergne, Frick, Vilter and York in the USA and Sterne in Great Britain. Ammonia refrigeration quickly became the preferred technique for brine chilling and ice making for brewing, meat-packing, cold storage and ice-skating rinks.

Since these early beginnings there have been many developments in refrigeration; some weakening ammonia's dominant position and others strengthening it. From an initial position of common technology, the industries in Europe and the United States have diverged, so it is not surprising to find that, one hundred and fifty years after the Carrés' first absorption system, there are considerable differences in technologies, attitudes and legislation. In Europe from 1950 to 1980, ammonia in industrial refrigeration was almost completely superseded by CFCs and HCFCs. Latterly these systems tended to be large pumped R-22 systems, or smaller packaged R-502 plants using direct expansion or the pumpless "low pressure receiver" system. Ammonia was only retained in very old plant, or where there was a strong tradition of its use, backed with appropriate local expertise, for example in breweries. Most cold stores and food factories, and all ice rinks built in the period 1970 to 1990 in the United Kingdom used halocarbons (principally R-22). Water chillers for air conditioning of buildings were almost exclusively halocarbon based; mainly R-12 centrifugal chillers for larger capacities and R-12 or R-22 chillers with multiple semi-hermetic reciprocating compressors in the smaller sizes. In other parts of Europe the extent of the change varied; central Europe retained more ammonia plant, but France, for example, enacted much tighter requirements. These dictate that any system containing more than 150kg ammonia must comply with rules on plant location relative to neighbouring buildings, and must be subject to local authority registration and technical oversight. Since small systems, with less than 150kg charge, are the ones most suited to R-22, this greatly restricted the ammonia refrigeration industry in France.

In the United States, the air conditioning market was more advanced and used many R-11 centrifugal chillers, as well as R-12. The industrial sector was treated as a niche within a much larger market, and opted to continue to use ammonia in very traditional ways. These include large, site installed systems comprising two or more temperature levels, with ammonia held in large receivers and pumped to freezers, cold stores and process users. It is estimated that there are about 2,000 facilities in the United States of America with an ammonia charge exceeding 10,000lbs (4,546kg), which is the threshold for registration of the installation with the Occupational Safety and Health Administration (OSHA). The largest of these plants contains over 400,000lbs (over 180,000kg) of refrigerant.

The consequences of CFC phase out

The divergence of the European and American markets for refrigeration and air-conditioning had a profound effect on their respective responses to the initial reports of ozone depletion. In the US legislation was enacted as early as 1977 limiting the use of CFCs in aerosol, rightly regarded as "total loss systems," but no moves were made against air conditioning, and in particular car air-conditioning. At that time car a/c was effectively also a total loss system as no attempt was made to recover refrigerant during vehicle servicing. In contrast in Europe, and particularly Northern Europe, aerosols were not targetted until much later, but the refrigeration and air-conditioning market was more tightly controlled at a much earlier stage. When the Montreal Protocol was first ratified in 1986, the European Community led the campaign for stricter controls. The protocol originally sought to reduce CFC production to 50% of base (1986) levels, but the EU proposed tighter limits and a complete phase-out long before this was established as the internationally agreed stance.

It was therefore clear that the commercial and industrial refrigeration industry in Europe, which had come to depend on R-12 and R-502 would need to find alternatives. HFCs like R-134a filled the gap in the commercial market, and for a long time R-22 was promoted as "part of the solution, not part of the problem." However it eventually became clear, with increased concern about global warming, that R-22's days were also numbered, and that this would come sooner rather than later in Europe.

HFCs were fundamentally unsuitable for larger industrial systems. They were relatively expensive, so that for the first

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time in the history of refrigeration the charge of an industrial plant would represent a significant proportion of the total capital investment in the plant. HFCs required the use of new lubricants, none of which was really suitable for use in a large system. They also seemed somehow to be more prone to leakage than their predecessors. In a short time, ammonia was "rediscovered" in Europe, and adopted with enthusiasm by the industrial market. However end-users were unfamiliar with ammonia, and service technicians were more used to "fully automatic" halocarbon plants, with automatic air purgers and oil return. It was not possible to return to the traditional ammonia systems, as were still being installed in the USA, and therefore European contractors developed new techniques. These included the use of ammonia in packaged chillers with low charge evaporators and the adaptation of the CFC-based low pressure receiver system to make it suitable for ammonia.

The influence of heat exchanger type on chiller system charge

Traditional water and glycol chillers use a shell and tube evaporator. For dry expansion operation the refrigerant is inside the tubes, but most ammonia chillers operate "flooded," with the water or glycol in the tubes and the ammonia liquid on the shell side. There are several advantages to this arrangement, but it results in a large ammonia charge relative to the cooling capacity. When air-cooled or evaporative condensers are used they also contain a significant quantity of liquid refrigerant, and so a traditional style of chiller, with flooded shell and tube evaporator and direct condenser, may contain as much as 1kg/kW (7.7lb/TR). If the liquid level in the flooded chiller is controlled ("low side float system") and a high pressure receiver is fitted, then the specific charge could rise to 1.5kg/kW (11.6lb/TR). Several alternative types of heat exchanger can reduce these figures. The most common is the plate heat exchanger, where thin corrugated sheets, usually of stainless steel, are compressed between thick steel endplates in a supporting frame. These exchangers were originally developed for liquid/liquid heat exchange in process industries, but required minimal adaptation for use as evaporators or condensers. Smaller units can be nickel brazed or even copper electro-tinned for use with ammonia, but above about 100kW (30TR) capacity the plate and frame configuration is necessary. In a standard gravity-fed system the plates and wet suction riser are nearly full of ammonia liquid, with gas bubbles rising through it. In the worst case, the specific charge of a gravity fed plate heat exchanger will not be much less than for a shell and tube even though the internal volume of the plate pack is relatively small. However if the plates are operated with a dry, or nearly dry suction line then the specific charge is likely to reduce to about 0.5kg/kW (3.9lb/TR) with a direct condenser (air-cooled or evaporative). If a plate condenser is also used, in conjunction with a cooling tower or dry air cooler, then the specific ammonia charge can easily be reduced to 0.1kg/kW (0.8lb/TR). Chillers of this type are used in very large sizes; up to 10MW (2,850TR) for mine cooling in South Africa; and have been applied for large cooling projects in public buildings such as Heathrow Terminal 5 and Oslo's Gardermoen airport.

There are several ways in which "nearly dry" operation of the plate evaporator can be achieved, including using a thermostatic or electronic expansion valve to control suction superheat or using a low pressure receiver vessel with "high side float" control. There are several types of packages now on the market using superheat control, but there is always a risk of liquid carryover to the compressor if a suction pot is not fitted, particularly under rapidly varying load conditions. The low pressure receiver system is "critically charged" and excess charge cannot get back to the compressor. It offers the efficiency and reliability of the gravity flooded system, but the receiver can be positioned anywhere relative to the evaporator, offering greater flexibility in packaged chiller design.

The plate and shell heat exchanger is a variant of plate heat exchanger suited for applications with high pressure on the secondary side. This comprises a stack of circular corrugated plates, laser welded on the seams and compressed into a steel shell. It gives a very compact arrangement, but unlike the plate-in-frame exchanger, it is not so easy to strip for cleaning. If a low charge evaporator is required, but cleaning of the secondary side is essential then a spray chiller should be considered. This is a shell and tube vessel, but with a pump feeding liquid to a sparge pipe above the tube bundle. The shell contains almost no liquid, but the tube surfaces are fully wetted, giving efficient operation across a wide range of capacities. There is virtually no risk of liquid carryover under any circumstances.

Extruded or fabricated "microchannel" heat exchangers have been developed for refrigeration applications, particularly as evaporators for carbon dioxide systems and condensers for R-134a chillers. To date these novel heat exchangers have not been applied to ammonia chillers, but the prospect is very appealing, as it should be possible to achieve the specific charge ratio of a plate to plate chiller without the penalty of a condenser water circuit on the heat rejection side of the chiller. One possible difficulty in the use of microchannel condensers with ammonia would be the behaviour of immiscible oil in the condenser, where the refrigerant passages are typically less than 1mm diameter. Another concern is the corrosion resistance of these all-aluminium heat exchangers as the expectation for operating life of ammonia equipment is generally longer than for commercial chillers.

In air cooler applications, such as cold storage and freezing, a recent development has been the use of an internal enhancement to improve the wetting of the inner surface of the tube. This effect is important for direct expansion evaporators and those in low pressure receiver systems, and it becomes increasingly significant as the operating temperature is lowered. In chill applications there is no difficulty in establishing wavy or annular flow in the cooler tubes, but in cold stores and blast or spiral freezers, where the mass flux is low compared to the volume flow, the flow regime is almost always stratified, and typically only 10–20% of the tube surface is wetted. Coupled with the use of aluminium tubes this arrangement can offer a significant improvement in system efficiency, of the order of 10%, while reducing the amount of liquid ammonia held in the evaporator during operation. Superheat control through thermostatic expansion valves is not preferred for ammonia air coolers because of the risk of leakage at the valve, and because prolonged operation with ammonia can cause valve seat erosion (wire drawing), leading to erratic and unreliable operation. Problems can also be caused on a large system if several DX coolers are defrosted together, particularly with large volumes of liquid returning in the supposedly "dry" suction at the end of defrost. The use of the enhanced aluminium coolers together with the low pressure receiver system eliminates these problems.

Minimum charge vs optimum charge chillers

In the early 1990's, as the European refrigeration industry looked to apply ammonia to water chillers for building services, there was a spate of development of so-called "minimum charge" chillers. The objective was to encourage operators previously unfamiliar with ammonia to use it in large chiller systems where the fluorocarbon alternatives were unacceptable. Most of these designs used plate heat exchangers as evaporator and condenser, but every other component in the system was also analysed and modified where possible to reduce the unit charge. A typical configuration used a gravity feed arrangement for the evaporator, but with the level controlled in the drop leg rather than in the receiver. The high pressure liquid from the condenser was expanded through an ejector into the plate inlet. The overfeed from the plates was fed to the side port of the ejector, creating a slight suction which was sufficient to overcome the pressure loss through the plates and induce flow from the receiver back to the plate inlet. There was no high pressure receiver on the unit; the low side receiver was sufficient to carry the total unit charge. With this arrangement it was possible to achieve a specific charge as low as 0.025kg/kW (0.2lb/TR), resulting in a charge of only 25kg (55lb) in a 1000kW (285TR) unit. However this type of unit attracted some criticism for several reasons. If there was any leak of ammonia, no matter how slight, the performance of the unit would be adversely affected. This would either cause the efficiency to be impaired, or it would require immediate attention from a technician to trace and fix the leak. As there was no high pressure receiver, if the expansion valve was controlled by a float on the low pressure side of the system then any excess charge in the plant would tend to back up into the plate type condenser. This would cause the unit to run inefficiently with a high discharge pressure. The idea of a unit in which the efficiency was so tightly dependent on achieving and maintaining exactly the right charge did not find favour with plant operators. Instead the concept of "optimum charge" was developed. It was recognised that it was not sensible to make the ammonia charge absolutely as low as it could be if this had adverse effects on reliability or efficiency. The optimum charge was that which was as low as it could be without risking gross inefficiency if a small amount of charge was lost. The low pressure receiver system described above achieved this goal. In normal operation there is a slight overfeed from the plates, typically 3–5% in a water chiller. This is collected in the low pressure receiver, where it is evaporated by subcooling the liquid feed from the condenser. If the unit is under-charged then the flow through the plates evaporates to dryness, and there is no overfed liquid available for sub-cooling. This gives a clear and easily recorded signal that the unit is undercharged, but has no significant effect on efficiency until a greater quantity of refrigerant has been lost. If the system is overcharged, the excess will lie in the low pressure receiver, and has no effect on efficiency or reliability unless the overcharge is so excessive that the receiver fills up and liquid returns to the compressor. In practice this requires so much additional refrigerant that it is highly unlikely. Optimum charge systems have become very common, and a benchmark specific charge of 0.1kg/kW (0.8lb/TR) seems to be generally accepted as a sensible target. A large system with plate evaporators and condensers was installed for Roche Pharmaceuticals at Welwyn Garden City in England. There are three water chillers, each of 2,500kW (720TR), which each required 238kg (524lb) ammonia at commissioning. It was stipulated in the specification that the charge was to be less than 250kg (550lb) per chiller. The use of low pressure receivers and plate heat exchangers has now been extended to a standard range of packaged water chillers with two compact screw compressors and capacities in the range 200kW to 800kW. These air cooled chillers are designed for outdoor location, with the control panel, compressors, oil system, receiver and evaporator incorporated within the body of the condenser which comprises two vertical coils and a fan deck.

Optimum charge in cold stores and freezers

The low pressure receiver, originally developed to provide compact packaged units using R-502 for cold stores, is also now used for ammonia plants. Initially it was thought that the very high latent heat of ammonia made it fundamentally unsuitable for this type of system. However careful design of some key components and attention to detail in installation have proved that such systems can be engineered to be cost effective in capital and revenue terms. Such systems on ammonia have been built in the United Kingdom since 1988, and over this twenty year period some significant development refinements have been introduced. The high latent heat means that the overfeed ratio in an ammonia low pressure receiver system is less than it would be in an equivalent R-502 system. As a result it is more difficult to ensure even distribution between evaporators and between individual tubes in an evaporator. However, using special distributors with careful design of evaporator circuits and enhanced aluminium coolers, good results can be achieved.

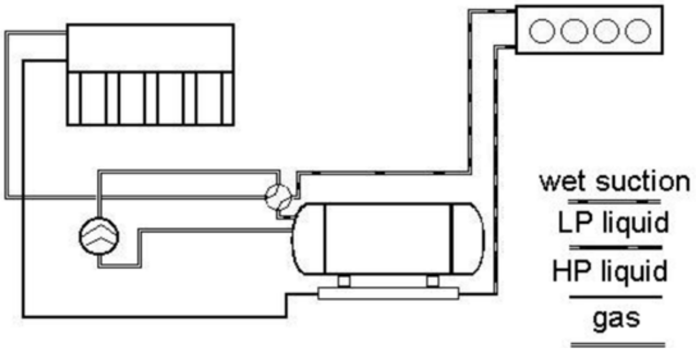

Figure 1 – Low charge low pressure receiver system for air cooling

The low refrigerant charge in the low pressure receiver system is the result of a combination of several factors. The receiver only contains gas in normal operation, provided the plant is charged correctly. The liquid line from the condenser to the plantroom is full of liquid, but it is usually short and like all ammonia liquid lines is small diameter. The expansion valves are mounted on the receiver package, which is usually located in the compressor plantroom, so the liquid line from the package to the evaporators contains a mixture of flash gas and liquid in the form of froth. The coolers typically contain a smaller amount of liquid than in a pumped circulation system, and the wet suction line, if the plant is charged correctly will carry about 10% liquid by mass (about 1% by volume). There is no high pressure receiver at the condenser outlet, and the system charge can be held in the low pressure receiver for maintenance. An ancillary glycol circuit is provided in the evaporative condenser to provide a simple but effective method of oil cooling, and automatic air purging is achieved with a small liquid pot at the condenser outlet which doubles as the high pressure float control chamber. Oil is returned automatically from the low pressure receiver to the compressor.

The result of these measures is best illustrated by reference to a typical installation. This case study is a composite distribution centre built in 2001. The centre provides distribution facilities for chilled and frozen produce to supermarket stores in the south-east of England, and comprises four temperature controlled chambers. The largest of these is 123m (410ft) at its widest point and 120m (400ft) long, and is held at +2°C(36°F). There are two smaller chill chambers, one at –1 °C (30°F) and one at +10°C (50°F). They are both 65m (215ft) wide and are 45m (158ft) and 75m (258ft) long respectively. All the chill ceilings are at 7m (23ft) and the total chill duty is 2600kW (750TR). The cold store is 110m (365ft) long and 80m (264ft) wide and has an 11m (36ft) ceiling. It is held at –25°C (–13°F) and has a calculated duty of 1150kW (330TR).

The cold store is served by three low pressure receiver systems, each with a Howden WRVi 255 compressor and evaporative condenser sized to meet one third of the plant capacity. The ammonia charge in each of these systems is 300kg (660lb), making less than one tonne charge for the total cold store, which has a volume of just less than 100,000m3 (3.5 million cubic feet). The chill chambers are fed with a chilled glycol system, again with three independent packs. Each pack has a low pressure receiver and plate heat exchanger, connected to two Howden WRV204 compressors and an evaporative condenser. The charge of each glycol chiller is 250kg (550lb). Thus the maximum charge in any single section of this large distribution centre is 300kg (660lb), and the total plant ammonia inventory is 1,650kg (3,600lb).

It is estimated that the equivalent pumped ammonia system comprising booster and high stage compressors, low stage pump set, intercooler, evaporative condensers and high pressure receiver would contain about 14,000kg (31,000lb) owing to the long liquid lines, large number of evaporators and size of suction accumulator and intercooler. In the United States market, the central plant system would be subject to the full requirements for hazard analysis and risk management under the OSHA regulations which have a lower threshold of 4,545kg (10,000lb). The low charge system however, would be within the limits by a factor of three, even when the total charge of all the systems on site is considered.

Options for larger industrial systems

Not all installations are suitable for the direct ammonia low pressure receiver system described above. Where there are a large number of chambers, where liquid distribution is expected to be difficult or simply where there are too many evaporators to suit the low pressure receiver then a central plant approach is preferred. It is still possible to achieve low charge by using ammonia in conjunction with another fluid. Traditionally for chill plant this would be ethylene or propylene glycol, and more recently in Europe for low temperature plant other salt solutions including potassium formate and potassium acetate have been introduced. However it has been recognised that additional benefits can be obtained by using carbon dioxide together with ammonia. In chill systems the carbon dioxide is used as a "volatile secondary" refrigerant, pumped at high pressure to the heat load, evaporated and returned to the condenser at a nominally steady temperature. For lower temperature applications, particularly in freezer plant, the carbon dioxide from the evaporator is compressed to a suitable high pressure before returning to the condenser.

This technique has been used over the last ten years in cold stores, distribution warehouses, plate freezer plants, blast freezer plants, tunnel freezers and spiral freezers. Four distribution centres similar in size and style to the plant described above have been completed in the United Kingdom. In comparison with the previous case study, the ammonia refrigerant charge is reduced by about 40%. Each system comprised a central pumped carbon dioxide system, feeding refrigerant at –5°C (23°F) to the chill areas and at –31°C (–24°F) to the low temperature cold store. The carbon dioxide is condensed in cascade with two independent ammonia systems to provide resilience in the event of a major ammonia system failure. Each ammonia system has a charge of approximately 500kg (1,100lbs) giving a total ammonia content of 1 tonne (2,200lbs).

Similar systems have been installed for blast and plate freezing. The specific ammonia charge in all cases is approximately 0.3kg/kW (2.4lb/TR) but this could be reduced significantly by using plate and shell ammonia condensers and cooling towers for the heat rejection, probably offering the same specific charge as the plate-plate water chillers of 0.1kg/kW (0.77lb/TR). On this basis the maximum refrigeration capacity of a system falling below the United States OSHA threshold of 10,000lbs (4,546kg) would be 128,000 TR (36 MW). The French threshold of 150kg would allow installation of a 500kW (150TR) system without any government restrictions on location, and 5 MW (1,500TR) without application of the stricter controls for ammonia systems.

Future possibilities

It is unlikely that current regulations governing the use of ammonia in industrial refrigeration plants will be relaxed in the near future. Possible exceptions are in France and Italy, where regulations might be brought more in line with the rest of Europe to gain benefit from the superior efficiency possible with industrial ammonia systems; however, even this small step is improbable. It is much more likely that the requirements for safety systems, personal protection and the associated documentation will become stricter. One example of this type of legislation is the recent introduction in the US of "Homeland Security" legislation requiring end-users to safeguard their installations against criminal or terrorist activity. At the same time construction standards will become more international. This has already happened in Europe where EN 378, *Refrigerating Systems and Heat Pumps—Safety and Environmental Requirements* has replaced the old national standards such as BS4434. It is possible that the international standard ISO 5149 will in the near future replace EN378 and ASHRAE 15. There is also the prospect of the introduction of more rigorous building code requirements associated with the use of ammonia. In this case the argument for low charge ammonia systems becomes very simple. If it is possible to avoid much of the difficulty and expense of designing and operating systems with large tonnage charges, then the market in the US will probably follow the Europeans down the low charge route, either with pumpless low pressure receiver systems, or with carbon dioxide/ammonia cascades. It is important to note that the very success of these new systems could be the trigger which initiates legislative moves against large ammonia charges. However on a more positive note, the market in Britain has embraced the low charge concept because it is inherently simpler, easier and therefore safer, and because when used appropriately it need not be any more expensive to install or to operate. There is no legal requirement for specific risk management measures, offsite consequence analysis or process safety management in Britain, provided the charge is less than 30 tonnes (66,000lbs), so the preference for low charge systems in Britain, and to an extent in the rest of Europe, would seem to be driven by economic and ease-of-use considerations, not legal restrictions.

Conclusion

It is possible to achieve significant reductions in ammonia charge in chillers and industrial systems through the adoption of a range of strategies. These do not carry any significant penalty in capital cost, although they place some constraints on the ways in which the system can be configured. Experience in the United Kingdom engineering these systems over the last twenty years demonstrates clearly that the charge reductions can be achieved provided there is a willingness to accept the constraints and modify traditional attitudes to system design. The energy efficiency of these systems is, on paper, no worse than traditional pumped circulation systems and in practice the use of reverse cycle defrost eliminates much of the additional energy penalty inherent in large pumped circulation systems, enabling these systems to achieve excellent energy consumption figures.

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